Application of Modal Analysis using Adaptive Schemes of Interference Cancellation for Power Line Carrier Communication Systems

VICTORIA UNIVERSITY OF TECHNOLOGY

Iqbal Gondal

B. E. (Pak.), M. E. (Aus.), AMIEE (UK), MIEEE (USA), MPEC (Pak.)

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I dedicate my work to my mother

"*Rehmat Bibi*".

Her soul was a great inspiration for the

completion of this work

SYNOPSIS

With the increasing complexities of power system control, protection, operation and SCADA, there is a need to have a very reliable telecommunication network to provide data transmission in steady state and transient conditions of the system. Integrity of the data should be verified with the use of different back-up communication systems eg. microwave, power line carrier (PLC), fibre optic and private telecommunication networks etc. PLC is a very convenient back-up and is available at a very low cost, as it uses the same line for power transmission and PLC signal propagation. Due to the presence of ehv signal on the line, PLC equipment eg. line trap shows inefficient behaviour in providing appropriate attenuation to the PLC signal at busbars. As a result, leakage signal interferes with the PLC signal on adjacent line sections, operating at the same frequencies, which ultimately limits the utility of the available PLC spectrum. In this thesis, adaptive interference cancellation schemes based on adaptive identification, fuzzy logic and artificial neural network theories have been implemented on PLC systems. Studies of these cancellation schemes were also extended on a laboratory model of power line, which was designed based on Modal Analysis. The development of these techniques can help in providing extra attenuation to the PLC signal at the busbars and hence the power industry could use the same frequencies on adjacent line sections to make the maximum use of PLC for the power system utilities.

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LIST OF ABBREVIATIONS

ACSR	Aluminium Conductor Steal Reinforced
ACPIC	Adaptive Cross-Polarisation Interference Cancellation scheme
A/D	Analogue to Digital Converter
AFLIC	Adaptive Fuzzy Logic based Interference Canceller
AMDSB-SC	Double Side Band Amplitude Modulation with Suppress Carrier
AMSSB	Single side band amplitude modulation
ANN	Artificial Neural Network
ANNIC	Artificial Neural Network Interference Canceller
ATP6	Alternative Transient Program version 6
BTF	Breaking Terminal Fault
C	Shunt capacitance of line
CC	Coupling capacitors
cm	Centimetres
COG	Centre Of Gravity (defuzzification method)
dB	Deci Bell
D	Diagonal matrix
D/A	Digital to Analogue Converter
DMA	Direct Memory Access
DR	Drain coil
DSP	Digital Signal Processing
DS-SSMA	Direct-Sequence Spread-Spectrum Multiple-Access
e	Earth
ehv	Extra high voltage
ERR	Crisp input for fuzzy logic tuner for canceller
EV	Expected Value
f	Centre frequency of PLC signal to calculate the parameters of system
FDM	Frequency division multiplexing
FLBIC	Fuzzy Logic Based Interference Canceller

FLC	Fuzzy Logic Controller
FM	Fuzzy Mean (defuzzification method)
γ	Propagation constant
γ^2	Eigen values of ZY
GVA	Gega Volt Ampere
HF	High Frequency
HPF	High Pass Filter (Coupling Capacitor)
Hz	Hertz
I_c	Modal values of current on the line
I_r	Receiving end current on the line
I_r^c	Modal values of current at receiving end
I_s	Sending end current on the line
I_s^c	Modal values of current at sending end
I/O	Input and Output
J	Performance Index
km	Kilometre
kV	Kilo Volts
LA	Learning Automata
LAN	Local Area Network
LCR	Inductance, Capacitance and Resistance
msec	milli second
mu	Average inter-channel mismatch correlation coefficient
MATLAB	Computing environment for high performance numeric computing and visualisation
MATRIXx	Computing environment for high performance numeric computing and visualisation
mH	Milli Henry
Ω	Ohms
P_k	Internal state matrix for RLS and SA methods
PA	Perturbation Analysis
PCM	Pulse Code Modulation
PLC	Power Line Carrier

PLS	Recursive Partial least Squares regression
PN	Pseudo Noise
PSS	Power System Stabiliser
Q	Current Eigen vector
QAM	Quadrature Amplitude Modulation
R+jL	Series impedance of the line
RF	Radio Frequency
RLS	Recursive Least Square
Rx	Receiver terminal
S	Voltage Eigen vector matrix
SA	Stochastic Approximation
SCADA	Supervisory control and data acquisition
STARIMA	Space-time Autoregressive Integrated Average
$\hat{\theta}_k$	Estimated parameters of line trap
t	Time for simulation
T	Pulse repetition interval
TNA	Transient Network Analysers
TRV	Transient Recovery Voltage
Tx	Transmitter terminal
U	Crisp output from fuzzy logic block for canceller
u_1,u_2	PLC signal for canceller
uF	Micro Farad
UT	Crisp output from fuzzy logic tuner for canceller
VF	Voice Frequency
V_c	Modal values of voltage signal
V_{can}	Leakage signal after cancellation
V_{CCL}	Estimated PLC signal leakage by cancellers
V_g	PLC signal generated with the use of MATLAB "sine wave or random signal"
V_r	PLC signal at receiving end
V_{rl}	Leakage signal at receiving end
V_r^c	Modal values of receiving end voltage

V_s	PLC signal at sending end
V_{s1}	Leakage signal at sending end
V_s^c	Modal values of voltage signal at sending end
V_{s1}^c	Modal values of leakage signal at send end
V_{s1t}	Estimates of signal leakage for kth value
XPIC	Cross-Polarisation Interference Canceller
W	Watts
WFM	Weighted Fuzzy Mean (defuzzification method)
X_k	Input and output state vector
Y	Admittance matrix of transmission line
y_1,y_2	Leakage signal values for canceller
Z	Impedance matrix of transmission line
Z^c	Characteristics impedance
Z_{LT}	Line trap impedance
Z_o	Surge Impedance

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CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

1.1 INTRODUCTION

Power line carrier (PLC) is widely used for the communication of RF signals over high voltage lines. The rapid development over the last few decades of power lines for long distance transmission has caused an increasing demand for PLC facilities [1]. PLC is applied to power lines for providing voice communication and many other vital services viz.

* protective relaying
* telemetering
* load-frequency control
* supervisory control
* fault location.

The power lines are very robust and use large conductors with generous spacing. It also provides reliable and low-attenuation path for carrier-current signals. Frequencies in the range of 30-300 kHz are commonly utilised in PLC. This frequency band is high enough to be isolated from the power frequency and associated noise, yet not so high enough so as to encounter excessive attenuation. Although it has been suggested [2] that frequencies somewhat lower than 30 kHz can be used, however it is difficult to couple them efficiently to the line by using coupling capacitors.

PLC is known to be more secure than microwave based lines and is as reliable as the transmission lines. Economically, the cost of PLC is reasonable as transmission lines house PLC and also its source of power supply. Due to the robust nature of the power lines it can be readily used as a path for carrier signals. The constructions of transmission towers are such that they can withstand natural hazards like sleet, snow, wind, floods etc. On many instances, under fault inception a power line is incapable of carrying power, but still has enough insulation for relatively low carrier voltage to provide reliable carrier operation.

A PLC system consists of three parts:

* terminal assemblies--comprising of transmitters, receivers and associated components
* coupling and tuning equipment
* high voltage system--which provides a suitable path for transmission of the high frequency energy between terminals.

Transmitters and/or receivers are required at terminals. Terminal equipment is usually the same and is independent of line length except for variations in transmitters output ≅10-100 W. Coupling to power line conductors is accomplished by using coupling capacitors. This is performed to conduct the carrier signal and blocking power frequency. In order to minimise the reactive loss at the frequency band centre, line towers are used. High voltage coupling capacitors must withstand many times the rated line voltage (≈400 kV). Line traps minimise the loss of carrier power and direct the signals over the line section. This involves large dimensions and very high manufacturing costs [3].

Lack of sufficient spectra is being recognised by many power utilities as a serious limitation to the future growth of PLC communications systems. In fact, spectrum usage has increased to the extent that additional channels are no longer possible. There is a wastage of spectral resources because of the manner in which interference between channels operating in the same frequency band is avoided [8].

1.2 BACKGROUND

In a typical application, several independent PLC channels can be in use on each line section of modern power network. As the line sections are joined at sub-station buses, there is bound to be interference between PLC signals. Isolation between channels at the same frequency is difficult to achieve. Normally 15-20 dB cross-bus attenuation is provided over the coupling bandwidth using reasonable size line traps. Conventionally "bus grounding" techniques, providing good levels of isolation are used. However, this requires several line traps and coupling capacitors, which is at a considerable high manufacturing cost. Isolation is usually achieved by limiting the reuse of a carrier frequency to every third line section. This gives advantage of propagation losses, which attenuates interfering signals in the same frequency band. The efficiency of frequency is thus reduced to one-third.

Naredo et al. [9] in their paper have examined some widely accepted coupling recommendations for PLC systems, which do not prevent modal cancellation. It is shown that computer system programs for calculating line frequency response may fail to detect modal cancellation conditions. A method of PLC system design for multi-transposed horizontal and delta transmission lines is proposed. A technique that makes use of shunt capacitors connected to a few points along the line is also discussed. The risk of modal cancellation is decreased and, in some cases, it can be eliminated. Evaluation of the electromagnetic field generated by a digital transmission system on multi-conductor PLC channels is presented by Cristina et al. [10]. In this reference it stated that the vertical component of the electric field and the horizontal component of the magnetic field are defined by approximate formulae of varying accuracy, depending on the frequency and the distance from phase conductors. Field sources are the currents travelling along the line, which are evaluated by means of an accurate simulation model of the transmission system and rigorous wave propagation algorithm. Frequency spectra and lateral profiles of the field components are computed for single-phase and two-phase couplings of a horizontal power line. Digital channel capacity is shown to increase as the pulse repetition interval (T) decreases. However, if T increases, the harmonic content of the input signal code increases and consequently, electromagnetic pollution rises for a given carrier channel. It is concluded that the electromagnetic interference level is an important constraint which must be taken into account when choosing T and more generally, in the design of the digital transmission system.

The effect of inter-channel mismatch on adaptive array interference cancellation for an arbitrary number of channels and arbitrary bandwidth waveforms for a particular adaptive array used in a multiple side-lobe canceller is analysed by Nitzberg [11]. A general equation giving the residue power as a function of the inter-channel mismatch, the radar bandwidth, and the array parameters is derived. To aid in clarifying the dependence of cancellation on inter-channel errors, a Tylor series expansion is obtained. It shows that the ratio of adapted power to the unadapted main power is greater than 1 mu (where mu is the average inter channel mismatch correlation coefficient) for all interference locations, power levels and any number of auxiliary antennas. The special simple geometry case of narrow band orthogonal direction is evaluated. For this case, the ratio of adapted to unadapted power is approximately equal to 1 mu. Graupe et al. [12] has described an approach for adaptive noise cancellation, which is based on adaptive control principles. The approach aims at creating a physical noise-reduced environment in the vicinity of noisy machinery, for a stochastic machine noise. The system described uses a single microphone, in contrast to previously described two-microphone systems. Computed results on two types of recorded industrial noise are presented to support the theoretical design.

Traditional approaches to the design and operation of HF (high frequency) systems have involved the specification of fixed parameters such as transmitter power, modulation format, data rate, etc. This is, however, sub-optimal for the HF band, which exhibits a time-varying channel capacity due to multi-path propagation, dispersion, fading and high levels of co-channel interference. These conditions often result in a considerable mismatch between available and desired channel capacities. Ideally, therefore, a system should be capable of adapting rapidly to changes in prevailing channel conditions. A number of adaptive communication systems have been designed which operate on 'traditional lines', ie. using a procedural approach by Chesmore [13]. The paper is essentially a discussion paper describing an alternative non-procedural approach exploiting knowledge-based techniques. The remainder of the paper introduces this approach and proposes radio system architectures for its implementation.

Amore et al. [14] have examined the possibility of transmitting digital signals on PLC channels. An accurate model of multi-conductor transmission line is used. A computer aided procedure is presented to evaluate channel transient response to any input digital signal code. The discrete convolution method uses the inverse Fourier Transforms of channel frequency response in amplitude and phase. The eye diagram approach [21] permits evaluation of channel performance. The "eye diagram" approach is employed to determine whether the numerical transmission is made with or without errors. A method is indicated for increasing channel capacity using an equalising circuit. Transmission can be made roughly sensitive to the terminal impedances of the transmission lines.

The proposed design criteria are applied to the study of a digital signal transmission on 400 kV three-phase PLC channels. Kohno et al. [15] proposed and investigated an adaptive canceller of inter-symbol and co-channel interference in a direct-sequence spread-spectrum multiple-access (DS-SSMA) system. This uses channel distortion and cross-correlation among pseudo noise (PN) sequences assigned to individual users. The use of DS-SSMA has been investigated to implement a local area network (LAN) by using a power line installed in a building wall, for which this approach had some advantages. The canceller is needed because the restricted transmission bandwidth of a power line makes it difficult to suppress co-channel interference. Since the canceller is adaptive, it can facilitate synchronisation and increase the simultaneous users in a channel with the restricted processing gain such as a power line. The error probability of the canceller is theoretically calculated for the steady-state case using a Markov model [15]. In this paper it is shown that computer simulation illustrates stable convergence properties.

Basic probabilities of the influences of induction between a power line and a parallel communication line are described by Horak et al. [16]. Corresponding magnitudes of short circuit currents in the case of one sided feeding are determined. The probability of occurrence of induced longitudinal voltage is analysed in connection with the cited CIGRE report [17]. The calculations are performed under certain simplified initial conditions including the analysis of the magnitude of the longitudinal voltage. This uses mathematical simulation with the application of the Monte-Carlo method, however, not as yet respecting the safety regulations and economical aspects. The report contains results of experimental studies of high frequency (HF) paths for a transposed ac 1150 kV power line. The attenuation and input impedance of paths with various couplings including the phase and earth wire couplings of a bundled earth wire with insulated components (an intra wire path) are investigated by Ishkin et al. [17]. A cross-talk attenuation between different paths and the influence of a three-phase-to-ground short-circuit on phase paths attenuation are investigated.

IEC recommendation 353 for line traps presumes that lightning over-voltages constitute the highest dielectric stresses. Morf et al. [18] described how, line trap insulation has to withstand these dielectric stresses. Tests performed in switching stations, however, have shown that the transient phenomena caused by disconnectors in networks with high system voltages subject line traps to even higher stresses. Newly developed tuning devices with a much higher dielectric strength make allowance for increases in the reliability of the PLC link as a whole. Morg et al. [18] present an improved line trap featuring these new devices and improved surge arresters which is able to withstand such stresses.

Due to the limitations of line traps in offering reasonable attenuation to PLC signals, some other means of interference cancellation should be used for PLC systems. Widrow et al. [39] have described general concept of adaptive noise cancellation, an alternative method of estimating signals corrupted by additive noise or interferences. The method uses a primary input containing the corrupted signal and a reference input containing noise correlated in some unknown way with the primary noise. The reference is adaptively filtered and subtracted from the primary input to obtain the signal estimates. The paper describes a number of applications of adaptive filtering eg. electrocardiography, the cancellation of periodic interferences in speech signals, and cancellation of broad-band interferences in the side-lobes of an antenna array. The work presented in this thesis is based on research published in reference 39.

Estimates of interferences or desired signals can be used very effectively for interference cancellations on communication networks. In recent digital microwave radio communication systems, multi-level modulation and dual-polarisation techniques have been applied to improve frequency utilisation efficiency. Frequency utilisation efficiency of 5 bits/s/Hz has been already achieved using a 16 QAM technique [47]. Moreover, a 256 QAM modulation system [48] is being developed to obtain 10 bits/s/Hz efficiency. However, this advanced system is greatly influenced by the propagation conditions. In order to combat multi-path fading, it is necessary for realisation of the 256 QAM system to develop both higher performance equalisers [49,50] and cross-polarisation interference cancellers (XPIC) [51-53]. Digital signal processing (DSP) technique is one of the most effective ways to attain higher performance, precise cancellation and equalisation. Matsue et al. [54] has presented more precise XPIC, applicable to multi-level QAM system, using digitised transversal filters. The paper shows analytical method of digitised XPIC performance for various modulations and interference conditions.

For the application of cross-polarised interference cancellers, level of interference can be estimated from the identified model of the interference sources. System identification becomes very vital for the parameter variant systems. The process of system identification has been applied to aircraft model structure determination and parameter estimation from flight data [55]. The formulation of aircraft dynamics is based on known rigid body equations of motion, the unknown structure and parameters. They are related to the aerodynamics forces and moments acting on the aircraft. However, the introduction of highly manoeuvrable and often inherently unstable aircraft has been presenting new challenges to aircraft identification and parameter estimations. The aircraft can perform rapid large amplitude manoeuvres, often extended to the stall and poststall region where non-linear and transient aerodynamic effect could be pronounced. This introduces a problem of determining how complex the model should be. Although a more complex model can be justified for more accurate description of aircraft motions. The high performance aircraft may have more control surfaces moved through a flight control system than conventional aircraft. Such a system can introduce a close relationship between the deflections of various surfaces and at the same time can preclude manoeuvres from being suitable for system identification. Klein [56] has proposed a general approach to high performance aircraft identification.

Chandler et al. [57] have described the system identification where the highest derivates are measured. A prior knowledge of the stability and control deviates is incorporated into the linear regression algorithm, through Ridge Regression and Mixed Estimation methods. The example problem considered a linearised fourth-order model of the F-16 aircraft pitch channel and includes appropriate measurement noise. The paper describes that even during short periods of low excitation, the short period parameter estimates are improved by utilising prior Phugoid information.

Industrial processes usually involve a large number of variables, many of which vary in a correlated manner. To identify a process model which has correlated variables, an ordinary least squares approach demonstrates ill-conditioned problem that is sensitive to changes in sample data. Qin [58] has proposed a recursive partial least squares (PLS) regression for on-line system identification of the ill-conditioned problem. PLS method is used to remove the correlation by projecting the original variable space to an orthogonal latent space. The paper describes the application of this method on a chemical process modelling.

Mahloch et al. [59] have proposed the solution for approximation of a possibly infinite-dimensional multi-input and multi-output system by a finite-dimensional system. Unlike most of the methods appeared in the literature, the method described in this paper does not assume a prior knowledge of an analytic expression eg. transfer function.

Improvements in identifying the parameters of the systems can be made with the combination of various identification techniques. Lee et al. [60] have used Perturbation Analysis (PA) with Stochastic Approximation (SA) and Learning Automata (LA) to improve the network performance in handling various types of messages by on-line adjustment of protocol parameters. Multiple-access computer networks are designed to provide communication between spatially distributed heterogeneous devices via. common media and flexibility for changes in the system configuration. They are, therefore, well suited to serve large-scale integrated systems like banking and brokerage, battlefield command and control, autonomous manufacturing and processing plants, and advanced aircraft and spacecraft. Since system requirements may widely vary according to the required specification of application. A computer network must be arranged the design stage by selection of appropriate protocols and assignments of default parameters [61-63]. However, since the conditions under which a network actually operates may change from those considered at the design stage, control and management actions are required to adjust the network parameters so that the design and operational objectives are satisfied. For example, an aircraft control system network, the AI-based decision support systems for aircraft management are expected to generate a significant amount of additional traffic when dealing with component failures or inflicted damage. Therefore, the network must adapt to the dynamic environment especially if it is required to serve a large collection of heterogeneous users.

The responsibility of adapting the network to the dynamic environment belongs to network management. The major components of network management are fault management, configuration management, and performance management. As it is stated in reference 60, the performance management has been addressed, which is responsible to manipulate the adjustable parameters of the protocol in the real-time so that the network can adapt itself to a dynamic environment. Conceptual design, development, and implementation of a performance management tool for multi-access computer communication networks based on PA, SA and LA [61-63] are presented.

Also, Stankovic et al. [64] made use of SA method for self-tuned tracking of stochastic references in the general delay case. The paper also describes global stability, asymptotic optimality, convergence of the adaptive control law in a Cesaro sense, and strong consistency of the parameter estimates.

Deutsch et al. [65] have presented a comparison study of different stochastic approaches with special application to a case of stochastic demand of the transportation problem. This paper describes comparison of space-time auto-regressive integrated average (STARIMA), expected value (EV) and stochastic approximation (SA). According to the paper's findings, STARIMA showed the best performance in forecasting the stochastic demand of four products of brewery from five plants to 64 distribution centres. While SA and EV stood at second and third places respectively.

Controllers requiring real-time parameter identification of the plants need two stages to generate control signals eg. system identification and control signal based on the estimates of parameters. On-line system identification is very time consuming and needs high computational capacity. Fuzzy logic can be used to design the controllers without system identification. To show the comparison and to overcome this problem, rule based and fuzzy logic based power system stabilisers were designed [66-68]. Hiyama et al. [68] have proposed the use of linear membership function for the development of power system stabiliser for multi-machine systems. Further this stabiliser [68] was improved by Shi et al. [69] and compared with the rule-based power system stabiliser [66]. The paper [69] showed that fuzzy logic based power system stabiliser with the use of non-linear membership is superior to rule-based stabiliser.

Fuzzy logic controllers are based on experts knowledge of the processes. Ramaswamy et al. [70] have made use of fuzzy logic controller to track a suitable trajectory by automating the tuning process using a simplified Kalman filters. Robustness of proposed design approach has been demonstrated on a non-linear six delayed neutron group plant that utilises estimated nuclear reactor temperature from one group delayed group observer. The paper has proposed use of linear membership function for inputs of controller in terms of temperature (error and change of error) of the reactor. Also, Chand [71] has proposed a fuzzy logic based tuner for continuos on-line tuning of proportional, integral and derivative (PID) controllers. Application of fuzzy logic appears to be very suitable for ill-defined systems.

With or without system identification, application of artificial neural network (ANN) can be another alternative with its vast applications to control complex process in the industrial world. Application of ANN has been described by Aicardi et al. [72] with its application to decentralise routing for input flows of tele-traffic to a node. In this paper, a communication network with stochastic input flows has been considered. The nodes which route the traffic are required in order to:

i) react instantaneously to the variations of their incoming flows so as to minimise an aggregate transmission cost;

ii) to compute or adapt the incoming flows;

iii) obtain some local information (eg. the characteristics of the system, possibly time-varying of the links connecting each node with its upstream and downstream neighbours).

The second requirement calls for a computational distributed algorithm. This fact and intractability lead to assign each routing node a multi-layer feed-forward neural network, which generates the routing variables. For these neural networks the stochastic input flows play the role of training patterns. The paper also highlights, that the weights of neural network are then adjusted by means of efficient algorithm based on back on back-propagation and SA.

Application of neural network has been made by Polcarpou et al. [73] in identifying the parameters of non-linear systems. This paper presents an approximation theory perspective in the design and analysis of non-linear system identification schemes using neural network and other on-line approximation models. The identification process is based on discrete-time formation models. Depending on the location of the adjustable parameters, networks are classified into linear and non-linear parameterised networks. Applications of conventional adaptive techniques, fuzzy logic and neural networks can be extended to power system and signal processing.

The traditional medium of PLC communication has limitations in respect of frequency allocation and channel availability. Dubey et al. [20] have suggested that optical fibre systems being characteristically wide band and interference free are not constrained with these problems. The concept of integrated operation power system has been recognised. Load dispatch centres are being provided at state system levels as well as regional levels. These centres have to be connected to various points of grid with high capacity, reliable and rapid communication system for data as well as voice communication. Power utilities are now largely aiming at independent dedicated communication systems. Optical fibre communication comes as a real backbone in this direction. No separate right-of-way and watchword staff are required as the fibre cable could either be clamped with the existing phase/earth wire of the power line or a composite earth wire could be planned for a new transmission line. The paper [20] starts with introduction to the physics of fibre optics and its evolution culminating into mono mode fibre system. It deals with the system engineering for data, video and text transmission. It also concludes why and how optical fibre technique should be adopted for the widely ranging operational communication requirements of the power sector keeping in view the hierarchical system for load dispatching.

Application of the fibre optics for power system protection also has been suggested by Aggarwal [22]. Fibre optics have extremely high bandwidth allowing for very large amount of information to be carried through a very thin fibre strand. Due to 100% dielectric nature of fibre optics, it is not affected by ground loops, inductive pick ups, cross-talk or lightning. Development of high capacity, long haul digital communication system with fibre optic links has made the development of digital current differential relays possible. Using time-division multiplexing of pulse code modulation (PCM) signals, it is possible to send the current signals of each phase to the remote end of the line obviating some of the problems. These problems include electromagnetic interference, limitations imposed by the rented pilot circuits etc. suffered by conventional current differential protection.

Travelling waves and surge phenomena in power systems are of importance in solving problems relating to PLC communication, protection of very long lines, fault location, switching of unloaded lines and calculation of recovery voltages on circuit breakers under short line conditions. A significant advance in the solution of such problems was made by Fallou [6], who, with an assumption of complete symmetry of the conductors, applied the concept of symmetrical components to the solution of travelling-wave phenomena. This method is limited, however in that it yields average values for surge impedances and propagation coefficients, and this unfortunately masks important effects produced by asymmetry of conductors [35]. In investigating radio interference arising from overhead power lines, Adam [46] introduced the use of matrix algebra methods in the distribution of radio-frequency currents in an asymmeterical system of conductors. It was valid for this investigation, to assume zero resistance in the conductors and infinitely conducting earth plane. The results were of a restricted nature but the method of analysis was important as a foundation for the complete solution of the problem. Furthermore, Wedepohl [35] extended the use of matrix theory to indicate the rapidly growing complexity of the problem with the increasing number of conductors when solving using classical methods.

The various waveforms of the transient recovery voltage (TRV) caused by a breaking terminal fault (BTF) were studied by Zhu [19]. The TRV characteristics of 500 kV circuit breakers in the north China power system are presented for 10%, 30%, and 60% of the rated short-circuit breaking current. It is shown that the TRV can exceed the IEC standard under certain operating conditions. When the short-circuit current is comparatively large, the initial TRV is greatly influenced by high-voltage line trapper of the PLC communication during the first few microseconds after current interruption.

Propagation of PLC signal on power lines, in terms of their natural modes on horizontal three phase lines, was investigated by Perz [23]. The analysis was carried out with the use of elementary algebra and paralleled by corresponding equivalents of matrix eigenvalue analysis. Propagation of the PLC signal for longer distance is due to the presence of mode 3 [24]. Aerial modes are the least attenuated modes, results have been developed based on the fault transient simulation of EHV transmission systems using Modal Analysis [25]. Travelling wave phenomena remained in action for longer time in faults without ground due to the domination of the mode 3.

For the application of spread spectrum system to the PLC system, knowledge of noise and transmission characteristics up to a few hundred megahertz are required for the system design. The use of the installed power lines for the LAN provides a convenient means of transmission with a simple and readily accessible interface. Since it is possible to use the wall sockets of the already installed power lines as a terminal for data transmission, the use of the power lines for the LAN application is feasible [26]. Before taking the installed power lines as data communication channel, it is necessary to consider the noise and transmission characteristics of the power line at high frequencies for the reliability of the communications. Different nature of the varying loads, fluctuating impedance, transmission loss and inefficiency of system equipment eg. line traps may cause serious noise and interference problems for the RF signals.

Transmission lines can be used for data communication up to 100 MHz reliably [27], the laboratory model results agreed closely with the theoretical results. The signals are attenuated up to 20 dB and their attenuation is affected by the connections of the wires.

1.3 OBJECTIVE OF THIS RESEARCH

The communication of RF signals takes place simultaneously with the transmission of the power signal without serious mutual interference. In large power systems, it is not possible to provide all communication needs by means of PLC because of limited frequency spectrum available. High voltage transmission lines provide very reliable means of communication. Normally lines operating at 33 kV and above are most prevalent to the PLC communication.

PLC spectrum for different applications eg. voice communication, telemetering and protection etc. varies from 15-500 kHz. The bandwidth of the frequencies used for different applications varies, depending on the nature of the data being transmitted and the security required against errors. Normally 4 kHz bandwidth is taken for VF (voice frequency) signal for reasonable recognition of the voice. For system protection and for each measured supervisory control, a bandwidth of 1 kHz is enough for reliable transmission of the measurements. These signals of 1 kHz bandwidth are normally multiplexed to form one channel of 4 kHz to give way to accommodate more number of channels in the existing PLC frequency spectrum. The transmission of VF signals and supervisory control signals can be conducted by multi-purpose equipment or by single-purpose equipment. The use of multi-purpose equipment increases the risk of false transmission of pulses in supervisory control systems. On the other hand, it may result in a falsified picture of the operating conditions within the network or in extreme cases, prevent operation of the system altogether. Another frequently adopted arrangement provides for the interruption of speech for fractions of a second to transmit network protection signals and similar information.

Despite the probability of these errors, inefficiencies of system equipment due to the presence of line traps may cause serious interference among different channels. Line traps act like low pass filters, as 50 Hz power signal with its large amount of current is catered to pass through to the busbar without any attenuation. This ultimately limits the efficiency of the line traps and makes it difficult to monitor and control the mutual interference of PLC signals, as a result, the number of channels for PLC applications is limited. Due to interference caused by line traps, same spectra of frequencies cannot be used on adjacent line sections. The efficiency of the line traps is limited due to their cost and size. Maximum crossbus attenuation that can be obtained is not sufficient enough to suppress the PLC leakage signal through to bus bar. This leakage signal causes crosstalk among different channels and also limits the use of frequency spectrum.

To overcome this problem, this research investigates adaptive interference cancellation schemes to cancel these interferences. Adaptive interference cancellation schemes are active filtering techniques. Generally speaking cancellation is achieved by adjusting the amplitude and phase angle of the reference signal so as to get maximum correlation with the main input, and then subtracting it from the main input. The adjustment proceeds until no correlation is detected between the output and reference input. From the literature review presented in Section 1.2, some ideas can be gathered to design cross-polarised interference cancellers based on system identification or without system identification. To develop suitable interference cancellation schemes, use of conventional adaptive schemes eg. recursive least square (RLS) and stochastic approximation (SA) along with fuzzy logic and neural network based techniques have been made. Application of RLS and SA method is very tempting methodology used to cancel the PLC leakage signal through the line traps. For this method, knowledge of the transfer function of line traps is not required. Depending on the previous knowledge of inputs and outputs of the line traps, RLS and SA methods identify the parameters of dynamic response of the line traps, and based on these estimated parameters expected output of the line traps is evaluated. With each iteration, estimates of the line trap parameters are improved adaptively and ultimately estimates of the expected output are improved. Then this expected output is subtracted from the actual output to cancel out the leakage of the PLC signal. These methods work efficiently with the frequency varying parameters of the line traps.

Fuzzy logic is applied to identify the pattern of the leakage signal with the use of MATRIXx software package. Use of linear and non-linear membership functions has been made to identify the level of interferences on the busbar. Then on-line identified patterns have been cross-polarised to attenuate the interferences on the busbar. Further, RLS method is used to identify the model of line trap and to produce the expected output of the device. Then, this expected output is corrected by making use of fuzzy logic by identifying the unwanted phase and magnitude effects introduced by the coupling capacitors.

Use of adaptive feedward artificial neural network has been made to act as interference canceller. In this research, canceller algorithms are tested using sinusoidal, random and modulated signals.

Modal Analysis is one of the best simulation schemes for the study of travelling wave phenomena on the transmission lines. Voltage and current signals on the transmission line are decomposed into their modal values. Different modes of these signals propagate with different velocities and show different levels of attenuation. Earth mode is the most attenuated as compared to aerial modes, so aerial modes are considered responsible for the propagation of the PLC signals for longer distance.

This work also shows the propagation study of PLC signals in terms of their modal values. For this particular application a well known ATP6 (Alternative Transient Program) is being used. The application of ATP6 also has been extended to find the distributed parameters of the given transmission lines from the given geometry of the lines. From these parameters, steady state and transient behaviours of different EHV systems have been studied and data obtained from these studies can be used for proper system protection schemes. Application of ATP6 also has been made to design optimum coupling and broadband line traps for the PLC systems.

Based on the computer simulation studies for PLC systems, using ATP6, MATRIXx and MATLAB (computing environment for high performance numeric computation and visualisation), designs of the transmission line model and its associated PLC components (broadband line traps and optimum coupling capacitors) have been developed and tested. Then the leakage signal through line traps to busbars was anticipated to cancel by appropriate design of the adaptive interference cancellers.

1.4 ORIGINALITY OF THE THESIS

The work presented in this thesis is based on Modal Analysis, adaptive control theory, fuzzy logic and artificial neural network for interference cancellation on PLC systems. Mathematical designs of adaptive cancellers based on the theory of natural modes have been presented in Chapter 2. Literature review presented in Section 1.2 shows the lack of implementation studies of adaptive filters and intelligent schemes on PLC model based on modal analysis for interference cancellation of The original contributions of this thesis are summarised as follows:

1. Two types of adaptive interference cancellers based on RLS and SA identification methods have been analysed and proposed;
2. Three types of adaptive interference canceller based on fuzzy logic with linear and non-linear membership functions have been proposed and implemented on PLC model;
3. Use of neural network has been made for adaptive interference cancellation on a PLC network;
4. PLC laboratory model has been designed based on Modal Analysis to test the performance of different coupling schemes;
5. PLC laboratory model was also used to test the performance of different interference cancellers in real-time environment;

6. Based on computer and laboratory simulation studies presented in Chapters 6-9, recommendations are made for the suitability of the cancellers for PLC systems.

1.5 ORGANISATION OF THE THESIS

The work presented in this thesis consists of ten chapters. In Chapter 1, introduction of PLC systems, with special consideration of problem definition of interference cancellation is described. This chapter further presents a brief literature review about the published work, which shows close associations with PLC application. Also, objective and contribution of the research along with organisation of thesis is outlined.

Chapter 2 describes the application of Modal Analysis Theory for modelling PLC systems along with its associated equipment eg. line trap, coupling capacitors and cancellers. Applications of identification techniques (RLS and SA) to PLC network have been described. Briefly, modelling of cancellers using fuzzy logic and neural network have been outlined. Chapter 3 describes the circuit parameters used for computer and hardware simulation of the PLC network and cancellers.

Based on the parameters described in Chapter 3, studies of modal values of PLC signal are performed using ATP6 and results are given in Chapter 5. Steady state and transient studies of the transmission line from Chapter 5 and circuit parameters from Chapter 3 are used to construct the test-bed laboratory model of PLC network along with its data acquisition facilities. This test-bed has been used to investigate the implementation of different cancellation schemes and couplings of various types.

Chapters 6 and 7 present simulation results of RLS method on computer and hardware simulated models of PLC systems. Chapter 8 describes application of SA method as a PLC interference canceller. Applications of fuzzy logic and neural network have been outlined in Chapter 9. Comparison of all used techniques in the thesis, conclusions and future work are given in Chapter 10.

Several appendixes are attached to provide additional details such as modal theory, circuit block diagrams and published work etc.

CHAPTER 2

MATHEMATICAL MODEL FOR PLC SIGNAL PROPAGATION USING MODAL ANALYSIS

2.1 INTRODUCTION

Accurate modelling of power system circuits for different applications eg. fault location, telemetry, system protection, transient and steady state studies of systems, PLC signal propagation and supervisory control of power systems etc. is a primary requirement for effective design of the described applications. To test the realistic model, the study of transient phenomena is carried out using some form of simulation. The accuracy of the modelling techniques mainly depends on the assumptions being made, calculation of system parameters (lumped or distributed) and the mathematical tools.

Different techniques can be used, for the simulation of the power system. Three of the most frequently used simulation tools are:

- The model called "simulators" or "Transient Network Analysers" (TNA) has been used by down scaling the analogue model in which transmission lines are represented by a large number of lumped Π-parameters and T sections [28,29]. Although it has always been a powerful tool for transient simulation, TNA is not convenient to simulate the distributed nature of line parameters [28,29]. Besides, in a line model with finite number of sections, it is not possible to cover the infinite frequency response bandwidth, so approximate response is unavoidable [30].

TNA proved to be a very useful tool for laboratory modelling of the transmission lines, which can be used for appropriate system equipment testing. In this work scaled down model of the transmission line was obtained from ATP6 modelling. The laboratory model was constructed for the application of PLC equipment and adaptive interference cancellation schemes on PLC systems. The tests showed very close resemblance to the actual line model using ATP6. The frequency response of the laboratory model described the behaviour of the lines carrying PLC signals. The results described in Chapter 7 helped to decide on the spectrum of the frequencies that can be used for PLC applications for this particular case.

- An obvious alternative to study power system transients is the use of digital techniques. Based on travelling wave phenomena, a number of methods are available to solve system equations (2.1 and 2.2):

$$dV / dX = -Z.I \qquad \text{.........................(2.1)}$$
$$dI / dX = -Y.V \qquad \text{..............................(2.2)}$$

These equations may be solved using the Laplace transformation [31,32,33]. Applied to system equations for the phase voltages, the method produces a number of independent second order differential equations for voltage in terms of distance. These are separated by transforming the voltage into independent modes which travel on the line without interaction. Once the modal waves are known, the phase voltages are evaluated by adding the forward and backward modal waves and using the inverse of modal transformation. This method considers the distributed nature of the line parameters, which is more realistic. This technique has been used for the modelling of the transmission line for the studies of the propagation of PLC signals.

- A third method is based on the well known lattice-diagram technique which is described by Bewley [34]. This method is based on the assumption of lossless or distorsionless propagation. The calculations are performed in terms of voltage wave increments which travel on the line. The behaviour of the travelling wave at point of discontinuity is determined by reflection and refraction coefficients. In single-phase calculations the coefficients are calculated from the individual line surge impedances. However, in three-phase studies, they are replaced by surge impedance matrices and in this way mutual effects between phases are taken into account. Line surge impedance matrix is evaluated at the transient predominant frequency or if this is not known, at a frequency band on the travel time of the line being subject to transient.

2.2 MODEL OF PLC SIGNAL ON TRANSMISSION LINES

In this work, the theory of natural modes is used for the solution of the travelling wave phenomena in polyphase systems to formulate the model for PLC signal propagation on the power lines. Complete analysis of theory of natural modes is presented in Appendix A.

PLC signal propagates on the transmission lines exactly like power signal but at PLC frequencies. The propagation velocity of the modal values of PLC signal depends on the signal frequencies. The modes have different propagation constants and different propagation velocities. The modes are related to the properties of the system used, in particular the formation of the impedance matrix. The propagation level of the injected signal from sending to receiving ends can be calculated at any point along the line from the knowledge of the modal values.

The currents due to the PLC signal, at both sending and receiving ends can be obtained in terms of boundary voltages (V_s and V_r) from the results of analysis presented in Appendix A:

$$\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} Y_o S \coth \gamma l S^{-1} & -Y_o S \operatorname{cosech} \gamma l S^{-1} \\ Y_0 S \operatorname{cosech} \gamma l S^{-1} & -Y_o S \operatorname{cosech} \gamma l S^{-1} \end{bmatrix} \begin{bmatrix} V_s \\ V_r \end{bmatrix} \qquad (2.3)$$

or

$$\begin{bmatrix} V_s \\ V_r \end{bmatrix} = \begin{bmatrix} S \coth \gamma l S^{-1} Z_o & -S \operatorname{cosech} \gamma l S^{-1} Z_o \\ S \operatorname{cosech} \gamma l S^{-1} Z_o & -S \coth \gamma l S^{-1} Z_o \end{bmatrix} \begin{bmatrix} I_s \\ I_r \end{bmatrix} \qquad (2.4)$$

Equation 2.4 can be represented in terms of modal values:

$$\begin{bmatrix} I_s^c \\ I_r^c \end{bmatrix} = \begin{bmatrix} Y^c \coth \gamma l & -Y^c \operatorname{cosech} \gamma l \\ Y^c \operatorname{cosech} \gamma l & -Y^c \operatorname{cosech} \gamma l \end{bmatrix} \begin{bmatrix} V_s^c \\ V_r^c \end{bmatrix} \qquad (2.5)$$

Usually it is more adequate to write the transmission network equations so that the end quantities are related to the receiving end quantities by a two port transfer matrix. This can be achieved by using equations A.30, A.31 and A.33 (Appendix A):

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} S\cosh \gamma l S^{-1} & S\sinh \gamma l S^{-1} Z_o \\ Y_0 S\sinh \gamma l S^{-1} & Y_o S\sinh \gamma l S^{-1} Z_o \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \quad \text{.................}(2.6)$$

For a single-circuit, 2-conductor line, the dimension of any of the matrices is given in equation 2.6 is (3x3). In modal form, equation 2.6 becomes:

$$\begin{bmatrix} V_s^c \\ I_s^c \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & -Z^c \sinh \gamma l \\ Y^c \sinh \gamma l & -\cosh \gamma l \end{bmatrix} \begin{bmatrix} V_r^c \\ I_r^c \end{bmatrix} \quad \text{.......................}(2.7)$$

2.3 MODEL OF LINE TRAPS

For the use of modal analysis for the PLC equipment (ie. line traps) the voltages and currents of PLC signal obtained on remote ends (V_S and I_S) are considered at the inner ends of the broad band line traps as shown in Figure 2.1. Broad band line traps are considered as band stop filters, their band width is mainly decided by the value of impedance at the particular spectrum of frequencies. For the simplicity of analysis, line traps are considered at the sending end only. The equivalent impedance of the line traps can be represented as:

$$Z_1 = \frac{1}{(2\pi f C_1)}$$
$$Z_2 = 2\pi f L_1$$
$$Z_3 = r_1 + \frac{1}{(2\pi f C_2)} + (2\pi f L_2)$$

where f is the PLC signal frequency, L_1 is the main line traps inductance which is the biggest and the most expensive part of the equipment, r_1 equals to the characteristics impedance of the transmission line and other components eg. C_1, C_2, and L_2 are for the resonance of the circuit. Total impedance of the line traps can be taken as:

$$Z_{LT} = \frac{(Z_1 Z_2 Z_3)}{(Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1)}$$

In the analytical analysis, principle of superposition has been adopted for the PLC and power signals. If V_S is the PLC signal voltage at the sending end and I_S is considered as the current flowing through the line traps due to V_S, then the level of the attenuated signal at the sending end busbar can be calculated as follows:

$$V_{s1} = V_s - (I_s Z_{LT}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.8)$$

Substituting the values of V_S and I_S in equation 2.8:

$$\begin{aligned} V_{s1} = & (S \cosh \gamma l S^{-1} V_r + S \sin \gamma l S^{-1} Z_o I_r) - \\ & (Y_o S \sinh \gamma l S^{-1} V_r + Y_o S \sinh \gamma l S^{-1} Z_o I_r) Z_{LT} \ldots\ldots\ldots\ldots\ldots (2.9) \end{aligned}$$

The leakage signal through busbar can be represented in modal form in terms of receiving end voltage and current:

$$V_{s1}^c = (\cosh \gamma l V_r^c - Z^c \sinh \gamma l I_r^c) - (Y^c \sinh \gamma l V_r^c - \cosh \gamma l I_r^c) Z_{LT} \ldots\ldots (2.10)$$

V_{S1} is the leakage signal through line trap which interferes with the PLC signals from the adjacent line sections. To avoid the interference, same frequencies are not used on the adjacent line sections, which ultimately limits the number of channels for PLC utilities. The efficiency of the line traps is limited due to their size and cost. Cancellation of the leakage signal on busbar can help to make use of the same frequencies on adjacent line sections which will improve the number of channels for the PLC utilities.

Line traps are fourth order low pass filters. Their low pass nature prevent any possible attenuation to the 50 Hz power signal. Transfer function of the line trap can be generalised as given below:

$$k \frac{s^3 + z_1 s^2 + z_2 s}{s^4 + p_1 s^3 + p_2 s^2 + p_3 s^1 + p_4}$$

Where k is the gain and z_1, z_2, p_1, p_2, p_3, and p_4 are constants. These constants depend on the realistic parameters (capacitive, inductive and resistive) of the line traps.

It was anticipated in this work to analyse the adaptive interference cancellation schemes for the cancellation of the leakage signal. The leakage signal can be constructed from its modal values as shown in equation 2.10.

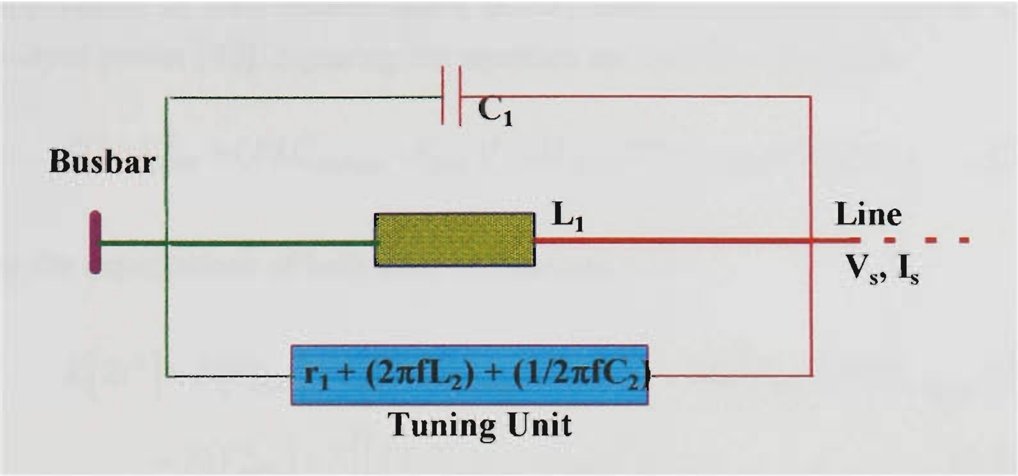


Figure 2.1 Schematic diagram of Line Traps with tunning unit

2.4 MODEL OF ADAPTIVE INTERFERENCE CANCELLER

Adaptive interference canceller uses "primary" input containing the corrupted signal or leakage signal and a "reference" input containing noise correlated in some unknown way with the primary noise. The reference input is adaptively filtered and subtracted from the primary input to obtain the estimated signal. Adaptive filtering before subtraction allows the treatment of inputs that are deterministic or stochastic, stationary or time variable. Adaptive filter differs from a fixed filter in that it automatically adjusts its own impulse response. Application of adaptive interference cancellation schemes for a PLC system appear to be very feasible as the inputs at both ends of the line trap are readily available to determine composite dynamic response characteristics of the line trap.

In order to adaptively cancel unwanted signal, it is necessary to have prior knowledge of the signal before the filter is to be designed, or before it could adapt. Figure 2.2 shows the adaptive interference canceller for PLC systems [39]. In the figure, V_{EHV}, $PLC_{Leakage}$, V_{CCL} and Zt are the 50 Hz power signal, PLC leakage signal through line traps to busbar, signal generated by adaptive canceller (which should be a very close replica of the leakage signal) and interference free power signal respectively. If four of the signals described are statistically stationary and have zero means, also V_{EHV} is uncorrelated with $PLC_{Leakage}$ and reference input. Suppose reference input is correlated with leakage signal. Then output can be taken as:

$$Zt = V_{EHV} + PLC_{Leakage} - V_{CCL}$$

The application of least-means-square (LMS) adaptive algorithm helps to adjust the total output power [40]. Squaring the equation and taking expectation:

$$Zt^2 = V_{EHV}^2 + (PLC_{Leakage} - V_{CCL})^2 + 2V_{EHV}(PLC_{Leakage} - V_{CCL}) \qquad (2.11)$$

Taking the expectations of both sides of equation 2.11:

$$E\left[Zt^2\right] = E\left[V_{EHV}^2\right] + E\left[\left(PLC_{Leakage} - V_{CCL}\right)^2\right] + 2E\left[\left(V_{EHV}\left(PLC_{Leakage} - V_{CCL}\right)\right)\right]$$
$$= E\left[V_{EHV}^2\right] + E\left[\left(PLC_{Leakage} - V_{CCL}\right)^2\right] \qquad (2.12)$$

The power signal $E\left[V_{EHV}^2\right]$ will be unaffected as the filter is adjusted to minimise $E\left[Zt^2\right]$. Accordingly, the minimum output power is:

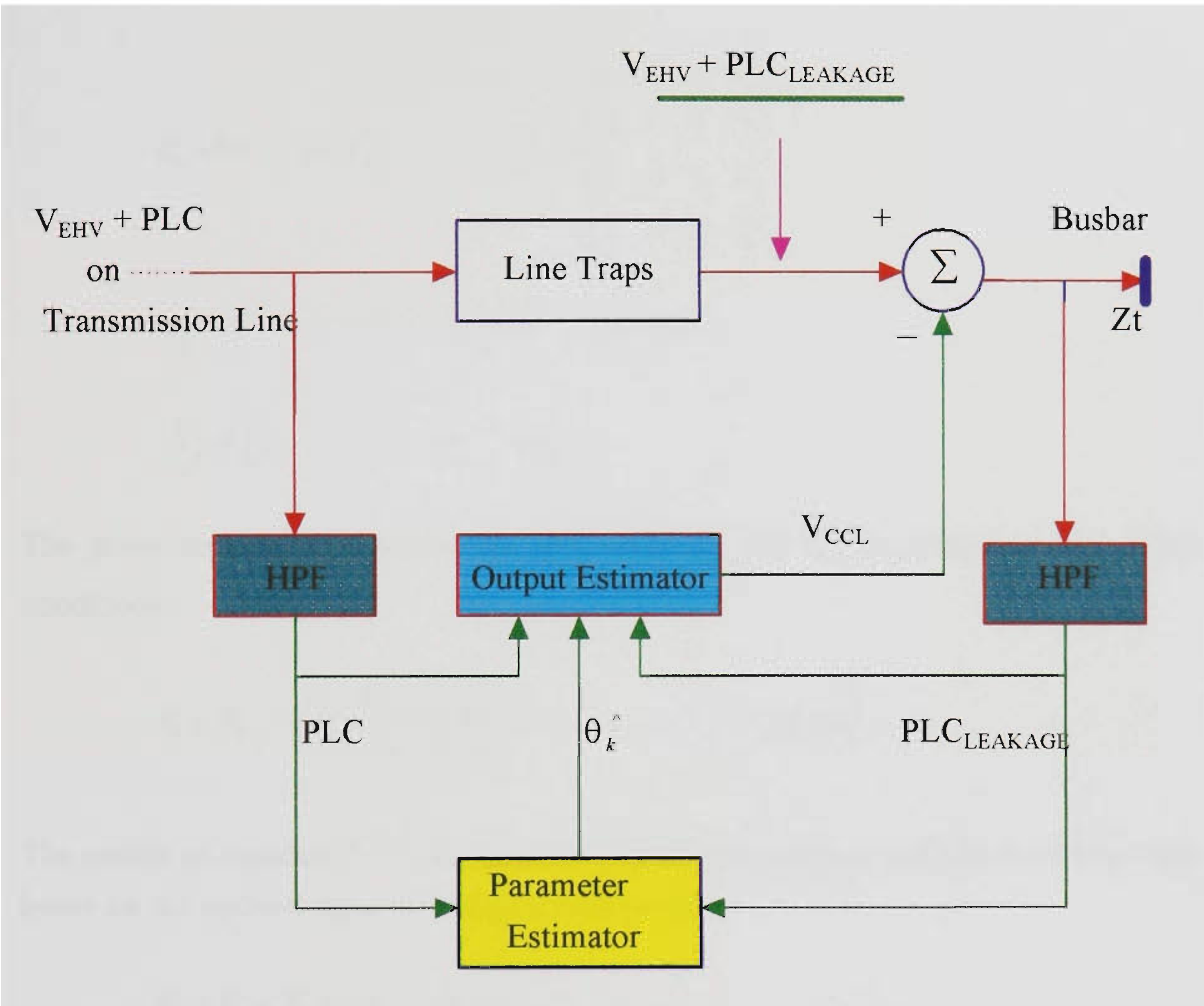
$$\min E\left[Zt^2\right] = E\left[V_{EHV}^2\right] + \min E\left[\left(PLC_{Leakage} - V_{CCL}\right)^2\right] \qquad (2.13)$$

When adaptive filter is adjusted so that $E\left[Zt^2\right]$ is minimised, $E\left[\left(PLC_{Leakage} - V_{CCL}\right)^2\right]$ is, therefore, also minimised. V_{CCL} will be the best estimate of the $PLC_{Leakage}$ if the above-mentioned conditions were fulfilled. Minimising the total output power maximises the output signal-to-noise ratio [4,5,7,8].

State vector of adaptive filter for interference canceller has been adopted to have four elements, because the line trap model is of the fourth order as described in Section 2.3.

2.5 MATHEMATICAL MODEL FOR RLS METHOD

The general review of adaptive interference canceller and line trap model of PLC system gives optimum choice of RLS method [41,42,43]. In this particular case, V_S (PLC signal from equation 2.6) and interference signal V_{S1} (from equation 2.9) are available on both ends of line traps. RLS method works very efficiently to capture composite dynamic response characteristics of the line trap (weighting coefficients) and to predict the expected interference being caused by the line trap. Interference is equal to the product of adjusted weighting coefficients and a vector of previous two states of input and output.



HPF = High pass filter (Coupling capacitors)

Zt = Power signal after adaptive cancellation of PLC leakage signal

$\hat{\theta}_k$ = Estimated elements of dynamic response of the Line Traps

V_{CCL} = Estimated PLC leakage signal through Line Traps

Figure 2.2 : Schematic diagram of adaptive interference canceller for PLC system

For initialisation θ_k (actual weighting coefficients), X_k (input and output state vector) and P_{k-1} internal state matrix are taken as zero. $\hat{\theta}_k$ are estimated weighting coefficients of line traps for kth state:

$$\theta_k = \begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix} \qquad P_{k-1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$u_1 = 0 \qquad u_2 = 0 \qquad y_1 = 0 \qquad y_2 = 0$$

$$X_k = \begin{bmatrix} y_1 & y_2 & u_1 & u_2 \end{bmatrix}'$$

The projection operator matrix for next state P_k can be obtained from the initial conditions:

$$P_k = P_{k-1} - \frac{P_{k-1} X_{k-1} X'_{k-1} P_{k-1}}{1 + X'_{k-1} P_{k-1} X_k} \quad \text{.......................(2.14)}$$

The results of equation 2.14 can be used to find the weighting coefficients of line traps based on the updated input and output state vector:

$$\hat{\theta}_k = \theta_k + P_k X_k (V_{s1} - X'_k \theta_k) \quad \text{...........................(2.15)}$$

Estimated output of line traps can be predicted based on the latest estimate of the parameters:

$$V_{s1t} = X'_k \hat{\theta}_k \qquad \text{....................................(2.16)}$$

Improved estimates of the weighting coefficients and internal state matrix are updated with previous values to find adaptively optimum values to have best possible estimate of leakage signal through the line trap. For recursive adaptation, updating is done as follows:

$$\theta_k = \hat{\theta}_k$$
$$P_{k-1} = P_k$$
$$y_2 = y_1 \qquad u_2 = u_1 \qquad y_1 = V_{s1(k)} \qquad u_1 = V_{s(k)}$$

These new values of input and output are used to make updated state vector for adaptive learning of the algorithm. The estimated output of the algorithm V_{s1t} is subtracted from the actual leakage signal (V_{s1}) through line trap to get the cancellation of the interference on the busbar. In computer and hardware simulation the estimated output of line trap was injected on to the busbar with negative sign to get the adaptive cancellation:

$$V_{can} = V_{s1} - V_{s1t} \qquad \text{.......................................(2.17)}$$

In this work, the above-mentioned mathematical model has been used for computer and hardware simulation of the PLC system and adaptive interference cancellation to test its practicality.

2.6 MATHEMATICAL MODEL FOR SA METHOD

Application of SA method for parameter estimation of line trap can be made to follow the same steps that were used to implement RLS method as explained in Section 2.5. PLC and PLC leakage signals (V_s and V_{s1} from equations 2.6 and 2.8 respectively) can be taken as inputs for this algorithm as well for parameterisation.

In this particular case V_S (PLC signal from equation 2.6) and interference signal V_{S1} (from equation 2.9) are available on both ends of line trap. SA method works very efficiently to capture composite dynamic response characteristics of the line trap (weighting coefficients). It also has a strong ability to predict the expected interferences being caused by the line traps. Interferences are equal to the product of adjusted weighting coefficients and a vector of previous two states of inputs and outputs. SA is simpler than RLS method in programming the algorithm as interference canceller. SA method uses internal state matrix as a scalar, contrary to RLS method. For the application of this approach, PLC was considered as a stochastic system, which was the true representation of the line trap behaviour. Using this algorithm, based on the previous estimates, the next state of interferences was predicted. For initialisation θ_k (actual weighting coefficients), X_k (input and output state vector) and P_k (internal state scalar) are taken as zero. In the simulation they are represented as follows:

$$\theta_k = [0\ 0\ 0\ 0] \qquad P_k = 0$$

$$u_1 = 0 \qquad u_2 = 0 \qquad y_1 = 0 \qquad y_2 = 0$$

$$X_k = [y_1\ \ y_2\ \ u_1\ \ u_2]'$$

The projection operator matrix for next state can be obtained from the initial conditions:

$$P_k = \left(\sum_{i=0}^{k} X_i' X_i \right)^{-1} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \ (2.18)$$

The results of equation 2.18 can be used to find the new weighting coefficients of line trap, based on the updated input and output state vector.

$$\hat{\theta}_k = \theta_k + P_k X_k (V_{s1} - X_k' \theta_k) \quad \dots\dots\dots\dots\dots\dots\dots (2.19)$$

Estimated output of line trap can be predicted from the latest knowledge of estimates of the line trap parameters:

$$V_{s1t} = X_k' \hat{\theta}_k \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \ (2.20)$$

Improved estimates of the weighting coefficients and internal state scalar are updated with previous values to find adaptively optimum values to have best possible estimate of leakage signal through the line trap. Updating is done as follows:

$$\theta_k = \hat{\theta}_k \qquad P_{k-1} = P_k$$

$$y_2 = y_1 \quad u_2 = u_1 \quad y_1 = V_{s1(k)} \quad u_1 = V_{s(k)}$$

The updating of parameters, input and output state vector and internal state scalar is done for adaptive learning of the algorithm from previous stochastic estimates to get the true estimate of next state. The estimated output of the algorithm V_{s1t} is subtracted from the actual leakage signal (V_{s1}) through line traps to get the cancellation of the interference on the busbar. In computer and hardware simulation, the estimated output of line trap was injected on to the busbar with negative sign to get the adaptive cancellation. Mathematically this is represented in equation 2.21:

$$V_{can} = V_{s1} - V_{s1t} \quad \dots\dots\dots\dots \quad (2.21)$$

The performance of the algorithm has shown poor results for initial estimates of interferences due to zero initial conditions. Performance index for the given algorithm can be analysed from equation 2.22:

$$Performance\_Index(J) = \sum_{i=0}^{k} \left(V_{s1} - X_i^{'}\,\hat{\theta_k}\right)^2 \quad ....(2.22)$$

Frequency variant non-linear behaviour of the line trap can also be analysed from the performance indicator eg. performance index. The algorithm presented in this section was used for the computer and hardware implementation studies of cross-polarisation adaptive interference cancellation on a PLC system. MATLAB software was used for the simulation of PLC model and SA algorithm as an interference canceller. For hardware implementations, laboratory power line model was used as a communication channel for PLC signals. Design details of power line model and line traps are described in Chapters 3 and 4.

2.7 FUZZY SET THEORY

Fuzzy set theory (fuzzy logic) is used to represent and reason with some particular form of knowledge. It is assumed that the knowledge would be expressed in a linguistic or verbal form. It should not be a mere intellectual undertaking, but must be operationally powerful so that the computer can be used for simulation. However, when using a language-oriented approach for representing knowledge about a certain system of interest, one is bound to encounter a number of non-trivial problems. Systems having no sharp boundaries can be considered having the property of vagueness [74,75].

The fuzziness of a property lies in the lack of well defined boundaries of the set of objects to which this property applies [74]. Let U be the universe of discourse, covering definite range of objects. Considering a subset F of U, where the transition between membership and non-membership is gradual rather than abrupt. The fuzzy set F certainly has no well defined boundaries. In fuzzy set theory, 'normal' sets are called crisp sets, in order to distinguish them from fuzzy sets. Considering C as a crisp set defined on the universe U. For any element u of U, either $u \in C$ or $u \notin C$. In fuzzy theory this property can be generalised, therefore in fuzzy set F, it is not necessary that either $u \in F$ or $u \notin F$ [76]. The generalisation is performed as follows:

For any crisp set C, characteristics function can be defined as: $u_c : U \Rightarrow \{0,1\}$. In fuzzy set theory, the characteristics function is generalised to a membership function that assigns to every $u \in U$ a value from the unit interval [0,1]. This set is called fuzzy set [74]. The membership function u_F of a fuzzy set F can be described as:

$$u_F : U \Rightarrow [0,1] \qquad \text{...(2.23)}$$

Every element u from U has a membership degree $u_F(u) \in [0,1]$. Generally fuzzy set can be expressed in terms of elements and the membership degree:

$$F = \{(u, u_F(u)) | u \in U\} \qquad \text{..(2.24)}$$

Use of fuzzy set theory was made successfully for adaptive interference cancellation on PLC network. Conventional design procedure was adopted for the implementation of Adaptive Fuzzy Logic Based Interference Canceller (AFLIC), using fuzzy tool in MATRIXx. Graphical representation is shown in Figure 2.3.

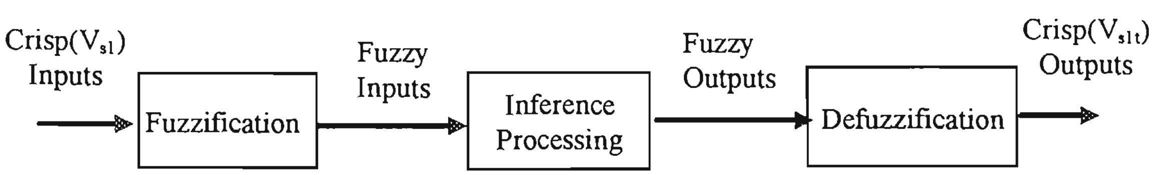


Figure 2.3 : Graphical representation of Adaptive Fuzzy Logic Based Interference Canceller

2.8 DESIGN MODEL OF ARTIFICIAL NEURAL NETWORK BASED INTERFERENCE CANCELLER

For interference cancellation on the given system, RLS, SA and AFLIC methods have been implemented successfully, results are given in Chapters 6-9. In this application, similar to the AFLIC algorithm, line trap identification was also avoided but network was trained to determine weighting coefficients and bias of the adaptive network. Adaptive training is used to update weighting coefficient and bias recurrsively. For supervised learning of ANN, both leakage signal and combined (leakage and PLC target (zero) signals) signals were used as inputs. Block diagram of Artificial Neural Network Based Interference Canceller (ANNIC) is given in Figure 2.4. Power signal is the only desired signal on the busbars. For the application of ANNIC, power signal was filtered out using coupling capacitors. In the working of canceller, PLC signal was considered as a vector of zeros, which was the ultimate requirement of the canceller.

Both the input signals were used to adapt the connection weights and biases for the network. These adaptively updated connection weights and biases were used to process the input stimulus presented at the input buffer. For the processes of learning and recall, MATLAB functions "initlin" and "adaptwh" [77] were used to obtained the true estimates of interferences and PLC signals. Interference cancellations on the busbar were obtained by cross-polarising the estimates of interferences in real-time mode.

This technique can be well used in the situations where the total signal is the sum of actual signal and also function of noise. Major applications can be in separating the engine and tyre noises from the actual signals in case of pilot voice from cockpit and mobile phone signal in car respectively. In this application, power signal was separated using high pass filter, so PLC signal was taken as zero reference signal. Canceller was tested for different signals having four different bandwidth, three channels having their separate carriers using single side band amplitude modulation (AMSSB) and double side band amplitude modulation with suppress carrier (AMDSB-SC). Three of the channels were multiplexed using frequency division multiplexing (FDM) technique.

In this chapter, analytical modelling of PLC network and PLC signals have been described with the use of modal theory of natural modes. Based on this model, various types of cancellers have been developed, their model descriptions are given in Sections 2.5-2.8. The modal analysis is a very convenient tool for the propagation studies of PLC signal on the line. Interference cancellers are based on adaptive digital fitters. Developed cancellers use PLC and leakage signals for interference cancellation. Mathematical analysis presented in Sections 2.2-2.6 show that modal analysis does not contribute in providing additional attenuation to the leakage signal. Models presented in this chapter were used for the computer and hardware simulation studies of the canceller.

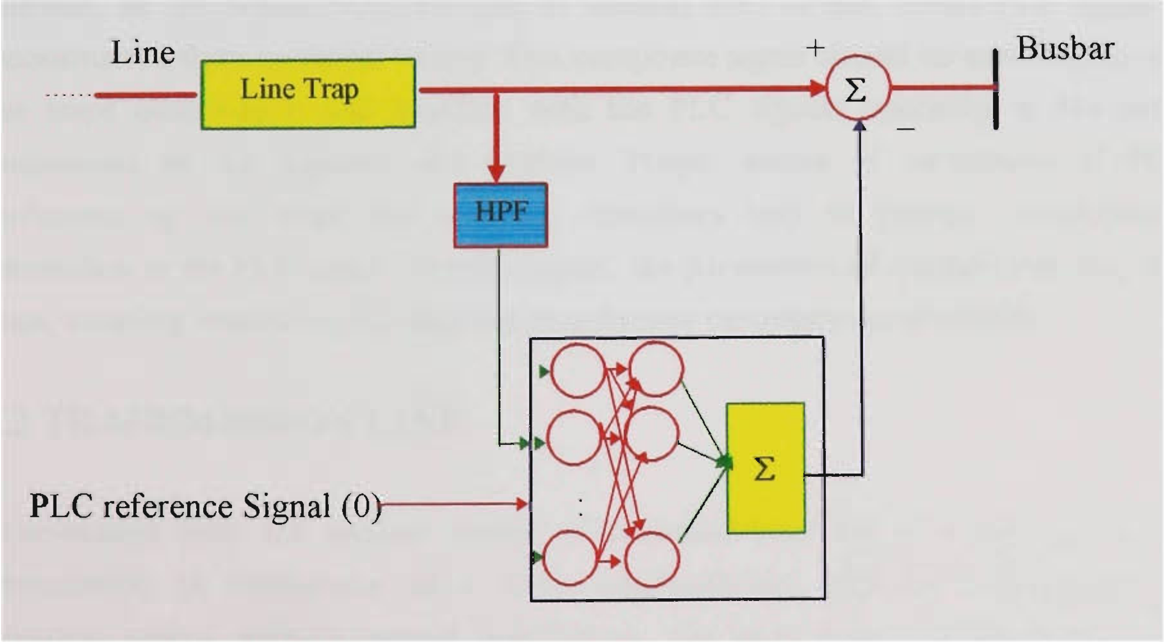


Figure 2.4 : Graphical representation of ANNIC for a PLC System

CHAPTER NO. 3

CIRCUIT PARAMETERS

3.1 INTRODUCTION

A system's behaviour mainly depends upon the nature of the parameters and type of the domain (frequency, time or discrete time) used for a particular application. For reliable propagation of PLC signals on the transmission lines and through the PLC equipment (line traps and coupling capacitor), parameters of concerned circuitry play a very important role. For the determination of attenuation and distortion levels of the signals on the transmission lines, knowledge of the impedance matrix and admittance matrix is a primary requirement. To find out the velocities of different modes of PLC signal, propagation constants are developed from the impedance and admittance matrices, on the boundaries (receiving or sending end) of line, where PLC signal is reconstructed from its modal values. This composite signal should be cancelled by the line traps otherwise it will interfere with the PLC signals operating at the same frequencies on the adjacent line sections. Proper choice of parameters of PLC equipment eg. line traps and coupling capacitors help to prevent unnecessary attenuation in the PLC signal. In this chapter, the parameters of transmission line, line traps, coupling capacitors and adaptive interference cancellers are presented.

3.2 TRANSMISSION LINE

Transmission lines are costless means of communication for PLC signals, as the transmission of intelligence takes place simultaneously with the transmission of electrical energy without mutual interference. On large power systems, it is not possible to provide all communication needs [44] by means of PLC because of the limited spectrum available. Inefficiency of the PLC equipment eg. line traps also limits the availability of the existing frequency spectrum. Transmission lines operating at 33 kV and higher voltages are the most prevalent for data communication. Lower voltage lines are usually tapped or looped through a greater number of stations between terminals, which increases the cost of maintaining a suitable path for communication signals. Tapping of the lines reduces the power of the communication signal due to leakage of signal through line traps at tapping points. Transmission lines are very reliable means of communication for data communication, even in case of short circuits, the communication of signals can be made successfully.

The ultimate goal of the transmission lines is to transmit power with minimum losses. Data transmission for power system utilities is an extra advantage, which should not interrupt the power transmission at any stage. The selection of the parameters for the design of transmission line is mainly for fulfilling the purpose of power transmission but data transmission is also kept in mind as well. Shunt capacitors are used at some points along the lines to improve the sensitivity of the PLC system response to the line parameter changes. In some cases, modal cancellation can be completely eliminated with the shunt capacitors [9]. Communication signal loss due to modal cancellation is a major concern in the design of PLC systems. An electromagnetic wave on a multi-conductor line can be considered as an ensemble of modes, each one with its own propagation velocity and attenuation [35].

3.2.1 Parameters Of Transmission Line For Simulation

In this work, PLC systems are connected to 500 kV ehv transmission line with bundled conductor in a horizontal configuration. Figure 3.1 describes the geometry of the line showing two earth wires on the top of the tower. Complete details of the line are described below:

Operating voltage	= 500 kV
Frequency of the system	= 50 Hz
Line length	= 400 km
Earth resistivity	= 250 Ω-m
Outside diameters of phase conductor	= 3.25 cm
Outside diameters of earth conductor	= 2.50 cm
Number of bundles in each conductor	= 4
Phase conductor size	= 4 x 54 / 7 / 3.25 ACSR
Ground wire conductor size	= 2 x 30 / 7 / 2.5 ACSR
Allowable sag	= 13.8 m
DC resistance of the phase conductor	= 0.0522 Ω/km

DC resistance of the earth conductor	= 0.36 Ω/km
Ratio of thickness to diameter of the phase tubular conductor	= 0.231
Ratio of thickness to diameter of the earth solid conductor	= 0.5

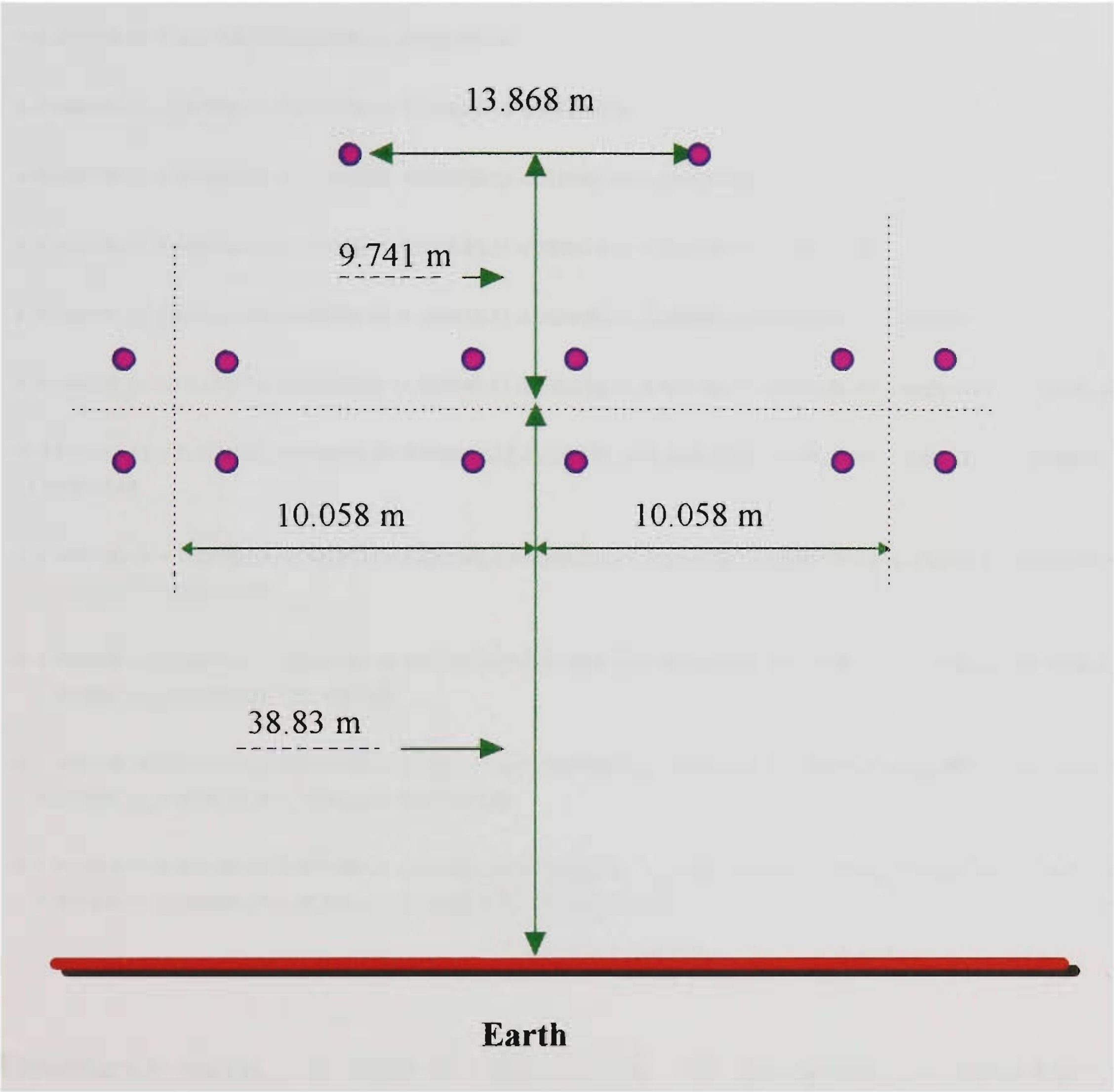


Figure 3.1 Transmission Line Construction

Based on the geometry of the transmission line in Figure 3.1, Z and Y matrices of the transmission can be found using ATP6 software. This method of finding transmission line parameters gives a choice of different types of parameters eg. Z matrix, Y matrix and also Z, Y matrices in their sequence (zero and positive) form. Z and Y matrices are given below in different forms:

Capacitance matrix, in units of [farads/km] for the system of physical conductors.

1 9.892976E-09

2 -4.154444E-11 1.195846E-08

3 -7.645313E-12 -1.341446E-11 1.005250E-08

4 -6.471943E-09 -4.163076E-11 -7.655479E-12 9.893138E-09

5 -7.648849E-12 -1.341593E-11 -7.072954E-10 -7.659020E-12 1.005250E-08

6 -7.557957E-12 -1.325363E-11 -7.052085E-10 -7.568006E-12 -6.311889E-09 1.005373E-08

7 -4.148719E-11 -4.480881E-09 -1.350413E-11 -4.157318E-11 -1.350561E-11 -1.334220E-11 1.195787E-08

8 -4.153980E-11 -3.474626E-09 -1.341593E-11 -4.162611E-11 -1.341446E-11 -1.325216E-11 -2.371634E-09 1.195846E-08

9 -4.148255E-11 -2.371634E-09 -1.350561E-11 -4.156854E-11 -1.350413E-11 -1.334074E-11 -3.475219E-09 -4.480881E-09 1.195787E-08

10 -7.554443E-12 -1.325216E-11 -6.311889E-09 -7.564486E-12 -7.052085E-10 -7.060655E-10 -1.334074E-11 -1.325363E-11 -1.334220E-11 1.005373E-08

11 -8.489279E-10 -4.153980E-11 -7.648849E-12 -8.474774E-10 -7.645313E-12 -7.554443E-12 -4.148255E-11 -4.154444E-11 -4.148719E-11 -7.557957E-12 9.892976E-09

12 -8.474774E-10 -4.162611E-11 -7.659020E-12 -8.487657E-10 -7.655479E-12 -7.564486E-12 -4.156854E-11 -4.163076E-11 -4.157318E-11 -7.568006E-12 -6.471943E-09 9.893138E-09

13 -1.242767E-10 -2.510633E-10 -2.320961E-11 -1.245836E-10 -2.323120E-11 -2.295184E-11 -2.487825E-10 -2.507589E-10 -2.484799E-10 -2.293039E-11 -1.241361E-10 -1.244426E-10 5.453252E-09

14 -1.241361E-10 -2.507589E-10 -2.323120E-11 -1.244426E-10 -2.320961E-11 -2.293039E-11 -2.484799E-10 -2.510633E-10 -2.487825E-10 -2.295184E-11 -1.242767E-10 -1.245836E-10 -1.913650E-09 5.453252E-09

Capacitance matrix, in units of [farads/km] for the system of equivalent phase conductors.

1 1.426381E-08

2 -4.394814E-10 6.522916E-09

3 -6.277266E-09 -4.394814E-10 1.426381E-08

Capacitance matrix, in units of [farads/km] for symmetrical components of the equivalent phase conductor. Rows proceed in the sequence (0, 1, 2), (0, 1, 2), etc.; columns proceed in the sequence (0, 2, 1), (0, 2, 1), etc.

0 6.912694E-09
0.000000E+00

1 3.171851E-10 3.236077E-09
-5.493807E-10 5.605050E-09

2 3.171851E-10 1.406892E-08 3.236077E-09
5.493807E-10 0.000000E+00 -5.605050E-09

Impedance matrix, in units of [ohms/km] for the system of physical conductors.

1 5.316680E-01
8.274928E-01

2 1.159068E-02 5.365832E-01
9.868073E-02 8.014656E-01

3 1.535689E-02 2.088207E-02 5.584502E-01
3.106794E-02 4.947646E-02 7.439008E-01

4 9.625161E-03 1.159159E-02 1.535846E-02 5.316692E-01
6.045188E-01 9.869994E-02 3.107239E-02 8.274846E-01

5 1.535715E-02 2.088209E-02 3.640335E-02 1.535873E-02 5.584502E-01
3.106901E-02 4.947660E-02 2.885327E-01 3.107346E-02 7.439008E-01

6 1.535873E-02 2.088495E-02 3.641191E-02 1.536030E-02 3.641531E-02 5.584673E-01
3.105161E-02 4.944800E-02 2.884992E-01 3.105606E-02 5.209167E-01 7.438723E-01

7 1.159159E-02 1.454116E-02 2.088493E-02 1.159249E-02 2.088495E-02 2.088781E-02 5.365860E-01
9.865166E-02 5.784896E-01 4.948775E-02 9.867087E-02 4.948789E-02 4.945928E-02 8.014533E-01

8 1.159068E-02 1.453975E-02 2.088209E-02 1.159158E-02 2.088207E-02 2.088493E-02 1.454116E-02 5.365832E-01
9.868048E-02 5.612867E-01 4.947660E-02 9.869970E-02 4.947646E-02 4.944786E-02 5.469453E-01 8.014656E-01

9 1.159158E-02 1.454116E-02 2.088495E-02 1.159249E-02 2.088493E-02 2.088779E-02 1.454258E-02 1.454116E-02 5.365860E-01
9.865142E-02 5.469453E-01 4.948789E-02 9.867062E-02 4.948775E-02 4.945915E-02 5.612745E-01 5.784896E-01 8.014533E-01

10 1.535846E-02 2.088493E-02 3.641531E-02 1.536003E-02 3.641191E-02 3.642047E-02 2.088779E-02 2.088495E-02 2.088781E-02
3.105055E-02 4.944786E-02 5.209167E-01 3.105499E-02 2.884992E-01 2.885042E-01 4.945915E-02 4.944800E-02 4.945928E-02

5.584673E-01
7.438723E-01

11 9.624461E-03 1.159068E-02 1.535715E-02 9.625090E-03 1.535689E-02 1.535846E-02 1.159158E-02 1.159068E-02 1.159159E-02
3.698011E-01 9.868048E-02 3.106901E-02 3.697791E-01 3.106794E-02 3.105055E-02 9.865142E-02 9.868073E-02 9.865166E-02

1.535873E-02 5.316680E-01
3.105161E-02 8.274928E-01

12 9.625090E-03 1.159158E-02 1.535873E-02 9.625719E-03 1.535846E-02 1.536003E-02 1.159249E-02 1.159159E-02 1.159249E-02
3.697791E-01 9.869970E-02 3.107346E-02 3.697929E-01 3.107239E-02 3.105499E-02 9.867062E-02 9.869994E-02 9.867087E-02

1.536030E-02 9.625161E-03 5.316692E-01
3.105606E-02 6.045188E-01 8.274846E-01

13 1.121292E-02 1.395481E-02 1.971709E-02 1.121377E-02 1.971773E-02 1.972029E-02 1.395612E-02 1.395481E-02 1.395611E-02
1.121304E-01 1.999226E-01 4.505354E-02 1.121546E-01 4.505740E-02 4.503165E-02 1.997713E-01 1.999117E-01 1.997605E-01

1.971965E-02 1.121279E-02 1.121364E-02 3.736373E-01
4.502780E-02 1.121171E-01 1.121413E-01 8.294106E-01

14 1.121279E-02 1.395481E-02 1.971773E-02 1.121364E-02 1.971709E-02 1.971965E-02 1.395611E-02 1.395481E-02 1.395612E-02
1.121171E-01 1.999117E-01 4.505740E-02 1.121413E-01 4.505354E-02 4.502780E-02 1.997605E-01 1.999226E-01 1.997713E-01

1.972029E-02 1.121292E-02 1.121377E-02 1.340872E-02 3.736373E-01
4.503165E-02 1.121304E-01 1.121546E-01 3.392191E-01 8.294106E-01

Impedance matrix, in units of [ohms/km] for the system of equivalent phase conductors.

1 1.499809E-01
3.415236E-01

2 1.831911E-02 1.570599E-01
4.724190E-02 5.571148E-01

3 1.946809E-02 1.831911E-02 1.499809E-01
1.689972E-01 4.724190E-02 3.415236E-01

Impedance matrix, in units of [ohms/km] for symmetrical components of the equivalent phase conductor. Rows proceed in the sequence (0, 1, 2), (0, 1, 2), etc.; columns proceed in the sequence (0, 2, 1), (0, 2, 1), etc.

0 1.897448E-01

5.890413E-01

1 -2.807644E-02 1.309684E-01

-1.392747E-02 -7.922386E-02

2 2.609977E-02 1.336385E-01 -1.340941E-01

-1.735117E-02 3.255604E-01 -7.381006E-02

Table 3.1: Parameters of ehv transmission line derived using ATP6 software

	Zero Sequence	Positive Sequence	Units
Surge impedance	5.33818E+02	2.82174E+02	**Magnitude(ohm)**
	< -8.92752E+00	< -1.11588E+01	**Angle(degree.)**
Attenuation	1.56262E-03	2.09646E-03	**db/km**
Velocity	2.74317E+05	2.56750E+05	**km/sec**
Wavelength	5.48634E+03	5.13500E+03	**km**
Resistance	1.89745E-01	1.33638E-01	**Ω/km**
Reactance	5.89041E-01	3.25560E-01	**Ω/km**
Susceptance	2.17169E-06	4.41988E-06	**mho/km**

Table 3.1 shows the parameters for a 400 km line that is used for the computer simulation. For fault location and transient studies, line is divided into four subsections of 100 km. Sources of different capacities from 3.5 GVA to 35 GVA are used for transient and steady state studies. Driving sources are represented in their source impedances.

3.2.2 Transmission Line Parameters for Hardware

To investigate the propagation of the PLC signal and interference caused due to inefficiency of the line traps on practical bases, hardware of the transmission line was constructed by scaling down the parameters of line obtained from computer simulation. The parameters were scaled down from 500 kV to 415 V. Series and parallel parameters were lumped for 100 km, to make 3-phase four Π circuits. Values of the parameters (series impedance R + jL and parallel capacitance C) were modified to the available values for the hardware. With the new modified values, accuracy of the line model was tested with the simulation tool (ATP6). The values used for the construction of the line model are:

Series resistance = 0.6 Ω/100 km-per phase
Series inductance = 30 mH/100 km-per phase
Shunt capacitance = 0.385 μF/100 km-per phase

The above mentioned parameters were used to make 3-ϕ Π-circuits for the required length of the line. The line was divided into four sections of 400 km. The characteristics impedance of the model line can be calculated as follows:

System frequency " f " = 50 Hz

Resistance for full length of line " R" = 0.576*4 Ω

Inductance for full length of line "L" = 30e-3 * 4 mH

Capacitance for full length of line "C" = .388e-6 * 4 μF

Let

$$S = 2 * \Pi * f * j$$

$$Z = R + S * L$$

$$Y = S * C$$

$$Z_c = \sqrt{(abs(Z/Y))}$$

$$= 278.3233\ \Omega$$

This line model was tested for a large spectrum of frequencies ranging from 10 Hz to 1 MHz. The performance of the line was acceptable for the PLC applications for the frequency less than 95 kHz. Graphical representation of the line model is shown in Figure 3.2.

3.3 LINE TRAPS

Line traps are used for the isolation of the carrier channel from certain detrimental conditions and also to isolate carrier channels from one another to prevent interference. Broad band line traps were used for the computer and hardware simulation of the system. Due to size and cost constraints of the line traps, interferences can be prevented to some extent. For complete isolation of the PLC signals at busbars, adaptive interference cancellation schemes appear to be very supportive for this kind of application. The schematic diagram of the line traps is shown in Figure 2.1.

The main coil and its tuning elements are always protected against lightning surges by suitable arresters. In the line model, operating voltage was within a safe limit eg. 415 Volts, protection against high voltage surges was eliminated. The parameter values used for the line traps for the hardware and computer simulation studies were as follows:

Inductance of the main coil " L_1 " = 0.300 mH

Capacitance in parallel with the coil " C_1 " = 0.0158 μF

Capacitance for the tuning circuits " C_2 "	=	$0.0030\ \mu F$
Inductance for the tuning circuit " L_2 "	=	1.200 mH
Resistance for the tuning circuit " R "	=	$300.0\ \Omega$

Required isolation level and spectrum of the frequencies depend on the selection of the parameters of the line traps. To obtain isolation for a certain spectrum of frequencies, appropriate choice of the capacitors and fine tuning of the main coil, play the major role.

3.4 COUPLING CAPACITOR

Different types of couplings can be used for injecting the PLC signal on the power lines, which mainly depends upon the required specifications and the allowable level of attenuation. Phase-to-phase and phase-to-ground couplings are mostly used in the power industry. Phase-to-phase coupling is more secure for injection of the signal on the line. If one phase becomes faulty, propagation of the signal will continue on the other healthy phase. From practical field studies, the efficiency of this type of coupling is higher but this type of coupling is more expensive. Phase-to-ground coupling is less expensive but the efficiency drops to a lower value. In this work, phase-to-ground coupling is used. Parameter values of the coupling capacitors depend on the spectrum of frequencies used for the PLC signals. In power system utilities, data transmission for the protection, telemetry and voice communication is conducted at different bandwidths. To separate the data for different applications, coupling capacitors are divided into two groups.

For simulation of the PLC system and adaptive interference cancellation, only one stage of coupling capacitors is used, as the data is considered only for voice communication. Drain coils are used to facilitate the current flow through to ground and also signal is picked up and injected across the drain coils, depending upon the nature of application (transmitter or receiver). Figure 3.3 shows the physical connection of the coupling capacitors with the transmission lines. The leakage signal through line trap is also sensed across the drain coil of coupling capacitors. That is used as an input for cancellers for the estimation of output signal of the line trap. This estimated output is used to cancel the interference caused by line trap. For computer and hardware simulation studies, central-phase-to-ground coupling is used because this type of coupling is the most optimum and its attenuation is less than that of any other phase to ground coupling [9].

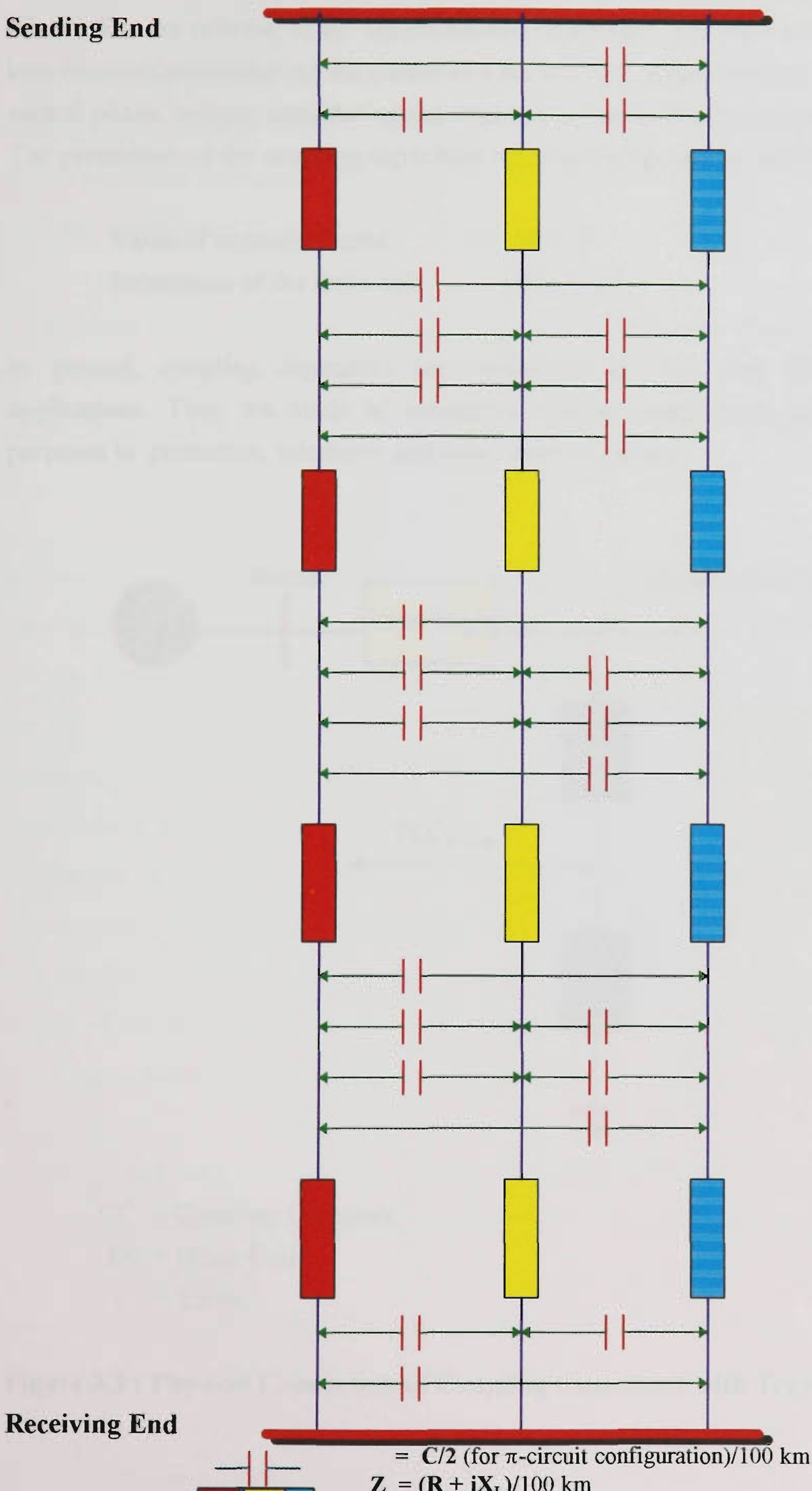
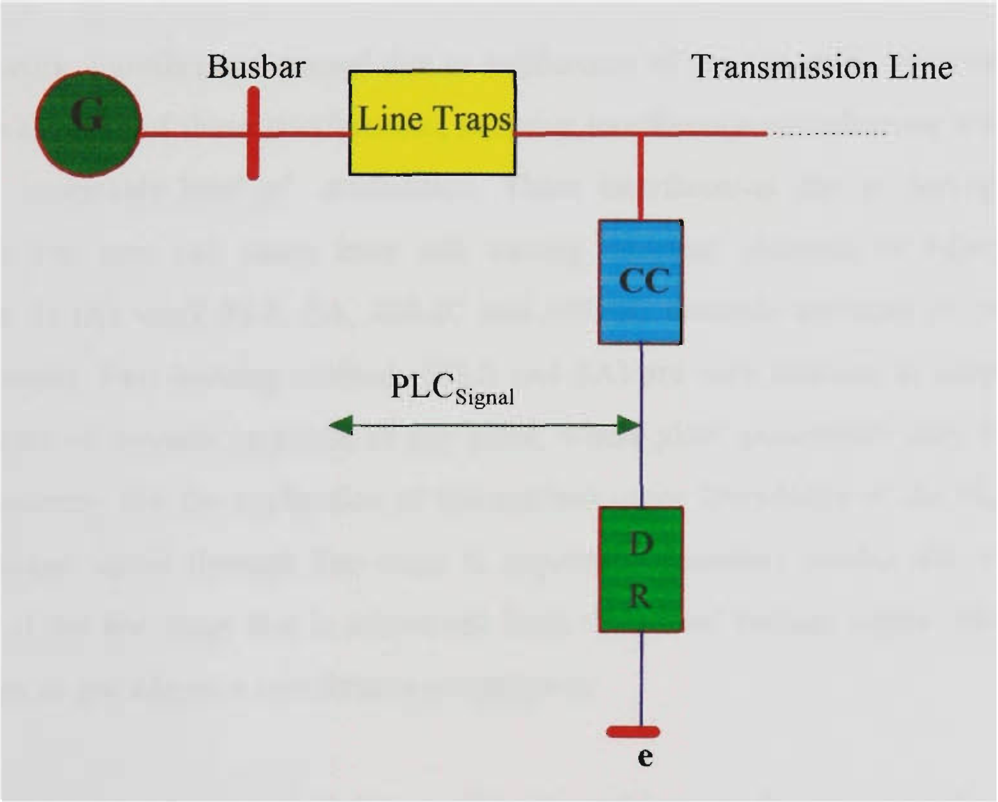


Figure 3.2 : Model of Transmission Line for Hardware Simulation

Couplings preventing modal cancellation and whose attenuation levels are below 20 dB [9] thus are referred to as "recommended couplings". For the studies of adaptive interference cancellation on the power line model, PLC signal is being injected on the central phase, without considering the attenuation caused by the coupling capacitors. The parameters of the coupling capacitors for required spectra are as follows:

Value of capacitors used	= 0.027 μF
Inductance of the drain coil	= 0.8443 mH

In general, coupling capacitors are considered as high pass filters for PLC applications. They are made of capacitive voltage transformers to serve all the purposes ie. protection, telemetry and data communications.



CC = Coupling Capacitor
DR = Drain Coil
e = Earth

Figure 3.3 : Physical Connection of Coupling Capacitors with Transmission Line

3.5 ADAPTIVE INTERFERENCE CANCELLATION

Falsified transmission of data on line may result in a fatal situation in power system control and operation. There are many factors, which may contribute to reach the situation of data corruption. The factors, which contribute to the interferences in the PLC signal propagation may be classified into two major groups:

a. Source with constant and unpredictable interferences eg. corona, switching operations and transient faults on the system etc.
b. Source of interferences due to inefficiencies of the PLC equipment eg. line traps etc.

In this work, interferences caused due to inefficiency of the line traps are studied. For the cancellations of these interferences, adaptive interference cancellations are used to get the acceptable level of attenuation. These interferences due to leakage signal through line trap can cause inter talk among different channels of adjacent line sections. In this work RLS, SA, AFLIC and ANNIC methods are used to cancel the interferences. Fast learning methods (RLS and SA) are very efficient in adapting the parameters of dynamic response of any plant, where plant parameters vary with time and frequency. For the application of this method, prior knowledge of the PLC signal and leakage signal through line traps is required. Cancellers predict the estimated output of the line traps that is subtracted from the actual leakage signal through the line traps to get adaptive interference cancellation.

Computer and hardware simulation studies of adaptive interference cancellation have been analysed using MATLAB, MATRIXx and ATP6 mathematical and designing tools. As mentioned in Section 3.2.2, a frequency spectrum of 15-75 kHz is suitable for transmission line model. However, frequency selection constraints due to limited data acquisition facilities further narrowed the frequency spectrum to the maximum of 50 kHz. Mathematical model and operations of the cancellers are explained in Chapter 2. For simulation, PLC signals have been generated using sinusoidal sources of required frequencies.

The parameters of the adaptive canceller algorithms depend upon the level of the PLC signal and leakage signal through line traps. For RLS and SA methods, internal state matrices are estimated on the latest values of the input and output of the line traps. The parameters defining the conventional adaptive algorithm vary with the varying behaviour of the line traps.

3.6 LOW PASS AND BAND PASS BUTTERWORTH FILTERS

For the true modelling of PLC signals for simulation, signal processing tool of MATLAB was used to create a random noise of bandwidth of 2 MHz. The constraints being imposed due to the parameters of hardware model of the transmission line and limitation of data acquisition facilities (data acquisition card PCL_818 can have a maximum sampling frequency of 100 kHz) forced to use the signals having frequencies less than 50 kHz. Chapter 4 describes the results of frequency response of the transmission line model under different coupling arrangements.

The signal used to analyse the performance of the PLC system is a digitised analog signal. To make the resolution of PLC signal very high, sampling frequency of 2 MHz was used. To create the signal for some particular channel of required band width, low pass and band pass butterworth filters were designed using signal processing tool of MATLAB. The signal of 2 MHz was passed through the filters to get the required signal. The parameters of the low pass filter are given below:

Order of the filter	=	4
Bandwidth of filter	=	80 kHz

Discrete time transfer function of the filter can be represented as:

$$H(Z)=\frac{10^{-4}(0.1329+0.5317Z^{-1}+0.7976Z^{-2}+0.1329Z^{-3})}{Z^{-1}-3.6717Z^{-2}+5.068Z^{-3}+0.7199Z^{-4}}$$

The filtered signals are taken as PLC signals at the transmitter terminal. Then these signals were used to test the performance of line traps and adaptive interference cancellers.

The parameters used for the computer and hardware simulation studies of PLC system are presented in this chapter. Selection of parameters of PLC equipment can be varied to suit required application and specifications. For the computer simulation of the required system, MATLAB, MATRIXx and ATP6 proved to be very flexible tools for the modelling of PLC network and complex cancellation algorithms. Frequency responses of line traps and coupling capacitors obtained using MATLAB helped to find appropriate parameters for required spectrum of frequencies. Results of the studies are presented in Chapter 6.

ATP6 software was used to study the steady state and transient behaviour of the PLC equipment under different operating conditions of the system. Studies of propagation of different modes of PLC signal on transmission line were studied, results are shown in Chapter 5.

CHAPTER 4

HARDWARE DESIGN OF PLC MODEL WITH ADAPTIVE INTERFERENCE CANCELLER

4.1 INTRODUCTION

Transmission lines are considered to be a very efficient means of data communication for power system utilities. Problems associated with the propagation of PLC signal on the line can be studied either by simulation or by using a laboratory model of the power network. The PLC network with its associated equipment has been simulated using ATP6, MATRIXx and MATLAB. Results are given in Chapters 5-9. The laboratory model of PLC network is presented in this chapter. The feasibility of different coupling schemes has been investigated on the model network.

The main focus in this work was to investigate the interference caused by the inefficient line trap and to suggest appropriate adaptive interference cancellers. Based on the laboratory simulation and hardware studies, recommendations have been made to extend this method for implementation on a practical system. Use of PLC communication is becoming more vital as the latest techniques for protection, fault location and telemetry etc. need more security in data transmission. To avoid any incorrect control operation, the integrity of data transmission should be verified from various modes of communication eg. fibre optics, microwave, PLC or manual. Various modes of communication have different advantages and disadvantages. Fibre optics immunity against most of the noises on the transmission line makes it the most effective of all modes. Power industry is making use of fibre as a mode of information communication. Fibre optic communication is mostly used in modern power systems.

Microwave communication can be used very efficiently for short distances. Normally transmission lines have lengths in hundreds of kilometres. Although, PLC is not completely immune from the noise on the transmission line, it has the ability to transmit the signal for a long distance. Availability and low cost make it attractive for the power industry to use for data transmission. For verification and security of data, PLC is considered a very reliable back-up for long distance communication of signals.

In this work, a PLC laboratory model has been designed and the major disadvantage associated with PLC networks (inefficiency of line trap) has been addressed. For hardware studies, data analysis was carried out using MATLAB on SUN and MATRIXx on Apollo workstations.

Some frequency constraints were observed in the hardware studies of the model. Frequency response of transmission line model suggested the use of frequencies less than 95 kHz. Frequency response for the central-phase-to-ground coupling is given in Figure 4.1. The next constraint appeared from data acquisition card (PCL_818) [78]. The maximum theoretical sampling frequency, which can be obtained was 100 kHz. For practical signals, frequency was limited to a maximum value of 50 kHz. In hardware and computer simulation studies, systems were tested for different spectra of frequencies. The following sections describe the major hardware features.

4.2 HARDWARE DESIGN OF LINE TRAPS

Line traps were designed using the parameters given in Section 3.3. The circuit was connected as shown in the Figure 2.1. Appropriate coils were selected to give the required level of inductance for the circuits. A LCR (inductance, capacitance and resistance) meter was used to test the accuracy of the required parameters. Connected circuit was tested to give the required level of attenuation. Level of attenuation can be adjusted with the appropriate variation of load. Line traps were connected on both sending and receiving ends of the central phase of the transmission line. PLC and leakage signals were monitored using CRO. Propagation of signal towards the receiving end was also observed by monitoring the three phases of line. Signal appeared on three phases due to lumped capacitor couplings in transmission line model. Details of line model are presented in Section 4.3.

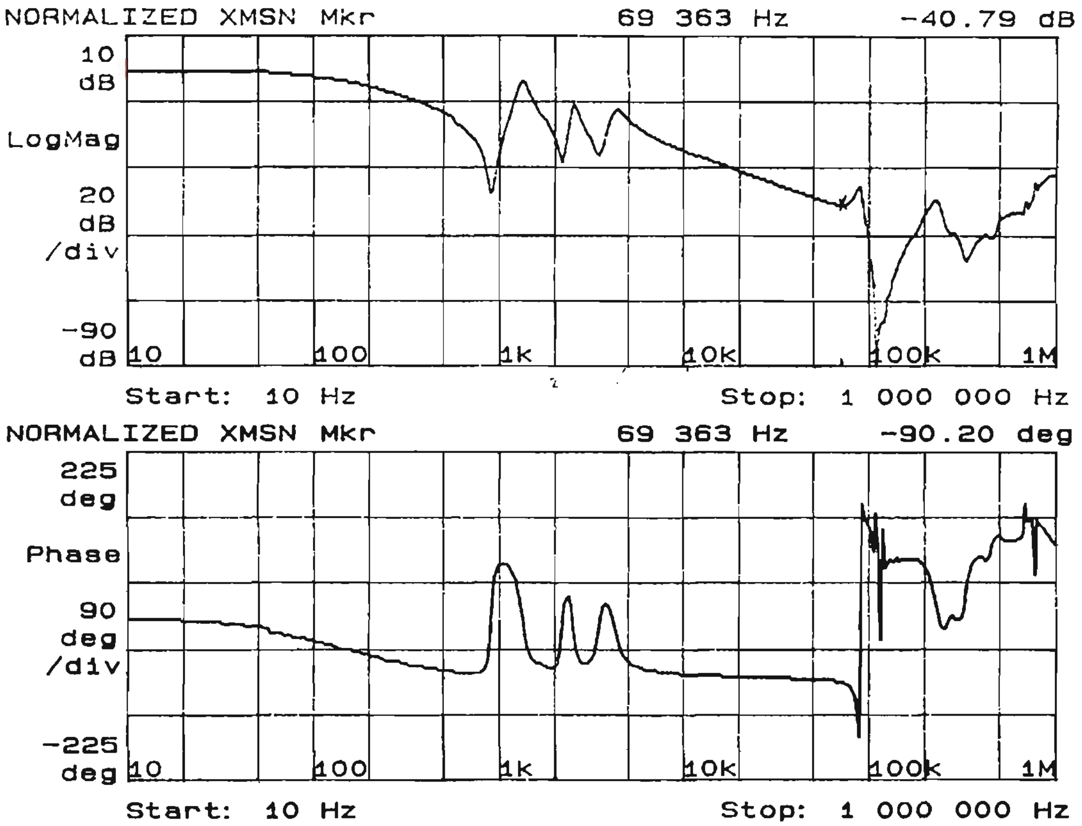


Figure 4.1: Frequency response of the line model using central-phase-to-ground couplings

Signal generator was used to conduct PLC signal on the central phase of the line. In this work single-phase-to-ground coupling was considered. Due to the main focus on interference cancellation, attenuation due to coupling capacitors was ignored. PLC signal was coupled without physical coupling capacitors. The behaviour of transmission line model, while acting as PLC signal channel, for various coupling schemes has been investigated in Section 4.3.

4.3 DESIGN OF TRANSMISSION LINE MODEL

The laboratory model of the transmission line was constructed from the knowledge of the computer simulation of line, using Modal Analysis. Parameters and geometry of line are given in Section 3.2. ATP6 is the most convenient tool for the computer simulation of transient and steady state behaviour of transmission lines with their associated network. Computer simulation results for steady state and transient studies of the transmission line are presented in Chapter 5, where studies of various modes in PLC signal have been investigated in terms of fault transient conditions.

4.3.1 Implementation of Laboratory Model

In the first stage of computer simulation, parameters of line were evaluated in Ω, H and F per kilometre length. Simulation of the line was done in distributed parameters for a length of 400 km. To construct a line model, parameters were scaled down to laboratory operating voltage of 415 V. The scaling down of line parameters was performed based on the operating voltages and characteristic impedance of the concerned lines. Details are given in Appendix E. The line was modelled using lumped parameters of lengths of 100 km each in four sections, a schematic diagram is shown in Figure 3.2. In the four π-networks, capacitance was divided into two halves to appear at remote ends of each section. Three phases were coupled through shunt capacitances, due to coupling, PLC signals also appeared on other phases as well. This verifies the fact, that in the presence of other phases, aerial modes become significant and make their return path from the outer phases [23]. Detailed description of mode propagation on three phases is given in Section 5.3.

For series impedance of line ($R + j\omega L$), inductance coils and very low adjustable resistors were used. Figure 4.2 outlines the circuit arrangement mounted on the laboratory wall. Figure 4.2 also shows the presence of shunt capacitance wired across three phases. At no load conditions, charging effect (Ferranti effect) of line was also investigated.

Figure 4.2: Photographic representation of a line model for PLC application

Due to no load conditions, a rise in voltage at the receiving end was significant. Practical experience shows that rise in voltage towards receiving end under no load conditions can be quite pronounced in the case of very long and ehv lines. Results are presented in Chapter 7 to verify the fact.

Transmission line model was also subjected to transient conditions. 1-phase-to-ground fault conditions were observed on the network at different instants of time of voltage to see the transients on the oscilloscope. When fault conditions were incepted at the peak of the voltage (Cosine wave form) significant transients were observed.

The transmission line model described above was used as PLC signal channel. Adaptive interference cancellation schemes were also tested on the same line.

4.4 IMPLEMENTATION OF DIFFERENT COUPLING SCHEMES ON POWER LINE MODEL

Conduction of PLC signal on power lines can be done using different coupling schemes. Optimum couplings are less expensive and offer low attenuation to PLC signal. In selecting optimum coupling schemes, there is always a trade off between expenses and attenuation. Practical power industry surveys show, two types of coupling are used in power system practices, eg. single-phase-to-ground and phase-to-phase couplings. In this work, single-phase-to-ground coupling is used in both computer and hardware simulation studies.

In hardware studies, the line was tested separately for power and PLC signals. Frequency response given in Figure 4.1 shows, satisfactory performance of the line at power signal. Other tests outlined in Section 4.3 also gave satisfactory results of the line on power frequency. In this work, more focus was on the behaviour of line on higher frequencies under different coupling arrangements. Circuit arrangement for the studies of couplings is presented in Figure 4.3. For adaptive interference cancellation, PLC and PLC leakage signals were sensed at two different points from the line, to provide inputs to canceller algorithms. Details for data acquisition are given in Section 4.5.

4.4.1 Couplings for Interference Cancellation

Computer simulation studies presented in Chapter 6 have suggested the use of an extra pair of coupling capacitors to sense input signals for cancellers. In the single-phase-to-ground coupling case, three separate sets of coupling capacitors should be used on each remote end to implement this technique on practical lines. They can be reduced to two in number, if the same set of coupling capacitors can be used as an input (PLC signal) for interference canceller and transmitter/receiver. Even if two sets of coupling capacitors were used, still two separate channels would be required to sense inputs for cancellers. The schematic diagram is given in Figure 4.4.

4.4.2 Studies of Different Coupling Schemes

In this study, phase angle and frequency responses of line model have been presented under different conditions of coupling for PLC signal. A spectrum and network analyser was used to analyse the behaviour of transmission line circuit for the frequency spectrum from 10 Hz to 1 MHz under different coupling schemes.

A network analyser was calibrated after connecting the channel leads. The sending and receiving ends of the line were connected as inputs to the network analyser. The required bandwidth of input signal was set. The device finds attenuation and change of phase angle of the connected channel for specified spectrum of frequencies. The response to any study can be plotted with a plotting facility for the device.

For a complete study of line under various coupling arrangements, input signal was coupled at different phases and also a combination of required phases was used to conduct the signal on the line. To find attenuation due to line, outputs were taken at different phases. For maximum power flow of the signal, matching impedances of 290 Ω were connected on remote ends of the line. Due to lumped parameters of the line construction, phase response of line was no longer constant. Results have been described in the Figure 4.1. Characteristic impedance of line is constant, but load on line is always changing. For maximum power flow in industrial practices, impedance matching unit combined with coupling capacitors give approximate matching of impedance to conduct PLC signal more efficiently.

For the studies of PLC signal propagation on model line, the following coupling schemes were studied:

- 1-phase-to-ground coupling
- phase-to-phase coupling
- 3-phase coupling

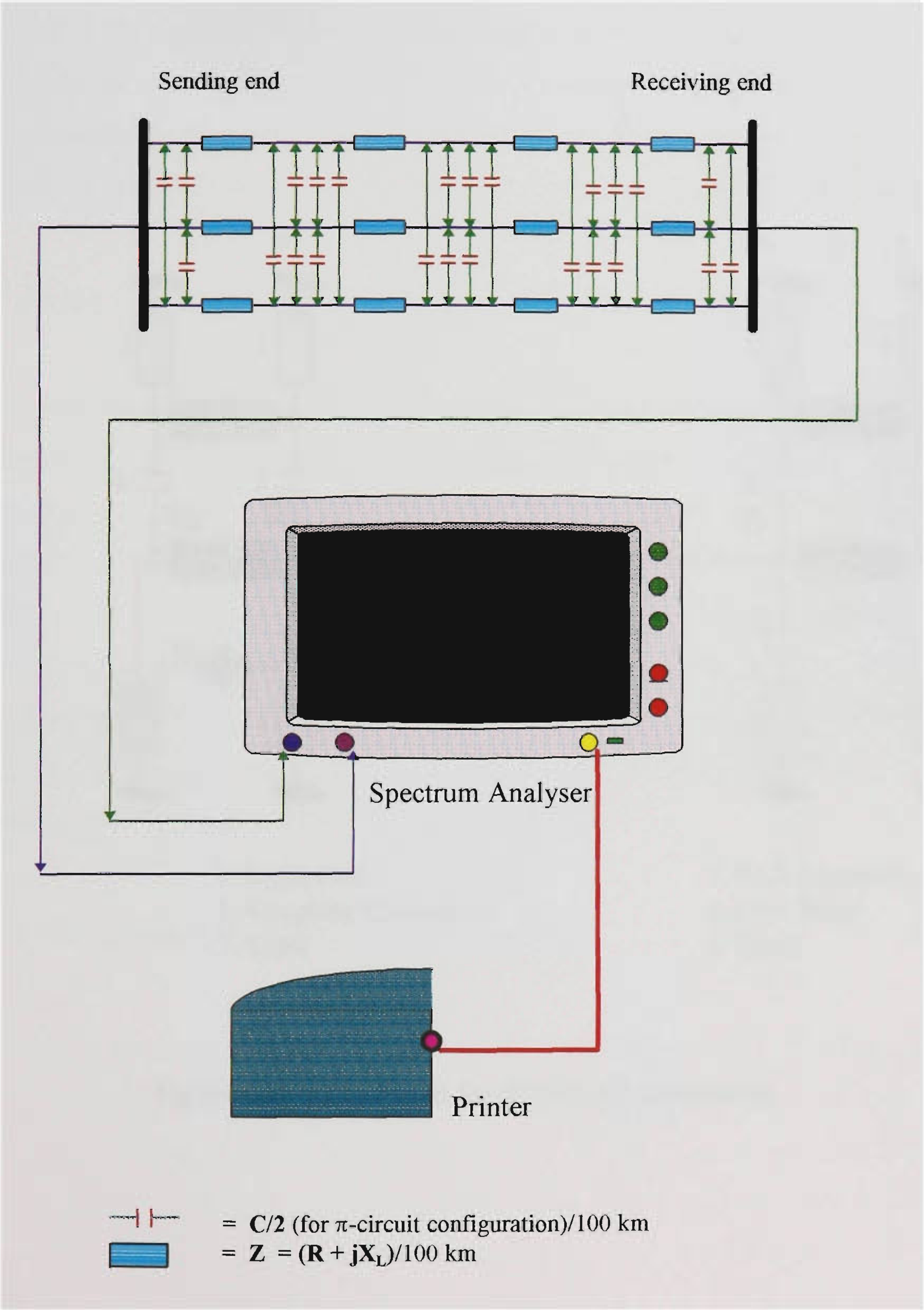


Figure 4.3 : Circuit arrangement for power line model network analysis

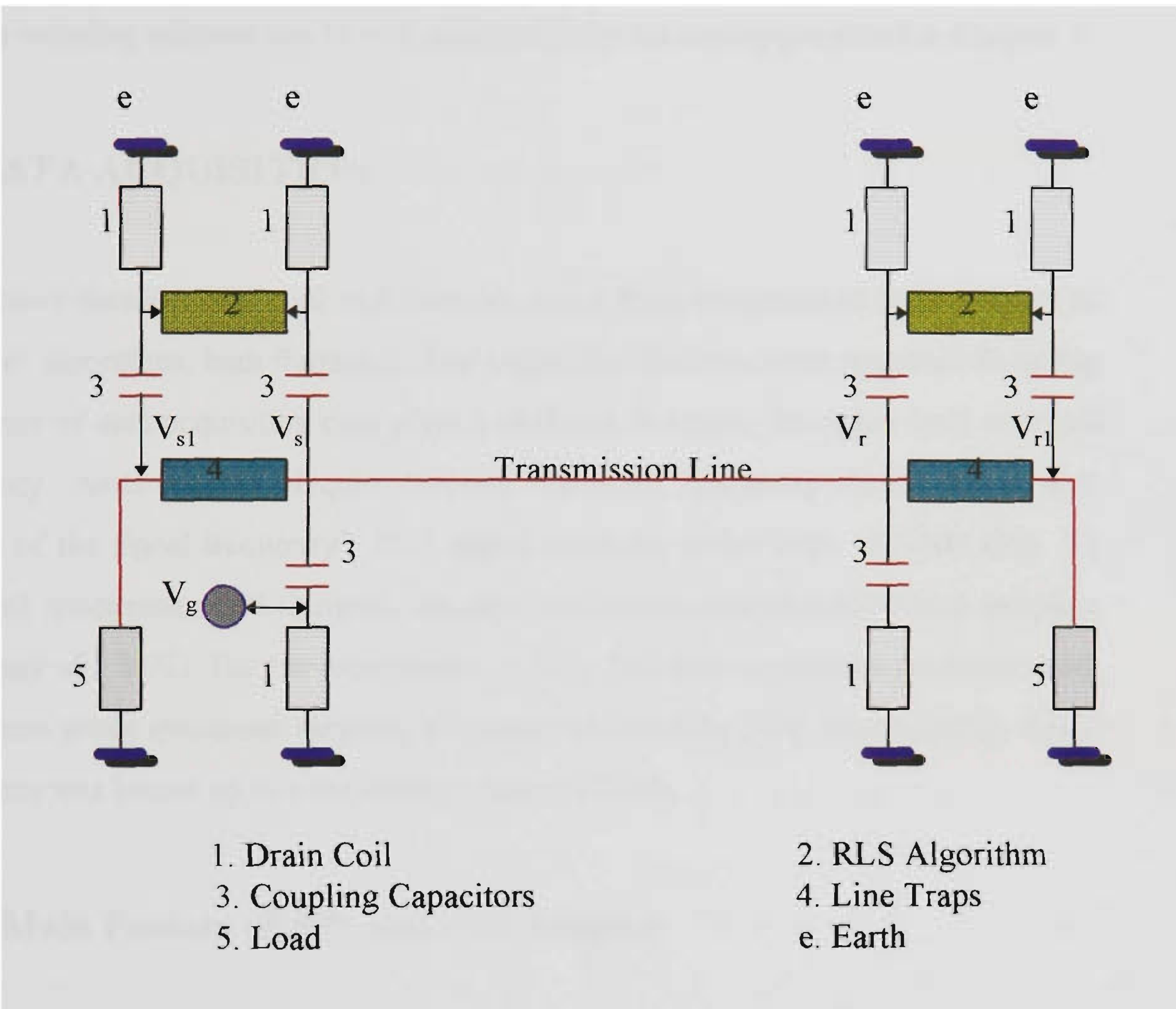


Figure 4.4 : PLC Model for MATLAB Simulation

For further investigation of PLC signal attenuation on the line model, the input of spectrum analyser was connected to one phase and output was taken from other phase. Presence of PLC signal on other phases showed nearly the same kind of magnitude and phase responses, which show that in multi-phase systems, aerial modes of PLC signal also propagate on outer phases [23]. Behaviour of the model transmission line under various coupling schemes can be well analysed from the results presented in Chapter 7.

4.5 DATA ACQUISITION

To retrieve data for PLC and PLC leakage signal from transmission line as inputs to canceller algorithms, high frequency data acquisition facilities were required. Sampling frequency of data acquisition card plays a vital role in setting the upper limit of signal frequency. According to Nyquist theorem "sampling frequency should be at least double of the signal frequency". PLC signal spectrum varies from ~15-500 kHz. To cover all spectrums of PLC signal, the data acquisition card should have a sampling frequency of 1 MHz. For the experiments, a PCL_818 data acquisition card was used, which can attain maximum sampling frequency of 100 kHz [78]. Theoretically, signal frequency was bound up to a maximum value of 50 kHz.

4.5.1 Main Feature of A/D and D/A Adaptor

The PCL_818 is a high performance, high speed, multi-function data acquisition card with programmable gain for the IBM PC XT/AT or compatible. The high-end specifications of this full size card and complete software support make it ideal for a wide range of applications in industrial and laboratory environments such as data acquisition, process control, automatic control and factory automation. The key features of this interface control card include:

- Switch selectable 16 single ended or 8 differential analogue input channel configuration.

- 12 bit successive approximation converter is used to convert analog inputs. The highest sampling rate is 100 kHz in DMA (Direct Memory Access) mode.
- A/D converted data can be transferred by program control, interrupt handler routine or DMA transfer.
- Two 12 bits D/A outputs channels can be used.
- 16 digital inputs and 16 digital outputs are available for interfacing.
- The versatility of the card can be enhanced with optional daughter boards.
- PCL_818 provides a powerful and easy to use software driver routines which can be accessed by the call statements.

4.5.2 The Driver Routines

Software driver routines are available in Pascal, C, C+ + and Basic. Driver libraries are available in four languages. The syntax of procedure calls to the PCL_818 are the same. There is only one procedure for PCL_818. The procedure name is "pcl818". The same procedure can be used for 27 useful functions, which are outlined in manual [78]. Out of five arguments for procedure, one argument assigns a function number. Every function is designed to perform specific operations. To perform a certain task, combinations of different functions are adopted in proper sequence. Use of PCL_818 software driver routine written in Pascal was made to program data acquisition card for this application.

4.5.3 Hardware Specifications of Interface Adaptor

For this particular application, data acquisition card PCL_818 was programmed to serve the appropriate need for PLC [78].

- For initialisation base I/O address of card to communicate with PC was selected $300 (Hexadecimal base address for PCL_818).

- Interrupt level was selected 3.
- Direct memory access (DMA) was selected for the transfer of data.
- For PCL_818, local A/D input range control mode was selected between local and remote modes.
- For local mode, a range of channel voltages was selected -10/+10 volts.
- PCL_818 was programmed to take 16 single ended A/D inputs.
- To select adequate pacer rate, 10 MHz input clock frequency was selected.
- To store data arrays, $7000 (Hexadecimal) was taken as a starting address for the memory.

Retrieval of data from PLC model system representing PLC and PLC leakage signal was performed using two separate channels of the data acquisition card. Data was transferred in direct memory access (DMA) mode and was stored in array form in a file. Figure 4.5 describes the sequence of different steps in flow chart form to accomplish the storage of signals data for the availability of signal processing.

Stored data was arranged to form input format for adaptive interference canceller, programmed using MATLAB and MATRIXx. The numbers of data samples for the signals were limited up to 500 to save memory space. These input data samples were enough to improve the knowledge of RLS and SA methods to estimate accurately parameters and output (leakage signal) of line traps.

4.6 DESIGN OF ADAPTIVE INTERFERENCE CANCELLER

For interference cancellation, unmodulated PLC and associated leakage signals were imported for adaptive canceller. The level of cancellation depends on how the data supplied to the cancellers is generated, whether it is deterministic or stochastic. The mode of data generation for PLC application was deterministic, as input signals for adaptive canceller were readily available.

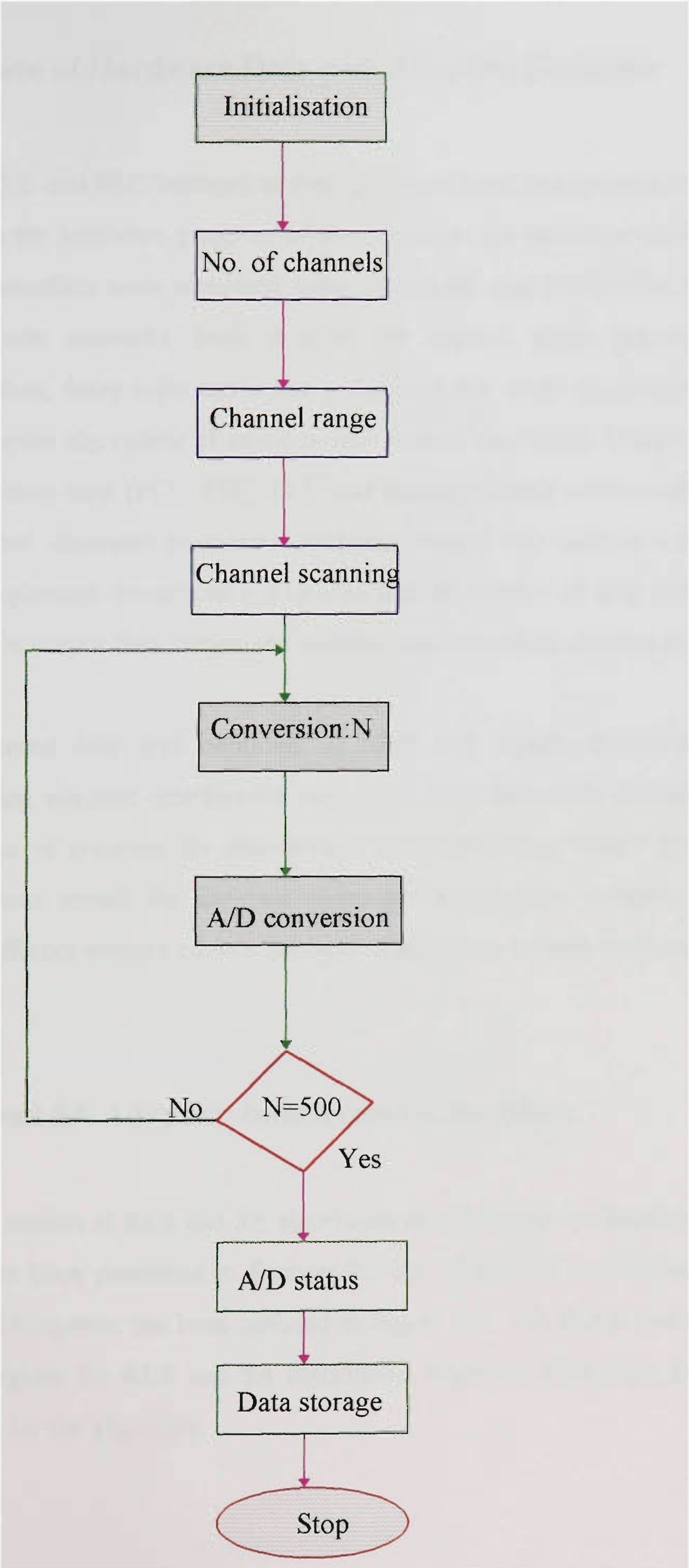


Figure 4.5: Flow Chart of procedure for hardware data storage

4.6.1 Interface of Hardware Data with Adaptive Canceller

The signals (PLC and PLC leakage) at their baseband level were stored in a file, to be used as inputs for hardware program of the canceller. As described earlier, adaptive interference cancellers were simulated using MATLAB and MATRIXx softwares on SUN and Apollo networks. Built in tools for control, signal processing, neural network, simulink, fuzzy logic and image processing etc. made programming easy for even very complex algorithms of adaptive interference cancellers. Using two channels of data acquisition card (PCL_818), PLC and leakage signals were stored in various files for different allowable frequency spectrums. Pascal was used as a programming language to implement driver routines to scan desired number of A/D channels and to store the data in output files. Schematic configuration of system is given in Figure 4.6.

Data from stored files was imported to SUN and Apollo networks for signal processing using adaptive interference cancellers. Data files were loaded in the very first instruction of program for interference cancellers using "load" function. Then loaded data was sorted for the two channels. Appropriate variable names were assigned to different vectors of data (arrays). These data vectors were used as inputs for cancellers.

4.6.2 RLS and SA Adaptive Interference Cancellers

Mathematical models of RLS and SA algorithms to implement as adaptive interference cancellers have been presented in Section 2.5-2.6. Graphical implementation of this method for PLC system has been outlined in Figure 2.2. MATLAB has been used to develop a program for RLS and SA algorithms. Imported data from hardware was used as inputs for the algorithm.

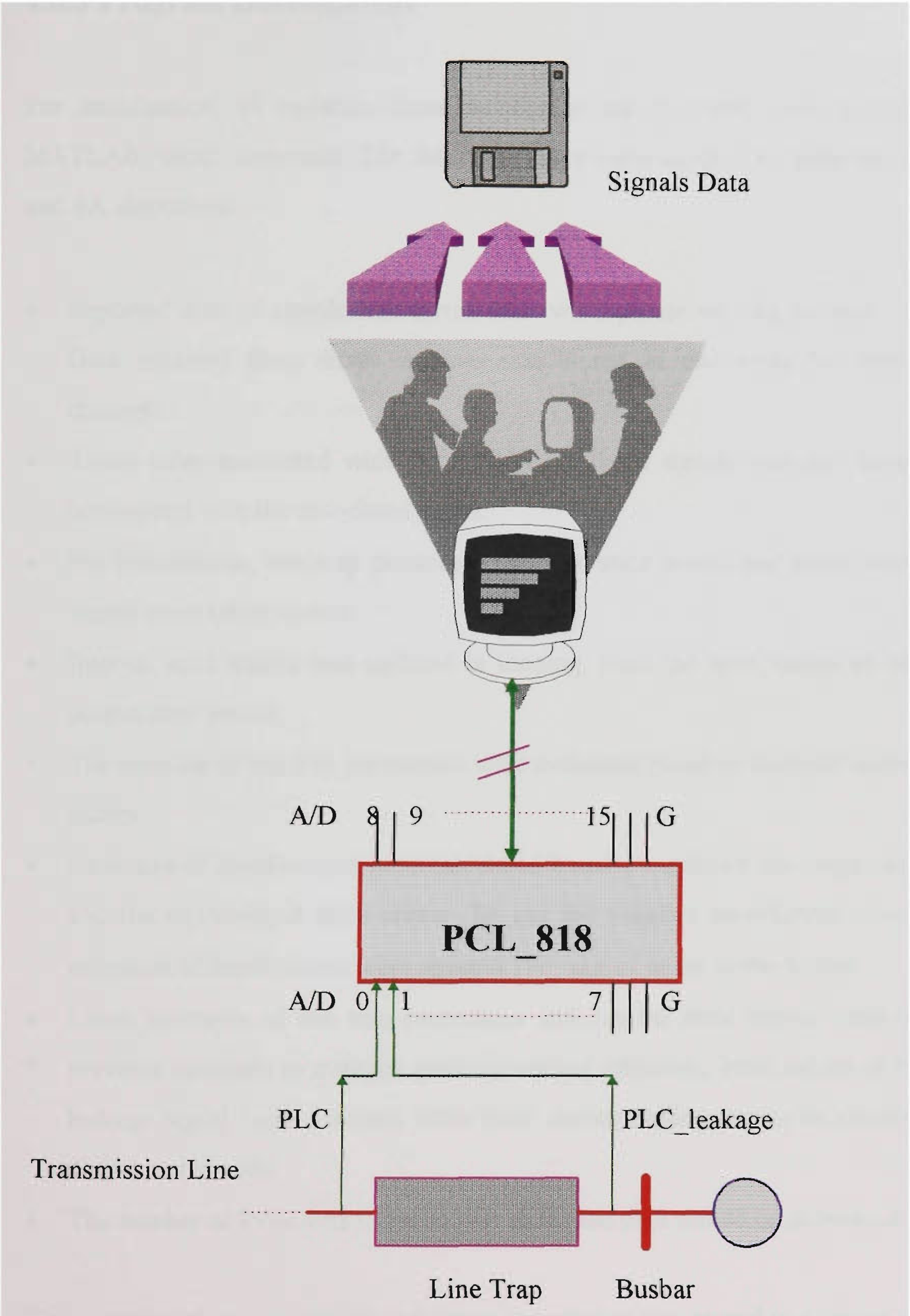


Figure 4.6 : Schematic diagram of Interface Adaptor for PLC model

4.6.3 Program Development

For initialisation, all variables from memory of the computer were cleared using MATLAB 'clear' command. The following steps were adopted to program the RLS and SA algorithms:

- Imported data of signals was sorted into two separate vectors for each channel. Data obtained from driver routines was stored in one array for both of the channels.
- Times array associated with the PLC and leakage signals was also arranged to correspond with the associated signal.
- For initialisation, line trap parameters, internal state matrix and input-output state vector were taken as zero.
- Internal state matrix was updated in looping, from the next values of input and output state vector.
- The estimate of line trap parameters were evaluated based on updated internal state matrix.
- Estimates of interferences were calculated based on updated line traps parameters and the input-output state vector. To get the adaptive interference cancellation, estimates of interferences were injected 180° out of phase to the busbar.
- Latest estimates of line trap parameters and internal state matrix were taken as previous estimates to evaluate more converged estimates. Next values of PLC and leakage signal were assigned from their corresponding arrays to update input-output state vector.
- The number of loops was taken so that all signals data should be processed.

The error signal, as a result of interference cancellation was stored in a vector array for plotting. PLC and leakage signals were plotted against time. The levels of PLC interferences before and after adaptive interference cancellation were plotted to compare the level of attenuation. Computer and hardware simulation results are presented in Chapters 7 and 8.

4.6.4 AFLIC Interference Canceller

Retrieved data from the PLC model network was also imported to Apollo network, where, fuzzy logic based interference canceller was designed. Theory behind the AFLIC design is given in Section 2.7. Implementation results and details about design are given in Chapter 9.

In this chapter, the hardware feature of PLC model and its associated networks are presented. Construction of laboratory power line model was developed from the computer simulation knowledge obtained using ATP6 package. The main objective of the power line model was to provide a realistic PLC model to test performance of different coupling schemes, line trap and adaptive interference cancellation schemes. Based on frequency response of line under different coupling schemes, single-phase-to-ground coupling scheme was selected to couple PLC signal on the line. Also the same coupling scheme was used to retrieve PLC and leakage signal from the line.

Figure 4.1 shows a photograph of a laboratory model of a power line. The power line model can be used to test different fault location techniques and also the line provides good ground to test the operation of modern protection relaying schemes. Adaptive interference cancellation schemes can assist to improve the integrity of protection relaying signals on a realistic system.

In this chapter, hardware models of interference cancellers have been designed. To develop a hardware program of a controller, mathematical tools of MATLAB and MATRIXx proved to be very flexible. Results obtained from the use of the RLS, SA, AFLIC and ANNIC methods for simulation and hardware of PLC models are presented in Chapters 6-9.

CHAPTER 5

SIMULATION OF DIFFERENT MODES OF PROPAGATION FOR PLC USING MODAL ANALYSIS

5.1 INTRODUCTION

Theory of natural modes is the best solution for the propagation study of PLC signal on transmission lines [35]. PLC signal at the sending end decomposes into its modal values and travels on the line with different modal velocities. The parameters of interest in understanding the behaviours of multi-conductor lines are the modal attenuation, velocity, distribution factors and the characteristic impedance matrix. In order to describe the properties of a line completely, it is necessary to do considerable amount of computational work, since frequency and earth resistivity also enter as parameters. A line is described by a number of modes. For earth wires, there will be additional modes. If the frequencies under consideration are below a value corresponding to a half wavelength spacing between towers, it is permissible to assume that the earth wire potential is uniformly zero, and there are then only as many modes as there are phase conductors [38].

According to the theory of natural modes, the HF signal along the line at any point can be resolved into its modal values. These modal values are related to the properties of the system used. PLC signal can be reconstructed from its modal values at any point along the line. Various modes propagate at different velocities, due to having different propagation coefficients.

Travelling wave and surge phenomena in power systems are of importance in solving problems eg:

- relating to PLC communication
- protecting short and ehv long lines
- switching the unloaded lines
- calculating recovery voltages of circuit-breakers under fault conditions.

Significant advances in the solution of such problems were made by Fallou [6], who with the assumption of complete symmetry of conductors applied the concept of symmetrical components to the solution of travelling-wave phenomena. This method is limited, as it yields average values for surge impedances and propagation coefficients, and this masks important effect produced by asymmetry of conductors. Under fault inception, a transient and steady state phenomena of electric network can be studied using either transient analysers or general purpose electromagnetic transient programs. In either case, one finds the time response (voltage and current as function of time) for any inter-connection of resistors, inductors, non-linear elements, switches, sources and transmission lines.

In this work ATP6 was used to find the time response of the PLC system under steady and transient conditions. ATP6 proved to be a useful tool for the studies of propagation of different modes of any signal on the power lines. The complete behaviour of the modes on the transmission line was investigated in terms of fault transient studies. The transients that emerged as a result of the faults involving earth and without earth, are important to describe the domination of modes for the signal propagation.

5.2 CALCULATION OF NATURAL MODES OF PLC

In order to study the natural modes of PLC signal, broad band line traps and central-phase-to-ground coupling were used. The schematic diagram of the circuit is shown in Figure 5.1. Behaviour of the PLC equipment was tested under steady state and transient conditions, results are shown in Section 5.4. The propagation of PLC signal on multi-conductor lines depends on the number of conductors even if only one conductor is energised. A line having only one conductor will show maximum attenuation in the injected signal which is due to the presence of only ground mode.

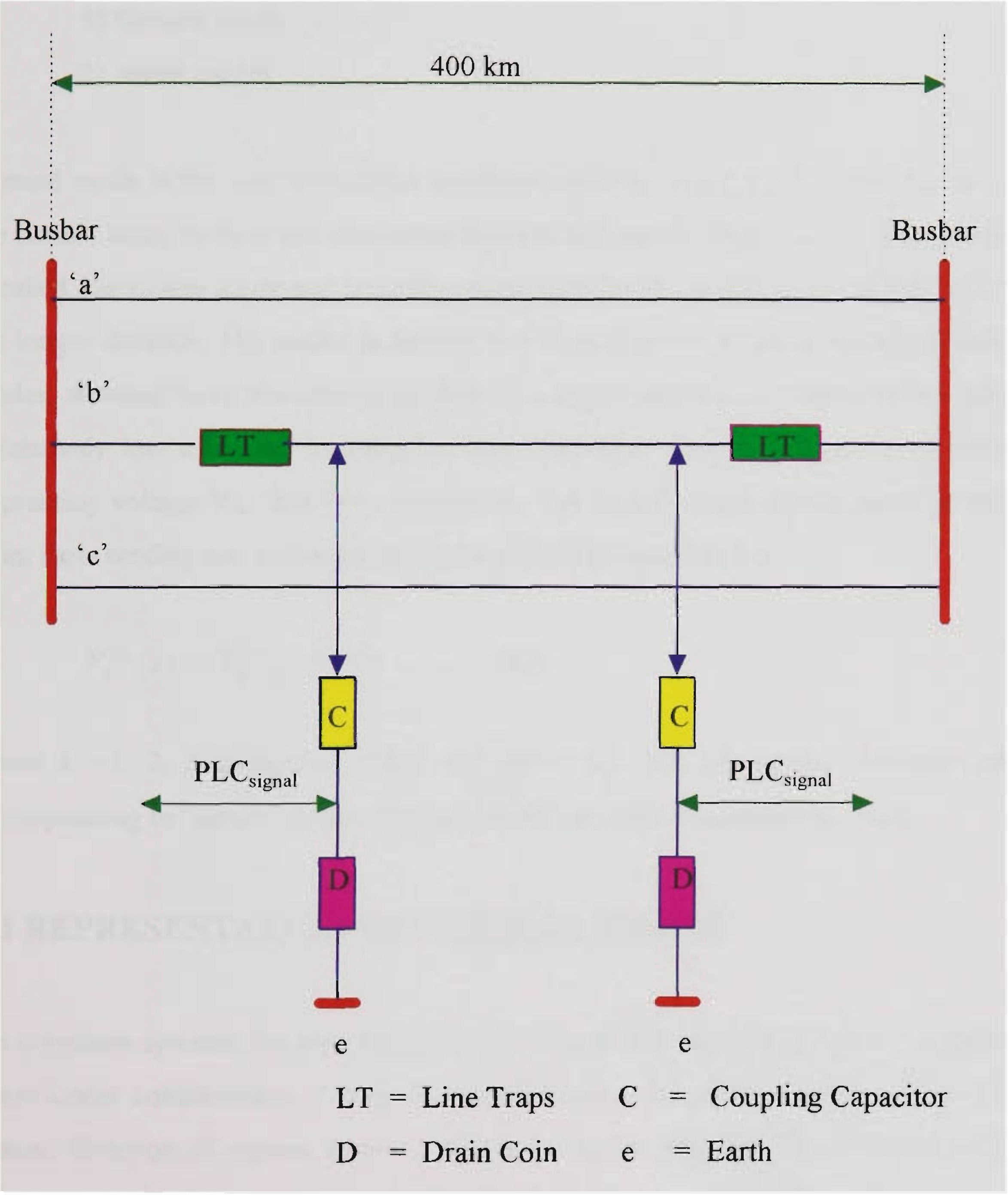


Figure 5.1 : Block diagram of the PLC system

Due to the presence of earth mode alone, the signal power decreases rapidly with the distance following the exponential law. A 2-Φ line will show less attenuation to the injected signal due to the presence of a second phase. A second mode between the two conductors carries the signal for larger distances. Mode 3 appears due to the presence of third conductor, which carries the signal for longer distance than that of mode 2 [23]. Natural modes can be classified into two main groups:

1) Ground mode
2) Aerial modes.

Ground mode is the most attenuated mode on the lines. There are two aerial modes, the second aerial mode is less attenuated than the first aerial mode. Second aerial mode is called line-to-line mode and is mainly responsible for the propagation of PLC signal for longer distance. The results in Section 5.4 show that due to the presence of aerial modes, standing wave phenomena persists for a longer distance. A reflection free with a relatively low loss long transmission line, connected to a high frequency source impressing voltage $V_{(o)}$ has been considered. The modal values of the signal at any point from sending end at any phase can be defined by equation 5.1:

$$V_k^{(n)}(x) = V_{k\ (o)}^{(n)}\ e^{-\alpha(n)x} \quad ....(5.1)$$

where k =1, 2, 3 designates phase and (n) = (1), (2), (3) is the particular set corresponding to "natural modes of propagation". α is the attenuation constant.

5.3 REPRESENTATION OF NATURAL MODES

On polyphase systems, the presence of three of the modes depends upon the particular phase under consideration. Taking into consideration the modal currents in various phases, direction of current flows of different modes depends upon the particular phase eg. mode 2 is not present on phase 2. Graphical representation of the different modes and their direction of flow can be properly understood by referring to Figure 5.2. The detailed description of the behaviour of the three modes for a single circuit 3-Φ system is documented:

Mode 1: The currents due to this mode flow in the same direction in all the three phases and are approximately equal in magnitude. From Figure 5.2 it can be seen that phase 1 has all the three modes and currents are flowing in the same direction.

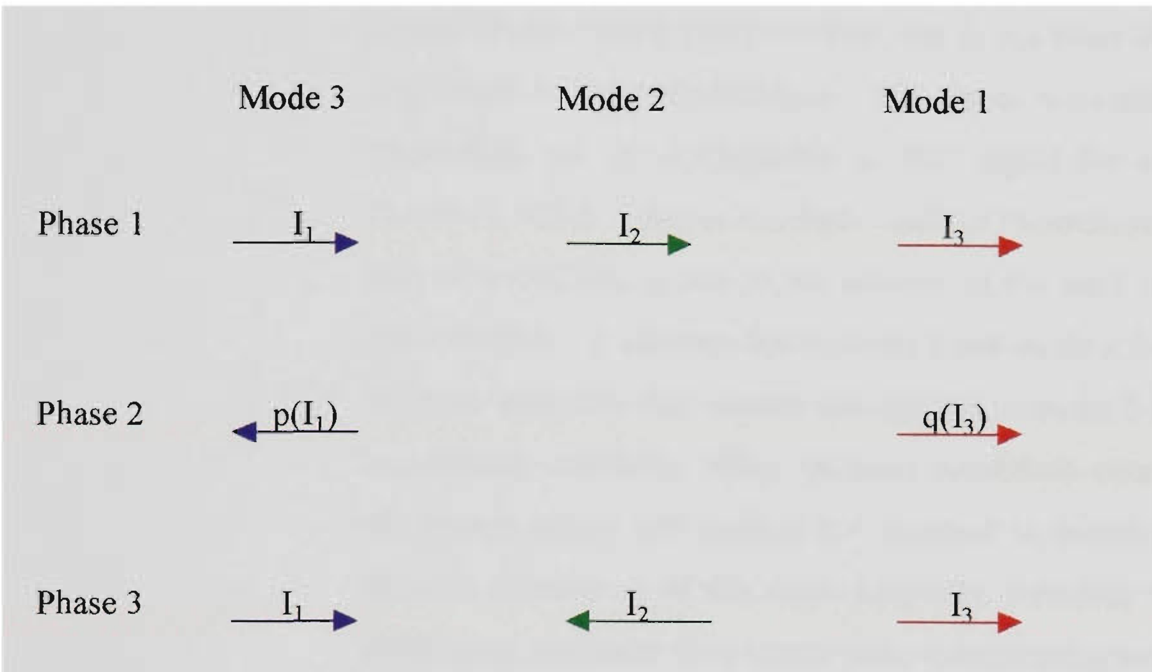


Figure 5.2 : Graphical representation of PLC modes

Due to the earth return, the attenuation is the highest with this mode. Transient studies involving ground, contain the domination of this mode, which ultimately affects the travelling wave phenomena. For details refer to Section 5.4;

Mode 2: The currents in the outer phases are equal in magnitude and flow in opposite directions. This is also called first aerial mode. The propagation of the PLC signal due to this mode has less attenuation than mode 1, which is due to the absence of earth return. On phase 2, the current flows due to the presence of mode 1 and mode 3 and are being controlled by the p and q factors, where p and q are voltage and current eigen vector matrices derived from the impedance matrix for the particular line. Mode 2 does not exist on the central phase.

Mode 3: Graphical representation of the modes clearly shows the current in the middle phase is twice that in the outer phases and flows in opposite direction. This mode is considered responsible for the propagation of PLC signal for longer distances, which is due to its relative lack of attenuation. The lack of attenuation is due to the absence of the earth return path. On phase 3, currents due to mode 1 and mode 3 flow in the same direction, but, current flowing due to mode 2 flows in opposite directions. When transient conditions occur on the power system and earth is not involved in return path, then the domination of this mode keeps the travelling wave phenomena persistent for a longer time. Results are presented in Section 5.4 to verify this fact.

The theory of natural modes allows one to determine propagation factors of different modes and ultimately to estimate the propagation performance of the PLC. In this work, performance of the modes has been studied in terms of fault transient studies.

5.4 STEADY STATE AND TRANSIENT STUDIES OF PLC CIRCUIT

Theory of natural modes is the one of the best solutions for the simulation of circuits connected with transmission lines ie. PLC systems etc. The circuits, connected with the ehv transmission lines should be able to withstand the steady state operating conditions of the power network. Due to system contingencies eg. switching operation, fault inception and lightning etc. transients appear on the power system. The connected circuits should be able to withstand high voltage surges. The high frequency transients are very hard to detect for the coupling capacitors. PLC equipment is protected against the high voltage surges. Figure 5.3 contains the detail circuit diagram of the PLC circuit. Due to transients, heavy amounts of current are expected, so the drain coil serves to direct the current to the ground.

For the given circuit, faults of various types and at different locations on the line were initiated. To provide the required protection, voltage controlled switches were used with appropriate time delay.

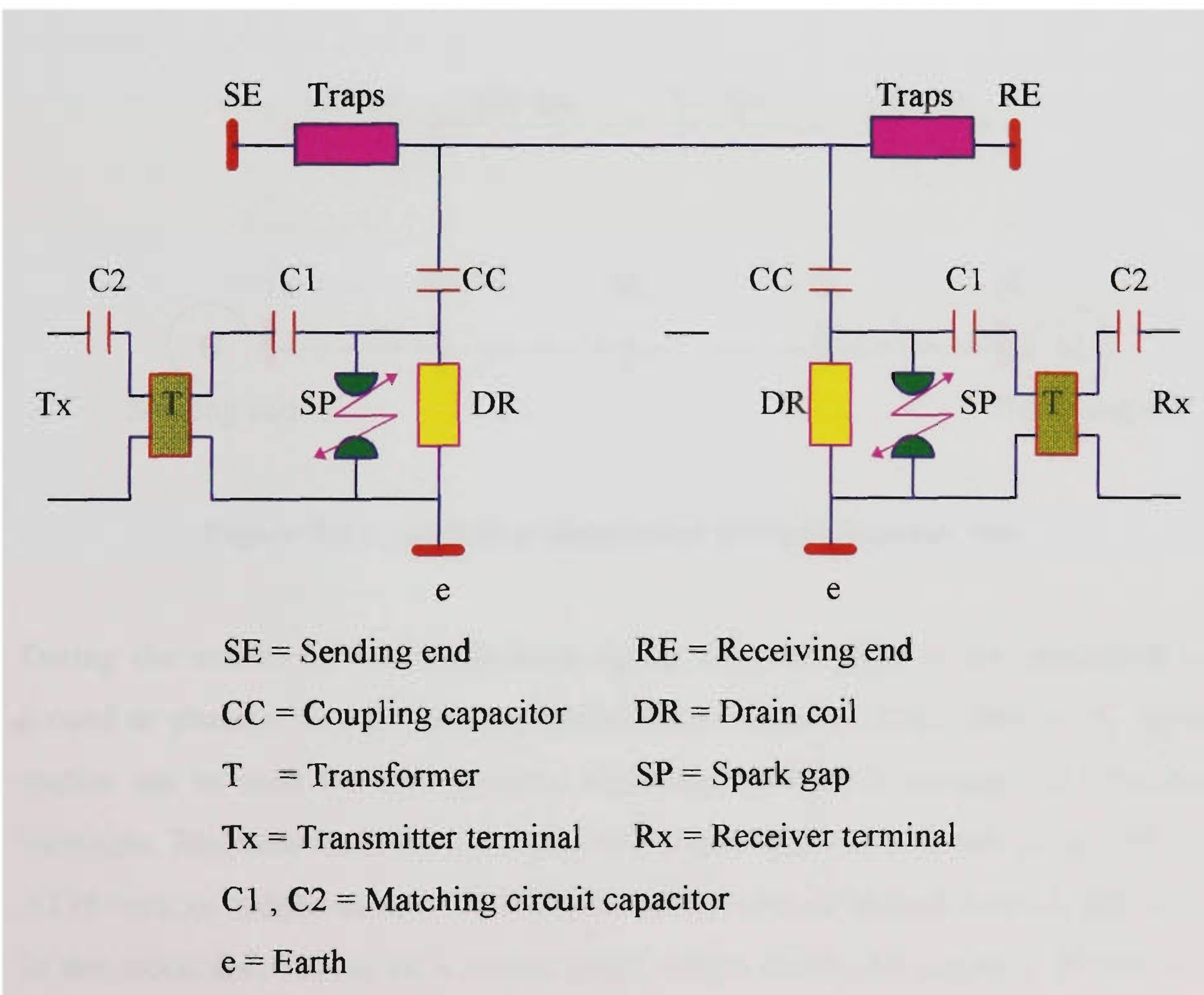


Figure 5.3 : Schematic diagram of PLC circuit for ATP6 simulation

During fault inception, time operated switches were used to initiate and terminate the faults. These switches are built in tools in the ATP6 software for the simulation of the power system equipment eg. circuit breakers, relays, spark gaps and electromagnetic contactors etc.

In this work, a 400 km ehv long transmission line was simulated. The full length of the line was subdivided into four subsections each 100 km in length as shown in Figure 5.4. Faults on the system can be classified into two major classes:

a) Steady state

b) Transient.

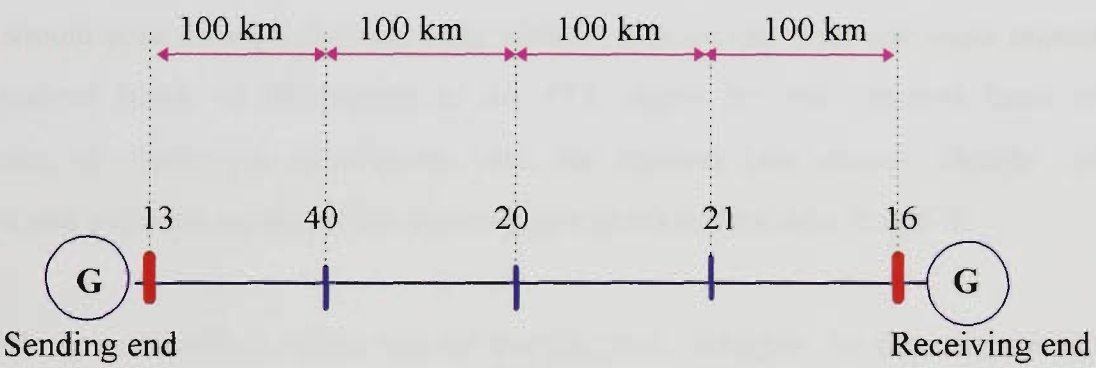


Figure 5.4 : Single line diagram of the transmission line

During the studies of the steady state faults, required phase(s) are connected to ground or phase(s) through some specified fault resistance. Data obtained by these studies can be used for fault location algorithm, as there is no need to filter the transients. Transient faults are simulated using time operated switches as part of the ATP6 data, so sudden changes in voltages and currents are expected on the network. In this work, the focus is on transient faults, which shows the presence of different type of modes.

Fault transient studies are performed at three different locations on the network ie. sending end, receiving end and in the middle of the circuit. Different types of faults are considered eg:

1) 1-phase-to-ground fault
2) 2-phase-to-ground fault
3) 3-phase-to-ground fault
4) phase-to-phase fault

The locations of the various faults have been selected to give a variety of results to investigate the nature of the modes. Input data file is give in Appendix D.

5.4.1 Steady State Studies

Steady state studies are provided to see the effect of line trap on ehv power signal. The line traps are considered as low pass filters, 50 Hz ehv power signal with its rated current should pass through the line traps without attenuation. The line traps should show required levels of attenuation to the PLC signal for the required band of frequencies, to reduce the interference with the adjacent line section. Details of hardware and software results of the line traps are given in Chapters 6 and 7.

Figure 5.5 shows the effect of line trap on the polyphase voltages. To demonstrate the comparison, at the sending end of the transmission system, waveforms on the three phases have been obtained on the busbar and the other side of the line trap. Both sets of the waveforms in Figure 5.5 are identical, showing no attenuation in the power signal due to the line trap. The waveforms do not show any attenuation and change in phase angle.

5.4.2 Transient Studies

Figure 5.6 describes the level of protection predicted for the given PLC system. A voltage operated switch was used to simulate the flashover. Due to transient conditions on the network, spectra of high voltage transients are impossible to detect with the coupling capacitors. Transmitter and receiver terminals along with matching units should be protected against high voltage spikes. The switch was simulated to provide the protection against the spikes of 2 kV or higher with some time delay. The operation of the switch was tested against the 1-phase-to-ground fault at the sending end. The results shown in Figure 5.6 describe the protection of the PLC receiver.

5.4.3 1-Phase-to-Ground Fault

From practical studies, probability of occurrence of 1-phase-to-ground fault is higher than any other type of fault on transmission lines. 1-phase-to-ground fault was considered at the sending end of the line in phase 'a'. Due to the presence of the earth, the sending end voltage on the faulty phase collapsed nearly to zero, as shown in Figure 5.7. The current in the faulty phase rose to a very high value with abrupt changes at the time of fault. The waveforms of voltages and currents in healthy phases were also disturbed due to electromagnetic and electrostatic coupling among the phases.

To see the worse case of this type of fault, an instance of fault inception was taken at 5.0 msec., which was the maximum peak voltage for the phase under study. Due to the fault at this instant of time, there was abrupt change in voltage from 408248 Volts (rms) to zero. Due to this abrupt change, severe transients can be seen in the healthy phases at the sending end. The effect of the fault was also studied at the receiving end. Voltage did not collapse to zero at this end, this was due to the presence of strong 35 GVA source at the receiving end. Severe transients were seen in the receiving end voltage waveforms, as given in Figure 5.7. Travelling wave phenomena remained in action for 3-4 cycles. Then the fault settled to steady state fault with lesser voltage values showing the presence of fault. Presence of modes and their effect are studied in Section 5.5. Similar kind of studies were made at the receiving end and the effects on the system were a replica of the fault studies at the sending end.

5.4.4 2-Phase-to-Ground Fault

2-phase-to-ground fault was considered in the middle of 400 km long transmission line. Two phases (a and b) were short circuited to ground using time operated switches. Operation time of the switches was given in switch cards of the input data file. Both of the switches were closed at the same time of .005 sec. and were opened at the same time of .04 sec. (total simulation time). Measurements of voltages and currents were taken at sending end, receiving end and at the middle of the transmission line. Figure 5.8 shows a 2-phase-to-ground fault at the middle of the transmission line. The effect of the fault on the remote ends (sending and receiving ends) was identical due to the location of the fault.

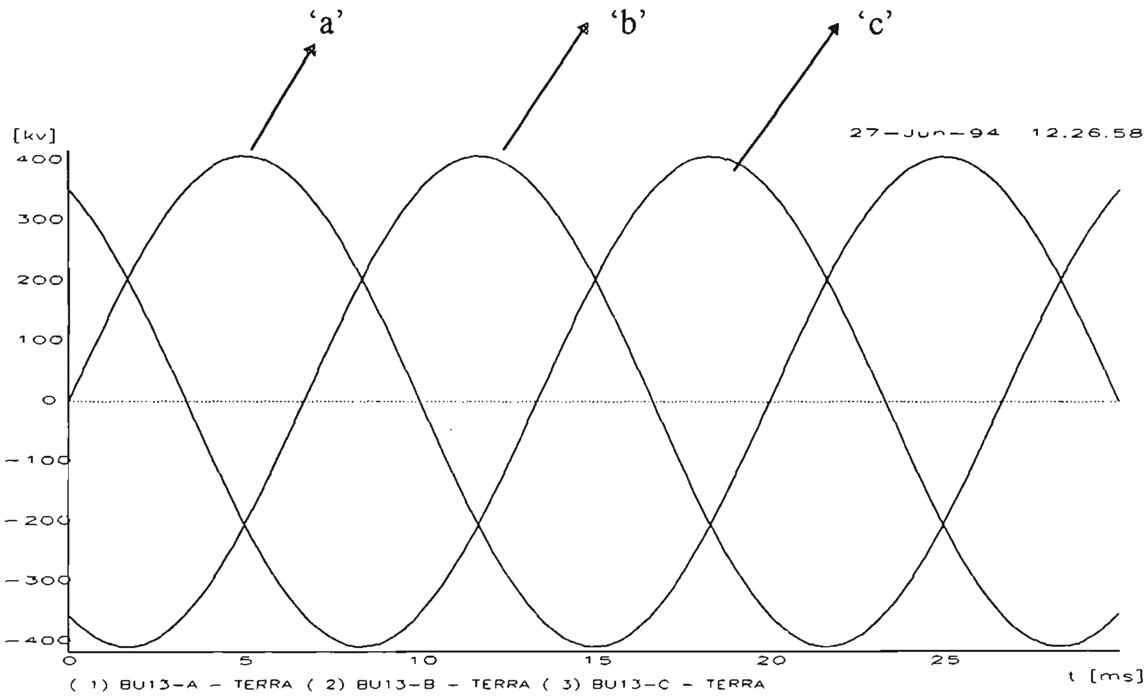
Waveforms at the remote ends showed the presence of transients in the two faulty phases. Due to electromagnetic and electrostatic coupling between phases, the healthy phase also showed the effect of the sudden change on the network, as shown in the Figure 5.8.

5.4.5 3-Phase-to-Ground Fault

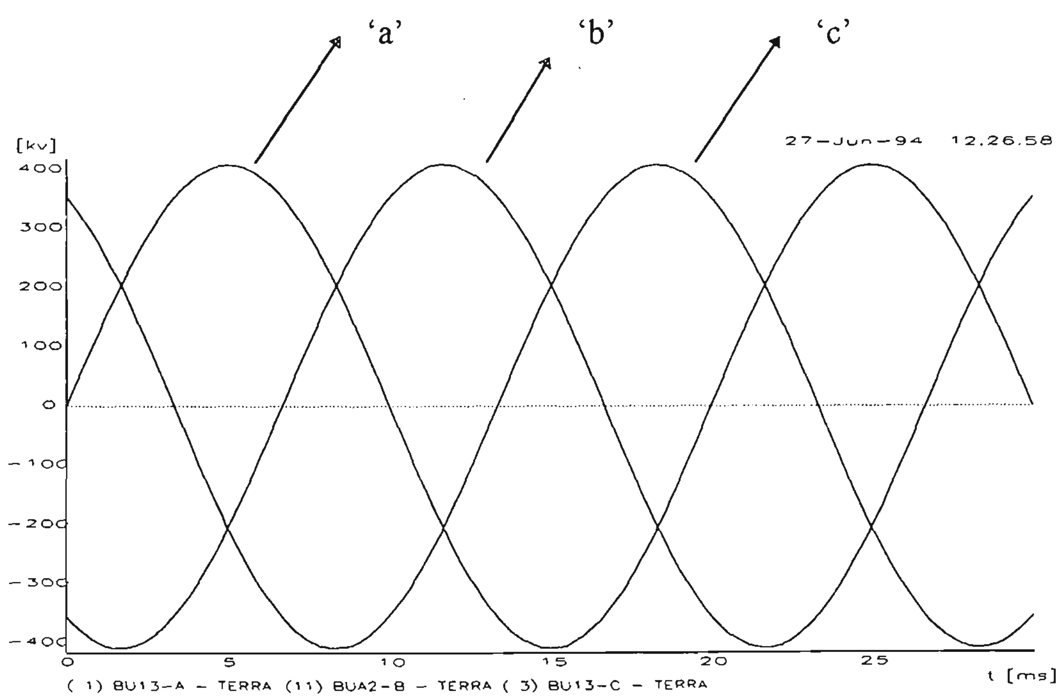
Figure 5.9 shows the behaviour of the system when it undergoes 3-phase-to-ground fault at the receiving end. Voltages of the three phases collapsed to nearly zero at the receiving end of the line at the instant of the fault. As a result, a very heavy amount of the current appeared in the three phases. The transients appearing at the sending end were not very significant due to a strong source of 35 GVA. The fault effects were realised due to the distortion in both voltage and current waveforms, as shown in the Figure 5.9.

5.4.6 Phase-to-Phase Fault

Figure 5.10 shows the waveforms of voltages and currents at the remote ends of the system under the influence of a phase-to-phase fault in the middle of the line. The effect on the travelling wave phenomena on both remote ends (sending and receiving end) was the exact replica of each other, since the fault was considered to be in the middle of the line. Time operated switches were closed at 5 msec. after the start of simulation.



Sending end voltage on the other side of the line trap



Sending end voltage at the busbar

Figure 5.5 : Effect of the line traps on the power signal at the sending end

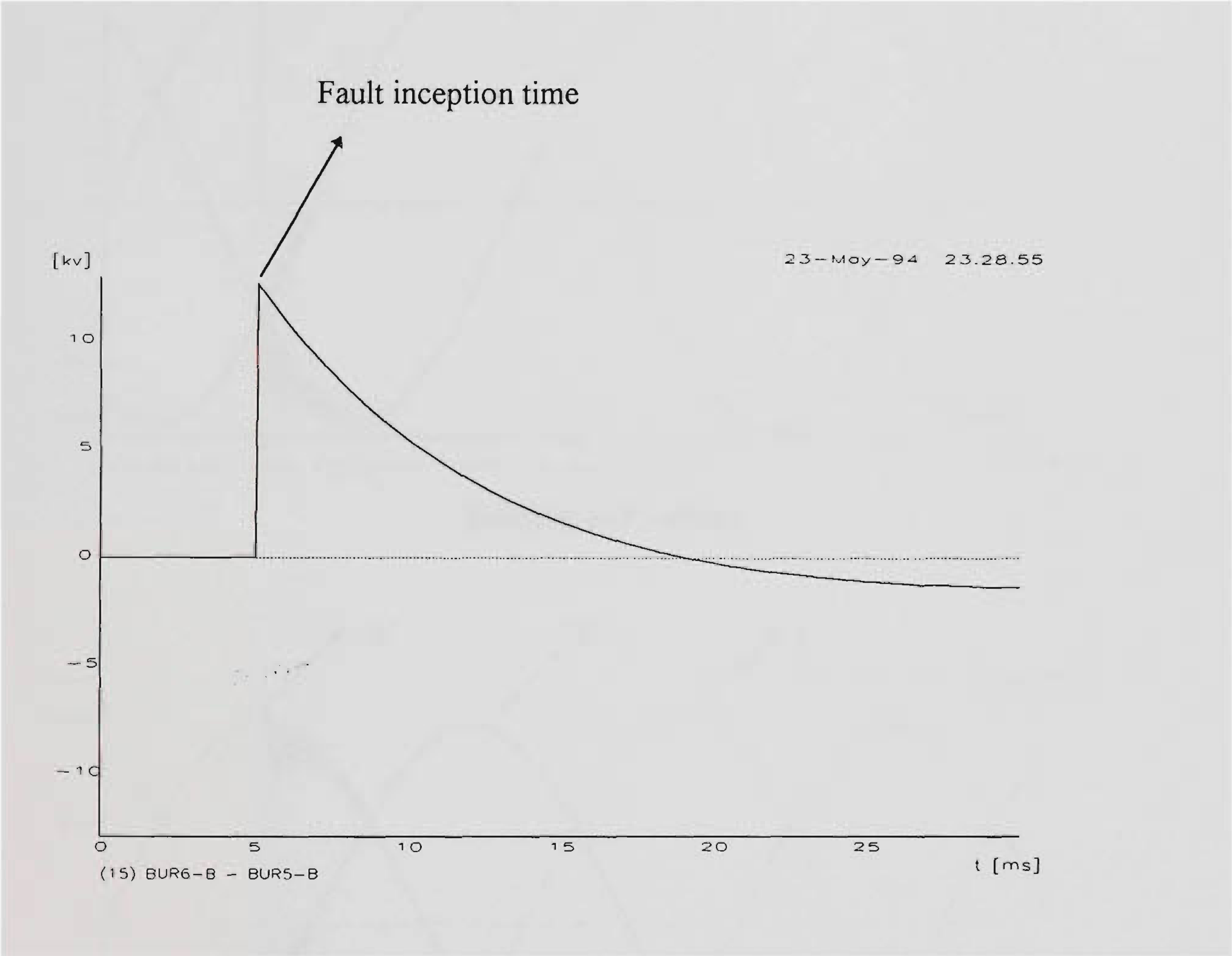


Figure 5.6 : Level of protection for PLC terminal equipment against high voltage transients

Fault inception time on phase 'a'

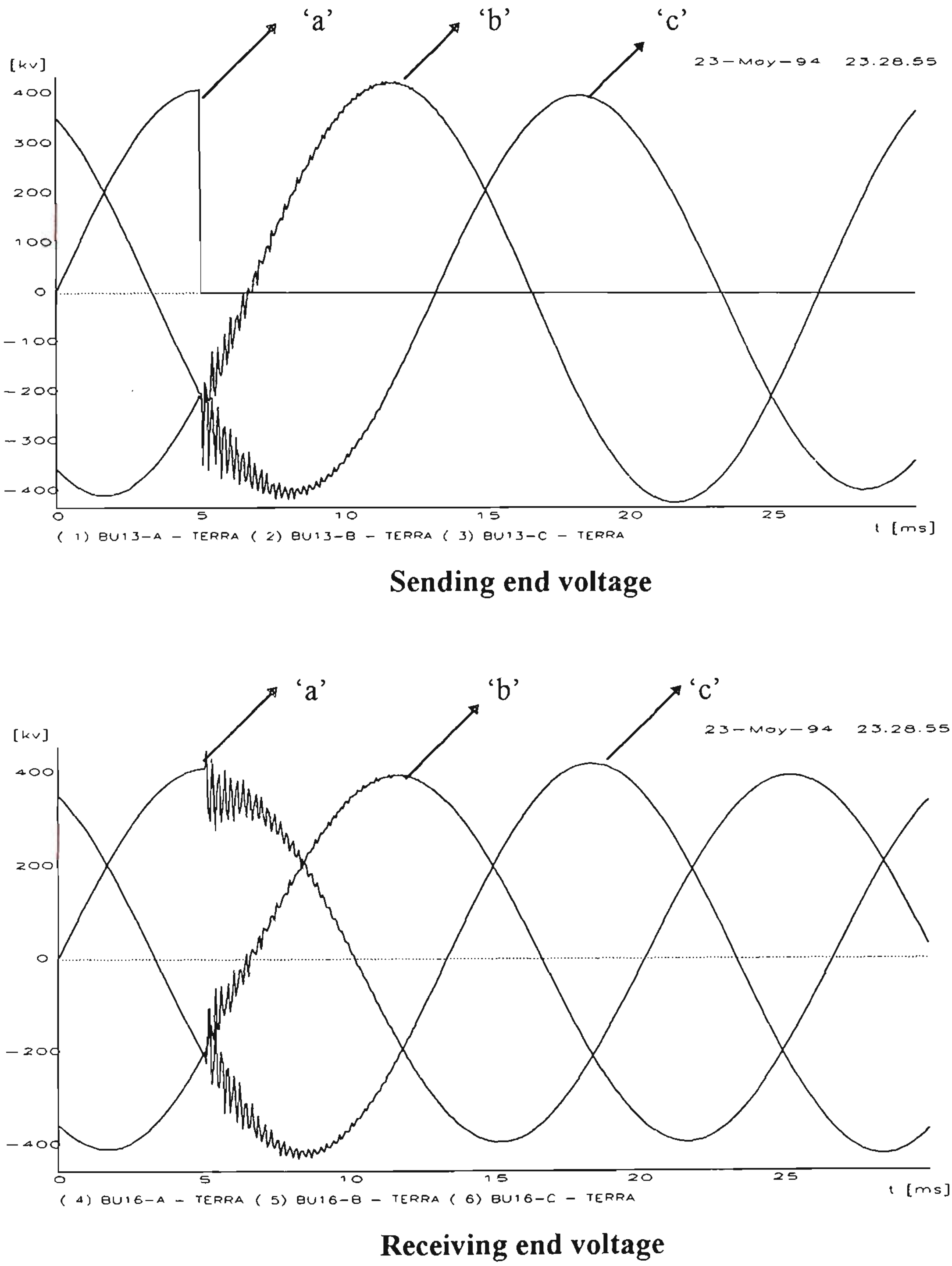
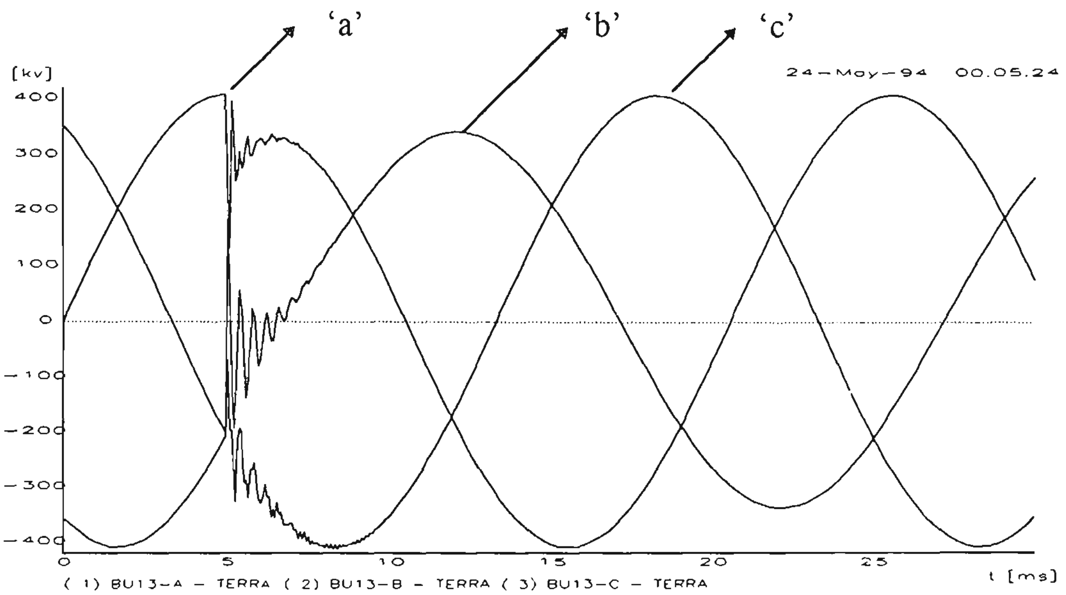
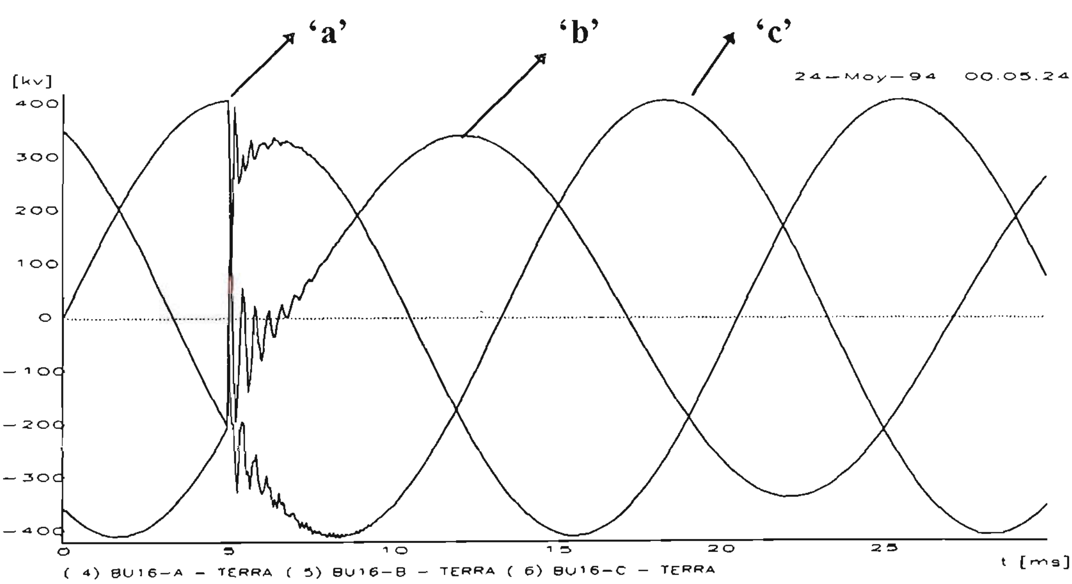


Figure 5.7: 1-phase-to-ground fault at the sending end

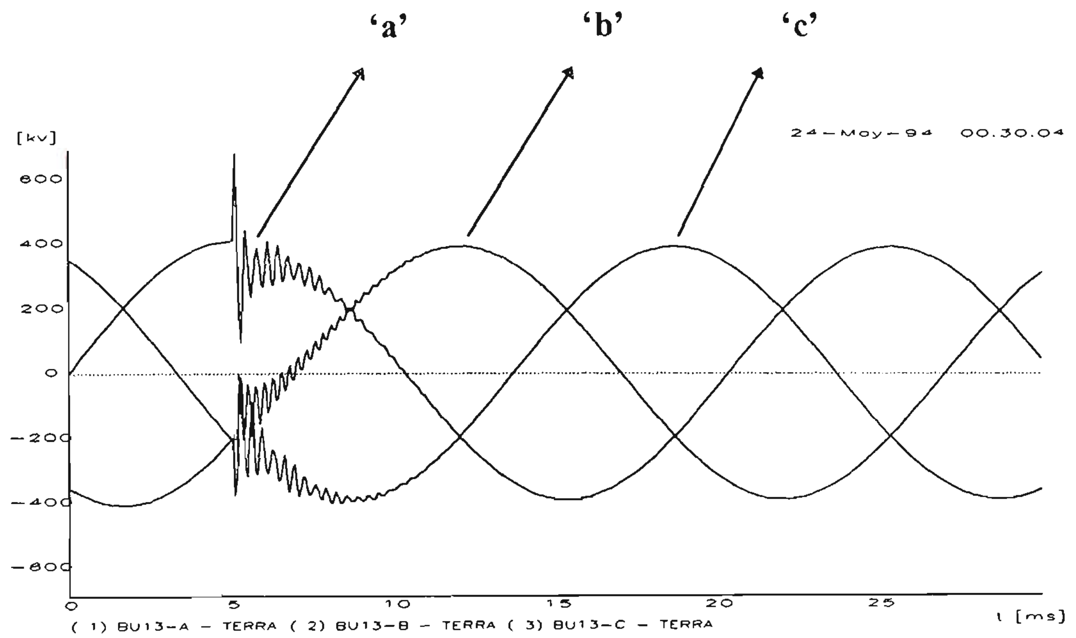


Sending end voltage

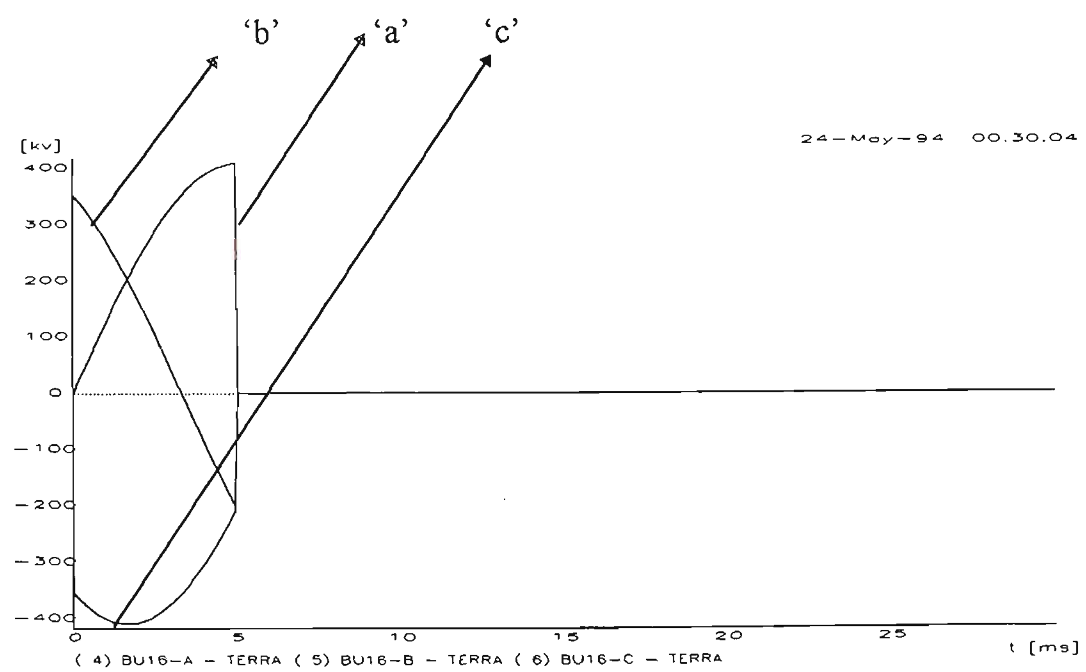


Receiving end voltage

Figure 5.8 : 2-phase-to-ground fault in the middle of the system

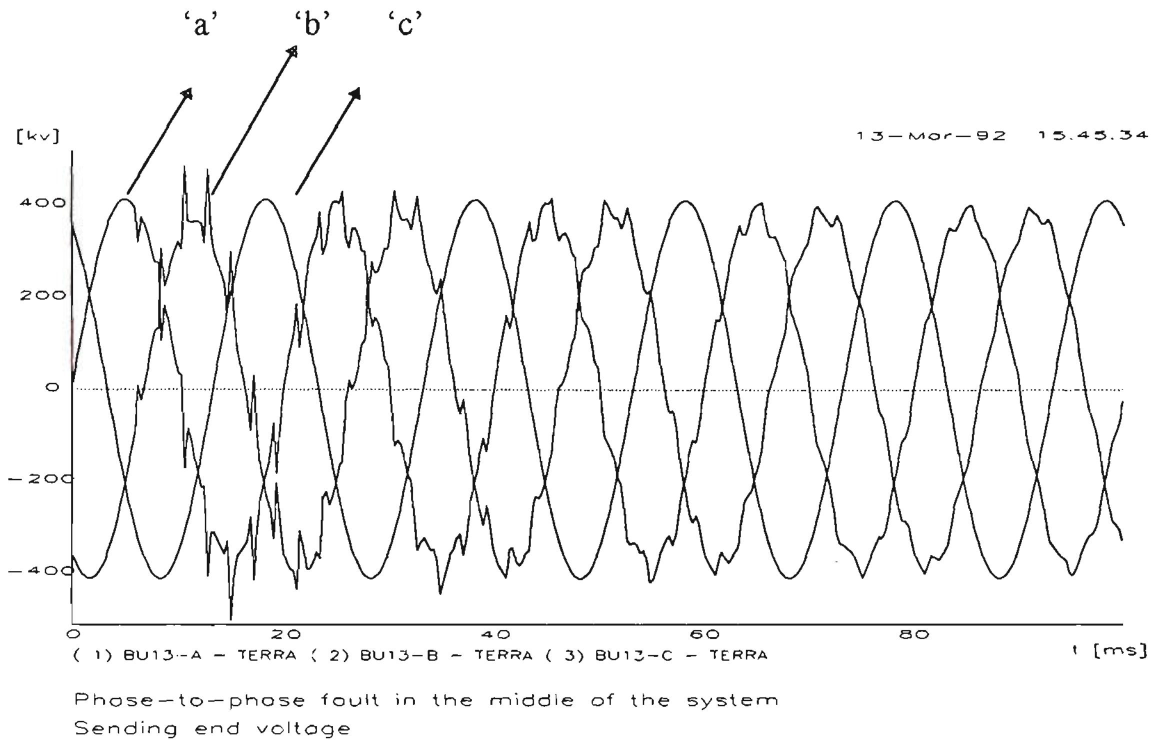


Sending end voltage

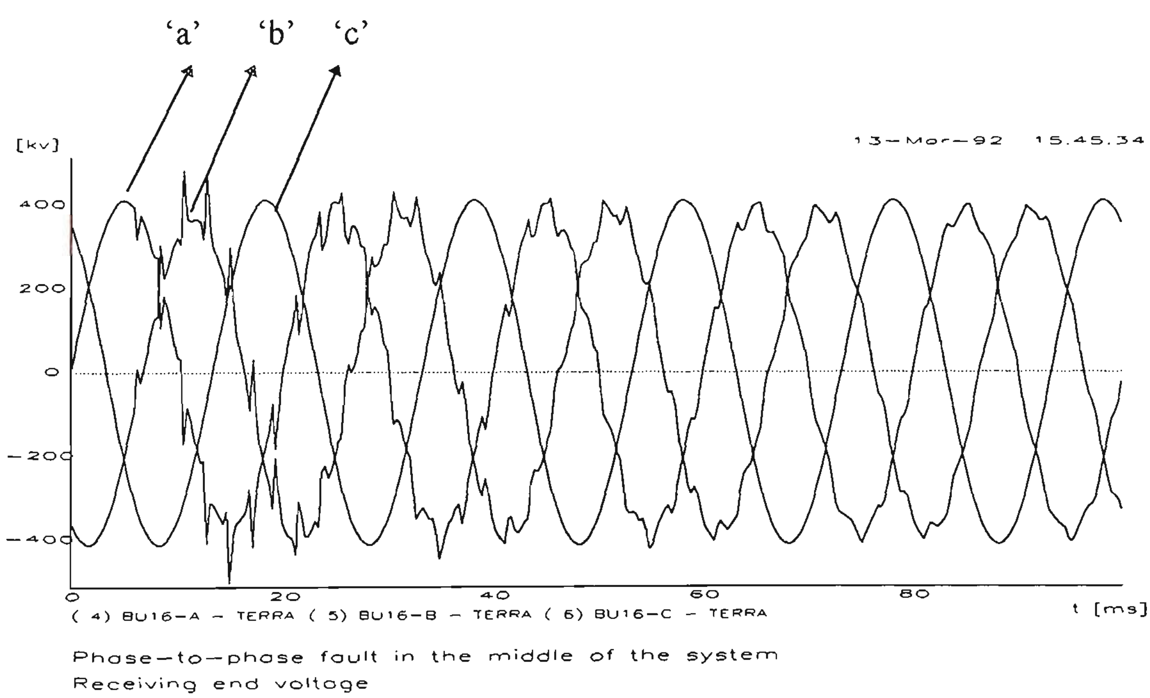


Receiving end voltage

Figure 5.9 : 3-phase-to-ground fault at the receiving end of the line



Sending end voltage



Receiving end voltage

Figure 5.10 : Phase-to-phase fault in the middle of the line

5.5 STUDIES OF NATURAL MODES OF PLC

Transient studies presented in Section 5.4 can be used to recognise the types of modes present in particular fault study. Domination of both types of the modes, (aerial and ground) depends on the nature of the fault. All types of transient studies will produce all types of natural modes on the line. If earth is considered as the return path for the fault current then ground mode would be the dominant mode in the travelling wave phenomena. In other case, if the fault is considered among the phases then aerial modes would be most dominant.

Due to fault inception or switching operation on the network, transients produced are considered up to the 10 kHz. These high voltage transients are hard to block by the coupling capacitors, so up to 2 kV protection for the PLC equipment is provided as shown in Figure 5.6. The nature of the spectrum of high frequency transients can be used to study the behaviour of different modes on the network.

Results of transient faults involving earth are given in Figures 5.7-5.9. These results show the behaviour of the travelling wave phenomena. Under these transient conditions, the ground mode is the dominant mode as the travelling phenomena dampened down very quickly within two cycles. In Section 5.3, it has been stated that due to the presence of earth return, mode 1 (ground mode) is the most attenuated. High attenuation due to the mode 1, attenuates the travelling wave phenomena.

Presence of aerial modes (2 and 3) can be investigated by considering phase-to-phase fault at the middle of the system (Figure 5.10). As there is no earth involved in this fault study, the waveforms show that due to the dominant aerial modes in all phases, travelling wave phenomena persist considerably longer than is the case for faults involving the earth.

For PLC signal propagation, the least attenuated aerial modes are the dominant mode for longer distance propagation. PLC injected signal on the transmission line decomposes into its modes. Like phase-to-phase transient studies, aerial modes are dominant in PLC modes, which make PLC signal propagate for longer distance.

In this chapter, steady state and transient studies of the PLC equipment have been presented to investigate the required level of protection for PLC equipment. These studies are also used to find out the behaviour of PLC signal on the transmission line, when it is decomposed into its modal values.

Figure 5.1 describes the connection of the PLC equipment with transmission line which has been simulated using ATP6 software. Distributed parameters of the untransposed line have been taken from Chapter 3. Section 5.2 describes the two major groups of the modes. Detailed description and graphical representation of the different modes have been presented in Section 5.3. The importance of the steady state and transient studies have been discussed in Section 5. Results of the detailed transient studies show the presence of specific types of modes.

CHAPTER 6

SIMULATION OF RLS ADAPTIVE INTERFERENCE CANCELLATION SCHEME

6.1 INTRODUCTION

The security of data transmission on power lines for protection, telemetry and supervisory control etc. is a matter of great concern for power system authorities. Transmission of falsified data may result in incorrect control operation of power systems, which may have fatal consequences. Typical situations in power system operation may occur due to mal-functioning of relay operations, circuit breakers and supervisory control etc., which may lead to financial and even human loss. In power system practices, operation of the protection relays and circuit breakers depend on the fault conditions of the power systems. For reliable system design and operation, these operations should be as minimal as possible to maintain a steady supply of power to consumers. Under fault conditions, measurement data should be communicated reliably for accurate operation of the required relays and circuit breakers. Different mean of communications eg. PLC, optical fibre communication, microwave and telecommunication lines, are used as back-up systems under various operating conditions for reliable transmission of the data.

In existing and new power systems, mixed use of optical fibre communication and PLC techniques can be the best solution for a reliable means of communication. Optical digital communication has superior performance with respect to immunity to interference and transmission capacity. However, economic constraints and technical considerations result in the continued application of the established PLC technology for particular applications. The robust PLC equipment exhibits distinct technical and economic advantages, where low to medium quantities of data have to be communicated over large distances [45].

PLC is considered a very reliable back-up for data communication even when the system is under transient conditions. Also propagation of the signal for longer distance on lines makes it more attractive. In terms of theory of natural modes, the propagation of PLC signal for longer distance on the transmission lines is possible due to the domination of the aerial modes [23]. The presence of aerial modes and earth mode have a dominant effect on the travelling wave phenomena under transient conditions [25]. ATP6 is a very useful tool for the studies of travelling wave phenomena for PLC applications [24]. Due to the non-user friendliness of ATP6 and being a difficult tool to handle complex problems eg. adaptive interference cancellation, MATLAB has been used. MATLAB with its flexible tools eg. control, signal processing, mathematical, neural network and simulink etc. is a good tool for the simulation of different applications and control of power systems. On-line help, debugging facilities, plotting and built-in tool for all required applications for the control and operations of the power systems are added features in MATLAB.

The presence of different interference sources eg. corona, lightning, switching operations and the inefficiency of the line traps etc. on the power systems for PLC applications makes it impossible to use the available spectrum of frequencies efficiently. The effect of some of the interferences can be reduced with proper planning and design of the power system eg. corona, lightning, switching operations etc. The interference due to line traps can be reduced using adaptive interference cancellation techniques. In this study, RLS method has been tested to provide the required level of attenuation to the PLC signal, so that the same spectrum of frequencies can be used on the adjacent line sections. In this work, the main focus is on interference cancellation, so the transmission line has been represented by its characteristic impedance.

Sources of interference for PLC signal, as described in Section 3.5, can be treated depending on their nature. It is very hard to predict the probabilities of contingencies on the power systems eg. switching operations, transient conditions and corona etc. The effect of unpredictable sources of interferences can be kept within the limit with proper planning and design of the power systems. Interferences caused due to the inefficiency of the PLC equipment eg. line traps, are constant in steady state operation (results are given in Section 6.4). The efficiency of line traps is limited due to the size and cost of equipment. To cancel these interferences, adaptive interference cancellation techniques are very useful and efficient to cancel the real-time interferences.

In the computer simulation studies of interference cancellation, RLS method is used to predict the level of interference. The mathematical model presented for RLS method in Section 2.5 has been used in this study. To find the practical level of interference on the PLC system, parameter values for line traps presented in Section 3.3 were used. For the computer simulation studies, PLC equipment was designed and simulated individually. The frequency responses of the line traps and coupling capacitors are presented in Section 6.2.

In this work, the major focus was on the study of interference caused by line traps, appropriate loads were connected on the busbars to get the required level of attenuation in PLC signal due to line traps. Due to hardware limitations, the spectrum of PLC signal was considered lower than 50 kHz. To produce signal for the required bandwidth, Butterworth low pass and band pass filters were used. These limitations were observed for the comparison of results from computer and hardware simulation studies. For computer simulation, the RLS method was further tested for different spectrums of frequencies using low and band pass filters.

6.2 SIMULATION OF PLC EQUIPMENT

As described earlier, the major focus in this work was to simulate the PLC interferences caused by the inefficiency of the line traps on the power system communication networks. To produce the realistic model of interference, different types of sources at the appropriate frequencies were simulated. The interferences were sensed at both receiving and sending ends of the transmission line using coupling capacitors. Different sets of parameters were used for the simulation of line traps and coupling capacitors to suit various bands of frequencies. The computer simulation results of the PLC model and its associated equipment are presented in the following section.

6.2.1 Simulation of Sources

To produce the realistic PLC signal for the required band of frequencies on the line, different types of sources were used. These sources were generated at a very high sampling rate, which resulted in a digitised analogue signal of the required frequency. The following signals were generated for the PLC simulation:

1) Sinusoidal signal at a specified frequency
2) Sinusoidal signal at a specified spectrum of frequencies
3) Random noise, up to a specified frequency
4) Modulated signals having certain number of channels.

The sampling frequency was kept very high (MHz) to get a realistic picture of the sine wave signal. The amplitude of the signals was measured in Volts. Signals were in time variant domain. For the generation of the sinusoidal signal, the following formula was used for particular frequency.

$$_g = \sin(2 * \pi * f * t) \qquad \text{.........................(6.1)}$$

where V_g is the generated signal, and f and t are frequency and time, any one of them or both of them can be variable, depending on the requirements. Graphical representation of these signals can be seen in their corresponding application sections.

6.2.2 Simulation of Line Traps

The parameters given in Chapter 3 were used for the simulation studies of the line traps. The line traps are considered as low pass filters. They can be designed to block all the bands of PLC applications or for a certain spectrum of frequencies, depending upon the application. The computer simulation program for line traps has flexibility to change the source frequency, line trap parameters and rated load current on the line. The program evaluates the total impedance of the line traps on a particular frequency and then calculates the attenuation in the signal due to the line trap parameters. Figure 6.1 shows the flow chart of the algorithm and programming strategy. Figure 6.2 shows the level of signal used to test the performance and the attenuated signal due to line traps. Figure 6.3 gives the level of attenuation in dB's offered by line trap at 60 kHz frequency.

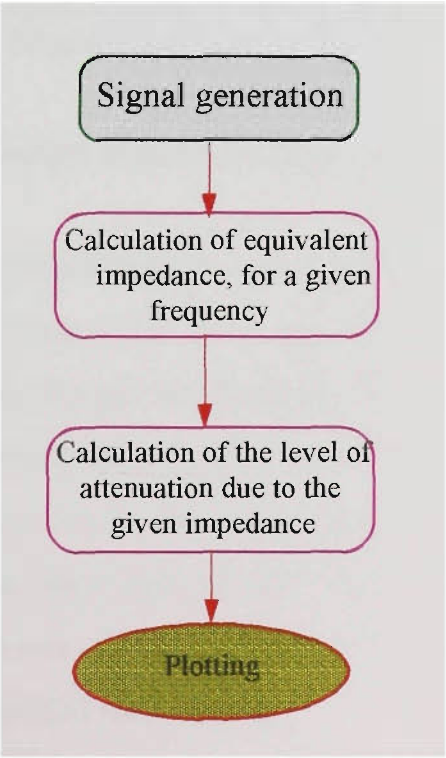


Figure 6.1: Flow chart for the simulation of Line Trap

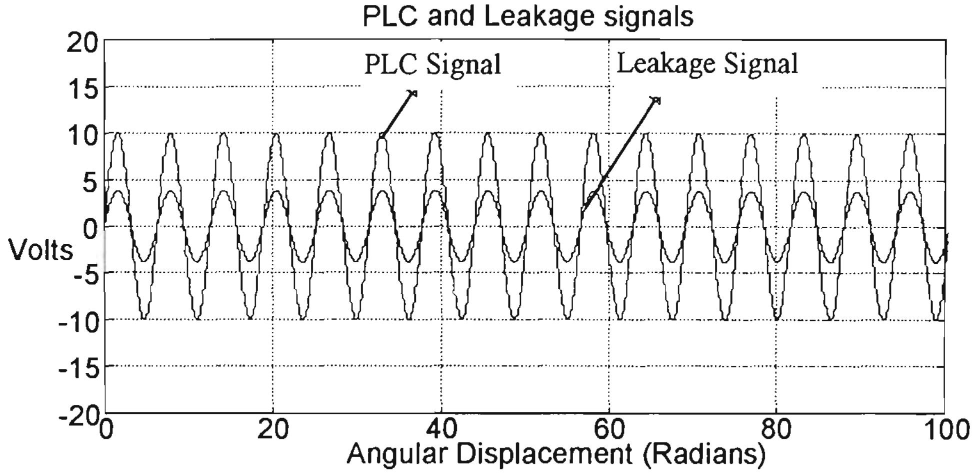


Figure 6.2: Performance of Line Trap at 60 kHz Frequency

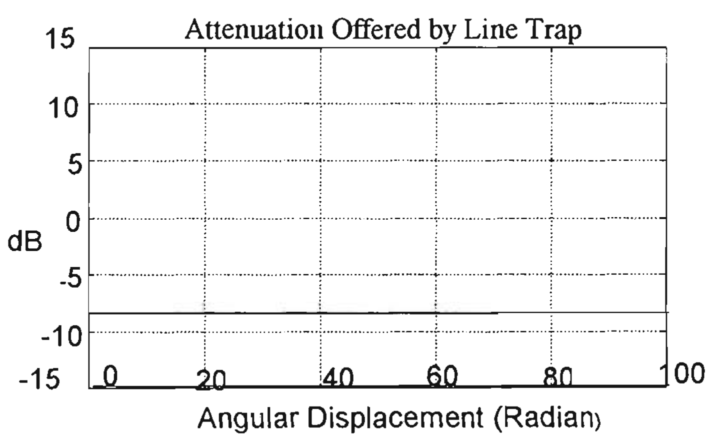


Figure 6.3: Level of Attenuation Offered by Line Trap at 60 kHz Frequency

In the second stage of the computer simulation, the frequency response of the line trap was evaluated. Frequency responses of the broad band and small band line traps were plotted separately. The program has got the flexibility to take any band of frequency for the simulation of the required set of parameters of the line traps. Figure 6.4 describes the frequency response for the line traps centred at 65 kHz which was used for the computer simulation studies of the adaptive interference cancellation. Figure 6.5 outlines the frequency response of the broadband line traps, which can be used to block the whole spectrum of the PLC frequencies.

The resonance of the circuit parameters decides the bandstop nature of the line trap. Parameters C_1 and L_1 from Figure 2.1 should have the same resonance frequency as the other circuit parameters eg. C_2 and L_2.

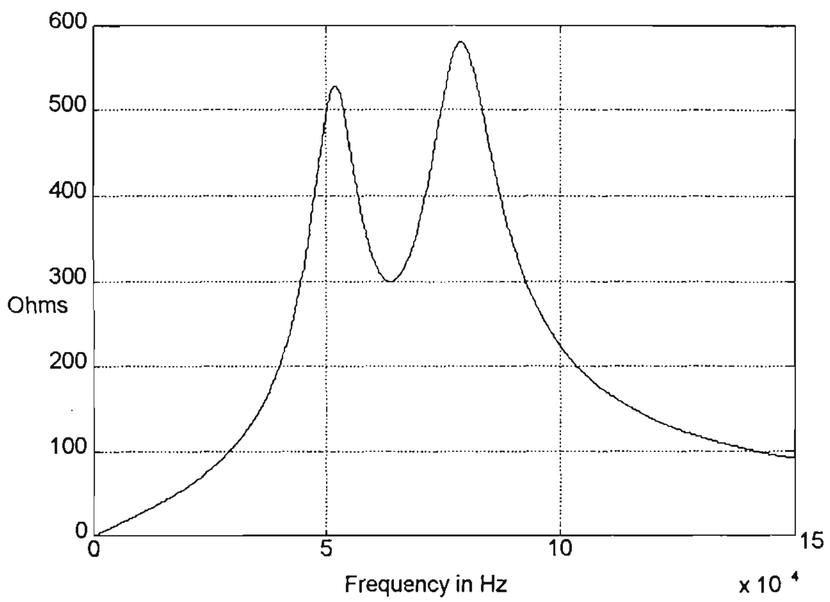


Figure 6.4: Frequency Response of Narrow Band Line Trap at Centre Frequency of 65 kHz

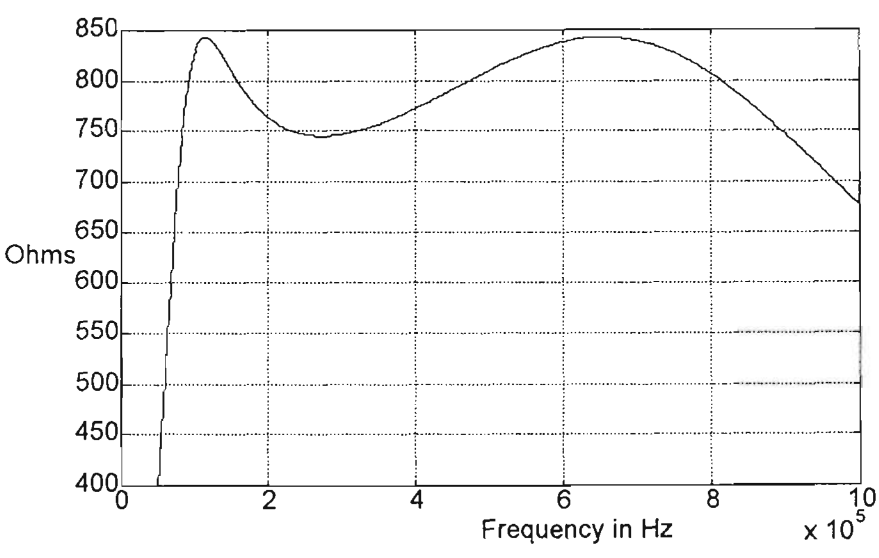


Figure 6.5: Frequency Response of Broad Band Line Trap

Line traps were also designed using the theory of natural modes (ATP6). In this work, simulation studies gave the broad view of the practical applications of the line trap circuits for PLC utilities. The level of the attenuation provided by this design method of line traps for the PLC signal can be seen in Figure 6.6.

The computer simulation studies show that the level of attenuation provided by the line traps is not adequate to avoid the interference caused by the same frequencies on the adjacent line sections. Despite the cost and size limitations, efficiency of the line traps cannot be increased. To overcome this problem, adaptive interference cancellation (RLS method) has been simulated using MATLAB as a computational tool to assist the line trap to get the appropriate attenuation level.

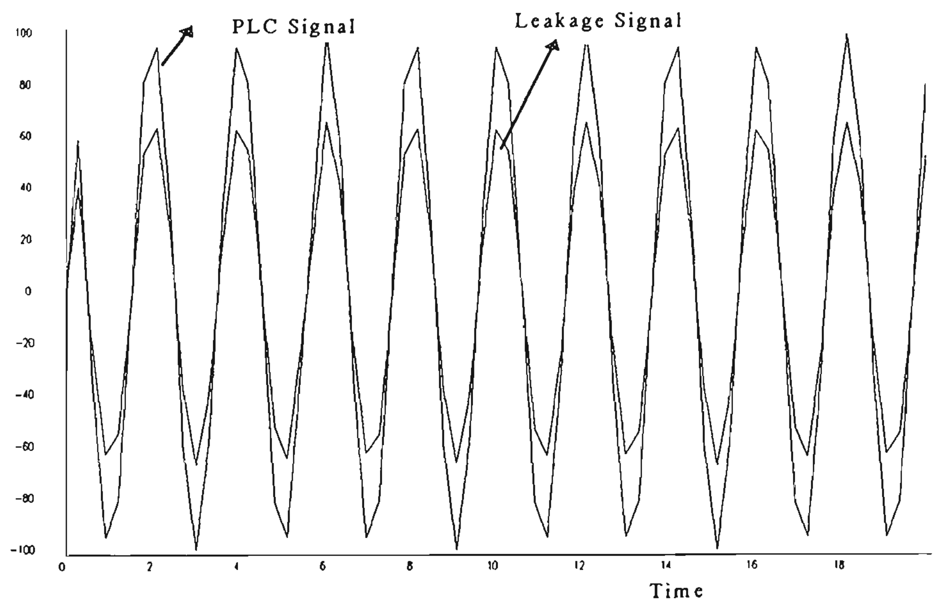


Figure 6.6: Assessment of line trap using ATP6

6.2.3 Simulation of Coupling Capacitors

In the computer simulation, coupling capacitors have been used for the filtering of the PLC and PLC leakage signals from the power signal. Due to the dominant nature of capacitive circuit at lower frequencies, the circuit showed very high impedance to the signal, blocking the power signal and its associated low frequency transients. Practical field survey shows that for different application eg. telemetry, protection and voice communication etc., coupling capacitors are divided into two units to make two stage bandpass filters. The first stage is to collect the protection signal and the second stage is to collect the data for voice communication. The function of both stages is the same, except its operation at different frequencies. In this work, only one stage of the coupling capacitors has been used to study the interferences and their adaptive cancellation.

The parameters for the coupling capacitors have been presented in Section 3.4. These parameters were used for the computer and hardware simulation studies of the PLC model and its associated adaptive interference cancellation algorithms. The flexibility of the computer simulation technique gives the option to design coupling capacitors having different sets of parameters.

In this study, the impedance response of the coupling capacitors has been found for a broad spectrum of frequencies. The attenuation caused by the coupling capacitors to the PLC signal was also evaluated on a particular frequency. Figure 6.7 shows the flow chart of the simulation program.

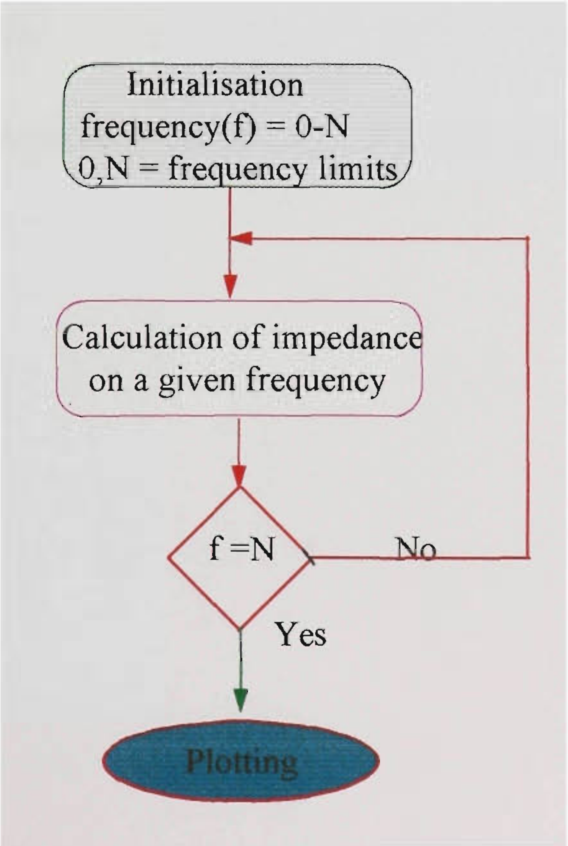


Figure 6.7: Flow Chart for the Simulation of Coupling Capacitors

Figure 6.8 shows the rate of change of impedance with the varying frequency. The attenuation due to the different coupling capacitors schemes has been studied on the hardware model of the transmission line. Results presented in Chapters 4 and 7 can be used to find the optimum coupling for the desired applications. In the computer and hardware simulation studies, central-phase-to-ground coupling has been used to couple the PLC signal on the line. The attenuation presented by the coupling capacitors to the PLC signal can be accurately estimated at 100 kHz frequency from Figure 6.9.

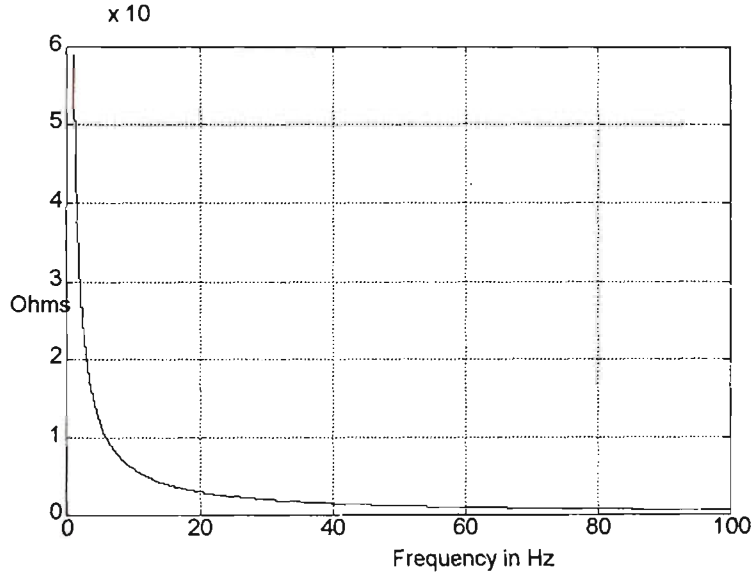


Figure 6.8: Frequency Response of Coupling Capacitors

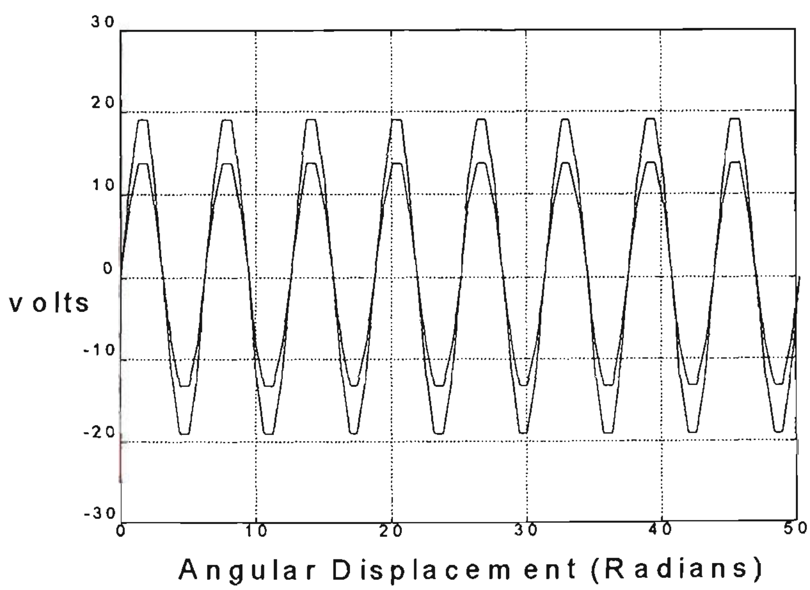


Figure 6.9: Attenuation Offered by Coupling Capacitors at 100 kHz Frequency

6.3 COMPUTER SIMULATION OF PLC MODEL

Propagation studies of PLC signal modes were performed on bundle conductors, on a 400 km long transmission line. Geometry and results of the line are given in Chapters 3 and 5. As described earlier, for the PLC system modelling, the transmission line has been represented by its characteristic impedance, because the transmission lines are normally represented by their characteristics impedances [88]. Simulation of PLC model using MATLAB mainly focuses on the interference cancellation.

To get the required level of attenuation from the line traps, the transmission line on both sending and receiving ends was connected with appropriate resistive loads. PLC signal was injected through coupling capacitors at the sending end of the line. The level of PLC signal on the transmission line has been calculated after consideration of attenuation presented by the coupling capacitors. Flow chart of the program is presented in Figure 6.10, which describes the logic of the developed algorithm and special application for the RLS method.

To test the working of RLS method for PLC application, PLC and PLC leakage signals were de-coupled through separate coupling capacitors as shown in Figure 4.4. For practical implementation of the algorithm, the same set of coupling capacitors can be used to couple the PLC signal for transmitter/receiver and RLS method. Economic aspects of the project can be improved with this scenario. In computer simulation studies, two separate sets of coupling capacitors have been used to couple the PLC signal and to retrieve the PLC signal for cancellers as outlined in Figure 4.4.

Computer simulation can be used to test the RLS method for required spectrum of frequencies. Butterworth low and band pass filters have been designed to filter out unwanted high frequencies. The parameters of the filter have been presented in Section 3.6. Computer simulation studies showed that it is efficient to use the RLS method for shorter bandwidth, rather than using one RLS loop for the cancellation of a whole spectrum of PLC signal.

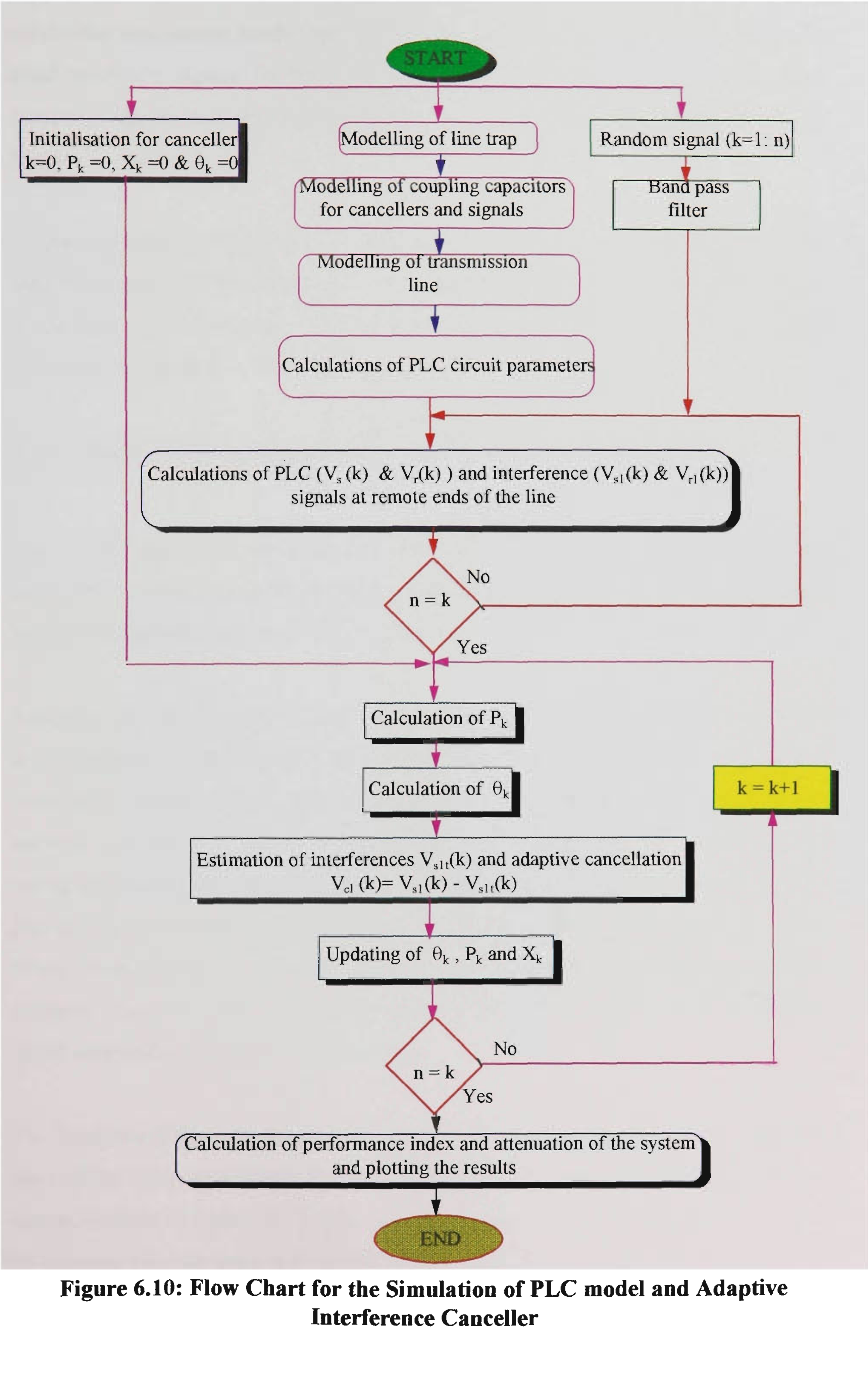


Figure 6.10: Flow Chart for the Simulation of PLC model and Adaptive Interference Canceller

After extracting PLC and PLC leakage signals from the line, signals can be further subdivided into smaller bandwidth. Then various RLS loops can be used to cancel the small bandwidth signals. On the PLC model, RLS method has been tested for single frequency signals and also for various spectra of frequencies. Results are given in Sections 6.4 and 6.5.

Computer programs evaluate the level of PLC signal and PLC leakage signal on the transmission line and stores them in vector forms. These vectors are presented as input to the RLS and other methods for the estimation of the leakage signal. Details about the computer simulation of the RLS method are given in Section 6.5.

6.4 COMPUTER SIMULATION OF PLC INTERFERENCE

Due to the limitation of line traps, PLC signal on one line section interferes with the PLC signal having the same frequency on the adjacent line section, which ultimately limits the available spectrum of PLC frequencies.

Transmission lines from the substations are fed from the common busbars. Line traps are responsible for the isolation of the PLC signals from various lines. Due to the inefficiency of the line traps, signals pass through to the busbars. If the connected line sections are operating at the same frequencies, the integrity of the data will be corrupted for all applications. PLC is not only the means of voice communication but is also used for protection and supervisory control. An operational command, as a result of any contingency on some specific part of network may propagate onto an undesired network. This may result in incorrect control operation of power system network, which may lead to economic or human loss.

The reliability of data transmission for power system applications is far more vital than most of the other applications. PLC is considered to be a very reliable back-up for the communication of signals for longer distances. Levels of interference can be reduced by assisting the line traps in improving their efficiency. It is very important to get a realistic picture of interference caused, due to line traps. The developed program calculates the impedance of the line trap on the given frequency, then uses this impedance to calculate the leakage signal. For further studies of the algorithm, PLC signal was also considered contaminated with random noise of required amplitude. These interferences were cancelled using RLS method. Details of these studies are given in Section 6.5.

6.5 COMPUTER SIMULATION OF ADAPTIVE INTERFERENCE CANCELLER

The nature of interference on the power networks is unpredictable. Cancellation of these interferences should be handled by a very fast learning method about the knowledge of interference on the PLC network. Theory and mathematical model of RLS method have been described in Chapters 2 and 3. A flow chart of the program is given in Figure 6.10. From the knowledge of PLC and leakage signals, dynamic response of the interference can be estimated. The start of simulation from initial conditions ($\hat{\theta}_k$, X_k & $P_k = 0$) makes initial response very poor. As the knowledge of algorithm improves about the PLC signal and leakage signal, dynamic response becomes more accurate. Error in actual and estimated interferences continues to reduce to about zero, so that the same frequency can be used on the adjacent line sections. The block diagram of the RLS method for the PLC interference cancellation is given in Figure 2.2. Selection of this adaptive interference cancellation technique is based on the following major factors:

- previous knowledge of two of the signals (PLC and leakage signals) is readily available for the estimation of the parameters of the line traps;

- the consideration of initial conditions from zero, makes the algorithm more attractive for the real-time situation, where previous knowledge of the system parameters is not available;

- estimated output is readily available from the latest estimates of line trap parameters and the current values of PLC and leakage signals.

RLS method has been tested for different conditions of PLC signals. Trace of parameter estimation has been outlined in Figure 6.11 for only one study. The waveforms show the convergence of system parameters to the optimum value. Initially the estimates of the parameters were poor, which were due to zero initial conditions. Within three cycles of signal, parameter estimation converged to optimum value.

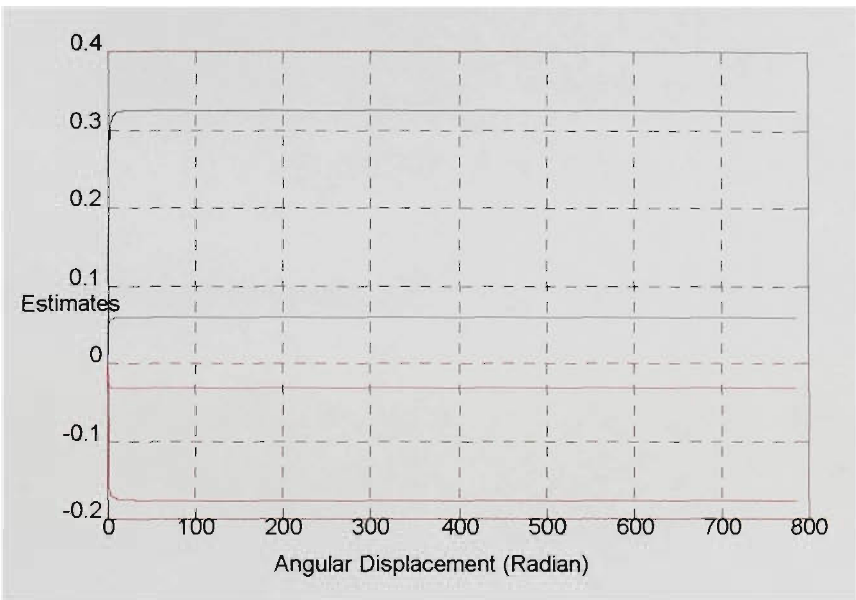


Figure 6.11: Convergence of Identification Parameters of Line Trap using RLS method

Computer simulation studies have been made for signals having single and a spectrum of frequencies. Figure 6.12 shows PLC leakage signal at 60 kHz and leakage signal after adaptive cancellation. Canceller and line trap provided - 89.3762 and -14.0542 dB attenuations to the leakage signal respectively. The comparison of the signal is made in terms of voltage level. After adaptive cancellation, the leakage signal was attenuated to nearly zero Volts within a few cycles. These results show the effectiveness of the algorithm. Table 6.1 shows the working of RLS method in terms of attenuation provided and performance index.

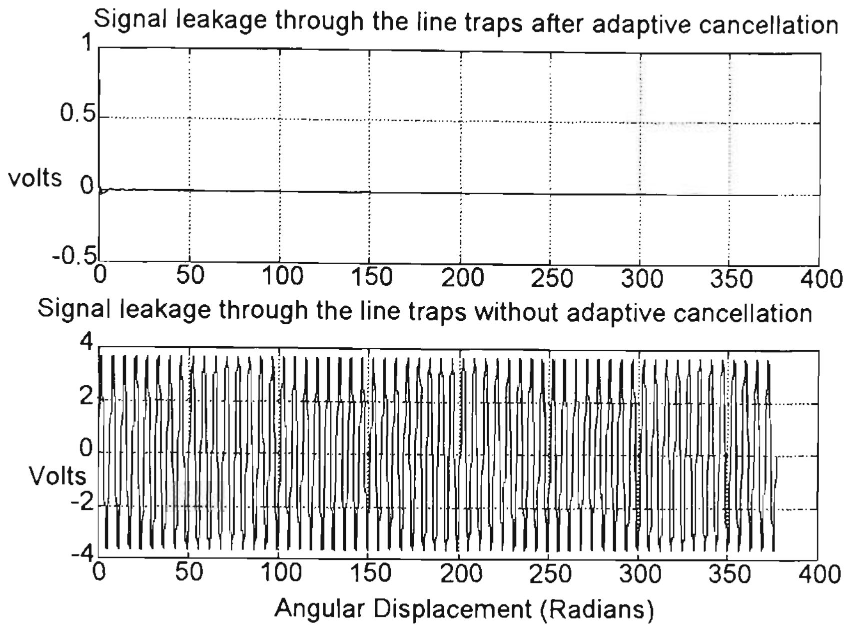


Figure 6.12: Performance of RLS Canceller at 60 kHz PLC signal

Table 6.1 : Simulation results for the application of RLS method

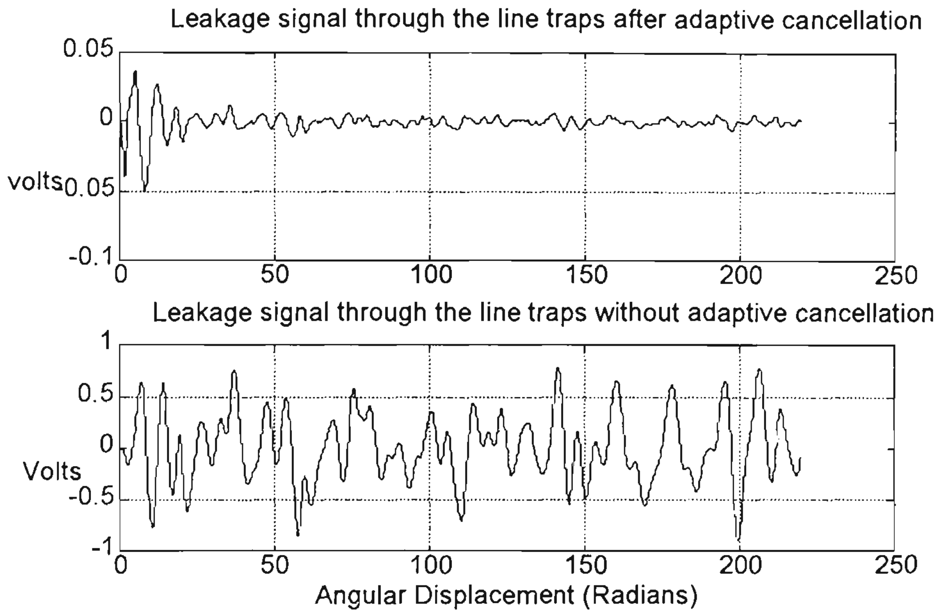
Frequency Spectrum (kHz)	Attenuation due to canceller (dB)	Attenuation due to line trap (dB)	Performance Index
5.0-50	-28.2065	-2.56130	.8449
50-100	-56.0635	-14.9349	.0400
100-150	-55.3004	-17.8324	.0252
150-200	-51.8858	-17.8444	.0327
200-250	-53.2563	-17.8638	.0301
250-300	-50.4798	-18.0075	.0387
300-350	-51.8697	-18.2294	.0431
350-400	-49.9439	-18.5010	.0491
400-450	-48.7656	-18.8066	.0754
450-500	-48.2663	-19.1360	.0979
5.0-500	-30.0944	-17.9293	41.54

Without adaptive cancellation, leakage signal has a significant ability to interfere with the PLC signal from the adjacent line section, operating at the same frequency. Figures 6.13-6.16 show a working of RLS method for different spectrums of frequencies. Graphical and tabular results can be used as a base to draw conclusions. RLS method works very efficiently for signals having small bandwidth. Results show that interference, after adaptive cancellations have been reduced to a very negligible value, as compared to the leakage signal. Tabular results show that this method appears to be very effective for the cancellation of interference for small bandwidth.

The algorithm also works efficiently for signals having higher bandwidth. Spectrum for PLC application is not very wide (15-500 kHz). To cancel the spectrum of PLC leakage signals, a few RLS loops would be enough for PLC application. The number of loops depend on the particular application and level of attenuation required.

Chapter 6 outlines the importance of the PLC model for computer simulation before the implementation of hardware of the system. MATLAB with its built-in tools proved to be a very effective tool for computer simulation studies of even very complex algorithm eg. RLS method. Results for PLC equipment design have been given separately in Section 6.2. Adequate design parameters were used for the computer simulation of the PLC model. Flow charts for all computer programs have been provided to clarify the algorithms. PLC model along with coupling capacitors for RLS method has been given in Figure 2.2 to outline the system used for modelling.

Results from Sections 6.4 and 6.5 show the importance of adaptive interference cancellation in a real-time situation. The RLS method has been tested for different conditions of PLC signals. Results from Section 6.5 show the ability of RLS method to find the dynamic response of line traps from the knowledge of input and output of the line traps. Line trap parameter variations have been outline in Figure 6.11.



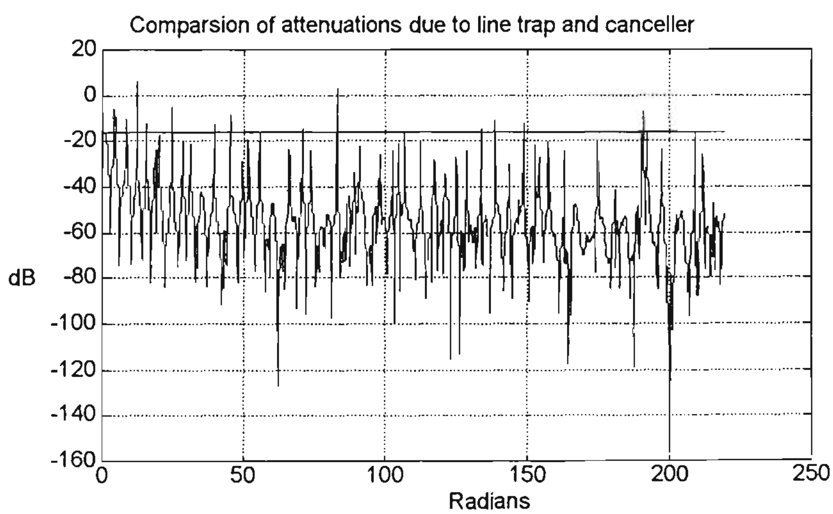


Figure 6.13: Performance of canceller for spectrum of 5-70 kHz frequencies

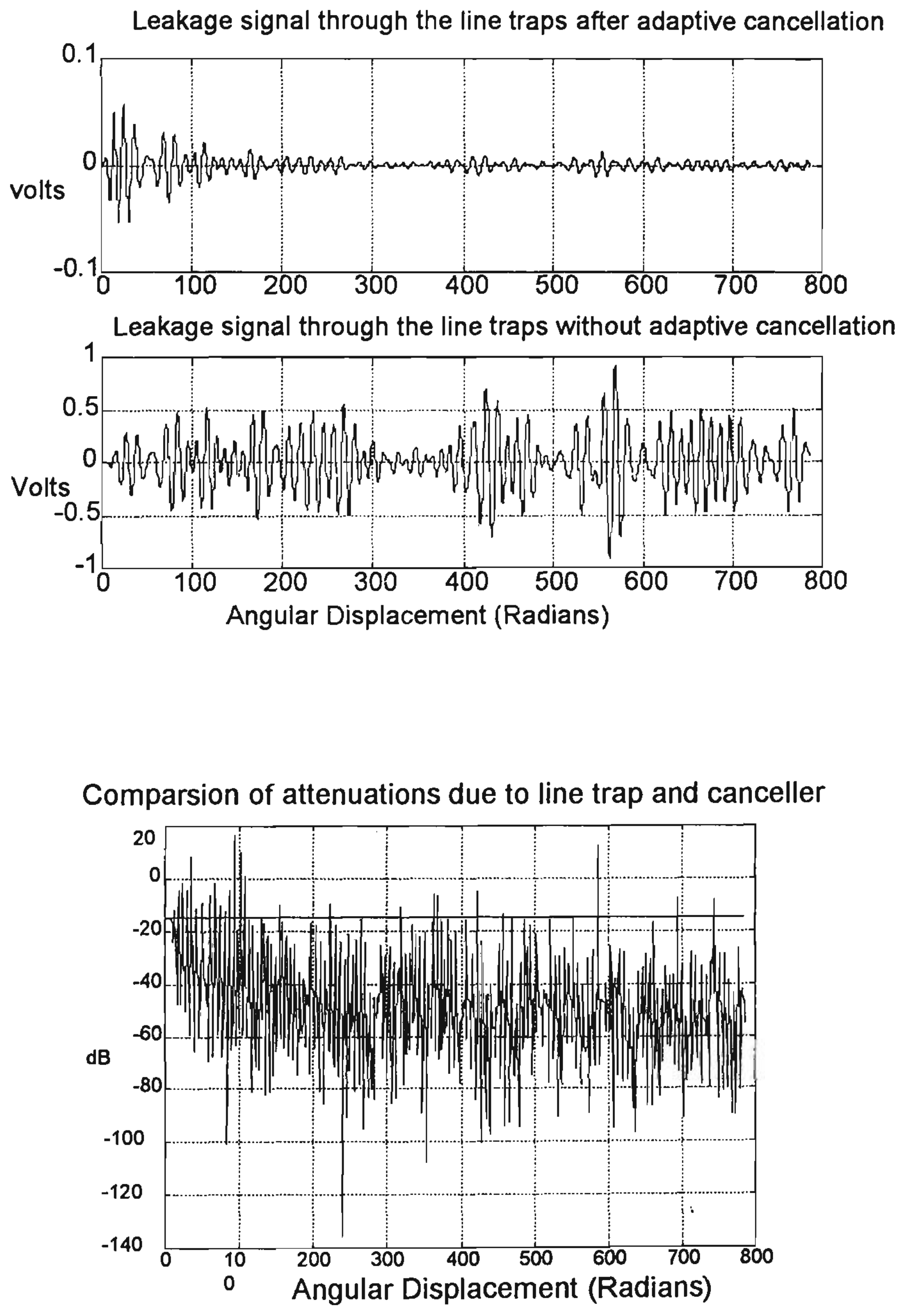


Figure 6.14: Performance study of RLS method for a spectrum of 100-150 kHz

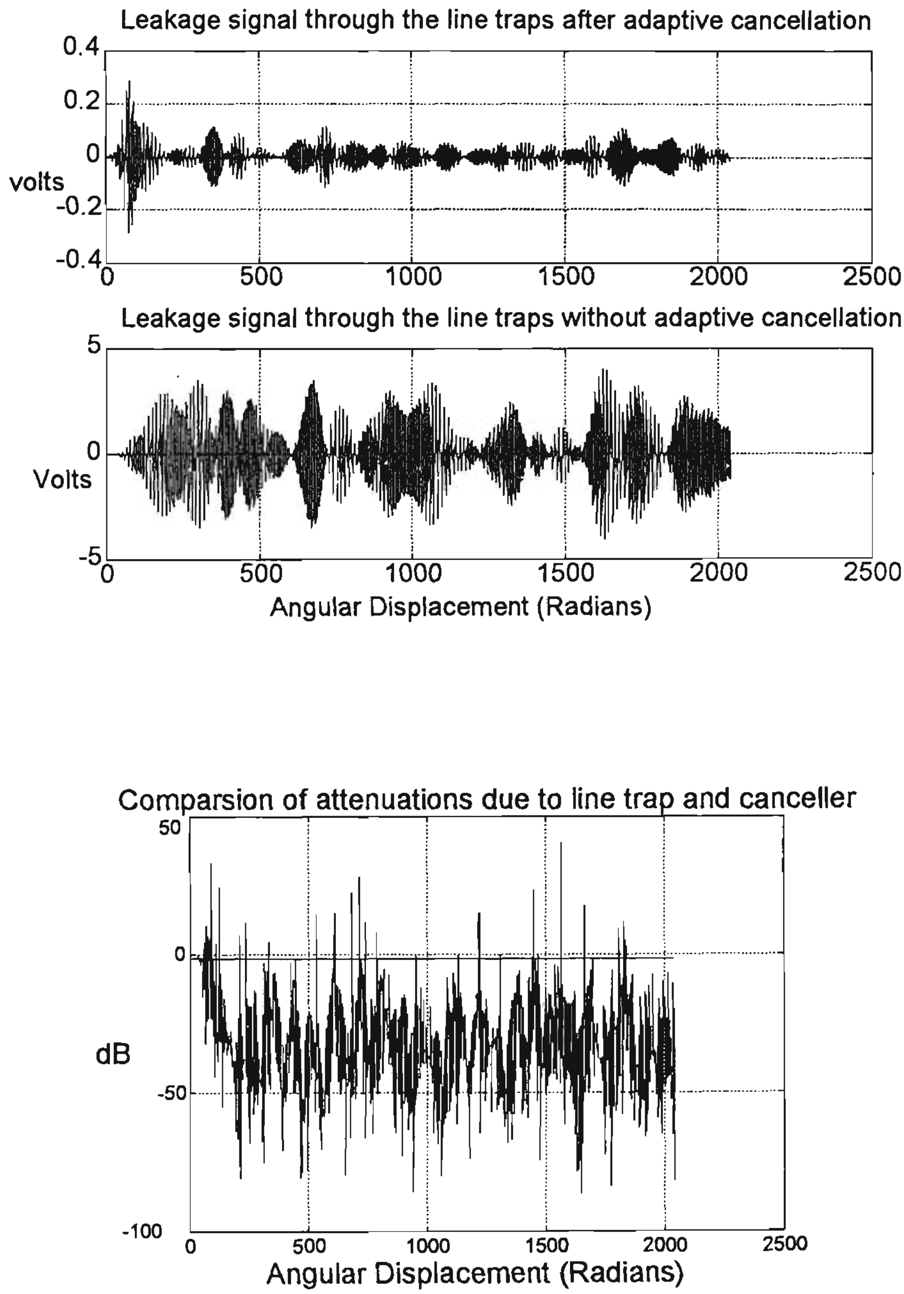


Figure 6.15: Operation of RLS canceller for spectrum of 300-350 kHz frequencies

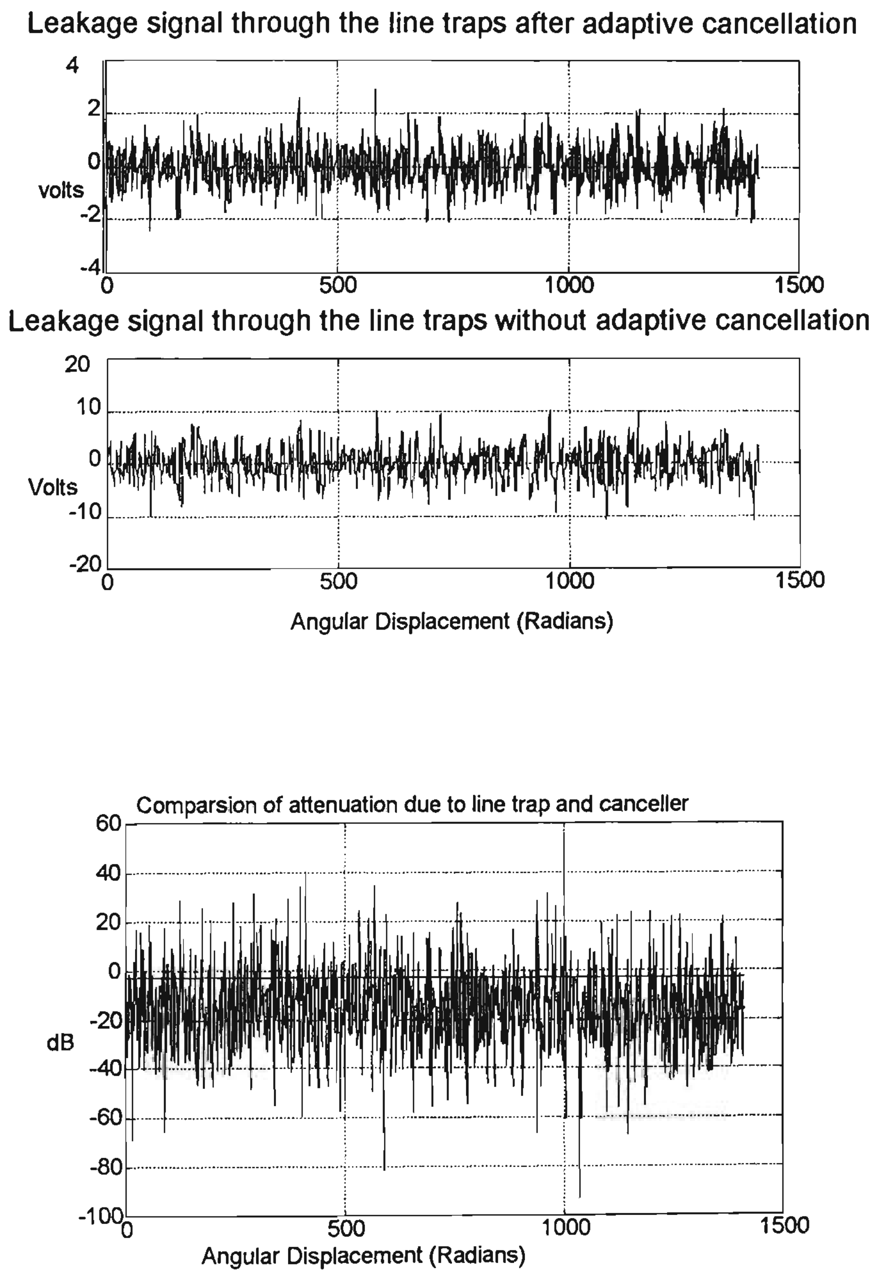


Figure 6.16: Working of RLS method for whole PLC spectrum (5-500 kHz) with the use of narrow band line traps

Computer simulation studies presented in this chapter were used to design the hardware models of PLC system and RLS algorithm. Results obtained using ATP6 presented in Chapter 5 were used to build the laboratory model of the transmission line for PLC application. Hardware parameters are given in Chapter 3. A hardware PLC model has been tested for different coupling schemes, the results are given in Chapter 7. Chapter 6 shows fair comparison with and without the use of adaptive interference cancellation scheme for PLC application. Results show that application of this method would be very effective in suppressing the interference, so that the same frequencies can be used for adjacent line sections. This will ultimately provide power industries with a stable financial outcome to improve their means of data communication.

CHAPTER 7

IMPLEMENTATION OF RLS METHOD

7.1 INTRODUCTION

The need for adaptive interference cancellation algorithms for implementation on PLC systems was discussed in Chapter 2. Mathematical model of RLS method was also developed to assist the line trap to attain satisfactory level of attenuation. Calculation of accurate parameters should be given primary importance for both computer and hardware simulation studies. Parameters for the construction of power line model were obtained from the computer simulation studies of 500 kV transmission line. The results are presented in Chapter 5. Different steps in designing and construction of a power line model has been outlined in Chapter 4. Behaviour of the modelled power line was tested for a wide spectrum of frequencies in assessing optimum spectrum of frequencies for PLC operation.

This chapter will mainly focus in assessing the performance of RLS algorithm in real-time situation. Accuracy of the algorithm depends on the true knowledge of input signals. Accurate evaluation of line trap parameters can be made, based upon the accuracy of coupling capacitors and transmission line parameters. The later has direct effect on propagation and time delay of the PLC signal.

Hardware construction of the PLC system presented in Chapter 4, allows the incorporation of desired source frequencies. This option facilitates to investigate the behaviour of the RLS method for different spectrum of frequencies. A few limitations were observed in assigning frequency allocation, which were due to constraints imposed by limited sampling frequency of data acquisition card (PCL_818), which is described in Chapter 4. This chapter will also highlight the advantages and disadvantages of conventional and non-conventional couplings in assessing the frequency response of the line under different coupling schemes.

7.2 BEHAVIOUR OF POWER LINE MODEL UNDER DIFFERENT COUPLING SCHEMES

Figure 4.3 describes a laboratory model of power line connected with spectrum and network analyser for the assessment of various coupling schemes. This technique was used to analyse the steady state response of conventional and non-conventional couplings on the line model. In this study, results will be presented to show the level of attenuation faced by the signal when it is injected and received on the remote ends of the same phase of line, which are referred to as conventional couplings. For non-conventional couplings, attenuation has been evaluated considering signal injection and reception on separate phases.

Non-conventional coupling studies suggested making use of line traps on those phases of line even if PLC signal is not conducted on the phases. In the case of phase-to-phase and 1-phase-to-ground coupling, PLC signals also propagate on non-coupled phases as well [23]. Non-conventional coupling studies suggested, if line traps are not used on non-coupled phases, PLC signals with its full power will interfere with the signals on the adjacent line sections operating on the same frequencies. Application of adaptive interference cancellation will not be helpful if these conditions occur on the system. "Conventional" and "non-conventional" couplings are discussed in more detail in subsequent sections.

7.2.1 Conventional Couplings

Conventional couplings, defined in the previous section are commonly used in power systems practices. Among conventional couplings, 1-phase-to-ground and phase-to-phase couplings are the least expensive and most efficient. Three-phase couplings are rarely used due to their high cost. Proposed technique has been used to investigate line response under three-phase couplings.

7.2.1.1 Single-Phase-to-Ground Coupling

Single-phase-to-ground coupling is one of the widely used couplings in power system practices [23]. In this research, central-phase-to-ground coupling was adopted to inject PLC signal on the line. The central phase of sending and receiving ends was taken as input and output for network analyser respectively. The response of the line was assessed for frequency ranging from 10-1,000,000 Hz. Figure 7.1 shows magnitude and phase angle responses, when the line was subjected to work using single-phase-to-ground coupling.

For a laboratory line model, lumped parameters were used to arrange four cascaded π circuits to represent 400 km line length. Due to the lumped nature of line parameters, magnitude and phase responses were not linear any more, as shown in Figure 7.1. At power frequency, magnitude and phase responses showed the possibility of maximum power flow in the line. Steady state operation of PLC signal on line model was considered up to maximum of 50 kHz, it has been described in Chapter 4. Figure 7.1 shows linearity of magnitude and phase responses of the line operating at spectrum of frequencies 5-50 kHz. For this spectrum of frequencies, rate of attenuation was linear. Attenuation presented due to this type of coupling varied nearly from 2-22 dB for the spectrum of interest. Attenuation levels for other types of couplings are presented and compared in subsequent sections of this chapter.

7.2.1.2 Phase-to-Phase Coupling

Phase-to-phase coupling is the recommended coupling for PLC utilities in Australia [86]. Figure 7.2 shows, line behaviour when the PLC signal was coupled to two phases. This type of coupling gives a boost to the integrity and reliability of information flow on lines at the expense of high economic cost as compared to single-phase-to-ground couplings. Figures 7.1 and 7.2 give true comparison of single-phase-to-ground and phase-to-phase couplings in term of attenuation offered to PLC injected signals.

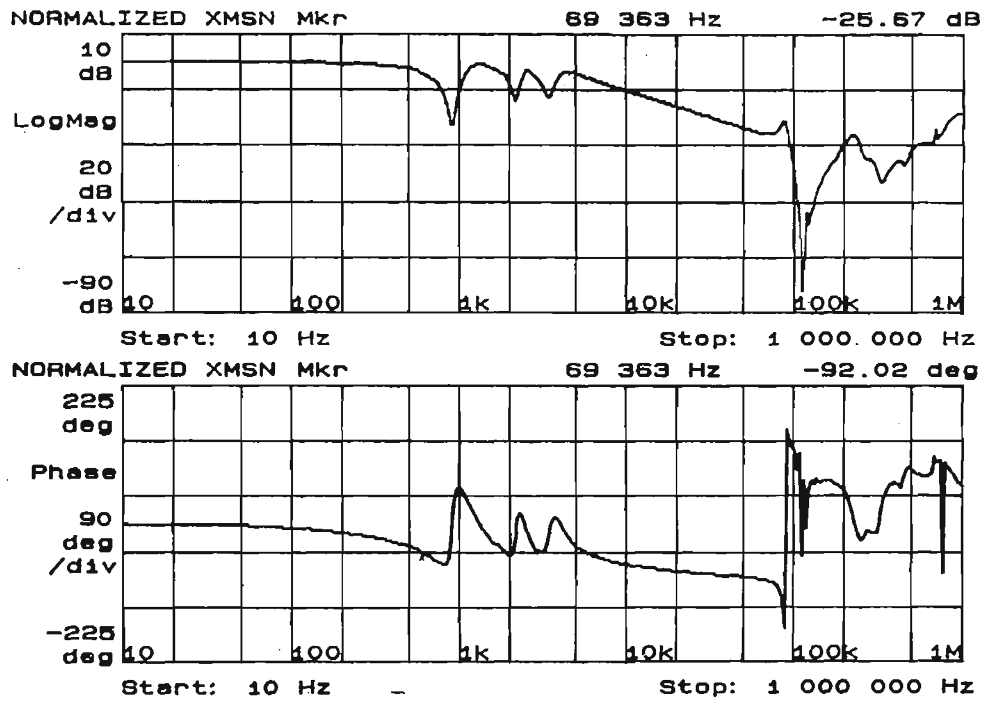


Figure 7.1: Performance of the line model with the use of central-phase-to-ground coupling

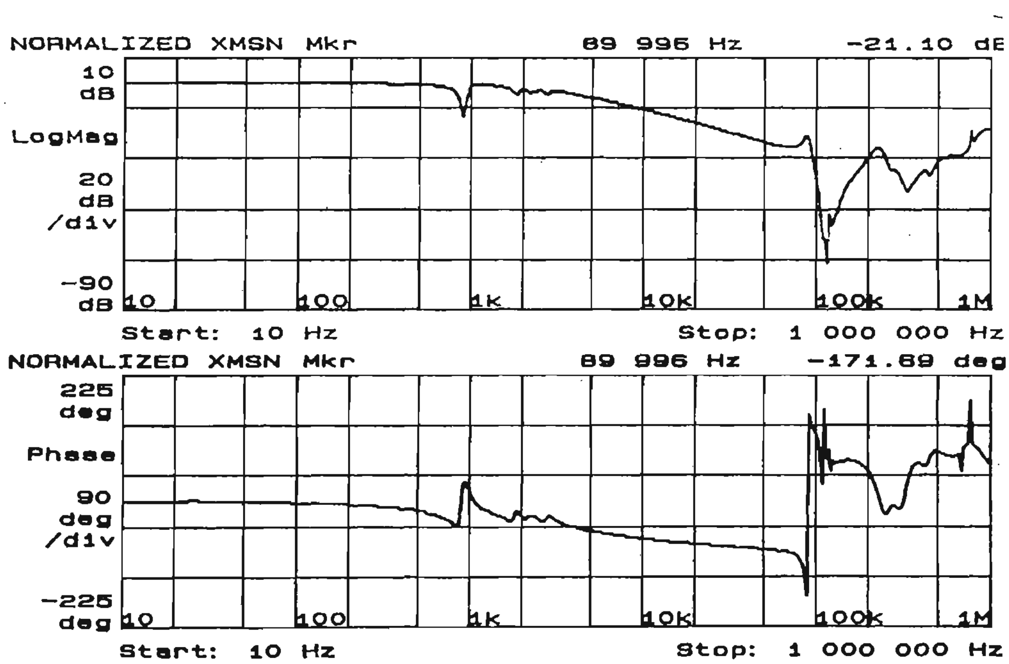


Figure 7.2: Use of phase-to-phase coupling on the power line model

Magnitude and phase responses were linear with this type of coupling, specially comparing frequency region among 0.8-35 kHz from Figures 7.1 and 7.2. Non-linearity observed in magnitude and phase responses under different coupling schemes can be blamed for lumping line parameters. Locations of poles and zeros in the transfer function of line model can be very critical at certain frequencies for the given line parameters. Results could be improved with excessive π-circuit cascading.

7.2.1.3 Three-Phase Coupling

Three-phase coupling is the most expensive and most efficient coupling, which is very rarely used in power system industries [23]. At the expense of high price, this type of coupling provides far more linear frequency and phase responses as compared to the other two types of conventional couplings. Results in Figure 7.3 show the behaviour of the power line model with three-phase couplings. Traces given in Figure 7.3 show that non-linearity being observed in case of the single-phase-to-ground and phase-to-phase couplings have been reduced to some extent. The behaviour of the line is very much improved even for a frequency spectrum of 0.5-5 kHz.

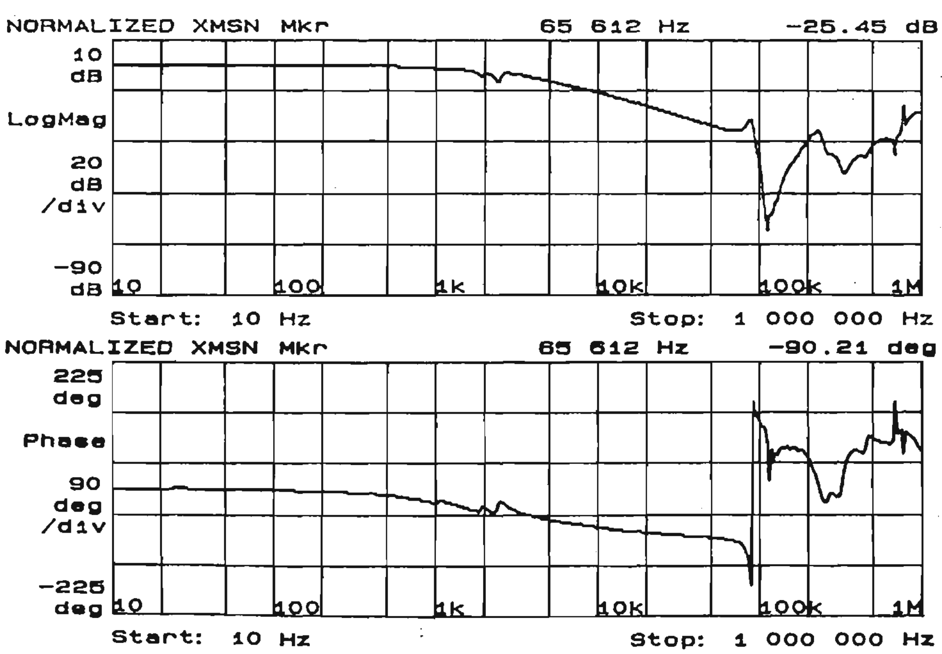


Figure 7.3: Test results for three-phase couplings

In conventional coupling studies, the behaviour of the line was very much non-linear for the said spectrum of frequencies, which made the line unusable for the frequency spectrum of 0.5-5 kHz. From this study, it appeared that three-phase coupling has compensated the effects induced due to the lumping of parameters of the power line model.

7.2.2 Non-Conventional Couplings

Assessment of conventional couplings led towards studies of non-conventional couplings. Results obtained from the studies of non-conventional couplings, verified some of the very important facts for the true representation of the line model. Some of the facts have been outlined in Chapter 4. Phases of line model were marked as top, centre and bottom. Studies that have been carried out in this research are listed below:

Table 7.1: List of non-conventional couplings

	Signal Injection	Signal Reception
1	Top	Bottom
2	Top	Centre
3	Bottom	Centre
4	Centre	Top

Figures 7.4-7.7 present results for non-conventional couplings. Comparing the results given in this section, it can be concluded that magnitude response showed better linearity when the signal was injected on the central phase and was received on top phase. These studies also showed the presence of PLC signals on the non-coupled phases, which was due to shunt capacitance of π-circuits among the phases. Presence of signal on non-coupled phase is considered due to the presence of different modes of the signals [23].

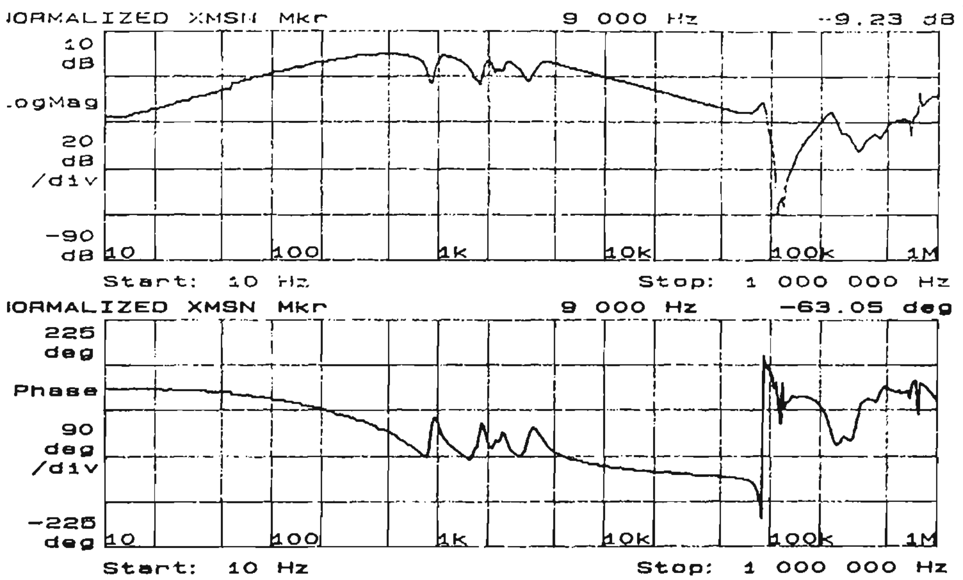


Figure 7.4: Studies of non-conventional couplings when signal injection and reception were performed on the top and bottom phases respectively

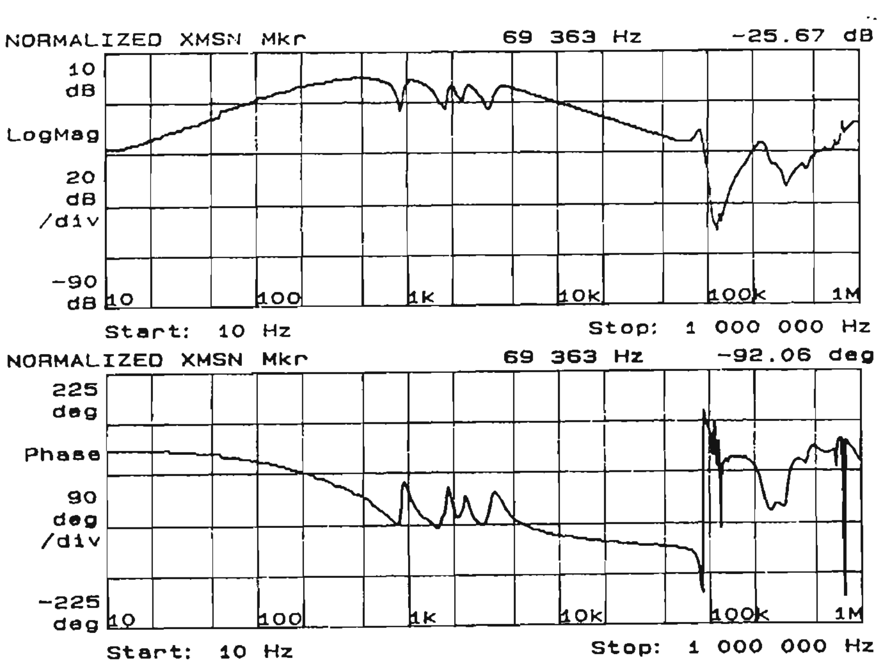


Figure 7.5: Frequency and phase responses of the line model with signal injection and reception on top and central phases respectively

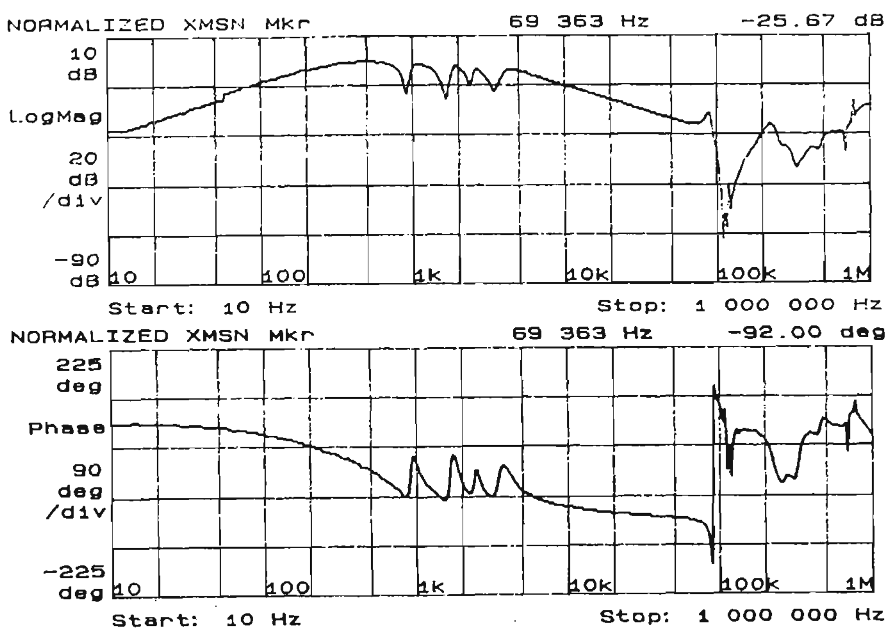


Figure 7.6: Behaviour of the line model with the signal injection and reception at bottom and centre phases respectively

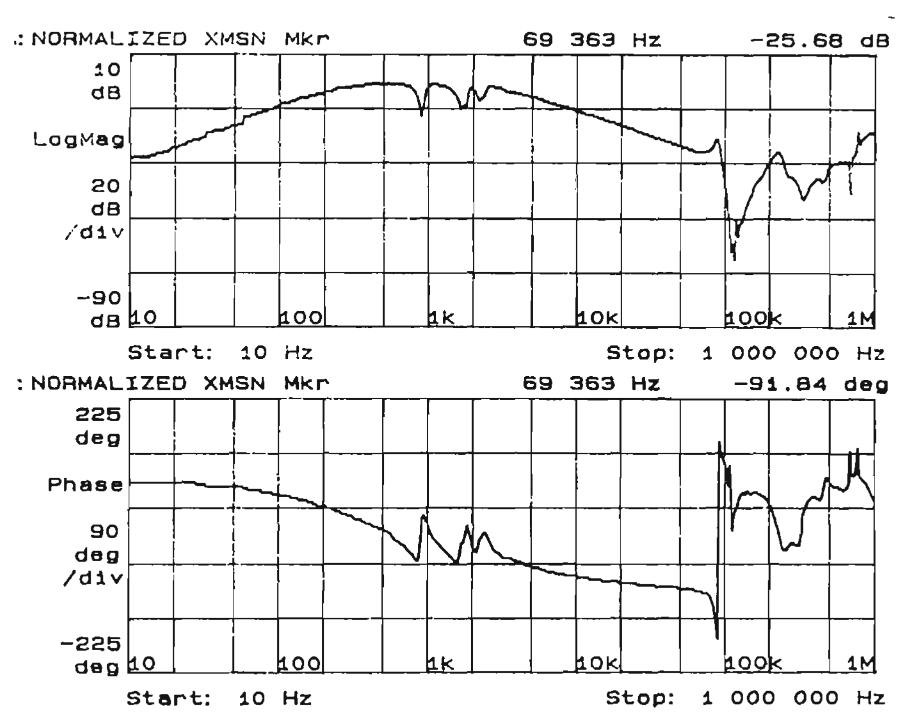


Figure 7.7: Test results for non-conventional couplings when signal was injected and received at central and top phases respectively

7.3 TESTING OF LINE TRAPS ON POWER LINE MODEL

Parameters of line trap given in Chapter 3 were used to simulate the PLC model along with its associated components. Results are given in Chapter 6. Considering computer simulation studies, broad band line traps were designed to suit the required spectrum of frequencies. Line traps were employed on both sending and receiving ends of the line model. Attenuation offered by the equipment was tested by loading the line with appropriate variable loads. As mentioned earlier, PLC signals were coupled and trapped at the central phase only. Behaviour of the line traps was assessed based on the level of interference, due to the leakage of the PLC signal through line traps.

Stored data was used to test the accuracy of different adaptive cross-polarisation interference cancellation techniques. In subsequent sections of this chapter, RLS method has been tested on the power line model.

7.4 IMPLEMENTATION OF RLS METHOD ON REALISTIC SYSTEM

In the previous chapters, RLS was taken as example to demonstrate the working of adaptive cross-polarisation interference cancellations techniques for PLC systems. RLS method cross-polarises its estimates about interferences due to line traps and then cancels these interferences in real-time mode from the concerned busbar. Test results for other interference cancellation techniques, using the same principle are presented in Chapters 8 and 9. Conclusions are drawn based on the assessment of different interference techniques.

Mathematical model, design procedure and simulation studies of RLS method are given in Chapters 2, 4 and 6 respectively. Also a method has been presented to retrieve the hardware data from the PLC laboratory model and to provide inputs to the controller. The implementation results of a designed controller for this application are presented in this section. Limitations imposed in selecting PLC operating spectrums forced hardware studies up to 50 kHz. Behaviour of line model and working of RLS method for different frequencies can be compared from the results of this section. Studies on the realistic system have been subdivided into two parts.

- Algorithm was tested on the line trap model with nominal loading on the system.
- Algorithm was tested on the line model with nominal loading on both sending and receiving ends.

7.4.1 Assessment of RLS Method on Line Trap Model

Using the parameters obtained from computer simulation studies, as presented in Chapter 6, a laboratory model of line traps was designed to foster lowpass filters for both sending and receiving ends. Referring to the attenuation studies of the designed line trap presented in Section 7.3, the RLS method was tested for different frequencies ranging from 5-50 kHz. Figures 7.8-7.11 outline the working of this algorithm with a frequency spacing of 5 kHz. Results of the implementation of canceller on the line trap are given in Table 7.2, when line trap was designed to show attenuation ≅ 10 dB.

Table 7.2: Results from the application of RLS method on line trap

Frequency (kHz)	Attenuation due to canceller (dB)	Attenuation due to line trap (dB)	Performance Index
5.0	-30.2048	-2.7153	1.311
8.5	-30.7922	-4.3724	.9312
10	-34.6805	-4.6612	.7537
15	-32.0370	-6.7692	1.080
20	-38.7811	-7.2505	.4261
25	-33.5866	-8.5100	.4668
30	-35.9990	-8.5116	.5684
35	-39.6538	-9.6227	.3844
40	-45.8730	-10.592	.2068
45	-43.0644	-10.885	.2754
50	-45.8481	-9.6717	.0126

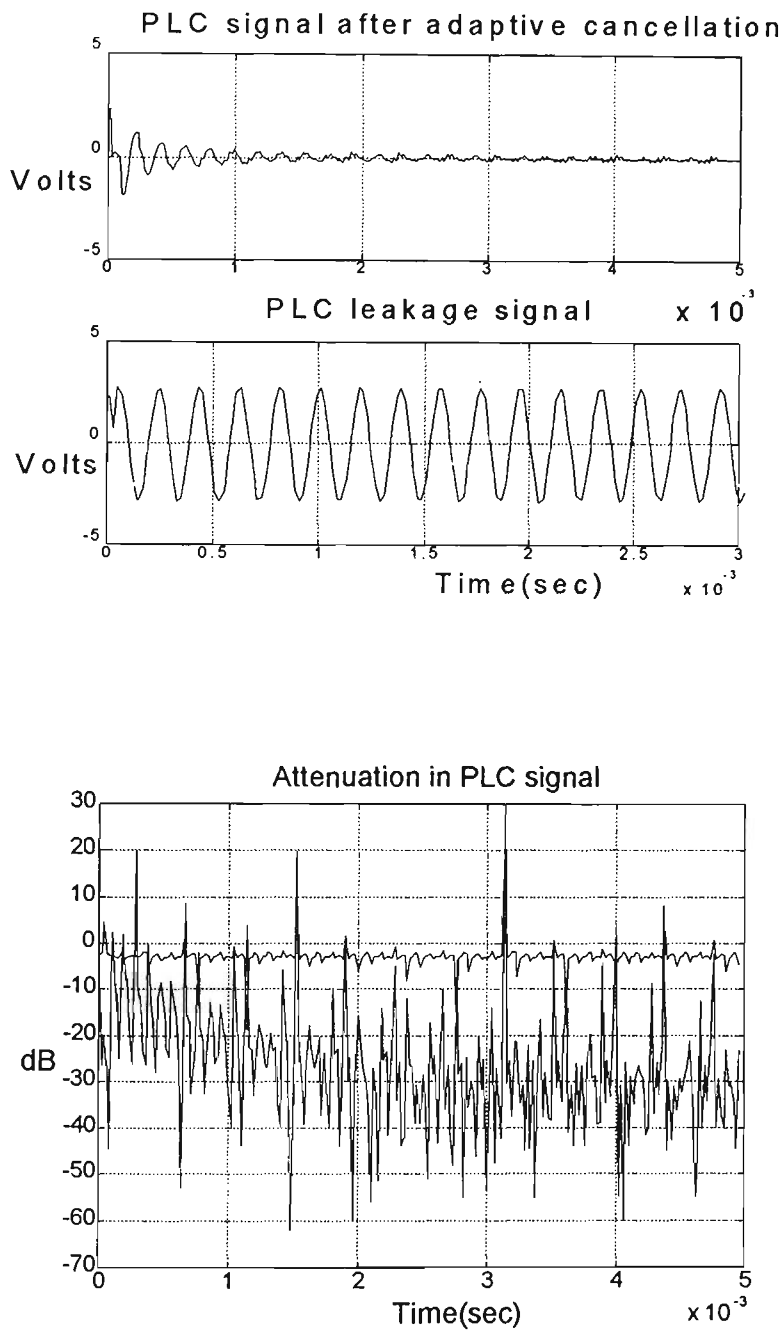


Figure 7.8: Performance of RLS Canceller on signal with very small bandwidth having centre frequency of 5 kHz

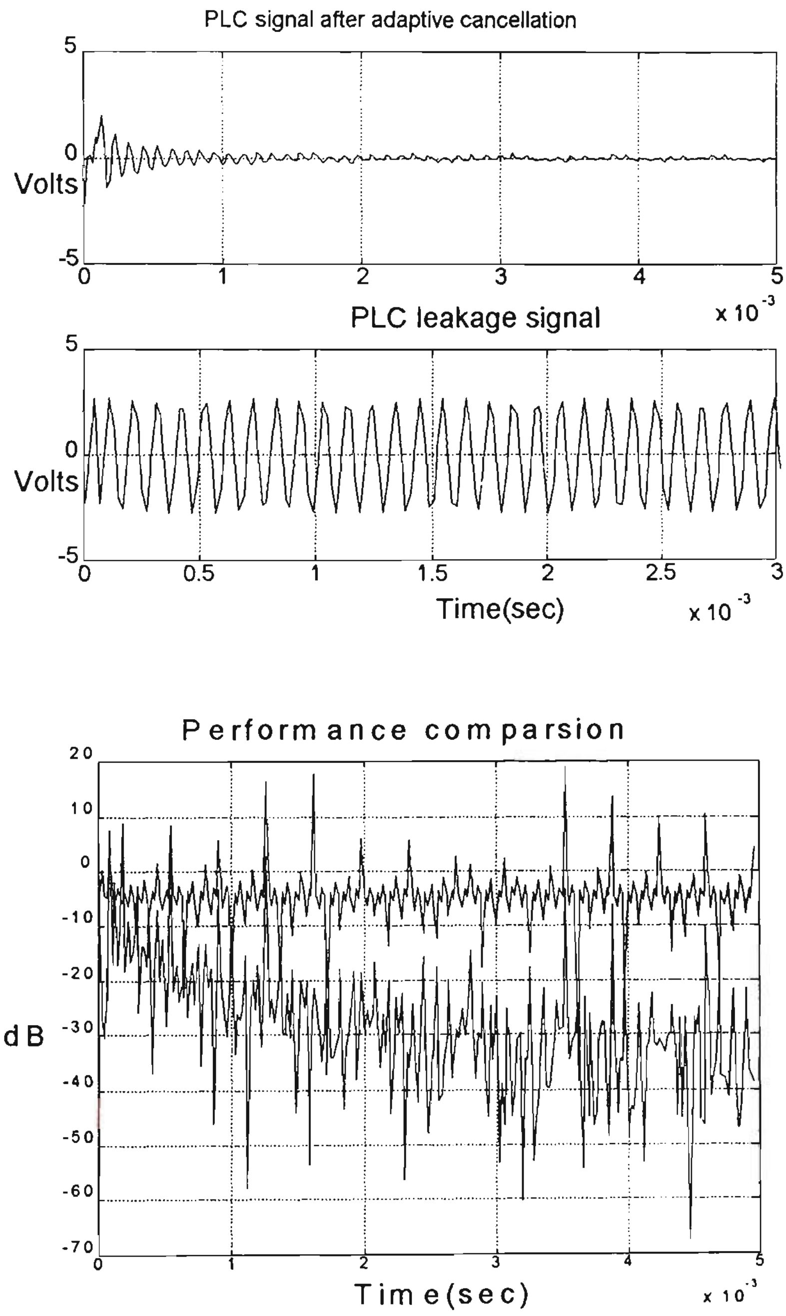


Figure 7.9: Application of RLS canceller on leakage signal having centre frequency of 10 kHz

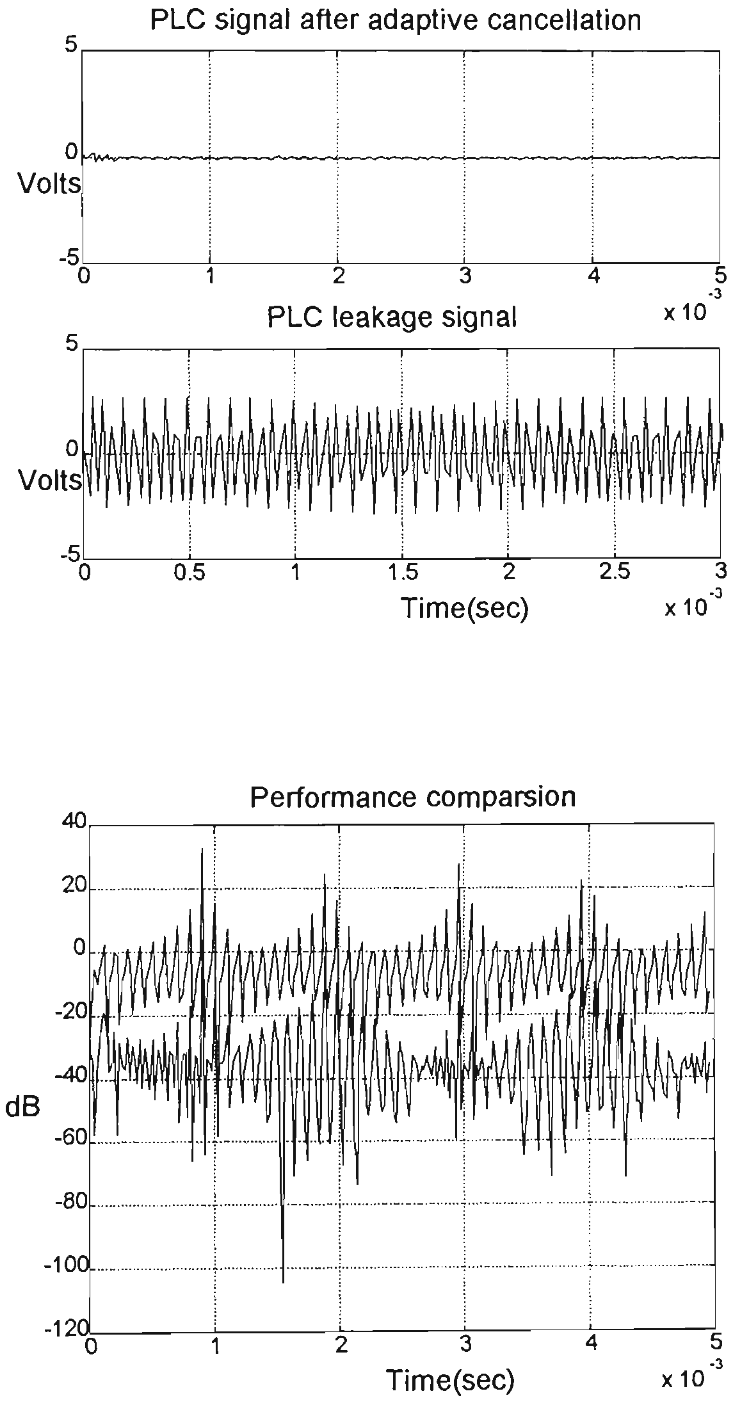


Figure 7.10: Performance evaluation of RLS algorithm on PLC having centre frequency of 20 kHz

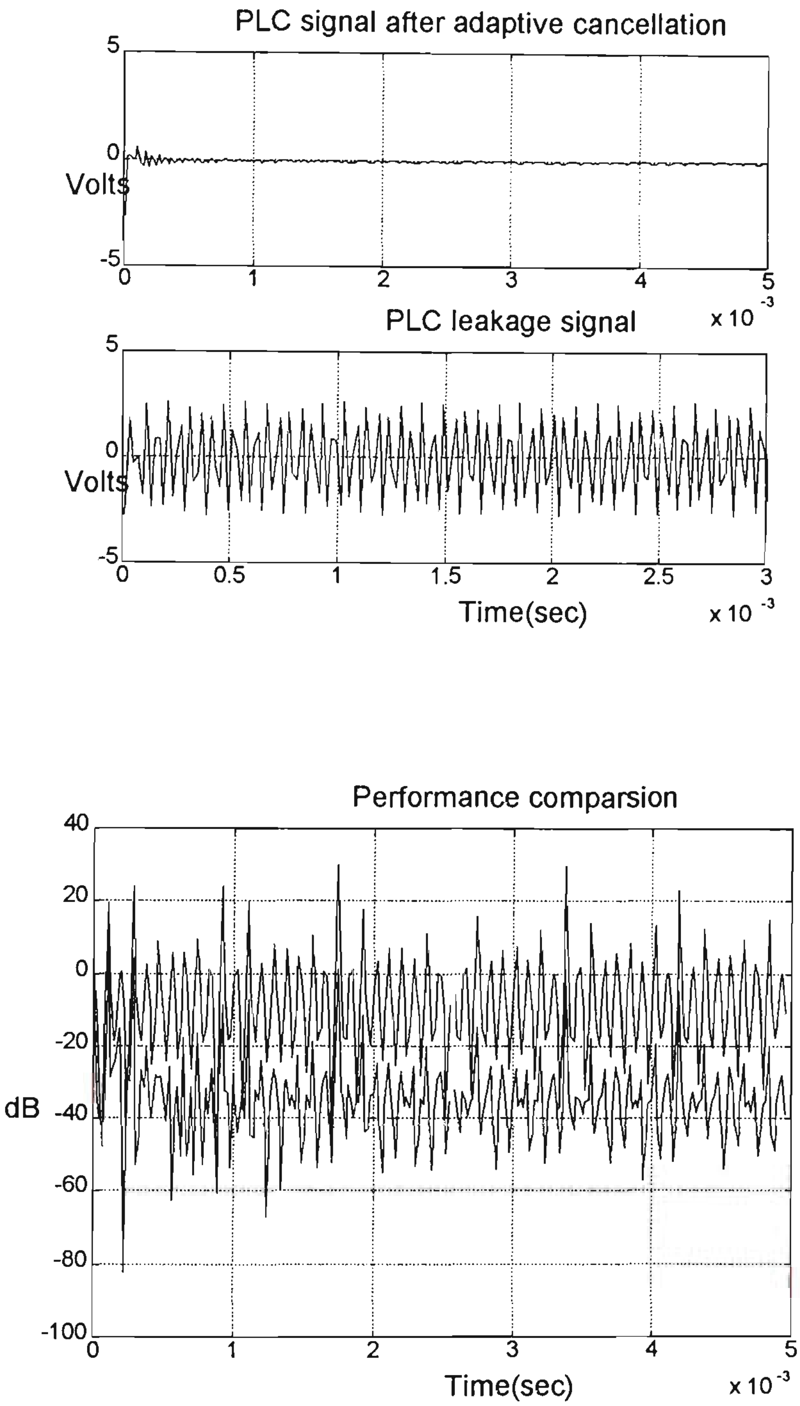


Figure 7.11: Application of RLS canceller on line trap model with operating signal having centre frequency of 30 kHz

For the studies presented in this section, only one set of line trap was used without connection to the line. Appropriate loading on the line trap gave a very close resemblance to the computer simulation results as given in Chapter 6. Variations in the performance of RLS method for different frequencies were due to the frequency-variant parameters of the line trap. True representation of PLC and PLC leakage signals was limited due to low sampling frequency of the data acquisition card. The slow sampling rate and the uneven pacing of data points further contributed in lowering the efficiency of the interference canceller. For the existing hardware simulation model, more consistent data points for the signals can be obtained using very high sampling frequency data acquisition card. This could improve the knowledge about the signals and ultimately the learning of algorithm would be more realistic. Design of the line trap was improved to give average attenuation of 20 dB. With the new design, performance of canceller was also improved. Results are given in Table 7.3.

Table 7.3: Results from the application of RLS method on line trap

Frequency (kHz)	Attenuation due to canceller (dB)	Attenuation due to line trap (dB)	Performance Index
5.0	-41.6209	-16.6947	.0958
8.5	-43.1412	-18.3518	.0661
10	-45.0565	-18.6406	.0460
15	-44.0551	-20.7486	.0528
20	-50.8295	-21.2299	.0313
25	-51.9516	-22.4894	.0272
30	-51.0853	-22.4910	.0211
35	-54.2478	-23.6021	.0150
40	-58.1120	-24.5714	.0083
45	-56.3790	-24.8652	.0137
50	-39.9323	-23.6511	.0533

7.4.2 Application of RLS Method on PLC Model Communication System

Modelled power line as presented in Figure 4.1 was used for the trials of RLS method on the realistic system for different frequencies within limited bandwidth. In this research, the main focus was to improve the reliability of line traps in transient and steady state conditions. Figures 7.12-7.15 outlines the performance of RLS method when applied across the line trap of the sending end of the line model. Studies were made on very low operating frequencies due to hardware constraints. PLC and PLC leakage signals were contaminated with the noise generated due to line characteristics. For PLC application, recognition of power signal and PLC leakage signal on busbar is very convenient. Both of the signals can be separated using coupling capacitors (highpass filter). On busbar, only presence of power signal was exempted. Any other signal on the busbar was regarded as interferences.

Figures 7.12-7.15 show the interference cancellation for the frequency spectrums centred at 15, 20, 25 and 30 kHz and results are given in Table 7.4 for line trap model showing attenuation less than 10 dB.

Table 7.4: Results from the application of RLS method on PLC model

Frequency (kHz)	Attenuation due to canceller (dB)	Attenuation due to line trap (dB)	Performance Index
15	-31.4148	-6.5306	.6702
20	-28.5405	-7.2167	1.285
25	-38.4660	-3.8408	.2307
30	-35.6935	-8.2113	.6939

Inconsistency in data points for different frequency spectrums is possible, which could contribute in lowering the performance of RLS algorithm for first few samples. With improved line trap model, performance of canceller was also improved. Results are given in Table 7.5.

Table 7.5: Results from the application of RLS method on PLC model

Frequency (kHz)	Attenuation due to canceller (dB)	Attenuation due to line trap (dB)	Performance Index
15	-42.1681	-20.5100	.075
20	-43.1765	-21.1961	.0482
25	-51.2018	-17.8202	.0367
30	-48.5297	-22.1907	.0392

Results in this section show that after 1 msec., the knowledge of algorithm about the line trap parameters was improved to its optimum value. To estimate the performance index of the algorithm for this application, data points up to 1 msec. were ignored to avoid the data range inaccuracy. Behaviour of the canceller between time limits from 0-1 msec. for different studies was different due to improvement in learning for different signals. Average value of the performance index for different studies was nearly 0.1. For the application of RLS on the line traps model, average attenuation provided by the canceller was nearly 52 dB.

Studies provided in this chapter outline the performance of the PLC model under different coupling schemes. From the studies presented in this chapter, recommendations have been made to select optimum couplings for desired networks. Studies of non-conventional couplings facilitated to verify the presence of the PLC signal on non-coupled phases that is due to the presence of aerial modes.

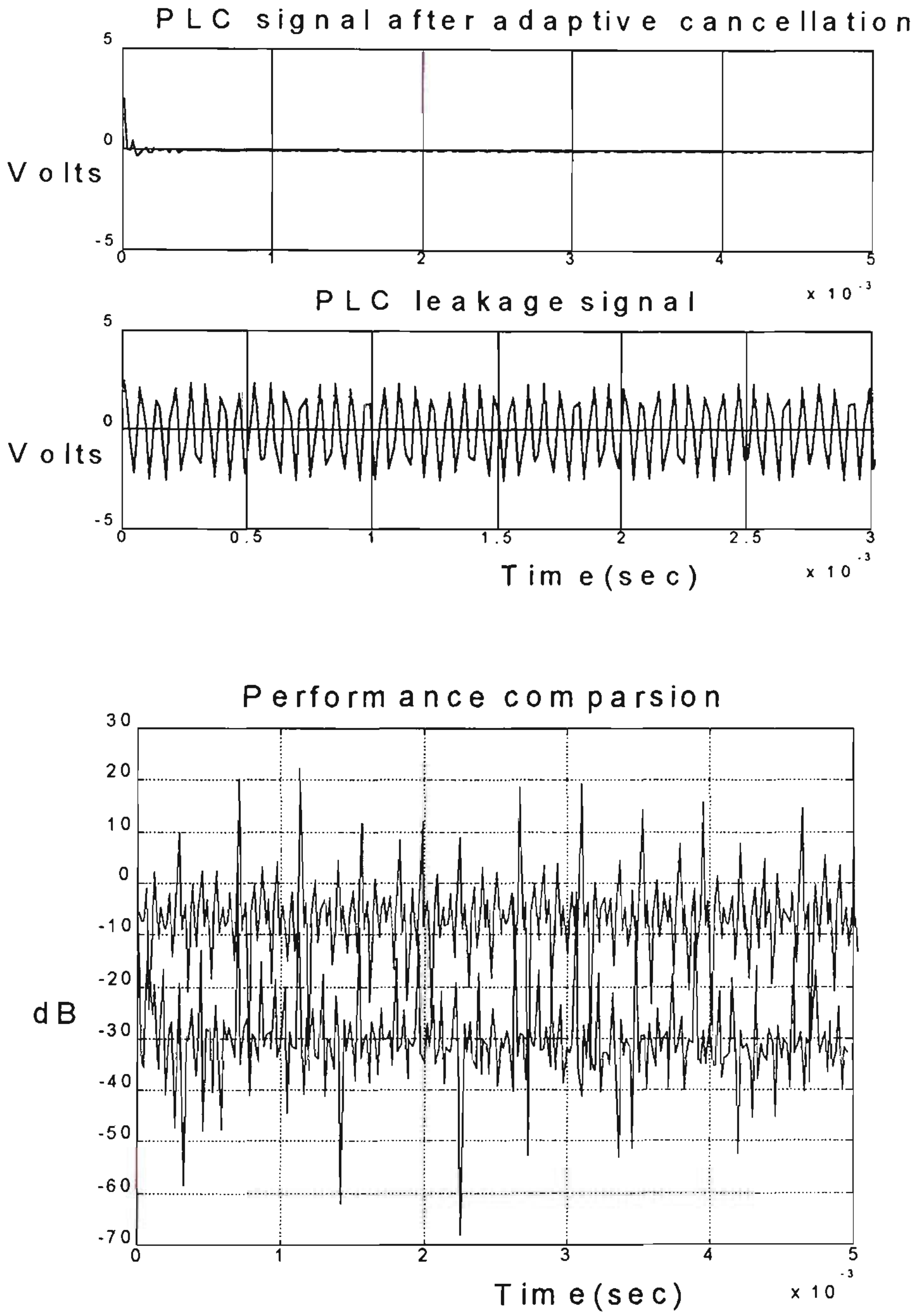


Figure 7.12: Performance of RLS canceller on the sending end busbar of the line model with low attenuation line trap using signal having centre frequency of 15 kHz

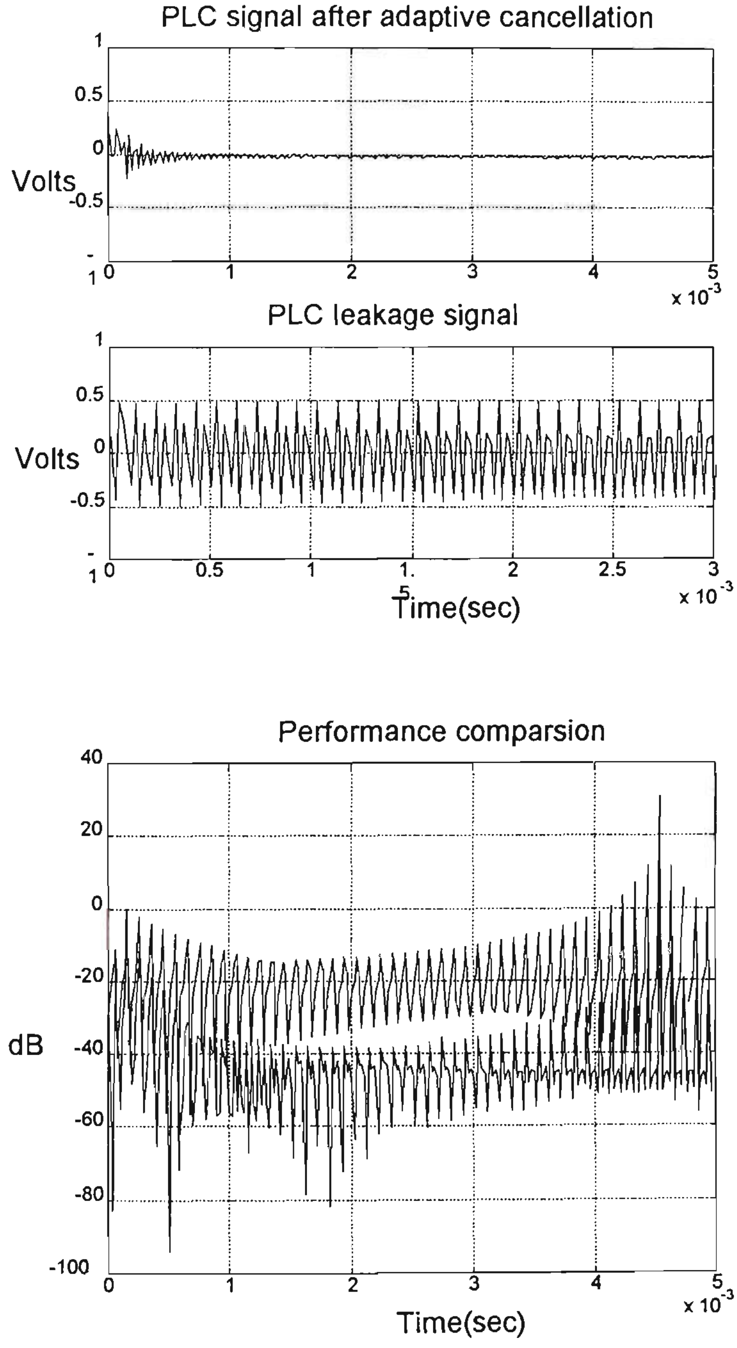


Figure 7.13: Performance of RLS canceller using efficient line trap with the use of signal having centre frequency of 20 kHz

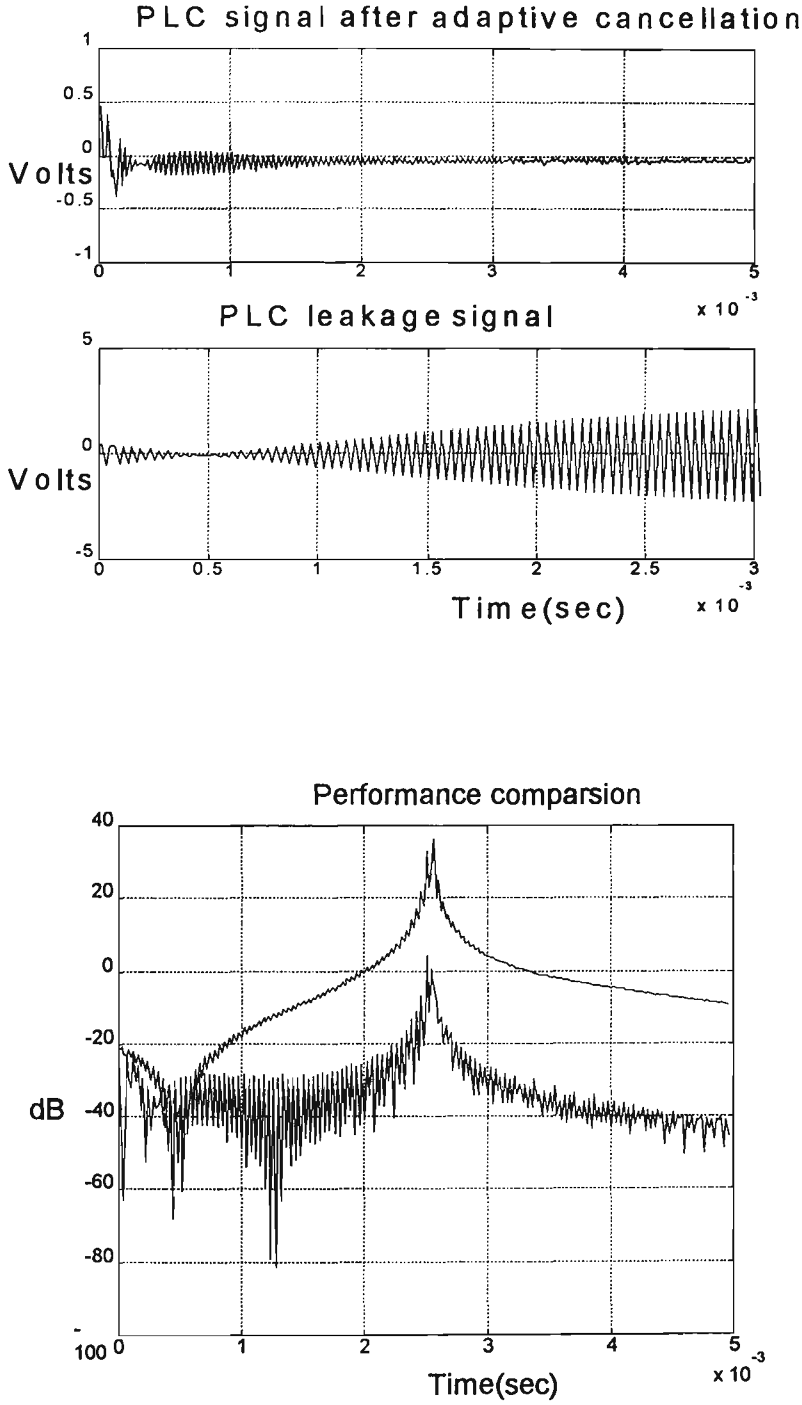


Figure 7.14: PLC signal attenuation studies with low performance line trap with the signal having centre frequency of 25 kHz

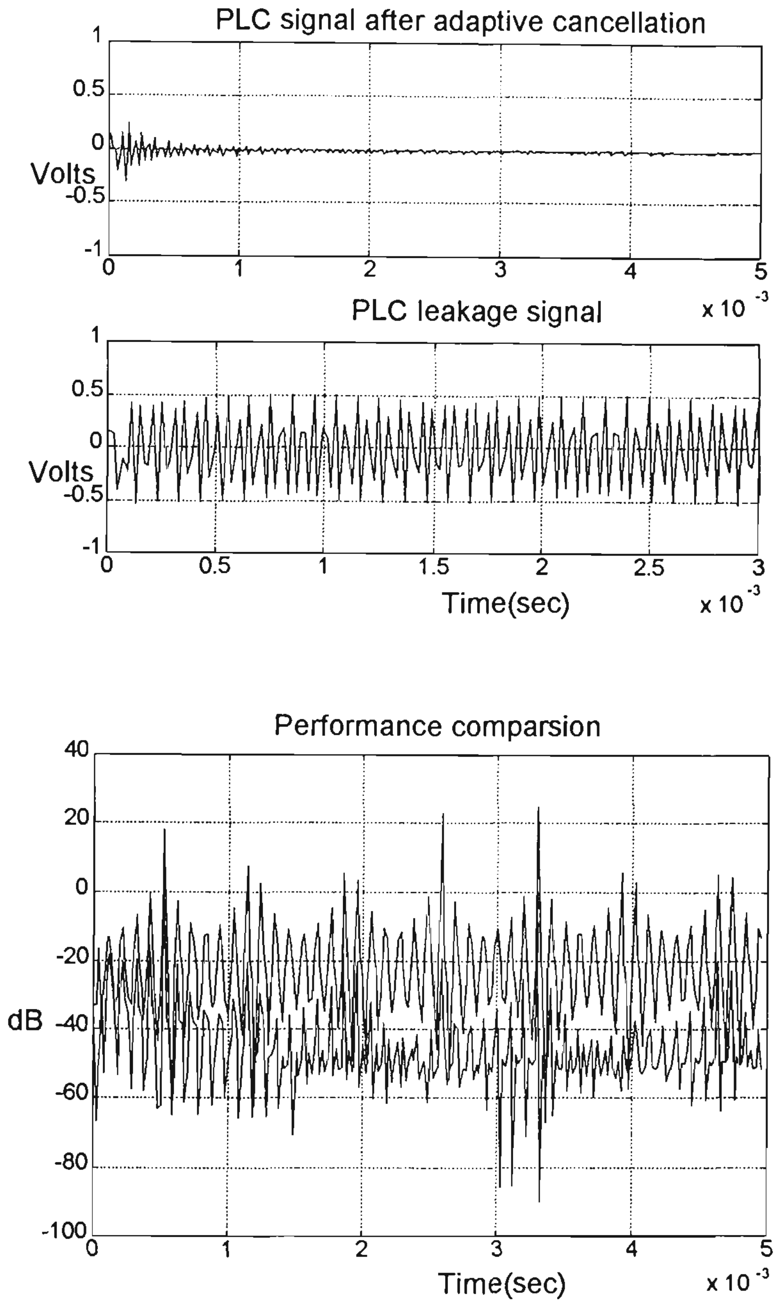


Figure 7.15: Performance evaluation of RLS canceller on line model using line trap offering high attenuation with the signal having centre frequency of 30 kHz

Representation of results for RLS method as a cross-polarisation adaptive interference canceller in graphical and tabular forms give a good overview of the working of the proposed algorithm. The method has been tested on both line traps and a complete PLC laboratory model. Results given in Tables 7.2-7.5 show a performance comparison of RLS method for different frequency spectrums with given data acquisition facilities. Results also concluded that, efficiency of canceller will improve if the line trap design is improved. Studies of RLS method on line also indicated the improvement of algorithm with the improved design of line traps. Results can be compared from Tables 7.4 and 7.5.

The results presented in this chapter can be used to predict that this algorithm will work satisfactorily on real power systems. Application of these techniques will be cost effective as well, because the suggested algorithm can make use of existing measuring equipment on the power network.

CHAPTER 8

IMPLEMENTATION OF STOCHASTIC APPROXIMATION

8.1 INTRODUCTION

The dynamic response of any desired system depends on the degree of accuracy of the parameters. In real-time systems, the parameters of a process change continuously. For adaptive control, time varying parameters should be updated recessively. Parameter estimation is used for system identification. Once a system has been identified correctly, then the system response can be estimated. In the previous chapters, RLS method was used to identify the dynamic model of line traps in a real-time system. In this chapter Stochastic Approximation (SA) method is used for the parameterisation of the line traps on a PLC system.

In earlier chapters, RLS method was used to outline the working of adaptive cross-polarisation interference cancellation (ACPIC) scheme. Application of SA method has been tested to work as an interference canceller for a PLC system. SA method was also tested as ACPIC for the same model and operating conditions like RLS method. Properties of SA estimation are briefly outlined:

- easy to implement
- easy to analyse when used in adaptive control
- slow in convergence for parameterisation
- not clear in optimisation.

8.2 MATHEMATICAL MODEL

For the computer simulation of the SA algorithm, MATLAB was also used as a simulation tool. Mathematical model for the canceller is given in Chapter 2. Comparing the mathematical complexities of the SA and RLS methods, SA method was easier to implement using MATLAB. Advantages and performance results are given in subsequent sections of this chapter.

8.3 COMPUTER SIMULATION OF SA ALGORITHM

For accurate estimation of line trap parameters, RLS method has been replaced with SA method. SA algorithm adopts the same steps as the RLS method with less computation time. Time comparison can be made in assessing the time taken by the computer programs for both algorithms (SA and RLS) using MATLAB as a programming language on a SUN Network SPARC10.

Time taken by SA method as an interference canceller = 13.6299 sec.

Time taken by RLS method as an interference canceller = 14.8506 sec.

Use of additional computational time consumed by the RLS method can be blamed for the additional mathematical calculations in calculating the internal state matrix (P_k). In RLS method, P_k is 4x4 matrix but for SA estimation, it is a scalar quantity. Mathematically it can be verified by comparing equations 2.14 and 2.18. Implementation of SA technique was also performed using the same PLC model, described in Section 6.3. Use of the same model also facilitated the comparison of the results from both (RLS and SA) adaptive interference cancellation schemes.

SA method being simpler in mathematical implementation as compared to RLS method, it also suffers the disadvantage of being slow in converging to the optimum parameters of the line traps. Figure 8.1 outlines the track for the convergence of parameters to the mean optimum values. Ripples in the waveform can be justified by blaming the frequency variant non-linear behaviour of the line trap and the system being stochastic.

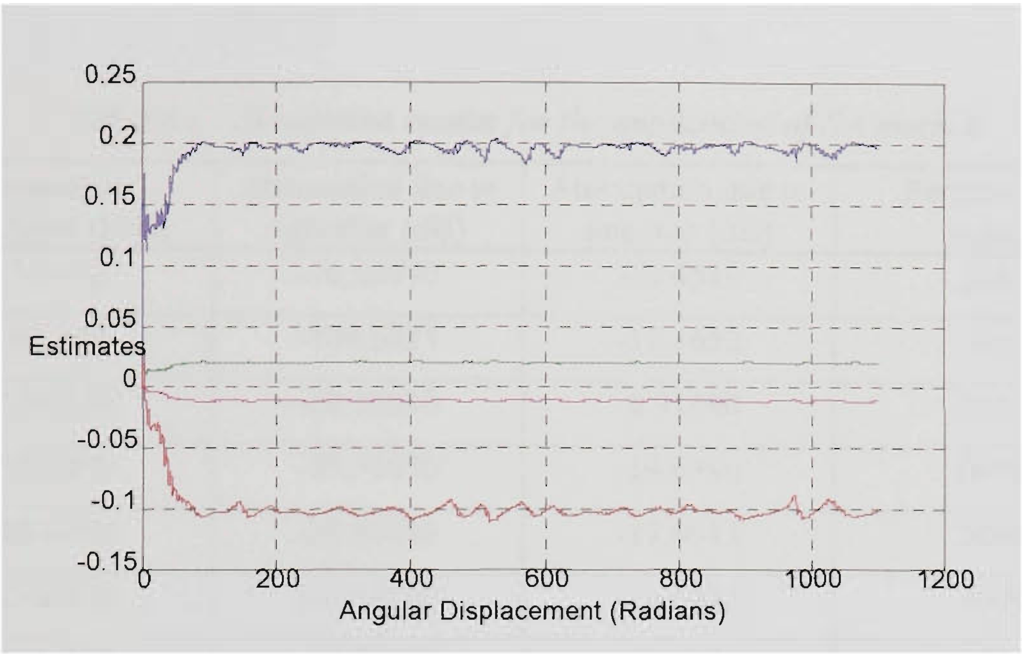


Figure 8.1: Convergence of line trap parameters using SA identification

For the simulation of SA method, the same programming strategy was used which has been described in Figure 6.10 in the form of flowchart. Performance of this algorithm was tested for different spectrum of frequencies. Results in Tables 8.1-8.5 highlight the important points of studies eg. performance index, attenuation due to the line traps and attenuation presented by SA method.

Overview of the simulation results listed in Table 8.1 gives the behaviour of the SA method in providing additional attenuation to PLC signals, for different spectrum, within allowable bandwidth of the PLC applications. Unsymmetrical variations in the behaviour of the canceller were due to frequency variant non-linear response of the line traps. Figure 6.5 shows the response of the line traps. Behaviour of the algorithm depends on the bandwidth and spectrum of the frequencies. If the concerned PLC spectrum falls in the non-linear region of the line traps response, then behaviour of canceller is unpredictable within controllable limits. Results listed in Table 8.1 show very close association between the performance of the adaptive canceller and the behaviour of the line trap. Cancellation study of the whole PLC spectrum gives a clear indication of the behaviour of the line trap showing high value of performance index (1.419).

Table 8.1 : Simulation results for the application of SA method

Frequency Spectrum (kHz)	Attenuation due to canceller (dB)	Attenuation due to line trap (dB)	Performance Index
5.0-50	-76.93070	-13.4510	.0165
50-100	-104.5423	-11.1652	.0130
100-150	-89.05880	-8.91480	.0124
150-200	-89.56670	-19.6390	.0030
200-250	-82.60050	-17.6913	.0046
250-300	-77.64210	-16.6472	.0070
300-350	-78.67540	-15.9792	.0086
350-400	-81.47930	-15.5543	.0159
400-450	-87.54370	-15.2402	.0118
450-500	-81.94010	-14.9828	.0161
5.0-500	-84.96320	-17.6913	1.419

Graphical representation of the results is shown in Figures 8.2-8.6. The computer simulation was run for 1 msec. Average attenuation presented by this algorithm was more than 80 dB. This much attenuation should show significant improvement in signal to noise ratio. The interfering signal from the adjacent line section would not have enough power to interfere with the PLC signal on the concerned line section, even if they are operating at the same frequencies.

8.4 HARDWARE IMPLEMENTATION OF SA METHOD

Working of SA method was also tested on the power line model, described earlier in Chapter 4. In implementing this method, the same procedure was adopted, as used for the RLS method. Design details have been presented in Chapters 4 and 5.

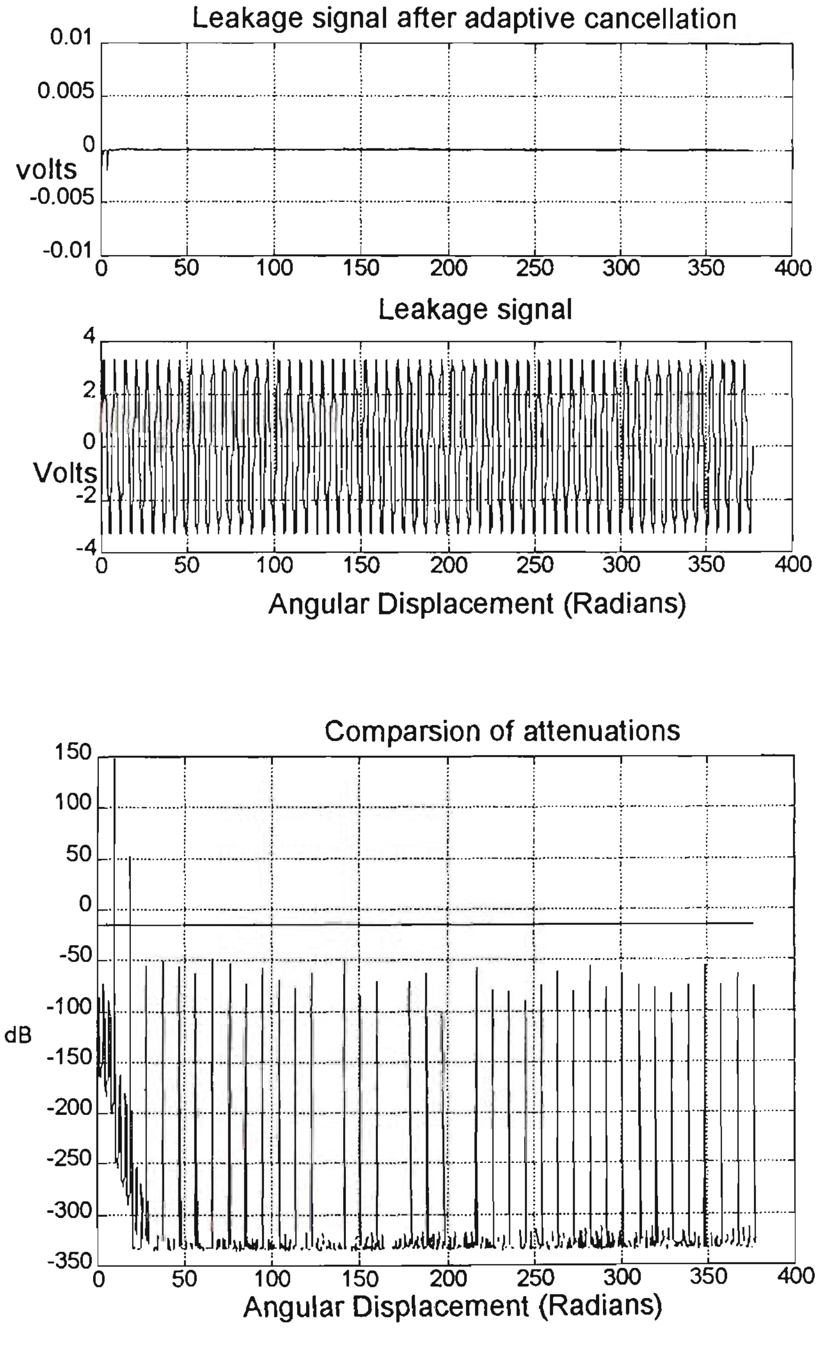


Figure 8.2: Application of SA method on PLC circuit for a signal having frequency of 60 kHz

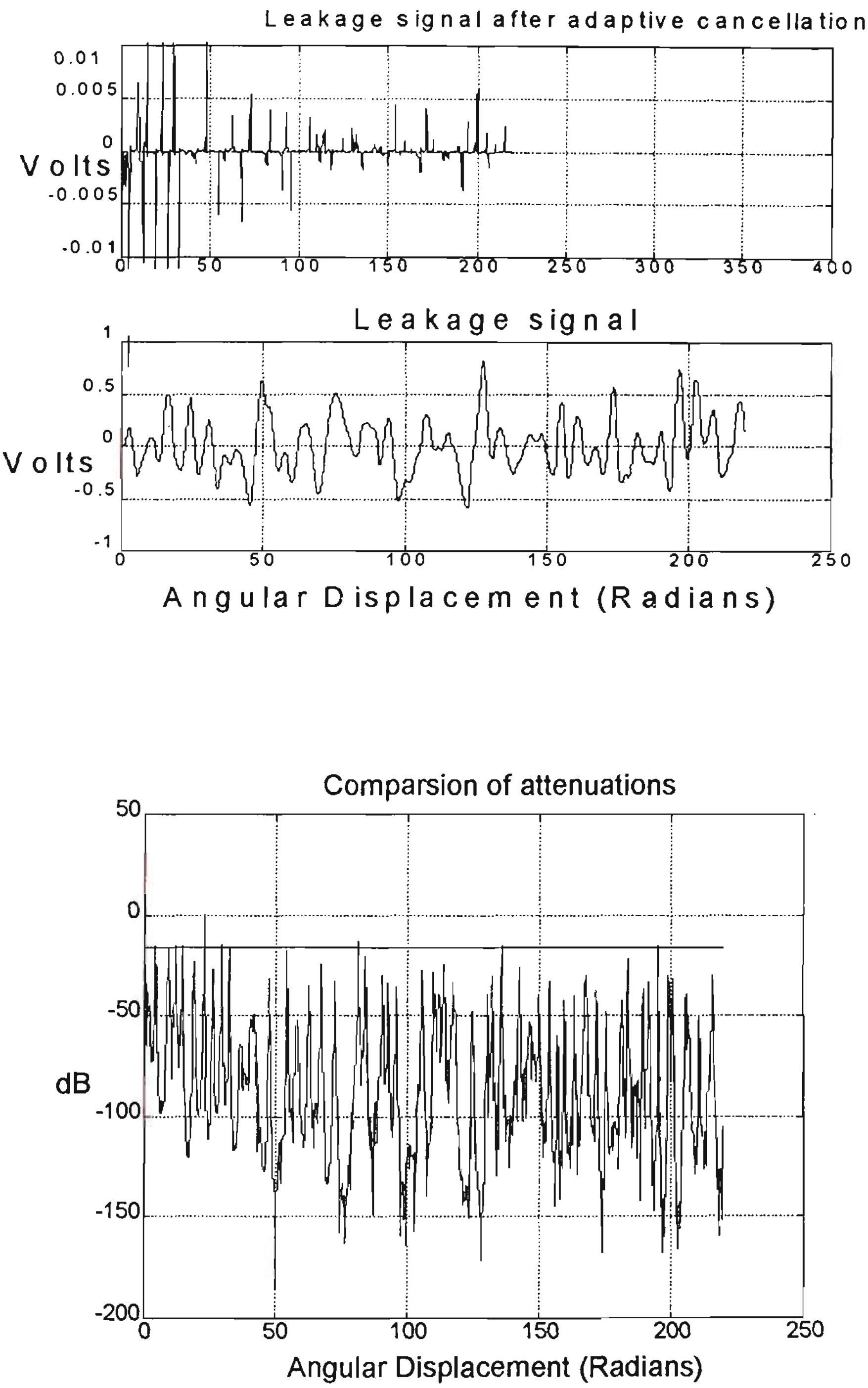


Figure 8.3: Performance of SA canceller for spectrum of 5-70 kHz

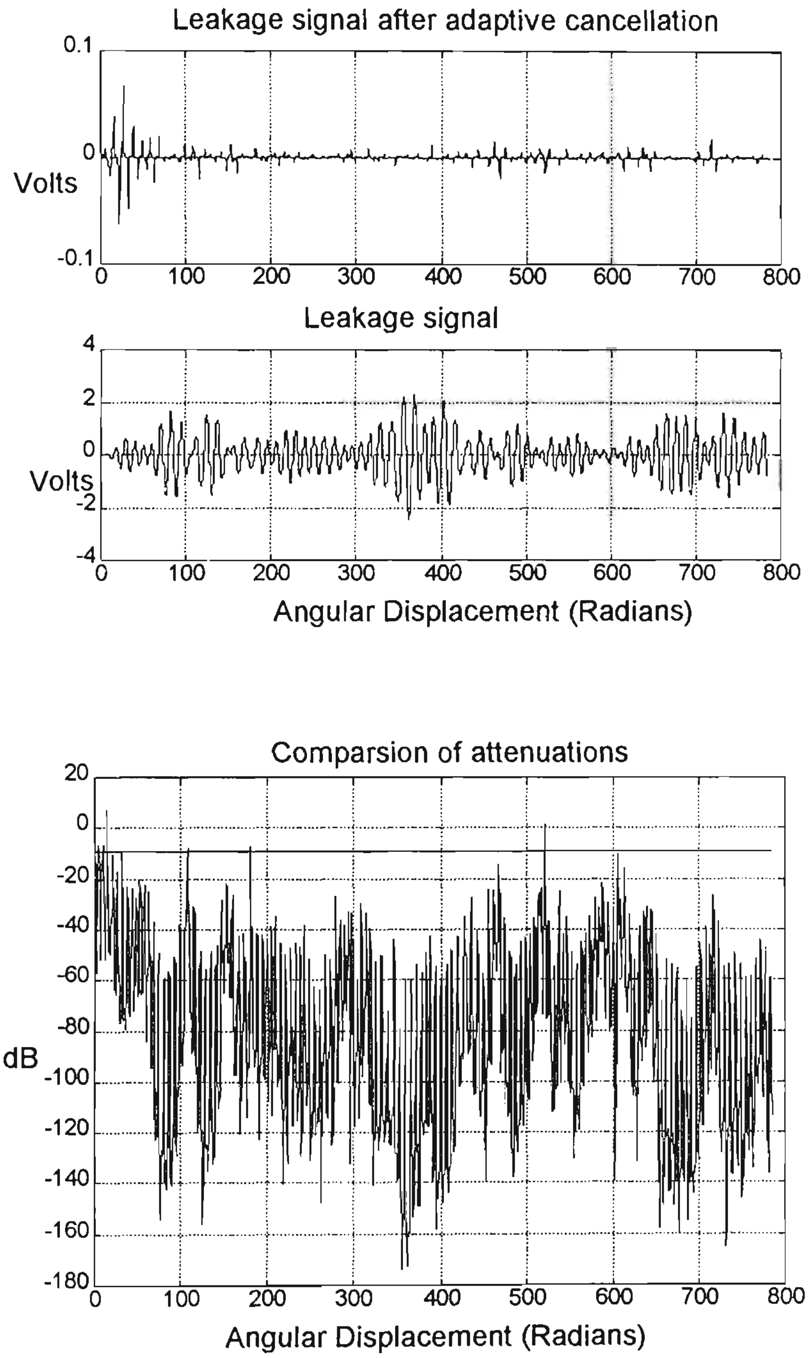


Figure 8.4: Application of SA canceller for signal having bandwidth of 100-150 kHz with broad band line traps

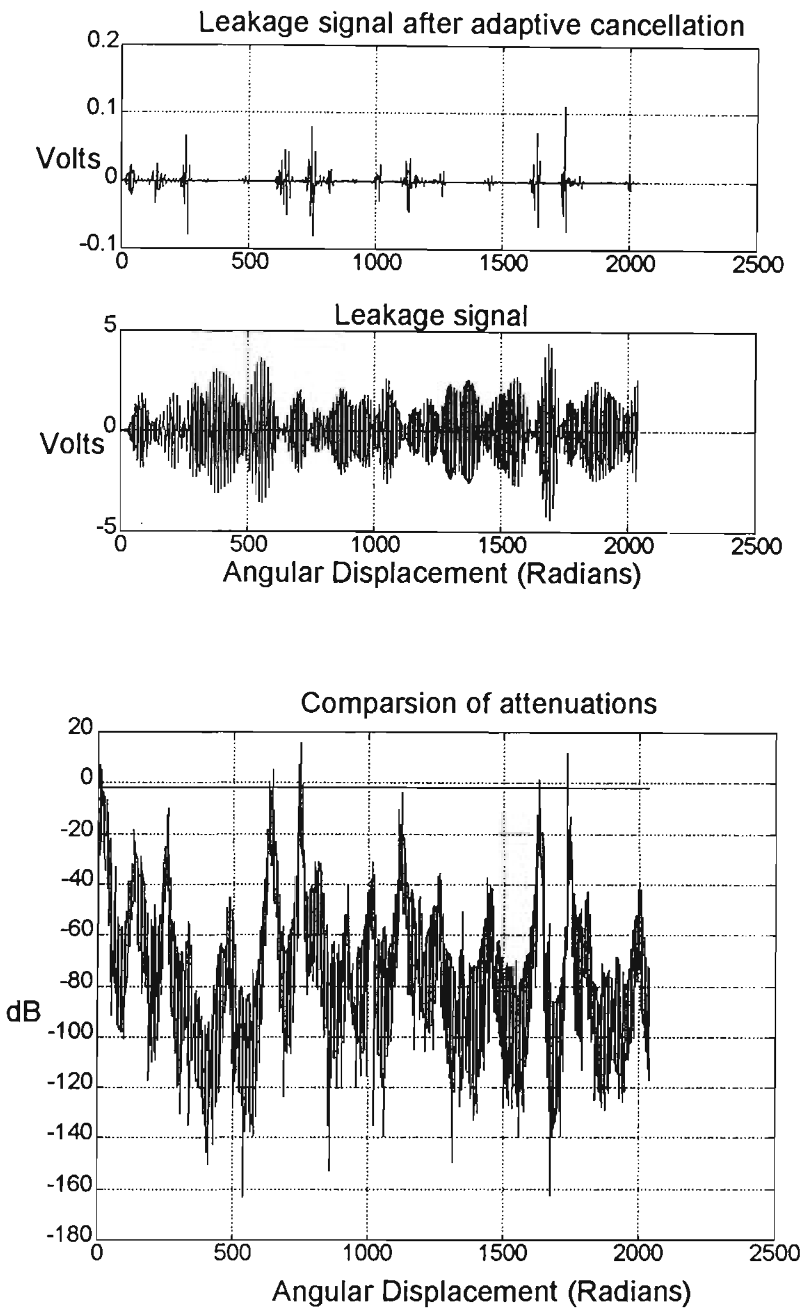


Figure 8.5: Working of SA canceller for spectrum of 300-350 kHz

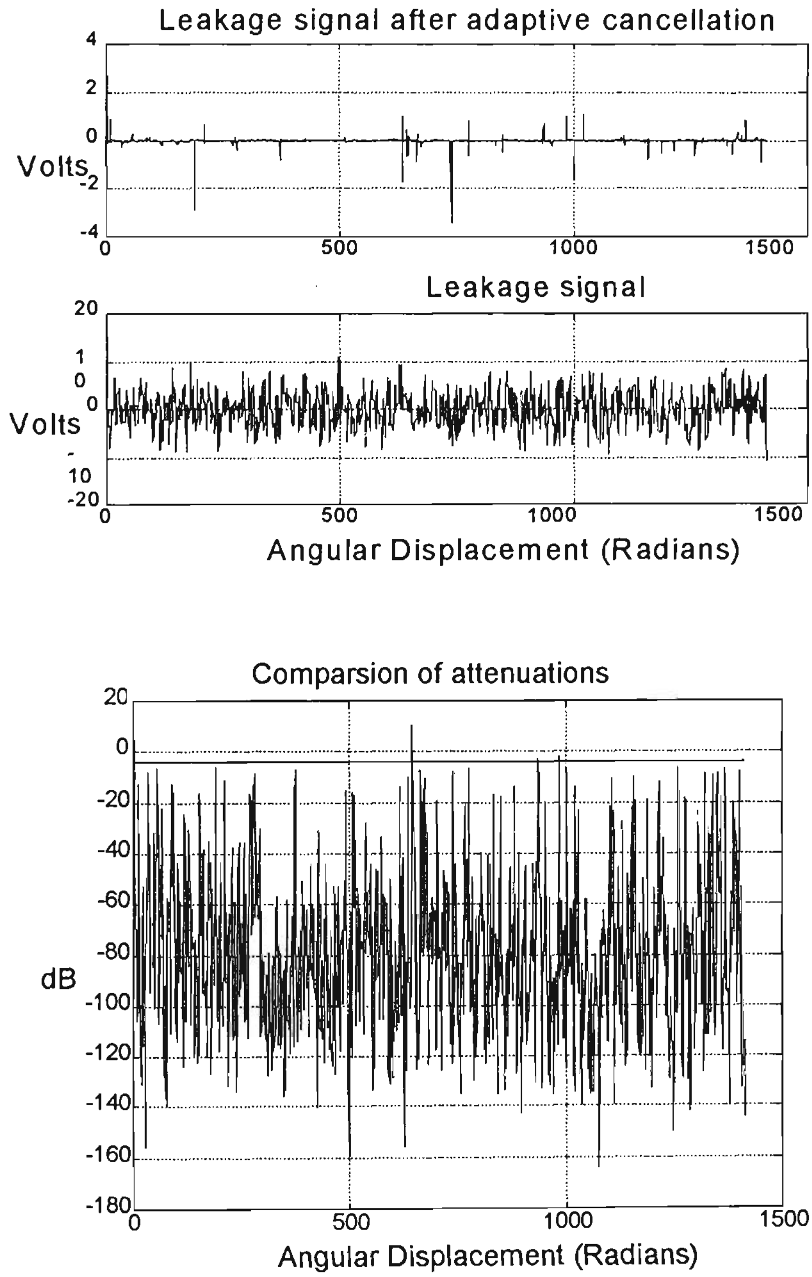


Figure 8.6: Performance of canceller for whole PLC spectrum using broad band line trap

Use of the same conditions for the implementation of both methods ie. RLS and SA, made the comparison very easy. Comparison studies are presented in Chapter 10.

Performance of this algorithm was also tested on the line trap model. In this phase of study, performance of line trap was considered very poor. Results are given in Table 8.2, showing the working of the canceller on low performance line trap.

Table 8.2: Application of SA method on a line trap with low attenuation

Frequency (kHz)	Attenuation due to canceller (dB)	Attenuation due to line trap (dB)	Performance Index
5.0	-77.9310	-2.7153	.000075
8.5	-87.8331	-4.3372	.0000059
10	-84.9092	-4.6612	.0000034
15	-85.7497	-6.7692	.0000030
20	-90.9132	-7.2505	.0000043
25	-93.7688	-8.5100	.000035
30	-97.8564	-8.5116	.0000006
35	-106.961	-9.622	.00000006
40	-114.811	-10.592	.00000002
45	-116.304	-10.885	.00000024
50	-81.2062	-9.6717	.0030000

With the variations in the efficiency of line trap, the performance of an adaptive canceller can be well understood by judging the changes in the attenuation offered by the canceller. In this case, the design of line traps was considered such that it offered attenuation ranging from 2.7 to 10.8 dB. Results in Table 8.2 show that attenuation due to line trap increased with the increasing frequency range, which indicate linear response of the line trap for this low band of the frequencies. As mentioned earlier, due to data acquisition limitations, only this band of frequencies was possible to be processed and some errors were observed at certain frequencies. These errors can be improved with the selection of a high sampling frequency data acquisition card. Performance at the centre frequency of 50 kHz of the canceller dropped to a smaller value. This drop was due to the errors appearing in retrieving the data from the line at the maximum sampling frequency of 50 kHz. Graphical results are shown in Figures 8.7-8.10.

These studies were carried out, for the signals having very small bandwidth. This algorithm can be extended for wider bandwidth, provided high sampling frequency data acquisition cards are available. To test the performance of cancellers under different conditions, leakage signal was attenuated five times. Results are presented in Table 8.3.

Table 8.3: Application of SA method on a line trap with high attenuation

Frequency (kHz)	Attenuation due to canceller (dB)	Attenuation due to line trap (dB)	Performance Index
5.0	-84.5537	-16.6947	.0000183970
8.5	-94.6525	-18.3518	.0000009545
10	-93.8293	-18.6406	.0000004561
15	-95.7861	-20.7486	.0000003033
20	-100.022	-21.2299	.0000008405
25	-92.4363	-22.4894	.018900000
30	-105.573	-22.4910	.000000170
35	-120.279	-23.6021	.000000003
40	-125.516	-24.5714	.000000001
45	-127.070	-24.8652	.000000053
50	-91.1857	-23.6511	.152200000

With new set of conditions, stored data for the input signals showed variations in the performance of the canceller. These variations were due to the behaviour of line trap and low sampling frequency for data steps. Cumulative effects of both conditions might have diverse effects on the performance of cancellers. New studies showed that overall efficiency of the canceller was improved with the increased attenuation of the line traps. Studies showed that with the new set of conditions, the performance index of the system also improved.

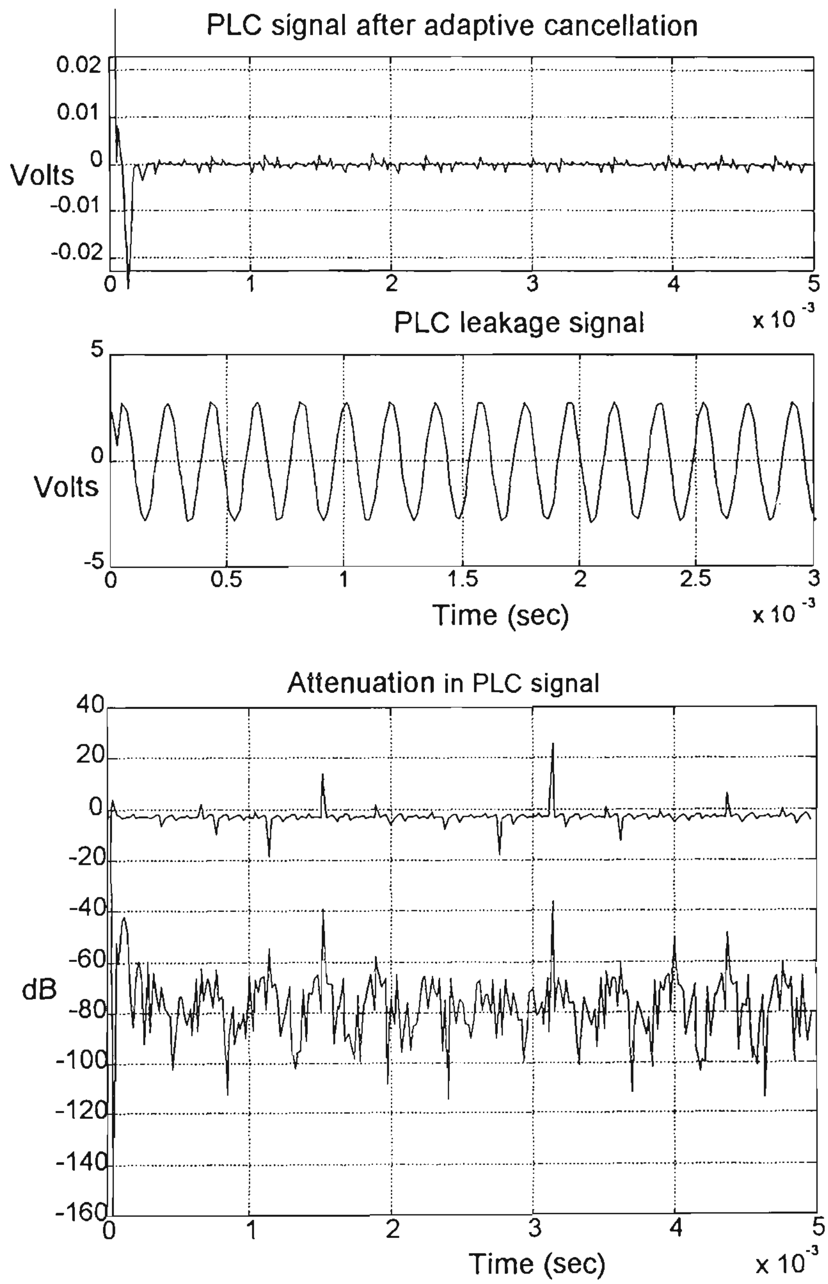


Figure 8.7: Performance of SA canceller on a signal having centre frequency of 5 kHz on line trap model with low attenuation

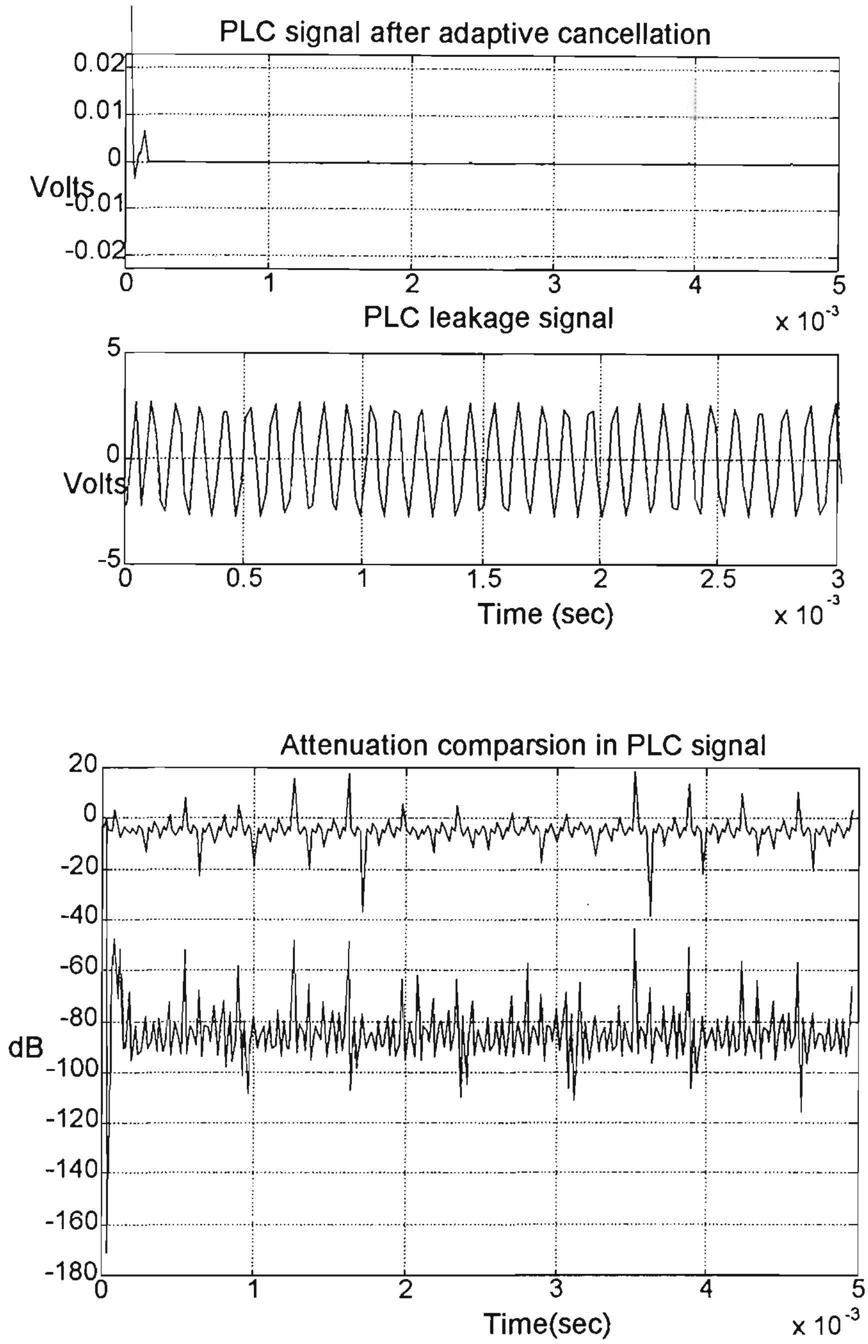


Figure 8.8: Test results of performance evaluation of canceller using the signal having centre frequency of 10 kHz

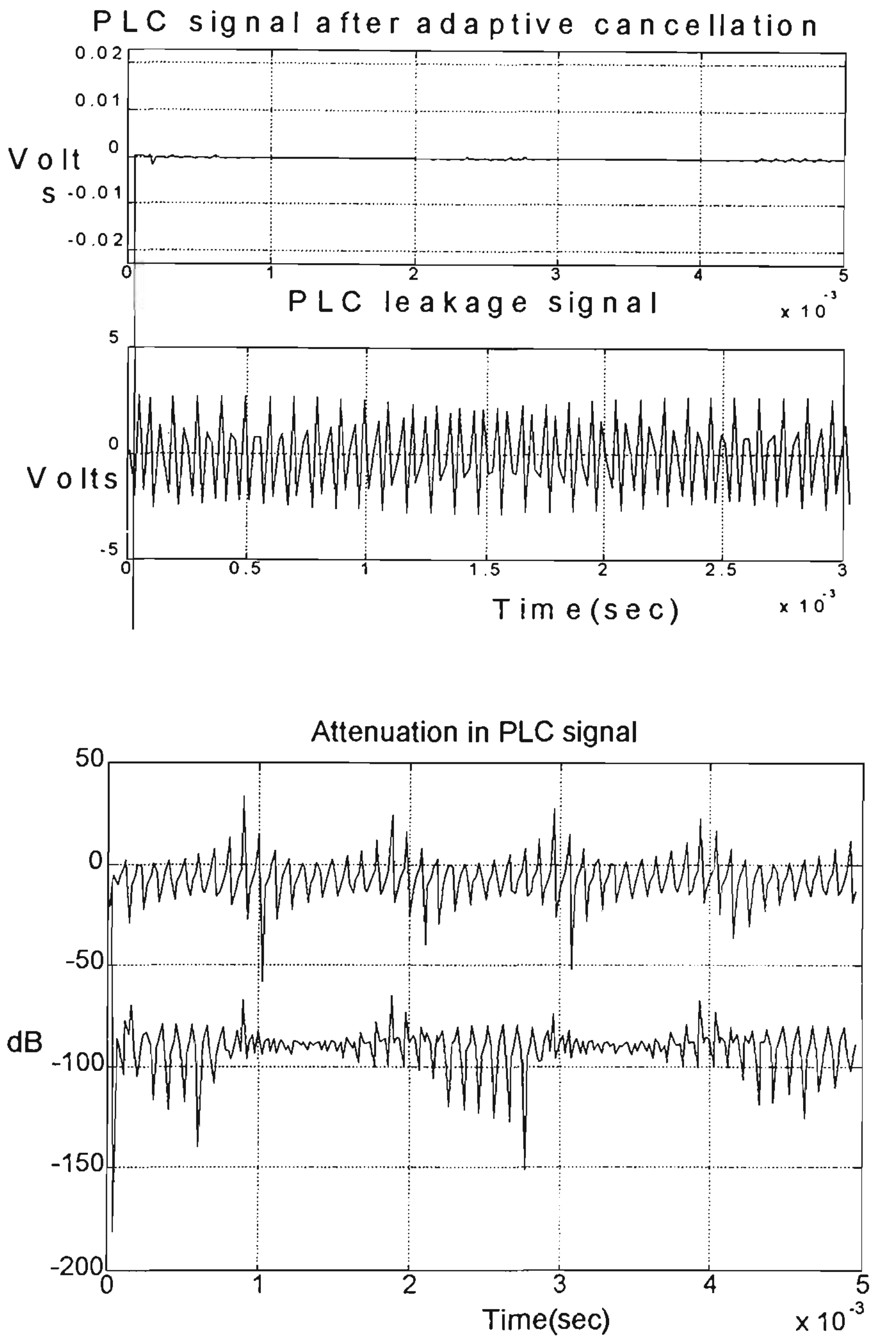


Figure 8.9: Application of SA canceller on line trap model with signal having centre frequency of 20 kHz

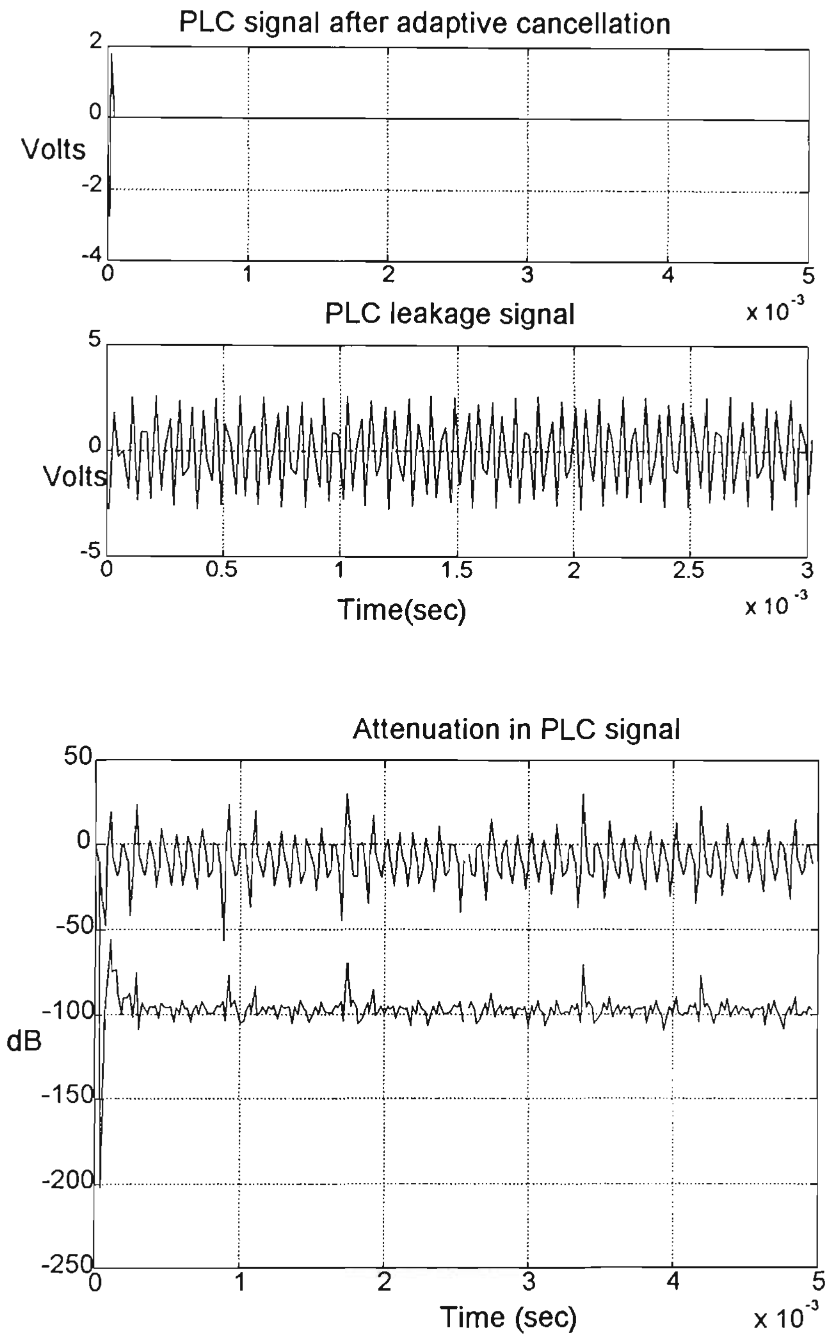


Figure 8.10: Application of SA algorithm on line trap model with the use of signal having centre frequency of 30 kHz

Application of SA method was also tested on a realistic PLC system using the power line model as a channel for the propagation of the signals. The limitations observed in designing the line model gave rise to the non-linearity of the line. Limited numbers of π-circuits, lumping the distributed parameters and behaviour of the line traps were responsible for making it a stochastic system. Retrieved signals from the line showing low attenuations were imported for signal processing. Results are given in Table 8.4.

Table 8.4: Implementation results of SA method on PLC model with low attenuation from the line trap

Frequency (kHz)	Attenuation due to canceller (dB)	Attenuation due to line trap (dB)	Performance Index
15	-81.8246	-6.5306	.0000053
20	-86.0431	-7.2167	.0000096
25	-94.0664	-3.8408	.0000046
30	-93.6282	-8.2113	.0000017

Predictions of the results cannot be made precisely, due to the variable conditions on the PLC model. Performance index shows very small value, indicating satisfactory outcomes. Figures 8.10-8.12 show the waveforms of these results. To test the performance of a canceller at higher attenuation levels, leakage signals were attenuated with the factor of five. Results are presented in Table 8.5.

Table 8.5: Results from the application of SA method on PLC model with high attenuation in the leakage signal

Frequency (kHz)	Attenuation due to canceller (dB)	Attenuation due to line trap (dB)	Performance Index
15	-92.7409	-20.5100	.00000043
20	-94.2978	-21.1961	.00000170
25	-97.4549	-17.8202	.00002670
30	-99.4241	-22.1907	.00000126

Results given in Table 8.5 show an improvement in the outcomes of the canceller. High attenuation offered by line traps resulted in improving the performance of the canceller. Figures 8.13-8.14 highlight the improvement in the performance of canceller.

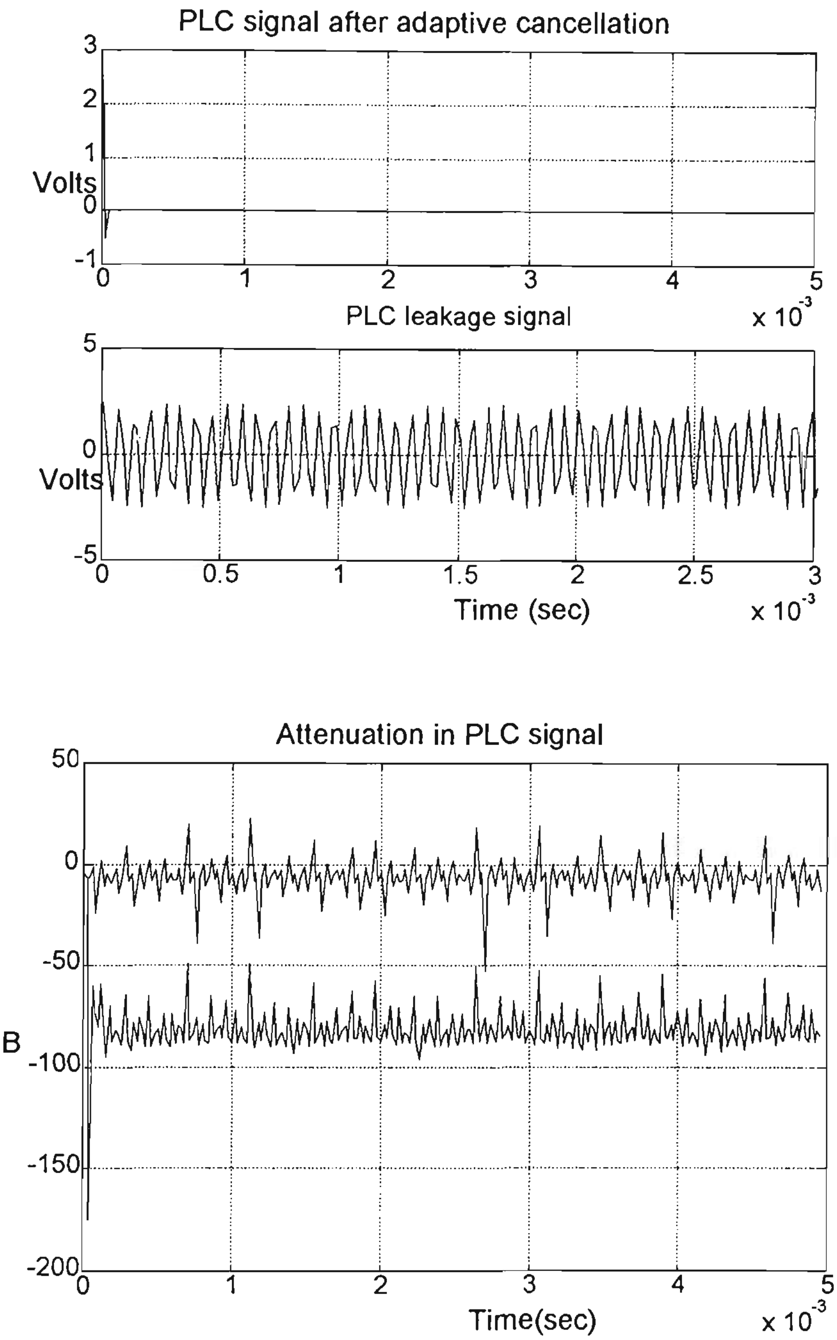


Figure 8.11: Performance of SA canceller on line model with the use of line trap showing low attenuation to the signal having centre frequency of 15 kHz

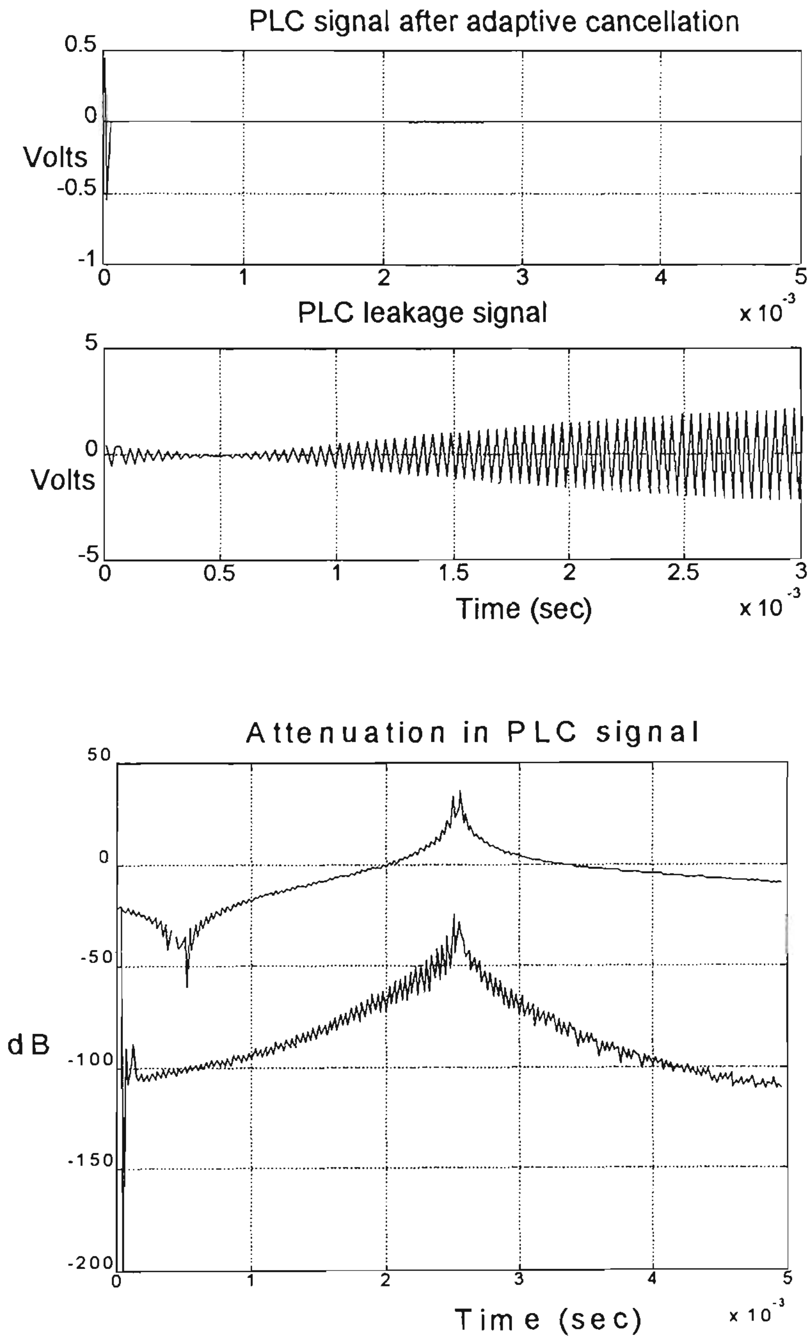


Figure 8.12: Behaviour of SA canceller on the line model with less efficient line trap using signal of 25 kHz frequency

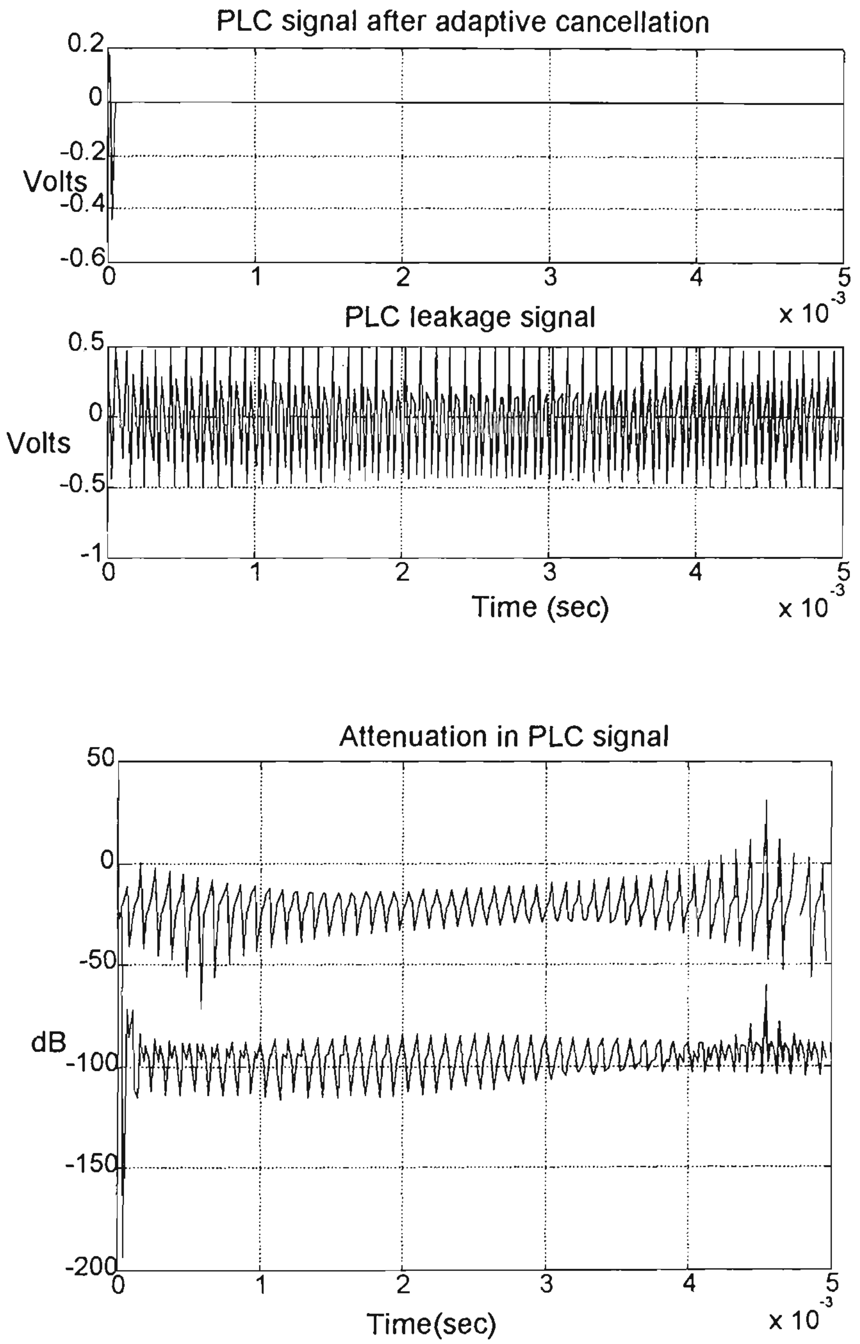


Figure 8.13: Use of efficient line trap for the performance evaluation of the canceller with the use of signal having frequency of 20 kHz

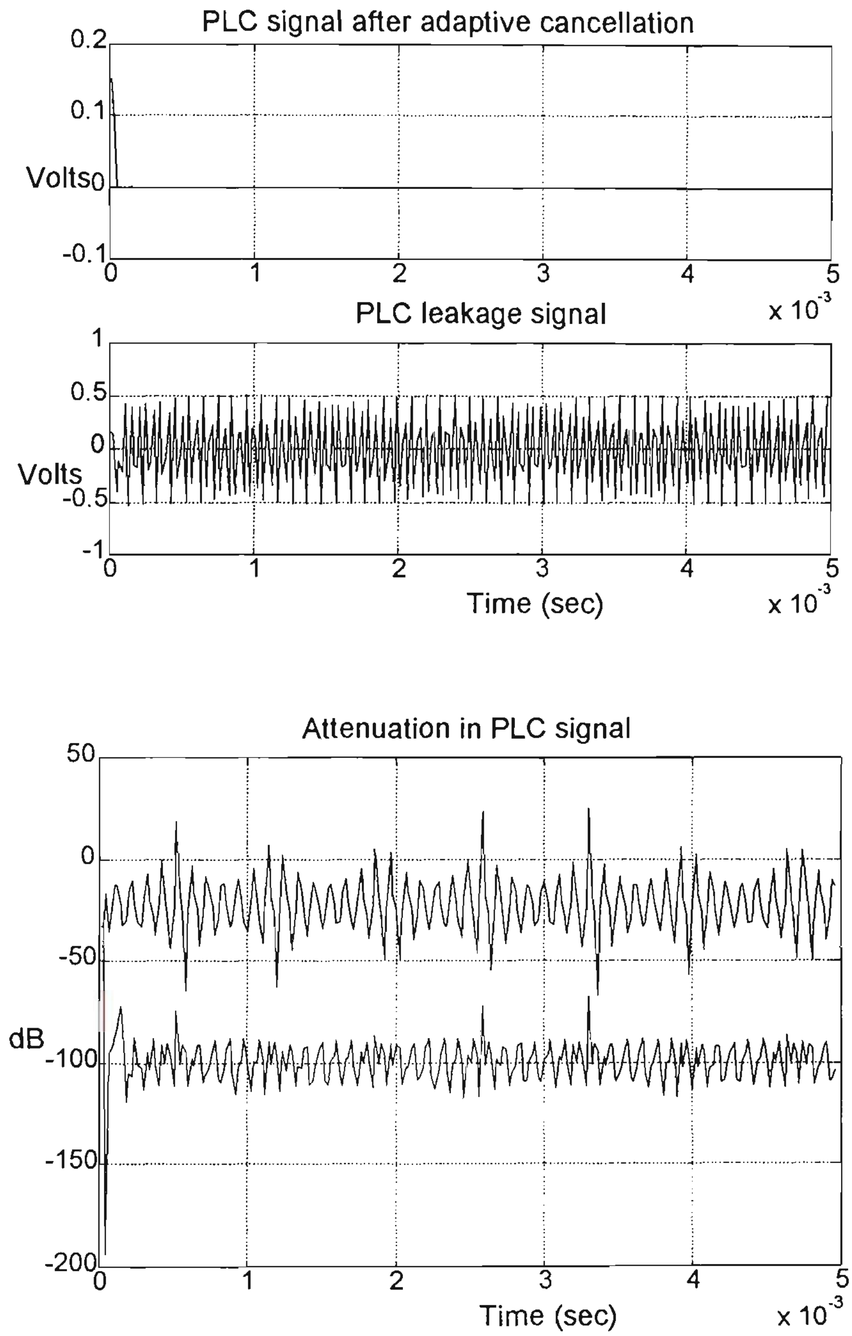


Figure 8.14: Application of SA canceller on the line model with the use of efficient line trap with the signal having centre frequency of 30 kHz

In this chapter, another approach has been used for adaptive interference cancellation on a PLC system. SA estimation has been implemented, using the same guidelines, that has been described in Chapters 6 and 7, in implementing RLS method. A mathematical model has been formulated to suit PLC applications. In realistic systems, propagation of PLC signals is considered in its modal values [23]. For interference cancellers, input signals (PLC and PLC leakage) are considered to be composed from their respective modes to construct the composite signals. SA method was also assumed to work using the conditions outlined in this paragraph.

Computer and hardware implementation studies have been described in Sections 8.3 and 8.4. Tabular and graphical results showed the efficient working of this algorithm for a PLC system. Consistency of the results can be rated as being poor, due to the design of power line model and behaviour of line trap. Attenuation presented by the canceller to the interferences has satisfactory value to improve the signal to noise ratio. Comparison of different interference cancellation techniques is presented in Chapter 10.

CHAPTER 9

INTELLIGENT INTERFERENCE CANCELLATION SCHEMES

9.1 INTRODUCTION

In previous chapters, implementations of different adaptive interference cancellation techniques for a PLC system have been presented. In implementing these techniques, real-time identification of the line trap was carried out using RLS and SA methods, which ultimately slowed down the response time. Clarification of this point can be well understood from the results given in Chapters 6-8. In the industrial world, applications of adaptive control techniques eg. self-tuning power system stabiliser (PSS) can offer better dynamic performance than fixed-gain PSS. Adaptive control techniques suffer major drawback of requiring model identification in real-time which is very time consuming, especially for a microcomputer with limited computational capacity. To overcome this problem, a rule-based PSS [66] and fuzzy logic based PSS [67,68] have been developed without real-time model identification. Furthermore, the performance of fuzzy logic based PSS has been improved by using non-linear membership functions [69].

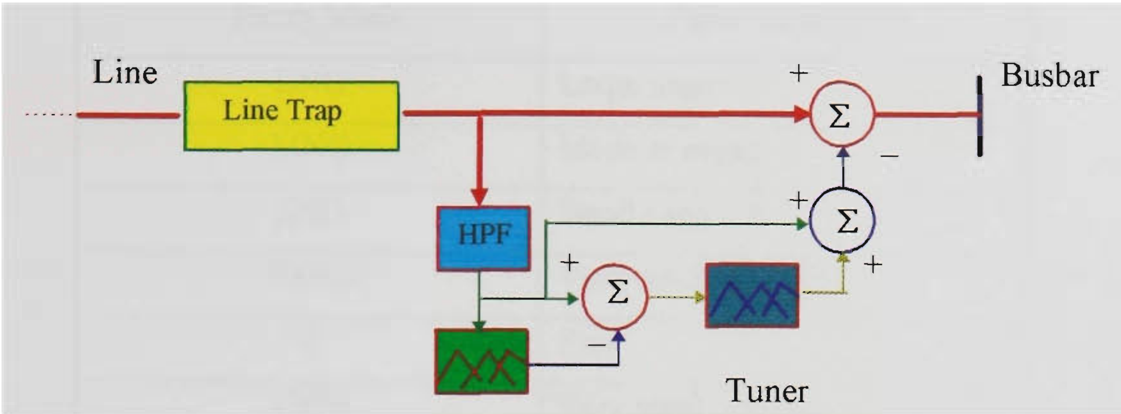
On-line model identification of line trap's response in PLC applications can be avoided using Fuzzy Logic Based Interference Canceller (FLBIC). For this application, only leakage signal is taken as input. FLBIC is supposed to co-relate the estimate of previous state of interferences in phase and magnitude with the leakage signal. MATRIXx package was used as a computer simulation tool for this system.

Implementation results of FLBIC on a PLC system are presented in Section 9.4. Also, a novel interference cancellation scheme has been presented in Subsection 9.4.4. Novel technique uses RLS method to identify the line trap dynamic model to generate the estimates of leakage signal and fuzzy logic theory to identify the effects introduced by the coupling capacitors. Finally in Section 9.6, design and implementation studies of the artificial neural network based canceller are presented.

9.2 FUZZY LOGIC PROCESSING

A fuzzy control system is a real-time expert system, which leads to a higher degree of automation for complex and ill-structured processes [74]. For the application of this automation technique, precise knowledge of inputs and outputs to describe system behaviour is the primary requirement. The knowledge of inputs can be defined in the rate of change of inputs, percentage change in inputs or simply magnitude of the inputs etc. Range of inputs and required outputs plays a very important role in determining the performance of fuzzy logic controller (FLC) and hierarchical structure (if used). Highly efficient FLC can be designed using hierarchical structure or adaptive self tuning phenomena. Adaptive self tuning FLC controller is more efficient than a hierarchical structure due to self tuning of output gain factors [79]. In this research, adaptive self tuning FLC design methodology has been adopted to design adaptive self tuning fuzzy logic based cross-polarisation interference canceller (AFLIC) for PLC applications.

In designing the FLBIC for PLC application, leakage signal was taken as input for FLC. FLC followed the track of input signal in producing the estimates of the previous state of the leakage signal. These estimates of the leakage signal were corrected by the adaptive self tuner. The model of the canceller along with the adaptive self tuner is given in Figure 9.1. The design of the FLBIC is outlined in subsequent subsections.



Fuzzy Logic Controller

Figure 9.1: Model of Fuzzy Logic Based Canceller with adaptive self Tuner

9.2.1 Fuzzification

The first step in implementing fuzzy logic controller is domain transformation. In domain transformation, crisp inputs are transformed into fuzzy inputs which is called fuzzification. The inputs of the fuzzy control applications are in non-fuzzy representation. For the implementation of fuzzy set theory, inputs should be transformed into symbolic representation. Membership functions map crisp inputs into fuzzy inputs and determine the degree of membership for those particular inputs [80].

For the implementation of AFLIC, two crisp inputs were taken. The first input for the main FLC was responsible for the co-relation of the control signal with the leakage signal. The second input was the error detected in co-relating the control and leakage signals. Second input was used for the tuner. In Figure 9.1, block diagram shows the input connection to both controllers. Computer simulation details about the canceller are given in Section 9.3. For fuzzification, both leakage and error signals were represented in nine membership functions. Labels for these membership functions, for required universe of discourse are expressed in Table 9.1.

Table 9.1: Crisp input (Y) and output (U) for the FLC as an interference canceller

Fuzzy labels	Signal description
LNG	Large negative
MNG	Medium negative
SNG	Small negative
VSNG	Very small negative
Z	Zero
VSPS	Very small positive
SPS	Small positive
MPS	Medium positive
LPS	Large positive

Control signals from both FLC and tuner were also divided into nine membership functions. Ranges of the signals were selected, based on the operational knowledge of the processes, for both FLC and tuner controllers.

As mentioned earlier, input to the tuner was an error in co-relation of estimates and actual leakage signals. The absolute level of the error was expressed in nine membership functions. Labels for these membership functions are listed in Table 9.2.

Table 9.2: Crisp input (ERR) and output (UT) for the tuner for FLC canceller

Fuzzy labels	Signal description
Z	Zero error
ESR	Extra small error
VSR	Very small error
SR	Small error
SMR	Small medium error
MR	Medium error
LR	Large error
VLR	Very large error
ELR	Extra large error

For each crisp input value, degrees of membership from the concerned memberships are evaluated. The next step is to evaluate rule strengths.

9.2.2 Inference Processing

In this step of fuzzy logic processing, also called rule evaluation, the fuzzy processor uses linguistic rules in determining the required control action in response to given fuzzy inputs. Rule evaluation, also referred to as fuzzy inference, applies the rules to fuzzy inputs, then evaluates the strength of each rule [80].

Presentation of knowledge by fuzzy rules is being done using a pre-defined set of linguistic terms and strict syntax. Commonly used logical operators eg. 'IF', 'AND' and 'THEN' are used to find the relations among antecedence, that result in the appropriate consequences. Rules are written on the basis of former knowledge about the process. Rules, use membership labels in their expressions. Based on the truth values of the antecedence, rule strengths are determined, that result in fuzzy outputs. Firing of certain rule depends upon the value of crisp input, which determines the fuzzy values of all the antecedence.

In designing AFLIC for PLC system, nine rules were formulated for both FLC and tuner, in providing appropriate attenuation to the leakage signal through the line traps. For PLC application, a canceller was designed to follow the leakage signal in magnitude and phase angle. In doing so, FLC was the major block for the estimation of the leakage signal. Further, the tuner was responsible for tuning the control signal from FLC to make the estimates very close to the actual leakage signal. Figure 9.1 shows the schematic diagram of FLC and tuner model. Designs of both FLC and the tuner were carried out using the same principles, therefore the number of membership functions and rules defining the signals were the same. Some of the rules controlling the behaviour of FLC are given below:

IF (Y *IS* LNG) *THEN* U *IS* LNG;
IF (Y *IS* MNG) *THEN* U *IS* MNG;

The logic of the rules controlling the tuner was identical to the FLC, some of the rules are given below, using input as error (ERR) and generating output tuning signal (UT):

IF (ERR *IS* Z) *THEN* UT *IS* Z;
IF (ERR *IS* ESR) *THEN* UT *IS* ESR;

For the tuner, classification of error (which resulted from the difference of FLC output and actual leakage signals as shown in Figure 9.2) was performed using the absolute values of the error and then, signs were assigned to the tuning signals. Then tuning signal was added to the FLC output (U) to get on-line cancellation of the interferences. Results are shown in Section 9.4.

9.2.3 Defuzzification

In the design process of the interference canceller, the final step was to transfer the fuzzy outputs from the rule base into a crisp values realisable by the system under control. This is done by dividing the output universe of discourse into several membership functions. Different defuzzification techniques can be used to obtain crisp outputs from the canceller. The best known defuzzification methods are centre of area or centre of gravity (COG), fuzzy mean (FM) or centroid, weighted fuzzy mean (WFM) and mean of maxima [81-85]. In this work, mean of maxima has been used as a defuzzification tool. This defuzzification method suffers inaccuracy in generating outputs due to its mathematical algorithm. This inaccuracy is compensated with high computational speed of the algorithm.

Defuzzification for both FLC and the tuner was performed using mean of maxima. Steady state error due to this technique can be assumed due to calculation of the mean of the membership function having maximum degree of membership.

9.3 PLC MODEL FOR AFLIC IMPLEMENTATION

In this research, various interference cancellation schemes have been tested on a PLC system. The assessment of RLS and SA methods have been presented in Chapters 6-8 respectively. Modelling of the PLC system was carried out using determinant values of PLC system along with its associated equipment. A detailed description of PLC model is given in Section 6.3. Figure 4.4 outlines schematic representation of PLC system for computer simulation, using MATLAB. Hardware modelling of a PLC system is given in Chapter 4, which has been used for the assessment of RLS and SA methods. Hardware results are presented in Chapters 7 and 8 respectively.

To test the performance of all adaptive interference cancellation schemes, the same PLC model was used to provide the same working conditions for all the cancellers, which ultimately facilitated in comparing the final results. Comparative results are presented in Chapter 10. As mentioned earlier, AFLIC was simulated using MATRIXx. For the use of same PLC model, PLC and leakage signals were generated from MATLAB simulation model and then were interfaced further with fuzzy logic based interference canceller, designed using MATRIXx. For the assessment of the canceller's performance, signals having different bandwidth were used to act as interference sources. Section 9.4 presents, description of the signals used for testing. PLC model, described in this section was used to generate all required signals. Based on the experience in dealing with PLC and leakage signals, a random signal of appropriate magnitude was also used to test the performance of AFLIC.

9.4 SIMULATION OF AFLIC FOR A PLC SYSTEM

Nature of interference for different communication systems depends on the use, application, structural design and on many other factors. In this research, PLC, a particular communication system for a power system has been investigated. Furthermore, to reduce the level of interference on the network, different techniques have been proposed. Extensive implementation studies for conventional adaptive interference cancellation algorithms were carried out and results are given in Chapters 6-8.

In this chapter, intelligent interference cancellation schemes based on fuzzy logic and Artificial Neural Network (ANN) are presented. In Sections 9.1-9.3, design descriptions of AFLIC have been presented. In this section, computer simulation results with linear membership function of AFLIC are presented. Use of non-linear membership function improved the design of the canceller, results are given in Subsection 9.4.2. Next, zero membership function was divided into left zero and right zero halves for the improvement of the algorithm. As a result, three membership functions were put into effect eg. left zero, single tone and right zero. Detailed description is given in Subsection 9.4.3. Design details, behaviours and application results of the three techniques are given individually in Subsections 9.4.1-9.4.3.

9.4.1 Design Of AFLIC Using Linear Membership Functions

Design of a fuzzy logic based controller mainly depends upon the system behaviour. System response can facilitate in selecting the ranges for the controller. As a result, the performance of a controller can be improved with the proper choice of ranges. In this research, ranges of FLC and tuner for AFLIC were adjusted based on the knowledge of leakage signal acquired from PLC model.

The operation of AFLIC in identifying the leakage signal was very systematic. Leakage signal from line trap was taken as crisp input for the FLC. Figure 9.1 shows schematic diagram for the canceller. The main task of FLC was to correctly identify the level of leakage signal. The error that resulted due to the inaccuracy of the FLC was identified by the tuner, which was added to the output of FLC to get adaptive tuning. Corrected estimates of leakage signal were cross-polarised to cancel the leakage signal. Method presented in this section resulted in very efficient interference canceller. Results are presented in subsequent sections of this chapter.

Design presented in this section used linear membership functions for the fuzzification of inputs to both FLC and tuner. Figure 9.2 shows representation of linear membership functions showing partition of universe of discourse from -1 to +1 for FLC block. The universe of discourse for tuner ranged from 0 to the value of error, resulted from the difference between leakage signal and estimates of leakage signal. In the design of canceller, range of input signal to FLC was normalised to the universe of discourse from -1 to +1, which was performed by dividing the signal with its maximum peak value. Then output from the FLC was multiplied with the same factor to restore the estimates of signal in actual range, but input signal for the tuner did not need any normalisation. Operation of tuner can be outlined as follows:

- tuner identified the polarity of the input signal;
- absolute value of the input signal was then identified;
- proper polarity was assigned to the estimates that assisted in approximating the leakage signal more accurately.

This criterion can be well understood from the Figures given in Appendix B, which shows block diagram used for computer simulation.

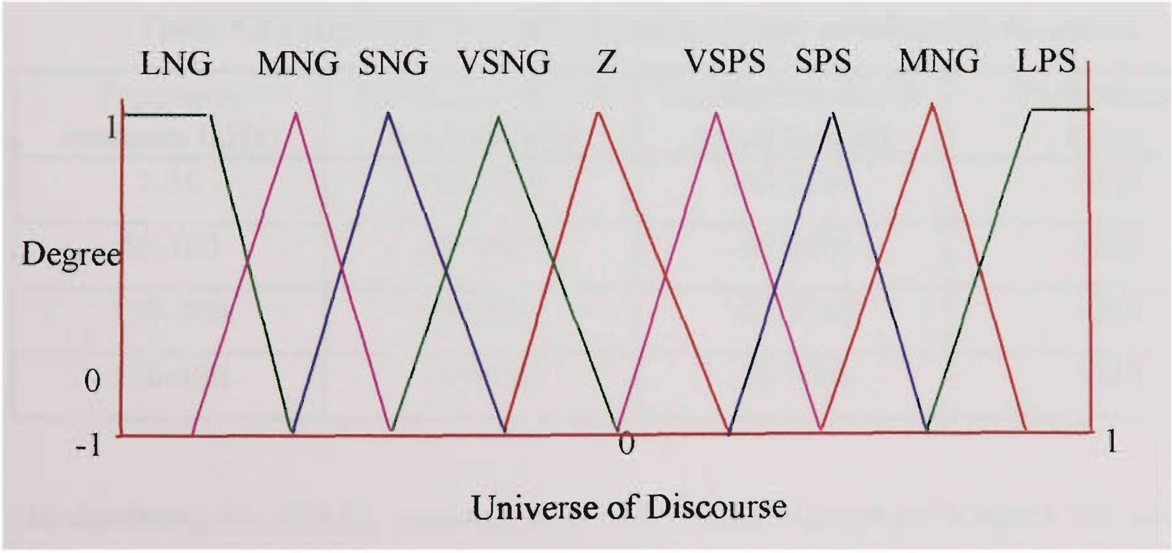


Figure 9.2: Representation of linear membership functions for AFLIC design

9.4.1.1 Test Results for Canceller Using Random Signal

For this study, random signal having amplitude of 30 Volts was used as an input for the canceller. System response was evaluated, with the use of sampling time of .02 sec. Due to low sampling frequency, appropriate time delays were used to synchronise the same state of leakage and its identified signals. Figure 9.3 shows the performance of the canceller for this input. The following observations were recorded:

Attenuation due the canceller = -42.8102 dB

Performance Index = 0.8721

9.4.1.2 Performance Evaluation Of Canceller Using Different Frequency Spectrums

Performance of canceller was also tested for signals having a different bandwidth of 50 kHz. These signals were generated from PLC model, simulated using MATLAB. Then signals were imported to interface with AFLIC, simulated in MATRIXx using real-time fuzzy logic tool. Table 9.3 shows results obtained from these studies in terms of attenuation and performance index:

Table 9.3 : Application of AFLIC using linear membership functions

Frequency spectrum (kHz)	Attenuation due to line trap (dB)	Attenuation due to canceller (dB)	Performance Index
5-50	-14.7938	-49.0355	.0229
50-100	-20.3427	-54.6104	.0238
150-200	-5.6321	-35.7761	.1362
350-400	-0.6920	-36.9808	.1533

In simulating the AFLIC, sampling time of 0.1 msec. was taken to match the sampling time of PLC model. To cover the whole PLC spectrum randomly, four different spectra were selected to test the performance of canceller. Results are given in Table 9.3. Figures 9.4 and 9.5 show the graphical representation of two observations.

Canceller's performance can be improved with a more precise choice of ranges for both FLC and tuner. Moreover, with the proper choice of distributions and intersections of membership functions for selected universe of discourse can further improve the efficiency of algorithm.

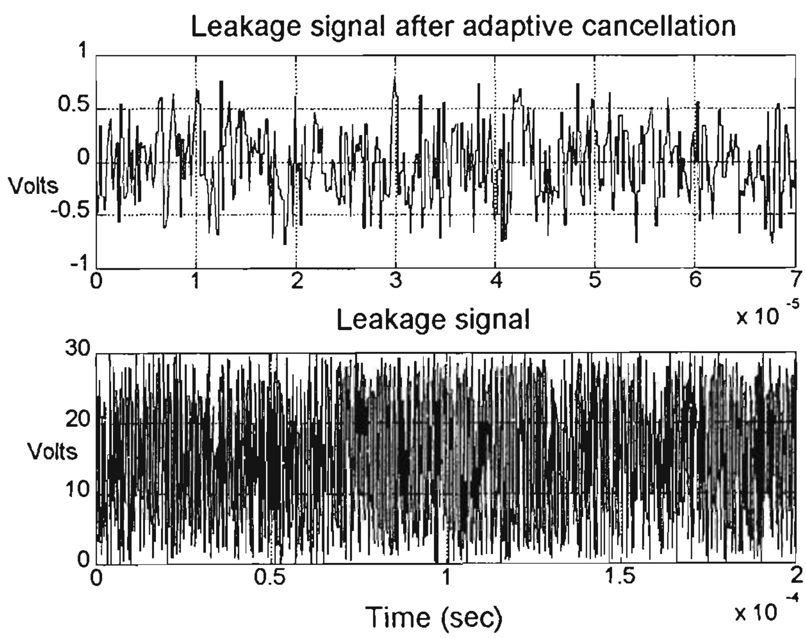


Figure 9.3: Performance of FLC based canceller with the use of random signal as a leakage signal

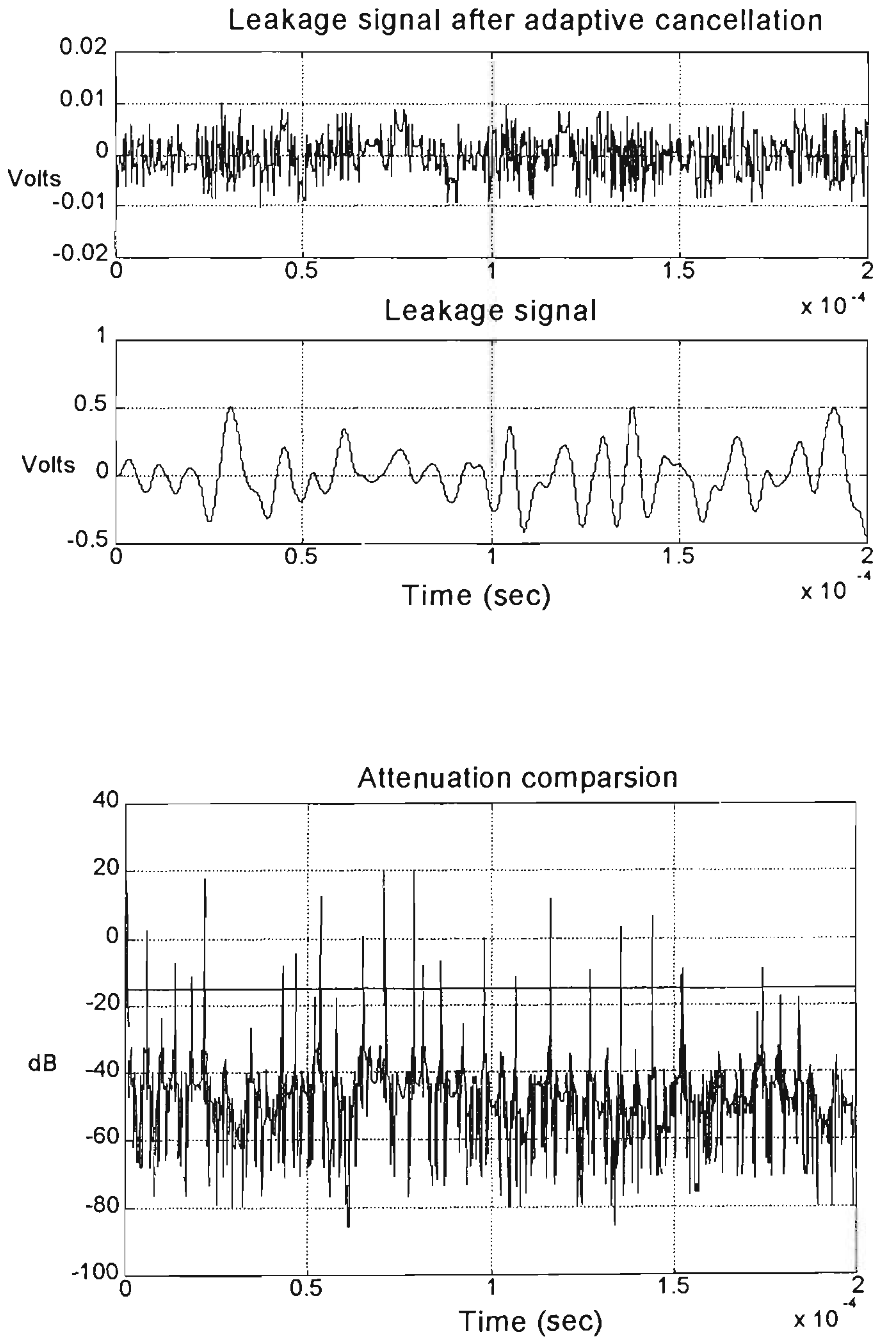


Figure 9.4: Performance of AFLIC with the use of signal having spectrum of 5-50 kHz

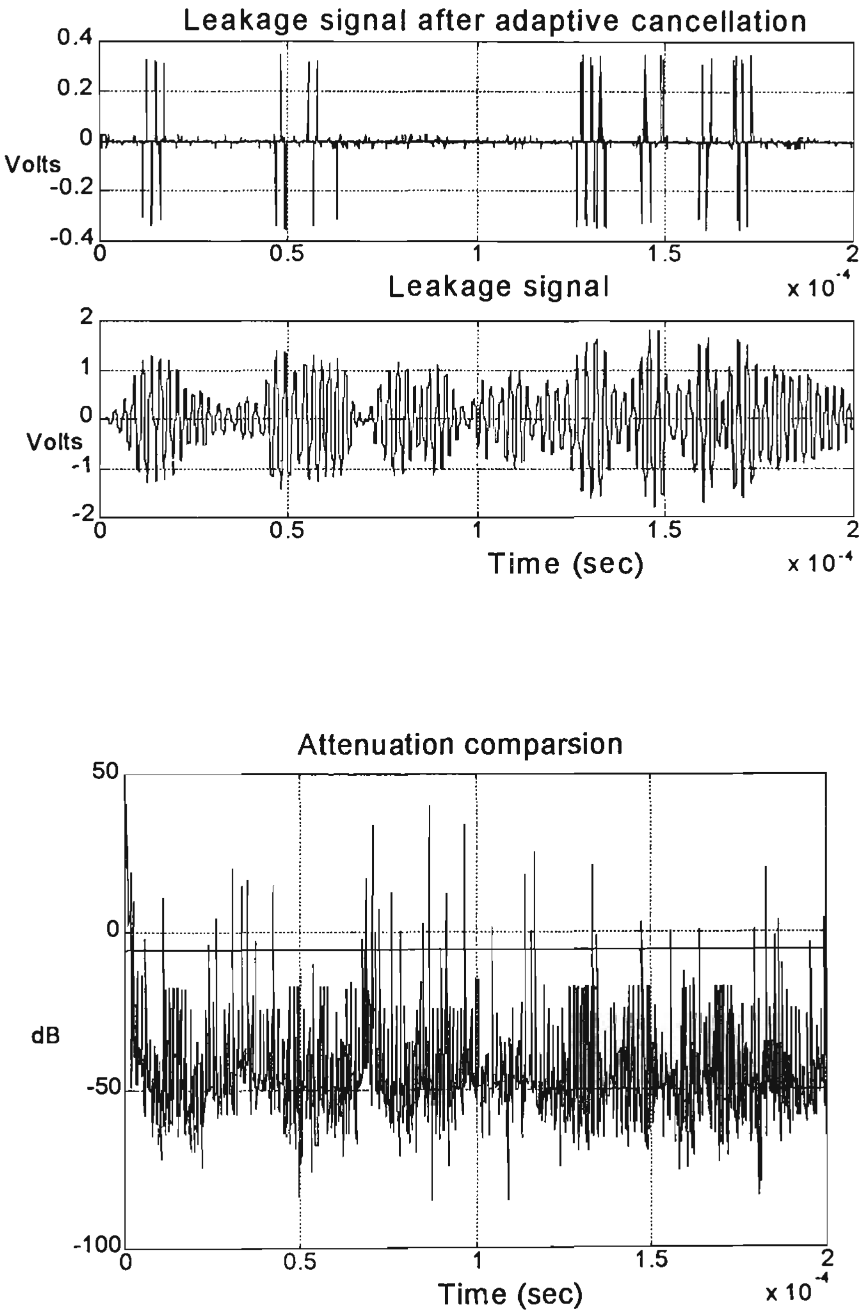


Figure 9.5: Application of AFLIC with the use of linear membership functions to cancel the interference with frequency spectrum of 150-200 kHz

9.4.2 Use Of Non-linear Membership Functions For The Canceller

Results presented in Subsection 9.4.1.2 were obtained with the use of linear membership functions. In this section, the same algorithm is presented with the use of non-linear membership functions. Figure 9.6 shows graphical representation of non-linear membership functions. Mathematically these memberships were represented as follows:

$$zero = \sin(0.4 * \pi * (X - 1.25))^{150} \qquad \text{.....................(9.1)}$$

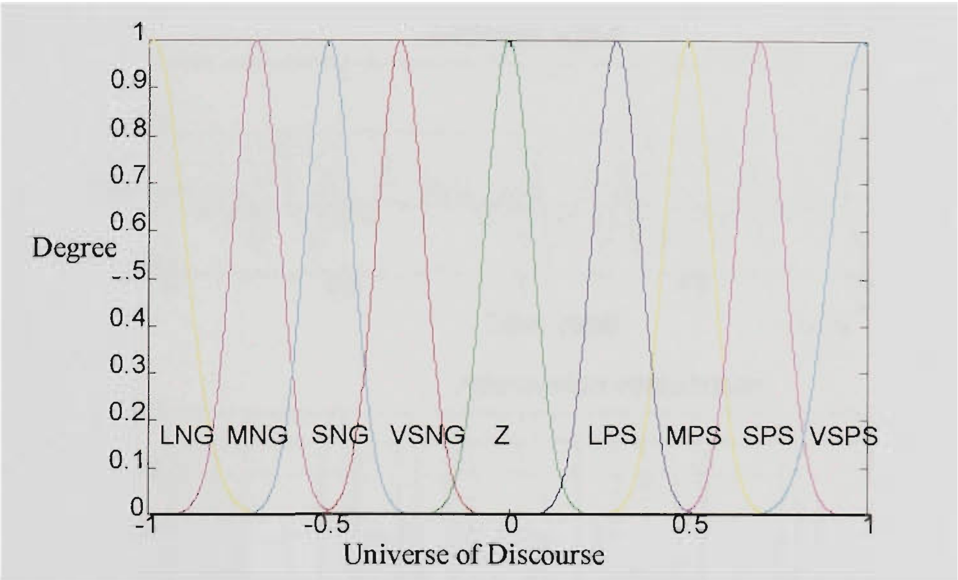


Figure 9.6: Representation of non-linear membership functions

Factors eg. 0.4, 1.25 and 150 were used to adjust the distribution of membership functions on the given universe of discourse. Table 9.4 shows improved results with the use of non-linear membership functions for both FLC and tuner.

Table 9.4 : Application of AFLIC using non-linear membership functions

Frequency spectrum (kHz)	Attenuation due to line trap (dB)	Attenuation due to canceller (dB)	Performance Index
5-50	-14.7938	-59.8668	.0066
50-100	-20.3559	-65.2290	.0070
150-200	-5.6268	-50.5421	.0249
350-400	-0.6920	-42.5312	.0809

Non-linear membership functions appear to be more accurate in handling the non-linear frequency response of the line traps. Furthermore, improvements can be made with the conventional adjustments for the membership functions as described in Subsection 9.4.1.2. Graphical results are presented in Figures 9.7 and 9.8.

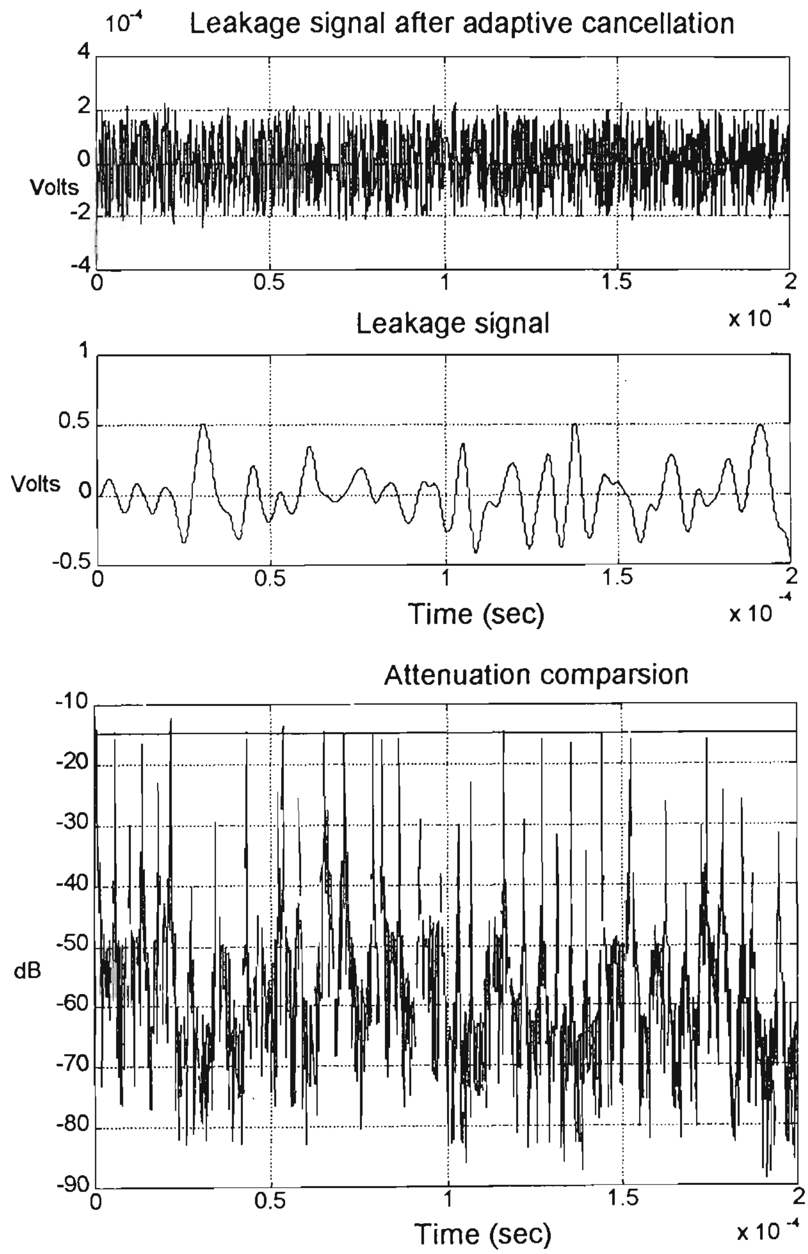


Figure 9.7: Use of non-linear membership function for the application of AFLIC in interference signal having frequency spectrum of 5-50 kHz

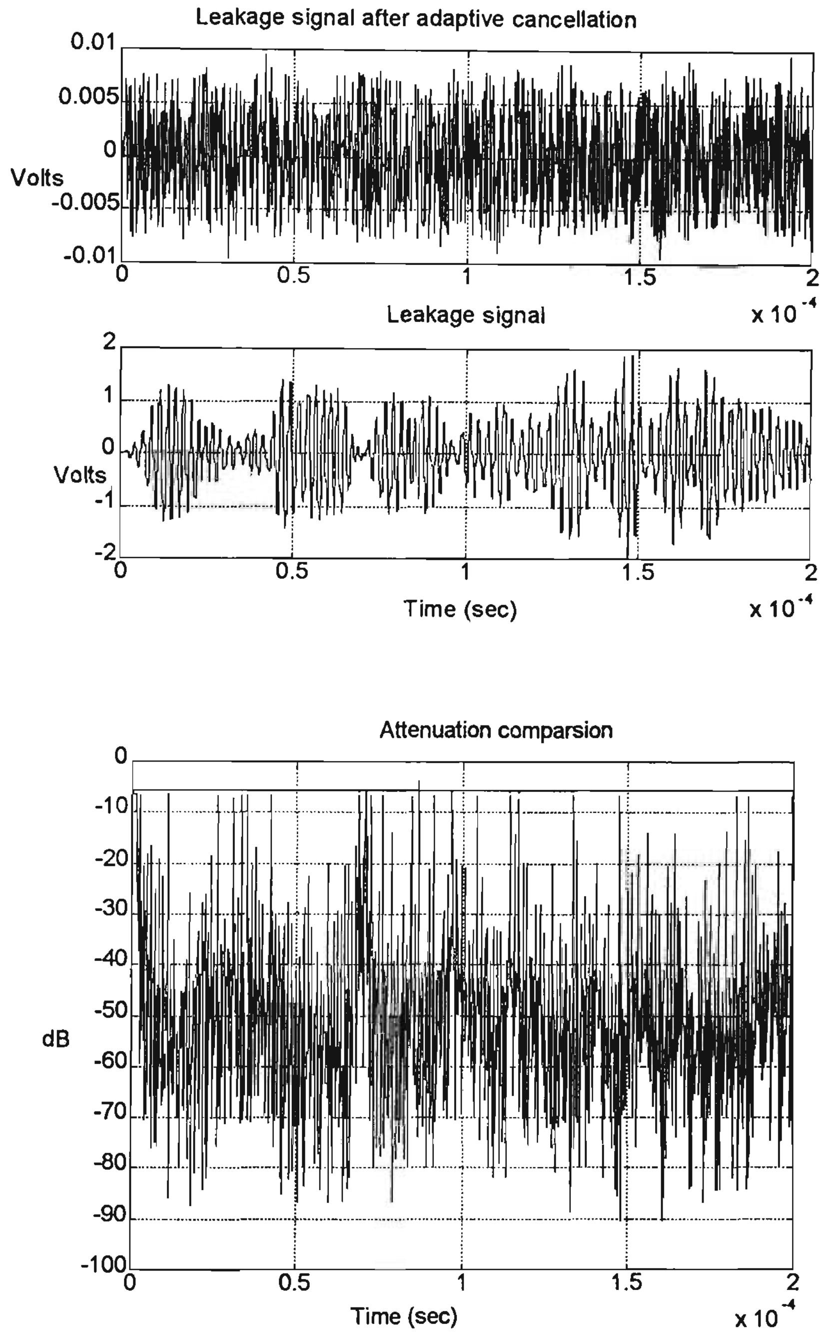


Figure 9.8: Application of AFLIC on a PLC network for the cancellation of interference having frequencies of 150-200 kHz

9.4.3 Improved Design Of AFLIC For The Identification Of Small Signal

Results from Subsection 9.4.2 showed, that the use of non-linear membership functions improved the overall performance of the canceller. Graphic results presented in Figures 9.7 and 9.8 show that canceller was unable to identify the difference in signals having zero or very small values. To overcome this problem, zero membership function for FLC was divided into three membership functions eg. left zero, single tone and right zero. Figure 9.9 shows the construction of three linear membership functions. For this application, FLC was subjected to work using linear and non-linear membership functions. Tabular results are presented in Table 9.5.

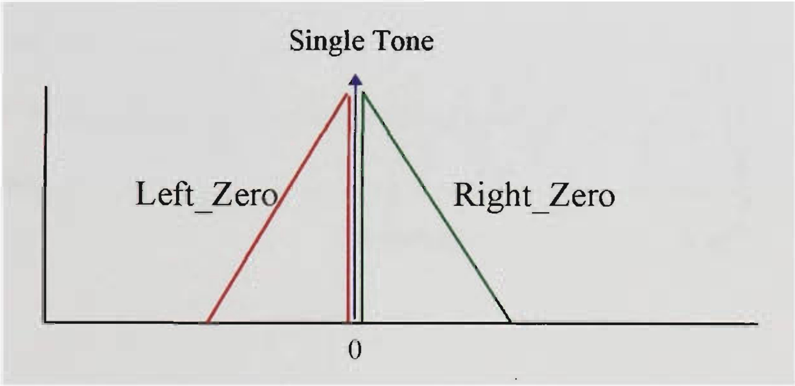


Figure 9.9: Graphical representation of zero membership function

Table 9.5 : Application of AFLIC using left zero and right zero membership functions

Frequency spectrum (kHz)	Attenuation due to line trap (dB)	Attenuation due to canceller (dB)	Performance Index
5-50	-14.7938	-56.3195	.0099
50-100	-20.3427	-61.9188	.0103
150-200	-5.6268	-48.9038	.0300
350-400	-0.6920	-39.5122	.1145

With this technique, identification for small signals was improved, as it is clear from the Figures 9.10 and 9.11. Use of left and right of membership function helped the defuzzification method in finding more accurate mean of maximum. Furthermore, results can be improved, if all the membership functions are divided in left and right halves. Ultimately it will increase the number of rules and computational time as well.

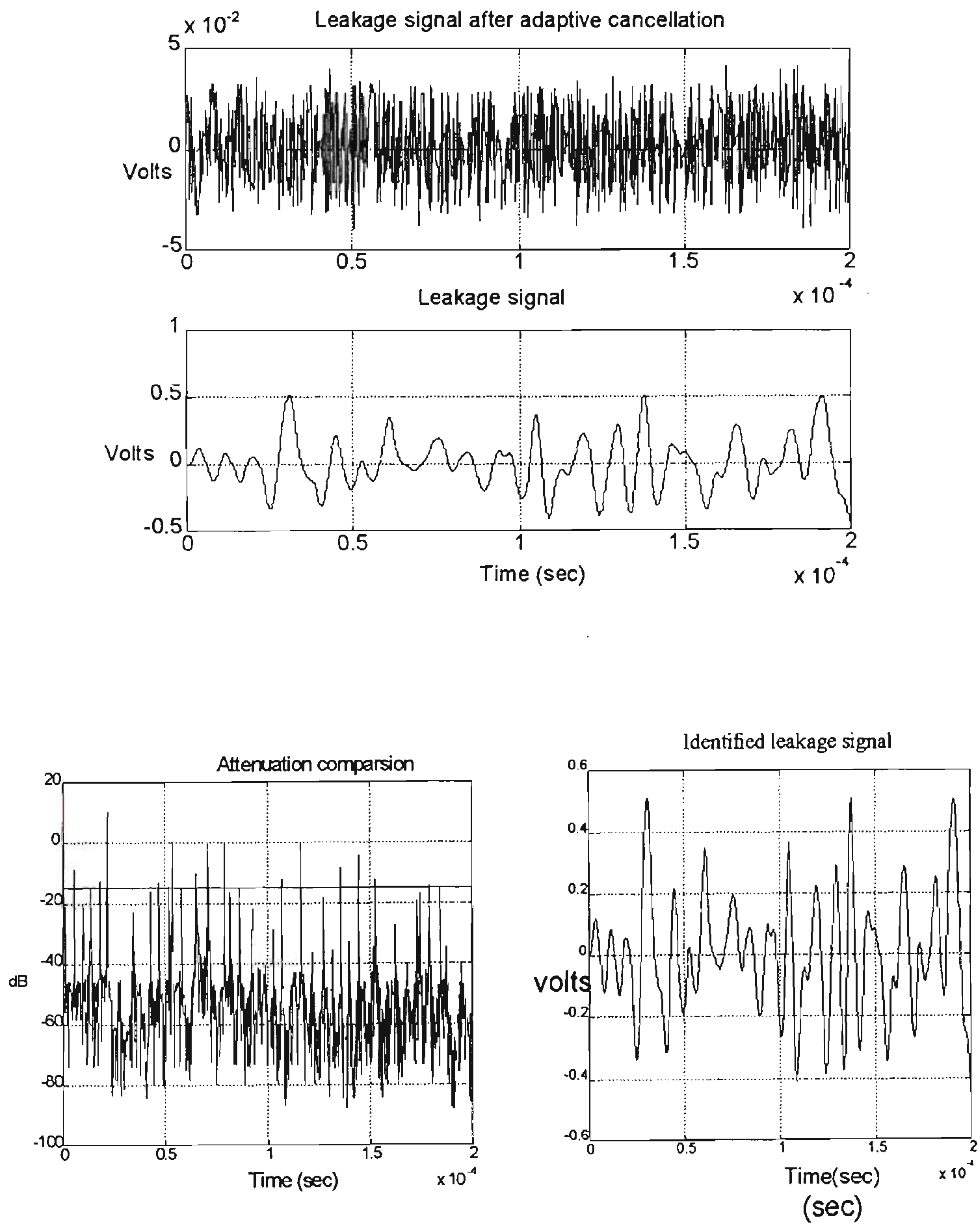


Figure 9.10: Application of AFLIC with the use of linear and non-linear membership functions on a leakage signal having frequency spectrum of 5-50 kHz

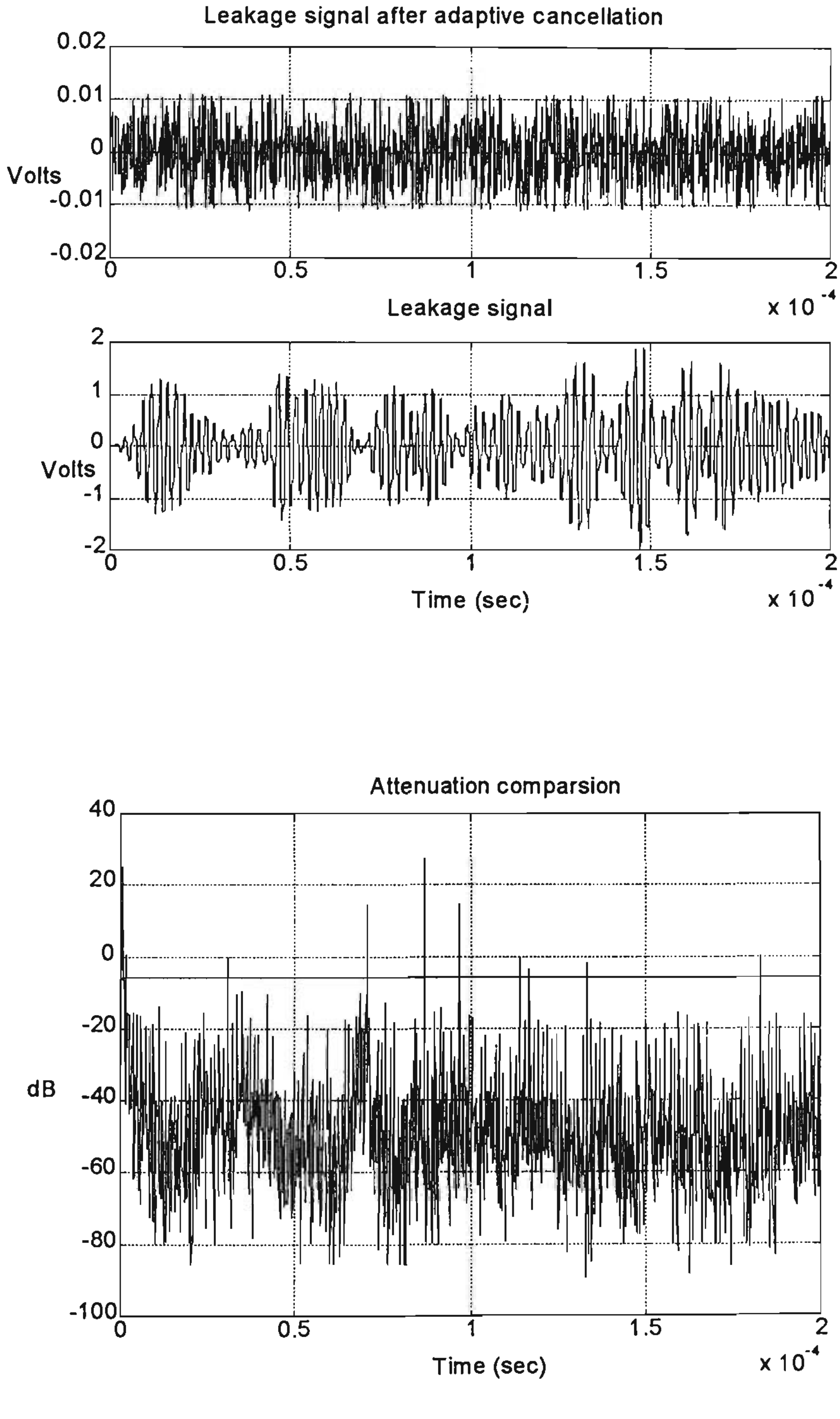


Figure 9.11: Application of AFLIC on PLC network with a special focus on the identification of small signal using frequency spectrum of 150-200 kHz

9.4.4 A Novel Adaptive Interference Cancellation Technique

In this technique, combined use of RLS and fuzzy logic has been made to estimate the level of interference accurately on busbar. The working of RLS technique in identifying and estimating the output of a system has been described in Chapter 6. In all other interference cancellation schemes, the operation of coupling capacitor was supposed to be ideal. This technique addresses the attenuation and phase shift introduced by the coupling capacitor with the use of fuzzy logic theory. Figure 9.12 shows the block diagram of this technique.

In the conventional way, RLS method was used to estimate the interference caused due to line trap. This technique makes sure that these estimates of interference have not been affected by the coupling capacitors. Attenuation and change in phase angle introduced by the coupling capacitors were estimated using two separate fuzzy blocks with three membership functions each. Figure 9.13 shows diagrammatical representation of membership functions used for estimating change in magnitude and phase angle across the terminals of coupling capacitors. These estimates were used to correct the output of RLS algorithm, so that the prediction of the interference on the busbar can be made correctly. This technique resulted in poor performance, which can be improved with the increased number of membership functions using non-linear representation. Novel technique offers a result to tackle variable operational behaviour of any filter used for signal processing. Table 9.6 shows results for a study of a 50 kHz bandwidth signal.

Table 9.6 : Application of Novel Interference Cancellation Technique

Frequency spectrum (kHz)	Attenuation due to line trap (dB)	Attenuation due to canceller (dB)	Performance Index
100-150	-14.7938	-15.0755	1.5979

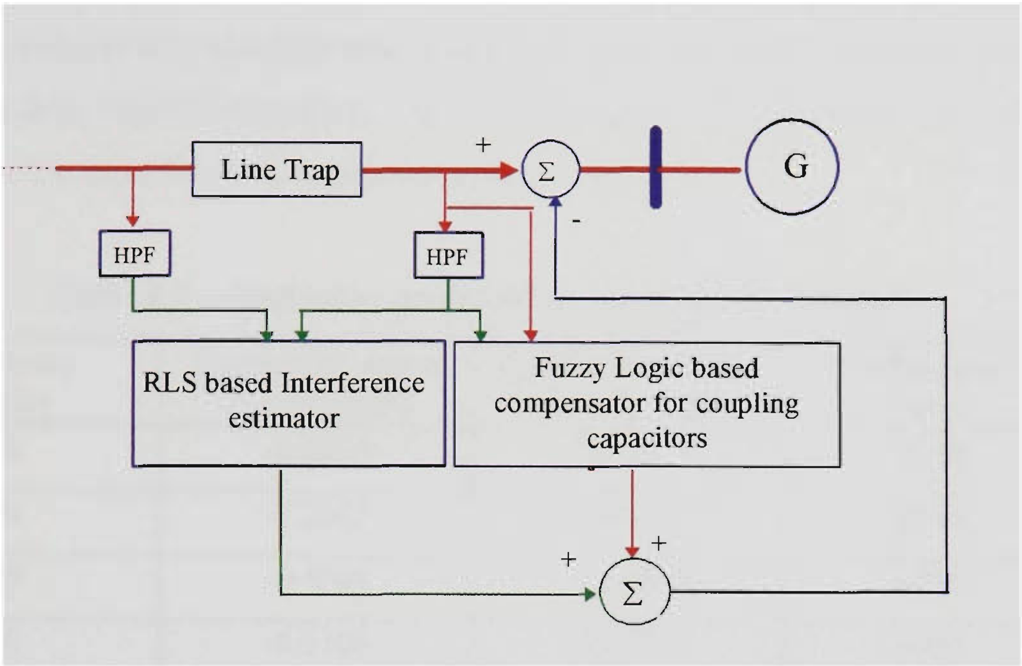


Figure 9.12: Block diagram of a novel interference cancellation technique

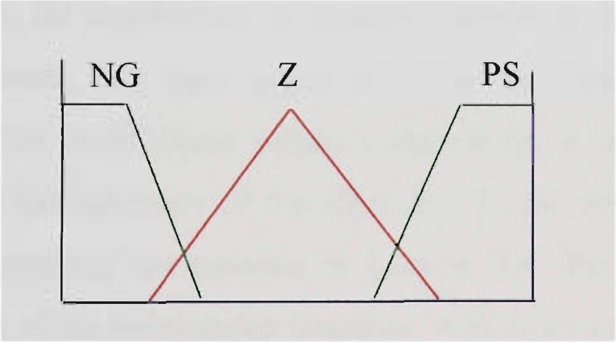


Figure 9.13: Representation of membership functions for fuzzy logic based compensator for canceller based on novel technique

9.5 IMPLEMENTATION OF AFLIC ON HARDWARE MODEL

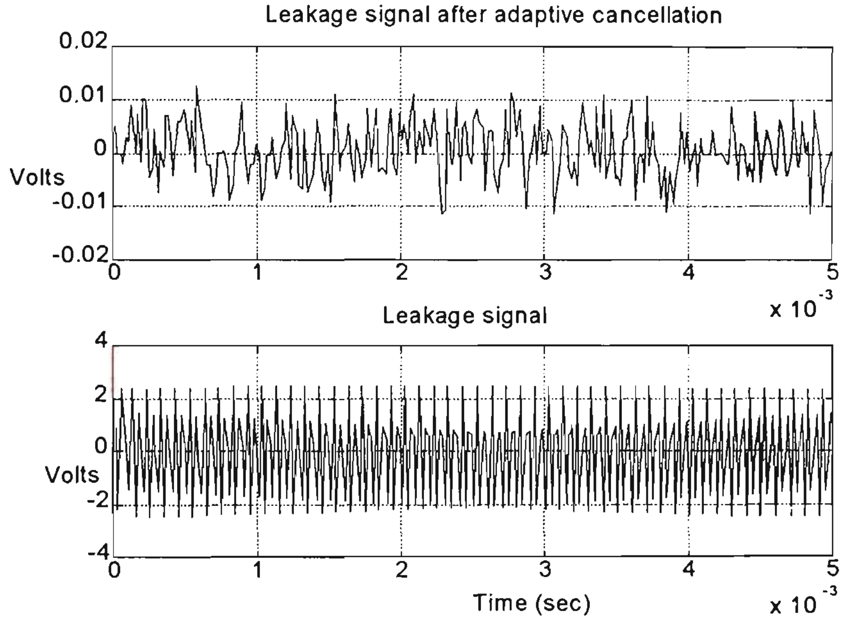
Hardware PLC model presented in Chapter 4 was also used to test the performance of fuzzy logic based canceller. Hardware data was imported to interface with MATRIXx. For this study, canceller having combination of linear and non-linear membership functions with left zero and right zero construction was used. As described earlier, due to limited data acquisition facilities, very small spectrum of frequencies was used to investigate the canceller. Test results are given in Table 9.7.

Table 9.7 : Application of AFLIC on hardware PLC model

Frequency (kHz)	Attenuation due to line trap (dB)	Attenuation due to canceller (dB)	Performance Index
15	-6.3466	-58.7697	.0038
20	-7.2013	-58.4797	.0044
25	-6.4596	-58.4625	.0039
30	-8.5108	-61.8019	.0035

Graphical results are presented in Figures 9.14 and 9.15. Hardware studies can be extended with the use of faster data acquisition card.

Application of fuzzy logic for interference cancellation appears to be a very efficient technique. For PLC systems, this logic appeared to be very flexible in designing different algorithms. Unlike conventional adaptive algorithms, it does not limit the designer from improving the efficiency of the algorithm. In the design of canceller, several stages of improvements are outlined in Section 9.4. Performance can be enhanced with fine tuning of the membership functions, with more precise selection of input and output data ranges for fuzzy blocks and with more numbers of membership functions etc. Even the whole concept of canceller can be changed. Fuzzy logic theory appears to be very versatile in designing controllers, financial forecasters and cancellers etc.



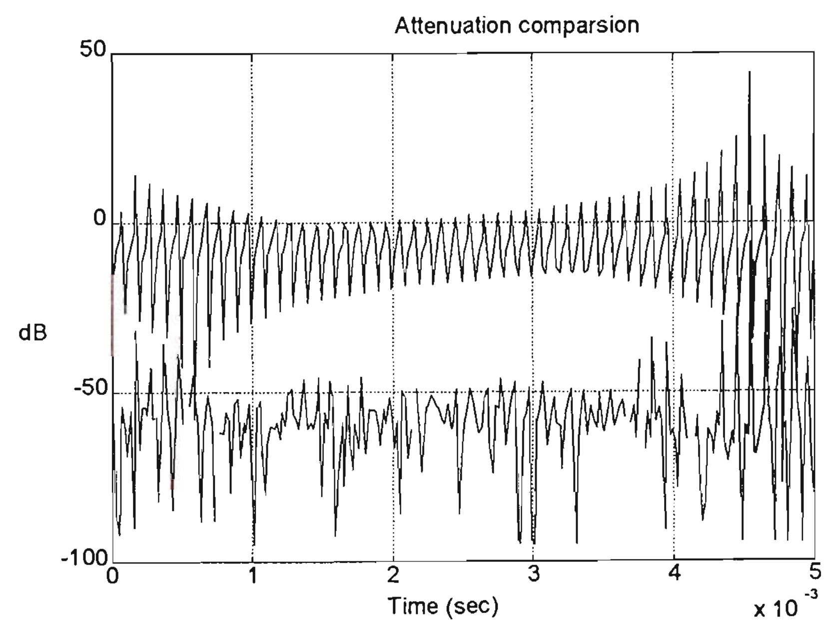


Figure 9.14: Performance of AFLIC on the line model to cancel the signal having centre frequency of 20 kHz

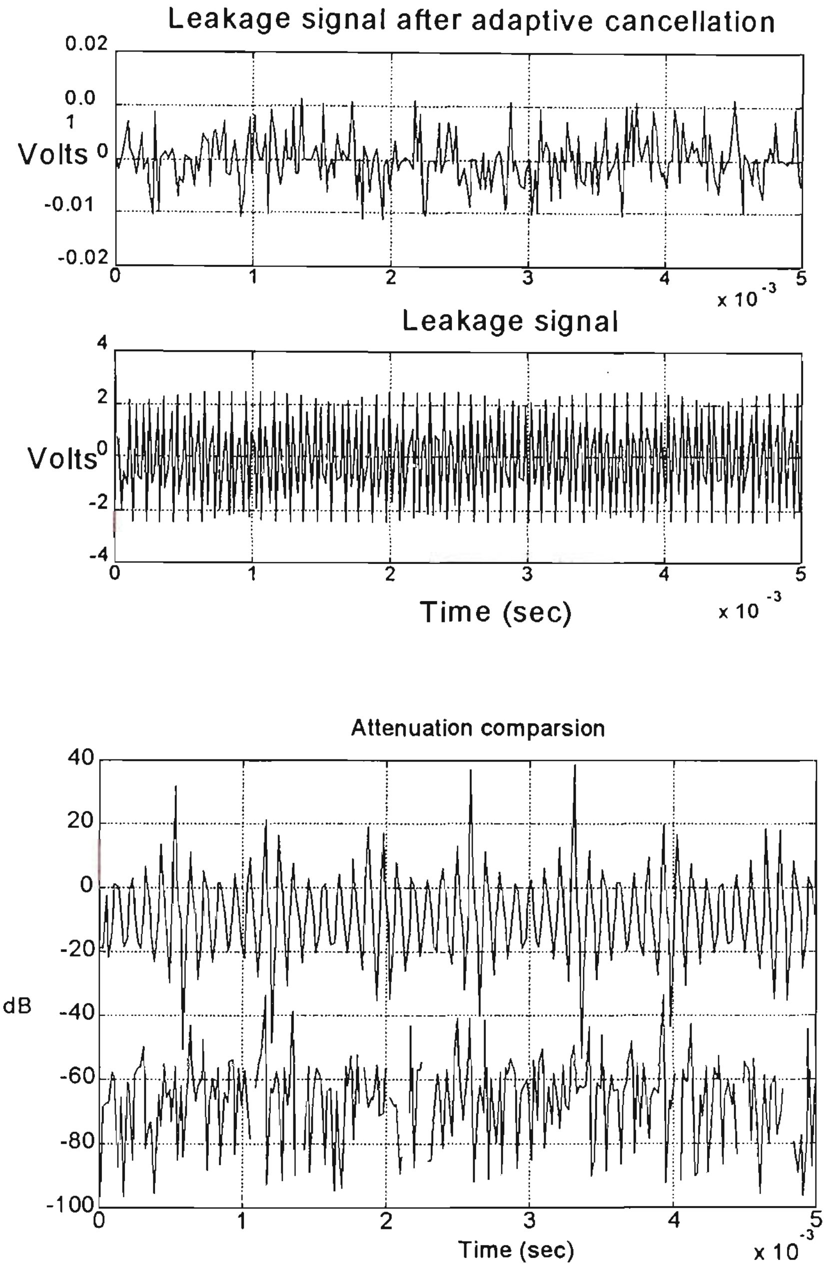


Figure 9.15: Test results of fuzzy logic based canceller on the model line with the signal having centre frequency of 30 kHz

9.6 APPLICATION OF ARTIFICIAL NEURAL NETWORK

In this work, various types of interference cancellation techniques have been discussed. These schemes were based on conventional and fuzzy adaptive theories. To highlight the working of these algorithms, implementation results for both computer and hardware simulation studies are presented. In this section, application of artificial neural network (ANN) has been investigated for interference cancellation on the same PLC model used for RLS, SA and AFLIC methods.

For design and computer simulation studies of the Artificial Neural Network Interference Canceller (ANNIC), MATLAB was used as a simulation tool. For training the network adaptively, PLC leakage and combined (PLC target (vector of zeroes) and leakage signals) signals were taken as input to adapt the connection weights and biases of the ANN. As mentioned earlier, the same PLC model was used to test all types of canceller algorithms, which facilitated in comparing the results. For ANNIC test studies, ANN tools were used from MATLAB. MATLAB functions ('initlin' and 'adaptwh') were used to design the network. For two input, ANN has one layer and one neurone. The connection weights and biases were updated adaptively. Design description of canceller is given in subsequent sections of this chapter.

9.6.1 Performance Of ANNIC For A Given PLC System

The application and design of ANNIC for PLC system have been discussed in Section 2.8. Supervised training of ANN was used to predict the level of interferences from the PLC model. PLC model descriptions are given in Section 6.3. Validity of canceller algorithm was tested for various patterns of PLC signals. Descriptions of signals are given with the tabular results in this section.

For the studies of different algorithms for interference cancellation, various designs for line traps were adopted. Parameters of the line traps were used to adjust the centre frequencies of the equipment. For the application of ANNIC a centre frequency of 100 kHz was chosen. Based on this design, studies for a required spectrum of the signals were made.

In first stage of studies, four different spectrums of frequencies having bandwidth of 50 kHz each were used. Required signals were generated from random signal with the use of bandpass filter. Table 9.8 shows test results for ANNIC.

Table 9.8 : Application of ANNIC on PLC model

Frequency spectrum (kHz)	Attenuation due to line trap (dB)	Attenuation due to canceller (dB)	Performance Index
50-100	-10.3057	-53.2746	.0687
150-200	-.9840	-90.5189	.1426
350-400	-.1281	-95.2365	.1020

Graphical results are shown in Figures 9.16 and 9.17 for the application on a signal having spectrums of 50-100 kHz and 150-200 kHz respectively. For these studies, network was trained using 2,000 points and then prediction of the interference was used to cancel the leakage signal. With the presentation of more data points to train the network, prediction of the network can be improved. Further studies were made for the signal having three channels with AMDSB-SC modulation, 20,000 points were used to train the network, as a result improved performance of the network was obtained. The same signal was tested for AMSSB modulation as well. Results for both modulation schemes are given in Table 9.9.

Table 9.9 : Application of ANNIC using AMDSB-SC and AMSSB modulation

Modulation Scheme	Attenuation due to line trap (dB)	Attenuation due to canceller (dB)	Performance Index
AMDSB-SC	-3.4807	-286.3441	.0509
AMSSB	-3.4807	-93.264	.1290

For the three channels, carriers of 115, 127 and 139 kHz were used with the sampling frequencies of 345, 381 and 417 kHz respectively and were multiplexed using FDM technique.

Application of ANN for prediction of interference or PLC signal was made successfully using adaptive scheme for finding the weights and biases for the network. Consideration of zero PLC signal on the busbar was taken as target error for the ANNIC. Design and implementation of the canceller were very convenient with the use of MATLAB toolbox for neural network.

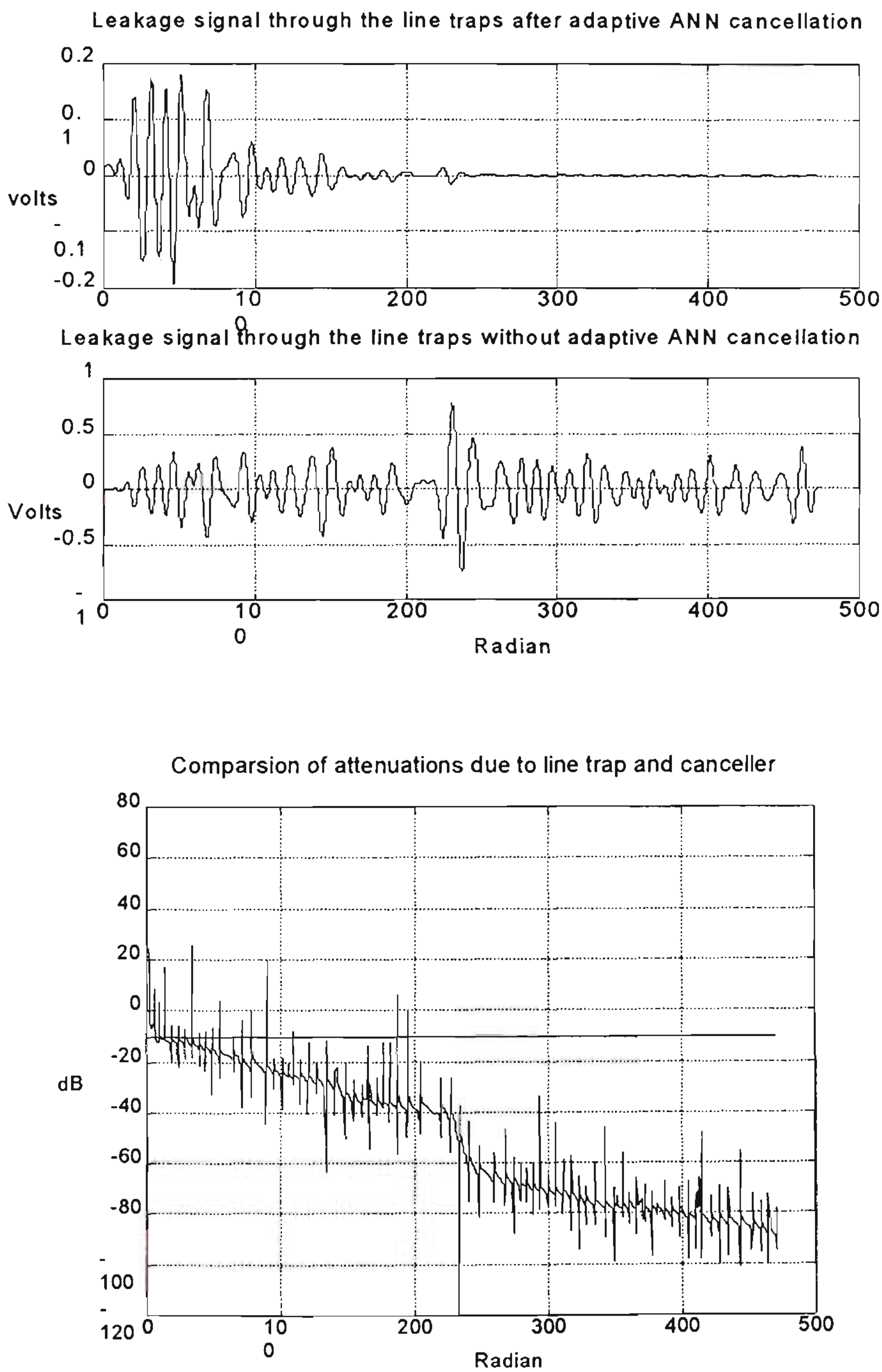


Figure 9.16: Application of ANNIC for PLC system to cancel the signal having spectrum of frequencies 50-100 kHz

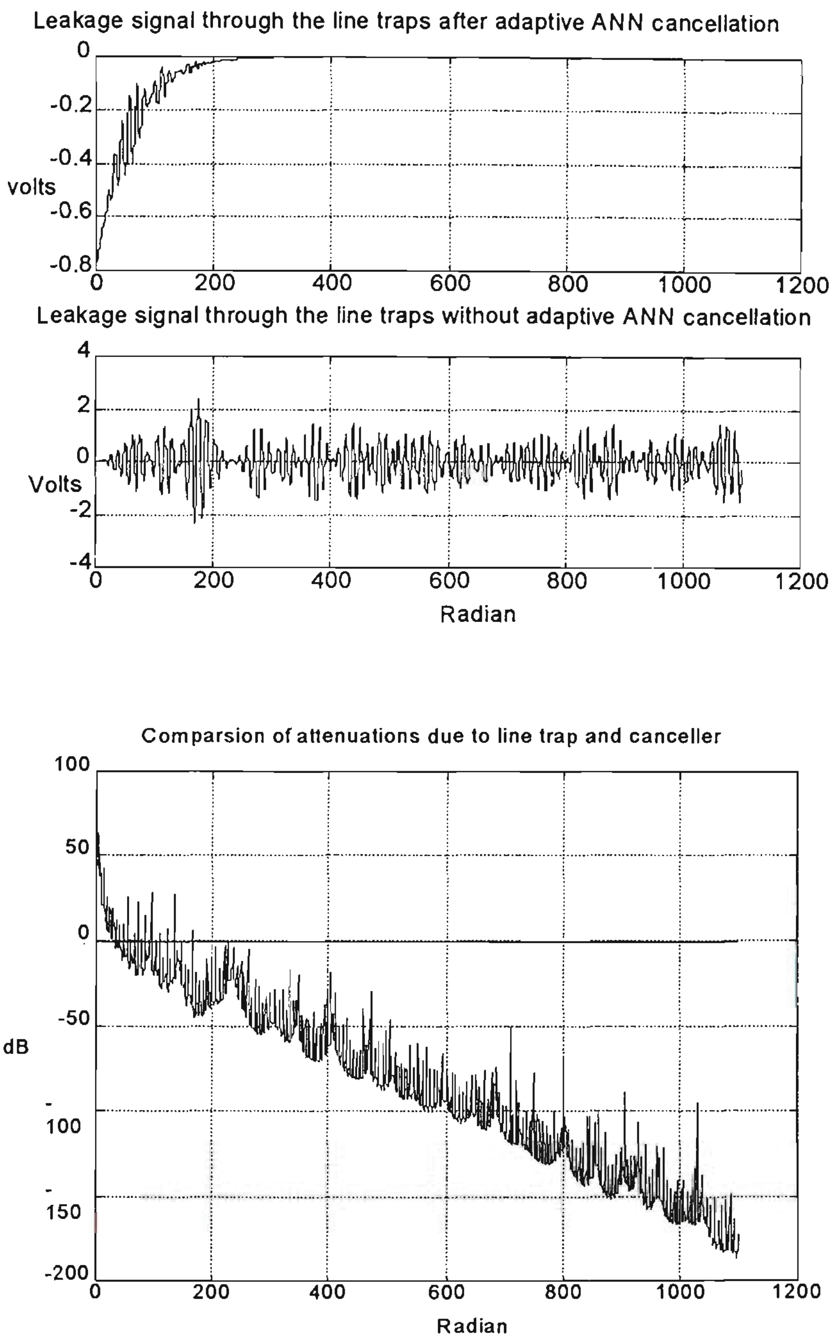


Figure 9.17: Working of ANNIC on PLC network to cancel the leakage signal having bandwidth of 50 kHz with the spectrum of frequencies 150-200 kHz

In this chapter, various algorithms for interference canceller have been presented. Design of these techniques was based on artificial intelligence and knowledge base systems. AFLIC was designed using fuzzy logic toolbox of the MATRIXx and implementation of the canceller was made using PLC model programmed in MATLAB environment. Interfacing of data from both packages has been described in Sections 9.3 and 9.4. Design and implementation of AFLIC using linear, non linear and left-right zero membership functions have been presented in Section 9.4. Also, application of novel interference cancellation has been presented in Subsection 9.4.4. Section 9.5 describes working of the canceller on laboratory model of a PLC system. In Section 9.6, use of MATLAB has been described for studies of ANNIC on PLC network. MATLAB and MATRIXx were very useful for the design and implementation of all the techniques presented in this chapter.

CHAPTER 10

COMPARISONS AND CONCLUSIONS

10.1 INTRODUCTION

With increasing demand of tele-traffic for power system control and protection, there is a need to improve the performance of existing telecommunication equipment and networks. Installation of fibre optic links can improve the reliability of data communication at the expense of high cost. Existing PLC networks have shortage of frequency spectrum due to the fact that the same frequencies cannot be used on the adjacent line sections. The same problem can be seen in mobile communication practices, the same frequencies are not used in adjacent cells of mobile networks [87].

This thesis suggests some adaptive techniques applicable to PLC networks so that same frequencies can be used on the adjacent line sections. Also, the thesis describes the modal values of PLC signal on the line. Based on these studies, a laboratory model of a PLC system was designed to study the performance of interference cancellation techniques.

In previous chapters, design and implementation studies of RLS, SA, AFLIC and ANNIC have been described. In this chapter, comparison of these techniques will be taken as a base to draw conclusions and to suggest future work.

10.2 COMPARISON OF TECHNIQUES

Applications of these techniques for PLC systems have some advantages and disadvantages due to algorithmic, computational or functional conditions. These schemes can be categorised into two major groups:

1) Interference is estimated after the identification of line trap dynamic model.
2) Interference is estimated without the identification of line trap dynamic model

RLS and SA techniques are the members of the former group whereas, AFLIC and ANNIC represent the later group of techniques. Based on the facts, the following comparison can be drawn.

1. RLS and SA techniques need on-line system identification, and then it can estimate the level of interferences. On-line system identification is very important and useful when system parameters are unknown or they are partially defined. In PLC application, line trap parameters are frequency dependant and the frequency of the signal is unpredictable. Application of these techniques was suitable for frequency variant parameters of the line trap. In this study, on-line system identification slowed down the interference cancellation process.

2. Consideration of zero initial conditions of system parameters, for both conventional adaptive techniques (RLS and SA) makes them more practical if the system parameters and inputs-outputs are unknown.

3. From experience, if system parameters are approximately known, then it is advisable to use known parameters for practical systems. This way convergence time for parameters from zero values to optimum values can be reduced significantly. Then the chance of losing the information in parameter convergence time can be minimised.

4. RLS and SA methods differ from each other in identifying the systems. Projection operator matrix (internal state matrix, P_k) plays a key role in identification of the systems in both RLS and SA methods. In RLS algorithm, P_k is considered 4 x 4 matrix, but, for SA method, it is a scalar, which ultimately reduces the computational time for SA based canceller. Time comparison is given in Section 8.3. SA method is slow in converging to the optimum values of parameters. Figures 6.11 and 8.1 show the trace of parameter convergence for line trap model identification with the use of both RLS and SA methods respectively.

5. SA method is easier to implement than the RLS method. Calculation of P_k is very simple for SA method as shown in the mathematical model of the algorithm in Section 2.6.

6. Average attenuation offered by SA method based interference canceller was much higher than RLS algorithm for the same conditions of system modelling. Comparison of the results can be made from Tables 6.1, 7.2-7.5 (RLS) and 8.1-8.5 (SA). Graphical results are also given in Chapters 6, 7 and 8. SA method utilises a stochastic approach in identifying the system, which appears to be a very successful technique for frequency variant non-linear line trap model.

7. Comparing the values of performance index, SA method showed much better performance than RLS based canceller.

8. To avoid system identification, fuzzy logic (AFLIC) and artificial neural network (ANNIC) based techniques were used to identify the pattern of leakage signal. System identification is time consuming and needs extra computational capabilities, which has been outlined in Section 8.1. MATRIXx was used for modelling of AFLIC but for ANNIC simulation MATLAB was used with its flexible tool boxes.

9. Fuzzy logic for this particular application appeared to be very versatile in designing interference cancellers. Representation of membership functions in a variety of ways, eg. linear, non-linear and left-right zero gave enough freedom to improve the performance of cancellers.

10. Fuzzy logic gave the freedom of thought to implement designed algorithms on complex and ill-structured processes. Application of this theory for the prediction of interferences was the best solution for a frequency variant non-linear system.

11. Performance of fuzzy logic based cancellers can be improved in a number of ways contrary to the conventional adaptive techniques (RLS and SA). eg.

    - A Proper choice of ranges for universe of discourse based on operational knowledge of crisp inputs (leakage and error signals from FLC) improved the performance of cancellers significantly.
    - Number and shape (linear, non-linear or unevenly distributed) of membership functions also played an important role in improving the efficiency of algorithms.
    - Distribution of universe of discourse among membership functions mainly depends on the probability of occurrence of data in some particular band of data set. It is preferable to use narrow stretched membership functions for the band of data sets, which has the maximum probability of occurrences. Wide and narrow stretched membership functions were used in identifying the phase lag or lead, introduced by the coupling capacitors.
    - Use of different formations of a general structure of techniques, eg. adaptive self tuned or hierarchical have a significant effect on the fuzzy logic controllers.
    - Proper choice of crisp inputs, and many other factors show significant effects on the algorithms.

12. In ANNIC cancellation technique, use of adaptive artificial neural network was made. Learning of the network was very time consuming even for a small number of examples. Application of this technique was made possible with the use of neural network tools from MATLAB. Various tools for many networks can be used for this particular application. Time consumed for processing 2001 points of data on AlphaStation 200 was 5.9561 sec.

13. At the expense of time and extra computation facilities, results of the ANNIC canceller were improved with additional examples of data points.

14. For same conditions of PLC model, the neural network based canceller gave different but acceptable results, for various attempts for training the network.

15. Considering the mathematical algorithmic complexities of all the techniques described in this work, fuzzy logic based cancellers appeared to be more practically applicable with their very simple designing strategies. With the use of this technology, representation of controllers by linguistic rules to stabilise ill-structures and vague systems, makes it more attractive to overcome engineering problems.

16. The applications where system identification is necessary, RLS and SA techniques can be used very efficiently.

17. The success of the applied techniques mainly rests on the application, need, suitability and technology used.

Comparisons drawn above can be used as a base to suggest the suitability of a certain technique for a particular engineering or non-engineering problem. These studies also indicate the comparison in assisting the line trap in providing enough attenuation to the PLC signals on the busbar.

10.3 CONCLUSIONS

Various adaptive interference cancellation schemes were implemented on both computer and hardware PLC models. Performance of these techniques was compared using performance index and attenuation provided by the cancellers as performance indicators. Results indicate that developed interference schemes have fulfilled the requirements, as set out in Section 1.4.

10.3.1 Modal Studies And Design

ATP6 was a very convenient tool for the simulation studies of modal values of PLC signal in terms of transient studies on 500 kV and 400 km long transmission line. Computer simulation results presented in Chapter 5 were used as a base to design a PLC model system, operating at laboratory voltage level, eg. 415 V. Hardware model design is given in Chapter 4 and in Appendix E. Also, PLC model system was used to study the behaviour of conventional and non-conventional coupling schemes. Chapter 7 shows, behaviour of line under model different coupling arrangements.

10.3.2 Design Of PLC Model And Its Associated Equipment

In Chapter 2, mathematical representation of PLC modal signals is presented using modal theory as described in Appendix A. On both sides of the line trap, PLC and leakage signals were considered as composite signals assembled from their modal values and were fed as inputs to the adaptive interference cancellation schemes. Application of Modal Analysis for the inclusions of line trap, coupling capacitors and interference cancellation schemes was made. The modelled systems are presented in Chapter 2. Some of the modelled algorithms are:

1) PLC and leakage signals;
2) Line trap and coupling capacitors;
3) RLS method;
4) SA method;
5) Application of fuzzy set theory;
6) Application of ANN.

Based on these models, computer and hardware simulation studies were performed to verify the working of the algorithms.

10.3.3 Real-Time Interference Cancellation

RLS, SA, AFLIC and ANNIC methods were used to estimate the level of interference on the busbars. These techniques gave satisfactory results when their estimates were cross-polarised to get interference cancellations. Comparisons of these techniques have been drawn in Section 10.2. Computer and hardware simulation studies are presented in Chapters 6-9. Interference cancellation techniques showed better performance in the computer simulation studies. Designed line traps were able to offer a maximum attenuation of $\cong$ 20 dB to the PLC signals. The attenuated signals still would have enough power to interfere with the PLC signals from adjacent line sections, operating at the same frequencies.

Suggested interference cancellation schemes were efficient enough to assist line traps in providing additional attenuation ranging from $\cong$ 30-300 dB. The levels of attenuation offered by the cancellers were mainly dependant on the algorithm of the cancellers, bandwidth of the signals to be cancelled and attenuation offered by line traps etc.

Computer and hardware simulation studies of the schemes were made based on the parameters described in Chapter 3. With these selected parameters, computer and hardware simulation studies for RLS method have been presented in Chapters 6 and 7 respectively, while, results for SA method are given in Chapter 8. Implementation results of AFLIC and ANNIC have been described in Chapter 9.

In this thesis, adaptive interference cancellation schemes have been developed and implemented on PLC systems, so that, re-use of the same frequencies can be made possible on the adjacent line sections. Studies showed that implementation of these developed techniques will help to enhance the use of allowed PLC spectrum of frequencies, that will help to improve the customer services. Techniques, presented in this work, are not only efficient for PLC systems, but they may be used for other engineering or non-engineering problems.

Some of the published work is given in Appendix C. On presenting this work, a great deal of interest was shown by the experts at national and international conferences.

10.4 FUTURE WORK

Although, interference cancellation schemes developed in this research were very efficient but improvement is possible in their implementation to the PLC networks. Working of these algorithms can be improved in many ways and their application can be extended. Some of the suggestion are given below:

1. Instead of using initial conditions zero for RLS and SA methods, if from system knowledge, approximate or exact values of parameters can be used, then performance of the cancellers would be improved. From frequency variant non-linear nature of line traps it is always difficult to find exact parameters.

2. For the computer simulation studies of cancellation schemes using MATLAB, the transmission line was represented by its characteristic impedance value. Distributed parameter based modelling of the line can be considered by developing power tools for MATLAB.

3. A complete power system tool box could be developed for MATLAB. That could be used with other tool boxes to simulate sophisticated protection systems, control systems, communication systems for SCADA, co-generation and renewable energy resources (wind, solar, tidal and hydro etc.) applications etc.

4. In this research, interference caused due to line traps and coupling capacitors were addressed. The application of interference cancellation schemes can be extended to include radiation effects, corona effects and effects with the mix use of PLC and fibre optic modes for communication needs of power systems.

5. To improve customer services, these schemes can be well used for on-line electricity meter readings to make extensive use of PLC networks.

6. Effects of presence of hybrids can be included in future work while considering the performance of the cancellers.

7. Performance of fuzzy logic based cancellers can be improved by making use of more accurate following factors:
   - defuzzification methods
   - distribution of membership functions,
   - ranges of data
   - and/or, revising the whole algorithms for this application.

8. In this research, appropriate hardware was built to test the performance of the techniques on the power line model in the laboratory. In future work, feasibility of implementation of these schemes on practical systems can be suggested.

REFERENCES

1. Sherif YS and Zahir SS, "On Power Line Carrier Communication (PLC)," *Microelectron. Reliab., vol 24, pp 781, 1984.*

2. Podszeck HK, " Carrier Communication Over Power Lines," *New York; Springer - Verlag, 1972.*

3. "Power Line Carrier Application Guide," *ECC-133-3B, GEC, Mobile Radio Products Dept, Power Line Carrier Product Section, Lynchburg Va, 1974*

4. Widrow B and Stearns SD, "Adaptive Signal Processing," *Englewood Cliffs, NJ, Prentice- Hall, 1985.*

5. Applebaum SP, "Adaptive Arrays," *IEEE Trans Antennas Propogat., vol AP-24, pp 573-598, September, 1976.*

6. Fallou JA, "Propagation des courants de haute frequence polyphases le long des linges aerieennes de transport d'energie affectees de courts-circuit ou de defauts d'isolement." *Bull. Soc. Franc. Elect., Series 5, 2 pp 787, 1932.*

7. Naredose JL and Soudach AC, " Extension of Senn's Method to the Analysis of PLC Systems applied to Delta Transmission Lines, " *IEE Proc, vol 136, Pt C, No 6, pp 353-360, November 1979.*

8. Morgan DR, Cray SE and Davidson GH, " Adaptive Interference Cancellation for Power Line Carrier Communication System," *IEEE Trans on Power Delivery, vol 6, no 1, pp 49-61, January 1991.*

9. Naredo Jose Luis and Soudack Avrum C, " Design of Power Line Carrier Systems on Multitransposed Delta Transmission Lines, " *IEEE Trans on Power Delivery, v 6 n 3, pp. 952-958, July 1991.*

10. Cristina S, Amore MD, Feliziani M and Mauro, " Electromagnetic Interference from Digital Signal Transmission on Power Line Carrier Channels, " *IEEE Trans on Power Delivery v n A, pp 898-905, 1989.*

11. Nitzberg, R, " Effect of Interchannel Mismatch upon Adaptive Array Cancellation, " *Proc IEEE Natl Radar conf (cat n 89CH2685-6), pp. 119-124, 1989.*

12. Graupe, Efron D and Adam J, " An Output - Whitening Approach to Adaptive Active Noise Cancellation, " *IEEE Trans on Circuits and Systems v38 n 11 pp. 1306-1313, Nov 1991.*

13. Chesmore ED, " Artificial Intelligence Techniques in HF System Design" *IEE Conference Publication n339. Publ by IEE, Michael Faraday House, Stevenage, Engl. pp.17-20,1980.*

14. Burrascano P, Amore MD, Cristina S and Salerno M, " Digital Signal Transmission on Power Line Carrier Channels: An Introduction, " *IEEE Trans on Power Delivery, Vol PWRD-2, n 1, pp. 50-56, January 1987.*

15. Kohno, Ryuji Imai, Hideki Hatori, Mitsutoshi Pasupathy and Subbaraya, " Adaptive Cancellation of Interference in Direct- Sequence Spread-S Multiple Access System, " *IEEE/IEICE Globe Telecommunications Conference Nov 15-18, Publ by Ohmsha Ltd, Tokyo, Japan. Available from IEEE Service Cent 87CH2520-5, Piscataway, NJ, USA, pp. 630-634, 1987.*

16. Horak, Keral Kluvanek and Pavol, " Application of Probability Access to the Determination of the influence of a Power Line on a Communication Line, " *Elektrotechonicky Obzor v 77 n 2 Feb p 79-85, 1988.*

17. Ishkin, Kecher VH, Knizhnik SI, Matveev RQ, Poltor VF, Shkarin ZA and Yu P., " Experimental Investigation of PLC Communication on a Transposed 1150 kV Power line, " *International Conference on Large High Voltage Electric systems Publ by CIGRE, Paris, Fr pp. 35. 10. 1-35. 10. 6, 1986.*

18. Morf, K Doser, B, " New Insulation Coordination For Line Traps Enhances Reliability of PLC Transmission, " *Brown Boveri Review v 74 n 9 pp. 486-493, Sep 1987.*

19. Zhu, Gongzhao Zhou and Yanyi, " Study of TRV for 500 kV circuit Breakers, " *IEEE, Power Engineering Soc, New York, NY, USA. Available from IEEE Service Cent 87CH2579-1, Piscataway, NJ, USA pp. 626-631,1987.*

20. Dubey RM and Sharma SC, " Journal of the Institution of Engineers (India)", *Part ET: Electronics & Telecommunication Engineering Division v69 pt 2 p 27 - 32, Nov 1988.*

21. Lucky RW,Salz J and Weldon EJ Jr., " Principles of Data Communications, " *Mc. Graw-Hill, New York , 1968.*

22. Aggarwal RK and Li HY"An Improved Modelling Technique of a Fibre Optical Digital System Protection Relay" *IEE International Conference on Advances in Power System Control, Operation and Management, Hong Kong, pp. 252-256, December 1993.*

23. Perz M C, "Natural Modes of Power Line Carrier on Horizontal Three-Phase Lines" *IEEE Summer General Meeting and Nuclear Radiation Effects conference, Toronto, Ont., Canada, pp. 679-689, June 16-21 1963.*

24. Gondal I and Kalam A "Simulation of Phase to Ground Coupling for Power Line Carrier Communication Systems Using Modal Analysis" *Second International Conference on Modelling and Simulation, VUT Melbourne, Australia, Vol 1 p 277-285, 12-14 July 1993.*

25. Gondal I and Kalam A "Fault Transient Simulation of EHV Transmission Systems" *AUPCE 92, QUT, Brisbane, Australia pp. 321-326, 1-2 October 1992.*

26. Van Der, Gracht PK and Donaldson RW "Communication using Pseudonoise Modulation on Electric Power Distribution Circuits", *IEEE Trans. on Communication, vol. COM-33, pp.964-974, September 1985.*

27. Masaoki Tanaka "Transmission Characteristics of a Power line used for Data Communication a high Frequencies" *IEEE Transaction consumer Electronics v35(1), pp. 37-42, Jan 1989.*

28. Carroll HK "Computer simulation of electrical transients in power systems" *Proc. of the IEE intentional symposium on circuit theory, 1973.*

29. Bickford JP and Doepel PS "Calculation of switching transients with particular reference to line energisation" *Proc. IEE, vol. 114, No. 4, April 1967.*

30. Battisson MJ "British investigation the switching of long ehv transmission lines" *CIGRE Report 13-02, 1970.*

31. Uram R and Ferro WE " Mathematical analysis and solution of transmission line transients-part I - theory" *IEEE Trans. on power apparatus and systems. vol. PAS - 83, November 1964.*

32. Uram R and Ferro WE " Mathematical analysis and solution of transmission line transients-part II - applications" *IEEE Trans. on power apparatus and systems. vol. PAS - 83, November 1964.*

33. Tran DK " Laplace analysis and computer simulation of transient current in power transmission lines", *pt 1 - single line with lossy earth return, pt 2 - polyphase systems with lossy earth return. Proc. IEE, vol. 124, no. 2, February 1977.*

34. Bewley LV " Travelling waves on transmission systems" *New York: Wiley, 1951.*

35. Wedepohl LM "Application of matrix methods to the solution of travelling wave phenomena in poly phase system." *Proc. IEE, Vol. 110, pp. no. 12, December 1963.*

36. Wedepohl LM and Mohmaed SET, "Multi conductor transmission lines. Theory of natural modes and Fourier integral applied to transient analysis." *Proc. IEE, vol. 116, No. 9, September 1969.*

37. Wedepohl LM and Mohmaed SET, "Apparent impedance of very long multi-conductor lines." *Proc. IEE, vol. 112, No. 11, November 1965.*

38. Wedepohl LM, "Electrical characteristics of the polyphase transmission systems with special reference to boundary - value calculations at power lines frequencies." *Proc. IEE, vol. 112, No. 11, November 1965.*

39. Widrow B, Glover JR, McCool JM, Kaunitz J, Williams CS, Hearn RH, Zeidler JR, Dong E and Goodlin RC "Adaptive noise cancellation: Principles and applications." *Proc. IEEE, vol. 63, No. 12, pp.1692-1716, December 1975.*

40. Chen HF, “Recursive system identification and adaptive control by use of the modified least squares algorithm." *Tech. Rep., Mcgill University, Montreal, 1970.*

41. Feintuch PL, "An adaptive recursive LMS filter." *Proc. IEEE, vol. 64, pp. 1622-1624, 1976.*

42. Fuchs JJJ, "The recursive least-square algorithm revisited." *Rep. IRISA Laboratorie Automatique, Rennes, France, 1980.*

43. Holst J, "Adaptive prediction and recursive parameters estimation." *Rep. TFRT 1013-1-206. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden, 1977.*

44. Bibliography of power system communication literature, *1920-1954. Trans. AIEE. vol. 75. pt. III. pp. 1-12. 1956.*

45. Morf KP “Mixed use of Optical Fibre Communication and PLC Techniques in Telecommunication Networks for Electrical Power Utilities” *International Conf on Advances on Power System Control, Operation and Managements, IEE. pp. 260-264 Hong Kong Nov 1991.*

46. Adams GE, “Wave Propagation along unbalanced hv Transmission lines” *Trans Amer. Inst. Elect. Engrs, 78, part III, pp. 639, 1959.*

47. Yamamoto H and Morita K, “4/5/6 L-DI Digital Microwave Radio System” *Rev. Elect. Commun. Lab., vol. 30, no. 5, pp. 836, 1982.*

48. Saito Y, Komaki S and Murotani, “Feasibility Considerations of high-level QAM multi-carrier system” *in proc. ICC’84,. pp. 22.8.1, 1984.*

49. Araki M, Tajima K and Matsue H, “Correction Technique for Multipath Fading in 4/5/6 L-DI Digital Microwave Radio System” *Rev. Elec. Commun. Lab., vol, 30, no. 5, pp. 873, 1982.*

50. Fenderson GL, Meyers MH and Skinner MA "Recent Advances in Multipath Propagation countermeasures for high-capacity Digital Radio Systems" *in Proc. ICC'85, pp. 39.2.1, 1985.*

51. Borgne M, " An Adaptive Cross-polsrization Canceller for Digital Radio Systems" *in Proc. ICC'85, pp. 39.6.1, 1985.*

52. Namiki J and Takahhara S, "Adaptive Receiver for Cross-polarization Digital Transmission", *in Proc. ICC,81, pp. 46.3.1, 1981.*

53. Araki M and Hashimoto A, "Performance of Cross-polarization Canceller having Transversal Filter" *Trans. IECE Japan., vol. j69-B, no. 1, 1986.*

54. Matsue H,Ohtsuka H and Murase T , "Digitalized Cross-polarization Interference Canceller for Multilevel Digital Radio" *IEEE Journal on selected areas in communication, vol. SAC-5, no. 3, pp. 493, April 1987.*

55. Valdislav K, "Estimation of Aircraft Aerodynamics Parameters From Flight Data" *Prog. Aerospace Sci., Vol. 26, pp. 1-77, 1989.*

56. Valdislav K, "Application of System Identification to High Performance Aircraft" *IEEE, Proc. of 32nd Conf. on Decision and Control, San Antonio, Texas, , pp. 2253-2259, December 1993.*

57. Chandler P, Pachter M, Mears M and Sheldon S, "Regression Techniques for Aircraft Parameter Identification from Noisy Measurements in Manoeuvring Flight" *IEEE, Proc. of 31st Conf. PM Decision and Control, Tucson, Arizona, , pp. 2311-2316, December 1992.*

58. Qin SJ, "Partial Least Square Regression for Recursive System Identification" *IEEE, Proc. of the 32nd Conf. on Decision and Control San Antonio, Texas, , pp. 2617-2622, December 1993.*

59. Mahloch SH and Rodriguez AA, "System Identification from a Frequency Response" *IEEE, Proc. of 31st Conf. PM Decision and Control, Tucson, Arizona, pp. 551-556, December 1992.*

60. Lee S and Ray A "Performance Management of Multiple Access Communication Network" *IEEE Journal on Selected Areas in Communications, vol. 11, no. 9, pp. 1426-1437, December 1993.*

61. Ray A, "Networking for Compuer-intergerated manufacturing" *IEEE Network, vol. 2, no. 3, pp. 40-47, May 1988.*

62. Manufacturing Automation Protocol (MAP) 3.0 Implementation Release, *Available through MAP/TOP Users Group, Dearborn, MI, 1990.*

63. Technical and Office Protocols (TOP) 3.0 Implementation Release, *Available through MAP/TOP Users Group, Dearborn, MI, 1991.*

64. Stankovic SS and Radenkovic MS, "On the Convergence of Self-Tuning Stochastic Servo Algorithms Based on Stochastic Approximation" *IEEE Trans. on Automatic Control, vol.34, no. 11, pp. 1192-1196, November 1989.*

65. Deutsch SJ, Patel MH and Assad AJD "Comparison of Stochastic Approaches to the Transportation Problem: *A Case Study" IEEE Trans. on Engineering Management, vol. 41, no. 2, pp. 152-163, May 1994.*

66. Hiyama T, "Application of Rule-based Stabilising Controller to Electrical Power System" *IEE Proc. C, vol. 136, no. 3, pp. 175-181, 1989.*

67. Hsu YY and Cheng CH "Design of Fuzzy Power System Stabiliser for Multimachine Power Systems" *IEE, Proc. vol. 137, Pt.C, no. 3, pp. 233-238, 1990.*

68. Hiyama T and Sameshima T, "Fuzzy Logic Control Scheme for on-line Stabilization of Multimachine Power Systems" *Fuzzy Set and Systems 39 pp 181-194, 1991.*

69. Shi J, Kalam A, Herron LH "Comparsion of Fuzzy Logic Based and Rule Based Power System Stabiliser" *IEEE, pp. 692-697, July 1992.*

70. Ramaswamy P, Edwards RM and Lee YK "Fuzzy Logic Controller For Nuclear Power Plant" *IEEE, pp. 29-34, January 1993.*

71. Chand S, "On-line, Self-Monitoring Tuner for Proportional Integral Derivative Controllers" *IEEE Proc. of the 30th Conf. on Decision and Control Brighton, England, pp. 1905-1906, December 1991.*

72. Aicardi M, Davoli F, Minciardi and Zoppoli R "Decentralised Routing, Teams and Neural Network in Communications" *IEEE, Proc. of the 29th Conference on Decision and Control, Honolulu, Hawai, pp. 2386-2390 i, December 1990.*

73. Polcarpou MM, Ioannou PA "Neural Networks as On-Line Approximators of Non-linear Systems" *IEEE, Proc. of the 29th Conference on Decision and Control, Tucson, Arizons, pp. 7-12, December 1992.*

74. Driankov D, Hellendoorn H and Reinfrank M, "An Introduction to Fuzzy Control", *ISBN 3-540-56362-8 Springer -Verlag Berlin Heidelberg, 1993.*

75. Black M, "Vagueness: An Exercise in Logical Analysis" *Philos. Sci., 4(1937)427-455, 1937.*

76. Wakileh BAM, Gill KF "Use of Fuzzy Logic in Robotics" *Computers in Industry, 1035-46, 1988.*

77. Demuth H and Beale M, "Neural Network Toolbox for use with MATLAB" *The Math Works, Inc., January 1994.*

78. Manual for Interfacing and data acquisition card *(PCL818), 1990.*

79. Ghanayem O and Reznik L, "Hierarchical versus Adaptive Fuzzy Logic Controllers: Design and Performance" *IEEE, ANZIIS, Brisbane, Australia, pp. 224-228, December 1994.*

80. Centre for Emerging Computer Technologies, "Motorola Fuzzy Logic Education Program" *Motorola, Inc, USA, 1992.*

81. Harris CJ and Moore CG, "Intelligent Identification and Control for Autonomous Guided Vehicles using Adaptive Fuzzy Based Algorithms" *Engineering application of Artificial Intelligence, Vol. 2, pp. 267-285, December 1989.*

82. Hellendoorn H, "Design and Development of Fuzzy systems at SIEMENS R&D" *Proceeding of 2nd IEEE International Conference on Fuzzy systems (Fuzzy IEEE 1993), San Fransisco (Ca), USA, pp. 1365-1370, March 1993.*

83. Jager R, "The rule of Defuzzification Methods in application of Fuzzy Control" *Proceeding IF AC Symposium on Intelligent Components and Instruments for Control applications, A. Ollero and E. F. camacho Delft, Netherland, 1992.*

84. Larkin LI, "A Fuzzy Logic Controller for Aircraft Control" *Industrial applications of Fuzzy Control, pp. 87-103, 1985.*

85. Pedrcz W, "Fuzzy Control and Fuzzy System" *Research study Press/J Wiley and Sons, 1989.*

86. Needham JL "Report of Communication Systems" *Session C7, Transmission Development Department, Department of Communications (DOC), Australia, pp. 1-26, 1987.*

87. Macario RCV "Cellular Radion Principles and Design" *McGraw-Hill Inc., 1993.*

88. Stevenson WD Jr "Elements of Power System Analysis" *McGraw-Hill Kogakusha, 1975.*

APPANDIX A

SOLUTION OF TRAVELLING WAVE PHENOMENA IN POLY-PHASE SYSTEM

In this work it is anticipated to extend the use of theory of natural modes for the solution of travelling wave phenomena in polyphase systems [35,36,37,38] to formulate the model for PLC signal propagation on the power lines. For this particular application, Figure A.1 shows conductor (1) of a practical n-conductor transmission line where the effect of electromagnetic and electrostatic coupling is shown. Consider a very small element; Δx in the line. The voltage drop ΔV_1 across the element at a certain frequency is:

$$\Delta V_1 = -(Z_{11}I_1 + Z_{12}I_2 + \ldots\ldots + Z_{1n}I_n)\Delta x$$
$$\Delta V_1/\Delta x = -(Z_{11}I_1 + Z_{12}I_2 + \ldots\ldots\ldots + Z_{1n}I_n)$$

or

$$dV_3/dx = -(Z_{31}I1 + Z_{32}I_2 + Z_{33}I_3 + \ldots\ldots\ldots\ldots + Z_{3n}I_n)$$

.

.

$$dV_n/dx = -(Z_{n1}I_1 + Z_{n2}I_2 + Z_{n3}I_3 + \ldots\ldots\ldots\ldots\ldots + Z_{nn}I_n)$$

For conductor 2,3..........,n the rate of change of voltages $dV_2/dx, dV_3/dx \ldots\ldots\ldots\ldots\ldots dV_n/dx$ are similarly evaluated so that :

$$dV_1/dx = -(Z_{11}I_1 + Z_{12}I_2 + \ldots\ldots\ldots\ldots\ldots\ldots + Z_{1n}I_n)$$

or in matrix form

$$\left[dV/dx\right] = -[Z][I] \ldots\ldots\ldots\ldots (A.3)$$

Further from Figure A1, the difference in the current between the ends of element Δx of conductor (1) is given by:

$$\Delta I_1 = \Delta I_{11} + \Delta I_{21} + \Delta I_{31} + \ldots\ldots\ldots + \Delta I_{n1}$$

where

$$\Delta I_{11} = -(V_1 + \Delta V_1)Y_{11}.\Delta x \cong -V_1 Y_{11}.\Delta x$$

($\Delta V_1 Y_{11}$ Δx being small value & so is neglected)

$$\Delta I_{21} = -(V_1 - V_2)Y_{12}\Delta x$$
$$\Delta I_{31} = -(V_1 - V_3)Y_{13}\Delta x$$
$$.$$
$$.$$
$$\Delta I_{n1} = -(V_1 - V_n)Y_{1n}\Delta x$$
$$\Delta I_1/\Delta x = -(Y_{11} + Y_{12} + \ldots + Y_{1n})V_1 + Y_{12}V_2 \ldots + Y_{1n}V_n$$

or

$$dI_1/dx = -(Y_{11} + Y_{12} + \ldots + Y_{1n})V_1 + Y_{12}V_2 \ldots + Y_{1n}V_n$$

applying this principle to the conductors 2,3,4 ....,n, the rate of change of currents with respect to x is given by:

$$\begin{bmatrix} dI_1/dx \\ dI_2/dx \\ . \\ . \\ . \\ . \\ dI_n/dx \end{bmatrix} = -\begin{bmatrix} Y_{11}+Y_{12}+\ldots+Y_{1n} & -Y_{12}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots -Y_{1n} \\ -Y_{21} & Y_{21}+Y_{22}+\ldots Y_{2n}\ldots\ldots\ldots -Y_{2n} \\ . & \\ . & \\ -Yn1 & -Yn2\ldots Yn1+Yn2+\ldots+Ynn \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ . \\ . \\ . \\ . \\ V_n \end{bmatrix}$$

or in a more general form

$$dI/dx = -[Y][V]\ldots\ldots\ldots(A.2)$$

Differentiating equation A.1 and A.2 with respect to x and for simplicity matrices [Z], [Y], [V], [I], [dV/dx] and [dI/dx] will be written from now onward without the matrix notation.

$$d^2V/dx^2 = -Z.dI/dx$$

and

$$d^2I/dx^2 = -Y.dV/dx$$

or

$$d^2V/dx^2 = ZYV\text{...........}(A.3)$$
$$d^2I/dx^2 = YZI\text{.............}(A.4)$$

The solution of the equations A.3 and A.4 is very difficult due to the fact that the second order rate of change of voltage and current in each phase is a function of the voltages and currents in all phases.

However, the solution obtained is the phase voltages and currents and are related to the component voltages and currents by the linear transformations [39].

$$V = S.V_c\text{.............}(A.5)$$
$$I = Q.I_c\text{...............}(A.6)$$

S = Voltage eigen vector matrix (eigen vectors of Z.Y)
Q = current eigen vector matrix

Where the [n x n] square matrices S and Q are so that the second order differential equations involve diagonal matrices only. Mutual effect are thus eliminated, making direct solution.

V_c = column vector matrix of the order [n x 1] of the n component voltages V_{c1}, V_{c2}, V_{c3},.........V_{cn} respectively.

I_c = column vector matrix of the order [n x 1] of the n component currents I_{c1}, I_{c2}, I_{c3}, ...I_{cn} respectively.

Substituting equations (A.5 & A.6) into (A.3 & A.4)

$$d^2V/dx^2 = S\,d^2V_c/dx^2$$

or

$$d^2V_c/dx^2 = S^{-1}ZYV$$

$$= S^{-1}ZYSV_c$$

so

$$d^2V_c/dx^2 = S^{-1}\,ZYSV_c$$

To simplify the analysis let

$$ZY = P$$

where

$$P_{ij} = \sum_{k=1}^{n} Z_{ik}.Y_{kj}\ldots\ldots\ldots\ldots(A.7)$$

$$d^2V_c/dx^2 = S^{-1}PSV_c\ldots\ldots\ldots(A.8)$$

The product $S^{-1}PS$ is diagonalised to become

$$[S^{-1}PS] = [\gamma_1^2\gamma_2^2\gamma_3^2\ldots\ldots\gamma_n^2]\ \ diag\ldots\ldots\ldots(A.9)$$

γ = propagation constant

Substituting in equation A.8, equation A.10 is obtained

$$\begin{bmatrix} d^2V_{c1}/dx^2 \\ d^2V_{c2}/dx^2 \\ . \\ . \\ d^2V_{cn}/dx^2 \end{bmatrix} = [\gamma_1^2\gamma_2^2\gamma_3^2\ldots\ldots\gamma_n^2]\ \ diag. \begin{bmatrix} V_{c1} \\ V_{c2} \\ . \\ . \\ V_{cn} \end{bmatrix}\ldots\ldots\ldots\ldots(A.10)$$

From equation A.10 can be represented as:

$$d^2V_{c1}/dx^2 = \gamma_1^2 V_{c1}$$
$$d^2V_{c2}/dx^2 = \gamma_2^2 V_{c2} \ldots\ldots\ldots\ldots (A.11)$$
$$.$$
$$.$$
$$d^2V_{cn}/dx^2 = \gamma_n^2 V_{cn}$$

Solving equation A.11 will give

$$V_{c1} = V_{c1}^{+} e^{-\gamma 1x} + V_{c1}^{-} e^{-\gamma 1x}$$
$$V_{c2} = V_{c2}^{+} e^{-\gamma 2x} + V_{c2}^{-} e^{\gamma 1x} \ldots\ldots\ldots\ldots (A.12)$$
$$.$$
$$.$$
$$V_{cn} = V_{cn}^{+} e^{-\gamma nx} + V_{cn}^{-} e^{\gamma nx}$$

or in general form

$$V_c = V_c^{+} e^{-\gamma x} + V_c^{-} e^{\gamma x} \ldots\ldots\ldots\ldots (A.13)$$

where $V_{c1}, V_{c2} \ldots\ldots V_{cn}$ in equations A.11 - A.13 are the modal voltages which are related to the phase voltages by square matrix of equation A.5 and A.6.

γ^2 = Eigen values of Z.Y.

Now considering the solution for the currents using equations A.3 - A.6:

$$d^2I/d^2x = YZI$$

$$I = QI_c$$

From equation A.7, P = Z Y. When the network considered is passive (transmission line), it can be said that:

$$Z = Z_t$$
$$Y = Y_t$$

and hence

$$d^2 I/dx^2 = (Y_t . Z_t) I$$

$$= (YZ)_t . I$$

or

$$d^2 I/dx^2 = P_t I \dots\dots\dots (A.14)$$

substituting equation A.6 into A.4:

$$d^2 I/dx^2 = Q d^2 I_c/dx^2$$
$$d^2 I_c/dx^2 = Q^{-1} d^2 I/dx^2$$
$$d^2 I_c/dx^2 = Q^{-1} P_t Q I_c \dots\dots\dots\dots (A.15)$$

where

$Q^{-1} P_t Q$ = current eigenvalues matrix which is diagonalised to be of the form:

$$Q^{-1} P_t Q = \left[\gamma_1'^2 \gamma_2'^2 \gamma_3'^2 \dots\dots\dots \gamma_n'^2\right] \; diag \dots\dots\dots\dots (A.16)$$

Now, for the diagonalisation of equations A.9 and A.16 the determinants (D) and (D') of $(P(P - \gamma_i'^2)$ and $(P_t - \gamma_i'^2)$ respectively must yield to zero [35].

$$D(P - \gamma_i^2) \quad = 0 \dots\dots\dots\dots (A.17)$$
$$D'(P_t - \gamma_i'^2) = 0 \dots\dots\dots\dots (A.18)$$

However, $P_t - \gamma_i'^2 = (P - \gamma_i'^2)_t$, because $\gamma_i'^2$ is a diagonal (contains only diagonal elements). Where $\gamma_i^2, \gamma_i'^2$ can be represented in forms eg $\gamma_1^2, \gamma_2^2, \ldots\ldots\ldots \gamma_n^2$ and $\gamma_1'^2, \gamma_2'^2, \ldots\ldots\ldots\ldots \gamma_n'^2$ respectively. Then,

$$D(P - \gamma_i'^2) = D'(P - \gamma_i'^2)_t = 0$$

and because the determinant of any matrix = the determinant of the transpose matrix, ie.

$$D'(P - \gamma_i'^2)_t = D'(P - \gamma_i'^2)$$

and

$$D(P - \gamma_i^2) = D'(P - \gamma_i'^2)$$

or

$$\gamma_i = \gamma_i'$$

ie. the voltage and current modal propagation coefficients are identical. It is sometimes useful to deal in terms of the components Z_C matrix and, from equations A. 1, A. 13 and A. 6:

$$dV/dx = -ZI \text{ where } \quad = SV_c \text{ , } I = QI_c$$

so

$$SdV_c/dx = -ZQI_c$$

or

$$dV_c/dx = -S^{-1}ZQI_c$$

and from equation A. 13 can be obtained

$$V_c = V_c^+ e^{-\gamma x} + V_c^- e^{\gamma x}$$

where γ, V_c^+ and V_c^+ are determined from equations A.9 and A.13 respectively. Differentiating equations A.13:

$$dV_c/dx = -\gamma e^{-\gamma x+}.V_c + \gamma e^{\gamma x}.V_c^- \text{ ....}(A.19)$$

where

$$e^{-\gamma x} = \left[e^{-\gamma 1x} e^{-\gamma 2x} \text{ ....} e^{-\gamma nx}\right] \ diag$$

From equation A.19 can be obtained

$$dV_c/dx = -\gamma V_c^+ e^{-\gamma x} + \gamma V_c^- e^{\gamma x} = -S^{-1}ZQI_c$$

or

$$V_c^+.e^{-\gamma x} - V_c^-.e^{\gamma x} = \gamma^{-1} S^{-1} ZQI_c$$

The product $(\gamma^{-1} S^{-1} ZQ)$ can be chosen to be diagonal. Thus replacing $\gamma^{-1} S^{-1} ZQ$ by Z^c gives the representation of the above equation:

$$_c^+ e^{-\gamma x} - V_c^- e^{\gamma x} = Z^c I_c \text{ ....}(A.20)$$

Equating A. 20 means that the modal component of currents are related only to the corresponding modal component of voltages. I_c of equation A.20 is of the form:

$$I_c = I_c^+ e^{-\gamma x} + I_c^- e^{+\gamma x} \text{ ....}(A.21)$$

where

$$I_c = \begin{bmatrix} I_{c1} \\ I_{c2} \\ . \\ . \\ I_{cn} \end{bmatrix} \quad I_c^+ = \begin{bmatrix} I_{c1}^+ \\ I_{c2}^+ \\ . \\ . \\ I_{cn}^+ \end{bmatrix} \quad I_c^- = \begin{bmatrix} I_{c1}^- \\ I_{c2}^- \\ . \\ . \\ I_{cn}^- \end{bmatrix} \quad Z^c = \begin{bmatrix} Z_1^c \\ Z_2^c \\ . \\ . \\ Z_n^c \end{bmatrix} \text{.......}(A.22)$$

The component voltages V_c and the component currents I_c given by equations A.13 and A.20 may be evaluated by solving the constants of integration from the defined boundary conditions. Once the component voltages and currents are known, the corresponding phase quantities may be evaluated from equations A.3 and A.4.

PLC signal propagate on the transmission lines exactly like power signal but at PLC frequencies. The propagation velocity of the modal values of PLC signal depends on the signal frequencies. The modes have different propagation constants and different propagation velocities. The modes are related to the properties of the system used, in particular the formation of the impedance matrix. The propagation level of the injected signal from sending end to receiving end can be calculated at any point along the line from the knowledge of the modal values. Addition of incident and reflected values of different modes gives the value of given particular mode at some particular point, which is specified by the distance x.

To investigate the level of signal voltages and currents at the boundaries one modal component is considered for simplicity .

$$V_{c1}^{+} e^{-\gamma 1x} - V_{c1}^{-} e^{\gamma 1x} = Z_1^c (I_{c1}^{+} e^{-\gamma 1x} + I_{c1}^{-} e^{\gamma 1x}) \text{......}(A.23)$$

Equation A.23 must be true for all values of x, and this can only be true if the coefficients of the exponentials are same, ie.

$$V_{c1}^{+} = Z_1^c I_{c1}^{+}$$
$$V_{c1}^{-} = -Z_1^c I_{c1}^{-}$$

At the sending end of the line:

$$x = 0, \qquad V = V_s$$

$$V_s = SV_c = S(V_c^{+} + V_c^{-})$$

$$V_s = S Z^c (I_c^{+} - I_c^{-}) \text{..........}(A.24)$$

and

$$I_s = Q.I_c = Q(I_c^{+} + I_c^{-})$$

At the receiving end of the line:

$$x = l, \qquad V = V_r$$

$$V_r = S.(e^{-\gamma l}.V_c^+ + e^{\gamma l}.V_c^-)$$
$$I_r = Q.(e^{-\gamma l}.I_c^+ + e^{\gamma l}.I_c^-)$$

From equation A.24 gives:

$$(I_c^+ - I_c^-) = (Z^c)^{-1}.S^{-1}V_s$$

$$(I_c^+ + I_c^-) = Q^{-1}I_s$$

This yields

$$I_c^+ = ((Z^c)^{-1}S^{-1}V_s + Q^{-1}I_s)/2$$
$$I_c^- = (Q^{-1}I_s - (Z^c)^{-1}S^{-1}V_s)/2$$

and

$$Q^{-1}I_r = e^{-\gamma l}((Z^c)^{-1}S^{-1}V_s + Q^{-1}I_s)/2 + e^{\gamma l}(Q^{-1}I_s - ((Z^c)^{-1}S^{-1}V_s)/2$$

or

$$Q^{-1}I_r = \cosh\gamma l\, Q^{-1}I_s - \sinh\gamma l\,(Z^c)^{-1}S^{-1}V_s$$

if the voltages and currents are represented in their modal values.

$$I_r^c = \cosh\gamma l Q^{-1}I_s - \sinh\gamma l (Z^c)^{-1}S^{-1}V_s \text{........}(A.25)$$

Now receiving end voltage can be evaluated;

$$S^{-1}V_r = e^{-\gamma l}V_c^+ + e^{\gamma l}V_c^-$$

$$= e^{-\gamma l}Z^cI_c^+ - e^{\gamma l}Z^cI_c^-$$

$$= e^{-\gamma l}Z^c((Z^c)^{-1}S^{-1}V_s + Q^{-1}I_s)/2 - e^{\gamma l}Z^c(Q^{-1}I_s - (Z^c)^{-1}S^{-1}V_s)/2$$

$$= \frac{(e^{\gamma l} + e^{-\gamma l})}{2}S^{-1}V_s - \frac{(e^{\gamma l} - e^{\gamma l})}{2}Z^cQ^{-1}I_s$$

$$S^{-1}V_r = \cosh\gamma l S^{-1}V_s - \sinh\gamma l Z^cQ^{-1}I_s$$

or

$$V_r^c = \cosh \gamma l V_s^c - \sinh \gamma l \, Z^c \, I_s^c \;..........(A.26)$$

V_r can be represented in the following notation;

$$V_r = S \cosh \gamma l S^{-1} V_s - S \sinh \gamma l Z^c Q^{-1} I_s$$

and since both Z^c and $\sinh \gamma l$ are diagonal

$$V_r = S \cosh \gamma l S^{-1} V_s - S Z^c \sinh \gamma l Q^{-1} I_s$$

$$= S \cosh \gamma l S^{-1} V_s - S Z^c Q^{-1} Q \sinh \gamma l Q^{-1} I_s$$

ie

$$V_r = S \cosh \gamma l \, S^{-1} V_s - Z_o \, Q \sinh \gamma l \, Q^{-1} \, I_s ....(A.27)$$

where polyphase surge impedance Z_o is as shown in equation A.28:

$$Z_o = S Z^c Q^{-1} ....(A.28)$$

and

$$Z^c = \gamma^{-1} S^{-1} Z Q$$

$$Z_o = S \gamma^{-1} S^{-1} Z ....(A.29)$$

Now $(Z_o)_t = Q_t^{-1} Z_t^c S_t$ and since Z^c is a diagonal hence:
It can be shown that $Q_t.S$ is diagonal:

$$Q_t.S = D = \text{diagonal matrix}$$

$$Q_t = S^{-1}.D = D^{-1} S ....(A.30)$$

$$(Q_t)^{-1} = Q_t^{-1} = SD^{-1}$$

Also

$$S_t.Q = D_t = D$$

$$S_t = DQ^{-1}$$

Hence

$$(Z_o)_t = S.D^{-1}.Z_t^c.D.Q^{-1}$$

or

$$Z_{ot} = S.Z^c.Q^{-1}$$

Thus equation A.30 is typically the same as that giving Z_O in equation A.28. This means that Z_O is a symmetrical matrix.

Equation A.25 and A.26 describe the modal current and voltage components at the receiving end of the line. Using these two equations, the polyphase network equations could be derived as follows:
From equation A.26:

$$\cosh\gamma l V_s^c - V_r^c = \sinh\gamma l Z^c I_s^c$$

$$I_s^c = .(Z^c)^{-1}(\sinh\gamma l)^{-1}(\cosh\gamma l V_s^c - V_r^c)$$

$$I_s^c = (Z^c)^{-1}\sinh^{-1}\gamma l.\cosh\gamma l V_s^c - (Z^c)^{-1}\sinh^{-1}\gamma\, l V_r^c$$

But

$$\coth\gamma l = \frac{\cosh\gamma l}{\sinh\gamma l} \quad \text{and} \quad \mathrm{cosech}\gamma l = \frac{1}{\sinh\gamma l}$$

$$I_s^c = (Z^c)^{-1}\coth\gamma l V_s^c - (Z^c)^{-1}\mathrm{cosech}\gamma l V_r^c \,..........(A.31)$$

Also from equation A.6.

$$I_s = QI_s^c$$

$$I_s = Q(Z^c)^{-1}\coth\gamma l V_s^c - Q(Z^c)^{-1}\operatorname{cosech}\gamma l V_r^c$$

or

$$I_s = Q(Z^c)^{-1}S^{-1}\,S\coth\gamma l\,S^{-1}V_s - Q(Z^c)^{-1}\,S^{-1}\,S\operatorname{cosech}\gamma l\,S^{-1}V_r$$

But also equation A. 28 gives $Z_O$which is = SZ^cQ^{-1} or

$$Z_o^{-1} = Y_o = Q(Z^c)^{-1}S^{-1}$$

Substituting in the equation of I_S above:

$$I_s = Z_o^{-1}.S\coth\gamma l\,S^{-1}V_s - Z_o^{-1}S\operatorname{cosech}\gamma l\,S^{-1}V_r$$

$$I_s = Y_o.S\coth\gamma l\,S^{-1}V_s - Y_o\,S\operatorname{cosech}\gamma l\,S^{-1}V_r..........(A.32)$$

Now from equation A.26 can be obtained:

$$I_s^c = \sinh^{-1}\gamma l(Z^c)^{-1}(\cosh\gamma l V_s^c - V_r^c)$$

Substituting the value of I_s^c in equation A.25:

$$I_r^c = \cosh\gamma l\ \sinh^{-1}\gamma l\ (Z^c)^{-1}(\cosh\gamma l V_s^c - V_r^c) - \sinh\gamma l(Z^c)^{-1}V_r^c$$

$$I_r^c = (Z^c)^{-1}(\cosh^2\gamma l\ \sinh^{-1}\gamma l - \sinh\gamma l)\ V_s^c - (Z^c)^{-1}\coth\gamma l.\ V_r^c$$

But

$$\frac{\cosh^2\gamma l}{\sinh\gamma l} - \sinh\gamma l = \frac{\cosh^2\gamma l - \sinh^2\gamma l}{\sinh\gamma l} = \frac{1}{\sinh\gamma l} = \operatorname{cosech}\gamma l$$

Substituting to get I_r^c

$$I_r^c = (Z^c)^{-1} \operatorname{cosech} \gamma l\, V_s^c - (Z^c)^{-1} \coth \gamma l V_r^c$$

$$I_r^c = Y^c \operatorname{cosech} \gamma\, l V_s^c - Y^c \coth \gamma\, l V_r^c \text{.........}(A.33)$$

Again from equation A.6, $I_r = QI_r^c$ substituting in A.33 we get:

$$I_r = Q(Z^c)^{-1} \operatorname{cosech} \gamma l\, S^{-1} V_s - Q(Z^c)^{-1} \coth \gamma l\, S^{-1} V_r$$

or

$$I_r = Q(Z^c)^{-1} S^{-1} S \operatorname{cosech} \gamma l\, S^{-1} V_s - Q(Z^c) S^{-1}\, S \coth \gamma l\, S^{-1} V_r$$

as $Y_o = Q(Z^c)^{-1} S^{-1}$, and substituting this to get I_r:

$$I_r = Y_o\, S \operatorname{cosech} \gamma l\, S^{-1} V_s - Y_o\, S \coth \gamma l\, S^{-1} V_r \text{............}(A.34)$$

Equations A.32 and A.34 can be rewritten in matrix form as:

$$\begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} Y_o S \coth \gamma l S^{-1} & -Y_o S \operatorname{cosech} \gamma l S^{-1} \\ Y_o S \operatorname{cosech} \gamma l S^{-1} & -Y_o S \operatorname{cosech} \gamma l S^{-1} \end{bmatrix} \begin{bmatrix} V_s \\ V_r \end{bmatrix} \text{...........}(A.35)$$

or

$$\begin{bmatrix} V_s \\ V_r \end{bmatrix} = \begin{bmatrix} S \coth \gamma l\, S^{-1} Z_o & -S \operatorname{cosech} \gamma l S^{-1} Z_o \\ S \operatorname{cosech} \gamma l\, S^{-1} Z_o & -S \coth \gamma l S^{-1} Z_o \end{bmatrix} \begin{bmatrix} I_s \\ I_r \end{bmatrix} \text{.......}(A.36)$$

Sometimes equations A.35 is required in terms of modal voltages and currents. Using equations A.30 and A.35 yield the required relation as:

$$\begin{bmatrix} I_s^c \\ I_r^c \end{bmatrix} = \begin{bmatrix} Y^c . \coth \gamma l & -Y^c \operatorname{cosech} \gamma l \\ Y^c \operatorname{cosech} \gamma l & -Y^c \coth \gamma l \end{bmatrix} \begin{bmatrix} V_s^c \\ V_r^c \end{bmatrix} \text{.........}(A.37)$$

Usually it is more adequate to write the transmission network equations so that end quantities are related to receiving end quantities by a two port transfer matrix. This can be achieved by using equations A.30, A.31 and A.33:

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} S \cosh \gamma l S^{-1} & S \sinh \gamma l S^{-1} Z_o \\ Y_o S \sinh \gamma l S^{-1} & Y_o S \sinh \gamma l S^{-1} Z_o \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \text{.......}(A.38)$$

It can be seen that equation A.38 gives the transmission network equations in terms of the well known "A B C D" constant matrix.

Where:

$$A = \cosh(\psi_1)$$
$$B = \sinh(\psi_1)Z_o$$
$$C = Y_o \sinh(\psi_1)$$
$$D = Y_o \cosh(\psi_1)Z_o$$
$$\cosh(\psi_1) = S\cosh(\gamma l)S^{-1}$$
$$\sinh(\psi_1) = S\sinh(\gamma l)S^{-1}$$

For a single-circuit, 2-conductor line the dimension of any of the matrices is given equation A.38 is (3x3). In modal form, equation A.38 becomes:

$$\begin{bmatrix} V_s^c \\ I_s^c \end{bmatrix} = \begin{bmatrix} \cosh\gamma l & -Z^c \sinh\gamma l \\ Y^c \sinh\gamma l & -\cosh\gamma l \end{bmatrix} \begin{bmatrix} V_r^c \\ I_r^c \end{bmatrix} \text{..........}(A.39)$$

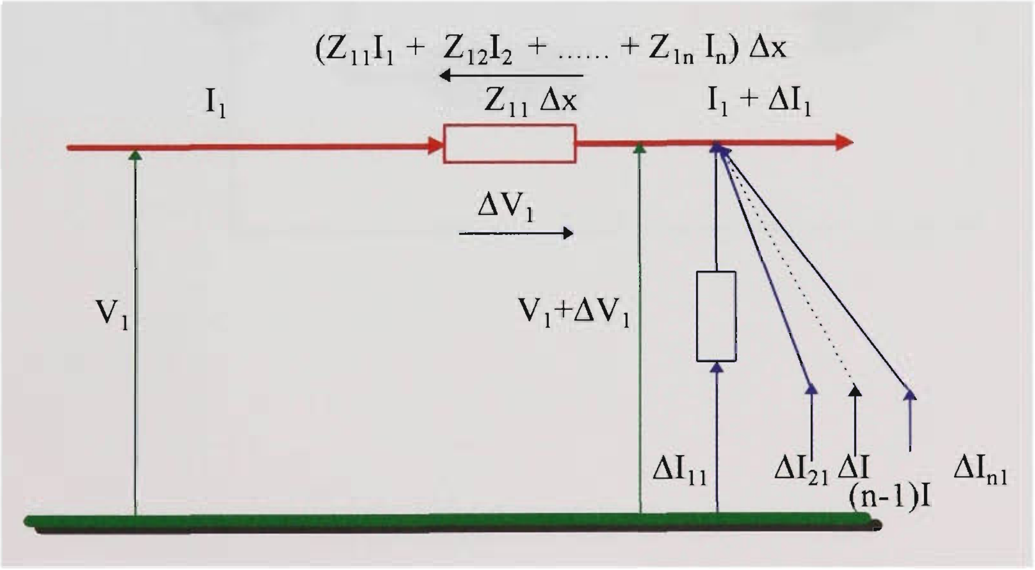
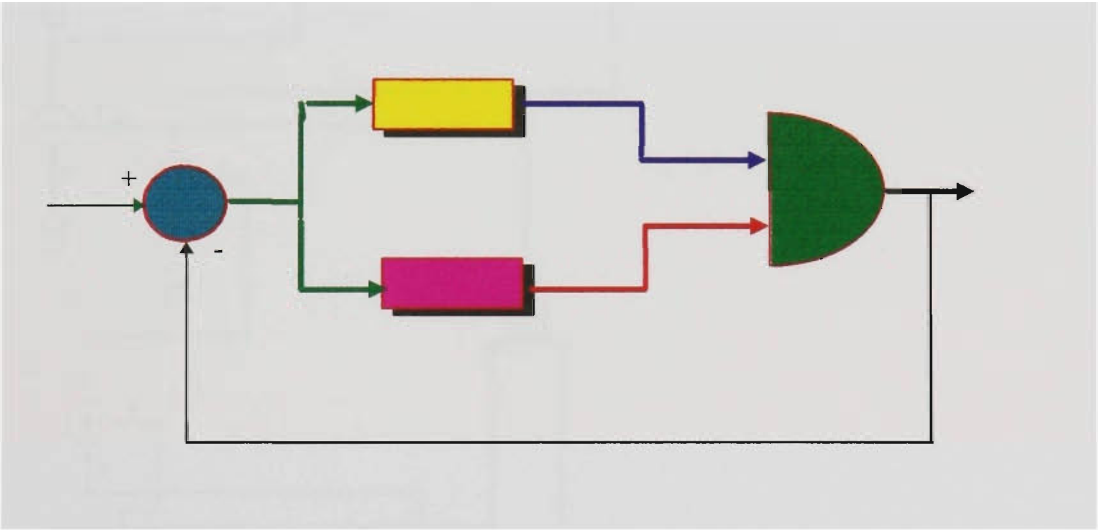


Figure A.1: Shunt and Series Couplings between the conductors of an n-conductors system

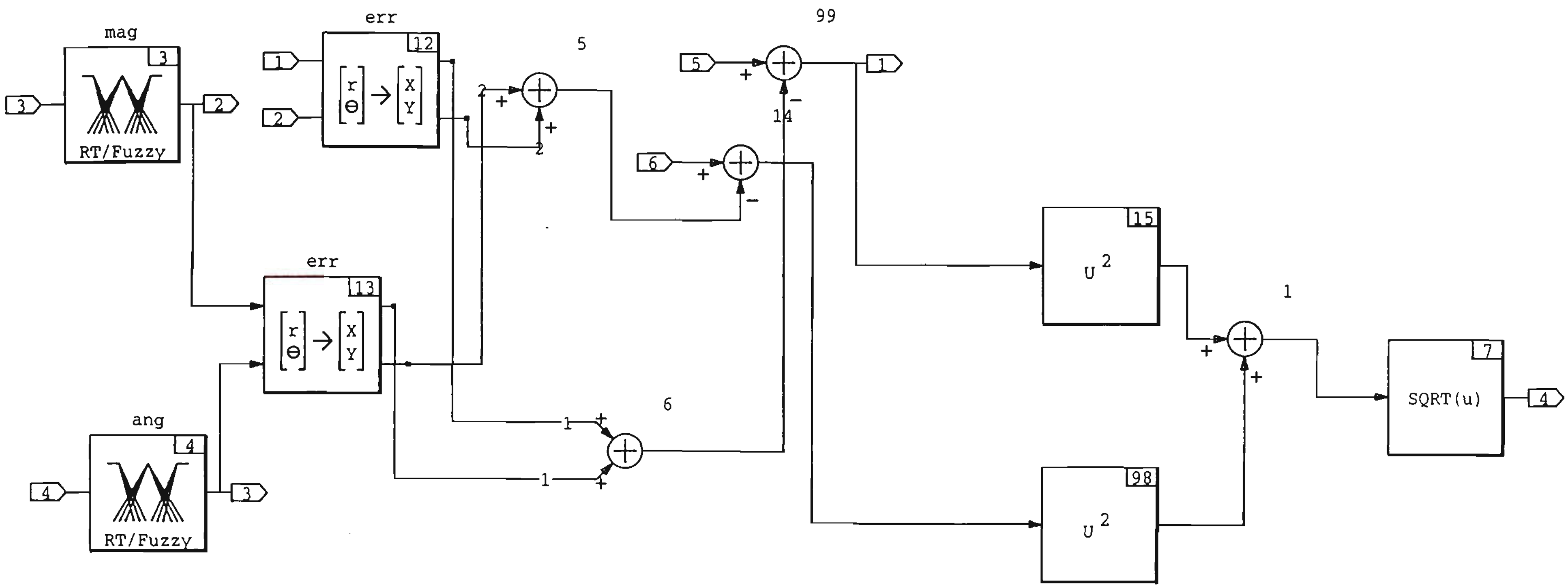
APPENDIX B

SIMULATION DETAILS

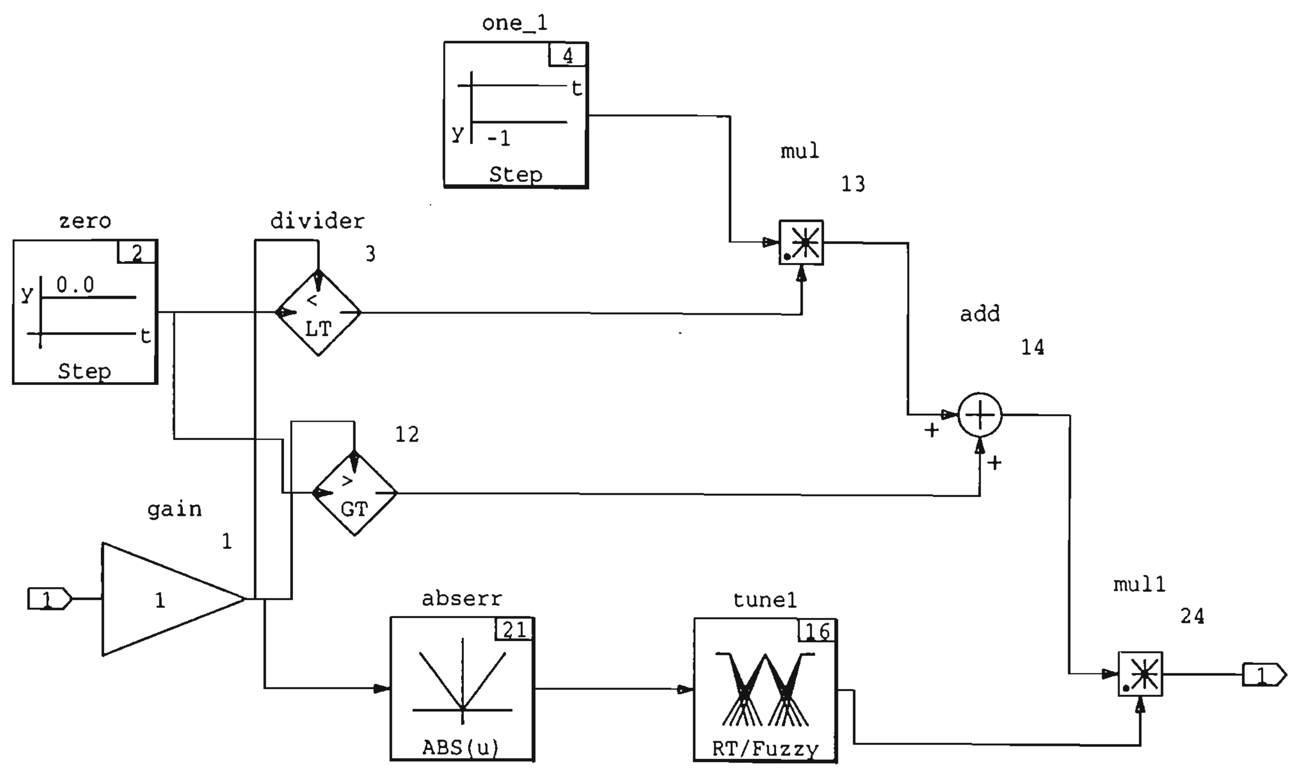


29-DEC-94

Discrete SuperBlock	Sampling Interval	First Sample	Ext.Inputs	Ext.Outputs	Enable
cc	1.	0.	6	5	Parent

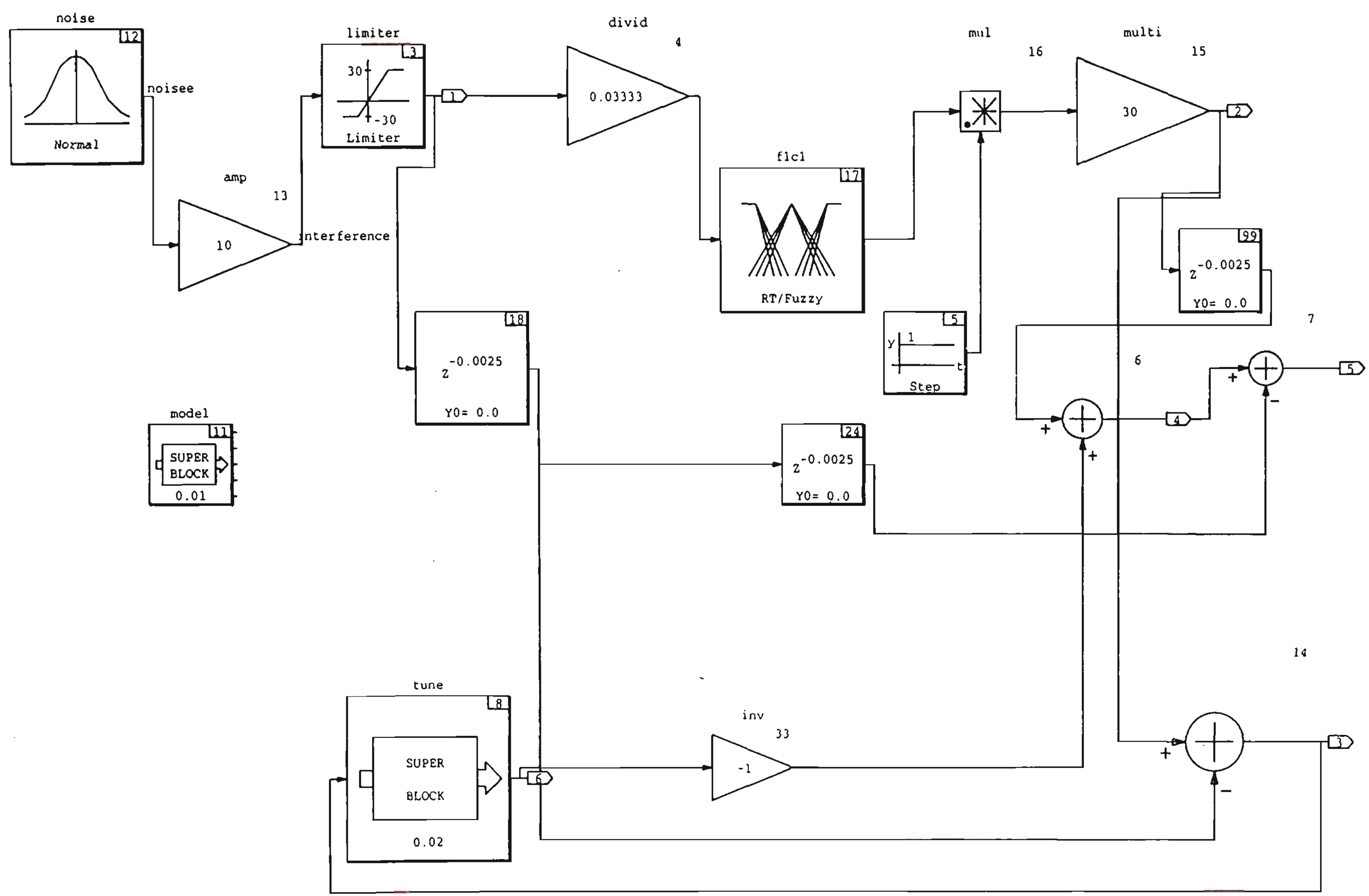


Discrete SuperBlock	Sampling Interval	First Sample	Ext.Inputs	Ext.Outputs	Enable
tune	0.0200	0.	1	1	Parent



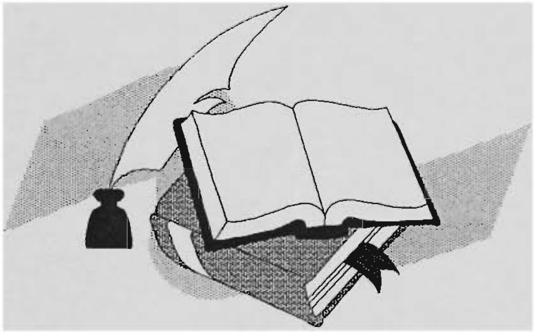
16-NOV-94

Discrete SuperBlock	Sampling Interval	First Sample	Ext.Inputs	Ext.Outputs	Enable
plc4	0.0200	0.	0	6	Parent



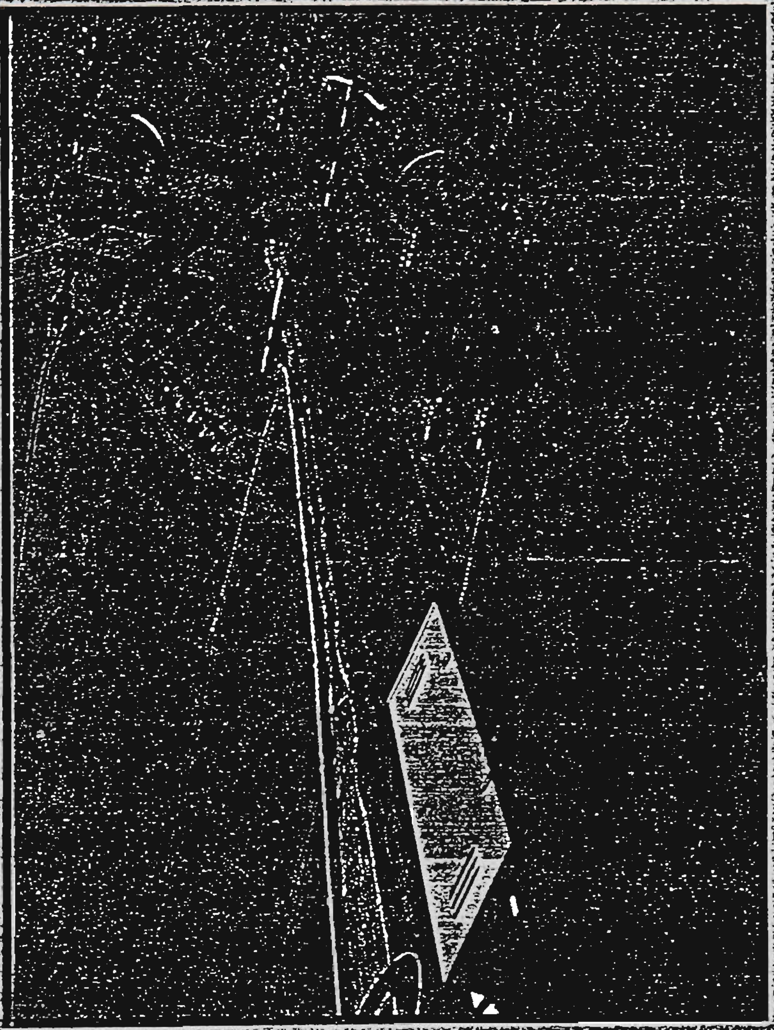
APPENDIX C

PUBLISHED WORK



AUPCEC 92

Australasia Universities Power and Control Engineering Conference



1-2 OCTOBER 1992

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CONFERENCE PROCEEDINGS

FAULT TRANSIENT SIMULATION OF EHV TRANSMISSION SYSTEMS

Iqbal Gondal Akhtar Kalam

Department of Electrical & Electronics Engineering
Victoria University of Technology
Ballarat Road, PO Box 64
Footscray
Victoria 3011

ABSTRACT The increased growth of power systems in both size and complexity imposes a requirement for ultralow overall fault-clearance times, and for this reason, much interest currently centres, in particular, on very high speed distance protection gear. Whilst dealing with very fast protection schemes, measurements must be made during a very short period of time, after fault inception. This paper is concerned in simulating the response of two different types of feeders (ie flat and teed type), using the ATP4 (PC based version of the well known EMTP program). Also various factors which can influence the fault-transient waveforms has been considered viz

source parameters
pre fault load
fault position
types of fault
fault instant

This paper concludes with a presentation of the results of studies associated with a long distance transmission system.

1. INTRODUCTION

The successful development of high-voltage transmission line protection schemes increasingly depends on more realistic and detailed simulations of the power systems under both steady state and fault conditions. Consequently, the power system modal analysis must be able to simulate the complex waveforms. The transients and travelling wave phenomena appear as unwanted noise superimposed on the sinusoidal primary system waveforms and may cause either an increase in the operating time or mal-operation of the distance relay.

Due to enormous growth of electrical power systems in both size and complexity, much effort has been made to enable an accurate simulation of power system design. The developments in system protection schemes has been retarded due to the insufficient knowledge of the precise waveforms.

The response of a transmission system following any sudden change in operating conditions such as fault initiation or switch operation may generally be classified as follows[1,5]:

1. an initial surge-period in which travelling wave effects predominate

2. a final steady-state period during which system voltages and currents are periodic

3. a dynamic or temporary period - a transient period linking stages 1 and 2.

On modern ehv systems, control of surge-period overvoltages allows relatively low insulation levels to be adopted. It is therefore important to predict the temporary period overvoltages so that the probability of insulation failure can be maintained at an acceptable low value. This is usually done through the study of transient phenomena using a realistic model for a typical power system where high level simulation is to be adopted.

Analogue models of actual systems called "simulators" or "Transient Network Analysers" (TNAs), usually consists of scaled down analogue models in which transmission lines are represented by a large number of lumped π-parameters and T section [2,3]. But the TNA is not convenient to simulate the distributed nature of line parameters [2,3].

Another method is based on the well known lattice-diagram technique described by Bewley [7] and was used in much of earlier work [8] for computer simulation of travelling waves in power systems. Again, this method is based on the assumption of lossless or distorsionless propagation.

For transmission systems involving the earth, however, line resistance and inductance vary significantly with frequency, in such cases Fourier Transform (FT) techniques can be effectively utilised. Fundamentally, the method requires the calculation of system response to be performed over a wide range of frequency and inverse Fourier Transform is used to obtained the response in the time domain. The theory of natural modes in relation to the multi-conductor powerline was highlighted by Wedephol [9].

Accurately simulating power system transients can serve two main purposes:

1: examines the effect of primary system waveforms on protective relays and the possibility of improving them if they prove inadequate

2. predicts system overvoltages according to which economical insulation levels are determined.

2. BASIC RELATIONSHIPS

When studying faults on high voltage transmission lines a whole spectrum of frequencies exist superimposed upon the transmission line. Consequently the assumption that the series and shunt parameters of the transmission line can be calculated separately is not valid, because, for the higher frequency components, the line length can approach and even exceed quarter wavelengths. As a result it is no longer possible to separate shunt and series parameters, the problem must be solved in terms of wave propagation.

2.1 Modal Analysis

The mathematical technique used to study the travelling waves was MODAL analysis, which was the theory of natural modes developed by Wedepohl [9].

Any multiconductor line section is defined by its series impedance matrix per unit length Z and corresponding shunt admittance Y. Each element of Z varies with frequency and is determined by the line conductor types, their physical geometry and the nature of the earth plane[6].

The modes of propagation for a multi-conductor system are calculated from the system parameters using the solution to the wave equation. This involves the solution of two second order differential equations as given in equations 1 and 2.

$$\frac{d^2V}{dx^2} = [Z][Y]V = [P]V \qquad (1)$$

$$\frac{d^2I}{dx^2} = [Y][Z]I = [P]^T I \qquad (2)$$

The solution of the two differential equations is difficult. This is done using the theory of natural modes and matrix function theory as developed by Wedephol [12] and commonly used in the digital simulation of faulted ehv transmission systems [4]. Briefly, the method involves finding the matrix of eigenvectors of the [Z] [Y] product ([Q] say) and the [Y] [Z] product ([S] say). In this way, the voltages and currents derived from each phase would be transformed to corresponding modal voltage quantities by means of the corresponding [Q] and [S] eigenvectors matrices [4].

Using linear transformations we can obtain the solution as shown in equation 3.

$$V = V_i e^{-\psi x} + V_r e^{\psi x} \qquad (3)$$

Where $\psi = Q\gamma Q^{-1}$, Q and γ are the voltage eigenvectors and propagation constants matrix respectively. V_i and V_r are incident and reflected voltages. [A B C D] parameters can be evaluated for the transmission line of length l.

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \qquad (4)$$

where

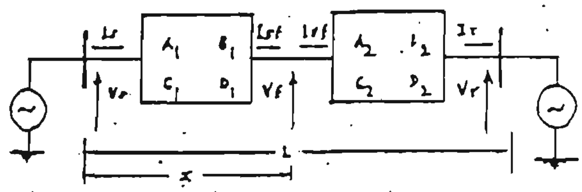
$A = \cosh(\psi\ l)$, $\qquad B = \sinh(\psi\ l)Z_0$

$C = Y_0 B Y_0$ $\qquad D = Y_0 A Z_0$

Where Z_0 and Y_0 are characteristics impedance and admittance respectively of the system.

2.2 Steady State Analysis

A faulted transmission system of line length l is given in Fig. 1 The transfer matrix function representing the untransposed line section up to the point of fault is given in equation 5.



Steady State Fault Model

Figure 1

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} V_f \\ I_{sf} \end{bmatrix} \qquad (5)$$

Where $A_1 = \cosh(\psi l)$

$B_1 = \sinh(\psi\ l)\ Z_o$

$C_1 = Y_o\ B\ Y_o$

$D_1 = Y_o\ A\ Z_o$

and $[A_2\ B_2\ C_2\ D_2]$ is found by substituting l by (x - l). It is possible to derive matrix equations for the steady state voltage at the point of fault V_{fs} and steady state currents at the terminating busbars I_s and I_r.

$$V_{fs} = (A_{r2} - B_2 B^{-1} A)\ V_{rs} + B_2 B^{-1} V_{ss} \qquad (6)$$

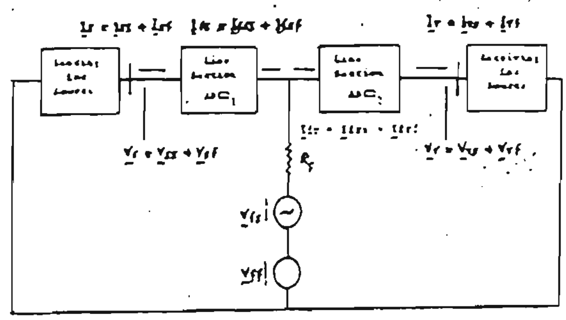
$$I_s = (C - D\,B^{-1} A)\ V_{rs} + D\,B^{-1} V_{ss} \qquad (7)$$

$$I_r = B^{-1} (V_{ss} - A\ V_{rs}) \qquad (8)$$

2.4 Transient Analysis

However, during fault conditions a wide spectrum of frequencies exist superimposed upon the overhead transmission line. As a result, the transient analysis cannot be done simply at the nominal system frequency, but must be done in the frequency domain using several discrete samples of complex frequency [10].

The transient analysis is completed in the frequency domain with each of the matrices in Fig. 2 being calculated for each samples of complex frequency. This relies on its ability to calculate the Z and Y matrices at various frequency samples. The transient response of the transmission line to fault inception is obtained by calculating the response of the de-energised circuit to the injected fault point voltage.



Superimposed Fault Transient Model

Figure 2

Hence it is possible to describe the matrix relationship between the sending end and the fault point using two phase polyphase relationship of equations 9-11.

$$V_{sf} = [-Z_{ss}]\ I_{sf} - E_{sf} \qquad (9)$$

$$V_{ff} = E_{ff} + R_f\ [I_{fsf} - I_{frf}]$$

$$= E_{ff} + R_f\, I_{ff} \qquad (10)$$

and

$$\begin{bmatrix} V_{sf} \\ I_{sf} \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} V_{ff} \\ I_{fsf} \end{bmatrix} \qquad (11)$$

Using these basic relationship it is possible to formulate a set of simultaneous equations relating each of the hypothetical current vectors (I_{sf}, I_{rf}, I_{ff}) to the three associate voltage vectors as given in equation 12.

$$\begin{bmatrix} I_{ff} \\ I_{sf} \\ I_{rf} \end{bmatrix} = \begin{bmatrix} Y_A & Y_B & Y_C \\ Y_D & Y_E & Y_F \\ Y_G & Y_H & Y_K \end{bmatrix} \begin{bmatrix} E_{ff} \\ E_{sf} \\ E_{rf} \end{bmatrix} \qquad (12)$$

Thus the total time domain response of say the sending relaying point (a) phase voltage at this stage would be

$$V_{sfa}(t) = V_{ssa}(t) + V_{sfa}(t-T_f)$$

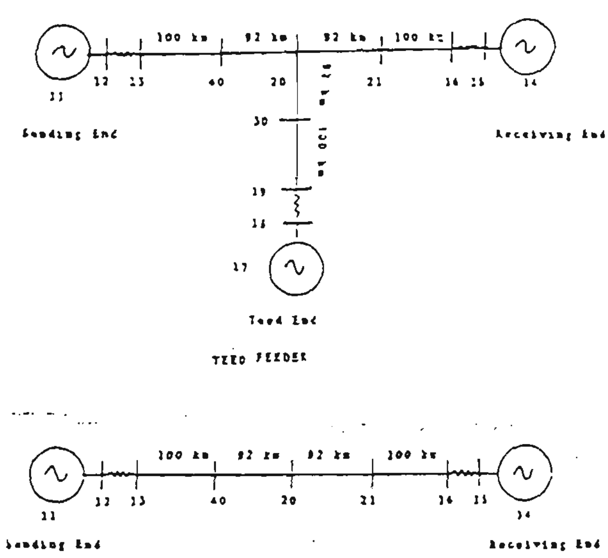
Where t = zero to observation time
and T_f = fault inception time

3. TRANSIENT FAULT STUDIES

3.1 Circuit Studied

A typical 500 kV horizontally constructed line have been considered for both the flat and teed feeder cases. Voltages and currents are measured at the ends of the systems before and after the fault inception. The line lengths are divided into different distances among busbars as shown in the Fig. 3. The data for these lines are

line length is 384 kM.
teed section length is 192 km
source ratings are 35 & 3.5 GVA.
power frequency 50 Hz.

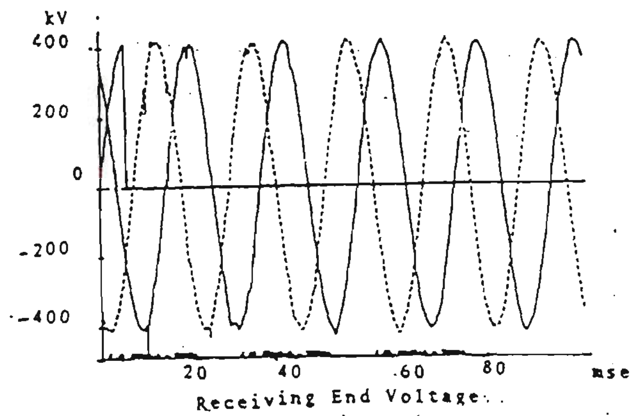


Simple source models of flat and teed feeders

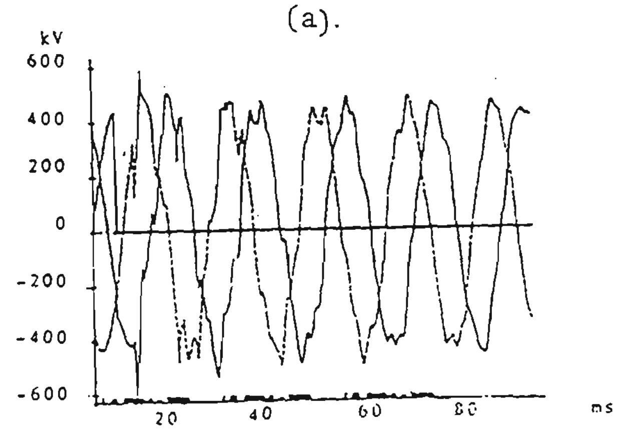
Figure 3

3.2 Effect of source parameters

The source parameters, particularly their capacities, significantly affect the fault transient waveforms. Low source capacity at the observation point significantly increases the distortion of the waveforms, particularly the voltages. In other words, a low source capacity (high source impedance) near the observation point forms a major point of electrical discontinuity from which high frequency components are easily reflected. Figure 4 shows the comparison of voltages when sources of 35 GVA and 3.5 GVA are used for flat feeder.



(a).



(b)

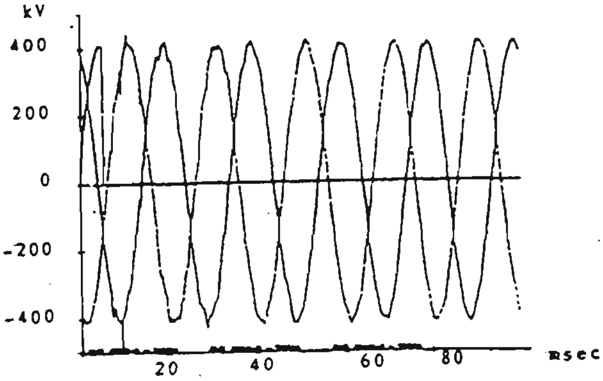
Figure 4 (a) Receiving end 35 GVA (b) Receiving end source is 3.5 GVA.

3.3 Effect of Pre Fault Load

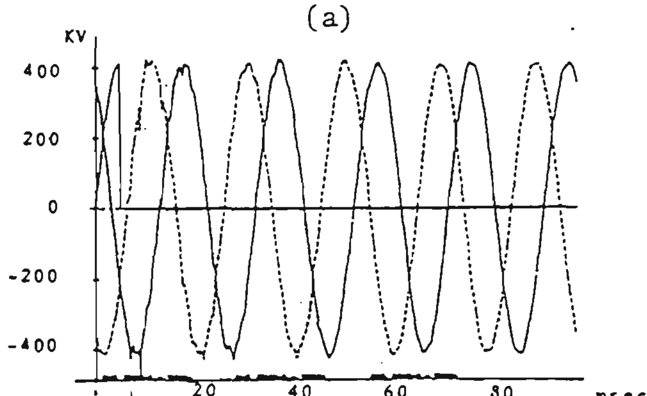
The voltage waveforms are not significantly affected by the prefault loading. Figure 5 shows the comparison between prefault loading and no loading for a-e fault at teed end on the teed feeder. The reason for this is that the prefault voltage at any point on the line is almost independent of the circuit loading.

3.4 Effect of Fault Position

The transient delay time for the travelling waveforms between the fault and the source discontinuities varies as the fault position varies. As the fault position advances along the line away from the observation point, travelling -wave phenomena becomes more prominent and this can be seen by comparing the waveforms of Fig. 6 where in the first case fault is at sending end while in the second case fault is in the middle of system for flat feeder.



(a)

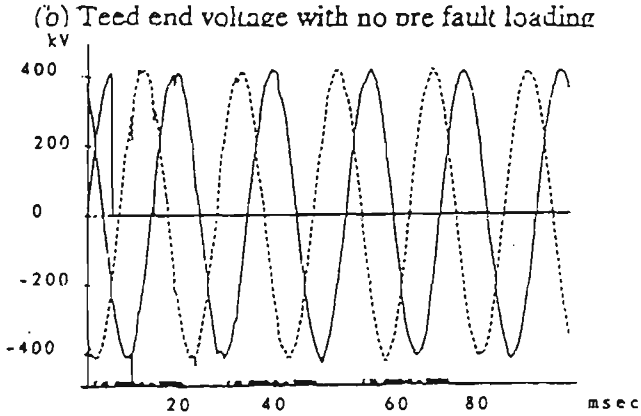


(b)

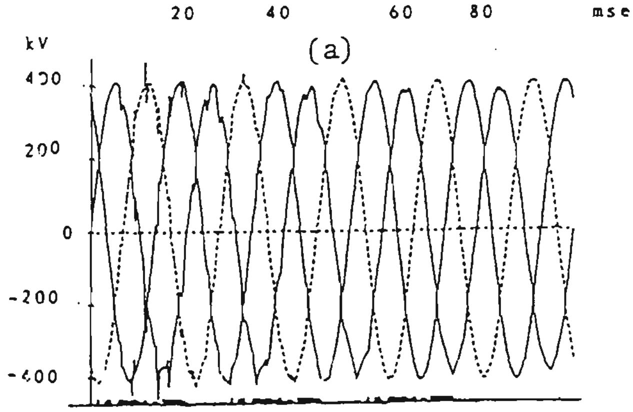
Figure 5 Effect of Pre Fault Loading

(a) Teed end voltage with pre fault loading

(b) Teed end voltage with no pre fault loading



(a)



(b)

Figure 6 Effect of fault position

(a) Fault (a-e) at the sending end.

(b) Fault (a-e) in the middle of the system.

3.5 Effect of Type of Fault

Faults not involving the earth give rise to the waveforms which are generally very distorted, due to the domination of aerial mode . Figure 7 shows phase-phase fault in the middle of the system, and comparing this waveform with the waveforms of Fig 6 it is clear that the travelling waves persist for considerably longer in phase-phase fault case.

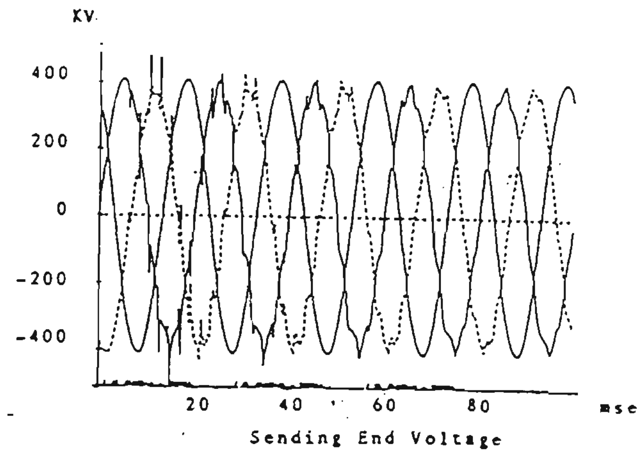


Figure 7 Effect of Type of Fault.

(a-b) fault at flat feeder.

3.6 Effect of Fault Instant

Faults at an instant of corresponding to the peak voltage of the faulted phase produces maximum travelling wave distortion Figure (4-7). Faults at an instance of time corresponding to zero voltage at faulted phase produces maximum offset of waveforms in particularly in the currents. In such cases, travelling wave distortion is significantly reduced because there is not that large of sudden voltage change at the point of fault. Figure 8 shows (ab-e) fault at teed end at zero instant of time.

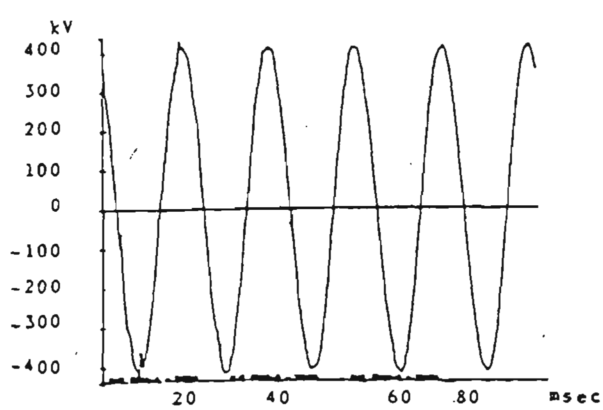


Figure 8 Effect of fault instant

4 CONCLUSIONS

The analysis of power systems implies the computation of network voltages and currents under given set of conditions. In many cases the computation is organised to give a particular kind of information for special purpose ie to determine the current flowing through ground to neutral in a particular situation to facilitate the setting of a relay.

The objective of this work was to accurately simulate faulted overhead transmission lines (flat and teed feeders). The system voltage was taken 500 kV.

It is seen that low source capacity at the observation point significantly increases the distorsion of the waveforms, particularly the voltage. The comparsion of two different sources (35 GVA and 3.5 GVA) is provided in the studies.

One very important point emerges is that the sound -phase voltage can contain very significant travelling wave components. Faults which occur near voltages zero in the faulted phase do not cause a sudden change in voltage levels, and travelling waves are therefore much less pronounced.

In order to provide proper protective systems, one must be able to identify the nature and morphology of the faults on the systems. These simulation studies provide the transient and steady state behaviour of the systems, basing on which proper protective systems can be designed.

The transient and steady state behaviour of power line carrier communication systems can be simulated using this alogrithm. The next part of the project is to simulate digital power line carrier communication systems, and finially efforts will be made to improve the quality of the power line signal.

5 BIBLIOGRAPHY

1. GERT, R.
'Temporary overvoltages. Their classification, magnitude, during shape and frequency of occurance.'
CLGRE Report 33-12, 1972.

2. CARROLL, D.P.
'Computer simulation of electrical transients in power systems.'
Proc. of the 1973 IEE international symposium on circuit theory.

3. BICKFORD, J.P. AND DOEPEL, P.S.
'Calculation of switching transients with particular reference to line energisation.'
Proc. IEE, Vol. 114, No. 4, April 1967.

4. JOHN, A.T. AND AGGARWAL, R.K.
'Digital simulation of faulted ehv transmission lines with particular reference to very-high-speed protection.'
Proc. IEE, 123, (4) pp 353-359, 1976.

5. HAUSPURG, A. et al.
'Overvoltages on the AEP 765 kV-systems.'
IEEE Trans. on power apparatus and systems.
Vol. Pas -88, No. 9, September 1969.

6. GALLOWAY, R.H., SHORROCKS, W.B., AND WEEPOHL, L.M.
'Calculation of electrical parameters for short and long polyphase transmission lines.'
Proc. IEE, 1964, 111, (12), pp. 2051-2059

7. BEWLEY, L.V.
'Travelling waves on transmission systems.'
New York : Wiley, 1951.

8. BARTHOLD, L. O. AND CARTER, G.K.
'Digital ,travelling wave solutions.'
AIEE Trans. PAS, December 1961.

9. WEDEPOHL, L.M.
'Application of matrix methods to the solution of travelling-wave phenomena in polyphase systems.'
Proc. IEE, Vol. 116, No. 9, September 1969.

10. KALAM, A.
'A computer method for solving fault-transient phenomena in ehv transmission systems.'
Proc. of International conference on modelling & simulation, Melbourne pp 195-203, 1987.

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SIMULATION OF PHASE TO GROUND COUPLING FOR POWER LINE CARRIER COMMUNICATION SYSTEMS USING MODAL ANALYSIS

A Kalam, I Gondal

SAVE ENERGY RESEARCH GROUP
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
VICTORIA UNIVERSITY OF TECHNOLOGY FOOTSCRAY
P.O. BOX 14428 MMC MELBOURNE
VICTORIA 3000

ABSTRACT. Power line carrier (PLC) is widely used for the communication of RF signals over high voltage lines. Different type of couplings can be used to provide efficient path for carrier band on power lines. In this paper steady state and transient behaviour of a phase to ground coupling will be investigated using MODAL ANALYSIS, this being the most accurate, convenient and widely used technique for the simulation of the transmission lines. Voltages and currents on the transmission line can be represented in their modal values. Also propagation of the PLC signal using central phase to ground coupling will be investigated in terms of modal values. Central phase to ground coupling appears to be most optimum coupling on untransposed lines that its attenuation is lower than that of any other phase to ground coupling. This paper will present the results of propagation of digital and analogue PLC signals on untransposed power line. Simulation will be carried out using the well known ATP4 (Alternative Transient Program).

1. INTRODUCTION

PLC on long ehv transmission lines is of great interest for fault location, telemetry, voice communication, power protection and telemetry. The power lines are very robust and uses large conductors with generous spacing. It also provides reliable and low-attenuation path for carrier-current signals. Normally in PLC the frequencies ranges from 15-500 kHz are utilised.

PLC is known to be more secure than microwave based lines and is as reliable as the transmission lines. Economically, the cost of PLC is reasonable, as transmission line house PLC and also its source of power supply. Under fault inception a transient and steady state phenomenas of electric network can be studied using either transient analysers or general purpose electromagnetic transients programs. In either case, one finds the time response (voltages and currents as function of time) for any interconnection of resistors, inductors, nonlinear elements, switches, sources and transmission lines.

Travelling waves and surge phenomena in power systems are of importance in solving problems relating to PLC communication, protection of short and ehv long lines, fault location, switching of unloaded lines and calculation of recovery voltages on circuit-breakers under fault conditions. Significant advance in the solution of such problems was made by Fallou [1], who with assumption of complete symmetry of conductors applied the concept of symmetrical components to the solution of travelling-wave phenomena. This method is limited it yields average values for surge impedances and propagation coefficients, and this masks important effects produced by asymmetry of conductors.

Formulas for the calculation of the natural modes of PLC on horizontal three phase lines have been developed by Perz [2,5] making use of elementary algebra and matrix eigenvalue analysis which resulted in understanding of high frequency noise produced by corona and propagation of natural modes of PLC signals on ehv transmission lines.

Most widely used coupling recommendations for PLC systems do not prevent modal cancellation [3]. Most useful and communally used coupling in PLC systems are:

- ground to phase coupling
- phase to phase coupling

In this paper a method is introduced to investigate the behaviour of coupling capacitors and line traps under steady state and transient conditions of the power system also results are presented showing behaviour of line traps and coupling capacitors under different types of faults and at different fault locations of the faults on the transmission systems.

2. CALCULATION OF NATURAL MODES OF PLC

The most convenient method presently known for solving propagation problems and transient behaviours of the line traps and coupling capacitors on multiconductor systems, such as power line, is based on the concept of natural modes. This concept is based on rigorous mathematical considerations of linear transformation and matrix algebra. It has a clear physical meaning and its application leads to practical and meaningful solutions. PLC or power (50 Hz) signals on power line can be resolved into three different modes. The natural modes have different propagation constants and propagation velocities. The modes are related to the properties of the system used, in particular the formation of the impedance matrix.

Natural modes can be classified into two main groups:

- ground mode : which the is most attenuated mode
- aerial modes: second aerial mode which is less attenuated than the first aerial mode.

These three modes in the three phases are graphically represented in Figure 1:

Phase 1: the currents flow in the same direction on all three phases and are approximately equal in magnitude. Due to the earth return, attenuation is the highest with this mode;

Phase 2: the currents in the outer phases are equal and opposite. There is no current flowing for this mode in the middle conductor. Attenuation is lesser than mode 1;

Phase 3: the current on the middle phase is roughly twice that in the outer phases and flows in the opposite direction. The attenuation is least with this mode.

Mode 3, referred to as line-to-line mode and it plays a very important role in long distance communication. The natural-mode analysis allows one to determine these factors and to estimate propagation performance of PLC, steady state and transient behaviour of line traps and coupling capacitors on power lines.

	Mode 3	Mode 2	Mode 1
Phase 1	$\xrightarrow{I_1}$	$\xrightarrow{I_2}$	$\xrightarrow{I_3}$
Phase 2	$\xleftarrow{p(I_1)}$		$\xrightarrow{q(I_3)}$
Phase 3	$\xrightarrow{I_1}$	$\xleftarrow{I_2}$	$\xrightarrow{I_3}$

Figure 1

2.1 Transmission Line Geometry

In this paper untransposed ehv transmission line is considered. It is of horizontal configuration [4] with bundle conductor and earth wires as shown in Figure 2a. The data for the line as shown in Figure 2b

line length is 400 km

operating voltage 500kV

power frequency 50 Hz

source ratings at both ends 35 GVA

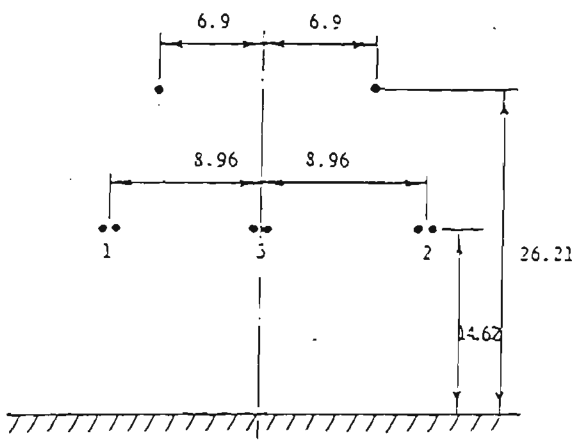

Figure 2a

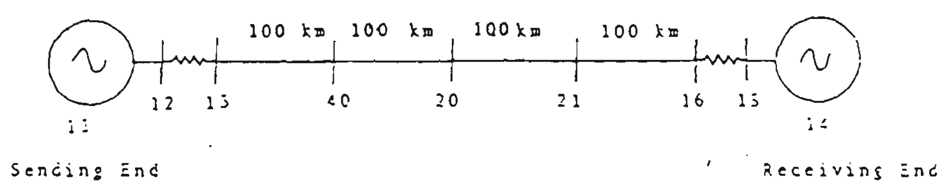

Figure 2b

2.2 Modal Analysis

The mathematical technique used to study travelling wave was MODAL Analysis which was theory of natural modes developed by Wedepohl [5]. The modes of propagation for a multiconductor system are calculated from the system parameters using the solution to the wave equation. This involves the solution of two differential equations as given in equations 1 and 2.

$$\frac{dV}{dx} = -ZI \qquad (1)$$

$$\frac{dI}{dx} = -YV \qquad (2)$$

where V is the phase voltage vector, I the current vector, Z the impedance matrix and Y the admittance matrix. On differentiating equations 1 and 2 second order differential equations involving only either voltage or current is obtained in equations 3 and 4.

$$\frac{d^2 V}{d^2 x} = Z\,Y\,V = P\,V \qquad (3)$$

$$\frac{d^2 I}{d^2 x} = Y\,Z\,I = P^t\,I \qquad (4)$$

Phase voltages and currents can be related to their modal values by linear transformations:

$$V = S\ V^{(c)} \qquad (5)$$

$$I = Q\ I^{(c)} \qquad (6)$$

S and Q are eigenvectors square matrix. On substituting the values of V and I in equations 3 and 4.

$$\frac{d^2 V^{(c)}}{dx^2} = \Gamma^2\ V^{(c)} \qquad (7)$$

$$\frac{d^2 I^{(c)}}{dx^2} = \Gamma'^2\ I^{(c)} \qquad (8)$$

where

$$\Gamma^2 = S^{-1}\,P\,S$$

$$\Gamma'^2 = Q^{-1}\,P^t\,Q$$

S and Q matrix are selected in such way that matrix Γ^2 and Γ'^2 are diagonal matrix. Consider a reflection free with relatively low loss long transmission line connected to a high frequency source impressing voltage V (o). Then modal values of the signal at any distance from sending end at any phase can be defined by equation 9

$$V_k^{(n)}\ (x) = V_k^{(n)}\ (o)\ e^{-\alpha(n)}\ x \qquad (9)$$

Where k = 1, 2, 3 designates phase and (n) = (1), (2), (3) designates the particular set corresponding to "natural modes of propagation".

3. SIMULATION

3.1 Line Traps and Coupling Capacitor

Transient and steady state studies have been made using central phase to ground coupling and broad band line traps on long transmission line. The coupling as shown in Figure 3 is optimum and its attenuation is less than that of any other phase to ground coupling [6]. Coupling preventing modal cancellation and whose supplementary attenuation levels are below 20 bB [7] thus are referred to as "recommended couplings".

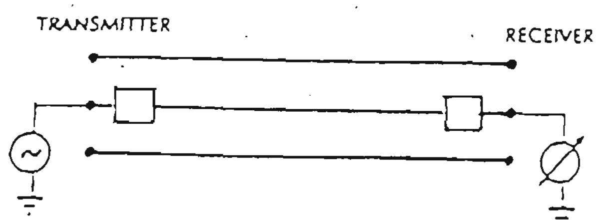

Figure 3

3.2 Steady State Studies

Behaviour of the line traps and central phase to ground coupling capacitors have been investigated using the principle of superposition. Power source at both ends were taken at 50 Hz frequency and high frequency source signal was not applied. Simulation on ATP4 was carried out and Figures 4a,4b,4c & 4d show results at receiving end, sending end, PLC transmitter terminal and PLC receiver terminal.

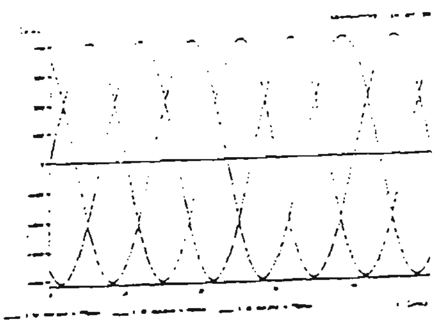

Figure 4a

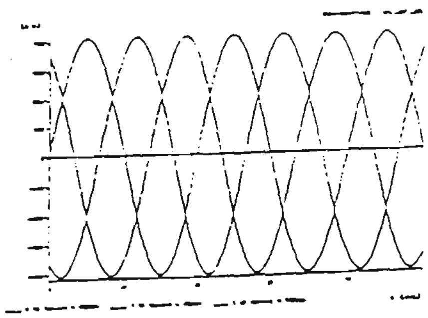

Figure 4b

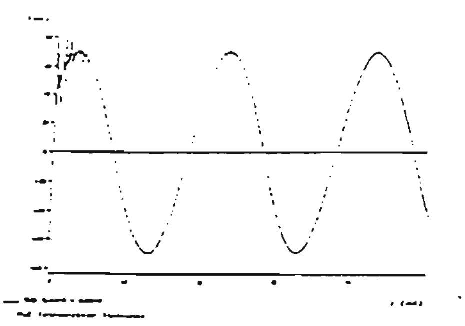

Figure 4c

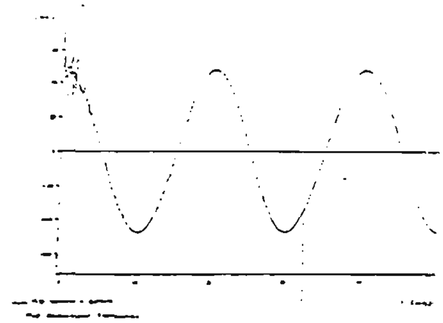

Figure 4d

3.3 Transient Studies

During transient conditions a wide spectrum of frequencies exit superimposed upon the overhead transmission line. As a result, the transient analysis cannot be done simply at the nominal system frequency, but must be in fréquency domain [8] using several discrete samples of complex frequencies. Alternative transient program technique is well developed to describe travelling wave phenomena for the systems. To study transient behaviour of the broad band line traps and central phase to ground coupling different types of faults can be initiated on the system under study at different locations.

3.3.1 Fault Conditions On the System

In faults involving earth, the earth mode dominate the faulted phase(s) whilst the aerial mode(s) dominate the healthy phase(s). As described earlier earth mode attenuates more than the aerial modes. Aerial modes are responsible for PLC propagation on long transmission lines. Healthy phases from Figures 5a,5b,5c,5d show that travelling wave phenomena persists longer due to aerial modes domination as compared to the faulty phase. Fault was initiated at the sending end. Voltages across the drain coil and coupling capacitor show the presence of high frequency transients, line matching unit is always protected upto 2kV voltage surges.

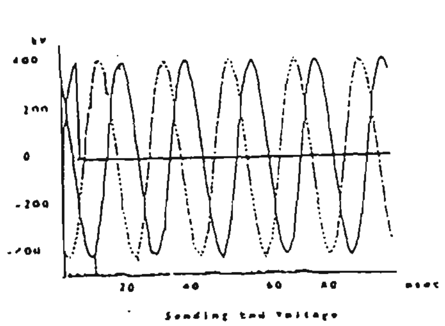

Figure 5a

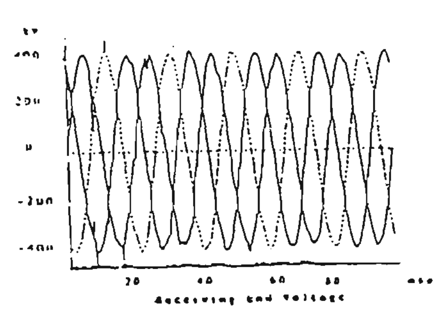

Figure 5b

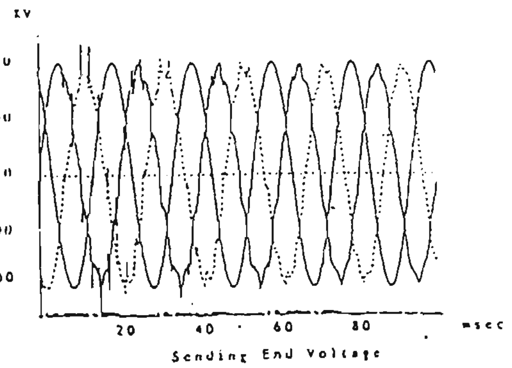

Figure 5c

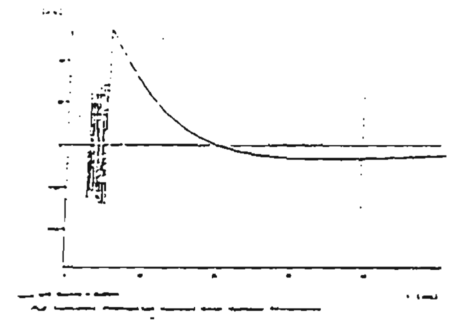

Figure 5d

4 CONCLUSION AND FUTURE WORK

This technique appears to be very useful and accurate to study the steady state and transient behaviour of any circuit working with power systems. Basing on these studies optimum coupling can be adopted to avoid unnecessary attenuation in the PLC signal under the given set of conditions of power system.

The objective of this work was to simulate central phase to ground coupling along with matching unit and broadband line traps under steady state and transient conditions using theory of natural modes. The simulation results shows that coupling capacitor has attenuated the power frequency signal under steady state conditions. Under transient conditions the high frequency transients passed through the coupling capacitors but circuit was protected against high voltage surges through sparking gap of 2 kV threshold. Under fault current conditions line traps showed satisfactory results.

The work is proceeding in assessing the frequency response of PLC system. Interference between different channels of frequencies will be further investigated and adaptive schemes of interference will be used to cancel the interference between the channels. The effect of radiation on the phase to ground coupling will also be investigated.

5 BIBLIOGRAPHY

1. Fallou, J. A.
"Propagation des courant de haunt frequence polyphase le long des lignes aerience de transport d'energie effectees de courts-circuits ou de defauts d'isolement", Bull. Soc. Franc. Elect., 1932, Series 5, 2, p. 787.

2. Perz, M. C.
"Natural modes of power line carrier on horizontal three-phase lines" IEEE Summer Gereral Meeting and Nuclear Radiation Effects Conferrence, Troonto, Ont., Canada, June 16-21 1963, p679 - 685.

3. Jose Luis Naredo V., Arum C. Soudack
"Design of power line carrier systems on multitransposed delta transmission lines", IEEE/PES 1990 Summer Meeting, Minneapolis, Minnesota, July 15 - 19, 1990, IEEE Transaction on Power Delivery, Vol. 6 No. 3, July 1991.

4. Kalam A., Gondal I.
"Fault transient simulation of ehv transmission systems" AUPCEC' 92, 1-2 October 1992, Proc. p. 321-326, QUT, Brisbane, Australia.

5. Wedepohl, L.M.
"Application of matrix method to the solution of travelling-wave phenomena in polyphase systems" Proc. IEE, Vol. 110, No. 12, December 1963.

6.Neredo Jose Luis A.
"Communication frequency response of high voltage power lines". M. A. Sc. Thesis Department of Electrical Engineering, The University of British Columbia, April 1987.

7. Senn W.H., Morf K.P.
Optimum power line carrier coupling arrangement on transposed single circuit power line", CIGRE, 1974, 328.

8. Kalam, A.
" A computer method for solving fault transient phenomena in ehv transmission systems".
Proc. of International Conference on Modelling and Simulation, Melbourne pp 195-203, 1987.

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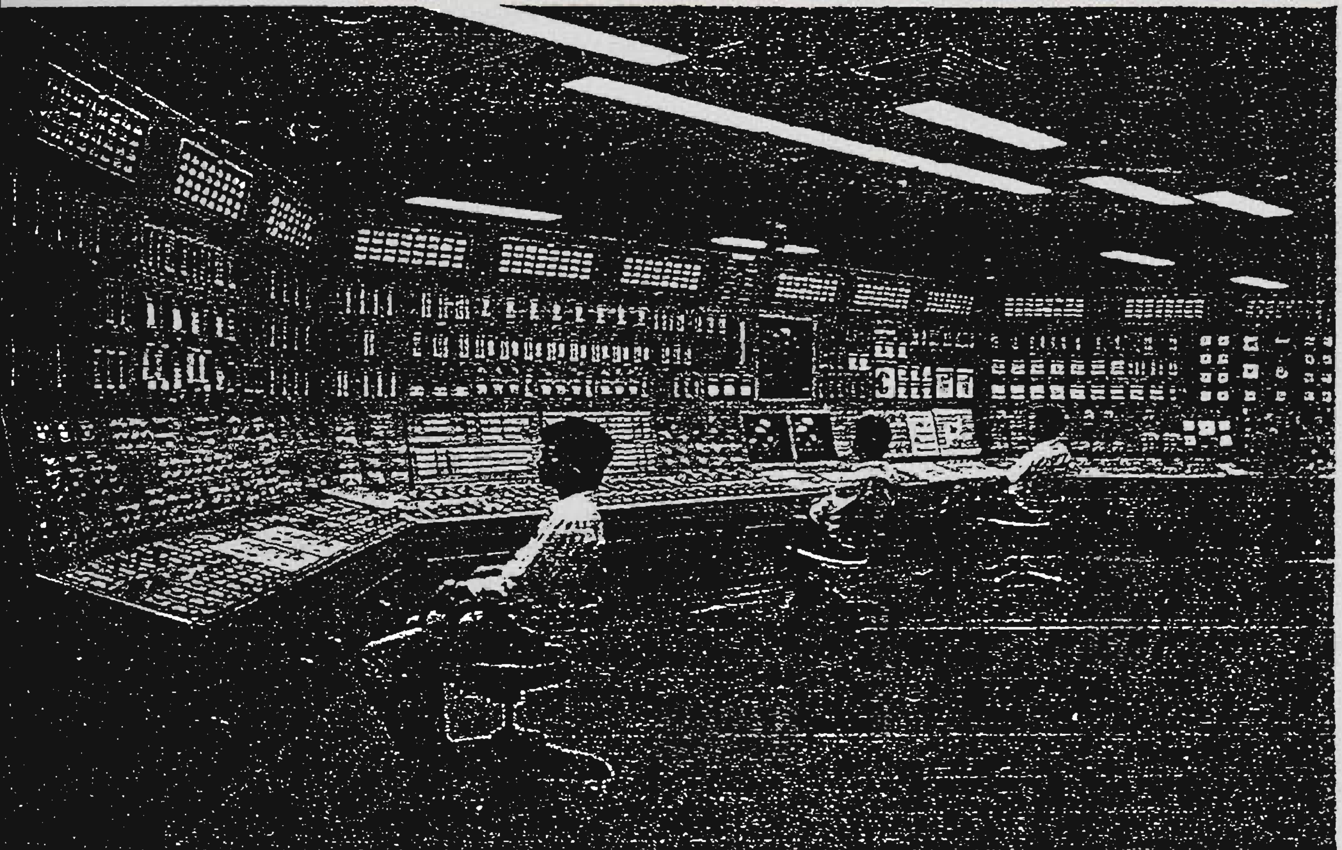


Editors
J. NANDA • M. L. KOTHARI

ADAPTIVE INTERFERENCE CANCELLATION FOR DATA COMMUNICATION ON POWER SYSTEM

I. Gondal, A. Kalam and L. Xia

Department of Electrical and Electronics Engineering,
Victoria University of Technology,
MMC, Melbourne, VIC.3000
Australia

Transmission lines are very reliable mean of data communication for different applications ie system protection, telemetry, voice communication and LAN etc. The integrity of the data transmission is always of great concern and the transmission of corrupted data may result in falsified control operation of the power system. Factors like corona, switching operations and transient faults etc. are major sources of interference for data communication on the power lines. Inefficiency of the line traps causes interference with the power line carrier (PLC) signal from the adjacent line sections. To avoid the inter talk among channels, it is necessary to avoid the use of the same frequencies on adjacent line sections. This ultimately limits the available spectrum of frequencies for PLC applications. Recursive least square (RLS) method appears to be a very useful tool for adaptive interference cancellation. Interferences are caused due to the signal leakages through line traps to the busbars.

The simulation of the system will be carried out using the well-known packages Alternative Transient Program (ATP6) and MATLAB The results will show the steady state and transient studies of the PLC equipments using ATP6 and the application of the RLS method for adaptive interference cancellation using MATLAB.

1. INTRODUCTION

The security of data transmission on power lines for protection, telemetry and supervisory control etc. is matter of great concern for power system authorities. Transmission of falsified data may result in incorrect operation of power system operation, which may lead to fatal consequences. Typical situations in power system operations may occur due to mal-functioning of relay operation, circuit breakers and supervisory control etc., which may lead to economical and human losses. In power system practices, operation of the protection relays and circuit breakers depend on fault conditions of the power systems. For reliable system design and operation, these operations should be as minimum as possible to maintain steady state supply of power to the consumers. Under fault conditions, communication of any measurement data should be communicated reliably for accurate operation of the required relays and circuit breakers. Different mean of communications eg PLC, optical fibre communication, microwave and telecommunication lines are used as back up under various operating conditions for reliable transmission of the data.

In existing and new power systems, mix use of optical fibre communication and PLC techniques can be the best solution for reliable means of communication [1]. In spite of superior performance of optical digital communication links with respect to immunity to the interference and transmission capacity and desirable objective of a fully digital system, economical constraints as well as technical considerations will result in the continued application of the established PLC technology for particular applications. The robust PLC equipment exhibits distinct technical and economical advantages, where low to medium quantities of data have to be communicated over large distances.

In term of theory of natural modes, the propagation of PLC signal for longer distances on the transmission lines is possible due to the domination of the aerial modes[2]. The presence of aerial modes and earth mode have dominant effect on the travelling wave phenomena in transient conditions [3]. ATP6 is a very useful tool for the studies of travelling phenomena for PLC applications [4]. To overcome some of the constraints imposed by ATP6, MATLAB with its flexible tools eg control, signal processing, mathematical, neural network, fuzzy control and simulink etc. is a good tool for the simulation of the applications and control of the power system.

Due to the presence of different interference sources eg corona, lightning, switching operations and inefficiency of the line traps etc., on the power systems for PLC applications, it is impossible to use the available spectrum of frequencies efficiently. The effect of some of these sources of interferences can be reduced with proper planning of the power system design eg corona, lightning, switching operations etc., the interference due the line traps can be reduced using adaptive interference cancellation techniques. In this paper, RLS method has been tested to provide the required level of attenuation to the PLC signal, so that the same spectrum of frequencies can be used on the adjacent line sections. Also transmission line has been represented by its characteristics impedance for interference cancellation.

2. PLC MODEL

This paper focus on the PLC model based on the representation of the transmission line in its characteristics impedance for interference cancellation. The signal at remote ends have been coupled using single phase to ground coupling. Also at both sending and receiving ends, PLC signal and PLC leakage signal have been provided as inputs to the RLS method through coupling capacitors. Figure 1 outlines the PLC model. At the remote ends, transmission line is grounded through appropriate loads to get the required level of attenuation by line traps. The parameters of PLC equipment are calculated on the PLC signal frequency, then attenuation due to these calculated parameters is estimated. The PLC signal V_g is represented by the sinusoidal signal. V_s and V_r are the PLC signals at the sending and receiving end of the transmission line respectively. V_s is obtained after attenuation of the coupling capacitors.

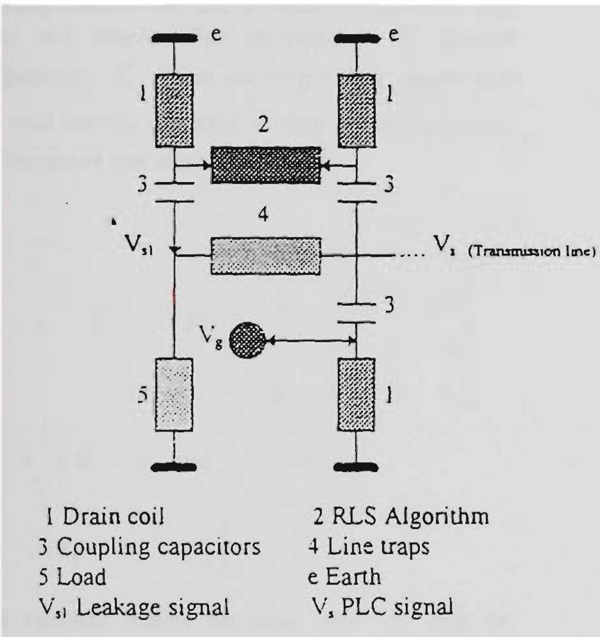


Figure 1: PLC Model for Simulation

2.1 Modal Analysis

The mathematical technique used to study travelling wave utilises MODAL Analysis which was theory of natural modes developed by Wedepohl [5]. The modes of propagation for a multiconductor system are calculated from the system parameters using the solution to the wave equation. This involves the solution of two differential equations as given in equations 1 and 2.

$$\frac{dV}{dx} = -ZI \qquad (1)$$

$$\frac{dI}{dx} = -YV \qquad (2)$$

where V is the phase voltage vector, I the current vector, Z the impedance matrix and Y the admittance matrix. On differentiating equations 1 and 2, second order differential equations involving only either voltage or current is obtained as shown in equations 3 and 4.

$$\frac{d^2 V}{d^2 x} = ZYV = PV \qquad (3)$$

$$\frac{d^2 I}{d^2 x} = YZI = P^t I \qquad (4)$$

Phase voltages and currents can be related to their modal values by linear transformations:

$$V = S\, V^{(c)} \qquad (5)$$

$$I = Q\, I^{(c)} \qquad (6)$$

S and Q are eigenvectors square matrix. On substituting the values of V and I in equations 3 and 4.

$$\frac{d^2 V^{(c)}}{dx^2} = \gamma^2 V^{(c)} \qquad (7)$$

$$\frac{d^2 I^{(c)}}{dx^2} = \gamma'^2 I^{(c)} \qquad (8)$$

where

$$\gamma^2 = S^{-1} P S$$

$$\gamma'^2 = Q^{-1} P^t Q$$

S and Q matrix are selected in such a way that matrix γ^2 and γ'^2 are diagonal matrix. Consider a reflection free, with relatively low loss long transmission line connected to a high frequency source impressing voltage V(o). Then modal values of the signal at any distance from the sending end at any phase can be defined by equation 9

$$V_k^{(n)}(x) = V_k^{(n)}(o)\, e^{-\alpha(n)} x \qquad (9)$$

where k = 1, 2, 3 designate phases and (n) = (1), (2), (3) designate the particular set corresponding to "natural modes of propagation".

Theory of natural modes has been used to simulate on ATP6 the fault transient behaviour of PLC circuit and to study the modes of the PLC signal. The transmission line length was taken as 400 km with bundle conductors, operating at 500 kV. For the s of adaptive interference cancellation, transmission line epresented by its characteristic impedance of 300 Ω.

RLS Method

general review of adaptive interference canceller and line model of PLC system gives optimum choice of RLS method 8] for interference cancellation. In this particular case, PLC al and interference signal are available on both end of line . RLS method works very efficiently to adapt time varying re of the parameters of the line traps (weighting ficients) and to predict the expected interference being ed by the line traps. Interference is equal to the product of sted weighting coefficients and a vector of previous two e of inputs and outputs. For initialisation θ_k (actual ghting coefficients), X_k (input and output state vector) and (internal state matrix) are taken as zero. θ_k' are estimated ighting coefficients of line traps for kth state.

$$\theta_k = [0 \quad 0 \quad 0 \quad 0] \qquad P_{k-1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$u_1 = 0 \quad u_2 = 0 \quad y_1 = 0 \quad y_2 = 0$$

$$X_k = [y_1 \quad y_2 \quad u_1 \quad u_2]'$$

he projection operator matrix for next state, P_k can be btained from the initial conditions:

$$P_k = P_{k-1} - \frac{P_{k-1} X_{k-1} X_{k-1}' P_{k-1}}{1 + X_{k-1}' P_{k-1} X_k} \tag{10}$$

The results of equation (10) can be used to find the weighting coefficients (parameters) of line traps based on the updated input and output state vector.

$$\theta_k' = \theta_k + P_k X_k (V_{sl} - X_k' \theta_k) \tag{11}$$

Estimated output of line traps can be predicted based on the latest estimate of the parameters:

$$V_{slt} = X_k' \theta_k' \tag{12}$$

Improved estimates of the weighting coefficients and internal state matrix are updated with previous values to find adaptive optimum values to have best possible estimate of signal leakage through the line traps. Updating is done by recursive adaptation as follows:

$$\theta_k = \theta_k' \qquad P_{k-1} = P_k$$

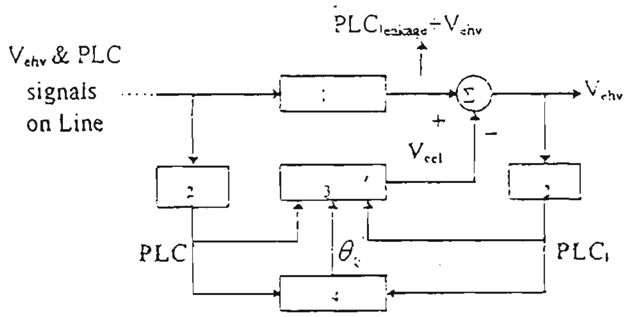
$$y_2 = y_1 \quad u_2 = u_1 \quad y_1 = V_{sl(k)} \quad u_1 = V_{s(k)}$$

These new obtained values of input and output are used to make updated state vector for adaptive learning of the algorithm. To get the adaptive interference cancellation, this estimated output of the line traps is injected with phase difference of 180° to the busbar to get interference cancellation.

$$Error = V_{sl} - V_{slt} \tag{13}$$

V_{sl} is the PLC signal leakage towards the sending end busbar due to the inefficiency of the sending end line traps. The graphical representation of the signals is presented in Section 4. Similarly V_{rl} is the PLC signal leakage towards the receiving end busbar. RLS method uses PLC signal (V_s) and PLC signal leakage (V_{sl}) as input to estimate the time varying parameters of the line traps and then based on these estimate of the parameters, estimated output of the line traps is evaluated which in fact is the PLC signal leakage.

As the knowledge of adaptive learning of the RLS method improves about the parameters of the line traps, the error reduces showing more attenuation in the PLC signal, so that the same frequency can be used on the adjacent line sections. The block diagram of the RLS method for the PLC interference cancellation is given in Figure 2.



(1) Line traps (2) Coupling capacitors
(3) Output estimator (4) Parameter estimator

Figure 2 : RLS Model for PLC System

The mathematical model of the PLC model and RLS method has been used for the simulation using MATLAB and ATP6. The following factors were considered in choosing the RLS method for this particular application:

* Previous knowledge of the two of the signal (PLC and leakage signal) is readily available for the estimation of the parameters of the line trap.

* The consideration of initial conditions from zero, makes the algorithm more attractive for this real time situation, where previous knowledge of the system parameters is not available.

TRANSIENT STUDIES

uring transient conditions a wide spectrum of frequencies exist iperimposed upon the overhead transmission line. As a result, ie transient analysis cannot be done simply at the nominal /stem frequency, but must be in frequency domain [9] using everal discrete samples of complex frequencies. Alternative ansient program technique is well developed to describe avelling wave phenomena for the systems. To study transient ehaviour of the broad band line traps and central phase to round coupling different types of faults can be initiated on the ystem under study at different locations.

3.1 Fault Conditions on the System

Faults involving earth, the earth mode dominate the faulted phase(s) whilst the aerial mode(s) dominate the healthy phase(s) [4]. As described earlier, earth mode attenuates more than the aerial modes. Aerial modes are responsible for PLC propagation on long transmission lines. Healthy phases from Figures 3 and 4 show that travelling wave phenomena persists longer due to aerial modes domination as compared to the faulty phase. Faults (1-phase to ground and phase-phase fault) were initiated at the sending end and in the mid of the system.

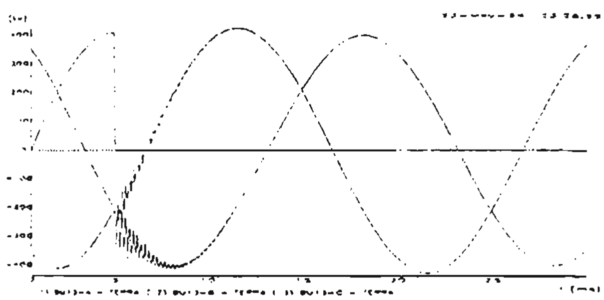


Figure 3: 1-phase to ground fault at the sending end

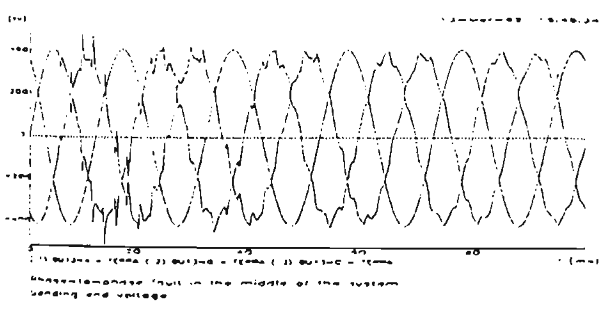


Figure 4: Phase-phase fault in middle of the system

4. SIMULATION OF INTERFERENCE ON THE PLC SYSTEM

Efficiency of the line traps is limited due to the fact that power signal with its rated current has to pass through the line traps without attenuation. The cost and size of the line traps also limit the efficiency of line traps. Due to the limitation of line traps, PLC signal on one line section interfere with the PLC signal having same frequency on the adjacent line section. Figure 5 shows the level of PLC signal and the interferences in terms of leakage signal to the busbar.

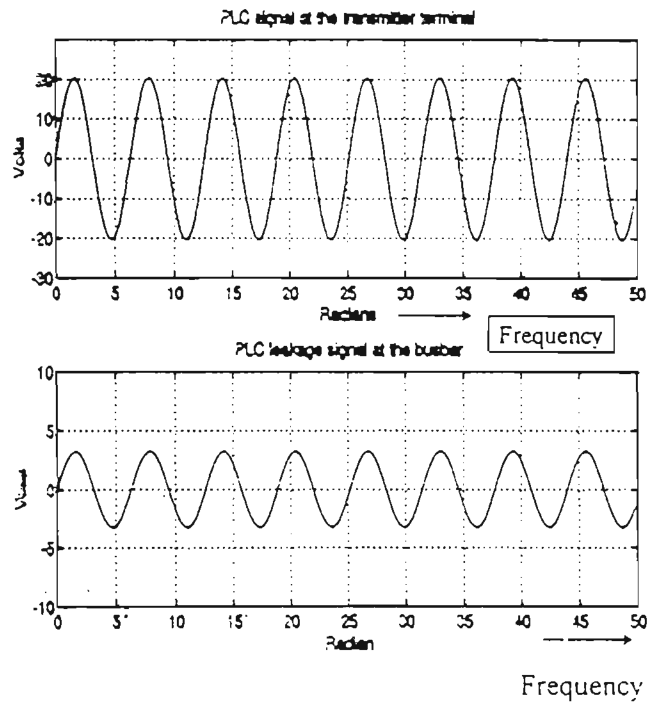


Figure 5: PLC and PLC leakage signals

5. SIMULATION OF RLS METHOD FOR ADAPTIVE INTERFERENCE CANCELLATION

The PLC leakage signal through the line traps to busbar causes reduction in the use of available spectra of PLC frequency. To provide the required level of attenuation on the PLC signal, RLS method was used to assist the line traps. In the simulation, PLC signal was injected on the line and then with the given parameters of line traps, the level of the interference was calculated. PLC signal and the level of interference signal were taken as input to the RLS method in order to predict the magnitude and phase angle of the interferences. The predicted data was injected to the busbar with 180° out of phase, and the error was plotted against frequency (radians). Figure 6 shows the performance of the RLS method.

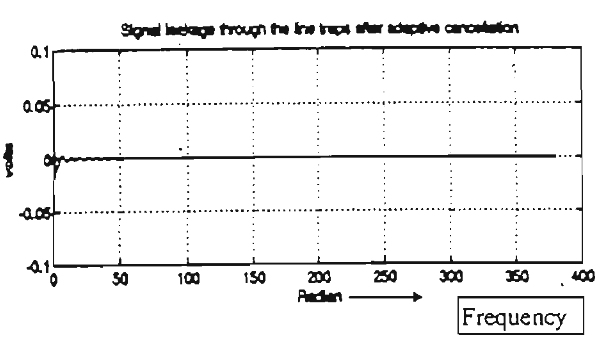


Figure 6: PLC signal after adaptive cancellation

It also shows that the algorithm works satisfactorily within a few cycles. Figures 5 and 6 highlight the importance of RLS method for adaptive interference cancellation on PLC system.

6. CONCLUSION AND FUTURE WORK

The use of MATLAB appears to be a very effective tool in handling any complex problems for the control and management of power system and its associated applications. The built in mathematical, signal processing and control tools etc, makes simulation very simple. The flexibility of the command and easy adaptation for the interfacing with other software makes MATLAB more versatile for the use in power systems applications.

ATP6 appears to be a very good tool for the simulation of transient conditions on the power network. From the transient studies of the network, proper level of protection and insulation can be estimated. Also, when studies were made on PLC network, the presence of different modes have been noted.

The objective of this work was to simulate the interference on the PLC system, and then to simulate the adaptive interference canceller for these interference using MATLAB. The PLC equipment were simulated using realistic parameters. Result shows the effectiveness of the RLS method for this application.

7. BIBLIOGRAPHY

1. Morf K P 'Mixed use of Optical Fibre Communication and PLC Techniques in Telecommunication Networks for Electrical Power Utilities" International Conf on Advances on Power System Control, Operation and Managements, IEE. p 260-264 Hong Kong Nov 1991.

2. Perz M C 'Natural Modes of Power Line Carrier on Horizontal three-phase Lines" Summer General Meeting and Radiation Effects conference, IEEE p 679 - 685 Toronto, June 16-21.

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5. Wedepohl, L M "Application of matrix method to the solution of travelling-wave phenomena in polyphase system" Proc. IEE, Vol. 110, No. 12, December 1963.

6. Feintuch, PL "An adaptive recursive LMS filter."Proc. IEEE, vol. 64, pp.1622-1624, 1976.

7. Fuchs, JJJ "The recursive least-square algorithm revisited." Rep. IRISA Laboratorie Automatique, Rennes, France, 1980b.

8. Holst, J "Adaptive prediction and recursive parameters estimation." Rep. TFRT 1013-1-206. Department of Automatic Control, Lund Institute of Technology, Lund, Sweden, 1977.

9. Kalam, A "A computer method for solving fault transient phenomena in ehv transmission systems". Proc. of International Conference on Modelling and Simulation, Melbourne pp 195-203, 1987.

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APPLICATION OF MATLAB FOR SIMULATION OF POWER LINE CARRIER COMMUNICATION SYSTEMS

I Gondal, A Kalam, L Xia

Save Energy Research Group
Department of Electrical and Electronics Engineering
Victoria University of Technology
P. O. Box. 14428 MMC
Melbourne VIC. 3000
Australia
iqbal@cabsav.vut.edu.au

Power line carrier (PLC) is a very reliable mean of data communication for control, protection and supervision of power systems. Propagation of the RF signal on power lines can be considered in its modal values which propagate at different propagation velocities like power signal. Conventional tools of simulation eg Alternative Transient Program (ATP6) for power systems makes PLC system simulation more complicated due to the unavailability of the tools for the simulation of complex control algorithms. MATLAB package appears to be very flexible tool for simulation of PLC systems and their associated control circuits. Steady state and transient interferences caused due to signal leakage through line traps can be cancelled using recursive least square (RLS) method. Fast learning RLS method is very efficient to cancel the interference even when circuit is in transient state.

This paper contains the simulation results of design of PLC equipments (line traps, coupling capacitor and adaptive interference cancellation schemes). The paper also highlights how adaptive interference cancellation can enhance the use of PLC frequency spectrum.

1. Introduction

The security of data transmission on power lines for protection, telemetry and supervisory control etc. is matter of great concern for power system authorities. Transmission of falsified data may result in incorrect control operation of power system operation, which may lead to fatal consequences. Typical situations in power system operations may occur due to mal-functioning of relay operation, circuit breakers and supervisory control etc., which may lead to economical and human losses. In power system practices, operation of the protection relays and circuit breakers depend on fault conditions of the power systems. For reliable system design and operation, these operations should be as minimum as possible to maintain steady state supply of the power to consumers. Under fault conditions, communication of any measurement data should be communicated reliably for accurate operation of the required relays and circuit breakers. Different mean of communications eg PLC, optical fibre communication, microwave and telecommunication lines are used as back-up under various operating conditions for reliable transmission of the data.

In existing and new power systems, mix use of optical fibre communication and PLC techniques can be the best solution for reliable mean of communication [1]. In spite of superior performance of the optical digital communication links with respect to immunity to the interference and transmission capacity and desirable objective of a fully digital system, economical constraints as well as technical considerations will result in the continued application of the established PLC technology for particular applications. The robust PLC equipment exhibits distinct technical and economical advantages, where low to medium quantities of data have to be communicated over large distance.

PLC is considered a very reliable back-up for data communication even when the system is under transient and fault conditions. Also propagation of the signal for longer distance on lines make it more attractive. In term of theory of natural modes, the propagation of PLC signal for longer distance on the transmission lines is possible due to the domination of the aerial modes [2]. The presence of aerial modes and earth mode have dominant effect on the travelling wave phenomena in transients conditions [3]. ATP6 is a very useful tool for the studies of travelling phenomena for PLC applications [4]. Due to the non-user friendliness of ATP6 and it being a difficult tool to handle complex problems eg adaptive interference cancellation, MATLAB has been used. MATLAB with its flexible tools eg control, signal processing, mathematical, neural network, fuzzy control and simulink etc. is a good tool for the simulation of applications and control of the power system. On-line help, debugging facilities, plotting and built-in tool for all required applications for the control and operation of the power systems are the added features in MATLAB.

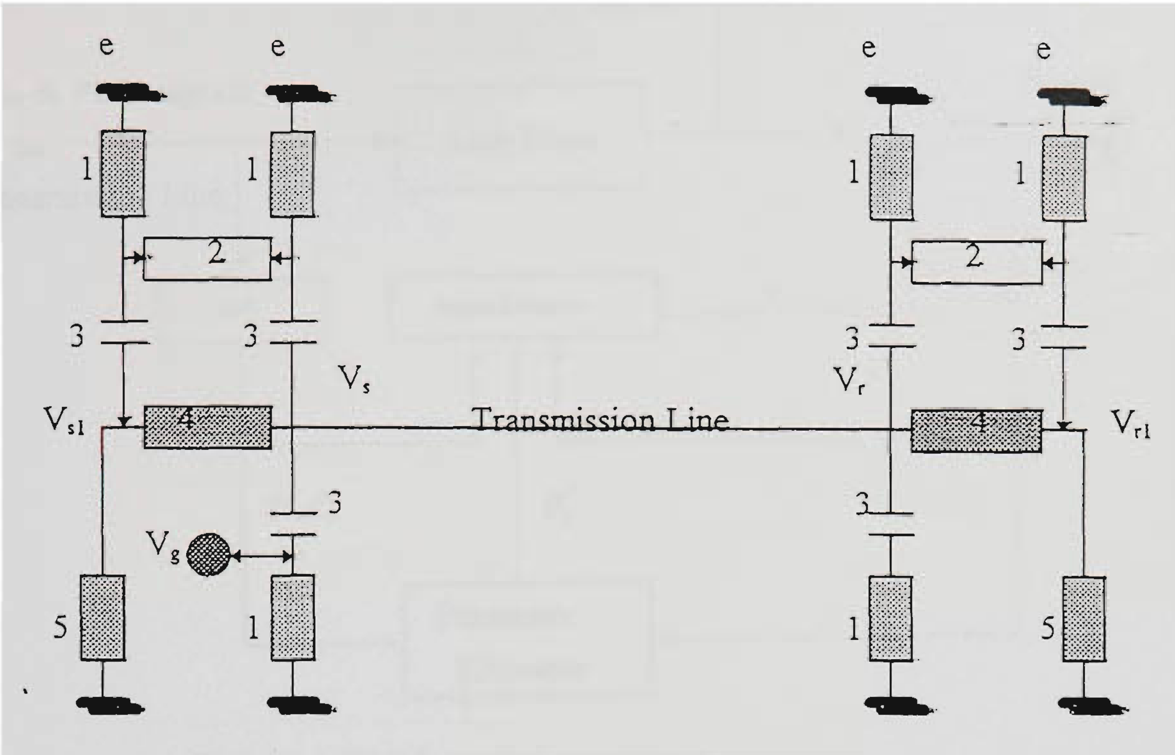
Due to the presence of different interference sources eg corona, lightning, switching operations and inefficiency of the line traps etc., on the power systems for PLC applications, it is impossible to use the available spectrum of frequencies efficiently. The effect of some of the interferences can be reduced with proper planning and design of the power system eg corona, lightening, switching operations etc. The interference due the line traps can be reduced using adaptive interference cancellation techniques. In this paper RLS method has been tested to provide the required level of attenuation to the PLC signal, so that the same spectrum of frequencies can be used on the adjacent line sections. In this paper main focus is on of interference cancellation, so the transmission line has been represented by its characteristics impedance.

2. PLC Model

This paper focus on the PLC model based on the representation of the transmission line by its characteristics impedance. The signal at remote ends have been coupled using single phase to ground coupling, also at both sending and receiving ends. PLC signal and PLC leakage signal have been provided as inputs to the RLS method through coupling capacitors. Figure 1 outlines the PLC model. At the remote ends, transmission line is grounded through appropriate loads to get the required level of attenuation by the traps. The parameters of PLC equipment are calculated on PLC signal frequency, then attenuation due to these calculated parameters is estimated. The PLC signal V_g is represented by the sinusoidal signal. V_s and V_r are the PLC signals at the sending and receiving end of the transmission line respectively. V_s is obtained after attenuation of the coupling capacitors. V_{s1} is the PLC signal leakage towards the sending end busbar due to the inefficiency of the sending end line traps. Graphical representation of the signals is presented in Section 4. Similarly V_{r1} is the PLC signal leakage towards the receiving end busbar. RLS method uses the PLC signal (V_s) and leakage signal (V_{s1}) as inputs to estimate the time varying parameters of the line traps and then based on these parameters, it estimates the output of the line traps. To get the adaptive interference cancellation, the estimated output of the line traps is injected with phase difference of 180° to the busbar.

$$\text{Error} = PLC_l - PLC_{el} \quad (1)$$

where PLC_l is leakage signal and PLC_{el} is estimated leakage signal.



1. Drain Coil 2. RLS Algorithm
3. Coupling Capacitors 4. Line Traps
5. Load e. Earth

Figure 1 : PLC Model for MATLAB Simulation

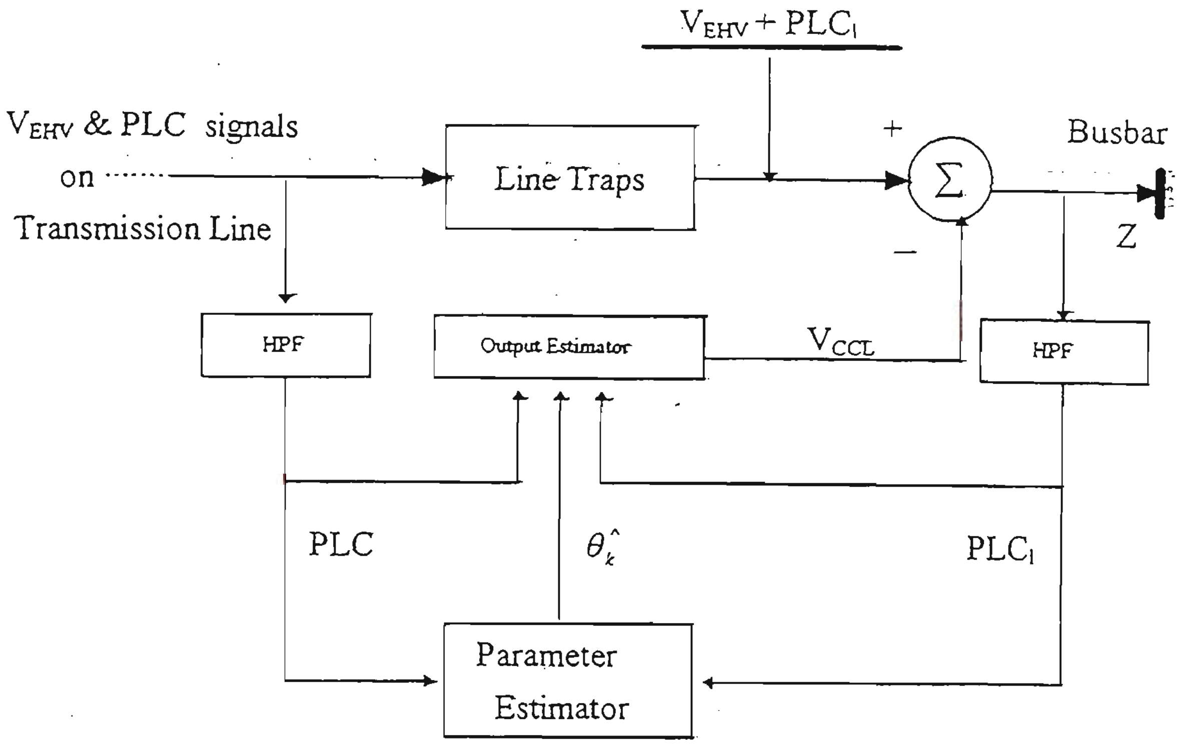
As the knowledge of adaptive learning of the RLS method improves the error reduces, showing more attenuation in the PLC signal, so that same the frequency can be used on the adjacent line sections. The block diagram of the RLS method for the PLC interference cancellation is given in Figure 2. The mathematical model of the PLC model and RLS method has been simulated using MATLAB. The following factors were considered in choosing the RLS method for this particular application:

* previous knowledge of the two of the signal (PLC and leakage signal) is readily available for the estimation of the parameters of the line traps;

* the consideration of initial conditions from zero, makes the algorithm more attractive for the real time situation, where previous knowledge of the system parameters is not available.

3. Simulation of the PLC Equipment

For studies of interference cancellation on PLC model system, MATLAB was used to design the line traps and coupling capacitors. The simulated algorithm have the flexibility to adopt any required parameters for a particular applications



HPF = High pass filter (coupling capacitors)
Z = Power signal after adaptive cancellation of PLC leakage signal
$\hat{\theta}_k$ = Estimated parameters of the line traps
V_{CCL} = Estimated PLC leakage signal through line traps

Figure 2 : Schematic diagram of adaptive interference canceller for the PLC system

3.1. Simulation of the Line Traps

Impedance response of the line trap determines the bandwidth for which it can be used as a bandstop filter. The power signal with its rated current is supposed to pass through the line traps with out attenuation. Hence for lower frequencies the line traps should not show any attenuation. The impedance response of the broad band line traps is shown in Figure 3. The parameters of the line traps were selected to give broadband response for all shown spectrum of the PLC frequencies.

3.2. Simulation of Coupling Capacitors

In these simulation studies, coupling capacitors are not only used for coupling PLC signal on line but also to sense the PLC leakage signal from busbars as well. The impedance response of the coupling capacitors along with the drain coil is shown in Figure 4. The simulation algorithm is developed in such a way that it can be used for any required set of parameters. The result shows the highpass nature of the coupling capacitors.

4. Simulation of Interference on the PLC System

Efficiency of the line traps is limited due to the fact that power signal with its rated current has to pass through the line traps without attenuation. The cost and size of the line traps also limit the efficiency of line traps. Due to the limitation of line traps, PLC signal on one line section interfere with the PLC signal having same frequency on the adjacent line section. Figure 5 shows the level of PLC signal and the interferences in terms of leakage signal to the busbar.

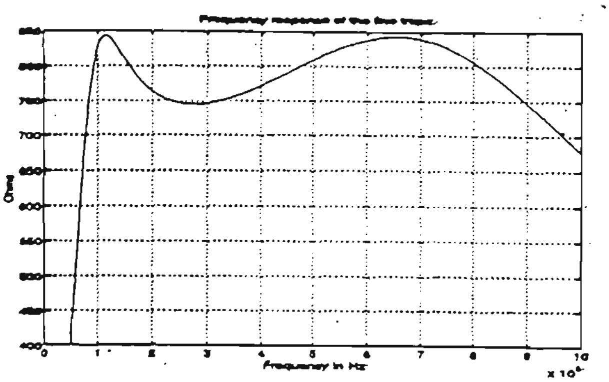


Figure 3: Frequency response of line traps

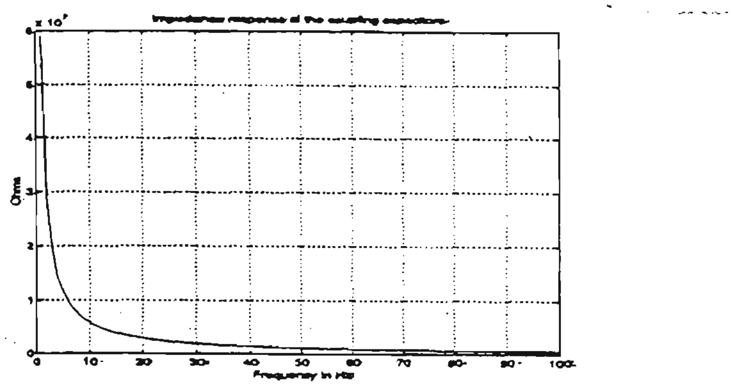


Figure 4: Frequency response of coupling capacitor

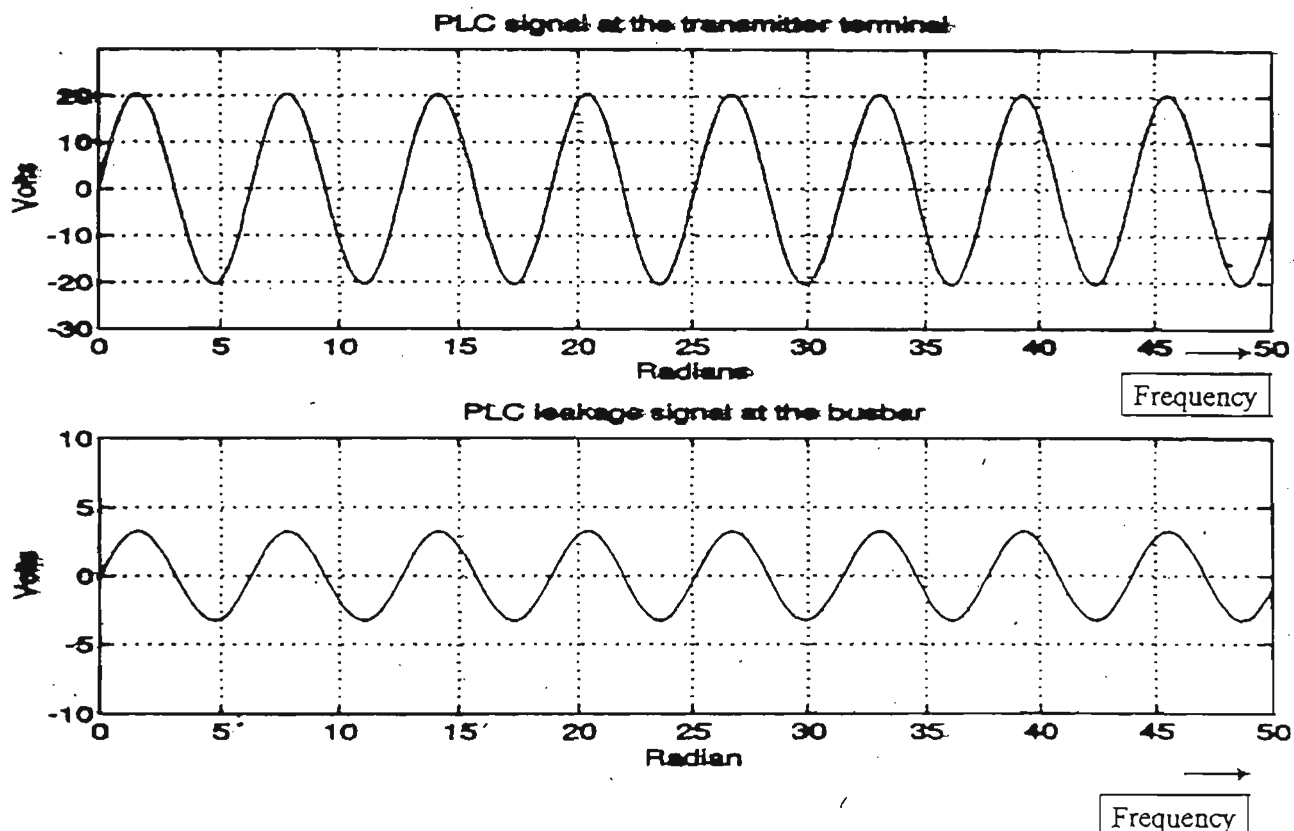


Figure 5: PLC and PLC leakage signals

5. Simulation of RLS Method for Adaptive Interference Cancellation

The PLC leakage signal through line traps to busbar causes reduction in the use of available spectra of PLC frequency. To provide the required level of attenuation on the PLC signal, RLS method was use to assist the line traps. In the simulation, PLC signal was injected on the line and then with the given parameters of line traps, the level of the interference was calculated. PLC signal and the level of interference signal were taken as inputs to the RLS method to predict the magnitude and phase angle of the interferences. The predicted data was injected to the busbar with 180° out of phase, and the error was plotted against frequency (radians). Figure 6 shows the performance of the RLS method. It also shows that the algorithm works satisfactorily within a few cycles. Figures 5 and 6 highlight the importance of RLS method for adaptive interference cancellation on PLC system.

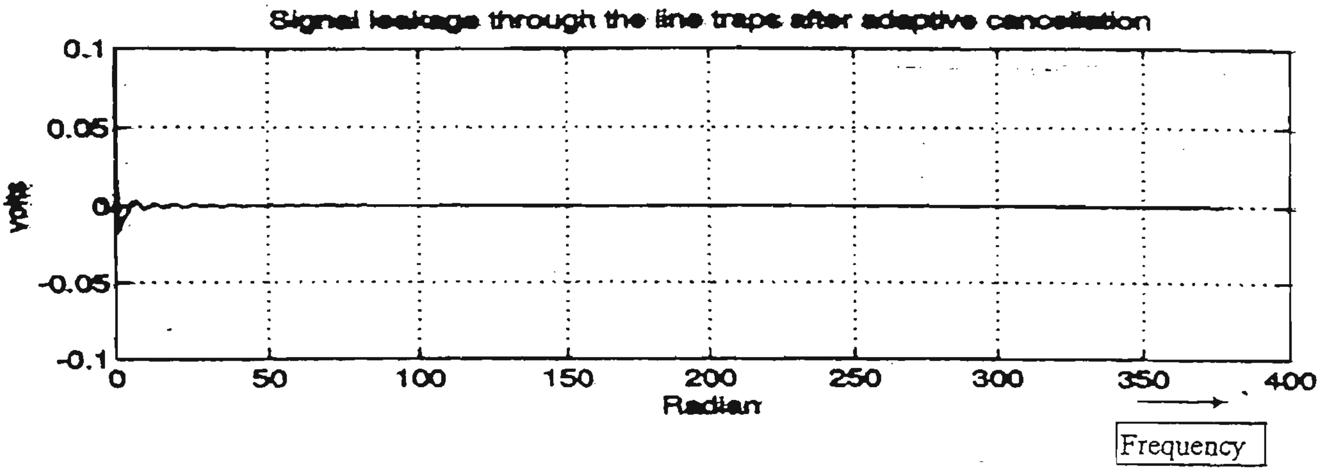


Figure 6 : Leakage signal after adaptive cancellation

6. Conclusion and Future Work

The use of MATLAB appears to be very effective tool in handling any complex problems for the control and management of power system and its associated applications. The built in mathematical, signal processing and control tools etc. makes simulation very simple. The flexibility of the commands and easy adaptation for the interfacing with other softwares makes MATLAB more versatile for the use in power systems applications.

The objective of this work was to simulate the interference on the PLC system, and then to simulate the adaptive interference canceller for these interference using MATLAB. The PLC equipment were simulated using realistic parameters. Results show the effectiveness of the RLS method for this application.

7. Bibliography

1. Morf K P "Mixed use of Optical Fibre Communication and PLC Techniques in Telecommunication Networks for Electrical Power Utilities" International Conf on Advances on Power System Control, Operation and Managements, IEE. p 260-264 Hong Kong Nov 1991.

2. Perz M C "Natural Modes of Power Line Carrier on Horizontal three-phase Lines" Summer General Meeting and Radiation Effects conference, IEEE p 679 - 685 Toronto, June 16-21.

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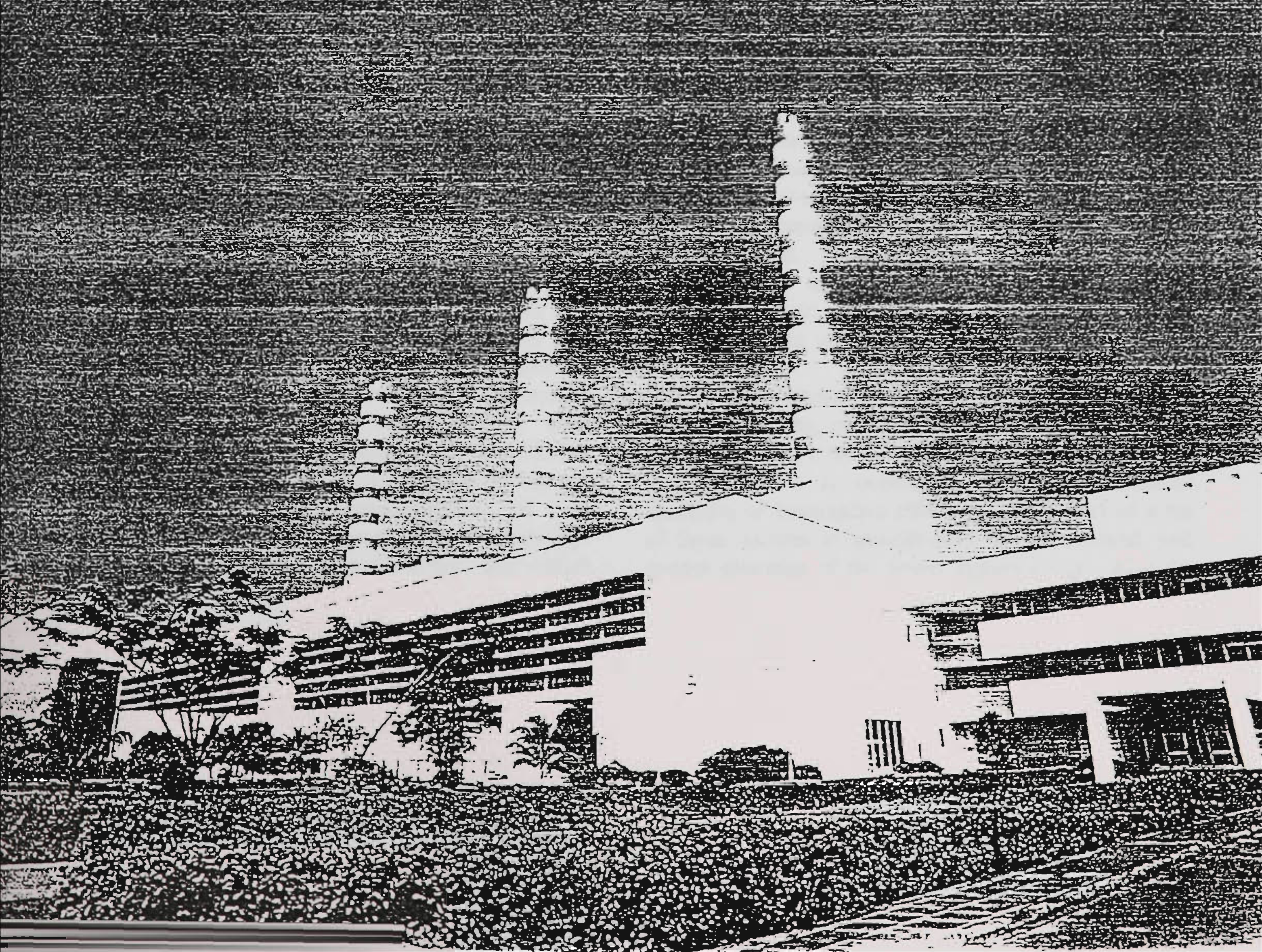

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APPLICATION OF MODAL ANALYSIS FOR THE STUDIES OF DIFFERENT COUPLING SCHEMES ON LABORATORY MODEL OF POWER LINE

I Gondal A Kalam L Xia
Victoria University of Technology
Australia

Abstract

This paper uses Modal Analysis to simulate ehv transmission line as a channel for power line carrier (PLC) signal. Based on simulation studies, the circuit is scaled down to operate at a voltage of 415 V - a desirable value for operation of the transmission line laboratory model. The attenuation level and rate of change of phase angle for different types of couplings are tested on this model using spectrum and network analyser. Single phase to ground coupling has been used for adaptive interference cancellation.

The paper highlights advantages of different coupling schemes with the aid of simulation and hardware results.

Keywords

Modal analysis, Coupling capacitors, Model power line, Adaptive interference cancellation

1 INTRODUCTION

The security of data transmission on power lines for protection, telemetry and supervisory control etc. is a matter of great concern for power system authorities. Transmission of falsified data may result in incorrect operation of the power system, which may lead to fatal consequences. Situations may occur due to malfunctioning of relay operation, circuit breakers and supervisory control, that may cause economical and human losses. In power system practices, operation of the protection relays and circuit breakers depend on fault conditions. For reliable system design, these operations should be as minimum as possible to maintain steady state supply of power to the consumers. Under fault conditions, communication of any measurement data should be communicated reliably for accurate operation of the required relays and circuit breakers. Different mean of communications eg PLC, optical fibre communication, microwave and telecommunication lines are used as back up under various operating conditions for reliable transmission of the data.

In existing and new power systems, mix use of optical fibre communication and PLC techniques can be the best solution for reliable means of communication. Optical digital communication has superior performance with respect to immunity to interference and transmission capacity. However economical constraints and technical considerations result in the continued application of the established PLC technology for particular applications. The robust PLC equipment exhibits distinct technical and economical advantages, where low to medium quantities of data have to be communicated over large distances [1].

In term of theory of natural modes, the propagation of PLC signal for longer distances on the transmission lines is possible due to the domination of the aerial modes [2]. The presence of aerial modes and earth mode have dominant effect on the travelling wave phenomena in transient conditions [3]. ATP6 (PC version of Electromagnetic Transient Program) is a very useful tool for the studies of travelling phenomena for PLC applications [4]. In order to overcome some of the constraints imposed by ATP6, MATLAB with its flexible tools eg control, signal processing, mathematical, neural network, fuzzy control and simulink etc. can also be used for the simulation of the applications and control of the power system.

Due to the presence of different interference sources eg corona, lightning, switching operations and inefficiency of the line traps etc., on the power systems for PLC applications, it is impossible to use the available spectrum of frequencies efficiently. The effect of some of these sources of interferences can be reduced with proper planning of the power system design. Also the iterference due to the line traps can be reduced using daptive interference cancellation techniques. In this aper, Recursive Least Squares (RLS) method has been ested on model power line to provide the required level f attenuation to the PLC signal, so that the same pectrum of frequencies can be used on the adjacent line sections.

2 MODAL ANALYSIS

The mathematical technique used to study travelling wave utilises MODAL Analysis which was theory of natural modes developed by Wedepohl [5]. The modes of propagation for a multiconductor system are calculated from the system parameters using the solution to the wave equation. This involves the solution of two differential equations as given in equations 1 and 2.

$$\frac{dV}{dx} = -ZI \qquad (1)$$

$$\frac{dI}{dx} = -YV \qquad (2)$$

where V is the phase voltage vector, I the current vector, Z the impedance matrix and Y the admittance matrix. On differentiating equations 1 and 2, second order differential equations involving only either voltage or current is obtained as shown in equations 3 and 4.

$$\frac{d^2V}{d^2x} = ZYV = PV \qquad (3)$$

$$\frac{d^2I}{d^2x} = YZI = P'I \qquad (4)$$

Phase voltages and currents can be related to their modal values by linear transformations:

$$V = S\,V^{(c)} \qquad (5)$$

$$I = QI^{(c)} \qquad (6)$$

S and Q are eigenvectors square matrix. On substituting the values of V and I in equations 3 and 4.

$$\frac{d^2V^{(c)}}{dx^2} = \gamma^2 V^{(c)} \qquad (7)$$

$$\frac{d^2I^{(c)}}{dx^2} = \gamma'^2 I^{(c)} \qquad (8)$$

where

$$\gamma^2 = S^{-1}PS$$
$$\gamma'^2 = S^{-1}P'S$$

S and Q matrix are selected in such a way that matrix γ^2 and γ'^2 are diagonal matrix. Consider a reflection free, with relatively low loss long transmission line connected to a high frequency source impressing voltage V(o). Then modal values of the signal at any distance from the sending end at any phase can be defined by equation 9

$$V_k^{(n)}(x) = V_k^{(n)}(o)\,e^{-\alpha(n)}\,x \qquad (9)$$

where k = 1, 2, 3... indicating the phases and n = 1, 2, 3... designate the particular set corresponding to "natural modes of propagation".

3 SIMULATION OF TRANSMISSION LINE

Theory of natural modes has been used to simulate fault transient behaviour of PLC circuit to study the nature of modes of the PLC signal.

3.1 Parameters of Transmission Line

In this paper, PLC systems are connected to a 500 kV ehv transmission line using bundle conductors having horizontal configuration. Figure 1 describes the geometry of the line showing two earth wires on the top of the tower. Complete details of the line are described below:

Operating voltage	= 500 kV
Frequency of the system	= 50 Hz
Line length	= 400 km
Earth resistivity	= 250 Ω-m
Outside diameters of phase conductor	= 3.25 cm
Outside diameters of earth conductor	= 2.50 cm
Number of bundle of in each conductor	= 4
Phase conductor size	= 4 x 54 / 7 / 3.25 ACSR
Ground wire conductor size	= 2 x 30 / 7 / 2.5 ACSR
Allowable sag	= 13.8 m
DC resistance of the phase conductor	= 0.0522 Ω/km
DC resistance of the earth conductor	= 0.36 Ω/km
Ratio of thickness to diameter of the phase tubular conductor	= 0.231

Ratio of thickness to diameter
of the earth solid conductor $= 0.5$

From the geometry of the transmission line, Z and Y matrices can be found using ATP6 software.

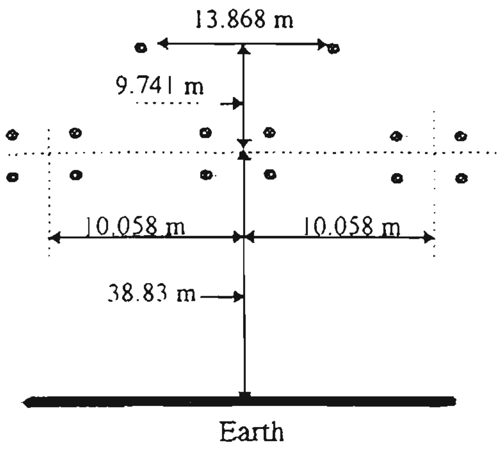


Figure 1: Transmission line construction

Results obtained in zero and positive sequence form were used to simulate the line for steady state and transients studies. Flat feeder configuration was used for line studies (Figure 2).

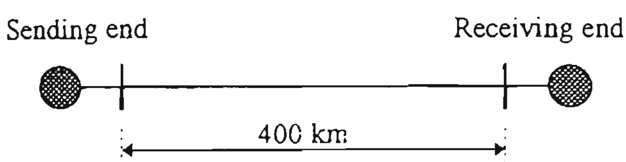


Figure 2: Transmission line model

3.2 Transient Studies

During transient conditions a wide spectrum of frequencies exist superimposed upon the overhead transmission line. As a result, the transient analysis cannot be done simply at the nominal system frequency, but must be in frequency domain using several discrete samples of complex frequencies. Alternative transient program technique is well developed to describe travelling wave phenomena for the systems [6].

In faults involving earth, the earth mode dominate the faulted phase(s) whilst the aerial mode(s) dominate the healthy phase(s). Earth mode attenuates more than the aerial modes [2]. Aerial modes are responsible for PLC propagation on long transmission lines. Healthy phases from Figures 3 & 4 show that travelling wave phenomena persists longer due to aerial modes domination as compared to the faulty phase. Figure 3 and 4 also show behaviour of the line under transient conditions.

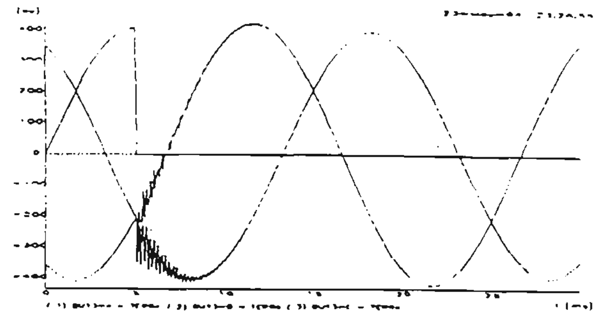


Figure 3: 1-phase-to-ground fault at sending end

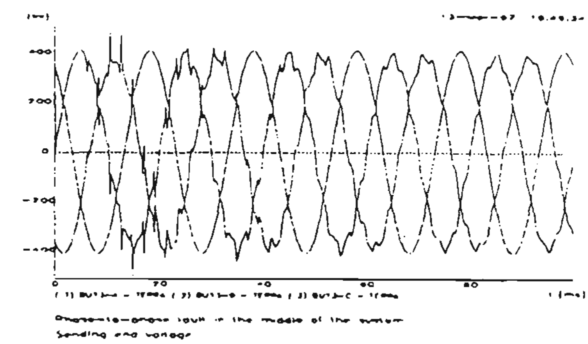


Figure 4: Phase-phase fault in the mid of system

4 HARDWARE DESIGN OF POWER LINE

Laboratory model of transmission line was constructed from the knowledge of simulation of line, presented in Section 3. Simulation of the line was done in distributed parameters for length of 400 km. To construct a laboratory model of the line, parameters were down scaled to voltage of 415 V.

Length of 400 km was modelled using lumped parameters for lengths of 100 km each in four sections. A schematic diagram has been shown in Figure 5.

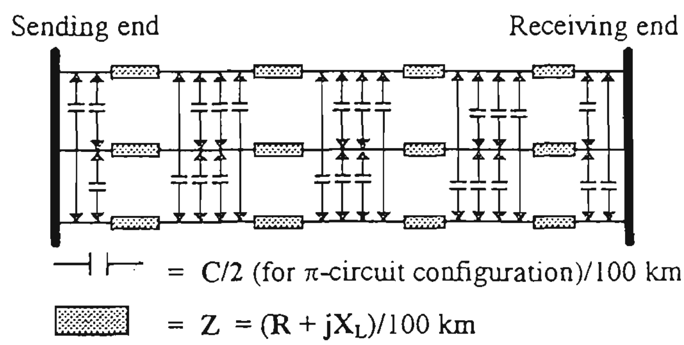


Figure 5 : Model of Transmission Line for Hardware

In the four π-networks capacitance was divided into two halves to appear at remote ends of each section. Three phases were coupled through shunt capacitances, due to the coupling PLC signal appeared on other phases. Model power line was tested for no load charging effects, transient conditions and for the attenuation of small signals on the line.

5 STUDIES OF COUPLING SCHEMES

Different types of couplings can be used for injecting the PLC signal on the power lines, depending upon the required specifications and the allowable level of attenuation. Phase to phase and phase to ground couplings are the most commonly used. Phase to phase coupling is more secure for the injection of the signal on the line, due to the fact that if one phase gets faulty, propagation of the signal will continue on the other healthy phase(s). Efficiency of phase to phase coupling is much higher than single phase coupling. In this paper, results of three phase coupling are also presented. This type of coupling could be very expensive and are very rarely used in power system practices.

To study the behaviour of a model power line under different coupling schemes, frequency and phase response of line were determined using a network and spectrum analyser. In order to do so, power line was disconnected from the power source. Particular phases were connected as input and output of the signal channel to the equipment through matching impedance to facilitate maximum flow of signal power. Figure 6 describes the behaviour of line under central phase to ground coupling. This coupling scheme was used to sense the PLC and its leakage signal as inputs for adaptive interference cancellation. Under phase to phase coupling, attenuation offered to the signal was reduced as compared to phase to ground coupling as shown in Figure 7. When signal was coupled using three phase couplings, frequency and phase response were nearly linear up to 90 kHz. Figure 8 shows the behaviour of line when it was subjected to work under three phase coupling.

Central phase to ground coupling has been used to inject PLC signal on the model power line. This type of coupling is the most optimum and its attenuation is less than that of any other phase to ground coupling [7].

6 ADAPTIVE INTERFERENCE CANCELLATION

Figure 10 outlines practical PLC model used for adaptive interference cancellation. Model power line was used to study the interference caused due to inefficiency of line traps. Efficiency of the line traps is limited due to the fact that power signal with its rated current has to pass through the line traps without attenuation. The cost and size of the line traps also limit the efficiency of line traps. Due to the limitation of the line traps, PLC signal on one line section interfere with the PLC signal having same frequency on the adjacent line section.

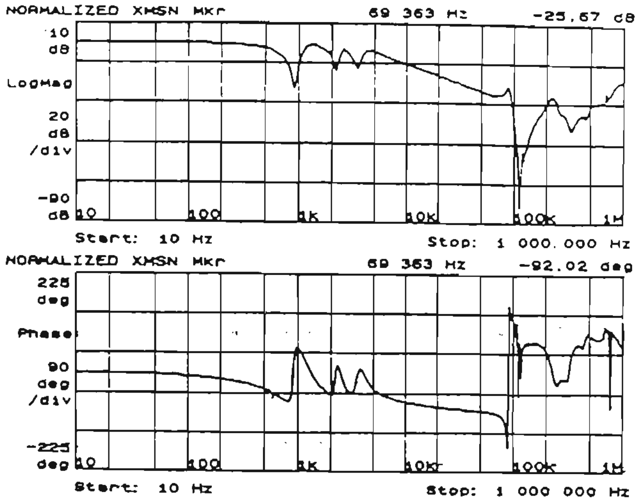


Figure 6: Central phase to ground coupling

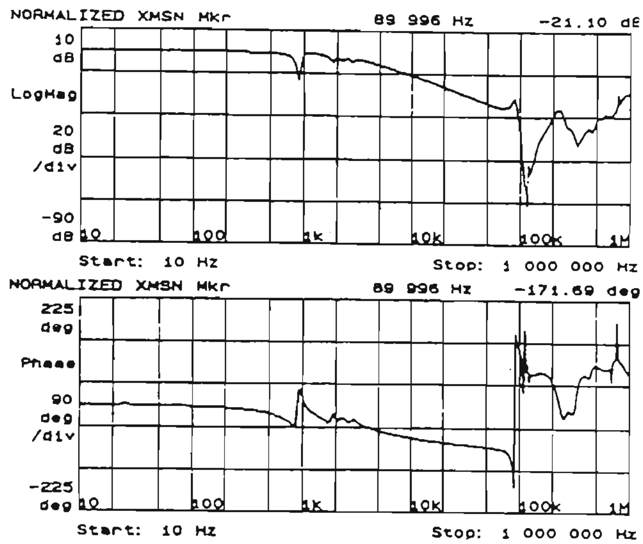


Figure 7: Phase-phase coupling

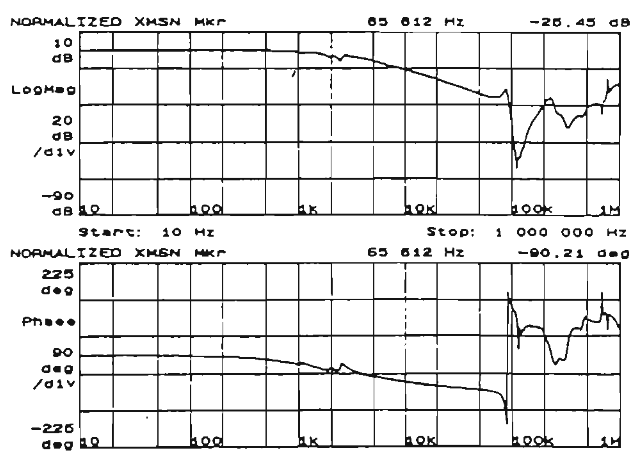
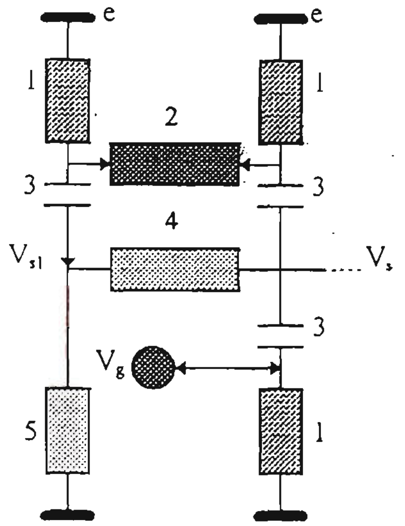


Figure 8: 3-phase coupling

The signal at remote ends have been coupled using single phase to ground coupling. Also at both sending and receiving ends, PLC signal and PLC leakage signal have been provided as inputs to the RLS method through coupling capacitors.



(1) Drain coil	(2) RLS Algorithm
(3) Coupling capacitors	(4) Line traps
(5) Load	(e) Earth
(V_{sl}) Leakage signal	(V_s) PLC signal

Figure 10: PLC Model for Simulation

At the remote ends, transmission line is grounded through appropriate loads to get the required level of attenuation by line traps. Figure 9 shows the level of PLC signal and the interferences in terms of leakage signal to the busbar.

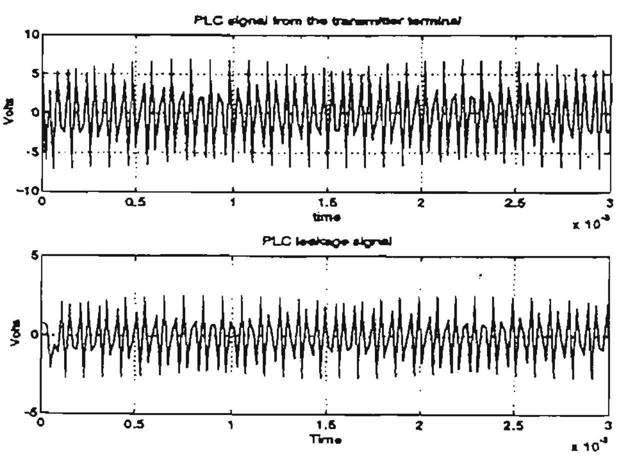


Figure 9: PLC and PLC leakage signal

6.1 Adaptive Interference Canceller

RLS method was used to cancel the interferences adaptively on the model line. PLC and PLC leakage signal were sensed across the line traps using data acquisition card. Then PLC and PLC leakage signal were presented as inputs to RLS algorithm using MATLAB package.

V_{sl} is the PLC leakage signal towards the sending end busbar due to the inefficiency of the sending end line trap. The graphical representation of the signals is presented in Figure 9.

RLS method uses PLC signal (V_s) and PLC signal leakage (V_{sl}) as input to estimate the time varying parameters of the line traps and then based on these estimate of the parameters, estimated output of the line traps is evaluated which in fact is the PLC signal leakage. To get the adaptive interference cancellation this estimated output of the line traps is injected with phase difference of 180° to the busbar to get interference cancellation.

$$Error = V_{sl} - V_{slt} \qquad (10)$$

Where V_{slt} is the estimated value of signal leakage. As knowledge of adaptive learning of RLS method improves about the parameters of line traps, the error reduces showing more attenuation in the PLC signal, so that the same frequency can be used on the adjacent line sections. The block diagram of RLS method for PLC interference cancellation is given in Figure 11.

The mathematical model of the PLC model and RLS method has been used for the simulation using MATLAB and ATP6.

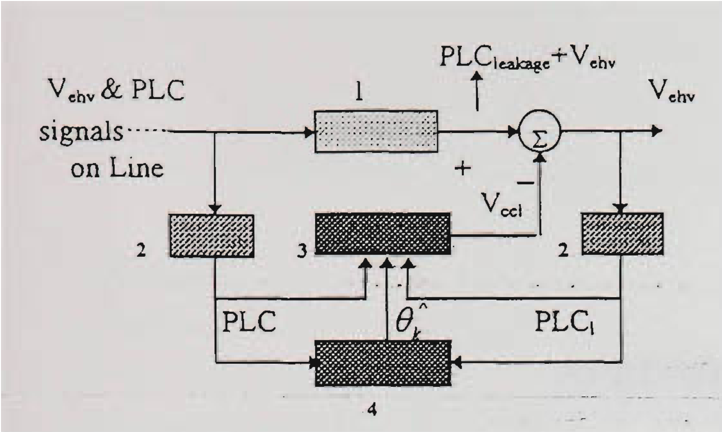
The following factors were considered in choosing the RLS method for this particular application:

* Previous knowledge of the two of the signal (PLC and leakage signal) is readily available for the estimation of the parameters of the line trap.

* The consideration of initial conditions from zero, makes the algorithm more attractive for this real time situation, where previous knowledge of the system parameters is not available.

The PLC leakage signal through the line traps to busbar causes reduction in the use of available spectra of PLC frequency. To provide the required level of attenuation on the PLC signal, RLS method was used to assist the line traps. PLC signal was injected on the line and then with the given parameters of line traps, the level of the interference was measured. PLC signal and the level of interference signal were taken as input to the RLS method in order to predict the magnitude and phase angle of the interferences.

The predicted data was injected to the busbar with 180° out of phase, and the error was plotted against time. Figure 12 shows the performance of the RLS method.



(1) Line traps (2) Coupling capacitors
(3) Output estimator (4) Parameter estimator

Figure 11 : RLS Model for PLC System

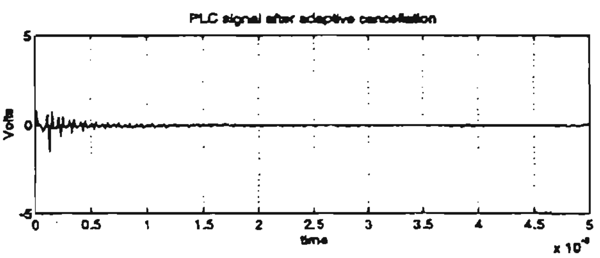


Figure 12: PLC signal after adaptive cancellation

7. CONCLUSION AND FUTURE WORK

The use of MATLAB appears to be a very effective tool in handling complex problems for the control and management of power system and its associated applications. The built in mathematical, signal processing and control tools etc. makes simulation very simple. The flexibility of the command and easy adaptation for the interfacing with other software makes MATLAB more versatile for the use in power systems applications.

ATP6 appears to be a very good tool for the simulation of transient conditions on the power network. From the transient studies of the network, proper level of protection and insulation can be estimated. Also, when studies were made on PLC network, the presence of different modes have been noted.

The objective of this paper was to design the laboratory model of power line to test different coupling schemes on realistic model. Central phase to ground coupling was used to inject the PLC signal on the line and to sense the data for RLS method. Result shows the effectiveness of the RLS method for this application.

It also shows that the algorithm works satisfactorily within a few cycles. Figures 9 and 12 highlight the importance of RLS method for adaptive interference cancellation on PLC system.

BIBLIOGRAPHY

1. Morf K P "Mixed use of Optical Fibre Communication and PLC Techniques in Telecommunication Networks for Electrical Power Utilities" International Conf on Advances on Power System Control, Operation and Managements, IEE. pp 260-264 Hong Kong Nov 1991.

2. Perz M C "Natural Modes of Power Line Carrier on Horizontal three-phase Lines" Summer General Meeting and Radiation Effects conference, IEEE pp 679 - 685 Toronto, June 16-21.

3. Gondal I, Kalam A "Fault transient Simulation of ehv Transmission Systems" AUPCEC 92 Proc. pp 321-326, October 1-2 1992, QUT, Brisbane, Australia.

4. Gondal I, Kalam A "Simulation of Phase to ground Coupling for Power Line Carrier Communication Systems using Modal Analysis" Proc. MS' 93 vol. 1 pp 277-285, July 12-14 Victoria University of Technology, Australia.

5. Wedepohl, L M "Application of matrix method to the solution of travelling-wave phenomena in polyphase system" Proc. IEE, Vol. 110, No. 12, December 1963.

6. Kalam, A "A computer method for solving fault transient phenomena in ehv transmission systems". Proc. of International Conference on Modelling and Simulation, Melbourne pp 195-203, 1987.

7. Neredo Josę Luis A. "Communication frequency response of high voltage power lines". M. A. Sc. Thesis Department of Electrical Engineering, The University of British Colombia, April 1987.

APPENDIX D

Simulation of PLC Model using ATP6

ATP6 is widely used for the transient and steady state studies of transmission systems along with their associated equipment. In this Appendix, input data file for the simulation of PLC system has been given.

```
C POWER LINE CARRIER COMMUNICATION SYSTEM FOR FLAT FEEDER
C LINE LENGTH IS 400 KM, OPERATING VOLTAGE IS 500 KV
C IN THE SIMULATION ONLY LINE TRAPS AND COUPLING CAPACITORS ARE INCLUDED
BEGIN NEW DATA CASE


C    00001111111111222222222223333333333444444444455555555556666666666777777777788888
C    789012345678901 (8)EACH 1234567890123456789012345678901234567890123456789 09

C ABSOLUTE TACS DIMENSIONS

 2.08E-5   .04    0    0    0         0
    4    4    0    1    0    0    0    1    0    0

0BU12-ABU13-A        1.E-4                        1
0BU12-BBU13-B        1.E-4                        1
0BU12-CBU13-C        1.E-4                        1
0BU25-BBUS2-B        1.E-4                        1
0BU2B-BBUS1-B        1.E-4                        1
0BU5B-BBUR1-B        1.E-4                        1
0BU25-BBUR3-B        1.E-4                        1

$UNITS, 0 ,   0
```

```
C (-------------------SENDING END COUPLING CAPACITOR AND LINE TRAPS-----------)

C 0BU12-BBUA2-B            .265
C 0BU12-BBUA2-B                 .009559
 0BU12-BBUA2-B        300   .8602 .002944
 0BU12-BBU2B-B                .003
 0BU2B-BBU25-B           .8443
 0BUS1-BBUS3-B                .022

C $DISABLE

TRANSFORMER          .2828 807   T1    1.0E06
             9999
 1BUS3-BBUS2-B       .1049 2.637 5.0
 2BUS4-BBUS5-B       .1049 2.637 2.5

C $ENABLE

0BUS4-BBUS6-B                  .011

C (------------------RECEIVING END COUPLING CAPACITORS AND LINE TRAPS---------)

0BU15-BBUA5-B             .265
 0BU15-BBUA5-B                 .009559
 0BU15-BBUA5-B        300   .8602  .002944
 0BU15-BBU5B-B                 .003
 0BU5B-BBU25-B            .8443
 0BUR1-BBUR2-B                 .022

C $DISABLE

 TRANSFORMER          .2828 807   T2    1.0E06
             9999
 1BUR2-BBUR3-B       .1049 2.637 5.0
 2BUR4-BBUR5-B       .1049 2.637 2.5
C $ENABLE
 0BUR4-BBUR6-B                  .011
```

$UNITS, 50, 50

```
0BU15-ABU16-A      1.E-4      1
 0BU15-BBU16-B     1.E-4      1
 0BU15-CBU16-C     1.E-4      1
 0BU2B-BBUS1-B     1.E-4      1
 0BU25-BBUS2-B     1.E-4      1
C 0BU18-ABU19-A    1.E-4      1
C 0BU18-BBU19-B    1.E-4      1
C 0BU18-CBU19-C    1.E-4      1
C 0BU40-A          1.E+6
C 0BU21-A          1.E+6
 0BU25-A           1.E-6
 0BU25-B           1.E-6
C 0BU25-C          1.E-6
C 0BU20-A          1.E-6
C 0BU20-B          1.E-6
C 0BU20-C          1.E-6
C 0BU13-ABU13-B    1.E-6
C 0BU18-CBU18-B    1.E-4
  BU13-A           1.E+6      2
  BU13-B           1.E+6      2
  BU13-C           1.E+6      2
  BU16-A           1.E+6      2
  BU16-B           1.E+6      2
  BU16-C           1.E+6      2
  BU20-A           1.E+6      2
  BU20-B           1.E+6      2
  BU20-C           1.E+6      2
  BUA5-B           1.E+6      2
  BUA2-B           1.E+6      2
C  BU19-A          1.E+6      2
  BU2B-BBU25-B     1.E+6      2
  BU5B-BBU25-B     1.E+6      2
  BUS6-BBUS5-B     1.E+6      2
  BUR6-BBUR5-B     1.E+6      2
  BU12-BBU2B-B     1.E+6      2
```

C BU19-C 1.E+6 2

C 51,52,53R(27-32),X(33-44) (0)R(27-32),XL(33-38),XC(39,44)

C 01234567890123456789012345678901234567890123456789012345678901234567890

C $DISABLE

```
51BU11-ABU12-A           7.143 {source is 35 GVA}
52BU11-BBUA2-B           7.143
53BU11-CBU12-C
51BU14-ABU15-A           7.143
52BU14-BBUA5-B           7.143
53BU14-CBU15-C
```

$DISABLE

```
51BU17-ABU18-A           7.143
52BU17-BBU18-B           7.143
53BU17-CBU18-C
```

$ENABLE

C 01234567890123456789012345678901234567890123456789012345678901234567890

```
-1BU13-ABU40-A       .189 1.875  .0069   100.0
-2BU13-BBU40-B       .134 1.0364 .0141   100.0
-3BU13-CBU40-C
-1BU40-ABU20-A       .189 1.875  .0069   100.0
-2BU40-BBU20-B       .134 1.0364 .0141   100.0
-3BU40-CBU20-C
C -1BU19-ABU30-A      .165  1.25  .0132   100.
-1BU16-ABU21-A       .189 1.875  .0069   100.0
-2BU16-BBU21-B       .134 1.0364 .0141   100.0
-3BU16-CBU21-C
-1BU21-ABU20-A       .189 1.875  .0069   100.0
-2BU21-BBU20-B       .134 1.0364 .0141   100.0
-3BU21-CBU20-C
```

BLANK CARD ENDING LINE CARD

```
C       01234567890 15-24 25-34 4567890123456789012345678901234567890123456789
C $UNITS, 0,0

 0BU13-ABU25-A     .005       .04
C 0BU13-BBU25-B     .0025      .05
C 0BU19-CBU25-C     .005       .01
C 0BUS1-BBUS2-B                .05

C { SWITCH USED TO BYPASS THE LINE MATCHING UNIT WHEN REQUIRED AT
SENDING END}

 0BUS1-BBUS2-B.005      .0005     1.5       2000                         3

C { FLASHVOER SWITCH THRESHOLD IS TAKEN AS 100 V AT SENDING END}

C 0BUR1-BBUR3-B                .05

  C{ SWITCH USED TO BYPASS THE LINE MATCHING UNIT AT RECEIVING END}

0BUR1-BBUR3-B.005      .0005     1.5       2000                         3

 C { FLASHOVER SWITCH THRESHOLD IS TAKEN AS 100 V AT RECEIVING END BUT
ACTUAL IS 2kV}

BLANK CARD ENDING SWITCH CARD

C     7890 11-20 21-30 31-40 41-50 678901234567890123456789012345678901234567890
C $DISABLE

14BU11-A  408248.   50.      -90.       0.                   -1
14BU11-B  408248.   50.     -210.       0.                   -1
14BU11-C  408248.   50.       30.       0.                   -1
14BU14-A  408248.   50.      -90.       0.                   -1
14BU14-B  408248.   50.     -210.       0.                   -1
14BU14-C  408248.   50.       30.       0.                   -1
```

```
C $ENABLE
C 14BUS6-B  100       200000     0        0 { 3.33E-6  1.67E-6} -1     {  0                    -1}
C 14BUR6-B  100       200000     0        0 { 3.33E-6  1.67E-6} -1     {  0                    -1}
C 18BUS2-B   2       BUS4-BBUS5-BBUS3-B
C 18BUR3-B   2       BUR4-BBUR5-BBUR2-B
C 14BU17-A  408248.   50.      -90.       0.                -1.
C 14BU17-B  408248.   50.     -210.       0.                -1.
C 14BU17-C  408248.   50.       30.       0.                -1.

BLANK CARD ENDING SOURCE CARD

C     7890 11-20 21-30 31-40 41-50 6789012345678901234567890123456789012345678901234567890
BLANK CARD ENDING OUTPUT CARD
BEGIN NEW DATA CASE
EOF
```

THIS FILE IS USED TO SIMULATE THE POWER LINE CARRIER COMMUNICATION SYSTEMS SIGNAL.

APPENDIX E

Scaling of the Parameters

ATP6 software was used for computer simulation of transmission line for PLC channel. Distributed parameters were used to represent the 400 km long ehv transmission line. Computer simulation results for transient studies are given in Chapter 5. For practical implementation of the adaptive interference cancellation schemes, PLC laboratory model was developed based on parameters and computer simulation studies given in Chapters 4 and 5 respectively. Operating voltage and characteristic impedance of the line played an important role in determining the factor by which the parameters were to be scaled down. For 500 kV transmission line, typical value of characteristic impedance is 300 Ω [36]. For simplicity, only resistive calculations are shown. The resistive parameters used in computer simulation of the line were as follows:

R_o (Zero Sequence) $= 0.165\ \Omega/\text{km}$

R_p (Positive Sequence) $= 0.0288\ \Omega/\text{km}$

It was intended to keep the characteristics impedance of the line model very close to 300 Ω. The positive sequence parameters (ie. resistive, inductive and capacitive values) were scaled down by a factor of 5, and the closest laboratory values were selected as used in Section 3.2.2.

R_o (Calculated scaled down zero sequence value) $= 0.033\ \Omega/\text{km}$

R_p (Calculated scaled down positive sequence value) $= 0.00576\ \Omega/\text{km}$

The calculated value of the characteristic impedance from selected parameters was 278.3233 Ω. These scaled down parameters were also used for transient studies using ATP6 to verify the accuracy of the line model. The computer simulation studies showed very close resemblance to the ehv transmission line.

The results presented in Chapters 4, 5 and 7 show the performance of the line using computer and hardware simulation studies. Based on these results, it can be concluded that the performance of the adaptive interference cancellers on the practical systems were be the same as operating on the line model.