Seasonal Scheduling of Energy Storage in Networks Incorporating PV Generation Systems

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ABSTRACT

Electricity usage has been increasing all around the world with the changing lifestyle and increasing population. Seasonal changes lead to changes in the output of Photovoltaic (PV) systems, causing power variations that feature frequency changes and voltage fluctuations. Well-designed integration of distribution energy could assist with the challenges of power quality, high system losses and peak load demand in localised distribution grids, called the micro grids. Energy Storage Systems (ESS) is an alternative solution to solve many problems in the grid. In many countries, the electrical distributors and regulators require large amounts of ESS to be installed to back up the grid in consideration of the intermittency of renewable energy resources such as wind and solar PV.

In many countries, distribution planners lack optimal tools and methods to operate the ESS with impact on distribution network reliability, capacity and power quality. Especially, distribution planners are conventional to static-mode power flow calculations, but in some cases to minimise the power and voltage quality issues, ESS needs Sequential-Time-Series (STS) analysis. In ESS, the batteries are connected in parallel to increase the reliability on the distribution system but due to the charge/discharge imbalance in the scheduling of ESS, power quality issues are arising in distribution networks. This charge/discharge imbalance can also affect the battery life due to circulating currents in the batteries. However, the battery life would be shortened due to increased number of cycles and deep discharge at a specific time could raise the over voltage issues in distribution systems.

This research aims to model seasonal scheduling of energy storage in networks incorporating PV generation systems. The research focuses on demonstrating the impact of seasonal variations on voltage quality in PV integrated networks. Based on the analysis, a charge/discharge schedule is developed taking account of seasonal variations. The key focus is to demonstrate the variations in the seasonal charge/discharge schedule of a battery storage system to meet ANSI (American National Standard Institute) steady-state voltage limits. One key benefits of this scheduling are efficient operation leading to increase the battery life, reduce losses in the transformer and improve power quality outcomes. The cycle life is given by the number of complete charge/discharge cycles that a battery can support before its capacity falls under a defined percentage of its original capacity with partial discharge having favourable impact on the battery life. With these outcomes, distribution planners can analyse and plan for current and future electricity demand using a seasonal approach.

This research covers seasonal charge/discharge scheduling of Energy Storage Systems (ESS) for various seasonal steady-state analysis validated for the chosen most severely affected buses in a case study network with specific periods in all seasons. A key outcome is the developed seasonal Charge (C) and Discharge (D) allocations and validation of the sufficiency of such a seasonal allocation in addressing power quality issues especially the required steady-state voltage limits. The charge and

discharge percentages have been chosen to implement partial charge or discharge to support the battery life. The work demonstrates the need for such a seasonal allocation schedule. The undertaken analysis validates a seasonal allocation would be sufficient to minimise Over Voltage (OV) and Under Voltage (UV) issues even in PV penetrated networks. The focus of this research is the allocation of charge/discharge schedules of the energy storage system using the sequential time series method. Research aimed to validate that a fixed seasonal charge/discharge schedule is sufficient to address the power quality issues in exchange for a complex and sophisticated scheme. Thus, the work intends to demonstrate the sufficiency of such a seasonal allocation approach.

The methodology in this thesis follows modelling of the EPRI CKT24 network with network data sourced from Sandia National Laboratories (SNL) and assessment of seasonal voltage quality issues for PV and no-PV cases. Steady-state analysis of the entire network has been performed with results elaborated for two selected buses. Phase C in the unbalanced case study network was observed to suffer most from the voltage power-quality issues and therefore efforts were directed towards a more detailed analysis of this phase. Further steady-state analysis of the chosen buses highlighted over voltage issues at times of low demand especially in the early hours of the day after midnight, made worse by the PV power that begins to be injected into the network subsequent to the sunrise. Spring and autumn seasons were observed to be the worst two seasons in the terms of power quality and the impact of PV penetration on the power quality.

Based on findings from the analysis of seasonal voltage variations, energy storage has then been modelled and incorporated into the existing EPRI CKT24 case study network model. Whilst the OpenDSS network model incorporated PV elements, this ESS modelling and incorporation was an original contribution in this dissertation. The storage elements were modelled as generators, which can dispatch power in charge or discharge modes within their rated specifications. A dynamic daily charge/discharge schedule has been developed consistent for the entire season to alleviate voltage quality issues taking consideration of seasonal requirements. In this thesis, a Sequential-Time-Series (STS) based seasonal charge and discharge schedule has been proposed using a storage controller that sets the charge/discharge schedules of the energy storage system in response to seasonal requirements. OPENDSS has been used to model the network power quality problems with OpenDSS compiling the network data into the MATLAB environment via a COM interface. The storage controller has been set and controlled through the MATLAB to OpenDSS interchange. Seasonal analysis was then performed using the various seasonal LoadShape allocations to demonstrate that a one-size fits allocation would not work at every season and a seasonal consideration is indeed required. Steady-state voltages have been demonstrated to be better controlled in the mid voltage range with such seasonal consideration. A key contribution is the seasonal analysis and validation of the sufficiency of a seasonal charge and discharge allocation strategy in meeting grid code requirements with respect to the bus voltages.

Student Declaration

"I, Santhosh Reddy Mekala declare that the Master by Research thesis entitled "Seasonal Scheduling of Energy Storage in Networks Incorporating PV Generation Systems" is no more than 60,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Signature

8/17/2020

X Santhosh Reddy Mekala

Santhosh Reddy Mekala

Signed by: Santhosh Reddy Mekala

Date: 17/08/2020

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Glossary and List of Acronyms

RES	Renewable Energy Sources
PV	Photovoltaic
STS	Sequential Time-Series
ESS	Energy Storage Systems
SNL	Sandia National Laboratories
PVPMC	Photo Voltaic Performance of Modeling Collaborative
QSTS	Quasi-Static-Time-Series
COM	Component Object Model
DSS	Distribution System Simulator
EPRI	Electric Power Research Institute
DG	Distributed Generation
VBA	Visual Basic Access
GUI	Graphical User Interface
UV	Under Voltage
OV	Over Voltage
LP	Linear Programming
NAS	Sodium Sulphur
HV	High Voltage
BESS	Battery Energy Storage Systems
PF	Power Factor
DGR	Distributed Generation Resource
DG	Distributed Generation
SOC	State of Charge
DOD	Depth of Discharge
PVDG	Photovoltaic Distributed Generation
LTC	Load Tap Changer
VREG	Voltage Regulator
ANSI	American National Standards Institute
PCC	Point of Common Coupling
$\mathbf{V_{min}}$	Minimum Voltage range
$\mathbf{V_{max}}$	Maximum Voltage range

Chapter 1

Introduction

1.1. Background

The population across the globe is growing significantly, and the utilisation of electricity has also been rapidly rising [1]. Deployment of Renewable Energy Sources (RES) is increasing day by day due to climate change policies and fossil fuel extinction [2]. To match the demand for electricity and implement sustainable development across the electrical industries, deployment of greener Photo Voltaic (PV) systems has been growing. The intermittency of PV systems, due to seasonal variations, has a significant impact on the capability of PV system in being used to meet the base-load grid power requirements. For example, at times of cloudy weather, the generation of the PV output would be minimal [3].

Grid energy storage has similarly become very popular which is used to store electrical energy at times of low demand directly from the grid or especially from intermittent power sources such as PV systems. The stored electrical energy is then often later dispatched back into the network when the demand is high or at times of high electricity prices. It is possible to address the challenges of power quality, high system losses and peak load demand in distribution grids with well-designed integration of distributed energy. Daily PV system management based on forecasting is not guaranteed because through forecast analysis, peak demand is predictable, but voltage stability is not [4]. Many researchers are concentrating on the daily analysis with the daily prediction of irradiance and temperatures affecting the PV system output. However, those predictions are not 100% accurate and many distribution systems are still facing high PV penetration issues based on a daily energy management philosophy [5, 6]. In this thesis, the seasonal approach has been investigated which enables a seasonal averages-based energy management approach rather than daily or weekly data which could be unreliable.

Sequential-Time-Series (STS) analysis will examine the seasonal issues at the case study distribution feeder with and without PV systems. The focus will also be on exploring how integrating an Energy Storage System (ESS) in the PV penetrated network and a seasonal allocation approach can minimise the power quality issues at the distribution feeder. The seasonal approach is based on quarterly analysis and the work herein aims to demonstrate the sufficiency of a seasonal allocation approach in addressing the quarterly power quality issues. This research has therefore studied integration of PV/Battery storage elements within a distribution system and focused on evaluating the viability of seasonal dispatch allocations in a case study network of real network and load data.

1.2. Research Objectives

This research aimed to develop the seasonal scheduling model of an Energy Storage System (ESS) incorporating PV/Battery storage elements integrated within a distribution network. The research focused on evaluating and comparing the viability of different allocation methods using the real network and load data. The research has explored various seasonal charge and discharge scheduling approaches with different rates of charge and discharge allocations in different seasons to minimise the voltage quality issues and the power supplied from the substation transformer. The distinct aims of this research are as follows:

- STS analysis of an exemplary distribution network using OpenDSS and MATLAB.
- Investigation of the power quality issues with and without PV systems.
- Modelling of ESS in a case study network model.
- Development of seasonal charge/discharge allocation schedules.
- Simulations to validate and compare the seasonal fixed allocation schedule to corroborate the need for a seasonal dispatch schedule.

The research shows that PV and battery ESS in a distribution network can reduce the power quality issues and maximise the efficiency of the system reducing the reliance on the grid for peak demand support. It also demonstrates the concept of how an integrated PV and Battery ESS can be managed based on a fixed seasonal dispatch schedule. The research focused on developing a seasonal solution for control and management of battery-stored electrical energy in a distribution network. This research is expected to benefit the power distribution industry; as this thesis will show that a seasonal fixed charge and discharge percentage allocation strategy can be sufficient in minimising power quality issues during high PV penetration and at times of lightly loaded network. This will result in alleviating peak load concerns and the need for expensive network augmentation. In this research, an attempt was made to undertake an all-season analysis during the heavily and lightly loaded demand times. Proper charge/discharge rates have been set to reduce the daily voltage issues in all seasons. The need for a seasonal charge/discharge schedule was also shown by analysing the impact of alternating between the seasonal dispatch schedules.

1.3. Methodology and Conceptual Framework

In this research, the subsequent procedure has been followed for the development of a distribution network model in MATLAB with integrated PV and energy storage models. Then, different allocation of charge/discharge schedules was developed based on the seasonal analysis of the load demand and power quality issues. Fig. 1.1 shows the entire procedure in undertaking this study, which involved seasonal simulation and analysis of the case study network with and without PV integration, ESS modelling, and seasonal dispatch schedule allocation to minimise the power quality issues.

The case study CKT24 distribution network data was collected from a joint project led by the Sandia National Laboratories (SNL) and Photo Voltaic Performance Modelling Collaborative (PVPMC) [7, 8]. A GridPV toolbox was used in both the interface software for the STS analysis. Two buses with severe power quality issues, were then selected for detailed analysis. The study then looked into examining the seasonal power quality issues at both buses with and without PV systems. The investigation on both buses for seasonal analysis has been carried out using the MATLAB software. ESS was then modelled and integrated into the existing network using STS analysis in OpenDSS and MATLAB software. Seasonal dispatch schedules were then developed and applied to the case study network to demonstrate the improvement in the power quality issues and the need for seasonal schedules indeed.

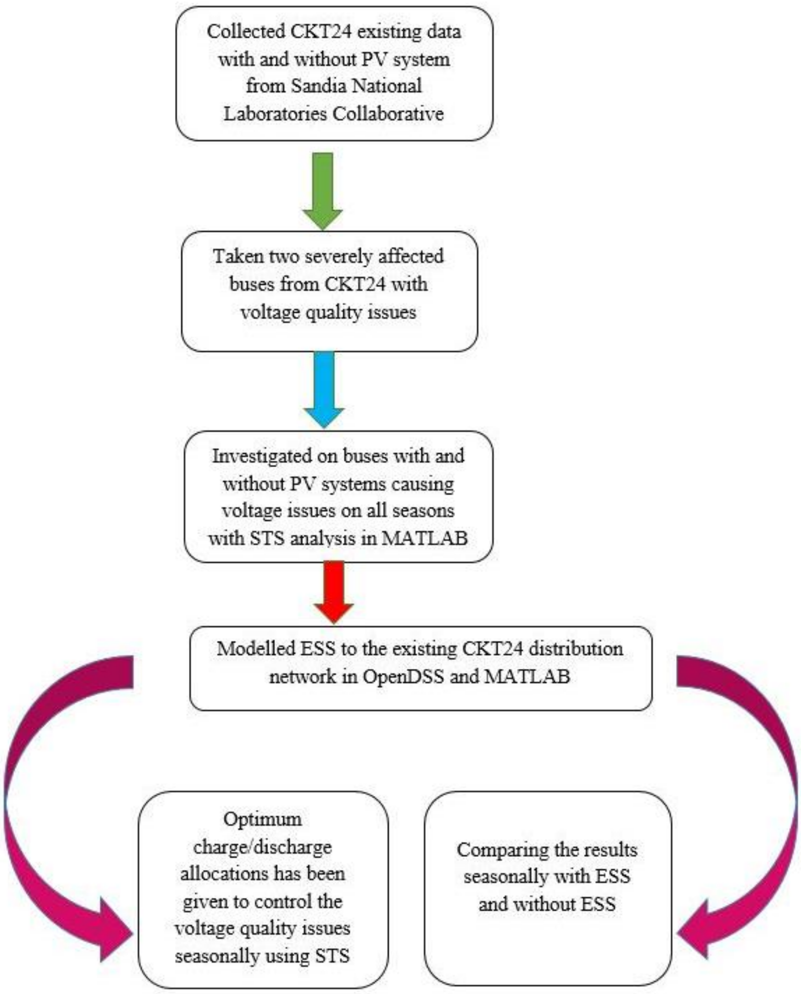

Fig. 1.1. A proposed methodology for the existing CKT24 distribution network.

1.4. Simulation Software and Tools

In this thesis, CKT24 case study network has been used for the various time-series analysis based on different seasons. To perform this Sequential-Time-Series (STS) simulation, a simulator has been developed and used to execute the STS seasonally. There are many tools available to execute the Quasi-Static-Time-Series (QSTS) simulation for steady-state power flow solutions such as CYMDIST, OpenDSS and GRIDLAB-D. Nevertheless, after careful analysis, OpenDSS was chosen to perform the STS simulation seasonally. For the seasonal investigation, OpenDSS is Component Object Model (COM) interfaced via a GUI tool in MATLAB to reduce the OV issues at BUS-X and BUS-Y in CKT24. The preceding sub-sections discuss all the simulation tools used in this thesis.

1.4.1. OpenDSS

OpenDSS stands for Open Distribution System Simulator. This software is an electric power Distribution System Simulator (DSS) for grid integration and modernisation efforts. This tool has been is developed by the Electric Power Research Institute (EPRI) [9]. OpenDSS primarily supports all the frequency domain (steady-state) analysis usually performed for the electricity distribution system. It also assists different types of study that are modelled to meet current smart grid demands. OpenDSS can dispatch analysis of daily, weekly, monthly and yearly Distributed Generation (DG) interconnection performance. The OpenDSS is implemented in the following three formats:

1. OpenDSS.exe
2. OpenDSSEngine.DLL
3. OpenDSSDirect.DLL

The first format is a stand-alone format, which is used for stand-alone executable programs. The second format is an in-process COM server DLL designed from different existing software platforms. Finally, the third format is a Stdcall DLL, which gives all functions of the COM server from languages but does not support COM interface, and only supports cloud server. In this thesis, the first stand-alone format is used to simulate the STS simulations seasonally.

OpenDSS program software can be used for many distribution solutions. In this thesis, it has been applied for a seasonal based storage modelling to address network voltage quality issues. This OpenDSS program was built to run in different modes, with the duty cycle power flow mode employed in this study. The COM interface was used to perform simulations in solution models from external tools to define the user interface models. Hence, the DSS will help to implement model data independently with fixed .dss text file circuit through the MS Office tool, via Visual Basic Access (VBA) in MS Excel. In this thesis modelling, the OpenDSS with COM interface of MATLAB was used to analyse the voltage quality issues by plotting the simulation results in MATLAB. The COM interface of OpenDSS and MATLAB is outstanding to source for fastest power flow simulations using Graphical User Interface (GUI). Fig. 1.2 shows the OpenDSS structure with the primary simulation engine consisting of different building blocks.

- OpenDSS scripts: User is able to modify the script as per their circuit and also solve the user scripts.
- COM interface: COM interface is able to interface with various software such as MATLAB, Python, and VBA have been used to operate the OpenDSS externally.
- User Written DLL: In this case, different models developed by the user (customised) are merged in the simulation engine by writing suitable DLL for them and linking that model to the engine.

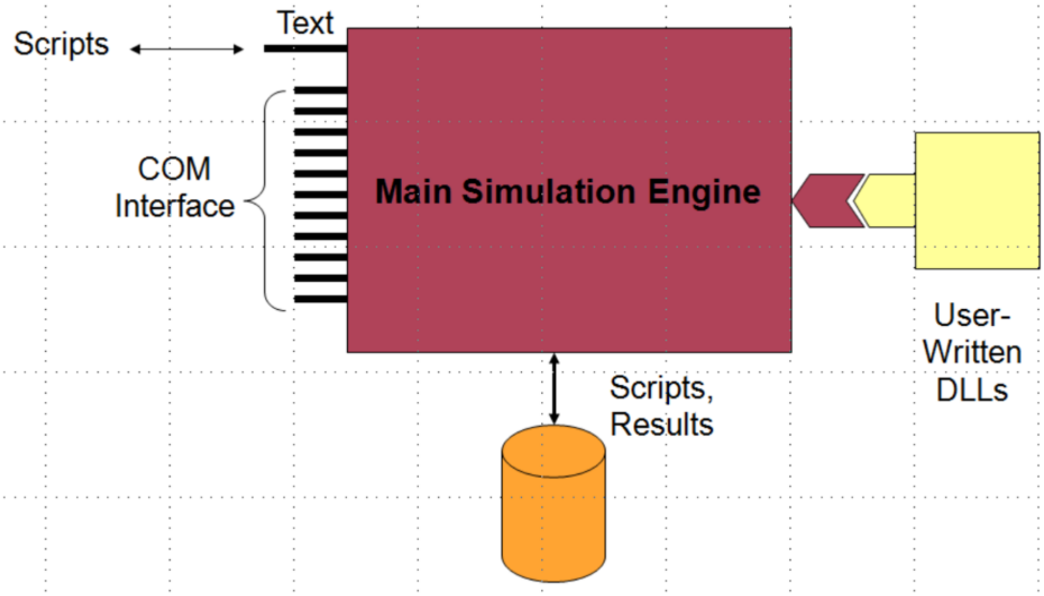

Fig. 1.2. OpenDSS Structure [10].

1.4.2. OpenDSS Solution Mode Using Graphical User Interface (GUI)

Fig. 1.3 shows the OpenDSS distribution network modelling using GUI. The EPRI test circuit data has been taken from PV Performance modelling collaborative website. PV performance modelling collaborative is a national laboratory of the U.S. called Sandia National Laboratories (SNL). The EPRI CKT24 distribution feeder data was collected from SNL. Then using the GridPV toolbox manual, the CKT24 was modelled and analysed with a Sequential-Time-Series (STS) for all seasons of one-year data. After collecting distribution feeder data from SNL, then using OpenDSS with COM facility, the MATLAB software was interfaced.

The MATLAB is an external program, which is interfaced with GUI via COM interface. OpenDSS also simulates many power flow solutions. In Fig. 1.3, the EPRI CKT24 distribution feeder model is defined and then using the external program and STS, the seasonal variation of voltages has been explored for PV and no-PV cases. However, the generator and the CKT24 substation parameters are the existing circuit data. All the line codes and the line element parameters are also the existing data of CKT24. All the loads are existing loads with the respective nodes at CKT24. With all the existing data, the voltage issues have been identified with time series simulation for every season. The STS analysis has been modelled in this thesis to identify 24-hour data of all seasons.

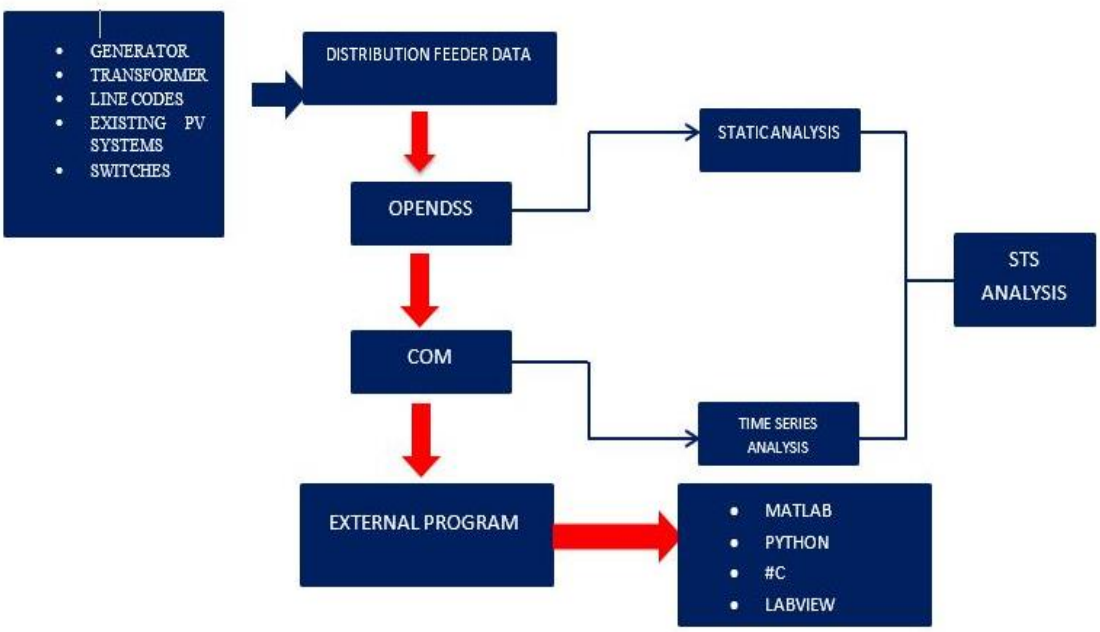

Fig. 1.3. OpenDSS distribution system modelling using GUI.

In Fig. 1.4 for STS analysis, there are few solution modes accessible in the OpenDSS such as dynamics, dynamic power flow, harmonics and power flow solution modes. In this thesis, the dynamic power flow solution mode has been taken to identify seasonal issues using STS. In dynamic power flow, there are few different modes to analyse the steady-state power flow simulations such as daily, yearly, duty cycle and peak day, as shown in Fig. 1.4.

GUI helps to model STS simulation for every season. OpenDSS is an open-source electrical distribution simulation tool, for which it is easy to change the source code as well as to customise the values of the OpenDSS existing test circuits. However, as explained above in Fig. 1.3, once the CKT24 feeder has been modelled the using user-friendly GUI, the BUS-X and BUS-Y have been selected randomly in CKT24. Fig. 1.4. shows that the seasonal variations simulation will identify seasonal voltage quality issues through dynamic power flow simulations, using OpenDSS and GUI interface in the MATLAB for external results. Both static and time-series analysis has been used in this GUI interface.

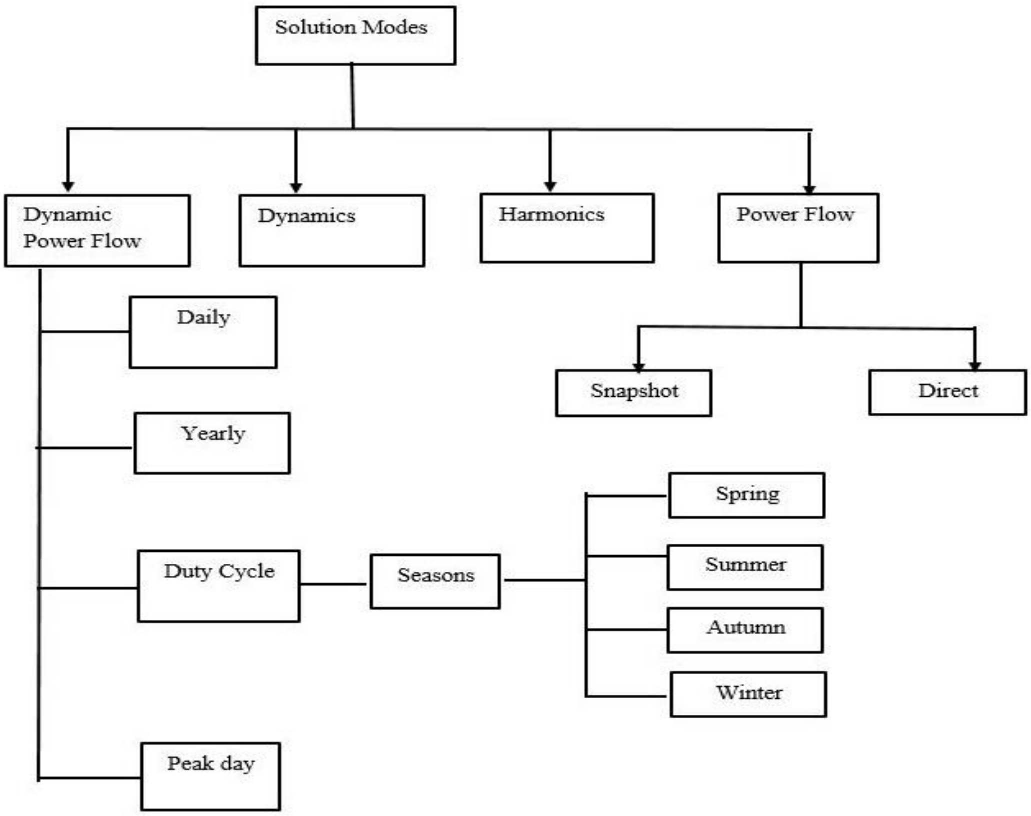

Fig. 1.4. Different solution modes accessible in OpenDSS.

1.4.3 MATLAB

MATLAB®, Matrix Laboratory is a high-level language for technical computing. It collaborates with visualisation, computation, and programming computing software for the development of logic, analysis and visualisation of data, and various numerical computation. The most significant features of MATLAB [11] are:

- Providing an environment for design, programming and solving complex problems.
- Capability to perform high-level technical computation.
- Integrating various components such as to guess the data and the tools, which help to custom the plots.
- Capability to integrate with various external applications such as PYTHON, JAVA, C, Excel.
- GUI interface has been used for STS simulations to vary the seasonal voltage changes with the OpenDSS COM interface, using external software, MATLAB, to plot the results.

In this thesis, different MATLAB functions have been applied to develop the STS simulations in order to identify all season's variations efficiently. Furthermore, the seasonal energy storage charge/discharge scheduling using STS controlling technique is also used. The voltage variations and seasonal charge/discharge scheduling optimisation techniques are modelled in MATLAB, which are interfaced with OpenDSS to obtain desired results.

1.4.4. COM INTERFACE

COM stands for the Component Object Model (COM) interface capability that makes it a much more powerful and efficient tool to perform STS simulation. The external program can utilise the functionalities of OpenDSS and control the flow of data from and to OpenDSS. The process is explained in Fig. 1.5. MATLAB software is one of the most widely used simulation tools. Furthermore, this thesis also takes the COM interface to analyse the STS simulation seasonally at different buses in CKT24. After interfacing, the GridPV toolbox is seen in the supplementary software in MATLAB. This GridPV toolbox can analyse two series, time-series and static analysis, both of which have been used for the analysis of the seasonal approach in this thesis.

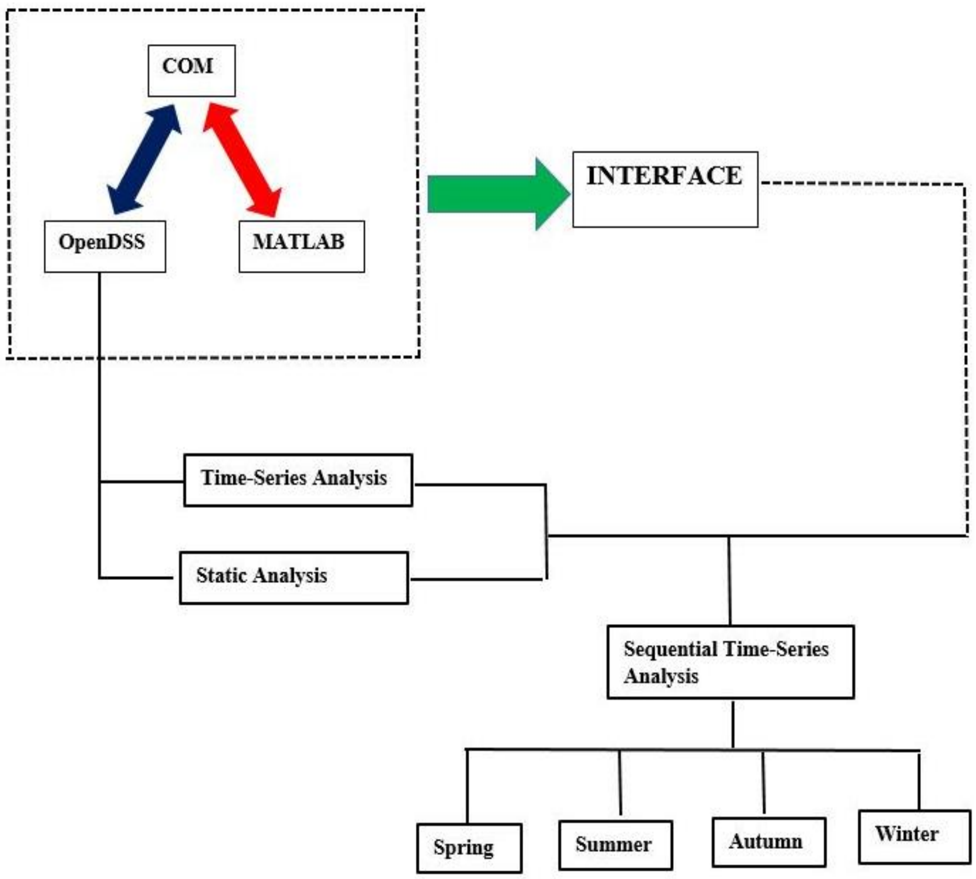

Fig. 1.5. Proposed model for OpenDSS and MATLAB.

1.5. Contribution to Knowledge and Significance

This section discusses the advantages of the proposed research in terms of new knowledge generation highlighting the significance of the work and benefits to the electrical power distribution sector. The work is expected to benefit the power distribution industry enabling greater integration of

PV and battery storage in electric grids. A fixed seasonal charge/discharge dispatch schedule allocation has been used in a network with existing installed PV capacity to minimise voltage quality issues, peak load concerns and to minimise the power supplied by the substation transformer.

1.5.1. Contribution to Knowledge

Presently, optimisation methods are attracting growing attention in distributed generation systems to stabilise the distribution network by controlling the discharge of electricity at critical times, i.e. when demand is more than supply at peak times [12]. This research aims to focus on the fixed seasonal scheduling of ESS composed of photovoltaic and battery energy storage systems interconnected to an electric utility grid. The research will lead to maximising the benefit from an integrated PV-battery storage system. Many researchers have focused on optimisation methods that consider only lithium-ion batteries [1, 13]. In this research, the novelty has been on the development of a fixed seasonal ESS dispatch seasonal scheduling applicable to any batteries. This will lead to increased utilisation of PV and battery storage systems, reducing voltage quality issues, peak load concerns and the need for expensive network augmentation. Most companies are using less expensive batteries but their rechargeable life cycles are also less compared to expensive batteries [13]. In this study, moderate discharge and charge allocations have been set in the storage controller to minimise the aging of the battery and extend the battery lifecycle. This seasonal dispatch scheduling will also have a positive impact on minimising the power supply requirements from the substation transformer also reducing transformer losses. The proposed research creates new knowledge by demonstrating:

- Analysis of an existing distribution feeder for with PV and without PV cases and comparison of voltage power quality issues,
- Modelling of various seasonal scheduling of charge/discharge for the controlled dispatch of stored energy under various weather and load scenarios.
- Demonstration of the need for a seasonal allocation schedule by cross application of seasonal schedules.
- The feasibility of a fixed seasonal dynamic allocation seasonal approach and likely benefits.

1.5.2. Statement of Significance

Electricity usage has been increasing day by day over the last few years in the electrical industry due to the increase of population [1]. The development of ESS usage has been marked significant raised for the application of distribution networks because ESS is more efficient and also back-up for the grids during peak-on times [1]. Integration of PV and battery systems in networks has the merit of improving the operation of the distribution system by ameliorating power quality, system reliability, and supplied power minimised at the distribution transformer [14]. One key benefits of this thesis is the proposed charge/discharge schedule allocations in controlling the operation of energy storage systems to operate across different seasons to improve network power quality outcomes. A key benefit are the developed seasonal Charge (C) and Discharge (D) allocation schedules and validation of the sufficiency of such a seasonal allocation in addressing power quality issues especially the required steady-state voltage limits. Over Voltage (OV) and Under Voltage (UV) issues were sufficiently addressed using such a seasonal allocation approach even when the network was PV penetrated. A fixed seasonal charge/discharge schedule was shown to be sufficient to address the power quality issues in exchange for a complex and sophisticated scheme. This will assist in the development of more cost-effective and failsafe designs due to its simplicity. Another significance of this thesis also includes life-cycle consideration of grid-integrated battery systems as charge and discharge percentages have been chosen to implement partial charge or discharge avoiding complete charge/discharge cycles.

The research will explore various seasonal ESS dispatch allocation approaches to decrease the reliance on the grid at times of peak demand leading to a reduction in cable and equipment losses. An added benefit is cost savings because when demand is more than peak supply capacity, energy may need to be imported from nearby substations to avoid interruption of power supply. As in the AC distribution supply, when the distance increases, power losses also increase. Here, the power losses can be reduced, and the savings of the energy delivered from the grid could be increased when PV and ESS are installed near the buses for reducing the amount of power that has to travel long distances [15]. The energy delivered from a standalone distributed generator is more economical and its output can be quickly varied depending on load requirements [14].

1.6. Thesis Outline

This thesis contains five chapters. The first chapter gives an overview of the thesis, background, significance and contributions to knowledge, methodology and simulation tools used in the research. Chapter 2 gives a comprehensive review of literature including challenges of PV and battery grid integration, different optimisation approaches, and benefits of ESS and potential adverse impacts if proper SOC and DOD are not followed. Correspondingly, the knowledge gaps and potential research directions for future development in this field have been identified. Following the literature review, Chapter 3 presents the steady-state analysis of the two selected buses for with and without PV system scenarios. Each bus in each season has been investigated with and without PV systems to identify the seasonal power quality issues. As the main contribution of this research, in Chapter 4, modelling of PV/battery grid integration using seasonal dispatch scheduling is presented. This includes the fixed seasonal charge/discharge allocations implemented to minimise the over voltage issues and to minimise the supplied power from the distribution transformer. Finally, Chapter 5 summarises the complete research work, highlights the research contributions, and draws the conclusions.

Chapter-2

Literature Review

2.1. Introduction

Microgrids, integration of distributed energy resources, and energy storage technologies are potential solutions to many existing challenges such as power quality and reliability in an effort to minimise system losses and peak load requirements. The proper optimisation of photovoltaic and energy storage systems is very critical for the smart deployment of these systems in the real-time energy management of distribution networks to fully attain their benefits [16]. This section reviews the literature for work in the optimisation of distributed energy resources and summarises work on optimal energy charge/discharge scheduling to identify shortcomings.

2.2. Integrated Photovoltaic and Energy Storage Systems in a Distribution Network

For the integration of PV systems, Linear Programming (LP) was used to optimise the energy storage in distribution networks. In [17], the LP is given as an old technique that was used to optimise the energy management of a dispatch schedule in a distribution network. The LP was used to minimise the peak loads using PV and battery storage systems. In [17], the simulation results showed peak load reductions, but one unaddressed issue was that efficiency would be decreased monthly due to the life cycles of lithium-ion Batteries. The work in [17] discussed the PV and battery system as a combined energy storage system, which can optimise energy management efficiently and economically. Thus, Seasonal Energy Storage Systems (ESS) can be potentially used to optimise the energy storage in off-peak and peak periods across all seasons. Batteries can be operated in an optimised schedule to save energy and improve the battery lifetime with potential reductions in the peak demand from the grid. Finally, these objectives may increase the battery life, minimise peak demand from the substation transformer, and manage the real-time energy by using an online energy management system in PV and battery systems.

In [14], lithium-ion batteries were used to decrease losses in a distribution feeder. Nevertheless, in cold climates, lithium-ion batteries experience extreme power losses, and therefore not ideal for cold parts of the world [18]. To optimise the battery life and size, Sodium Sulphur (NAS) batteries can be used because they would increase the savings of the local distributor and improve the charge/discharge costs of seasonal ESS [19]. NAS batteries are one of the advanced batteries for High Voltage (HV) installations because lithium cannot operate at HV. Authors in [20] demonstrated the optimisation of a grid-connected PV system using a metaheuristic based battery control method. Metaheuristic-based battery control method was a simple algorithm, which was used for higher penetration levels to get an optimum solution for optimisation problems. In [20], the authors explained three strategies of optimisation problems such as state of charge, the insight of discharge and efficiency over a cycle of the batteries. The key project objectives were to reach 100 % renewable penetration by using PV systems and Battery storage. This seasonal ESS is expected to be the significant provider for the future grid-connected distribution networks.

2.2.1. Integrated Photovoltaic systems in a grid

The authors in [21] reviewed the integration of PV systems in electrical grids as one of the cleanest renewable energy sources. However, researchers were unable to manage the energy with one source of energy because of excess demand on the consumer side. The main concern in [21] is the management of peak energy demand. The key focus of the work was on the review of specific optimisation techniques and identified that integrating PV and battery storage systems as the optimum method of managing the energy in peak time. Photovoltaic systems are one of the significant sources of renewable energy, followed by wind and geothermal. Photovoltaic systems are considered as significant sources of renewable energy because they are the most prominent ones that are available in the nature. They are free of cost and with less maintenance requirements when compared to wind or other renewable resources [22]. Despite numerous advantages, there are few drawbacks of PV systems that affect the grid due to low irradiance during the winter season. Solar energy is otherwise called the "non-dispatchable resource" [23]. To overcome the problem of insufficient amount of solar energy in winter seasons, researchers investigated the use of battery banks for energy storage, which need not be used in off-peak times [24],[25]. There is a deficiency of control over the output power injected into the grid by PV systems. That is the PV output cannot be predicted or controlled. The inability of generating on-demand power triggers stability and reliability concerns [25]. In this thesis, the objective is to provide a cost-effective simple solution for integrated photovoltaic systems embedded in a grid in an effort to alleviate some key challenges associated with operating photovoltaic systems in a distribution network.

2.2.2. Energy Storage Systems in a Distribution Network

Energy management is an essential aspect of distribution systems due to increasing electricity demand all over the world. Overloading on the consumer side is the burning problem. It occurs when there is a vast increase in consumption, resulting in more demand than the available supply capacity. Researchers found that Battery ESS is a perfect option for solving the unpredictability and intermittency concerns of RES in distribution networks [26]. Many scientists have proven experimentally that energy storage using batteries is one of the most economical and efficient methods of balancing the electricity networks in a grid. There is a wide range of different battery types that may be used. For example, lead batteries are well established both for automotive and industrial applications and have been successfully applied for utility energy storage. There are also ranges of contending advancements in energy storage technologies including Li-ion, sodium-sulphur and flow batteries that are used for energy storage [27].

The application of Energy Storage Systems (ESS) with renewable energy resources stands out amongst the most practical answers for the smoother infiltration of RES in electrical distribution networks [28],[29],[30],[31]. The interface between the distribution network and source of generation is achieved via inverters to manage the required Power Factor (PF) [32]. In a technical point of view, ESS can supply reactive power in order to operate at peak loads, which can occur when PV systems are producing no or little real power. This allows the ESS to provide variable reactive power, continuously allowing the ability to regulate the voltage more closely [33]. ESS and its management play a prominent role in the excellence and efficiency of electric power systems. In [34], the authors proposed an optimal allocation of ESS units in distribution systems to optimise battery storage and energy management.

2.2.3. PV/Battery Grid Integration in a Distribution Network

PV/Battery grid integration in a distribution network can solve the problems of electric utilities and improve the continuous and uninterrupted supply of electrical power to consumers. This also reduces the peak demand changes by using ESS because of avoiding consumption of electrical energy from other substation in peak times.

According to discussions in [35],[36], battery adoption can alleviate peak demand challenges in a grid-connected distribution system. In [36], researchers have reviewed technical aspects of ideal energy storage capacity, dispatch scheduling, and implementation costs for the seasonal ESS. Seasonal ESS was given as a solution to optimise the peak load and meet the capacity of integrated battery systems. The study has modelled and simulated such systems in software. Seasonal ESS can help to avoid the problems, when the consumer demand is higher, as it is standalone system. The global population increase and the corresponding increase in the electricity demand is necessitating such innovative solutions. Implementation of these are very critical in meeting the extra demand while increasing efficiency and reducing losses.

Peak demand in power systems is rapidly increasing all over the world, and distributed networks are more and more reliant on renewable sources. The demand for power supply and generation has increased in line with the customer demand. This means that more efficient utilisation of generation, transmission and distribution systems may assist electricity distributors in increasing the utilisation of available network capacity and delaying network investments. Consequently, the available capacity of a distributed network can be increased to align with the peak load demand increase. This can be best achieved by using the seasonal ESS as ESS is more efficient and economical in addressing the future challenges of the electrical grid. Seasonal ESS can improve battery lifetime and reduce the substation transformer losses without relying on other substations to meet the increase in the consumer load.

2.3. Optimisation Methods

In [21], the author discussed a multi-target improvement for seasonal ESS dispatch. The aims of the study were achieved with a quadratic objective and linear constraints with observed energy generation improvement using angle inclination [37]. Age costs were displayed as one of the key expenses brought about by the utility to deliver the power from the substation. Grid operation costs, shared by the utility, were used for the optimal scheduling of the seasonal ESS. The reduction of system losses and energy delivered from the grid due to seasonal ESS were studied. Optimisation methods highlight three benefits. These are shaving of the peak load, reduction of system loss and energy supply from the grid, and accommodation of the variability of the distributed generation resources [14].

2.3.1. Shaving of Peak Load

In [38], researchers identified that in new distribution networks, the energy storage depends on weather conditions. Varying conditions were given as factors that may affect the amount of storage and integration with the grid. The study focused on installation of more PV systems to manage the peak load and to improve the power output of renewable energy resources. To achieve this, Combined PV and Battery storage was given as the ultimate technique, as an off-grid storage solution, to balance the peak load reduction. The reduction of peak load was studied in detail [38], and peak load reduction and changes that affect the outcome were simulated using the OpenDSS software. The optimum strategy was cost savings during night and daytime by charge and discharge the batteries. Authors in [38] proved the modelling outcome of the proposed solution in OpenDSS. United States electrical systems are discussed as an example network, which are overloaded across the winter and summer seasons because of the demand growth in certain areas. Summer and winter overloads occur from afternoon until midnight. During non-peak times, from midnight to till afternoon, PV and battery storage systems can be operated in the charge mode. They will then play a significant role in shaving the peak load at on-peak times when they can be discharged when the load is more than the available capacity. This charge/discharge operates daily, and the energy flow should be monitored daily by the energy management system [39].

2.3.2. Minimising Transformer Supplied Power with ESS

Prajapat et. al. focussed in [40] on the reduction of system losses and energy delivered from the grid. The work followed a complicated approach and involved monitoring of the real-time grid data in reducing losses with the ideal utilisation of the prevailing transmission system [40]. Many researchers carried out investigations on transmission losses for better operation of networks with improved and higher performance. In [41], authors explained about some calculations of transmission losses. To avoid system losses and for getting better efficiency, smart grids were discussed as the futuristic invention for many grid-connected systems. Smart grids usage has increased in a short time to execute outstanding results with excellent efficiency. In [42], the authors discussed inclusive design and implementation of on-line load angle measurement for real-time transient stability improvement of synchronous generators in a smart grid. The research work discussed in [43] addressed real-time data monitoring and management by optimising with seasonal ESS when the consumer energy demand is at its peak [44]. This optimisation can improve system reliability and efficiency in the grid-connected system [45]. The reduction of system losses and improvement of energy delivery using integrated ESS at grid micro grids were also reviewed and simulated using the MATLAB software in [46].

2.3.3. Variability Accommodation of the Distributed Generation Resources (DGRs)

In late ’90s, there was extensive development in the Distributed Generation Resource (DGR) technologies due to the limitations on conventional generation of power in electrical grids [47]. As renewable energy resources are not likely to be reliable in most cases, integration of photovoltaic and battery storage came into existing networks to solve the issues of peak demand problems in the distribution network [48]. In [47], the authors have researched alternative random planning methods to decrease the life cycle cost of DGR’s and reduce transformer losses in grids. The research work in [49] proposed Optimal Placement and Distributed Generation (OPDG). In general, the optimal location of a distributed generation is a type of generation which would intensify to reduce the size, optimal number, and bus location of OPDG. Few decades ago, the Newton Raphson method was used to identify the problems of OPDG units inter-connected at weak network busses, and to assess the voltage profile and power losses on the buses [49]. OPDG units may reduce the problems at weak network buses with better voltage profile and fewer power losses [50]. With optimal placement, power losses were reduced by almost 15%, and the voltage drop was improved by 8.72% by four OPDG units as discussed in [49]. Seasonal optimisation and sizing strategy were used to simulate these stages in [37] and [47].

2.4. Seasonal Load Variation in the Distribution Systems

In [51, 52], the authors have explored the analysis of the seasonal load variations. The PV generation output can practically be at either its minimum or maximum level depending on weather patterns across all seasons. However, due to the reverse power flow in a distribution system, these can cause voltage quality issues across all seasons [53]. Energy storage is a distribution system across all seasons plays a crucial role to minimise the voltage quality issues. Grid-integrated seasonal energy storage can reshape seasonal voltage fluctuations, reducing power quality issues and reducing transformer losses. These days, most literature focuses on battery technology life and cost assessments and does not distinguish the potential benefits of the seasonal energy storage to improve the effective solutions. A fixed seasonal charge/discharge dispatch schedule could minimise the transformer loading and voltage quality issues. Due to the extinction of fossil fuels and a trend towards the utilisation of renewable energy sources, a standard voltage stability control scheme would be inadequate for daily, monthly, and yearly control of the grid. Therefore, seasonal load variation with sequential power flow analysis is given as a potential solution for the brief analysis of the impacts of climate change on seasonal stability issues. In [53], researchers stated that ESS could be used to manage the power between the utility grid and PV generation also regulating the voltage stability. Nevertheless, in [54], the authors stated that maximum charging can cause under-voltage issues and maximum discharging could raise over-voltage concerns. These voltage variations can practically occur in all seasons. In this dissertation, the EPRI Test Circuit 24 (CKT24) has been taken as a case study to focus on analysing the seasonal voltage quality issues brought about by high PV penetration in the analysed case study network.

2.4.1. PV Systems Impact on Seasonal Variations

In [55], researchers have explained about the Morphing method, which is to predict the hourly solar irradiation data as a future reference. In this work, a Simulink model was developed as a technique to predict the solar irradiation. If solar energy is not sufficiently available in a particular season, then there will be no alternate backup energy from the grid. Researchers explained in [56], the summer season has the highest irradiance and the winter season has the lowest irradiance. This implies that seasonal changes can effect on the PV system's irradiance input which leads to minimum PV generation output in the winter season. Other than irradiance, PV systems can also cause high PV penetration issues in the distribution systems. In [57], authors described that the distributed energy sources could control the voltage mitigation issues in a network. Maximum charge and discharge levels were given as factors that can also cause Over Voltage (OV) or Under Voltage (UV) issues. The work discussed in [58] explored 3P tracking system of solar energy, and raised concerns on what strategies to implement if the solar energy was entirely not available. The focus was on predicting the weather patterns to improve the assessment on the solar energy output availability.

2.4.2. Optimal Charge/Discharge Allocation in ESS

The optimal allocation of charge/discharge scheduling is important to control the voltage issues. In [54, 59, 60], researchers have explained about the optimal site allocation of energy storage systems and their sizing for cost reduction and maximum operational benefits in the distribution network. Optimal allocation of ESS can also reduce the DG losses, improvement in the voltage profile and increase the ageing of the batteries. Nevertheless, if a battery is charged/discharged to its maximum or minimum levels everyday across the year, it will effect on the batteries life. The authors have explained in [61, 62] that a deep discharge of the battery can increase the rechargeable cycles of the battery, which in turn decreases the life of the battery. In this thesis, distributed ESS is being used to minimise the voltage issues at different buses in different seasons because every bus has different a load variation profile. If a single energy storage is used across the distribution system, then it is difficult to manage the voltage issues in the distribution network seasonally. That would require the battery to be charged or discharged with maximum percentage and then the number of cycles of the battery would be increased and the battery life would be decreased. In this thesis, PV/Battery grid integration will be used as a solution to manage electricity demand at on-peak hours by using a seasonal dispatch scheduling. By using an appropriate seasonal charge/discharge dispatch schedule, the transformer losses will be minimised, and the voltage profile will be improved all seasons.

2.4.3. Seasonal Charge/Discharge Scheduling

Batteries have two significant modes, which are the charge, and discharge modes. Batteries can store and dispatch energy at particular times when required. Using the two modes, the energy stored or dispatched seasonally can be optimised with respect to time. In [63], the authors stated that the summer average load consumption is more than the spring, autumn and winter seasons. Due to the minimum load consumption utilised by consumers in the spring, autumn, and winter seasons, there is a possibility of voltage quality issues across these three seasons. Due to this seasonal variation, the impact on the bus voltage profile would be severe [64, 65]. In this thesis, the rate of charge/discharge scheduling will be developed based on the lightly loaded network as that experiences more severe voltage quality issues than heavily loaded season. The seasonal load effect is considered in this thesis and the scheduling of charge and discharge will be given analysed across all seasons to control the voltage profile [66].

2.4.4. Time Series Analysis in Energy Storage Systems (ESS)

Due to the rising demand on PV systems and ESS in the current trend, power plants are taking decisions based on the demand of electricity and grid condition. These conditions include current feed-in, weather data and consumer demand. In addition, time series observations have been taken sequentially throughout the year, but no such model exists that clearly explains seasonal voltage variations and whether they can be addressed using fixed settings for each season [67]. For solving these challenges, many power plants are focusing on developing strategies on time-series based simulations. Time-series based solutions are critical for the operation of the grid. Otherwise, any unpredictability generation of load leads to a violation of the electricity grid parameters. Especially, when demand is unpredictable at peak hours in the summer season due to large utilization on consumer side. Therefore, demand side management is important, but it is not always helpful for unprecedented consumer load [68]. The key short coming in [69], using Quasi-Static Time Series (QSTS) analysis, is that different seasons cannot be identified. Furthermore, the use of the temporal decomposition method can only reduce the run time of QSTS simulation program in the OpenDSS environment for one-year mitigation error. For seasonal analysis on the other hand, the annual will be divided as seasons. So, the use of STS provides quicker and faster simulation for mitigation errors.

The key weakness in [70, 71] was that although voltage regulation is maintained in between 0.95 to 1.05 p.u, due to intermittency of PV Systems, the voltage may fluctuate during peak time and also the tap changer position has influenced the frequency response of the transformer. Moreover, using QSTS, for the integration of PV analysis in a distribution system, the voltage fluctuations will be grown larger due to the high PV penetration. The key shortcoming in [72, 73] was that the works did not address voltage fluctuations at a specific time in the Energy Storage System. Moreover, storage systems with deeper discharge for one day or one week is more expensive to run. In [74], the authors have explained that battery life depends on the number of cycles of charge and discharge, and the peak current and temperature. Therefore, deeper charge/discharge will affect the life of the battery, but a shallow charge/discharge allocation could help to increase the battery life.

The main key shortcoming in [75] was that the literature review focused on technology cost assessments and did not characterize the potential grid benefits of seasonal storage to capture the most cost-effective solutions. In [75], the authors haven't clearly explained about the seasonal variations and feasible solutions. Moreover, the given energy storage techno-assessment is only an approach for energy storage techno-assessment cost comparison. Therefore, in [75], the authors weren't clear about the how the proposed charge/discharge allocations could assist in avoiding a reduction of battery life. This approach hasn't proposed any solution to how seasonal electricity fluctuates in the grid, when PV systems are installed at the distribution systems.

2.5. Conclusion

This literature review has presented a review of research work and developments in the area of utilisation and development of ESS in distribution networks. This Chapter has first discussed the integration challenges of PV systems in distribution networks and the use of integrated energy storage combined with PV systems to optimise the grid energy requirements in peak and off-peak periods. After that, seasonal load energy storage and control was discussed as an approach that could play a pivotal role in energy distribution systems to control PV penetrations and voltage regulations. In addition, the integrated energy storage systems can also be used to provide reactive power for better voltage regulation and for reduction of system losses and energy delivered from the grid. The seasonal approach with a fixed seasonal charge and discharge scheduling plays a major role to have the potential to give a good overview of steady-state analysis of the network. This could then be used to develop a simplistic, yet effective integrated energy storage management and control system. ESS with seasonal charge/discharge scheduling allocation can be an ideal solution for most future grids to control the seasonal power quality issues.

Chapter-3

Seasonal Impact on Voltage Quality Issues at EPRI CKT24

3.1. Introduction

In Chapter 3, the CKT24 case study is presented to study the time-series behaviour of the CKT24 real-time distribution network with grid-integrated PV systems. The focus is on exploring the impact of seasonal variations on the voltage quality issues. The broader objective aims to demonstrate the need for an adaptive battery integration scheme that considers seasonal variations. Electricity usage has been increasing all around the world based on changing lifestyle and increasing population. The share of the grid-integrated PV systems has been increasing day-by-day in the past few decades, and also the consumption of electricity is increasing at a rate more than the generation capacity [76].

The Chapter has been divided in to eight sections which is described below. The Chapter begins with an overview of the EPRI CKT24 technical data and proceeds with a study on the seasonal assessment of daily bus voltage fluctuations at two selected buses within the EPRI CKT24 network. Electrical Power Research Institute (EPRI) has few practical distribution networks with grid-integrated test circuits such as the CKT5, CKT7, and CKT24. One of these real-time EPRI distribution networks, namely the CKT24, has been chosen for detailed investigation as the case study in this research, which includes 7.5 MW Photovoltaic Distributed Generation (PVDG) capacity. Two buses in the CKT24 network have been chosen for the detailed analysis and this Chapter will focus on analysing the daily voltage profile variation at these two buses specifically highlighting the Over voltage (OV) issues [77, 78].

This chapter will further investigate the seasonal impact on the system voltages explored due to the integration of PV in each season. Nowadays, the installation of PV systems in distribution systems is increasing rapidly. Due to the variability of irradiance or unpredictability in the planning and performance of PV systems, the voltage quality issues occur at the distribution feeders [78]. In [79], researchers state that PV systems can cause the voltage and power fluctuations due to seasonal changes. In this Thesis, the analysis will focus on comparing the daily bus voltage profiles for the with-PV and no-PV cases. The impact of the PV power output on the system voltages will therefore be quantified along with seasonal comparisons.

3.2. Technical Details of EPRI CKT24 Distribution Network

The EPRI CKT24 network diagram with its significant components is illustrated in Fig. 3.1. The EPRI CKT24 distribution system voltage rating is 34.5 kV and has a peak demand of 28.45 MW. EPRI CKT24 includes 843 transformers (step-up and step-down), and the longest 3-Phase path is 6.88 km, with a 13.2 kV rating as shown in Fig. 3.1. The green coloured square boxes in Fig. 3.1 show the three capacitor banks of the EPRI CKT24 network, which are located at three different locations of the distribution system. These three capacitor banks are rated 1200 kVAr, 1200 kVAr, and 900 kVAr, as shown in Fig. 3.1. The red-coloured rhombus, located at the centre of the network, shows the Load Tap Changer or Voltage Regulator (LTC/VREG) connected to the distribution feeder [80].

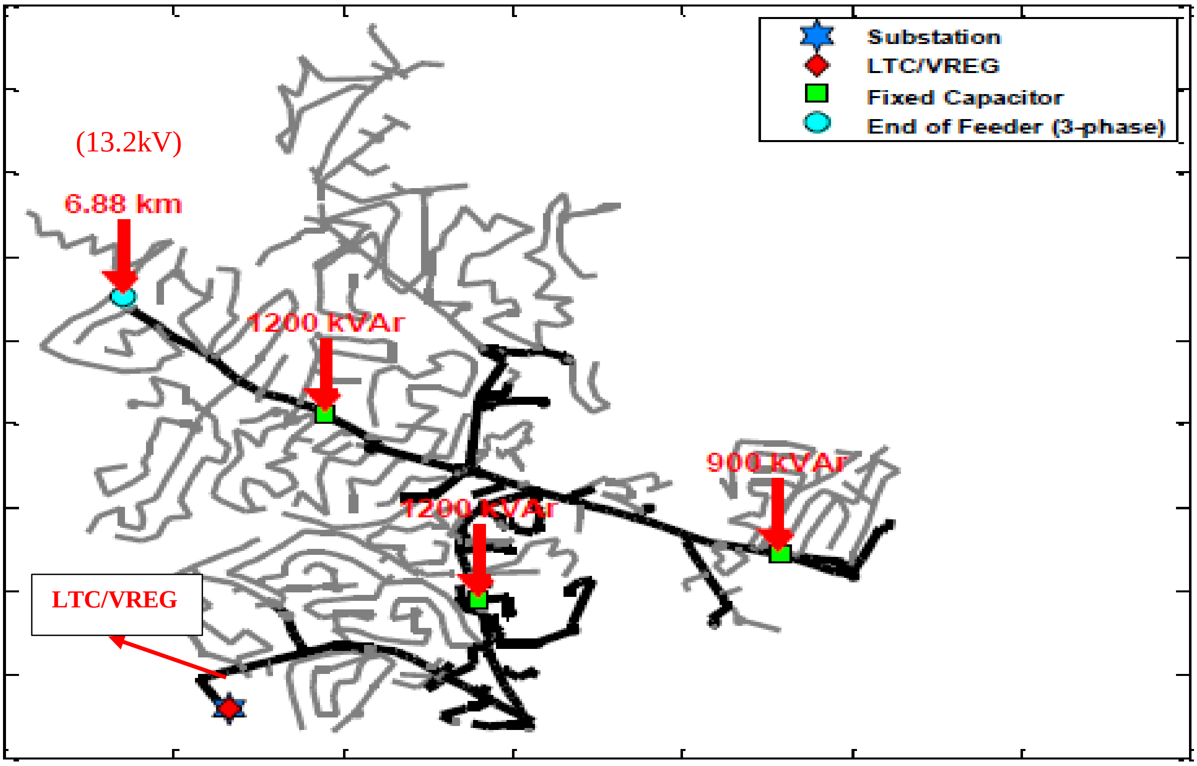

Fig. 3.1. EPRI CKT24 Network Diagram [81].

There is a substation transformer with a rating of 230 kV/34.5 kV with the load-tap changer set-point fixed at the rating of 123 kV and further characteristic details as shown in Table. 3.1. In [76, 82] , the authors found that due to high PV deployment, a chance of voltage quality issues can occur at the VREG point due to the substantial decrease of load demand.

Commonly, there are three types of voltage regulation devices used in the distribution systems. These are the Load-Tap Changers (LTC), Line Voltage Regulators (VREG) and Switched Capacitors. In the CKT24 distribution network, large PV deployment could affect the performance of these three regulation devices depending on the load, location, and operational settings. When PV systems are installed at the distribution systems, power quality issues are expected [82].

Table. 3.1. Characteristics of EPRI CKT24 [81].

Characteristics	Rated values
System voltage (kV)	34.5
Number of Customers	3885
Service Transformer connected kVA	69373
Total feeder kVAr	3300
Sub-transmission Voltage (kV)	230
3-Phase Short Circuit Current at Secondary Substation (MVA)	422
Total Primary Circuit (km)	119.091
Percent Residential by Load	87

In CKT24, all three-phase load profiles have been taken as the case study data. In this thesis, the one-year data has been divided into seasonal periods to acquire seasonally based profiles. In the U.S., there are four seasons: spring, summer, autumn, and winter. In Table. 3.2, the timestamp details of these seasons corresponding to an hour-based sampling of the real data are shown. The three-phase one-year simulation results are discussed later in Section 3.3.

The spring season last from the 1st of March to the 31st of May and covers the simulation timestamps from the 1417th to the 3623rd hours. Summer is from June to August and the timestamp range 3624 to 5832 hours includes the relevant data sets. September to November includes the autumn covering the 5833 to 8017 timestamp hours. Finally, winter last from the 1st of December up until the end of February and covers the simulation timestamp range from the 8018th to the 1417th hours.

Table. 3.2. Seasonal details of EPRI CKT24

Date	Seasons	Hours
1st March to 31st May	Spring	1417 - 3623
1st June to 31st August	Summer	3624 - 5832
1st September to 30th November	Autumn	5833 - 8017
1st December to 28th February	Winter	(December: 8018 – 8760, January and February: 1 - 1417)

3.3. Load Profile of CKT24

The load profile of CKT24 for Phase-A, Phase-B, and Phase-C are shown in Fig. 3.2 and 3.3 below. These three-phase load sets of data were taken from the EPRI website for the whole period of one year (8,760 hours). In this whole period, the maximum peak demand load is 28.45 MW, and the minimum load of 6.06 MW. The load profile of all phases is taken in one-hour timestamp simulation for the whole year. The time-series simulation formulas were discussed in the methodology. These EPRI CKT24 load profiles have been used for the one-year time-series analysis of the real-time distribution system [81]. Fig. 3.2 shows the p.u. load profile for all phases over the one-year period. As shown, the load consumption is at highest levels during summer and winter. The average three-phase load power shows a similar trend.

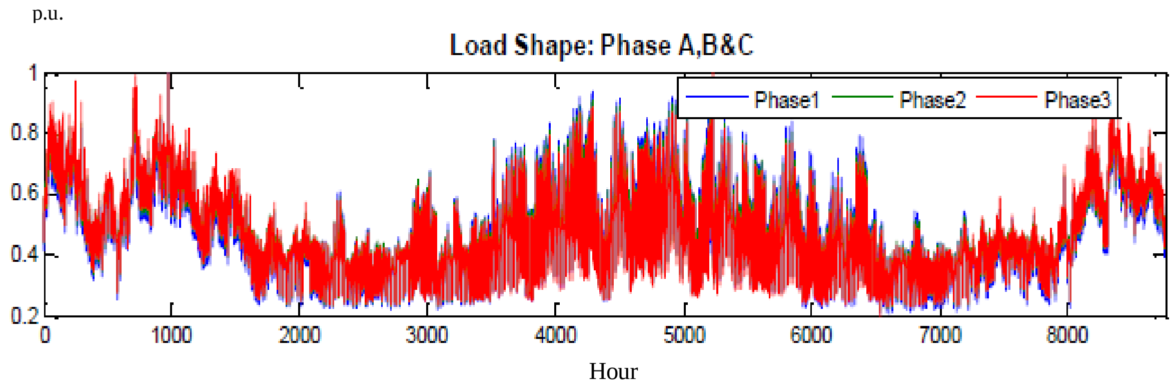

Fig. 3.2. EPRI CKT24 Load shape: Phase-A, Phase-B &Phase-C for one year [81].

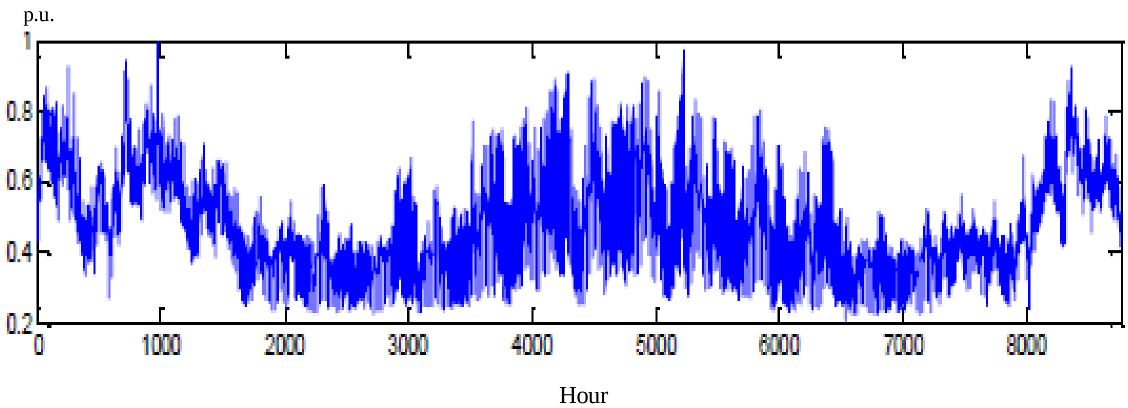

Fig. 3.3. Average Three Phase EPRI CKT24 load shape for one year [81].

3.4. Problem Statement on CKT24

Electric power consumption of consumers varies with time and seasons. This change in seasons affects the load profile and supply requirements, particularly at times of overload by the customers. Consequently, in designing for the operational strategy of an energy storage system such as charge/discharge, several factors need to be taken into consideration.

These include the varying load demand impacted by seasonal changes and changes in the seasonal and daily generation output of PV systems. The key objective in this chapter is to demonstrate how a dynamic charge/discharge strategy may be required at selected buses where Under-Voltage (UV) or Over-Voltage (OV) issues may be a problem.

Thus, the CKT24 network data is used as a case study network, including the actual real-time data of residential customers and the actual generation output of PVs during all seasons. The network was simulated as such that the time-series simulation captures the daily and seasonal changes in the load profile as well as the power output of the installed PV system.

In CKT24, the voltage quality issues are occurring due to the integration of PV system, as it will be demonstrated in this thesis. In general, researchers have determined that there is a reverse power flow potential due to increased PV systems power injection, and that high PV system injection affects the voltage profile due to changes in the output of the PV systems with seasonal variations [83].

In CKT24, the voltage quality issues are more serious due to rising PV penetration in the distribution system. Simultaneously, high PV penetration causes various Over-Voltage (OV) or Under-Voltage (UV) violations due to the grid-integration of PV systems at distribution networks [84]. The focus of the broader research is modelling of an Energy Storage System (ESS) and seasonal allocation of change/discharge schedules to reduce such voltage quality issues for the four seasons, including spring, summer, autumn, and winter. These four seasons were taken based on U.S. weather scenarios because the EPRI CKT24 is a U.S. distribution system.

3.5. EPRI CKT24 Limitations on PV Penetration

As discussed above, the case network already experiences OV issues made worse by PV penetration in the distribution system. In addition to this PV penetration, the distribution system also experiences voltage unbalances, reliability issues, stability issues, and power quality issues [83]. The authors explained in [83] that when some active power sources are connected to the feeder voltages, then there is a chance of increased voltages. In the following sub-sections, the case study has been simulated and analysed in line with key American grid code standards for grid voltage steady-state voltage limits when PV systems are connected to the grid or distribution feeders [83].

According to the American National Standards Institute (ANSI) [85], “Present regulations require to maintain their substations and PV systems terminal bus voltage within 0.95 to 1.05 PU (ANSI C84.1 -2011 Range A)” while injecting power into the distribution systems [86]. PV systems with high capacity can cause a rise in the voltage. Since the CKT24 is lightly loaded, power injections from high capacity PV systems often escalate such over-voltage and peak load problems [87].

Thus, it is critical to examine the effect of PV systems on the voltage quality issues due to seasonal variations. As per Fig. 3.4, the reverse flow at CKT24 is contributing to the problem. These over-voltage issues are increasing due to non-reversible controls operating at the substation when the load is operating at a minimum. For instance, researchers stated that CKT24 has a rated peak load of 6 MW and distributed generation up to 1.7 MW [88]. All the voltages in the distribution system of the U.S. need to comply with the ANSI C84.1 Range A standard [85].

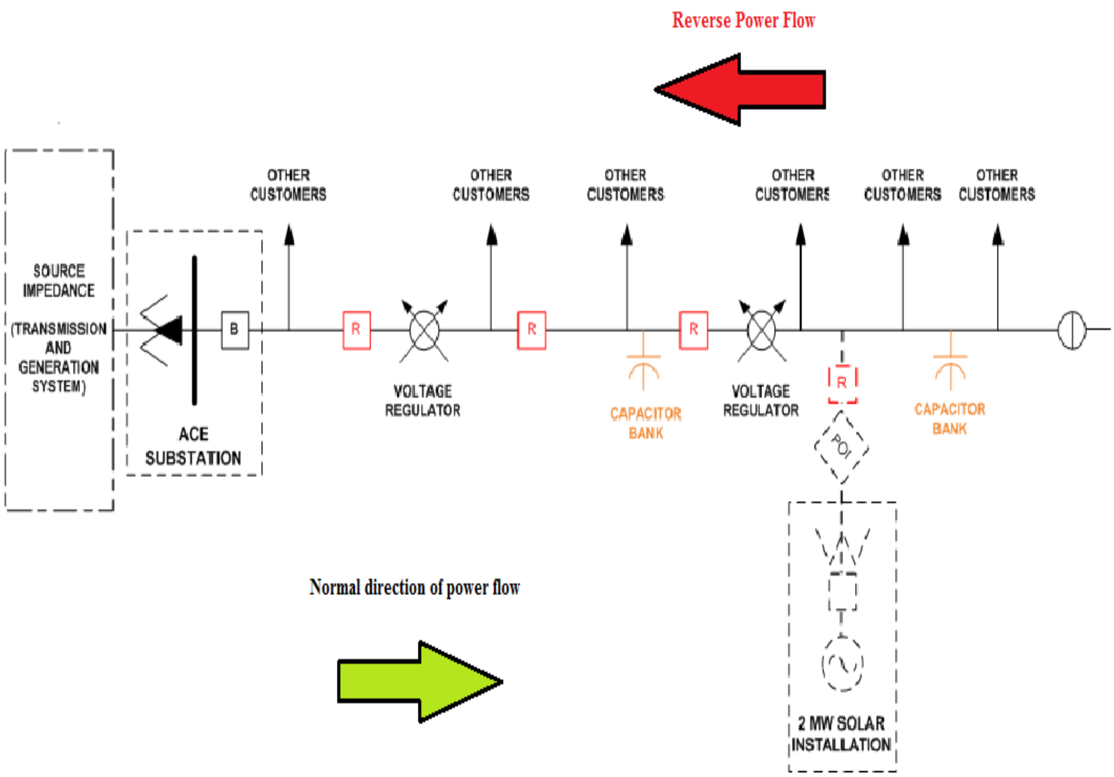

Fig. 3.4. Typical circuit diagram Power flow at CKT24 [89].

3.6. PV System Impact on CKT24

Existing installed PV systems in CKT24 are creating voltage quality issues. The PV systems are injecting currents into the distribution feeder, causing voltage rises at the PV PCC due to reverse power flows, and due to this reverse power and load variations, the voltage fluctuations vary seasonally. In general, the voltage fluctuations depend on both impedance and current injection of the circuit path between the PV PCC and Upstream Voltage Regulator (VREG) near the existing PV system [90].

Fig. 3.5 illustrates the voltage profile of CKT24 for all phases concerning distance at CKT24 without any PV systems. As shown, the voltage per unit needs to be between 0.95 (p.u.) and 1.05 (p.u), and all three phases are operating within the ANSI range.

According to ANSI standards, the voltage profile must be within the ± 5% range. So, the voltage has to operate with ±5% tolerance [91]. Many studies have proven that due to high PV penetration, the voltage rise occurs at the distribution system at times due to decreased power consumption [78]. Phase C has the worst voltage profile compared to the other two phases, as the Phase-C voltage is higher than the other two phases and close to the upper limit of 1.05 p.u. In general, for all phases, we can see a drop in the phase voltage as we move further away from the substation. As shown in Fig. 3.5, the case study network does not experience any OV or UV issues with no PVs installed.

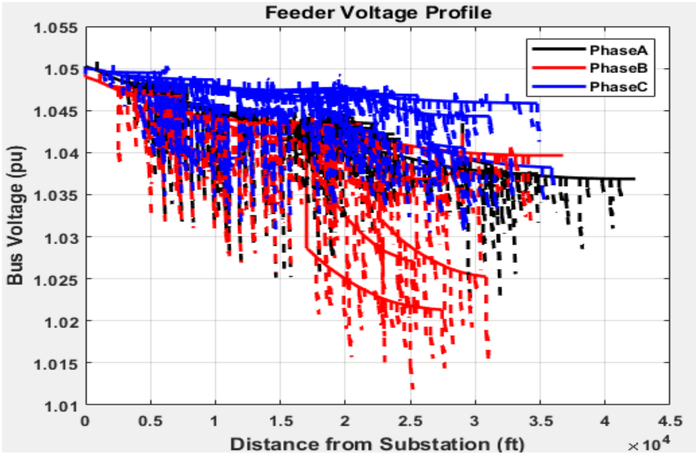

Fig. 3.5. Voltage profile with No PV system at CKT24.

Fig. 3.6 shows the PV installed case at the CKT24 feeder, which shows an OV problem primarily at Phase-C. The yellow stars indicate the location of the distributed PV systems with respect to distance from the substation distributed on all phases. It is clear that Phase-A and Phase-B are more heavily loaded than Phase-C. Hence, the reverse power from the PV system is only having an adverse impact on Phase-C. The Phase-C voltage clearly rises above the 1.05 p.u. limit especially at buses where the PV systems are installed. This shows that a focus on Phase-C is required in this research.

This study and inclusion of Energy Storage System (ESS) charge/discharge strategy considers Phase-C only, due to the more significant load and PV impact on this phase. As shown, the bus voltages have increased more than the range at specific locations due to reverse power flow from the PV systems installed nearby, and the objectives of ESS strategy could be to regulate the bus voltages to overcome these issues at Phase-C ensuring operation between the permissible voltage ranges permitted by the ANSI standard.

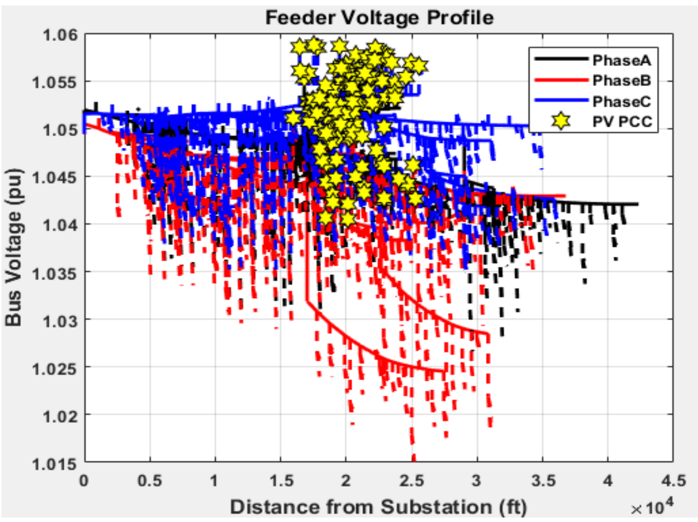

Fig. 3.6. Voltage profile with PV system at CKT24.

3.7. Voltage Violations Seasonally Impact on CKT24 at Phase-C

Many researchers have found that drastic weather changes between the four seasons can impact the power output of PV systems; furthermore, weather variables such as rainy or cloudy weather can also be experienced at times, within any one season. Countries are adding PV systems to their distribution feeders for backup or additional standalone renewable generation to the grid, but the PV output is intermittent, and large fluctuations can be perceived due to changes in the weather. In [15, 16] this impact on PV generation output is examined; and in [14], the study investigates seasonal changes as a major factor in voltage flickering.

This section aims to explain and analyse voltage violations for every season within the CKT24 network, using the one-day load profile for the analysis of each season, and to identify over-voltage power quality issues with and without PV systems at BUS-X and BUS-Y at Phase-C. The time series simulation is conducted with fluctuating load demand impacting voltage and power variations at Phase-C. The locations of BUS-X and BUS-Y are shown in Fig. 3.7. The voltage tends to drop below its operating voltage at distribution feeders when load increases.

Thus, distribution networks have to be designed to minimise voltage fluctuations due to increases in load power consumption. The integration of PV systems in a distribution system can improve the voltage profile. Nevertheless, if the power generated by the PV system distributed generation is higher than the usual local demand at the Point of Common Coupling (PCC), then the surplus power flows back to the grid. Distributed generators may result in excess power generation which may create reverse power in the feeder causing OV issues at particular low load buses within the feeder [92].

The OpenDSS and MATLAB COM interface using the GUI toolbox of real-time simulation has been used to determine the BUS-X and BUS-Y voltage profiles for each season in this thesis. The one-year hourly, historical data was used to explore the voltage quality issues at CKT24 for BUS-X and BUS-Y. For every season, the one-minute data was further taken to highlight the voltage quality issues at BUS-X and BUS-Y for one day per each season.

BUS-X corresponds to the ‘N283701’bus number, which is connected to the overhead line of ‘Line.05410_339448OH’.Whereas, BUS-Y correlates to the ‘N292246’ bus number, which is connected to the overhead line of ‘Line.05410_339659OH’. BUS-X and BUS-Y have three phases with a base voltage of 132 kV. Table 3.3 and Table 3.4 show the technical data of BUS-X and BUS-Y.

Table. 3.3. Technical details of BUS-X.

BUS-X	**values**
Bus Name	(N283701)
Number of Phases	(3)
Nodes	(1,2,3)
Voltage Angle	(0.0767 radians)
Voltage per unit	(1.0525 p.u.)
Voltage	(139.7 kV)
Phase Voltages	(139.7 kV, 139.6 kV, 139.8 kV)
Base Voltage	(132 kV)

Table. 3.4. Technical details of BUS-Y.

BUS-Y	**Values**
Bus Name	(N292246)
Number of Phases	(3)
Nodes	(1,2,3)
Voltage Angle	(0.0617 radians)
Voltage per unit	(1.0581 p.u.)
Voltage	(140.5 kV)
Phase Voltages	(140.5 kV, 140.4 kV 140.6 kV)
Base Voltage	(132 kV)

Fig. 3.7 categorises bus voltages in terms of the steady-state voltage magnitudes. In this chapter, BUS-X is chosen due to its proximity to the substation. BUS-Y has its proximity to the PV system. Both buses have their technical data, outlined in Table. 3.3 and Table. 3.4.

All PV systems are concentrated at the cenralised location at far end of the network as that has resulted in lesser challenges. The darker red colurs indicate regions of the network where the volatges are at their higest levels. As shown, buses close to the installed PV sustems are at higher voltages. BUS-X and BUS-Y correspondly were chosen as they are within the region of the network most imapcted by PV penetration.

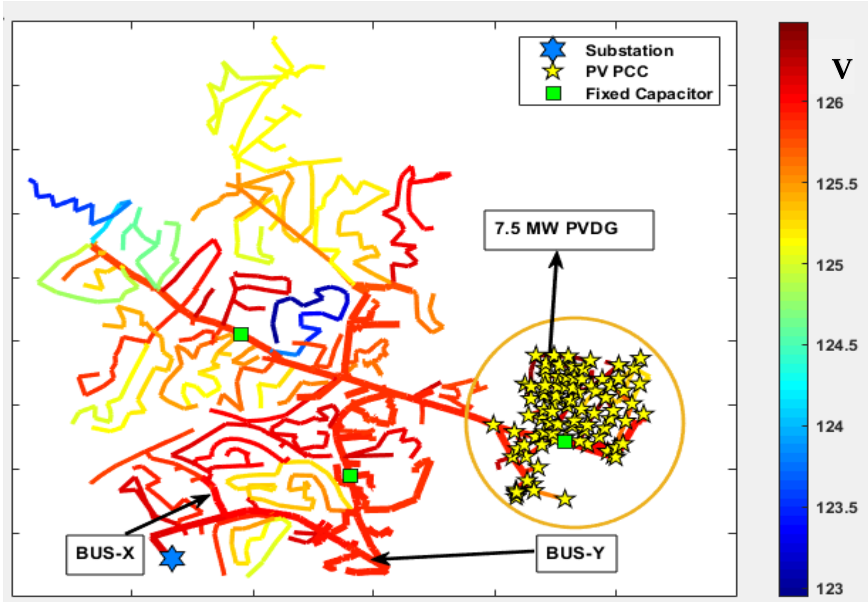

Fig. 3.7. Geographical visualisation of CKT24.

3.7.1. Voltage Quality Issues with and without PV at BUS-X in Spring Season

This section highlights voltage quality issues at Phase-C of BUS-X due to PV system generation capacity and load fluctuations. At BUS-X, Phase-C experiences more serious voltage quality issues than the other the two phases. Therefore, in this section, the Phase-C simulation results have been plotted for with and without PV cases to highlight the voltage quality issues. As shown in Fig. 3.8, the Phase-C voltage is operating above the ANSI operating range for both with and without PV system cases.

In Fig. 3.8 (a), the blue graph represents BUS-X Phase-C one-minute time-series simulation for a one-day peak voltage profile of the spring season on the 9th of May without any PV generation. The 9th May 2016 was identified as a peak day in the whole spring season and chosen for detailed analysis. In undertaking the with-PV and no-PV analysis, the PV-data was removed from the base data to enable an assessment of the bus voltage without-PV case.

This was done by editing the script code modelling the network in MATLAB. BUS-X Phase-C voltage is higher than the upper limit between midnight (3072nd hour) to 7 am (3079th hour) on the 9th of May for the no-PV case. Therefore, OV issues last for a total of seven hours.

In Fig. 3.8 (b) the red-coloured graph shows the voltage profile for the one-minute one-day time-series simulation for the PV case. It is possible to see that with PV generation; voltage fluctuations are more severe than the no-PV generation case. In distribution generation, voltage fluctuations occur due to load variation in time [93]. As shown in Fig. 3.8 (b), voltage fluctuations occur between 12 am to 10 am (3072nd hour to 3082nd hour) for the with-PV case.

For the no-PV case, the bus voltage was below the upper limit from 7 am to 10 pm (3079th hour to 3094th hour). The bus voltage varied far below the upper limit from 10 am to 10 pm (3082nd hour to 3094th hour) for the with-PV case. However, as previously stated and shown in Fig. 3.8 (b), the voltage violations are more serious than the no-PV case depicted in Fig. 3.8 (a), for the with-PV case, the bus voltage exceeds the upper limit for an extra three hours in the morning.

As concluded, in spring PV, systems are causing more overvoltage fluctuations due to load variations at BUS-Xin both the with-PV case and without-PV case and therefore in this case study; the seasonal ESS optimal charge/discharge allocation concept enhanced the voltage profile and quality at the distribution feeder.

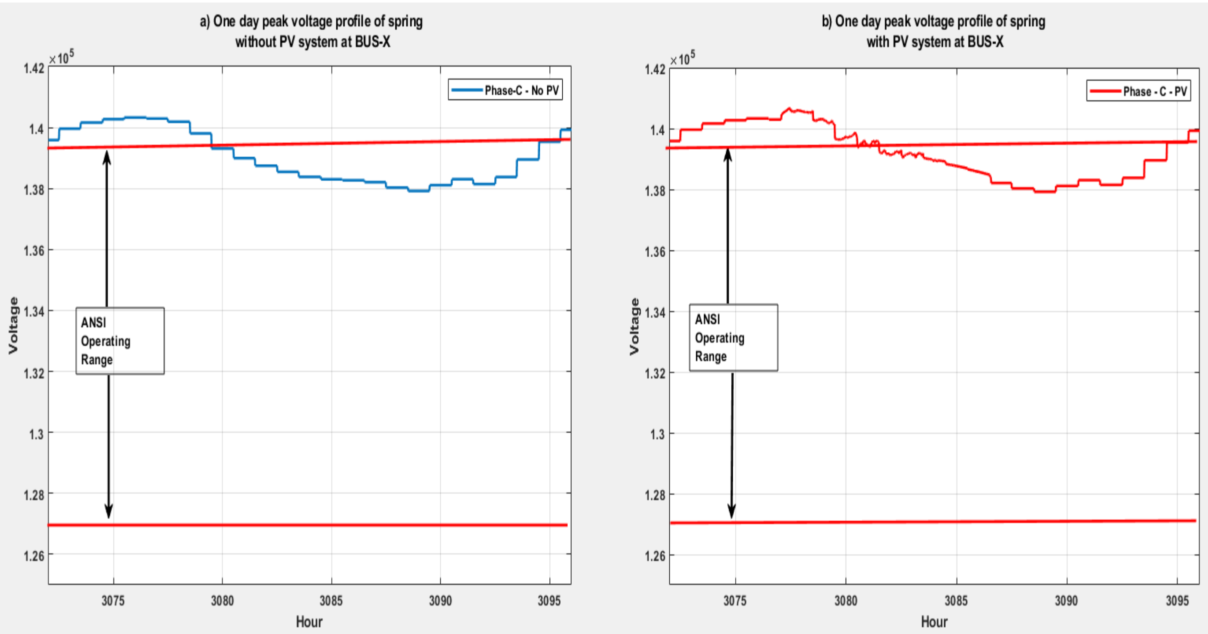

Fig. 3.8. Daily voltage profile in spring season with and without PV system at BUS-X.

3.7.2. Voltage Quality Issues with and without PV systems at BUS-X in Summer Season

This section will highlight the Phase-C voltage quality issues with and without PV systems at BUS-X in CKT24 for the summer season. The maximum PV system generation is also possible in the summer season due to high irradiance during this time [94]. Voltages are fluctuating less due to PV generation output because load consumption is higher in summer as compared to other seasons.

In Fig. 3.9 (a), the issues are less when compared to the spring season because of increased power consumption by consumers in the summer season. As shown in Fig. 3.9 (a), the bus voltage is higher than the upper limit of the ANSI operating range even with the no-PV case. In this case, study, the peak day voltage profile of summer was taken to compare the voltage issues between summer and other seasons. Normally, the summer season lasts between June and August of every year in the U.S. In this case study of the summer season, i.e. 1st June to 31st August, the hourly data varied between

3624th hours to 5832nd hour, but during these months, the highest voltage occurred on the 3rd July, which lasts from the 4394th hour to 4418th hour. In Fig. 3.9 (a), the OV issues are eventuating from 12 am to 5 am, i.e. 4394th hour to 4399th hour for the no-PV case. Whereas, in Fig. 3.9 (b) the OV issues are arising from 12 am to 7 am, i.e. from the 4394th hour to 4401st hour. Therefore, in summer, the OV issues are more severe at BUS-X in Phase-C when the PV system is installed at the distribution system. In Fig. 3.9 (a), the voltage is operating within the ANSI limits from 4399th hour to 4416.5th hour, i.e. 5 am to 10.30 pm for the no-PV case. However, as shown in Fig. 3.9 (b) the voltage is operating below the upper limit from 4401st hour to 4417th hour, i.e. 7 am to 11 pm in the with-PV case. In the summer season, the OV issues last an extra 2 hours when compared to the no-PV case.

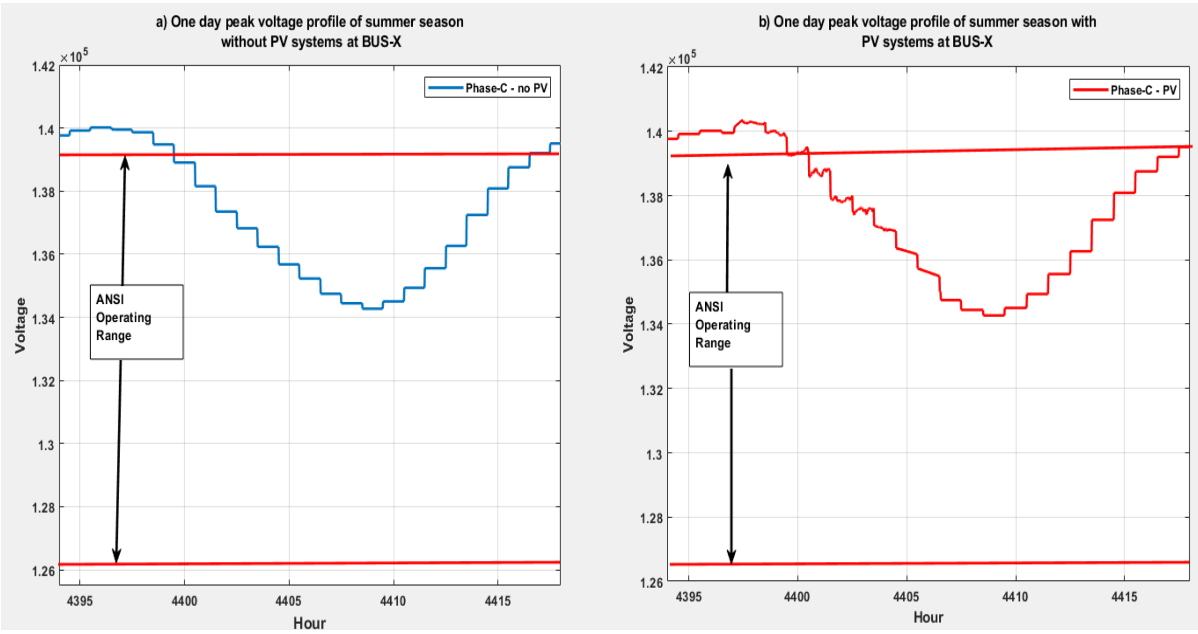

Fig. 3.9. Daily voltage profile in summer season with and without PV systems at BUS-X.

3.7.3. Voltage Quality Issues in Autumn Season with and without PV systems

This section will discuss voltage quality issues in the autumn at CKT24. Usually, the power consumed by consumers during autumn should be less than the summer and spring seasons. This case study on the autumn season will compare the voltage quality issues in autumn for PV and no-PV cases. Fig. 3.10 shows the voltage quality issues at CKT24 in the autumn season, with daily autumn data used. Normally, in the U.S., the autumn season is from September to November. The hourly time-stamp range is from 5833rd hour to 8017th hour, from 1st September to 30th November.

The OV issues can be seen above the ANSI standards between 12 am to 4 am, i.e. 6604th hour to 6608th hour, and after 5 pm until midnight, i.e. from the 6621st hour to 6628th hour. The voltage is operating within the range of ANSI standards from 4 am to 5 pm, i.e. 6608th hour to 6621st hour. Therefore, for the no-PV case in the autumn season, OV issues are half of the day, i.e. 11 hours. In Fig.

3.10 (b), the OV issues can be seen from 6604th hour to 6611th hour, i.e. 12 am to 7 am for the with-PV case. After 7 am, no voltage issues exist between 7 am and 5.30 pm, i.e. 6611th hour to 6621.5th hour. The OV issues are again rising after 5.30 pm until 12 am in 24 hours, which means from the 6621.5th hour to 6628th hour for the with-PV case. In the no-PV case, OV problems are observed for almost half the day; therefore there are more significant OV problems in the autumn when compared to the spring and summer season, and it can be concluded that the ESS concept will overcome these OV issues and try to improve the optimal voltage profile in the autumn season.

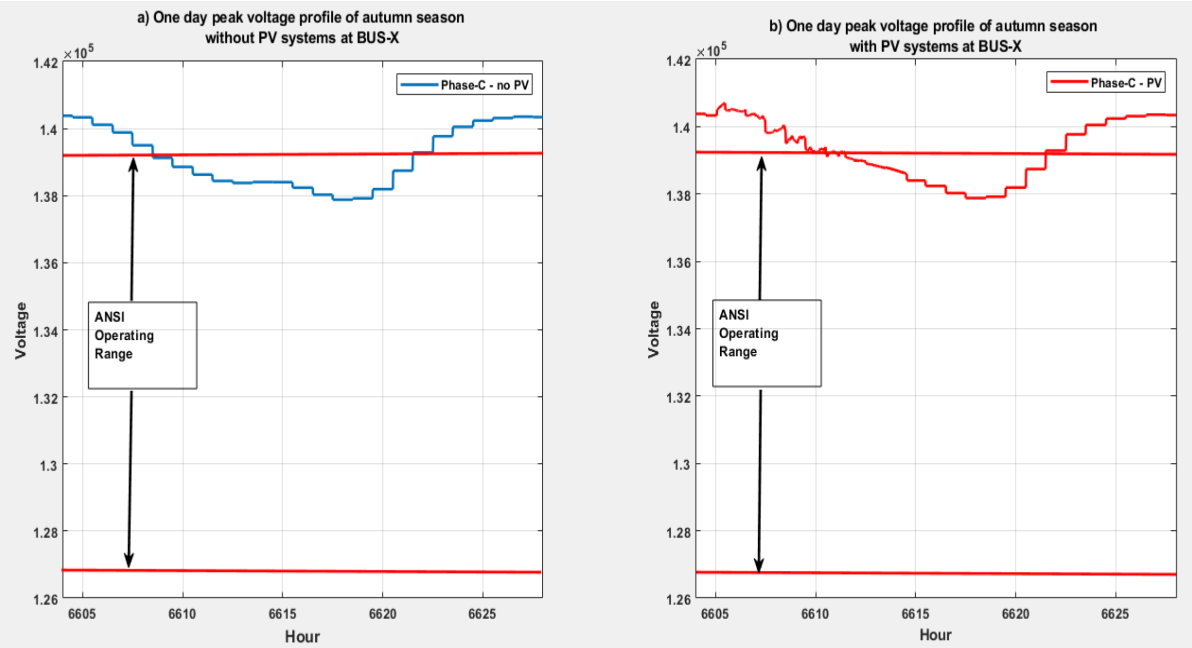

Fig. 3.10. Daily voltage profile in autumn season with and without PV systems at BUS-X.

3.7.4. Voltage Quality Issues in Winter Season with and without PV Systems

This section discusses the voltage quality issues in the winter at CKT24. The voltage fluctuations in winter frequently happen because of the residential load. Due to heating demands, load consumption is higher [95]. The BUS-X Phase-C data has been taken to explore voltage fluctuations during the winter season. Fig. 3.11 shows the voltage quality issues at CKT24 in the winter season. Regularly, in the U.S., the winter season starts in December and ends in February. So, for December data from the 8017th hour to 8760th hour is taken and for January to February it has been taken from the 1st hour to 1419th hour, and. In these three months, the winter's peak voltage is occurring in December. In Fig. 3.11 (a), the bus voltage is higher than the ANSI range from 12 am to 5 am, i.e. 8017th hour to 8022nd hour with the no-PV case. Whereas, in Fig. 3.11 (b), the OV issues are occurring from 12 am to 6 am, i.e. 8017th hour to 8023rd hour in the with-PV case.

In the winter season, the peak voltage is five hours for the no-PV case, and six hours with the PV case as depicted, and the rest is within the limit. Therefore, in the winter season, the with-PV case surpasses no-PV case by only one hour, which is less as compared to spring, summer, and autumn seasons. In the winter season, by implementing the ESS concept, OV issues could be lessened to operate within the ANSI limit; and the voltage profile and quality at BUS-X's distribution feeder could be enhanced with energy storage systems.

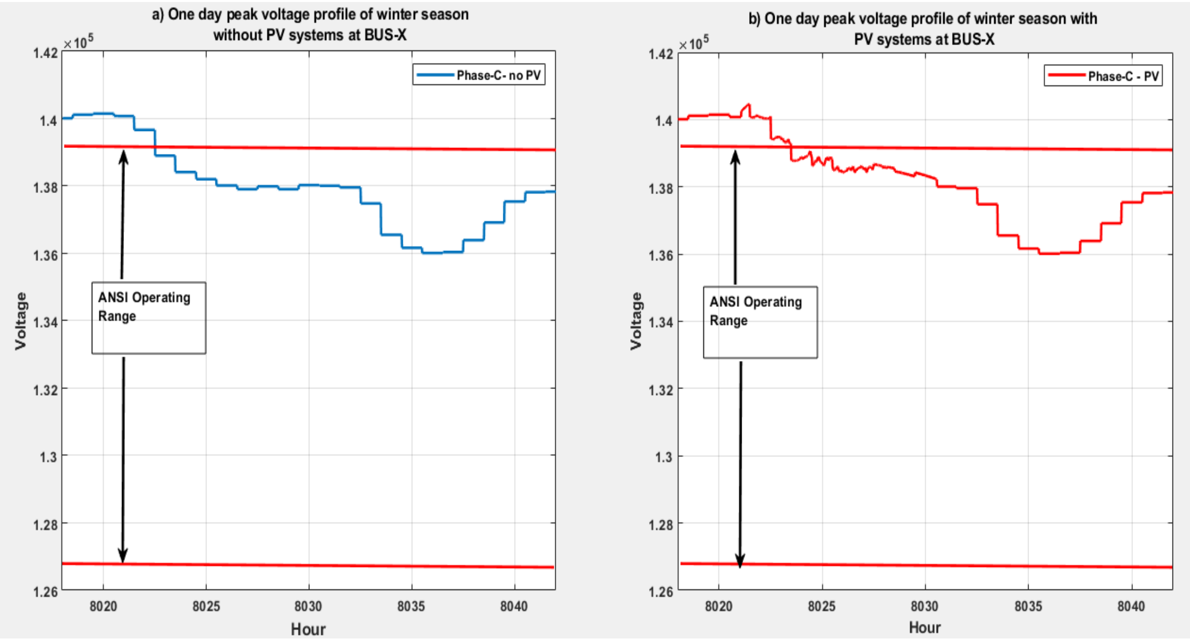

Fig. 3.11. Daily voltage profile in winter season with and without PV systems at BUS-X.

3.7.5. Seasonal Voltage Quality Issues Comparison at BUS-X

This section will discuss an all season's comparison of voltage issues at BUS-X. All season's one-day voltage profile at BUS-X in CKT24 is shown below in Fig. 3.12. Like every season, the voltage profile is increasing with PV systems due to reverse power flow. The autumn and spring seasons see higher OV issues than in summer and winter when more power is consumed.

In Fig. 3.12 (a), the spring season OV issues are occurring between 12 am to 7 am, i.e., 3072nd hour to 3079th hour with no-PV case but when PV systems are installed at the distribution feeder this nominal voltage at BUS-X has OV issues, and also the OV issues are varying in between 12 am to 10 am in the with-PV case. In this spring season, the peak hours are between midnight until early morning at even is in the no-PV case. So, for the with-PV case, the OV issues are seen for three extra hours than the no-PV case. A shown, the spring season is the worst performer in terms of the OV issues and PV generation during this season makes the most adverse impacts. In Fig. 3.12 (b), the summer season OV issues are less than the spring season because the OV issues are between 12 am to 5 am, i.e., 4394th hour to 4399th hour with no-PV. Whereas, in the spring season, the OV issues are two hours more with the no-PV case. In summer, for the with-PV case, the OV issues are occurring from 12 am to 7 am, i.e.

from the 4394th hour to the 4401st hour. In the summer season, one hour has decreased when compared to the spring season with-PV case.

In Fig. 3.12 (c), OV issues in the autumn are more severe than the spring season and summer seasons. In the autumn, the OV issues are quite different because OV issues are occurring between 12 am to 4 am and after 5 pm until midnight. In a day, for the with the no-PV case, the issues last almost 11 hours, but for the with-PV case, the voltage violation lasts 13.5 hours. Therefore, almost more than half of the day, the OV issues are occurring in the autumn season. In Fig. 3.12 (d), in both winter and summer with no PV, system installed, OV issues occur from 12 am to 5 am, but in winter from 5 am onwards, it operates within the ANSI limit whereas in summer OV issues are also noted from 10 pm. For the with-PV case in the winter season, OV issues are less than all other seasons, as shown in Fig. 3.12.

This case study highlights the impact of seasonal fluctuations on bus voltage to beyond the limits of ANSI standards at BUS-X, which causes a massive impact on power quality of the network. It can be seen that day-by-day PV systems installation is increasing at the distribution systems, but not with PV/Battery grid integration. However, using the ESS concept, the voltage profile can be improved at BUS-X, therefore removing the need for customers to regulate the load in all seasons.

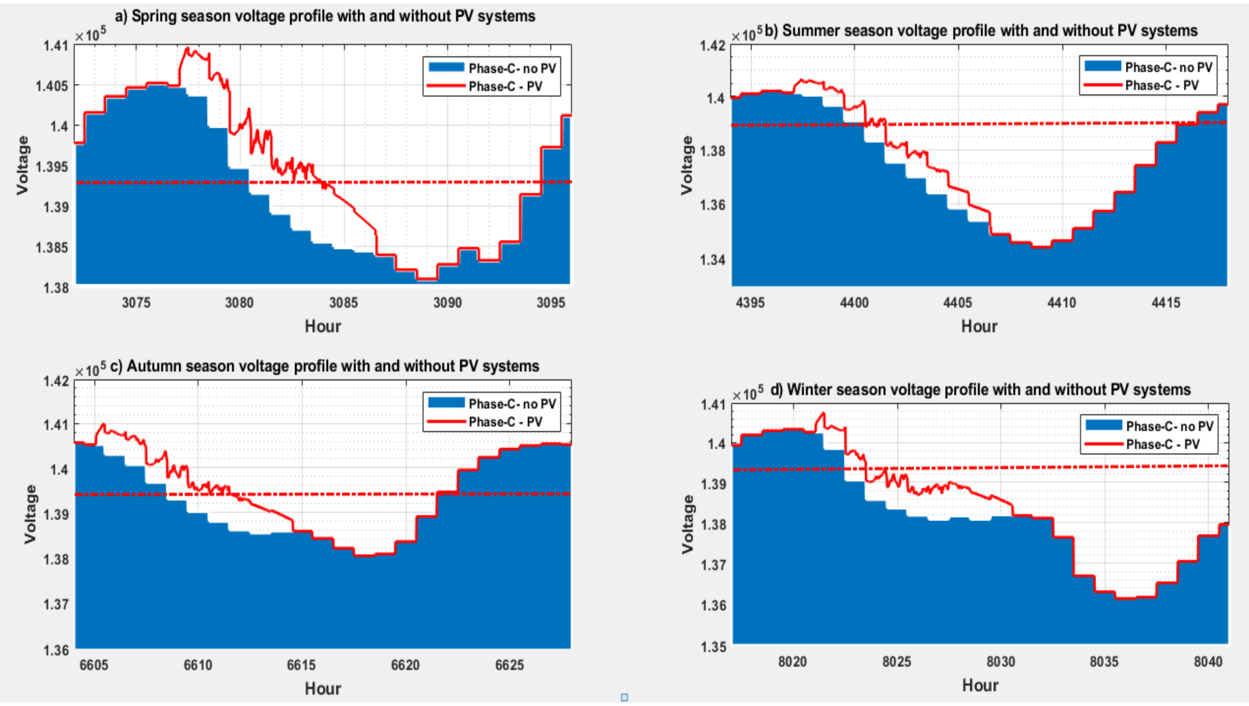

Fig. 3.12. All seasons one-day peak voltage profile with and without PV systems at BUS-X.

3.7.6. Voltage Quality Issues with and without PV at BUS-Y in Spring Season

It has been recognised that during the spring season, BUS-Y experiences more OV issues in CKT24. In Fig. 3.13 (a), daily voltage profile during the spring season for the without-PV system has been taken at BUS-Y, which is close to PV system installation. Here, without PV, voltage surpasses the ANSI limit from 12 am to 9 am (3072nd–3081st hour) and from 9 pm until midnight, whereas voltage stabilises to within the ANSI from 9 am until 9 pm (3081st –3093rd hour), indicating load consumption increases in the day, i.e. morning to the late evening, 9 am until 9 pm (3081st hour–3093rd hour).

In Fig. 3.13 (b) with a PV system, the OV issues are more than the ANSI limit in the spring season in between 12 am to 11 am, i.e., from 3074th to 3085th hour. Consequently, from 11 am until 9 pm, i.e., 3085th hour to 3093rd hour, the voltage is within the service range. As can be seen in comparing Fig. 3.13 (a) and Fig 3.13 (b), in the spring season, the installation of PV systems leads to a rise in OV issues increased, with voltage intensifying, when PV systems were installed at the distribution system. Therefore, the ESS concept will be applied to enhance the voltage profile at BUS-Y in the spring season in this case study.

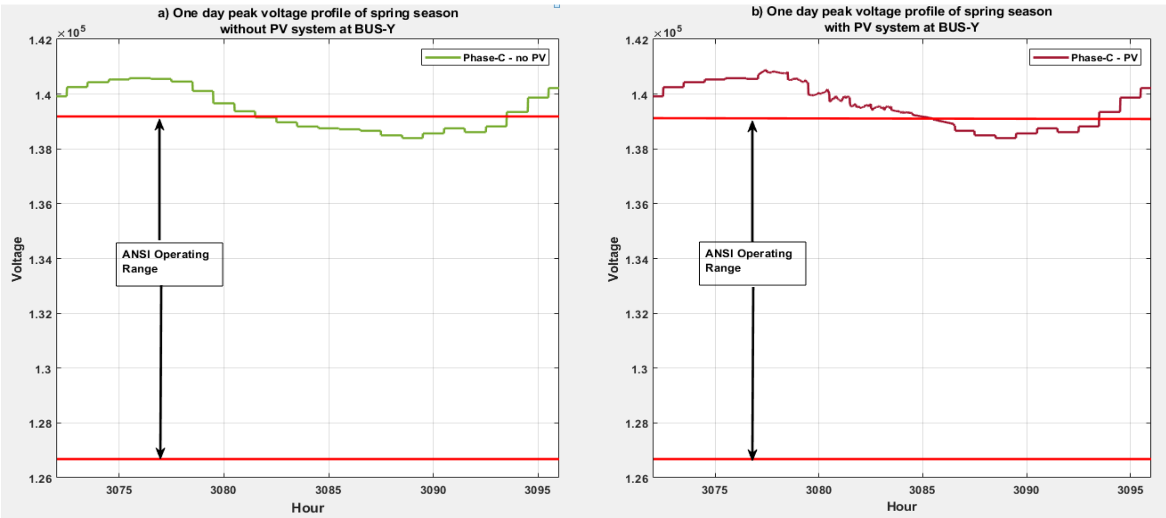

Fig. 3.13. Daily voltage profile in spring season with and without PV system at BUS-Y.

3.7.7. Voltage Quality Issues with and without PV at BUS-Y in Summer Season

This section will discuss the voltage quality issues with and without PV systems at BUS-Y in the summer season. In the summer season at BUS-Y, the peak voltage profile has been identified on 3rd July. In Fig. 3.14 (a), the daily voltage profile has taken at BUS-Y without PV systems. As shown in Fig. 3.14 (a), the summer OV issues are emerging in between 12 am to 6 am (4394th hour to 4400th hour) with the no-PV case. However, with the PV case, the OV issues are resulting slightly more than with the no-PV case. In Fig. 3.14 (b), the OV issues are occurring in between 12 am to 7 am, i.e., from 4394th hour to 4401st hour for the with-PV case.

Nevertheless, with the no-PV case, the voltage is controlling within the service range from 6 am to 10 pm (4400th hour to 4416th hour). With PV, the voltage is within the service range during the morning until night, i.e. 7 am until 10.30 pm (4401st hour to 4416.5th hour). In summer, during the morning until evening, the load consumed by the utilisers is more than during the night. Thus, these OV issues are less when compared to the spring season; however, when PV systems are expecting a maximum output, OV issues are higher than the service range in the summer more so than in other seasons. In this case study, by adding energy storage systems, the ESS could balance the voltage profile, and therefore voltage quality issues could be reduced in the summer season at BUS-Y in CKT24.

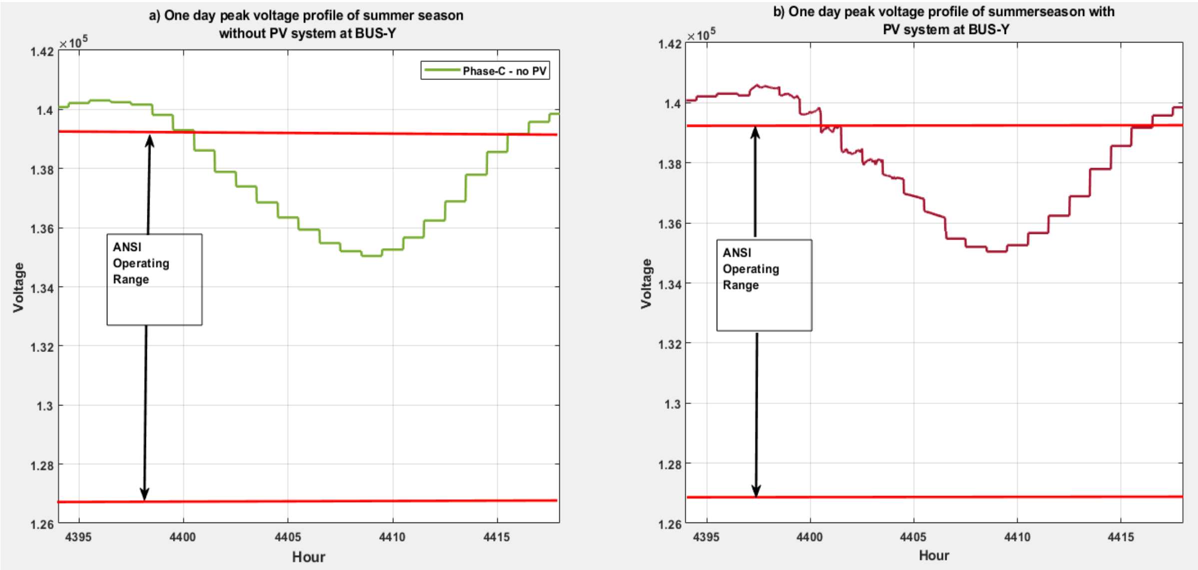

Fig. 3.14. Daily voltage profile in summer season with and without PV system at BUS-Y.

3.7.8. Voltage Quality Issues with and without PV at BUS-Y in Autumn Season

This section will illustrate the voltage quality issues in the autumn season at BUS-Y. Here, the consumers utilise less load in the autumn season compared to other seasons. In the autumn season, the peak voltage profile has been addressed as on 3rd October. However, due to lighter load in the autumn season on 3rd October, the voltage fluctuations have been increased at BUS-Y during this season. In Fig. 3.15 (a), the OV is more from midnight to early morning, i.e. from 12 am to 6 am (6604th hour to 6610th hour) with the no-PV case. During daytime in the autumn season with the no-PV case, the BUS-Y is heavily loaded from 6 am until 5 pm (6604th hour to 6621st hour) which is shown below in Fig. 3.15 (a); after 5 pm, the OV issues were raised until midnight on 3rd October.

In Fig. 3.15 (b), the OV issues are recognised with PV case from 12 am to 11 am (6604th hour to 6614th hour) on 3rd October. During this time, the BUS-Y is lightly loaded, and the OV issues are more during this time in the with-PV case. After 11 am until 5 pm (6614th hour to 6621st hour), the voltage is within the service range of ANSI in the with-PV case. During the evening, from 5 pm to 12 am (6621st hour to 6628th hour) the customers are utilising less load in the autumn season at BUS-Y, for the with-PV case. Based on these voltage issues in both with and without PV cases, it can be seen that in autumn, there are higher OV issues at BUS-Y and consumers are utilising less load, in comparison to the other three seasons.

In this case study, in the autumn season OV issues occur for almost half the day without PV, and for even more than this time period with PV; therefore using the ESS concept at BUS-Y could significantly improve these OV issues, thereby also operating voltage within the ANSI standards range.

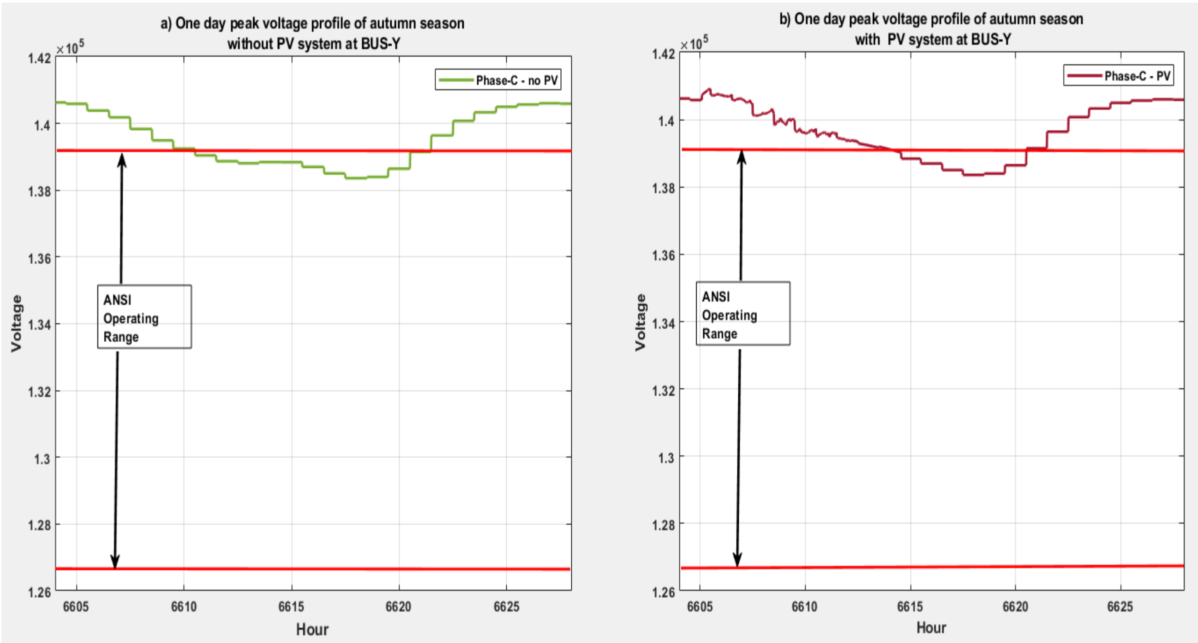

Fig. 3.15. Daily voltage profile in autumn season with and without PV system at BUS-Y.

3.7.9. Voltage Quality Issues with and without PV at BUS-Y in Winter Season

This section will describe the voltage issues with and without PV at BUS-Y in the winter season. In this winter season, the peak OV issues have been identified on 1st December at BUS-Y. Specifically, in the winter season-, the load utilisation is higher when compared to the autumn and spring seasons but is less than the summer season. In the winter season at BUS-Y, the OV issues are less compared to all other seasons. To investigate OV issues in the winter season at BUS-Y, daily voltage has been taken in this case study.

The Fig. 3.16 (a) below shows the OV issues in winter season without PV on 1st December. In Fig. 3.16 (a), the OV issues are occurring from 12 am to 6.30 am (8017th hour to 8023.5th hour) due to being heavily loaded on 1st December. However, after 6.30 am, which means from 8023.5th hour to 8041st hour, the voltage is operating within the range of ANSI standards with the no-PV case. In Fig. 3.16 (b), the OV issues are increased with-PV because these occur from midnight until 8 am (8017th hour to 8025th hour) in the with-PV case on 1st December.

When PV systems are connected to the distribution, there is an increase in OV issues by 1.5 hours. Therefore, the OV issues are increasing in winter when PV systems are installed at the distribution systems. For the winter period, OV issues could be dropped to below the ANSI limit by applying the ESS concept and energy storage systems can have a positive impact on the voltage profile and quality at the distribution feeder at BUS-X.

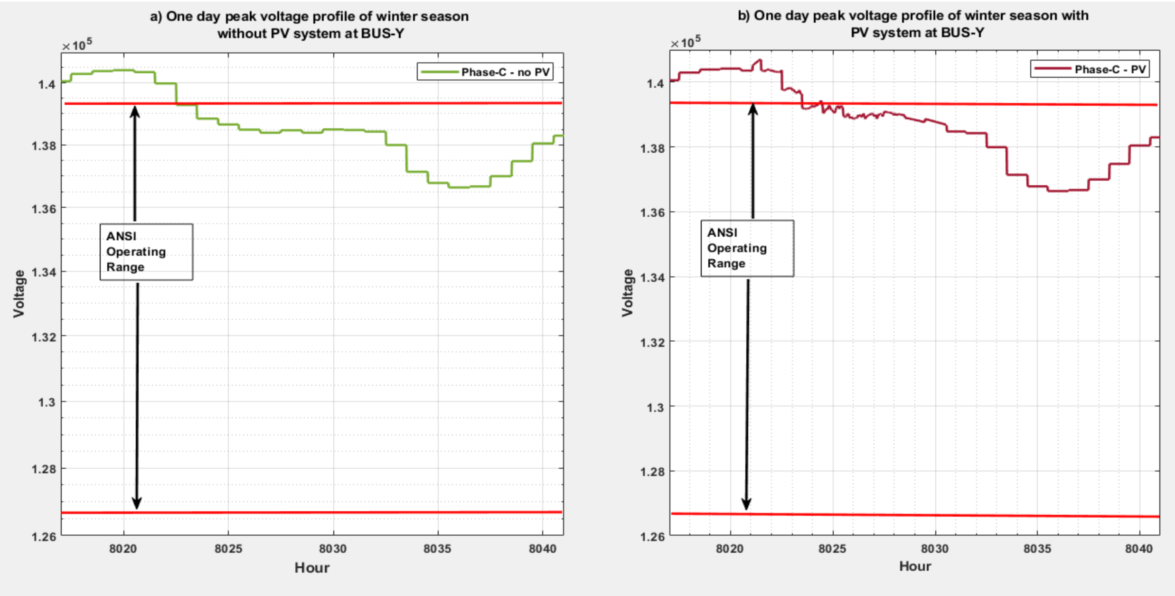

Fig. 3.16. Daily voltage profile in winter season with and without PV system at BUS-Y.

3.7.10. Seasonal Voltage Quality Issues Comparison at BUS-Y

This section will illustrate a comparison of all seasons OV issues at BUS-Y in CKT24. In this case study, at CKT24, it is recognised that due to several conditions, the voltage may increase at any season. In Fig. 3.17, spring, summer, autumn and winter one-day voltage profile at BUS-Y in CKT24 is shown to compare the OV issues across different seasons. Like every season, the voltage profile is increasing with PV systems due to reverse power flow. Findings at BUS-Y show that OV is more negatively impacted during autumn and spring than in summer and winter, indicating that more power is utilised during summer and winter.

In Fig. 3.17 (a), the spring OV issues are emerging between 12 am to 9 am (from 3072nd hour to 3081st hour) with the no-PV case, and then the voltage is below the upper limit after 9 am until 9 pm (from 3081st hour to 3093rd hour). After 9 pm, the voltage has been increased again until midnight. It means more load consumption is happening during the morning to the late evening, i.e., 7 am until 9 pm (3081st hour to 3093rd hour) with the no-PV case. In Fig. 3.17 (a), the OV issues are more than the summer and winter season but less than the autumn season. In the spring season, the voltage at BUS-Y is occurring between 12 am to 11 am (from 3074th to 3085th hour) for the with-PV case. Consequently, from 11 am until 9 pm (3085th hour to 3093rd hour), the voltage is within the service range. However, OV issues increased when PV systems were installed at the distribution system. In the spring season at BUS-Y, the voltage had increased when PV systems were installed at the distribution feeder.

In Fig. 3.17 (b), the summer season OV issues are marginally less than the spring season because the OV issues are in between 12 am to 6 am (4394th hour to 4400th hour) with no-PV at BUS-Y. Whereas, in the spring season, the OV issues are 3 hours more with the no-PV case. Nevertheless, with the PV case, the OV issues are resulting slightly more than with the no-PV case. In Fig. 3.17 (b), for the with-PV case, the OV issues are occurring in between 12 am to 7 am (from 4394th hour to 4401st hour). Nevertheless, with no-PV, the voltage is controlling within the service range from 6 am to 10 pm (4400th hour to 4416th hour). With-PV, the voltage is within the service range during the morning until night, i.e. 7 am until 10.30 pm (4401st hour to 4416.5th hour). In the summer season, one hour has decreased when compared to the spring season with a PV case. In Fig. 3.17 (c), the OV issues in the autumn season are more than all other seasons due to being lightly loaded. In the autumn season, the peak voltage profile has been identified on 3rd October. However, due to lighter load in the autumn season on 3rd October, the voltage fluctuations have been increased at BUS-Y in the autumn season.

In Fig. 3.17 (c), the OV is more from midnight to early morning, i.e., from 12 am to 6 am (6604th hour to 6610th hour) with the no-PV case. During daytime in the autumn season with the no-PV case, the BUS-Y is heavily loaded from 6 am until 5 pm (from 6604th hour to 6621st hour) as shown below in Fig. 3.17 (c); after 5 pm, the OV issues were raised until midnight on 3rd October. In Fig. 3.17 (c), the OV issues are recognised with-PV from 12 am to 11 am (6604th hour to 6614th hour) on 3rd October.

During this time, the BUS-Y is lightly loaded, and the OV issues are more during this time than with no-PV. In the with-PV case, after 11 am until 5 pm (from 6614th hour to 6621st hour), the voltage is within the service range of ANSI. During the evening and morning, i.e. from 5 pm to 12 am (6621st hour to 6628th hour), the customers are utilising less load in the autumn season at BUS-Y. Based on this voltage issues with and without PV cases in the autumn season, The OV issues identified have more in autumn than all other seasons because almost half day peak voltage without PV and more than half-day peak voltage with PV generation is happening in the autumn season. Fig. 3.17 (d) shows the OV issues in the winter season without PV on 1st December. In Fig. 3.17 (d), the OV issues are occurring in between 8017th hour to 8023.5th hour (from 12 am to 6.30 am) after that the voltage is operating within the service range due to being heavily loaded on 1st December. However, after 6.30 am (from 8023.5th hour to 8041st hour), the voltage is operating within the range of ANSI standards with the no-PV case.

In Fig. 3.17 (d), the OV issues are increased in the with-PV case because the OV issues are occurring from midnight until 8 am (8017th hour to 8025th hour) on 1st December. Therefore, OV issues are increased by 1.5 hours when PV systems are connected to the distribution, which means the OV issues are increasing in winter when PV systems are installed at the distribution systems. Moreover, in the winter season, the OV issues are less than all other seasons, as shown in Fig. 3.17.

This case study has addressed that the voltage is increasing more than the service range of ANSI standards due to seasonal change. Day-by-day PV systems installation is increasing at the distribution systems but not PV/Battery grid integration. Due to climate changes, the OV issues are occurring more at this distribution system, which is causing a massive impact on power outages; however, using the ESS concept, the voltage profile will be improved at BUS-Y and also customers does not have to regulate the load in all the seasons.

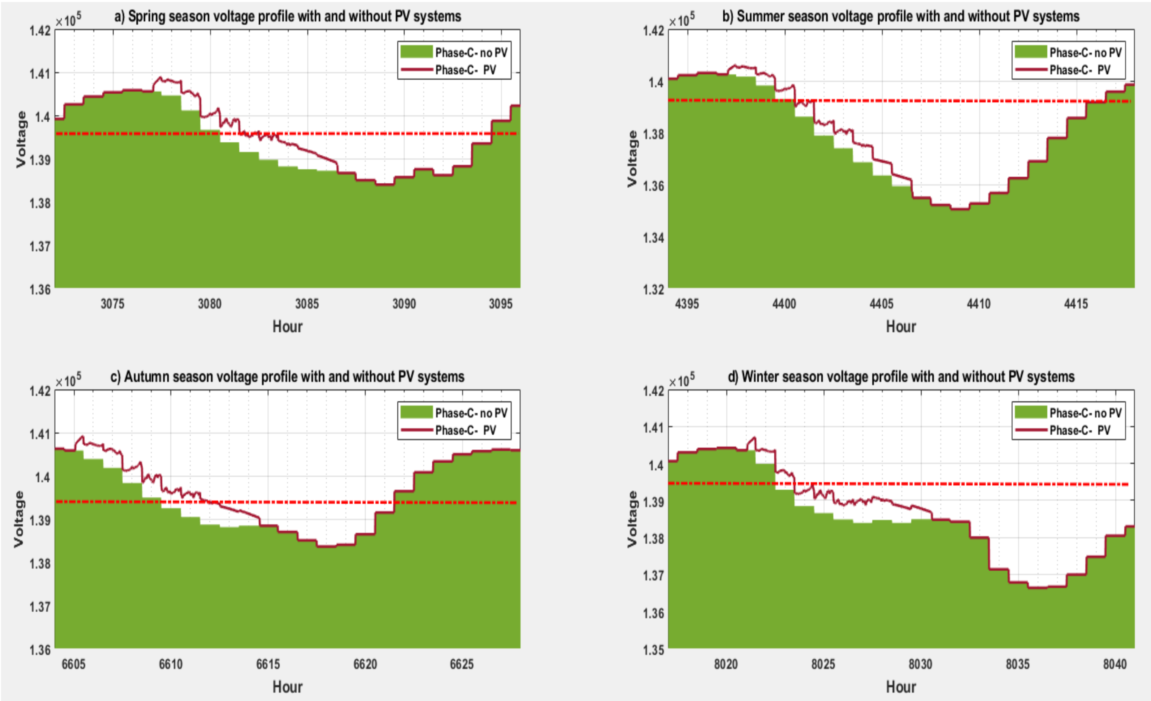

Fig. 3.17. All seasons one-day peak voltage profile with and without PV systems at BUS-X.

3.8. Conclusion

This chapter has focused on studying the time-series behaviour of the case study CKT24 network with and without integrated PV systems. The key objective was to analyse the steady-state network voltages and identify any OV or UV concerns evaluating the impact of seasonal variations over the same. Phase C in the unbalanced network was observed to experience OV issues especially at times when the network was lightly loaded. The OV issues were worsened in the PV penetrated analysis especially after the sunrise when the network was still lightly loaded. The network has been analysed in detail using two selected buses for different seasons. Power quality issues were worst during the spring, and autumn seasons. The analysis has been demonstrated the need for dynamic management of seasonal energy storage system charge/discharge schedule to minimise the voltage quality issues in distribution networks.

Chapter-4

Modelling and Scheduling of Energy Storage Systems Based on Seasonal Patterns

4.1. Introduction

This chapter outlines the modelling of Energy Storage Systems (ESS) on seasonal bases with distinct scheduling of charge/discharge profile as per each season. Technology has been advancing at a fast pace over the last few decades, and many researchers are researching ESS with grid-integrated PV systems to control power quality issues at the distribution systems. In [96], researchers explained the trends and challenges of grid-connected PV systems at distribution systems.

The main challenges in grid integrated PV systems are high PV penetration at particular times in the year and high variability in the PV output depending on the seasonal irradiance profile. Due to this high PV penetration, OV issues are often occurring in distribution feeders. In this study, an ESS will be modelled in the case study CKT24 network and seasonal charge, and discharge allocations will be provided as a means of addressing the power quality issues. Integrating ESS with PV systems cannot address all issues but help to minimise steady-state voltage violations if the appropriate scheduling of charge/discharge dispatch of storage systems is undertaken to manage the peak demand during peak hours and store excess energy during the off-peak hours.

In this chapter, the key objective is the modelling of PV/Battery grid integration in CKT24, and the scheduling of the system's charge/discharge allocation percentages considering seasonal variations. In Chapter 3, the OV issues and their seasonal comparison were identified. The modelling will focus on controlling the scheduling of charge/discharge dispatch seasonally. In any ESS, the common consideration is the charge/discharge factor which can balance the load demand and supply to address the power quality issues [97]. Due to PV/Battery grid integration, power quality control is delicate. If batteries are not charged or discharged using the proper schedule, this will also affect the ageing and performance of the battery life.

In this study, the analysis has been carried out in the OpenDSS and MATLAB platforms based on Sequential-Time-Series (STS) power flow analysis. First, the model description and parameters used in the existing PV system model and the incorporated ESS modelling are explained. Then, charge and discharge schedules are developed for each season to maximise the benefits from the utilisation of the ESS. Finally, comparisons are provided to highlight seasonal schedule variations. The analysis and results are also provided in this chapter.

4.2. Model description

This section discusses the modelling of ESS on a seasonal basis in the OpenDSS and MATLAB platforms. The key focus of ESS modelling will be the seasonal scheduling of charge/discharge dispatch of ESS in Phase-C of BUS-X and BUS-Y. These two buses have been selected for analysis in this Thesis and steady-state voltage profiles at these buses were further investigated in Chapter 3. Recommended seasonal Charge (C) and Discharge (D) levels will be quantified and time series plots of the Phase-C voltage magnitude will be provided comparing before and after the modelling of the ESS. Plots of the voltage magnitude versus charge and discharge allocations for a 24-hour duration in each season will be provided to highlight the need for seasonal variations in the allocation.

The existing PV system and network data were collected from the Sandia National Laboratories (SNL) [98]. This data was separated into four seasons as per U.S. National Weather Service (NWS) [99]. After separating the data using STS analysis, data sequences for each season was created labelled as spring, summer, autumn and winter as shown in Fig. 4.1. To separate the data of one year in OpenDSS and MATLAB, a COM interface was used via the Graphical User Interface (GUI) in MATLAB.

PV systems were modelled using the existing PV system historical one-year load data of CKT24. For all seasons, load data with a resolution of one second on one-day peak voltage profile with and without PV system cases were taken to identify power quality issues. ESS was modelled at both buses, i.e., BUS-X and BUS-Y. After installing the ESS at BUS-X and BUS-Y, a storage controller was designed to implement the charge/discharge schedule (on a lightly loaded day) in all season in consideration of the voltage tolerance limits dictated by ANSI. To control the network voltage magnitudes, Charge (C) and Discharge (D) levels were set with seasonally varying schedules in MATLAB to control the voltage magnitudes within the ANSI limits. In the OpenDSS, the default values of Voltage lower and upper thresholds were set as 0.9 p.u. and 1.1 p.u.

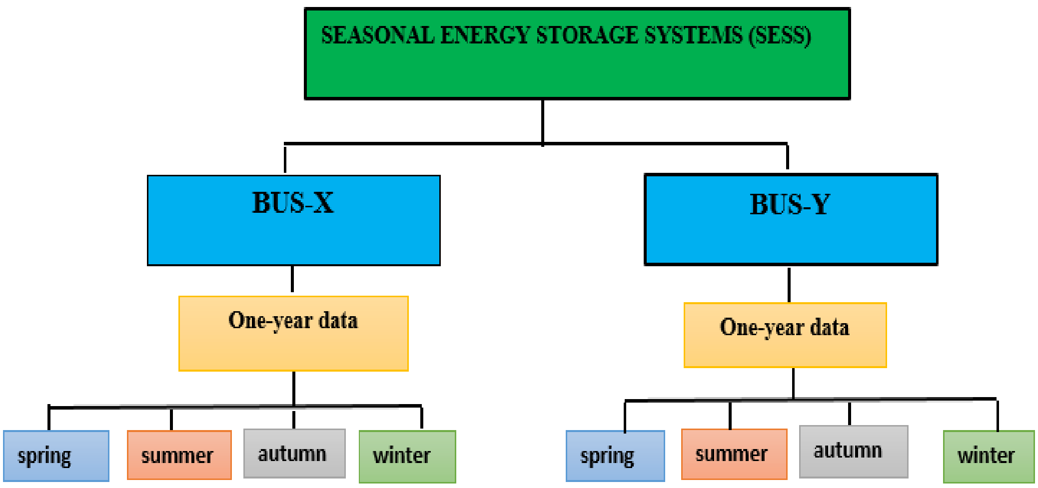

Fig. 4. 1. Tree-projection flowchart for two buses in seasonal ESS.

Fig. 4.2 shows the procedure of toolchain detailed modelling in MATLAB and OpenDSS and the procedure of scheduling charge/discharge dispatch modelling of the ESS at BUS-X and BUS-Y. The following steps were followed for the simulation procedure in MATLAB.

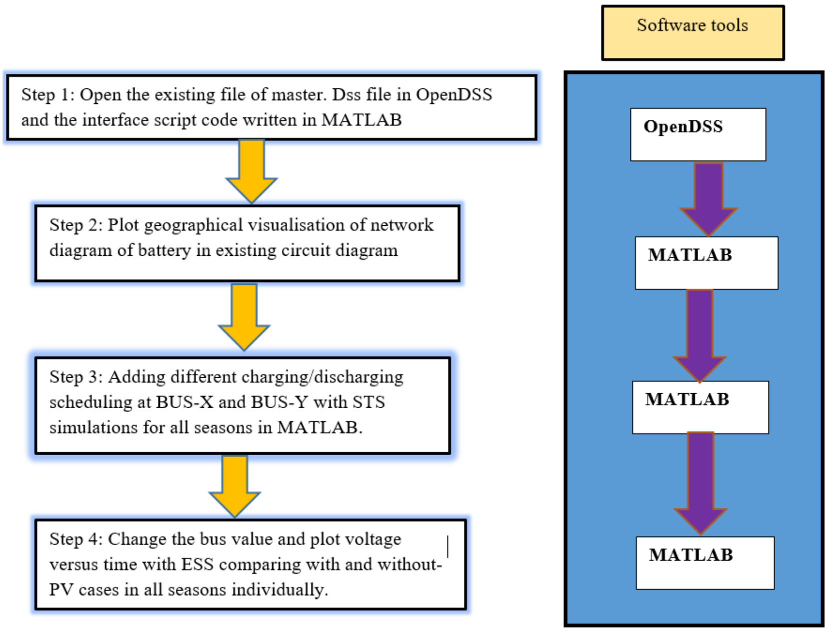

Fig. 4. 2. Detailed toolchain level of seasonal ESS.

STEP 1: A master.dss file is first opened in OpenDSS and using the MATLAB com interface, buses for analysis are selected using the following master.dss script code. The OpenDSS Script codes 1 and 2 were first opened and solved in OpenDSS, before proceeding with further STS steps in MATLAB. If OpenDSS simulation is solved without any errors, then Step 2 begins.

Script 1: New Circuit.ckt24 Bus1=N283701 pu=1.05 basekV=230 R1=0.63 X1=6.72 R0=4.07 X0=15.55

Script 2: New Circuit.ckt24 Bus1=N292246 pu=1.05 basekV=230 R1=0.63 X1=6.72 R0=4.07 X0=15.55

STEP 2: The following script code below is executed for the geographical visualisation of the CKT24 case study network, and to plot voltage graphs for BUS-X and BUS-Y. For both buses, plotting the geographical visualisation of CKT24 per-unit bus voltages, the Script 3 was used, and Script 4 was used for the geographical visualisation of CKT24 on a voltage base of 132 kV, as BUS-X and BUS-Y are 132 kV buses.

Script 3: figure; plotCircuitLines(DSSCircObj,'Coloring','voltagePU','EndOfFeederMarker','on') [8]

Script 4: figure; plotCircuitLines(DSSCircObj,'Coloring','voltage132') [8]

STEP 3: After executing geographical visualisation, two ESS were first modeled and added to the two buses. Then using STS analysis, charge/discharge load shapes were set with minimum/maximum allocation percentages with voltage limits set to 0.95 p.u. and 1.05 p.u. SOC is the level of the charge capacity of an electric battery, which is measured in percentages with 0% signifying an uncharged battery and 100% a battery fully charged. DOD is the inverse of the SOC. 0% DOD indicates a fully charged battery and 100% a depleted battery. Deep discharge of the battery, higher than 50%, was not implemented to extend the life of the battery [74]. These STS were executed in MATLAB in one-peak day control mode for all four seasons with the static mode in duty cycle.

STEP 4: Change the bus number for BUS-Y, edit the load shapes and repeat Steps 1-3.

4.3. Modelling of Seasonal Energy Storage Systems in CKT24

4.3.1. OpenDSS Storage Model Concept

The storage element in CKT24 is mainly modelled as a generator, which can dispatch power in charge or discharge modes within its rated specifications. The storage elements were added to BUS-X and BUS-Y within the CKT24 case test feeder. To control the Sequential-Time-Series (STS) simulation, a storage controller was used with the energy storage model developed from the OpenDSS generator model. The storage controller code was written in .dss script in MATLAB and interfaced with OpenDSS. The storage controller was controlled independently.

In OpenDSS, the storage model has a snapshot power-flow mode to simplify the specific storage elements in the power flow control as shown in Fig. 4.3. It has three modes, which are 'Idle', 'Charge' and 'Discharge'. However, the state of 'Idle' was not used in this study to improve battery performance. Fig. 4.3 shows that based on the storage element; the power will be discharged only when the charge level (*kWhStored*) is more than the specific reserved level. The storage element will only charge when the *kWhStored* is less than the kWhRated. The dispatch schedule is defined in percentages, and STS mode was used for optimal scheduling to improve the battery performance. In this storage model, there are a few control modes of significance. The following combination of modes was used in the sequential power flow analysis. Those control modes are [100]:

a) **STATIC MODE:** This Static mode is the traditional solution for one specific season or location. Power flow analysis is carried out manually with the storage device model set to charge/discharge at specified rates. This static mode distributes limited planning for limited condition and does not execute time-series simulation.
b) **TIME MODE:** The time mode is used to trigger the storage element at a specific location of the times to charge or discharge at a particular constant level [66].
c) **PEAK SHAVE MODE:** Peak shave mode is used to trigger the discharge at peak times using a storage element at a specific location at specific peak values. It aims to generate sufficient

power to limit the actual load power at a particular value. In this mode, to charge the storage, triggering is used separately.

d) **LOAD FOLLOWING MODE:** The load-following mode is the same as peak shave mode, but it cannot discharge at a specific given time. It will control the net load power using the storage controller at the value of time triggering.

e) **LOAD SHAPE MODE:** The load shape mode will control the charge and discharge cycle based on a predefined load shape. By using the load shape mode, it is possible to undertake seasonal storage planning without requiring many complicated algorithms.

f) **DYNAMICS MODE:** The dynamics mode is an advanced mode of power flow analysis for modelling the control of the frequency on Microgrids.

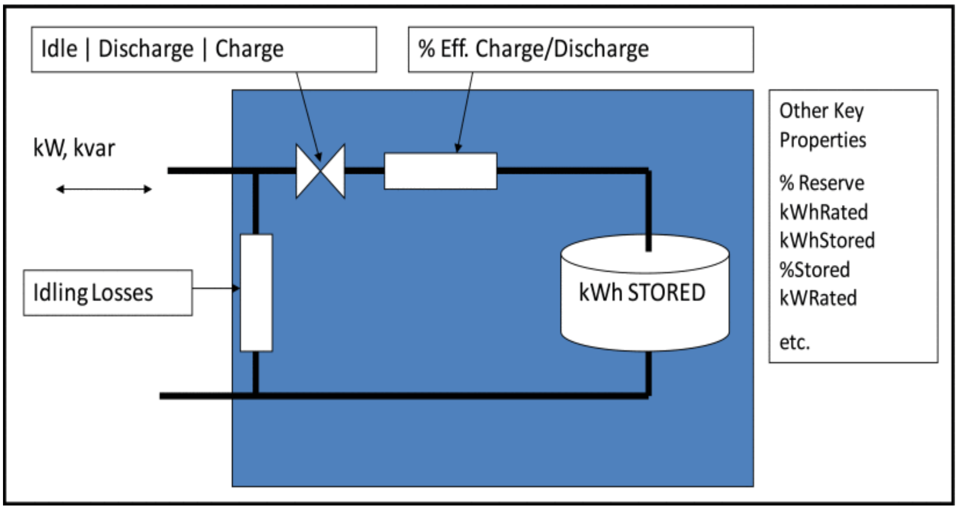

Fig. 4. 3. EPRI OpenDSS storage model basic concept [100].

EPRI implemented the following simulation modes in the OpenDSS software. The a-f modes are designed especially for sequential power analysis from 1 minute to 1 hour and up to one year of power and voltage evaluations [100]. The storage controller, developed in this thesis, for seasonal control of charge/discharge rates is based on the Load-Shape mode.

4.3.2. OpenDSS Storage Controller Model Concept using MATLAB

Fig. 4.4 shows the basic EPRI concept of OpenDSS storage controller, which controls the energy using one of the above six modes. For seasonal power flow simulations, the storage element acts as a generator or load in CKT24 relying upon scheduling charge/discharge rates. The storage controller in script code was implemented in MATLAB using the COM interface. It neither generates nor consumes energy from the selected buses, but only monitors the power at a specific point, and controls the battery charge or discharge based on the given charge/discharge schedule rates. One key concern herein is to perform distribution planning of CKT24 to control the over-voltage issues seasonally using this storage controller. The yearly simulation was separated with STS using a MATLAB script code for

BUS-X and BUS-Y. In this manner for all seasons, using existing PV systems, storage elements and the storage controller, the sequential power flow simulations were implemented using two different algorithms for all seasons at BUS-X and BUS-Y.

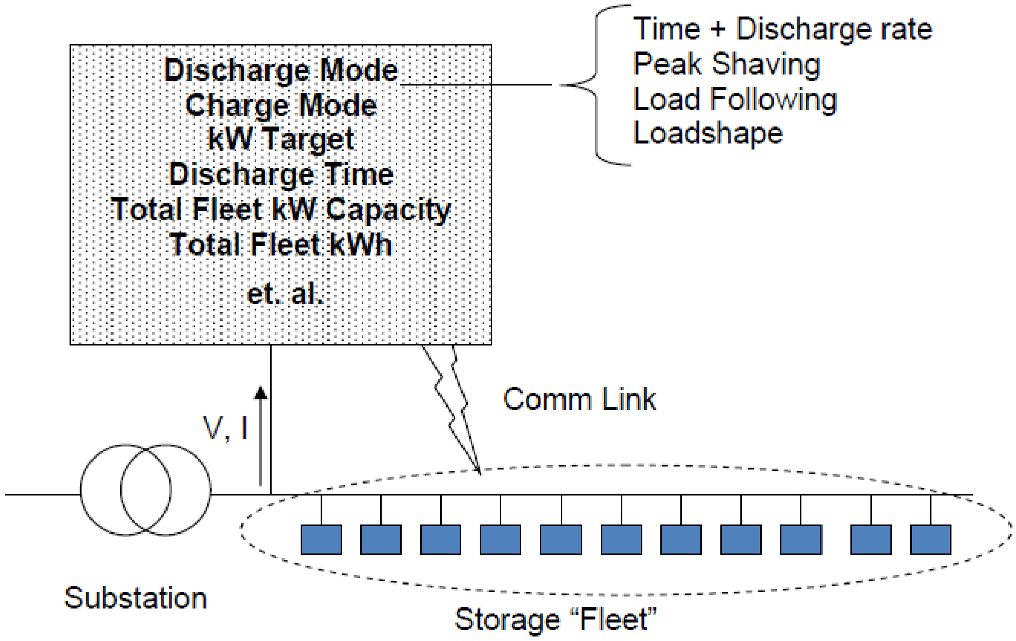

Fig. 4. 4. OpenDSS storage controller concept [100].

In this thesis, to control the storage controller seasonally, the following operating modes were used for charge and discharge dispatch control. However, the modes between the storage element and storage controller are quite different modes to operate in the OpenDSS. For discharge mode control, there are five modes in OpenDSS, and for charge control, there are two modes [67].

1. **DISCHARGE MODE:** Five different operating modes to discharge explained below [67] :

 a) **PeakShave:** The PeakShave operating mode is the default discharge mode, which controls storage in a monitored element within a bandwidth called the % kWB or kW value specified by the kWTarget property. In this operating mode, the storage fleet turns off automatically, when the stored energy runs out. The primary concept of *PeakShave* mode is that it keeps the monitored element below the kWTarget value. In this mode, the monitored element is typically a transformer or line element that may be considered as overloaded at the kWTarget value.

 b) **Follow:** The load-following mode is also a discharge mode, which controls the time by triggering, and it resets the kWTarget value to the current monitored element power. After that, it will strive to discharge storage if the power in the monitored element is less than kWTarget. Once, the storage fleet is adjusted to discharge, then the follow mode actions will be the same as like PeakShave mode with some exceptions of different kWTarget value.

c) **Support:** The support mode is precisely the opposite of the PeakShave mode. In this mode, the storage is dispatched to maintain the power in the monitored element above the kWTarget value. The support mode is typically used to support the power output falls off in the renewable generation like cloud transients, etc.

d) **LoadShape:** In this load shape mode, both are charge and discharge modes follow a per unit load shape. The zero value is not used in this thesis because the zero is defined as idling.

e) **Time:** In time mode, the storage element is controlled by a specific time of the simulation. For instance, the time-discharge trigger property has taken in hour decimal value as 2.5=2.30. In this mode, the storage fleet will turn off itself when their storage falls off to the reserve value. In this mode, the discharge rate is set by the % RateDischarge property.

2. CHARGE MODE

The charge mode has two operating modes, which are defined below:

a) **LoadShape:** In this load shape mode, the charge mode units are negative quantities. The zero value is not used in this thesis.

b) **Time:** In charge time mode, the storage elements are set to trigger for charge at a specific time. Elements will change to the idle state once the storage element is charged or the storage controller changes the operating mode. The % RateCharge property is used in charge mode.

4.3.3. Properties Details of the Storage Element and Storage Controller used in CKT24

The storage element has a few technical property details as shown in Table. 4.1. Based on the following property details, the script code was written in MATLAB, and the simulation program run using the COM interface of OpenDSS. The script code for setting the property details of the storage element is defined below, modified from the 'grid PV' toolbox [17, 19]:

Script 5: DSSText.Command = 'New Storage.Battery bus1=N283701 phases=3 daily=solar_24_hour state=charge dispMode=Loadshape kV=24 kW = 10000 kWrated=25000 kWhrated=100000 kWhstored=8000';

Script 6: DSSText.Command = 'New Storage.Battery bus1=N292246 phases=3 daily=solar_24_hour state=charge dispMode=Loadshape kV=24 kW = 10000 kWrated=25000 kWhrated=100000 kWhstored=8000';

The script code (5) was used for BUS-X and the script code (6) for BUS-Y in MATLAB to set the property details of the two storage elements. The storage controller has few technical property details as well. With STS analysis, the storage controller is controlled with the duty-cycle mode in the static control mode. The property details in Table. 4.2 were used for the storage controller script coding in OpenDSS and MATLAB. A storage controller is added for each bus separately to control the energy storage at the chosen bus.

Script 7: DSSText.Command = 'New StorageController.Battery terminal=1 element=line.fdr_05410 %Reserve=50.0 ModeCharge=LoadShape ModeDischarge=Loadshape daily=battery_24_hour ElementList=Battery EventLog=yes';

Table. 4.1. Technical property details of the storage element.

Property Name	Description
Bus 1	N283701 (BUS-X) & N292246 (BUS-Y)
kV	Specified Phase-Phase kV at BUS-X and BUS-Y.
kW	The positive kW value defines the discharge, and the negative value defines the storage element is charge. This charge/discharge depends on dispatch mode internally
pf	Default power factor (1.0)
conn	Wye connection is used as a default
mult	Load
State of the Battery	Charge/Discharge
kWstored	Stored energy in the Battery
dispmode	Follow

Table. 4.2. Technical property details of the storage controller.

Property Name	Description
Element	The element is to be a line or transformer element, which is controlled by the monitor.
%reserve	Using the %reserve, the storage controller can change the reserve percentage.
Terminal	The default terminal is taken as 1
kWTarget	KWTarget is used for discharge. The storage is depleted until the storage is dispatched to try to hold power.
Mode discharge	Discharge operating modes has explained in 4.2.2.
Mode charge	Charge operating modes has explained in 4.2.2.
TimeDischargeTrigger	To discharge the storage fleet, the discharge time charge time trigger has used with follow mode.
TimeChargeTrigger	To charge the storage fleet, the discharge time charge time trigger has used with follow mode.
%RatekW	It sets the kW discharge rate in % of rated capacity for each element of the fleet. Applies to TIME control mode or anytime discharge is triggered by time.
Duty	Dispatch load shape object, If any, for Duty cycle solution mode.

4.4. Seasonal Modelling of CKT24

This section will explain the seasonal fixed storage scheduling of charge/discharge rates. Storage is connected at both buses. The storage controller rate of charge or discharge is allocated to the storage fleet. STS based network simulations of the chosen case study network take place using real-time network data to show the impact of the storage controlled on minimising OV issues.

The rates of charge/discharge were adjusted at an hourly rate. On the existing historical data of with and without PV cases and ESS was modelled optimally based on the voltage limits. In a Sequential Power flow of one year comes in a sequence of seasons such as the spring, summer, autumn and winter with each season being almost three months. The Charge (C) and Discharge (D) load shape allocations will control the charge and discharge cycles based on predefined load shape percentages and are a significant part in the ESS because through an ideal C and D allocation, ESS can increase or decrease the voltage levels in the distribution systems.

State of Charge (SOC): SOC is defined as a state of charge, measured in percentages. The State of Charge (SOC) denotes the measurement of how much energy that left in a battery. The level of the SOC varies from 0% to 100%. The primary function of the SOC is calculated with the integration of the current capacity over time. SOC function is used to control the peak demand requirements and address voltage quality issues.

During the Over Voltage (OV) or Under Voltage (UV) violations, the percentage of charge is controlled based on the voltage limits. The optimal allocation of percentage of charge is given at a specific hour based on the PV output. The percentage of charge is given with respect to time of the day to control the voltage within the limits based on the PV generation output. To satisfy the electrical requirements of a distribution network the objective functions are subjected to different operating constraints to limit the boundaries of ANSI limit. To maintain the bus voltage within the ANSI limits, the optimal rate of charge is set to control the bus voltage within the 0.95 to 1.05 p.u. range with ±5 % tolerance. The bus voltage magnitude must lie within the range of 0.95 to 1.05 p.u. with ±5 % tolerance as given by Equation (1).

$$V_{min} \leq V\ (t,\ day) \leq V_{max} \quad - (1)$$

Where,

V_{min}= ANSI standard minimum voltage range.

V_{max} = ANSI standard maximum voltage range.

Depth of Discharge (DOD): DOD is defined as Depth of Discharge in the battery, measured in percentages. If the Depth of Discharge percentage is more during peak times, then the bus voltage will rise in line with the discharge percentage. The discharge scheduling was given based on the voltage limit as in Eq. (2). The script code below shows the overall simulation sequence.

Data= one annual year [spring, summer, autumn, winter]

1. Run the annual year data at Chosen Buses
2. Spilt data into seasonal periods with and without-PV
3. If Bus Voltage > V_{max}, Initiate Charge.
4. Set Rate of Charge based on V_{max} - V_{bus}
5. If Bus Voltage < V_{min}, Initiate Discharge.
6. Set Rate of Discharge based on V_{bus} – V_{min}
7. Run the fixed scheduling of charge and discharge dispatch for spring season.
8. Run the fixed scheduling of charge and discharge dispatch for summer season.
9. Run the fixed scheduling of charge and discharge dispatch for autumn season.
10. Run the fixed scheduling of charge and discharge dispatch for winter season.
11. Compare voltage magnitudes versus time in all seasons.
12. **End break**

The rate of seasonal rate of charge and discharge varies accordingly in every season. The following subsections explain the allocation of seasonal charge and discharge percentages for a daily cycle, and comparisons are provided with and without PV-cases for the two buses.

4.4.1. Operation of Seasonal Charge and Discharge states

This section illustrates the operation of the seasonal charge and discharge allocation of the storage element governing power flow and losses within the two possible states. The Storage element can operate either in standalone mode or as is in the case of this thesis, it can be controlled by a StorageController, which commands its active power dispatch [101].

The storage component is interfaced to the grid and the power flow is performed in the storage element. In addition, the power flow within the storage element can be calculated correspondingly in all OpenDSS solution modes. However, the power flow in the storage element has to be solved at a specific time to identify seasonal power flow. In this thesis, for STS simulations, the time interval of the time varying simulation was selected as t+Δt, where 'Δt' indicated a specific size of the time step. The following nomenclature is used in the below equations:

- $P_{in}[t]$: The storage power flow in a charge state at a specific time;

- P_{out}[t]: The storage power flow in a discharge state at a specific time;
- ηinv[t]: The inverter efficiency at t;
- η_{ch}: charge efficiency;
- η_{dch}: discharge efficiency;
- E[t]: stored energy at a specific time (t);

I. Charge State:

Fig. 4.5 shows the operation of the storage element in the charge state. The storage element enters into the charging state if kWhStored is less than kWhRated.

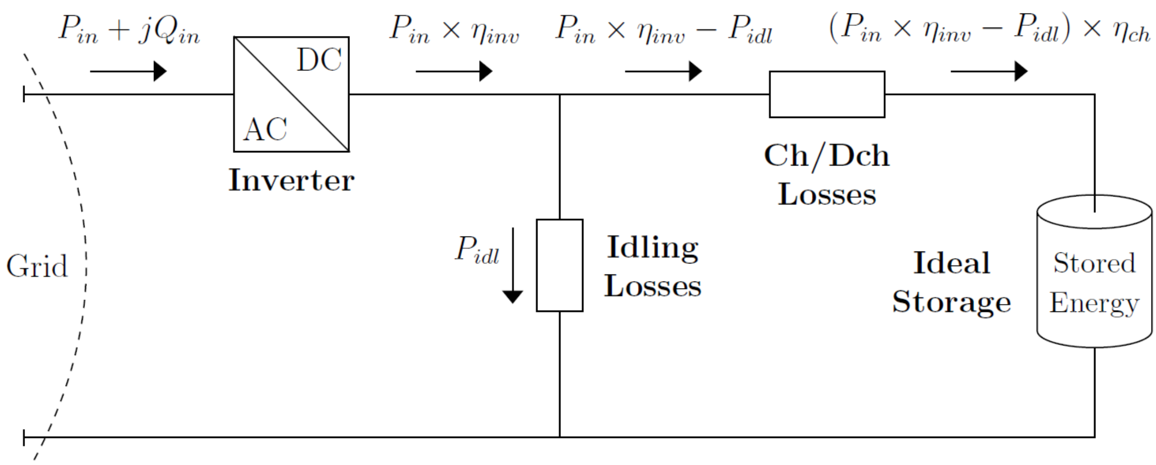

Fig. 4. 5. The Operation of a storage element in a charge state [101].

The storage element of the electricity grid interface is controlled in the OpenDSS power flow solution as P_{in} [t], and the inverter losses in a charge state can be determined from (2).

$$P^{ch}_{losses}[t] = P_{in}[t] \times (1 - \eta_{inv}[t]) \qquad - (2)$$

In this thesis, the idling losses have not been considered because the idling state has been removed as those losses impact on the battery life assessment. So, the power flow at the DC side of the inverter is P_{in} [t] x η_{inv} [t], and the charge state losses have been calculated, without the idling state, as the storage inverter losses as in (3) [101].

$$P_{losses,ch}[t] = (P_{in}[t] \times \eta_{inv}[t]) \times (1 - \eta_{ch}) \qquad - (3)$$

Thus, the total losses are calculated without idling state as

$$P_{ch,losses,total}[t] = Losses^{ch}_{inv}[t] + P_{losses,ch}[t] \qquad - (4)$$

The charge efficiency without ideal storage can be determined from (5)

$$P^{ch}_{eff}[t] = P_{in}[t] - P^{ch}_{losses,total}[t] \qquad - (5)$$

Finally, the energy stored in a specific time step simulation, t + Δt, is given by:

$$E[t + \Delta t] = E[t] + P^{ch}_{eff}[t] \times \Delta t \qquad - (6)$$

II. Discharge State:

The Storage element is able to enter into a discharge state if the amount of energy stored is larger than the capacity of energy to be held in the normal operation mode. Fig. 4.6 depicts the operation of the storage element in the discharge state.

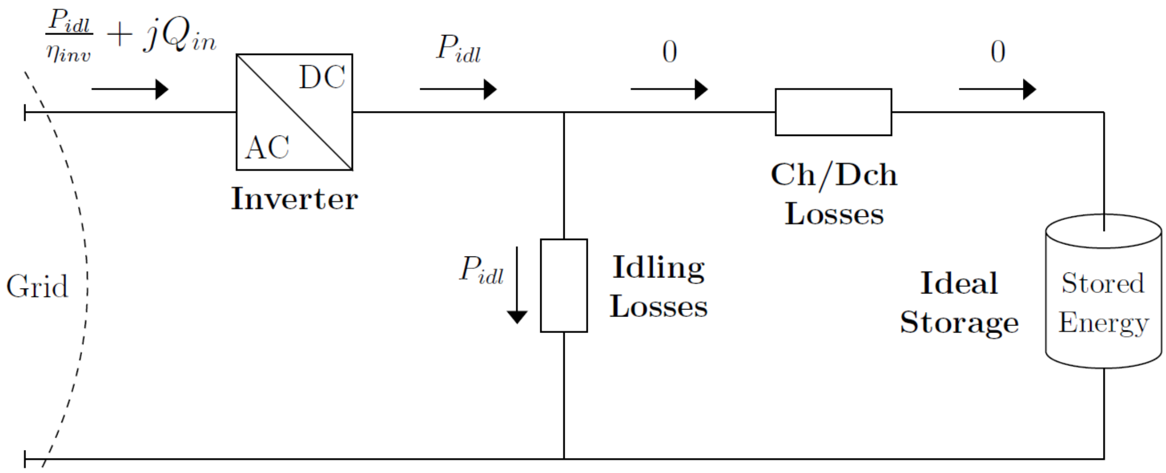

Fig. 4. 6. The Operation of a storage element in a discharge state [101].

$P_{out}[t]$ is the storage power flow of a discharge at a specific time controlled in the power flow solution. So, the inverter losses are determined from (7).

$$P^{dch}_{losses,inv}[t] = P_{out}[t] \times \left(\frac{1}{\eta inv[t]} - 1\right) \qquad - (7)$$

In this thesis, the ideal storage does not apply on the DC side of the storage inverter. So, without idling losses, the discharge state losses are determined by:

$$P_{losses,dch}[t] = (P_{out}[t] / \eta_{inv}[t]) \times ((1/\eta_{dch}) - 1) \qquad - (8)$$

The discharge state total losses, without idling losses, are therefore calculated from (9)

$$P^{dch}_{losses,tot}[t] = P^{dch}_{losses,inv}[t] + P_{losses,dch}[t] \qquad - (9)$$

The discharge state efficiency $P^{dch}_{eff}[t]$ is determined by the application of Eq(10)

$$P^{dch}_{eff}[t] = P_{out}[t] + P^{dch}_{losses,tot}[t]\ [W] \qquad - (10)$$

The energy stored in a specific time step simulation, t + Δt, is given by:

$$E [t + \Delta t] = E[t] - P^{dch}_{eff} [t] \times \Delta t$$

4.4.2. Seasonal Scheduling Allocation

Table. 4.3 show the boundaries of the seasonal percentage of charge (C) and discharge (D) allocations. Charge and discharge percentages have been allocated to control the voltage between the tolerance limits given as the 0.95 ↔ 1.05 p.u. range with ±5% tolerance. These are the charge and discharge LoadShape percentages controlled by the storage controller. The allocations have been set in the storage controller seasonally with sequential power flow. If the charge and discharge percentage allocations are not set accordingly, the bus voltage may violate the steady-state limits. For instance, the winter percentage of charge has the lowest variance between 22% to 24% signifying that less charge will occur during the winter compared to the spring percentage of charge which can increase as much as 80%. Hence, during spring it is possible to charge at higher rates.

In autumn, the load demand is less compared to the other seasons, and therefore discharge needs to take place at a lower rate. DOD is never set higher than 50% to increase the battery life and the number of rechargeable cycles. No idling was modelled in this study as idling can drain the battery affecting the life of the battery.

Table. 4.3. Percentage of Charge and Discharge Allocations.

Season	Percentage of Charge **(C)** **(BUS-X)**	Percentage of Discharge **(D)** **(BUS-Y)**
Spring	$25\% \leq C\ (t) \leq 80\%$	$25\% \leq D\ (t) \leq 50\%$
Summer	$30\% \leq C\ (t) \leq 80\%$	$30\% \leq D\ (t) \leq 50\%$
Autumn	$30\% \leq C\ (t) \leq 67.5\%$	$25\% \leq D\ (t) \leq 30\%$
Winter	$22\% \leq C\ (t) \leq 24\%$	$28\% \leq D\ (t) \leq 40\%$

In Table. 4.4, every season has a unique C (%) and D (%) with respect to time. In spring and summer seasons, the percentage of charge can rise as high as 80% during the early morning due to the low customer demand. However, the percentage of charge is never that high in autumn or winter because the demand is high due to heating loads. In winter, the lowest levels of charge take place with an average charge allocation of 23%. In autumn, 18 hours of charge can be tolerated compared to 13 hours in winter. Only 6 hours of discharge can be tolerated in autumn, compared to the winter season when up to 11 hours of discharge can take place. In autumn, the percentage of discharge percentages are also lower compared to any other season. In autumn, as shown the daily average discharge allocation is 28% lower than the discharge allocation in any other season. This is because the network is more lightly loaded duding this season compared to any other season. A lower discharge allocation enables to increase the battery life, as battery is not discharged at deep rates during the autumn season.

Table. 4.4. The optimal rate of charge and discharge summary across all seasons.

	Spring		**Summer**		**Autumn**		**Winter**	
C: Charge | D: Discharge								
Time (Hours)	C (%)	D (%)	C (%)	D (%)	C (%)	D (%)	C (%)	D (%)
00.00	40		50		55		22	
01.00	50		60		60		22	
02.00	60		70		65		23	
03.00	70		80		675		22.8	
04.00	80		80		65		22.8	
05.00	70		80		60		23	
06.00	60		70		55		24	
07.00	60		60		50		24	
08.00	50		45		45		24	
09.00	40		35		40		24	
10.00	30		35		40		24	
11.00	25		42		30		23.8	
12.00	25		42		30		24	
13.00		25		30		25		30
14.00		25		30		25		32
15.00		30		30		30		34
16.00		50		50		30		36
17.00		40		40		30		40
18.00		30		30		30		38
19.00		30		30	30			36
20.00		30		30	35			34
21.00	40		30		40			32
22.00	50		40		45			30
23.00	60		50		50			28
Daily Average	51	33	**50**	34	**48**	28	**23**	34

4.5. Battery Life Assessment

Fig. 4.5 shows the periodic distribution of daily percentage of charge allocations across the different seasons and potential impact on the battery life. As shown, minimum percentage of charge levels have been set in winter due to the high load demand, but in summer, high percentage of charge levels can be tolerated with due to the high PV power. Spring and autumn have similar profiles to the summer. The percentage of charge levels were never set very high all the time to eliminate the negative impact on the battery lifetime. Fig. 4.6 shows the breakdown of daily percentage of discharge allocations. The percentage of discharge allocation is the highest during the summer period at a specific time corresponding to high load demand. However, this was limited to one-hour every day throughout the season and therefore should have the minimal impact on the battery lifetime. Except the summer period, all allocations are below 40% in consideration of the battery lifetime.

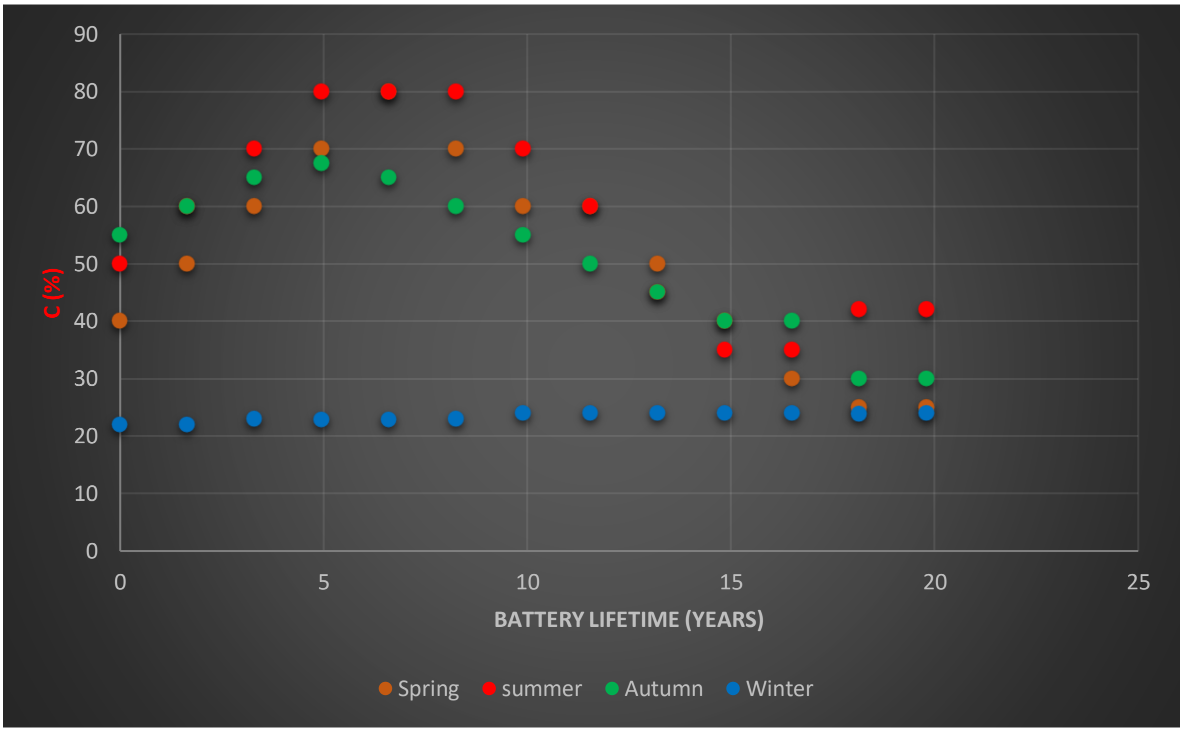

Fig. 4. 7. Seasonal Battery Life Assessment upon the Charge Allocation Percentages.

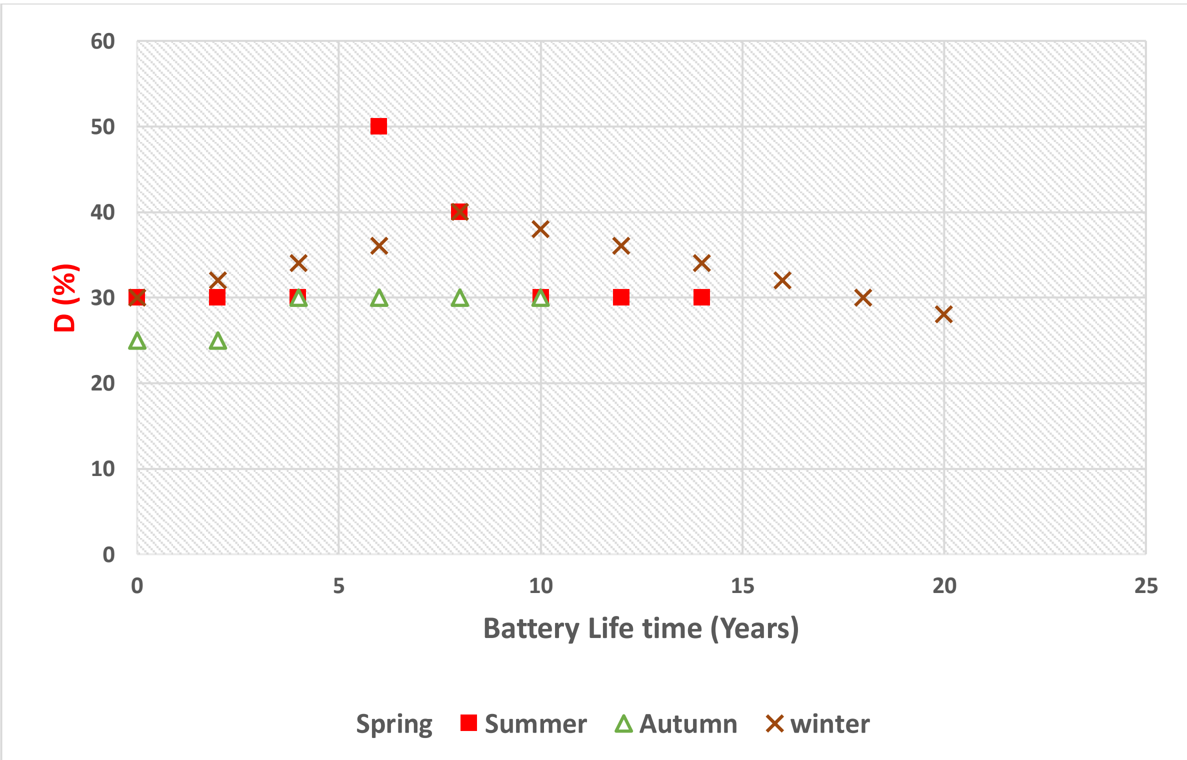

Fig. 4. 8. Seasonal Battery Life Assessment upon the Discharge Allocation Percentages.

4.6. Simulations and Results Based on Seasonal Scheduling

4.6.1. PV/Battery Grid Integration Results at BUS-X

The voltage plot after PV/Battery integration at BUS-X is shown in Fig. 4.7. The arrow points to BUS-X, where the ESS has been added. Two ESS units have been considered at two buses to control energy storage individually. As shown in Chapter-3, CKT24 experiences seasonal OV issues at BUS-X and BUS-Y. The ESS units were added to the CKT24 with the existing PV system configuration. The grid integration of PV/Battery could help to minimise the transformer losses and reduce seasonal over-voltage issues.

The proposed grid integrated PV/Battery network diagram of EPRI CKT24 has modelled in Fig. 4.7 at BUS-X to minimise the OV issues at BUS-X seasonally. Script A1 in Appendix A was written in MATLAB to integrate the battery storage units with the existing PV system configuration in CKT24. As shown in the script, a new storage controller and new three-phase storage units have been added at BUS-X. The rating of the battery storage system is 24 kW. Other rates values of the added ESS include 25000 kWh rated and 100,000 kWh stored.

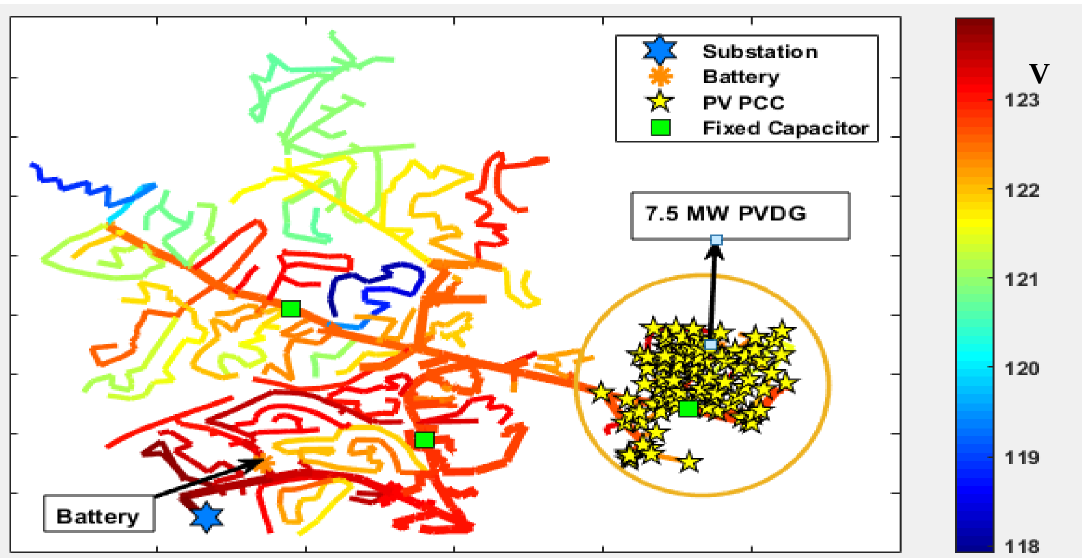

Fig. 4. 9. Simulation results of grid integrated PV/Battery network diagram of CKT24 at BUS-X.

4.6.1.1. Spring Season at BUS-X in CKT24

The script code A2 in Appendix A was used for allocating the rate of charge/discharge percentages based on the LoadShape information. The day of execution was the 9th May, which had the voltage profile of spring. As shown in Fig. 4.8, after the integration of the ESS units at Bus-X, the OV issue was avoided. After the addition of the ESS, the previously experienced OV issues from the 3072nd to the 3082nd hours are no longer seen as the ESS is charge throughout this period. During the afternoon, from 1 pm to 8 pm (3085th hour to 3092nd hour), the rate of discharge is only given between 25 to 50%. Even though discharge occurs from 1 pm to 8 pm, this has not caused any OV issues, as the load demand is high during this period. At around 9 pm, ESS charges again, but without any power quality impact. The bus voltage goes down to 136 kV well within the permissible range.

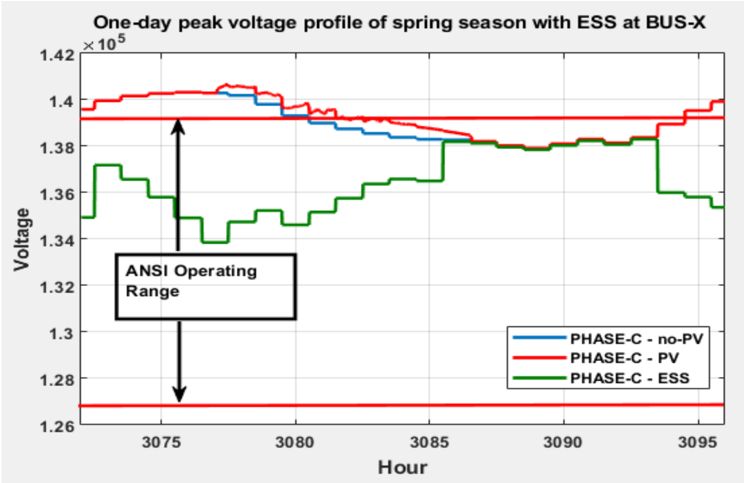

Fig. 4. 10. Seasonal scheduling of charge/discharge dispatch in the spring season at BUS-X.

4.6.1.2. Summer Season at BUS-X in CKT24

The script A3 in Appendix A was used for setting the optimal rate of charge/discharge percentages based on the summer LoadShape information. In summer, the 3rd July was taken as the day of analysis. As shown in Fig. 4.9, after the integration of the ESS at BUS-X, the OV issues from 4394th hour to 4402nd hour was solved.

In the summer season, the battery is charged until noon with different rate of charge throughout this period. During the afternoon, from 1 pm to 8 pm, the rate of discharge was given from 30% to 50% without any OV impact. The bus voltage does not exceed the limits throughout the simulation.

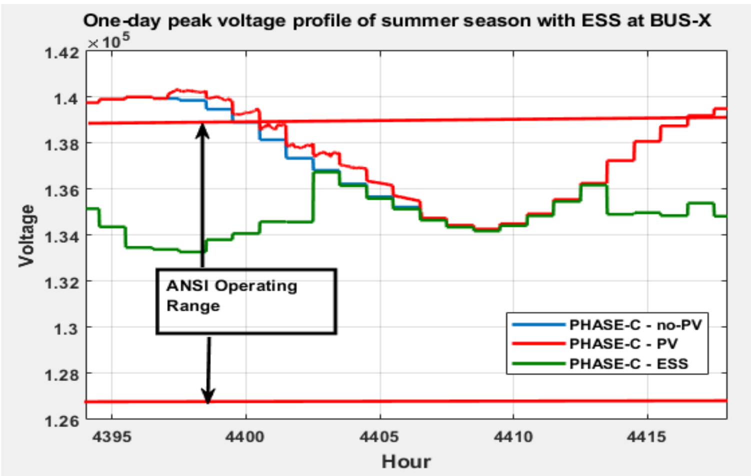

Fig. 4. 11. Seasonal scheduling of charge/discharge dispatch in the summer season at BUS-X.

4.6.1.3. Autumn at BUS-X in CKT24

The script code A4 in Appendix A is used for the allocation of charge and discharge percentages, completely different from the spring and summer season percentages. The charge period in the autumn season is from 12 am to 12 pm with percentages ranging from 30% to 67.5 %.

The battery is discharged for only 6 hours, which is the least compared to other seasons. The OV issues in the autumn season were seen from the 6604th hour to 6612th hour on the 3rd October. As shown, after the integration of the ESS, the OV issue was eliminated. As shown in Fig. 4.10, from 1 pm to 6 pm, the battery is in discharge mode with discharge percentages ranging from 25% to 30% without causing any OV issues.

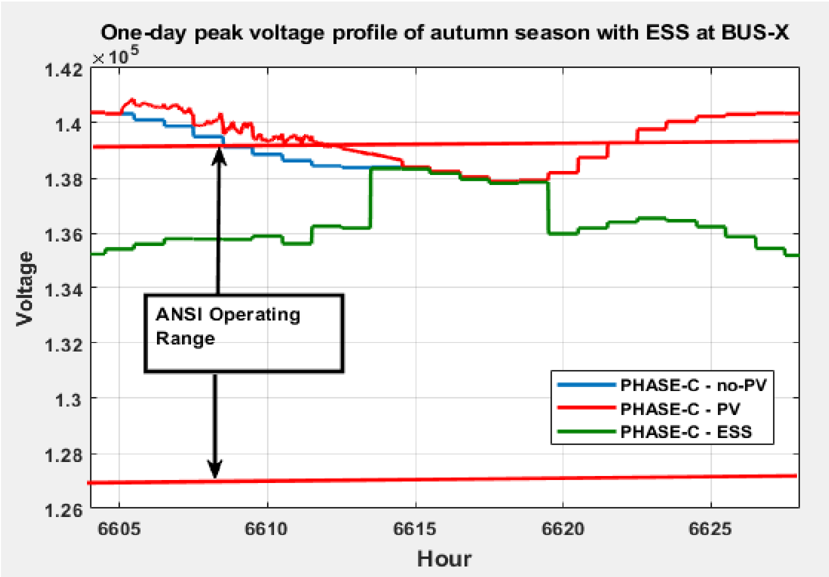

Fig. 4. 12. Seasonal scheduling of charge/discharge dispatch in the autumn season at BUS-X.

4.6.1.4. Winter Season at BUS-X in CKT24

The script A4 in Appendix A was used for the allocation of winter charge and discharge percentages. In winter, the day of analysis was 1st December. Fig. 4.11 shows the outcome of the integration ESS on the bus voltage. The battery is in charge mode from the 8017th hour to the 8029th hour (from 12 am to 12 pm) with percentages ranging between 22 to 24%. From 1 pm to 11 pm, the battery is in discharge mode with percentages between 28 to 40%. ESS integration resolved the OV issues without causing any voltage violations even during discharge.

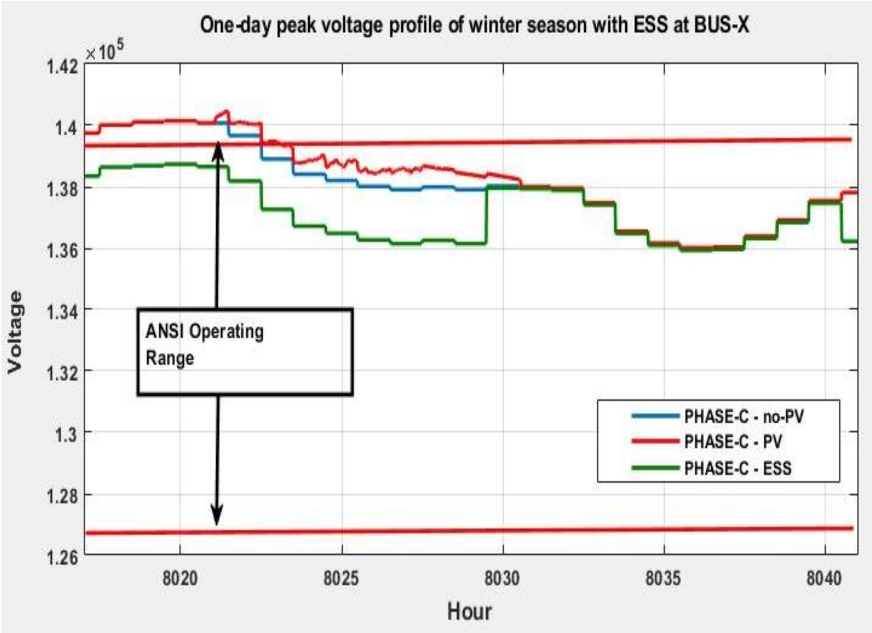

Fig. 4. 13. Seasonal scheduling of charge/discharge dispatch in the winter season at BUS-X.

4.6.1.5. Seasonal Comparison of Dispatch Scheduling at BUS-X

This section presents an analysis of each season, where different seasonal load shape allocations have been applied to demonstrate the need for a seasonal based approach in PV/ESS optimisation. The focus is on an all-season comparison with optimal scheduling of the charge/discharge dispatch at Bus X.

Fig. 4.12 shows the winter analysis using all four seasonal charge/discharge LoadShape allocations. As shown by Fig. 4.12, for any allocated schedule other than the Winter schedule, UV issues are experienced demonstrating that if optimal scheduling is not given seasonally, then the bus voltage may exceed beyond the limits.

Fig. 4.13 shows the spring season analysis separately applying the different seasonal load shape allocations. As shown, other than the summer load shape discharge and charge schedules, the two other allocation approaches would result in OV and UV issues. Fig. 4.14 shows the summer season analysis using the different load shape allocations. In this instance, the spring allocation produces a sufficient profile but autumn and winter schedules result in UV issues. As shown in Fig. 4.15, which shows the autumn season analysis, except the autumn schedule, every other seasonal allocation produces undesirable outcomes.

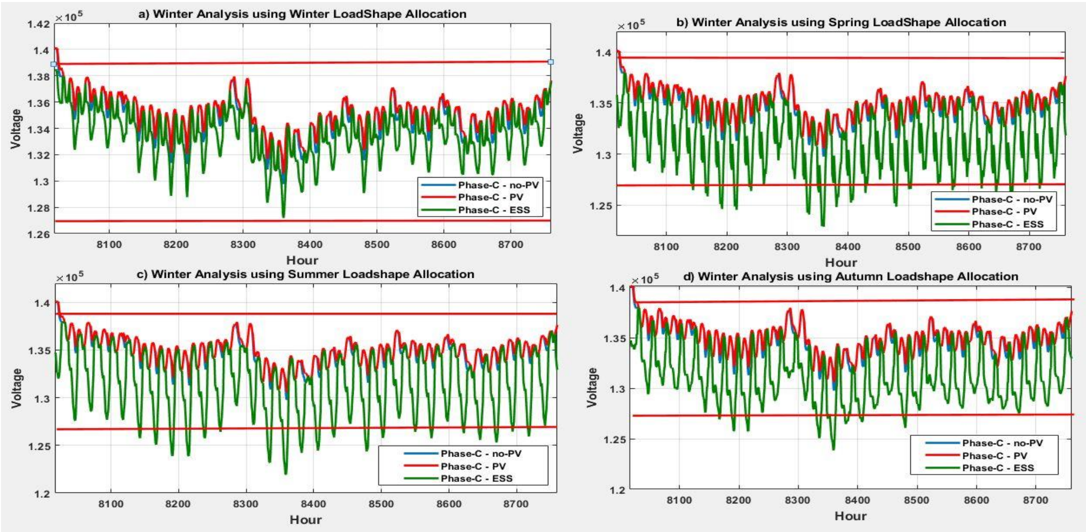

Fig. 4. 14. Winter season analysis using different seasonal LoadShape allocations at BUS-X.

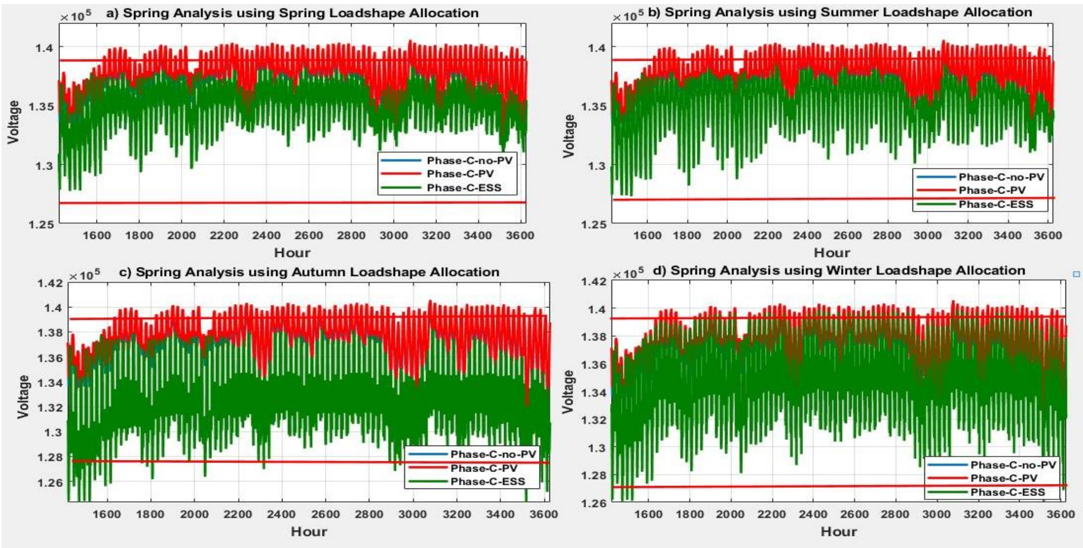

Fig. 4. 15. Spring season analysis using different seasonal LoadShape allocations at BUS-X.

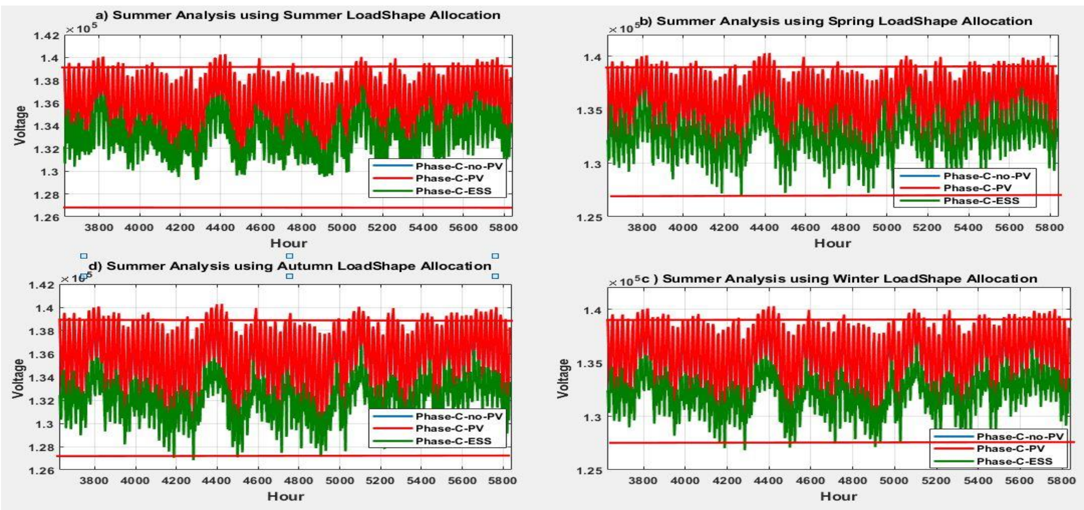

Fig. 4. 16. Summer season analysis using different seasonal LoadShape allocations at BUS-X.

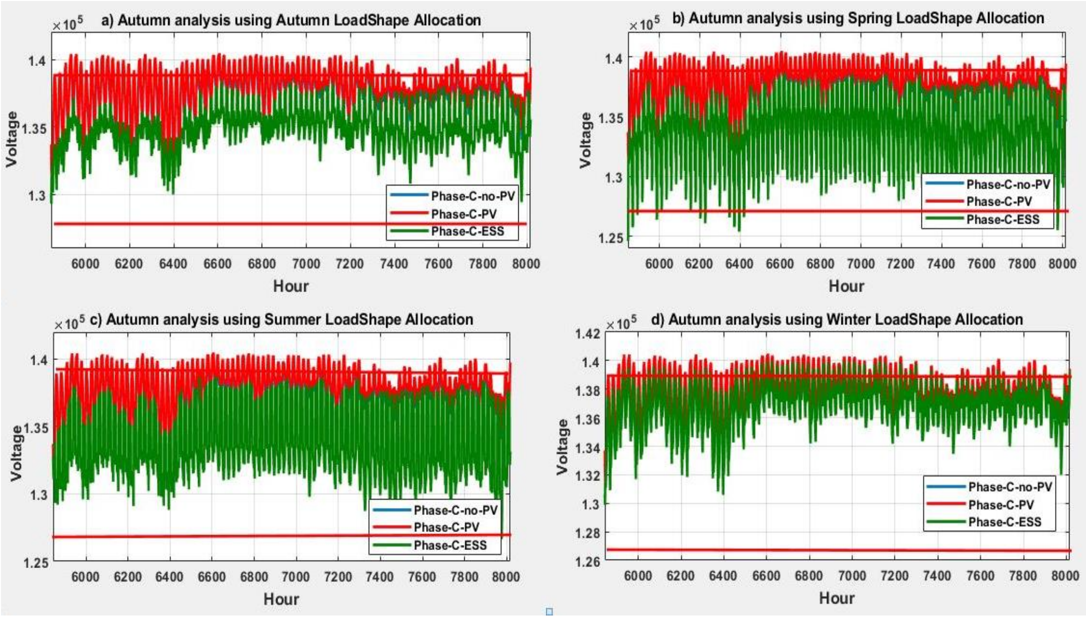

Fig. 4. 17. Autumn season analysis using different seasonal LoadShape allocations at BUS-X.

4.6.1.6. Power Supplied from the Substation Transformer

Table. 4.5 show the power supplied by the substation transformer for with and without ESS cases for all seasons. As shown, ESS reduces the loading on the distribution transformer in CKT24. In spring season for one day, the transformer load is around 101.35 MVA without ESS, but with ESS, the power supplied from the transformer reduces to 96.21 MVA.

The transformer-supplied power is highest during a summer day compared to any other season. The transformer supplied power reduced to 157.80 MVA from 163.58 MVA after the integration of the ESS during the analysed summer day.

Table. 4.5. Substation Transformer Power Flows at BUS-X.

Substation Transformer MVA Power Flow		
	No ESS (MVA)	**With ESS (MVA)**
SPRING	101.3542	96.21
SUMMER	163.5779	157.8973
AUTUMN	102.621	97.22956
WINTER	117.8338	115.6506

4.6.2. PV/Battery Grid Integration Results at BUS-Y

Script A1 was used in MATLAB to integrate the ESS units with the existing PV system configuration at BUS-Y in CKT24. As shown in the script, a new storage controller and a new three-phase storage were added at BUS-Y. The rating of the battery storage system is similar to the BUS-X case with 8000 kWh-stored capacity.

4.6.2.1. Spring Season at BUS-Y in CKT24

The Script code A2 was used for allocating the charge and discharge allocations in spring season at BUS-Y with the same spring optimal percentages. As shown in Fig. 4.16, after the integration of the ESS units at Bus-Y, the OV issue was resolved. At BUS-Y, the OV issues were more serious than BUS-X, but with the same dispatch schedule, OV issues have been resolved which occurred between the 3072nd and 3084th hours. Discharge does not also cause any steady-state voltage limit violations.

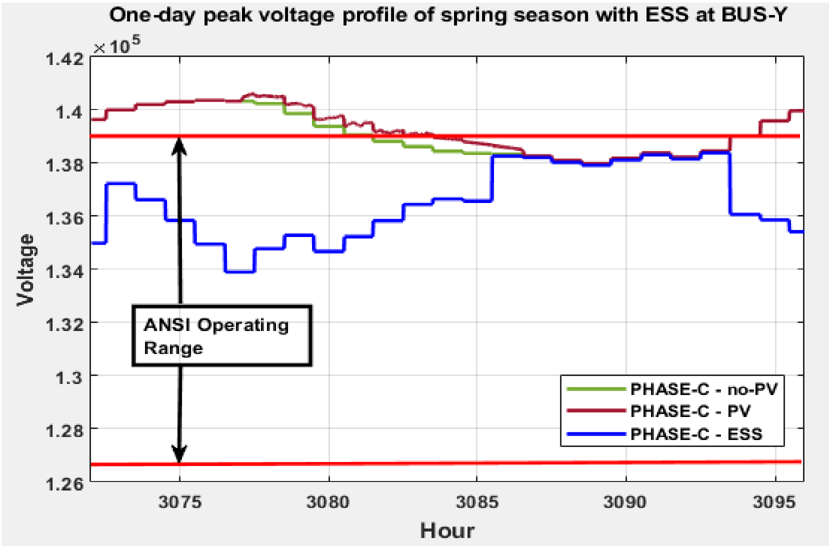

Fig. 4. 18. Seasonal scheduling of charge/discharge dispatch in the spring season at BUS-Y.

4.6.2.2. Summer Season at BUS-Y in CKT24

The same BUS-X optimal summer scheduling was also used for BUS-Y as shown in Fig. 4.17. As shown, OV issues can be avoided with the inclusion of the ESS and discharge does not cause any OV problems during the periods of discharge. We can see that during the summer season, the 132 kV bus voltage can rise up to 140 kV without any ESS. The bus voltage can however be reduced as low as 134 kV after the addition of ESS.

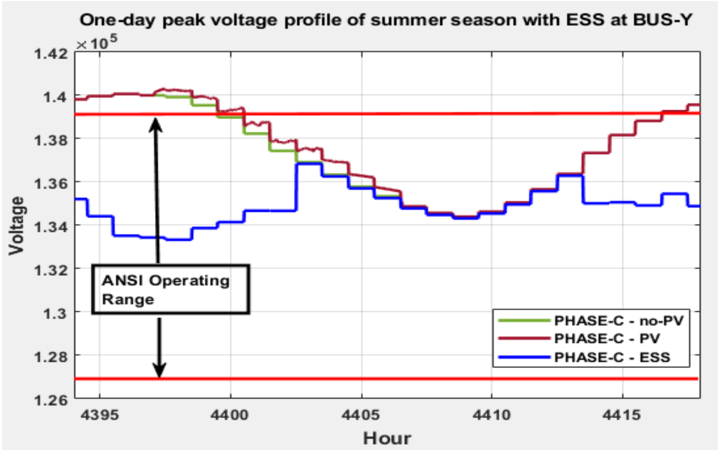

Fig. 4. 19. Seasonal scheduling of charge/discharge dispatch in the summer season at BUS-Y.

4.6.2.3. Autumn Season at BUS-Y in CKT24

The similar script code was used for BUS-Y as the BUS-X optimal scheduling script. As shown below in Fig. 4.18, the 132 kV BUS-Y voltage can rise as high as 141 kV during early hours of the morning but with this addition of the ESS systems and autumn specific scheduling, the bus voltage can be lowered to around 136 kV.

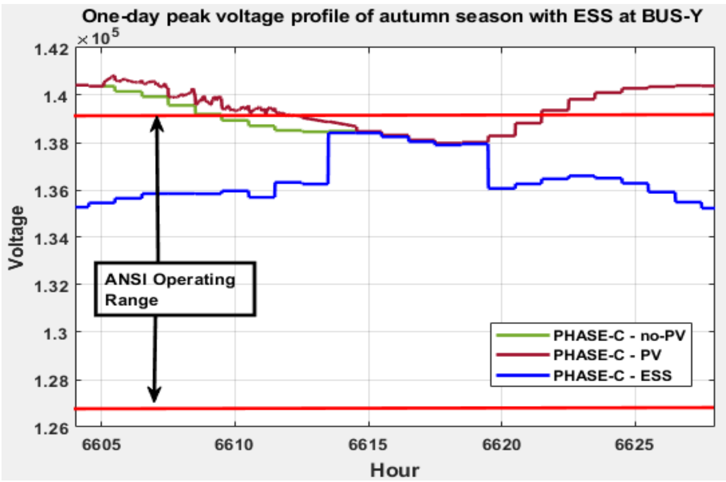

Fig. 4. 20. Seasonal scheduling of charge/discharge dispatch in the autumn season at BUS-Y.

4.6.2.4. Winter Season at BUS-Y in CKT24

The script code A4 in Appendix A was used for winter season at BUS-Y for the allocation of winter charge and discharge percentages for the daily analysis. In winter season using the same BUS-X optimal charge and discharge percentages, the BUS-Y OV issues can be resolved. This shows that throughout the same network, the same seasonal Loadshape allocation can be applied regardless of the location.

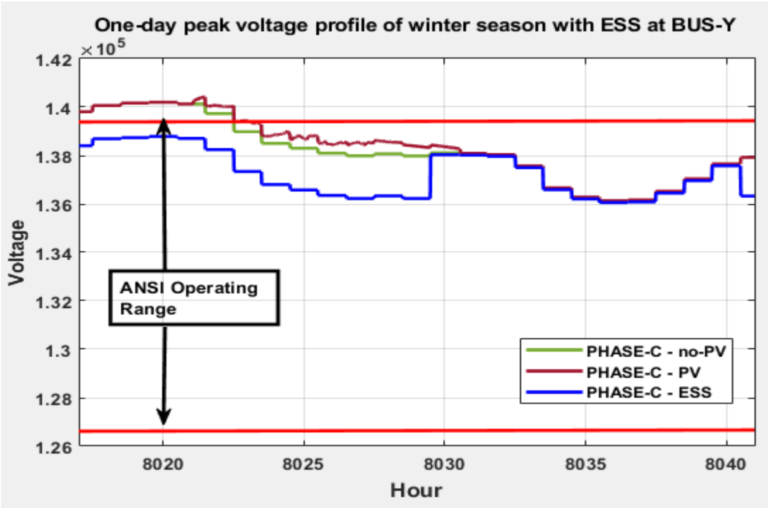

Fig. 4. 21. Seasonal scheduling of charge/discharge dispatch in the winter season at BUS-Y.

4.6.2.5. Seasonal Comparison of Dispatch Scheduling at BUS-Y

This section discusses an all-season comparison for Bus Y where different seasonal C and D load shape allocations have been applied to demonstrate the impacts on the steady-state bus voltage. The analysis begins with the summer period as shown in Fig. 4.20. As shown, the summer and spring allocations produce the best results where the bus voltage will be centred on the midpoint of the permissible voltage range. For the spring analysis shown in Fig. 4.21, only the spring C and D allocations were observed to control the bus voltage within the permissible range without producing any UV or OV violations. A similar result is observed for the autumn and winter analysis, where only the autumn and winter C and D allocations consecutively result in an acceptable bus voltage profile. As shown, for Bus Y, a more dedicated seasonal approach is required and compared to Bus X.

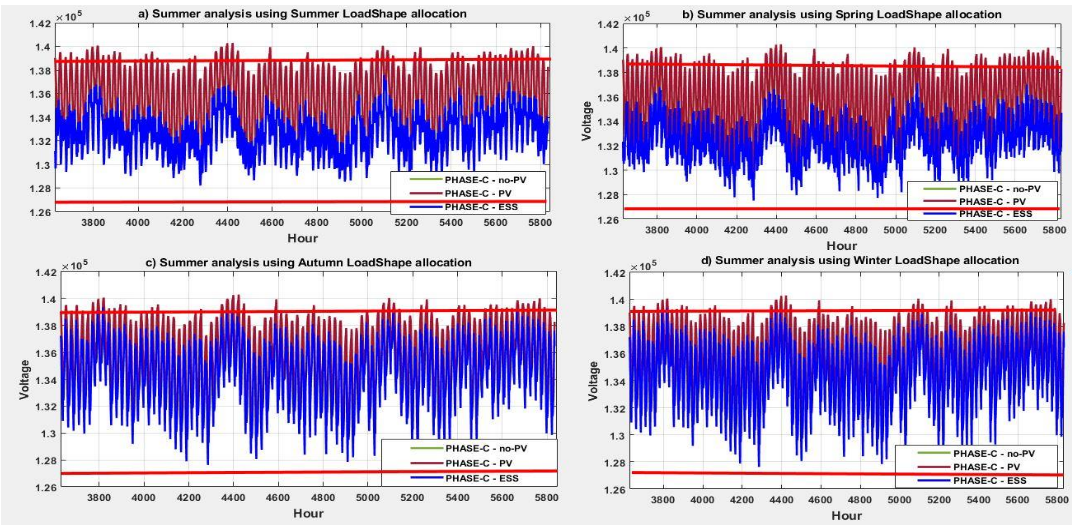

Fig. 4. 22. Summer season analysis using different seasonal LoadShape allocations at BUS-Y.

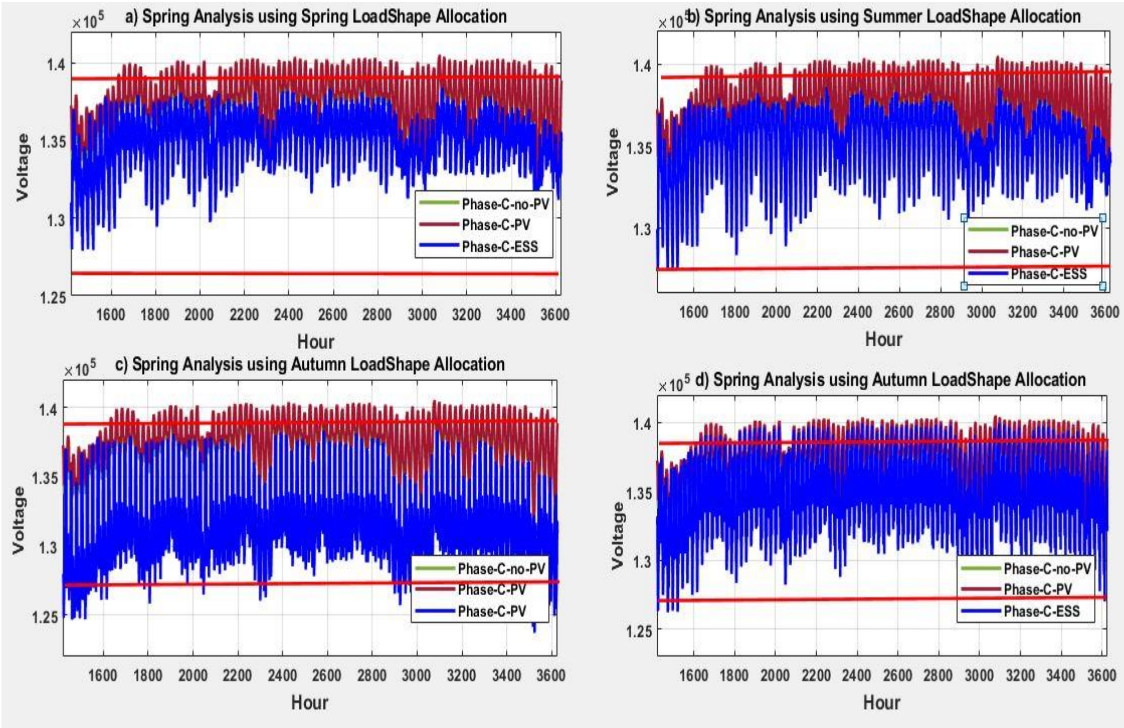

Fig. 4. 23. Spring season analysis using different seasonal LoadShape allocations at BUS-Y.

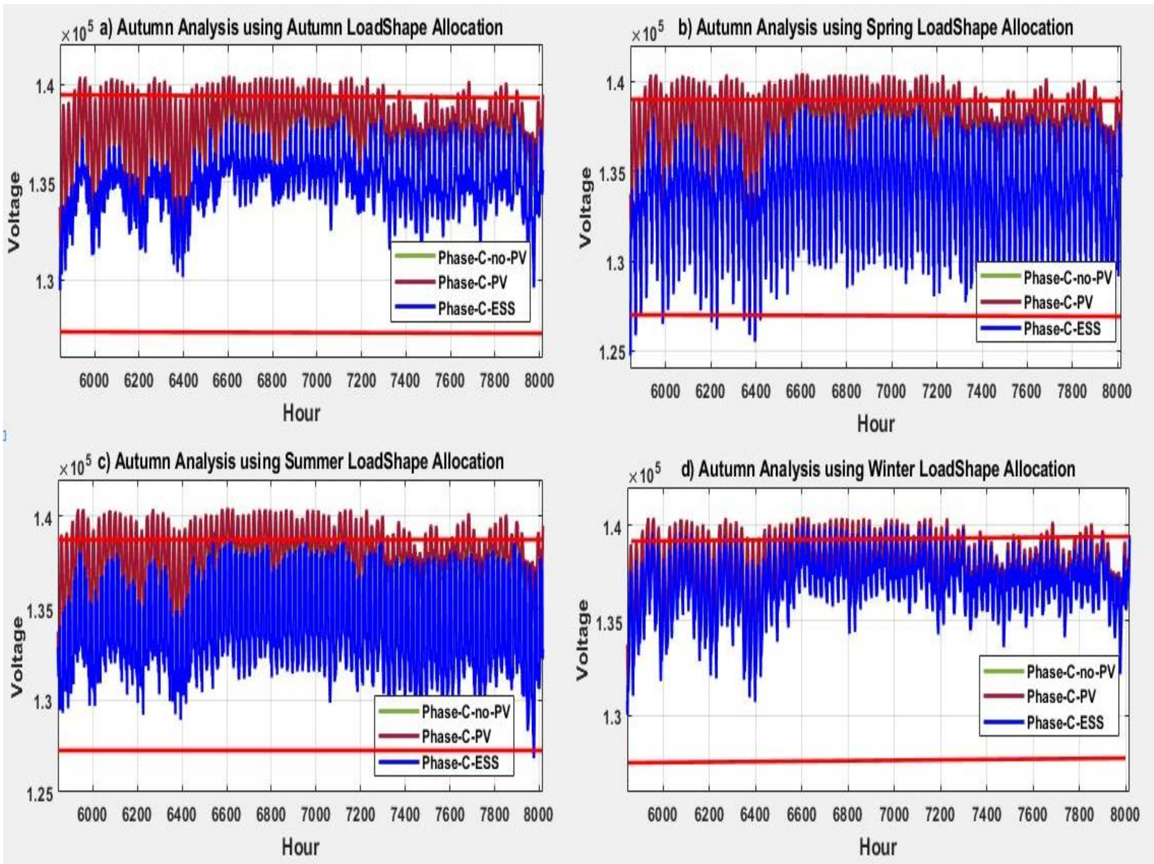

Fig. 4. 24. Autumn season analysis using different seasonal LoadShape allocations at BUS-Y.

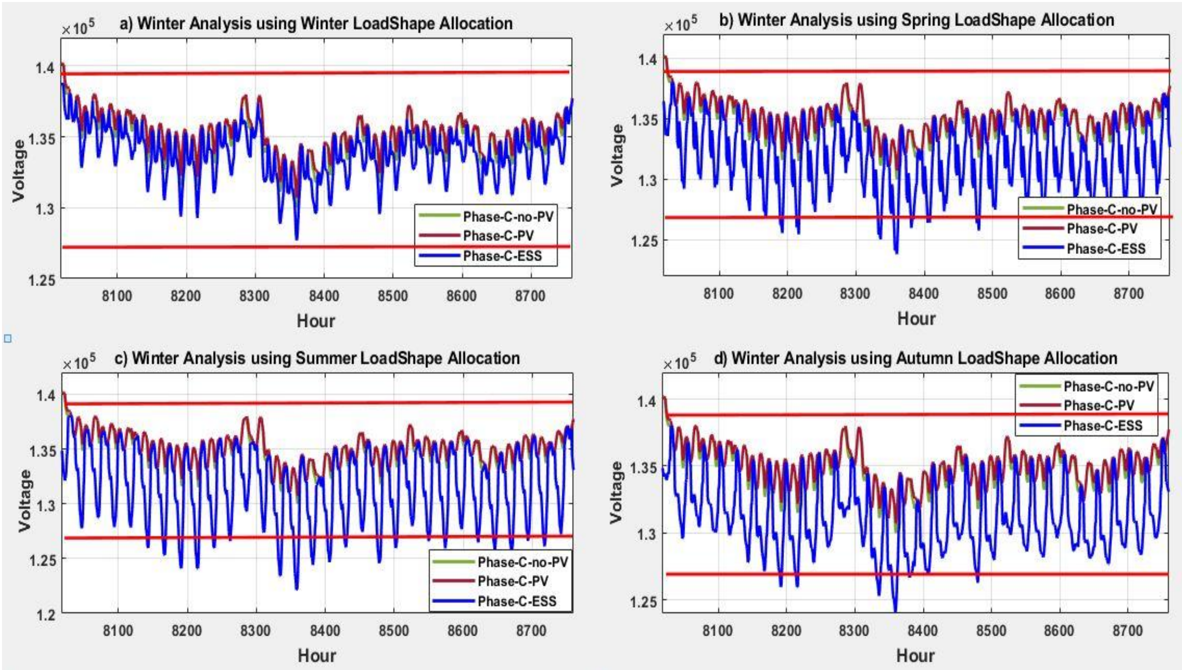

Fig. 4. 25. Winter season analysis using different seasonal LoadShape allocations at BUS-Y.

4.6.2.6. Power Supplied from the Substation Transformer at BUS-Y

Table. 4.6 show the power supplied by the substation transformer for with and without ESS cases for all seasons with no-PV generation. As shown in Table. 4.6, ESS reduces the loading on the distribution transformer in CKT24. Except in summer, all season transformer loading at BUS-Y is more than that of BUS-X. The spring and autumn seasons have the almost similar daily transformer load at BUS-Y. As shown, ESS reduces the loading on the substation transformer.

Table. 4.6. Substation Transformer Power Flows at BUS-Y.

Substation Transformer MVA Power Flow		
	No ESS (MVA)	**With ESS (MVA)**
SPRING	101.9952	96.70434
SUMMER	161.0781	155.4986
AUTUMN	102.9677	97.36312
WINTER	117.9041	115.6461

4.7. Conclusion

This chapter has focused on modelling and comparison the seasonal dispatch scheduling of an ESS in a case study distribution network. It has been shown that different dispatch schedules need to be employed across the seasons and a one size fits all scheduling approach is not suitable. For both analysed buses, it has been shown that the ESS systems can be used to address the OV issues and appropriate LoadShape allocations can be developed for any season. ESS units were also shown to reduce the peak demand issues and lower the power demands from the substation transformer.

CHAPTER-5

Conclusions and Future work

5.1. Key Findings and Contributions

In the future, energy storage systems will be largely distributed in networks to decrease system losses and improve the efficiency of the system. Renewable energy generation, such as PV systems, is increasing across the globe, but simultaneously fossil fuels are being depleted whilst the electricity demand has been increasing. Storage systems will be essential in future smart grids to minimise the issue in the distribution systems and to support the peak load demand at the grid whenever it is required. This research has focused on seasonal analysis of network load demand of a case study distribution system and development of seasonal energy-storage dispatch allocations leading to cost-effective energy management decisions on the power delivery grids.

Battery energy storage systems can provide active and reactive power playing an important role in the power quality management of distribution networks. The joint grid integration of PV and battery systems could also help to minimise the transformer losses and reduce seasonal over-voltage issues. For example, the analysis, presented in this thesis, has shown that for the analysed CKT24 case study network, the loading on the substation transformer can be reduced by 6 MVA by integrating ESS on the network with no-PV penetration. For both analysed buses, the largest reduction on the grid supplied power through the transformer (around 5.5 to 6 MVA) was observed during the summer season, which is very ideal in terms of operation of a distribution network.

In this dissertation, a seasonal charge (C) and discharge (D) allocation approach has been proposed to deal with mainly over-voltage issues within the case study network. Sufficiency of such an approach with respect to the control of bus voltages within grid code set limits has as well been demonstrated. Special attention has been paid to ensuring increased battery life with minimum discharge allocation percentages set across all seasons. Every season was given a unique C (%) and D (%) LoadShape allocation with respect to time. In spring and summer seasons, it was observed that the percentage of charge can be increased as high as 80% during the early morning due to the low customer demand. In autumn or winter, the percentage of charge had to be lower as demand was higher due to heating loads. In winter, the lowest level of charge was an average charge allocation of 23%. In terms of charge durations, the key finding is as follows: In autumn, 18 hours of charging state can be tolerated compared to 13 hours in winter. Only 6 hours of discharging state can be tolerated in autumn, compared to the winter season when up to 11 hours of discharging can take place.

In this dissertation, the key findings addressed the variability and intermittence of PV output on nodal voltage variation. Deployment of some capacity of energy storage can assist in voltage regulation and eliminate the power quality concerns. In addition, energy storage improves absorptive ability of grid to PV and help to increase the capacity of PV generation access. The output of PV systems shows large fluctuations due to many environmental parameters also impacted by seasonal weather patterns. This work has focused on a fixed seasonal charge-discharge allocation modelling of energy storage within PV penetrated networks. If PV require long-distance transmission lines for access to the nearby substation (such as PV located at remote areas), the voltage power quality issue can potentially be worse and the demand for energy storage for voltage regulation purposes far greater. Using seasonal allocations, a relatively straightforward control approach can be developed not requiring sophisticated control schemes. Many simulation studies have been provided in this thesis to demonstrate the need for a seasonal focus whilst showing that a seasonal fixed allocation schedule is often sufficient. Yet, it has been shown that different dispatch schedules need to be employed across each season and a one size fits all scheduling approach is not suitable.

ESS operates to voltage regulation and improving voltage quality, in the meantime, it also conducts to peak shaving and valley filling, as well as obtaining value which come from inter-temporal arbitrage and reduces transmission line overloads. However, the high cost of energy storage is its bottleneck of promotion and application. With various energy storage technologies become more mature, the price of energy storage deems to further decline, in that case, the advantage of using energy storage to improve voltage quality will be greater.

The analysis including the load demand and steady state bus voltages has been conducted for the heavily loaded and as well as lightly loaded network to investigate patterns of voltage quality issues. In the analysed case study network, over-voltage issues occurred during the lightly loaded network all throughout the year, but particularly in spring and autumn seasons. The observations demonstrated overvoltage issues especially in the early hours of the day, when the load demand was low, made worse by the power that begins being injected into the network from sunrise onwards. This period of low load demand presented itself as a period of potential battery charge period. Battery discharge period followed after the load demand peaked in the network with both discharge and charge allocations set paying attention to avoidance of deep discharge with favourable impacts on the battery life.

The load demand decreases at night, but still maximum charge during the lightly loaded network can also cause under-voltage issues. Consumers are utilising heating and cooling equipment on the seasonal wise increasing the load demand especially in summer and winter. Maximum discharge during a heavily loaded network is also risky and can potentially raise over-voltage issues. Therefore, it is significant to control the charge and discharge allocation of energy storage optimally during the day across all seasons to avoid any voltage quality issues. This seasonal approach scheduling can be applied to all types of batteries with favourable outcomes.

This research analysed sequential time power-flow analysis as an extension of the typical static mode of power flow analysis in distribution system analysis. In this sequential-time power flow simulation, both the static and time-series data have been investigated with and without PV systems across all seasons. The rate of charge/discharge allocations and periods have been set to address primarily overvoltage issues at the two chosen buses, which are more severely affected buses across all 6058 buses in the CKT24 distribution network. One limitation of the research discussed in this thesis is the fact that only the worst phase (Phase-C) has been considered in both buses. Further analysis is recommended in future work to analyse the impact of the recommended seasonal charge and discharge LoadShape allocations on the steady-state voltages of the various buses.

Dynamic power-flow simulation mode of inverter-based storage models requires more than 30 parameter values. This is intimidating for distribution planners. For distribution planners and analysts, the seasonal approach is recommended as it is easier to analyse and forecast for the future electricity demand to develop standard models leading to cost-effective approaches to control the power delivery grids. The most significant outcome of this research are the developed seasonal rate of charge and rate of discharge allocations and validation of the sufficiency of such a seasonal allocation in addressing power quality issues, especially the required steady-stage voltage limits. Consequently, a key recommendation, to operators of power system networks, in this thesis is to investigate the feasibility of such a fixed seasonal charge/discharge allocation approach before more complex approaches are explored.

5.2. Future Work

The dissertation presented in this research is a significant contribution to the knowledge in seasonal scheduling of PV/battery grid integration. Battery storage is certainly the next most disruptive technology in the power sector to assist in a reduction of peak consumption levels. Low-cost energy management of storage could transform the power landscape. Utilities need to consider a radical shift in their grid-system planning approaches with investments in software and advanced analytics to modernize the grid and change traditional system planning approaches. A seasonal analysis approach is one such paradigm that can support such a shift. Future work could focus on further analysis of more real networks and consideration of contingency scenarios concerning seasonal planning of ESS operation within distribution networks.

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APPENDIX A – MATLAB SCRIPT CODES

Script A1 – ESS Modelling for Bus X and Bus Y

```
[DSSCircObj, DSSText, gridpvPath] = DSSStartup;

DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt24_master.dss"'];

DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt24_distributedpv.dss"'];

DSSText.Command = 'New generator.solar bus1= N283701 kV=132 kW=2600 pf=1
conn=wye duty=solar_24_hour Model=1';

% BUS-X

DSSText.Command = 'New Storage.Battery bus1=N283701 phases=3 daily=solar_24_hour
state=charge dispMode=Loadshape kV=132 kW = 10000 kWrated=25000
kWhrated=100000 kWhstored=8000';

DSSText.Command = 'New StorageController.Battery terminal=1 element=line.fdr_05410
%Reserve=50.0 ModeCharge=LoadShape ModeDischarge=Loadshape
daily=battery_24_hour ElementList=Battery EventLog=yes';

% BUS-Y

DSSText.Command = 'New generator.solar bus1= N292246 kV=132 kW=2600 pf=1
conn=wye duty=solar_24_hour Model=1';

DSSText.Command = 'New Storage.Battery bus1=N292246 phases=3 daily=solar_24_hour
state=charge dispMode=Loadshape kV=132 kW = 10000 kWrated=25000
kWhrated=100000 kWhstored=8000';

DSSText.Command = 'New monitor.PV Generator.solar 1 ppolar=no mode=1';

DSSText.Command = 'New monitor.Battery Storage.Battery ppolar=no mode=1';

DSSText.command = 'solve';

figure; plotCircuitLines(DSSCircObj,'Coloring','voltagePU','EndOfFeederMarker','on'
```

Script A2 – Spring Voltage Analysis

```
%BUS-X summer peak day voltage profile in MATLAB
[DSSCircObj, DSSText, gridpvPath] = DSSStartup;
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt_24_master.dss"'];
DSSText.command = 'Set mode=duty number=1440 hour=3072 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
figure; plotMonitor(DSSCircObj,'fdr_05410_Mon_VI');
hold on
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt24_distributedpv.dss"'];
DSSText.command = 'Set mode=duty number=1440 hour=3072 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure; plotMonitor(DSSCircObj,'fdr_05410_Mon_VI');
hold on
DSSText.command = 'clear';
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt_24_master.dss"'];
DSSText.Command = 'New loadshape.solar_24_hour 24 1 mult=(-0.4 -0.5 -0.6 -0.7 -0.8 -0.7
-0.6 -0.6 -0.5 -0.4 -0.3 -0.25 -0.25 0.25 0.25 0.30 0.50 0.4 0.3 0.3 0.3 -0.4 -0.5 -0.6)';
DSSText.Command = 'New loadshape.battery_24_hour 24 1 mult=(-0.4 -0.5 -0.6 -0.7 -0.8 -
0.7 -0.6 -0.6 -0.5 -0.4 -0.3 -0.25 -0.25 0.25 0.25 0.30 0.50 0.4 0.3 0.3 0.3 -0.4 -0.5 -0.6)';
% BUS-X
DSSText.Command = 'New generator.solar bus1=N283701 kV=132 kW=2600 pf=1
conn=wye duty=solar_24_hour Model=1';
DSSText.Command = 'New Storage.Battery bus1=N283701 phases=3 daily=solar_24_hour
state=charge dispMode=Loadshape kV=132 kW = 10000 kWrated=25000
kWhrated=100000 kWhstored=8000';
%
% BUS-Y
DSSText.Command = 'New generator.solar bus1=N292246 kV=132 kW=2600 pf=1
conn=wye duty=solar_24_hour Model=1';
DSSText.Command = 'New Storage.Battery bus1=N292246 phases=3 daily=solar_24_hour
state=charge dispMode=Loadshape kV=132 kW = 10000 kWrated=25000 kWhrated=100000
kWhstored=8000';
%
DSSText.Command = 'New StorageController.Battery terminal=1 element=line.fdr_05410
%Reserve=50.0 ModeCharge=LoadShape ModeDischarge=Loadshape
daily=battery_24_hour ElementList=Battery EventLog=yes';
DSSText.Command = 'New monitor.PV Generator.solar 1 ppolar=no mode=1';
DSSText.Command = 'New monitor.Battery Storage.Battery ppolar=no mode=1';
DSSText.Command = 'set mode=daily step=1s number=(1 24 *)';
DSSText.command = 'Set mode=duty number=1440 hour=3072 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure; plotMonitor(DSSCircObj,'fdr_05410_Mon_VI')
```

Script A3 – Summer Voltage Analysis

```
%BUS-X summer peak day voltage profile script code in MATLAB
 [DSSCircObj, DSSText, gridpvPath] = DSSStartup;
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt_24_master.dss"'];
DSSText.command = 'Set mode=duty number=1440 hour=4394 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure; plotMonitor(DSSCircObj,'fdr_05410_Mon_VI');
 hold on
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt24_distributedpv.dss"'];
DSSText.command = 'Set mode=duty number=1440 hour=4394 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure; plotMonitor(DSSCircObj,'fdr_05410_Mon_VI');
hold on
DSSText.command = 'clear';
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt_24_master.dss"'];
DSSText.Command = 'New loadshape.solar_24_hour 24 1 mult=(-0.5 -0.6 -0.7 -0.8 -0.8 -0.8
-0.7 -0.6 -0.45 -0.35 0.35 0.42 0.42 0.3 0.3 0.30 0.5 0.4 0.3 0.3 0.3 -0.3 -0.4 -0.5)';
DSSText.Command = 'New loadshape.battery_24_hour 24 1 mult=(-0.5 -0.6 -0.7 -0.8 -0.8 -
0.8 -0.7 -0.6 -0.45 -0.35 0.35 0.42 0.42 0.3 0.3 0.30 0.5 0.4 0.3 0.3 0.3 -0.3 -0.4 -0.5)';
% BUS-X
DSSText.Command = 'New generator.solar bus1=N283701 kV=132 kW=2600 pf=1
conn=wye duty=solar_24_hour Model=1';
DSSText.Command = 'New Storage.Battery bus1=N283701 phases=3 daily=solar_24_hour
state=charge dispMode=Loadshape kV=132 kW = 10000 kWrated=25000
kWhrated=100000 kWhstored=8000';
%
% BUS-Y
DSSText.Command = 'New generator.solar bus1=N292246 kV=132 kW=2600 pf=1
conn=wye duty=solar_24_hour Model=1';
DSSText.Command = 'New Storage.Battery bus1=N292246 phases=3 daily=solar_24_hour
state=charge dispMode=Loadshape kV=132 kW = 10000 kWrated=25000 kWhrated=100000
kWhstored=8000';
%
DSSText.Command = 'New StorageController.Battery terminal=1 element=line.fdr_05410
%Reserve=75.0 ModeCharge=LoadShape ModeDischarge=Loadshape
daily=battery_24_hour ElementList=Battery EventLog=yes';
DSSText.Command = 'New monitor.PV Generator.solar 1 ppolar=no mode=1';
DSSText.Command = 'New monitor.Battery Storage.Battery ppolar=no mode=1';
DSSText.Command = 'set mode=daily step=1s number= (1 24 *)';
DSSText.command = 'Set mode=duty number=1440 hour=4394 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure; plotMonitor(DSSCircObj,'fdr_05410_Mon_VI')
```

Script A4 – Autumn Voltage Analysis

```
%BUS-X autumn peak day voltage profile script code in MATLAB
[DSSCircObj, DSSText, gridpvPath] = DSSStartup;
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt_24_master.dss"'];
DSSText.command = 'Set mode=duty number=1440 hour=6604 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure;
plotMonitor(DSSCircObj,'fdr_05410_Mon_VI');
hold on
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt24_distributedpv.dss"'];
DSSText.command = 'Set mode=duty number=1440 hour=6604 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure;
plotMonitor(DSSCircObj,'fdr_05410_Mon_VI');
 hold on
DSSText.command = 'clear';
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt_24_master.dss"'];
DSSText.Command = 'New loadshape.solar_24_hour 24 1 mult=(-0.55 -0.6 -0.65 -0.675 -0.65
-0.6 -0.55 -0.5 -0.45 -0.4 -0.4 -0.3 -0.3 0.25 0.25 0.3 0.3 0.3 0.3 -0.3 -0.35 -0.4 -0.45 -0.5)';
DSSText.Command = 'New loadshape.battery_24_hour 24 1 mult=(-0.55 -0.6 -0.65 -0.675 -
0.65 -0.6 -0.55 -0.5 -0.45 -0.4 -0.4 -0.3 -0.3 0.25 0.25 0.3 0.3 0.3 0.3 -0.3 -0.35 -0.4 -0.45 -
0.5)';
% BUS-X
DSSText.Command = 'New generator.solar bus1=N283701 kV=132 kW=2600 pf=1
conn=wye duty=solar_24_hour Model=1';
DSSText.Command = 'New Storage.Battery bus1=N283701 phases=3 daily=solar_24_hour
state=charge dispMode=Loadshape kV=132 kW = 10000 kWrated=25000 kWhrated=100000
kWhstored=8000';
%
% BUS-Y
DSSText.Command = 'New generator.solar bus1=N292246 kV=132 kW=2600 pf=1
conn=wye duty=solar_24_hour Model=1';
DSSText.Command = 'New Storage.Battery bus1=N292246 phases=3 daily=solar_24_hour
state=charge dispMode=Loadshape kV=132 kW = 10000 kWrated=25000 kWhrated=100000
kWhstored=8000';
%
DSSText.Command = 'New StorageController.Battery terminal=1 element=line.fdr_05410
%Reserve=50.0 ModeCharge=LoadShape ModeDischarge=Loadshape
daily=battery_24_hour ElementList=Battery EventLog=yes';
DSSText.Command = 'New monitor.PV Generator.solar 1 ppolar=no mode=1';
DSSText.Command = 'New monitor.Battery Storage.Battery ppolar=no mode=1';
DSSText.Command = 'set mode=daily step=1s number=(1 24 *)';
DSSText.command = 'Set mode=duty number=1440 hour=6604 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure;
plotMonitor(DSSCircObj,'fdr_05410_Mon_VI')
```

Script A5 – Winter Voltage Analysis

```
%BUS-X winter peak day voltage profile
[DSSCircObj, DSSText, gridpvPath] = DSSStartup;
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt_24_master.dss"'];
DSSText.command = 'Set mode=duty number=1440 hour=8017 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure;
plotMonitor(DSSCircObj,'fdr_05410_Mon_VI');
hold on
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt24_distributedpv.dss"'];
DSSText.command = 'Set mode=duty number=1440 hour=8017 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure;
plotMonitor(DSSCircObj,'fdr_05410_Mon_VI');
 hold on
DSSText.command = 'clear';
DSSText.command = ['Compile "' gridpvPath 'ExampleCircuit\ckt_24_master.dss"'];
DSSText.Command = 'New loadshape.solar_24_hour 24 1 mult=(-0.22 -0.22 -0.23 -0.228 -
0.228 -0.23 -0.24 -0.24 -0.24 -0.24 -0.24 -0.238 -0.24 0.30 0.32 0.34 0.36 0.4 0.38 0.36 0.34
0.32 0.3 0.28)';
DSSText.Command = 'New loadshape.battery_24_hour 24 1 mult=(-0.22 -0.22 -0.23 -0.228 -
0.228 -0.23 -0.24 -0.24 -0.24 -0.24 -0.24 -0.238 -0.24 0.30 0.32 0.34 0.36 0.4 0.38 0.36 0.34
0.32 0.3 0.28)';
% BUS-X
DSSText.Command = 'New generator.solar bus1=N283701 kV=132 kW=2600 pf=1
conn=wye duty=solar_24_hour Model=1';
DSSText.Command = 'New Storage.Battery bus1=N283701 phases=3 daily=solar_24_hour
state=charge dispMode=Loadshape kV=132 kW = 10000 kWrated=25000
kWhrated=100000 kWhstored=8000';
%
% BUS-Y
DSSText.Command = 'New generator.solar bus1=N292246 kV=132 kW=2600 pf=1
conn=wye duty=solar_24_hour Model=1';
DSSText.Command = 'New Storage.Battery bus1=N292246 phases=3 daily=solar_24_hour
state=charge dispMode=Loadshape kV=132 kW = 10000 kWrated=25000 kWhrated=100000
kWhstored=8000';
%
DSSText.Command = 'New StorageController.Battery terminal=1 element=line.fdr_05410
%Reserve=10.0 ModeCharge=LoadShape ModeDischarge=Loadshape
daily=battery_24_hour ElementList=Battery EventLog=yes';
DSSText.Command = 'New monitor.PV Generator.solar 1 ppolar=no mode=1';
DSSText.Command = 'New monitor.Battery Storage.Battery ppolar=no mode=1';
DSSText.Command = 'set mode=daily step=1s number=(1 24 *)';
DSSText.command = 'Set mode=duty number=1440 hour=8017 h=60 sec=0';
DSSText.command = 'Set controlmode=static';
DSSText.command = 'solve';
%figure;
plotMonitor(DSSCircObj,'fdr_05410_Mon_VI')
```