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Electric Vehicle (EV) in Home Energy Management to Reduce Daily Electricity Costs of Residential Customer

U Datta[1]*, A Kalam[2] and J Shi[3]
[1,2,3]College of Engineering and Science, Victoria University, Melbourne, Australia, 8001

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Exploiting energy storage capacity of proliferating EVs in present power system may contribute to minimize adverse impact of EV charging and electricity operating costs of residential customers. This study investigates an electric vehicle (EV) charging/discharging strategy in home energy management system (HEMS) to evaluate economic benefit of different operation modes in dynamic pricing schemes. Three different operation modes i.e. grid-to-vehicle (G2V), vehicle-to-grid (V2G) and vehicle-to-home (V2H) and their relative financial advantage using single and dual EVs are investigated without affecting customer comfort of EV for driving. The proposed economic analysis is carried out for a single residential customer for one day. Numerical studies show that reducing electricity consumption from grid in peak pricing periods using V2H is more beneficial than V2G or G2V in term of economy as selling energy to the grid is technically inflexible and financially competitive.

Keywords: Electric Vehicle, Battery Storage, Energy Cost Reduction, Peak Demand

Introduction

With plug-in facility, EV is emerging with several new applications such as vehicle-t-to-grid (V2G) and vehicle-to-home (V2H)[1] that has the potentiality to contribute in regulating power system voltage[2], frequency[3] and in other wide ranged application. EV is utilized in reducing peak load demand throughout peak pricing period to minimize electricity purchasing costs of consumers[4-6]. A charging control strategy is adopted to employ EV in HEMS[7-8] but EV is mostly used as storage device. Nevertheless, depleting EV battery throughout the day could potentially disrupt consumer's comfort of driving whenever needed. One of the most dynamic potentialities of EV in V2H mode is the capability of providing an uninterrupted power supply during an unplanned outage[9-10]. However, study considered that EV is available at home most of the time which is not a practical scenario for full time day employee. In this paper, an EV charging/discharging control strategy based on electricity pricing is presented to minimize daily electricity costs of customer by minimizing grid consumptions during peak pricing periods.

*Author for Correspondence
E-mail: ujjwal.datta@live.vu.edu.au

EV in smart V2H and V2G development

Integrating EV in V2H and V2G

EV is technically equipped to be connected with either grid (V2G) or home (V2H). In both cases, EV increases grid reliability by providing uninterrupted power supply during power outage. In comparison to V2H, V2G comprises complex infrastructure and also increases losses due to their distant location. Therefore, EV for V2H application has ample prospect than V2G in terms of control strategy and complexity exists in V2G deployment. Moreover, present rules and regulation by utility companies and net metering pricing for selling excess energy to the grid are always a threat for implementing V2G in real electric grid. EV placements as G2V, V2H and V2G operating modes for a typical residential customer are shown in Figure 1.

EV Operating Mode

The EV battery is interfaced with utility and house load point through power electronics based bi-directional AC/DC converter. The converter controls power flow direction between battery-to-home loads (discharge) and grid-to-battery (charge). The main considered operating modes are G2V, V2G and V2H to reduce operating costs for a consumer having single and dual EVs. Furthermore, comparative economic benefit of V2H and V2G during peak

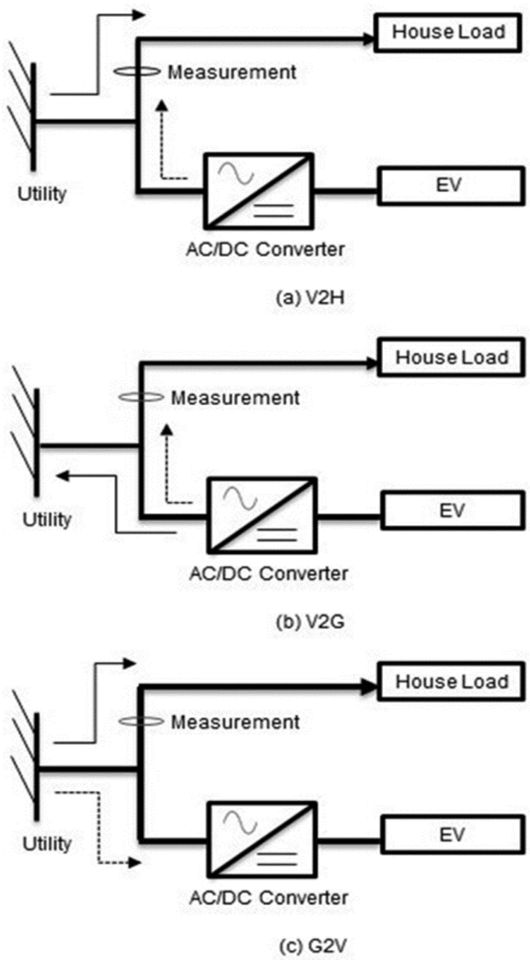

Fig. 1 — Structure of EV in different operating modes

pricing time and charging only (G2V) are also compared. The level of EV support varies according to available number of EVs to any particular customer. To demonstrate our control method, we assumed that the same amount of energy is exchanged in V2G and V2H operating modes. The selection is intentional to demonstrate economic feasibility of each operating mode.

Power and EV battery SOC calculation

At any time, power balance equation must be satisfied,

$P_{EV\text{-}actual}(t)=\{(P_{load}(t)+S(t)*P_{EV\text{-}actual}(t)$, if t=charging/discharging
$=\{P_{grid}(t)=P_{load}(t)$, otherwise) ...(1)

Where, t = time (hour)
P_{grid} = Grid power
P_{load}= Home load demand
S= Status of EV {plugged-in (S=1), unplugged (S=0)} at time t
$P_{EV\text{-}actual}$= Actual EV power output depending on S value.

The sign of $P_{(EV\text{-}actual)}$ is subject to EV status and charging/discharging phenomena. In discharging mode, EV power is considered as negative (-ve) and positive (+ve) for EV charging. In this paper, we assumed that typical EV plugged out time is 7 am in the morning and plugged-in time is 4 pm in the afternoon. However, it is also taken into consideration that EV could be plugged-out anytime. Therefore, we have designed charging/discharging strategy to maintain a minimum level of SOC to ensure driving flexibility for planned/unplanned evening activities. If the consumer owns more than one EV, higher power can be drawn from one of the EVs i.e. until battery reaches to a minimum level of SOC. The calculation of EV battery SOC is based on following coulomb counting method. The value of plugged-in SOC at the end of the day depends on driving distance, SOC at plugged-out time, speed, etc. Daily driving and its impact on EV battery SOC are not taken into account in this analysis. Hence, it is estimated that SOC at plugged-in time is 0.6 considering full charged EV (SOC=1) is depleted to 0.6 during both way driving between home and office.

Formulation of EV charging/discharging strategy and energy pricing

EV charging/Discharging strategy

This section describes the proposed EV charging/discharging strategy based on dynamic pricing and EV battery SOC to resolve power management difficulties in smart HEMS. The wide suggested planning to reduce electricity costs of a customer is to charge EV battery during off-peak periods and discharge it during peak periods. It is worth to mention that not only planning but also implementing simplicity from customer’s perspective is given the most priority. EV for V2G, G2V and V2H is constrained by EV status, battery SOC and power threshold for EV power injection. At any given point, household can either import or export power. To export excess power to the grid i.e. EV for V2G purpose, EV should meet house load demand. Therefore, for EV battery charging/discharging in G2V, V2H and V2G application are expressed as follows:

$P_{EV\text{-}actual}(t)=\{(G2V$, $P_{EV\text{-}charge}(t)$ if off-peak$_{min}\le t\le$off-peak$_{max}$ and $SOC(t) \le SOC_{max}$
0 otherwise

$=\{V2H, -\{P_{load}(t) - P_{threshold}\}$ if $peak_{min} \leq t \leq peak_{max}$, $SOC(t) \geq SOC_{min\text{-}threshold}$ and $P_{load}(t) > P_{threshold}\}$
$P_{EV\text{-}charge}(t)$ if $\text{off-peak}_{min} \leq t \leq \text{off-peak}_{max}$ and $SOC(t) \leq SOC_{max}$

0 otherwise

$=\{V2G, -P_{EV\text{-}discharge}(t)$ if $peak_{min} \leq t \leq peak_{max}$, $P_{EV\text{-}discharge}(t) > P_{load}(t)$ and $SOC(t) \geq SOC_{min\text{-}threshold}$

$P_{EV\text{-}charge}(t)$ if $\text{off-peak}_{min} \leq t \leq \text{off-peak}_{max}$ and $SOC(t) \leq SOC_{max}$

0 otherwise … (2)

Where,
$P\_(_{EV\text{-}charge})$= EV charging power
$P\_{}_{threshold}$= Planned peak load reduction threshold
$P\_(_{EV\text{-}discharge})(t)$ = EV discharge power

Thus, the power at grid connection point will be negative resembles power exporting to the grid. The controller must ensure that battery SOC(t) stays within customer preferred level to make sure driving resolution is always conceivable. The maximum SOC value is 1 and the minimum SOC value is 0.2 to ensure a safe Depth-of-discharge (DOD). However, the minimum SOC boundary completely depends on the number of EVs and customer preference. We have considered that with one EV, the minimum SOC should be higher so that EV owner has the flexibility to use EV at any time.

Energy pricing

The main objective is to minimize electricity costs and to achieve this target, different charging/discharging plan is proposed according to EV status, off-peak and peak pricing, the number of EVs and available SOC. Since the pricing for off-peak and peak are different and also the price of electricity selling is different from purchasing, two separate pricing calculation methods are adopted in this analysis. The basic pricing technique when there is no EV is shown in equation (3)

$$\sum C_{total}(t)=P_{load}(t)*C_{e\text{-}off\text{-}peak\,(t)} + P_{load}(t)*C_{e\text{-}peak}(t) \quad \ldots (3)$$

$C_{total\,(t)}$ = Total costs of electricity
$C_{e\text{-}off\text{-}peak}$ = Costs of electricity/kWh (off-peak) from $\text{off-peak}_{min}(t)$ to $\text{off-peak}_{max}(t)$
$C_{e\text{-}peak}$= Costs of electricity/kWh (peak) from $peak_{min}(t)$ to $peak_{max}(t)$

The calculation of total electricity costs when EV is not used for feeding load demand during peak pricing periods and EV is charged during low pricing periods (G2V),

$$\sum C_{total}(t)=\{P_{load}(t)+S(t)*P_{EV\text{-}charge}(t)\}*C_{e\text{-}off\text{-}peak} + \{P_{load}(t)*C_{e\text{-}peak}(t)\} \quad \ldots (4)$$

The additional cost of EV charging is reflected by EV charging power multiplied by EV status. If one of the values i.e. EV status or EV charging power is zero, then the total contribution of EV is zero on the total electricity costs. Since EV is scheduled to be charged during low pricing period, overall outcome of electricity costs will be less than peak time EV charging and this is one of the important steps in HEMS to reduce consumer's overall electricity costs. The calculation of total electricity costs when EV feeds partial house load demand during peak pricing periods and charged during low pricing periods is expressed as follows:

$$\sum C_{total}(t)=\{P_{load}(t)+S(t)*P_{EV\text{-}charge}(t)\}*C_{e\text{-}off\text{-}peak} + [P_{load}(t)-S(t)\{P_{load}(t) - P_{threshold}\}]*C_{e\text{-}peak}(t) \quad \ldots (5)$$

EV power feeding to house load demand for the period of peak pricing will contribute to the reduction of overall electricity costs. However, the amount of load feeding and energy savings by EV battery depends on available EV capacity and electricity price at peak periods. It is remarked that costs related to investments, battery degradation, control and bidirectional communication arrangements are not taken into account in this research work. In the case of V2G mode of operation, energy pricing is calculated as follows,

$$\sum C_{total}(t)=\{P_{load}(t)+S(t)*P_{EV\text{-}charge}(t)\}*C_{e\text{-}off\text{-}peak} + \{P_{load}(t) - S(t)*P_{EV\text{-}discharge}(t)\}*C_{e\text{-}peak\text{-}sell}(t) \quad \ldots (6)$$

Where,

$C_{e\text{-}peak\text{-}sell}$ = Energy selling price to the grid

In V2G, EV SOC depletes faster than typical V2H. Therefore, at a point when EV capacity is not sufficient to continue V2G operation, energy pricing will be switched to no EV case as in equation (3) during peak periods and EV charging as G2V during off-peak periods as in equation (4). EV during V2G role produces total zero electricity consumption from the grid and sells additional energy to the grid with a rate provided by the utility.

Numerical Studies and Discussion

This section discusses typical residential load demand profile in Springfield, Missouri, USA[11] and associated daily energy pricing by Ameren, the utility company. EV will only be used to reduce household loads in peak pricing period given that EV battery is not completely discharged for single EV and late night charging at low pricing period. In case of dual EV, one EV is considered for HEMS whereas the other EV remains inaccessible for V2H and V2G but is available for charging during off-peak time, grid-to-vehicle (G2V). Comparative economic analysis of EV with and without reducing peak demand and charging in off-peak is presented to demonstrate how an EV performs in different operating modes. The same amount of energy exchange is considered for comparing economic performance of V2G and V2H. Based on dynamic energy pricing and operation modes, multiple case studies are investigated for single EV and they are as follows-

Case-1: Without any EV

Case-2: Charging EV during off-peak periods (G2V) with no support in peak pricing periods

Case-3: EV to reduce peak energy consumption (V2H) and charging during off-peak periods (G2V)

Case-4: EV to sell energy (V2G) and charging during off-peak periods (G2V)

In addition, Case-2 to Case-4 are repeated for dual EV for the same load profile. Equivalent amount of energy exchange is considered to compare the economic performance of V2H and V2G. The selected EV capacity is 35kWh with 240/30A basic charging rate and takes 5.5 hours to get fully charged from zero[13].

House load demand with and without EV

This section represents daily load demand on the 1st day of the month with a time period of 24 hours. A simple power management strategy is proposed to schedule EV charging/discharging in V2G and V2H to reduce electricity operating costs. We assume EV plugged-out time is 7 am and plugged-in time is 4pm. Three operating modes are explored and they are V2H, V2G and G2V. The EV SOC at plugged-in time for V2G and V2H is assumed to be 0.6.However, the actual SOC value would be different if the actual driving is considered which is not in the scope of this study. The SOC value for G2V depends on whether any particular operation mode is selected. The plugged-out SOC for all operating modes is 1.

In general, battery DOD is higher in the case of V2G compare to V2H. However, as this study focuses on providing comparative economic benefits of V2G against V2H, we assume the same level of DOD for both modes. Furthermore, different level of DOD is considered when a customer owns more than one EV as higher DOD from one EV may not impede customer's comfort of driving at any time in the evening to early morning. With HEMS, EV charging at low pricing periods mainly overnight is a very common and highly proposed strategy. Therefore, we ignored the case of uncontrolled charging i.e. peak charging. The house load profile, EV battery SOC, EV status for single EV and all the cases are shown in Figure 2. Total power calculation at the point of common coupling is subject to specific case type i.e. Case-2 to Case-4 are valid if EV is connected to the grid (EV status = 1), otherwise it will be always Case-1.

Case-1: This is a basic residential customer load profile without any EV owned by the customer. Hence, demand response during peak pricing period is the only option to reduce electricity costs.

Case-2: In this case, EV refrains supplying any energy during off/peak periods. EV is only charged (G2V) during low pricing period throughout the night. Since EV is not contributing in reducing peak energy consumption, the total load remains the same during those periods and as EV is charged at night, the total energy consumption increases nearly 6 times compare to Case-1 from 1 am to 5 am as shown in Figure 2 and Figure 3.

Case-3: EV delivers energy to meet a portion of house load demand (V2H) during peak pricing period providing that battery SOC is sufficient. In this case, total load demand during late night charging increases related to Case-2 as SOC decreases to a lower value by providing energy in peak periods as shown in Figure 2 and thus charging energy (cost) is higher than Case-2. It is evident as shown in Figure 3 and Table 1 that with two EVs, it is possible to draw more energy from EV (higher DOD), feeding complete load demand during peak periods as shown in Figure 3.

Case-4: Point of common connection allows exporting or importing power once at any given time, EV feeds total load demand and then supplies additional EV energy to the grid (V2G via V2H). The volume of exporting power can be any value within SOC boundary and depending on customer preferences. The amount of total energy supplied by EV is 8.6984 kWh for single EV and 12.6984 kWh for dual EV during peak pricing periods (V2H) as outlined in Table 1, given that the preferred EV SOC is 0.35 for single EV and 0.25 for dual EV. It can be

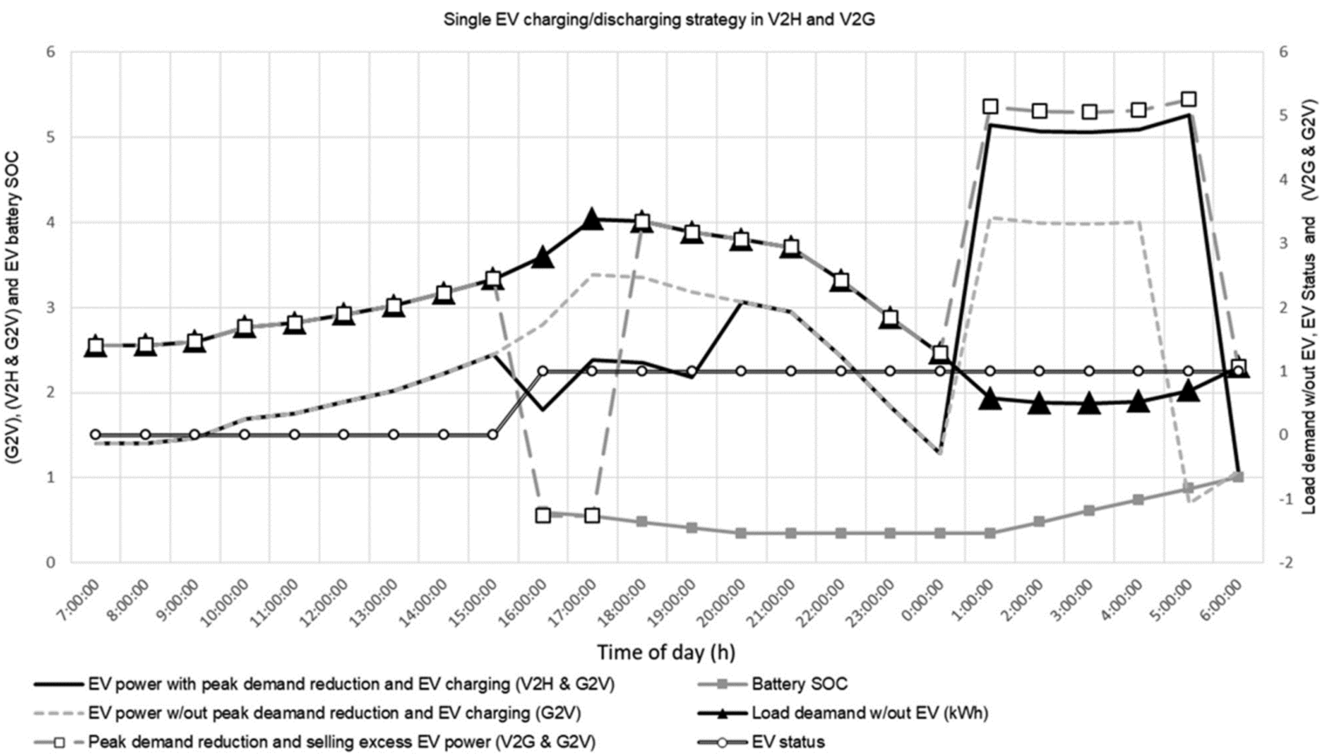

Fig. 2 — Single EV charging/discharging strategy in different operating modes

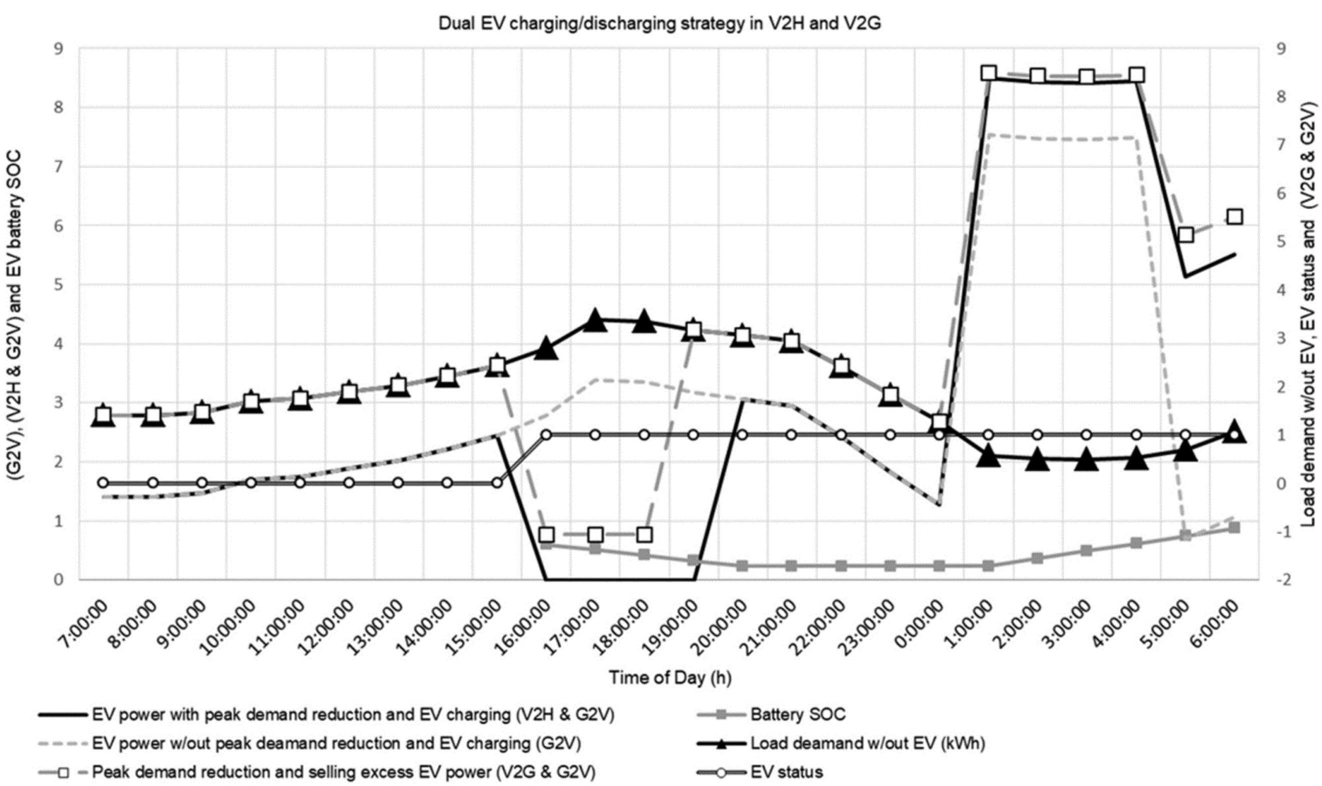

Fig. 3 — Dual EV charging/discharging strategy in different operating modes

Table 1 — EV participation in V2H and V2G during peak periods

Time	EV status	Single EV			Dual EV		
		V2H (kWh)	V2G (kWh)		V2H (kWh)	V2G (kWh)	
		Energy fed	Energy sold	Energy fed	Energy fed	Energy sold	Energy fed
16:00:00	1	1.79327	1.2627	2.79327	2.79327	1.0591	2.79327
17:00:00	1	2.37976	1.2627	3.37976	3.37976	1.0591	3.37976
18:00:00	1	2.34803	0	0	3.34803	1.0591	3.34803
19:00:00	1	2.17733	0	0	3.17733	0	0
Total (kWh)		8.6984	2.5254	6.1730	12.6984	3.1774	9.521

Table 2 — Dynamic electricity pricing in Summer

On-peak/off-peak	Time	Purchasing rates (kWh)	Selling rates (kWh)
On-peak	2 pm -7 pm (Mon-Fri)	31.5 ¢	-
Off-peak	7 pm – 2 pm	7.87 ¢	-
	All day on weekends		-
Summer	All hours	-	2.68¢

seen that with 8.6984 kWh supplying capacity within the specified SOC of 0.235, customer can meet 2 hours peak load (V2H) and can sell 2.5254 kWh (V2G) to the grid as shown in Figure 2. The amount of sold energy is 3.1774 kWh (V2G) when customer owns dual EV, followed by feeding total load for 3 hours as shown in Figure 3. EV battery SOC, G2V and combined V2H & G2V are presented in the graph using primary axis. Load demand without EV, EV status and combined V2G & G2V are presented using secondary axis (right).

Dynamic electricity pricing

Ameren, the local utility company offers different electricity pricing in Springfield, Missouri, USA region. Electricity price ranges from fixed rates, time varying daily rates and energy selling in summer and winter[13-15]. According to the company policy, net metering is applicable if energy supplied by the customer exceeds electricity supplied by the company and is priced differently at their fixed rates for summer and winter periods. Different cost structures throughout the day in summer are outlined in Table 2. To sell energy, customer requires installing an additional bi-directional meter which costs about $320[16]. However, no communication and establishments costs are included in the total cost calculation.

Economic analysis

To demonstrate prospective financial profits of EV in HEMS, several operation modes are investigated. The daily electricity operation cost under no EV, V2H, V2G and G2V are discussed. A summary of comparative analysis is outlined in Table 3. Table 3 shows that comparing to no EV in Case-1, G2V operation modes with single EV in Case-2 increases total daily electricity costs by 15.49% to charge EV overnight. However, uncontrolled charging during peak periods will increase total cost more than off-peak charging. On the contrary, the total cost is $ 6.1286 if EV is used as V2H during peak and G2V during off-peak which is 24.98% less than G2V in Case-2 and 13.37% less than no EV in Case-1. The total cost is $ 6.8563 if customer wants to feed total house demand and sell excess energy to the grid. However, it is evident from Table 1 that selling energy (V2G) reduces total cost compare to V2H by $0.7277 for exchanging the same amount of energy i.e. V2H provides 55.4% higher economic benefit than V2G. The foremost underlying principle for lower price in selling energy to the grid is lower energy selling price which is only $ 0.0268/kWh in comparison to $ 0.315/kWh purchasing costs. If customer maintains two EVs, higher energy is possible to be extracted from one of the EVs. However, One of the EVs is not participating in V2H and V2G operation, it is charged (G2V) during off-peak pricing along with other EV. Table 1 shows that dual EV allows 12.6984 kWh energy exchange (V2H). With V2G mode, 9.521 kWh is used to feed total load demand for 3 hours and 3.1774 kWh is sold to the grid (V2G). Comparative economic analysis shows 43.96% higher cost benefit of V2H over V2G. The cost benefit is mainly as a result of lower selling price/kWh of energy to the grid as shown in Table 3.

Table 3 — Comparative economic benefit of G2V, V2H and V2G

Operation modes	EV charging/discharging strategies	Energy exchange (kWh)	V2G energy (kWh)	Single EV	Energy exchange (kWh)	V2G energy (kWh)	Dual EV
	Pricing without EV	8.6984	2.523	7.0742	12.6984	3.1774	7.0742
G2V	Pricing with EV, w/out peak load reduction and charging only			8.1697			8.1697
V2H & G2V	Pricing with EV, w/ peak load reduction and charging			6.1286			5.1708
	Peak load reduction benefit over no EV			0.9456			1.9034
	Peak load reduction benefit over no peak reduction			2.0411			2.9989
V2G & G2V	Pricing With EV, w/ peak load reduction and selling to the grid			6.8563			6.0865
	Peak load reduction and energy selling benefit over no peak reduction			1.3134			2.0832
	Comparative benefit ($) of V2H over V2G			0.7277			0.9157

Conclusion

In this paper, several charging/discharging strategies in different operation modes (V2H, V2G and G2V) are presented to evaluate economic performance considering customer comforts with single and dual EV circumstances. Results of comparative analysis show that EV in V2H is economically profitable than V2G for exchanging same amount of energy during peak pricing periods. The main hurdle with V2G is inflexible rules and regulations by the utility to sell energy to the grid and also low price/kWh. Instead of charging only (G2V) and selling energy (V2G), V2H provides considerable reduction of daily electricity costs in the case where customer possesses one and dual EV. The peak EV discharging could benefit more with increasing battery efficiency. Customer defines EV discharging boundary to make sure sufficient SOC is available to drive the vehicle if needed. Including daily EV driving profile to estimate the actual battery SOC, no-load battery self-discharging and V2G or V2H impact on battery lifetime will also be considered in future work. Technical and economic benefits of EV battery and renewable energy system with storage system can also be investigated in future work to demonstrate maximizing cost benefit by utilizing EV storage capacity.

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