Chapter

The Strategies of EV Charge/ Discharge Management in Smart Grid Vehicle-to-Everything (V2X) Communication Networks

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Abstract

Electric vehicles (EVs) are at the forefront of the revolutionized eco-friendly invention in the transportation industry. With automated metering infrastructure (AMI) communications in houses, smart EV charging stations, and smart building management systems in smart grid-oriented power system, EVs are expected to contribute substantially in overall energy planning and management both in the grid and the customer premises. This chapter investigates and provides an in-depth analysis on the charge/discharge management of EV in vehicle to home (V2H), vehicle to drive (V2D), vehicle to vehicle (V2V), vehicle to grid (V2G), vehicle-to-building (V2B), and grid to vehicle (G2V). The planning and control of energy exchange of EV is the main focus considering EV availability in multiple places during the daytime and in the evening. Indisputably, EV participating in V2G or V2H affects the state of charge (SOC) of EV battery, and therefore proper scheduled charge/discharge plan needs to be embraced. The structures of EV in various operation modes and approaches are presented for implementing the energy planning and charge/discharge management of EV in different operation modes. The simulation results demonstrate the effectiveness of the proposed charge/discharge management strategy and regulation of EV SOC in accordance with the energy management plan of EV owner.

Keywords: electric vehicles (EVs), vehicle to home (V2H), vehicle to grid (V2G), vehicle to vehicle (V2V), grid to vehicle (G2V), vehicle to building (V2B), vehicle to drive (V2D), charge/discharge management, SOC constraints

1. Introduction

With the increasing concern of greenhouse gas (GHG) emissions, many attempts have been suggested and already placed in action for clean energy practice. Electric vehicles (EVs) are one of the revolutionized modern technologies in the transportation industry that has drawn the greater attention of market investors, governments, and customers. EVs are considered to have a significant contribution in reducing GHG emissions. However, in order to access the EVs impact on the way to clean energy and climate change, this requires the appropriate transformation and deployment of economy regulations by the governments [1, 2].

In recent years, the developments in different areas of EV technologies are focused on scheduled charging problem [3], minimizing fuel consumption with a variable driving schedule [4], increasing battery charger efficiency [5], and energy incentive policy for EV [6]. However, with the development of smart grid concept and the availability of bidirectional charging facility, EVs are considered to play a diverse role that can bring several benefits in the smart city power grid [7]. This will provide the opportunity for EV to enact as a power source and exchange energy with the grid for delivering multiple services [8]. The pricing-controlled EV charging in a smart city can reduce the additional burden on the network during peak time and subsequently provide economic benefit [9]. The study in [10] concluded that an optimized investment and operation is imperative to achieve a considerable amount of economic advantage. However, an extensive survey analysis by the study in [11] argued that profitability depends on several factors such as types and prices of regulation services and market regulations. The increasing penetration level of intermittent renewable energy sources has a positive impact on reducing GHG emissions. However, the grid voltage, frequency, and power quality are adversely affected due to the nature of their variable power output. The power grid needs to compensate and balance power differences to maintain a stable grid operation. EVs can provide significant support in compensating such power imbalances.

With the increased energy capacity of EV batteries, the energy requirement of the grid, charging/discharging flexibility of EVs, and concepts of vehicle to home (V2H), vehicle to grid (V2G), and vehicle to vehicle (V2V) have become more desirable for grid-connected operation. The V2H can provide multiple energy services of a house through smart building management systems during peak periods [12] and reliability enhancement when a load shedding occurs [13]. In V2H, EV can be coordinated for flexible load scheduling [14] and optimal energy management with photovoltaic generation [15], thus increasing the benefit of implementing V2H [16]. In V2G/V2V, EV can be exploited to minimize network variations and impact positively in the grid operation [17]. Few experimental studies have also been carried out to show the effectiveness of EV in different operation modes [18, 19]. Nevertheless, in order to participate in providing ancillary services, an efficient charging/discharging strategy for EV must be considered. Regardless of operation modes, smart energy management of EV can ensure reduced energy consumption from the grid and thus provide direct economic benefit to the customers [20].

This chapter proposes an in-depth analysis and discussion on EV energy management in V2D, V2H, V2V/V2G/V2B, and G2V. The key objective is to describe various approaches in EV battery charge/discharge control strategies in different operation modes, including the modeling of charge/discharge management methods, types of ancillary services, and feedback regulations to provide the aforementioned services. An energy pricing plan is included in charge/discharge of EV for "vehicle to everything (V2X)" services which is able to compute the economic advantage of providing V2X services and G2V.

The rest of the chapter is organized as follows. Section 2 presents the concept of grid services and existing typical EV energy capacity. The structure of EV in different operation modes is discussed in Section 3. Feedback regulation strategy in implementing V2X technology is described in Section 4. The management of EV battery charging/discharging in numerous operation modes is explained in Section 5. Simulation studies are demonstrated in Section 6, and the conclusion is drawn in Section 7.

2. Energy capacity of EV and V2X concept

The battery energy capacity is one of the most important factors in planning EV for V2X services. This is particularly important as depleting EV battery for V2X without an appropriate plan may threaten EV availability for V2D. The capacity of currently available battery ranges from a few kWh to 100 kWh [21]. The battery capacity of Ford Focus electric 2018 car is 33.5 kWh, Nissan LEAF 2018 is 40 kWh, Chevy Bolt 2018 is 60 kWh, Tesla Model 3 is 80.5 kWh, and Tesla Model X or Tesla Model S is 100 kWh [21]. Although battery capacity is not the only parameters that decide EV for V2X, it firmly indicates the distance that can be covered before the next charging event is required. In some cases, large EV battery capacity does not necessarily mean long distance coverage such as Tesla Model X has lower mileage (383–475 km) with higher kWh than Tesla Model 3 (499 km) [22]. Therefore, EV for V2X can be planned if sufficient state of charge (SOC) of EV battery is available at the end of the journey and the estimated energy requirement for next journey. Nevertheless, these ratings are fairly indicative assumptions, and actual energy consumptions per traveling distance may vary in real condition depending on several factors such as battery age, maintenance of the EV, nature of driving, number of passengers, weather conditions, etc.

In order to charge/discharge, i.e., load/energy supplier, EVs are plugged in at home or in a charging station through a charging outlet. EVs come with onboard unidirectional or bidirectional battery charger and range from various charging hours depending on charging current, battery capacity, and actual SOC of EV battery before charging. In recent years, a quick charging facility is also available that allows fast EV charging, ranging from 30 minutes to an hour [23]. This improves the flexibility of EV charging and increases the reliability for driving whenever required. However, longer plugged-in time in a charging station allows EV to deliver energy as a source and participate in providing ancillary services for a certain period of time.

Apart from V2D, there are various evolving notions of EV application in V2X which can be defined as follows:

- V2G allows feeding energy to the grid in the case of energy shortage in the grid, mainly during a lower power output from renewable energy sources (RESs).

- G2V allows obtaining energy from the grid and charging the vehicle. In addition to scheduled charging, EV can be charged during the peak generation periods of RESs.

- V2H allows meeting the partial or total load demand of a house. The preference can be given to peak periods only to maximize the economic benefit of EV for V2H.

- V2V allows EV to transfer its energy (charge/discharge) to another EV through the local grid or EV aggregator. Nonetheless, using the local grid may not be energy efficient considering the distance, time of charging, and costs.

- V2B performs similar to V2V/V2G but is limited to within the building. This feature allows efficient charge/discharge management of EVs and the energy management planning for the building (smart building management system).

These concepts of EV provide the flexibility of energy planning for home, building, and the grid. Thus EV will play a key role in the future smart grid. Nevertheless, in addition to the above concepts, V2D is the foremost priority before planning of EV for V2X. Therefore, all the roles of EV including the basic V2D are preferred for analysis, and their values, controls, practical outcome, and usefulness are explored in this study.

3. The structures of EV operation modes

This section discusses the structures of EV in different operation modes and the supports it may provide during the operational periods.

3.1 Structure of V2H

Typically, EV is preferred to be charged in the car park at home during overnight. This provides the flexibility to charge the vehicle and drive whenever necessary. With a bidirectional battery charger, the setup of EV for V2H can be formed. **Figure 1** shows the EV structure in V2H for exchanging energy with home energy demand. The same connection with the power conversion system can be used to charge EV (G2V) according to the specified energy management scheme. The power conversion system (PCS) allows feeding the energy demand of home partially or totally. PCS can be incorporated with small-scale RESs such as small wind turbine or roof-top solar generation panels through the central home controller. In **Figure 1**, the dashed blue line denotes EV discharging power flow for feeding home load demand (V2H). The solid blue line represents power flow direction to the grid (V2G), and solid green line symbolizes EV charging power flow (G2V). PCS provides the flexibility to regulate power flow and control charge/discharge of EV in G2V and V2H. Some of the very significant and unique features for V2H operation are as follows:

- V2H can involve one or two EVs and therefore comprises of significant amount of energy capacity to meet a typical home load demand.
- V2H facility is simple to implement, and some car manufacturers are already giving the opportunity to employ EV for V2H.

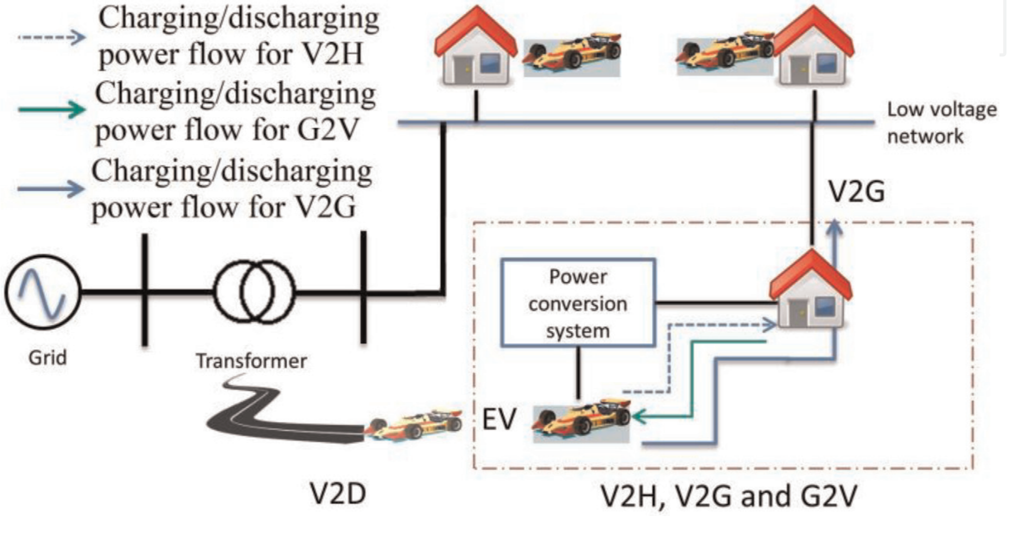

Figure 1.
Structure of V2D, V2H, V2G, and G2V at home.

- V2H can reduce peak demand and smooth home load demand profile or possibly can result in net zero energy purchase from the grid.
- Energy pricing based V2H can acquire financial gain to the owner and maximize the techno-economic benefit of EV for V2H.
- V2H is able to reduce the negative impact of RESs by operating as a storage device.
- The energy losses can be minimized through the use of V2H, thus increasing the efficiency of the grid.
- V2H can increase the operational flexibility in a smart home management system, thus improving the overall reliability of power supply at home.

3.2 Structure of V2G

A single EV with limited kWh capacity has an insignificant impact on the grid. However, as the number of EVs increases, a potential impact on grid level performance can be significant. The capacity could range from MWh to GWh, considering global target toward replacing the conventional fossil fuel-based cars with EVs. Hence, V2G structure comprises of a significant number of EVs connected to the grid. The structure of V2G is shown in **Figure 2**. The solid blue line and solid green line represent the power flow in V2G and G2V, respectively. EV may participate in V2G through an aggregator which comprises other necessary energy management

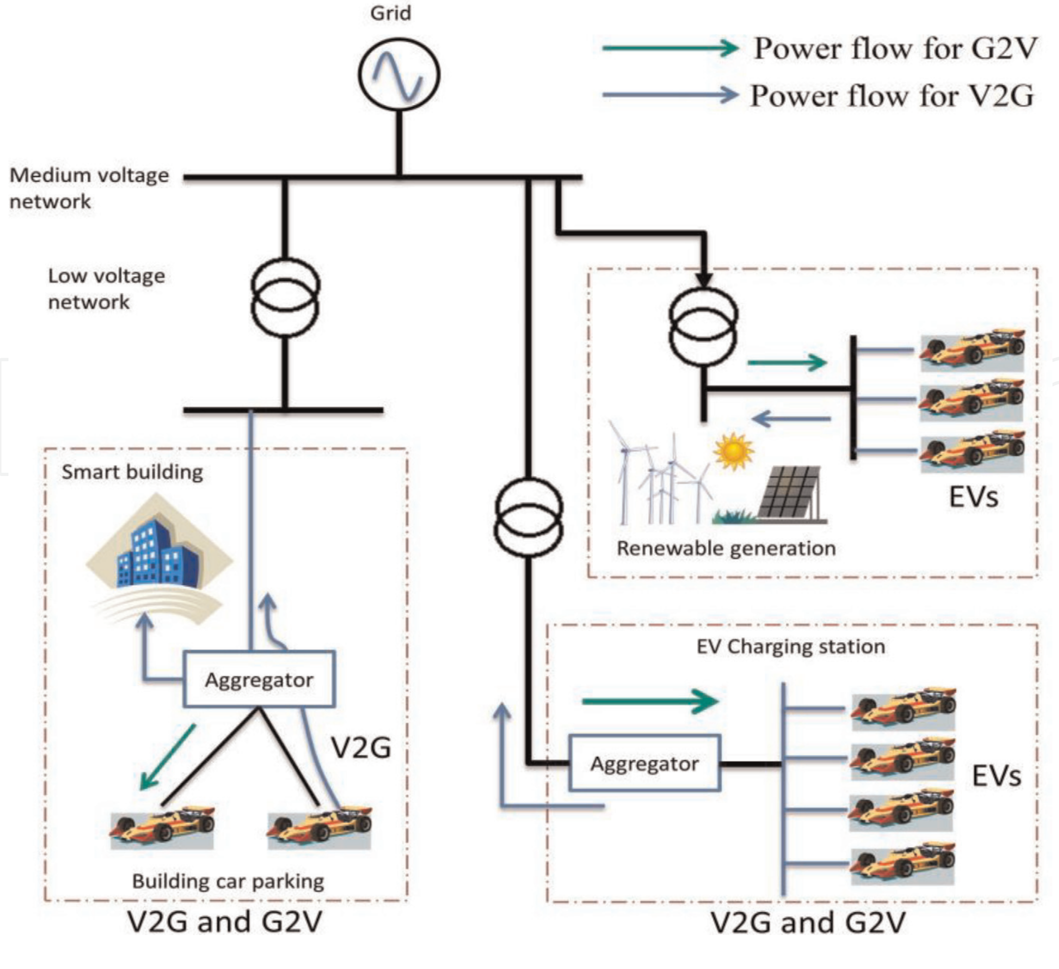

Figure 2.
Structure of V2G and G2V at commercial locations.

planning and controllers to facilitate V2G services. The aggregator can be placed at different locations such as charging station, parking lots, renewable energy farm, and smart building with other grid infrastructures to provide V2G services. Since V2G comprises many EVs, aggregator plays a key role in allocating and controlling power flows between various EVs. EVs for G2V can be connected to different grid voltage level through the associated transformers and distribution feeders. Mainly, EVs in a charging station are connected to the medium voltage network, whereas at home or buildings, EVs are connected to a low-voltage network. Some of the very significant and unique features for V2H operation are as follows:

- V2G comprises of a combination of many EVs, from a few to a hundred and more.
- The control of power flow of individual EVs is more complex but able to offer greater flexibility in energy regulation.
- V2G can provide both active and reactive power based on requirements.
- V2G through EV aggregator can provide a significant amount of power regulation capability to the grid.
- The large-scale EV battery storage provides the flexibility for energy planning based on RESs prediction and also in mitigating real-time power imbalances due to prediction error.
- In an isolated microgrid (MG), V2G can provide better stability and improved reliability performance, thus minimizing stress on baseload units.

3.3 Structure of V2B/V2V

V2B/V2V is of a similar kind of service as in V2G but in a reduced scale. V2V can be formed within a small community or a small isolated system to share energy according to suitable energy planning and available energy capacity as shown in **Figure 3**. V2V can add further flexibility in reducing grid variations due to integrated RESs in the community or MG. V2V can be implemented using direct V2V connection [24] or traditionally through the grid. On the other hand, V2B service is limited to a smart building, where EV can participate in overall energy management of the building. This allows integrating RESs in the building roof, regulating energy consumptions based on actual electricity pricing and maintaining owner-defined EV battery SOC. A greater perspective of energy planning, saving, economic gain, and EV SOC for V2D is possible to obtain through V2B. When EVs are operating in V2B/V2V, they can easily participate in V2G operation. The unique features of V2V/V2B can be summarized as follows:

- V2B/V2V consists of interaction between two or more EVs, and the control of EVs can be more complex than V2H, but it is simpler than V2G.
- V2B/V2V involves smart homes and car parking lots in a community or in a building for sharing energy among them.
- The energy losses in V2B/V2V vary according to individual vehicle location and the amount of energy sharing. The losses can be higher than V2H but they are lower than V2G.

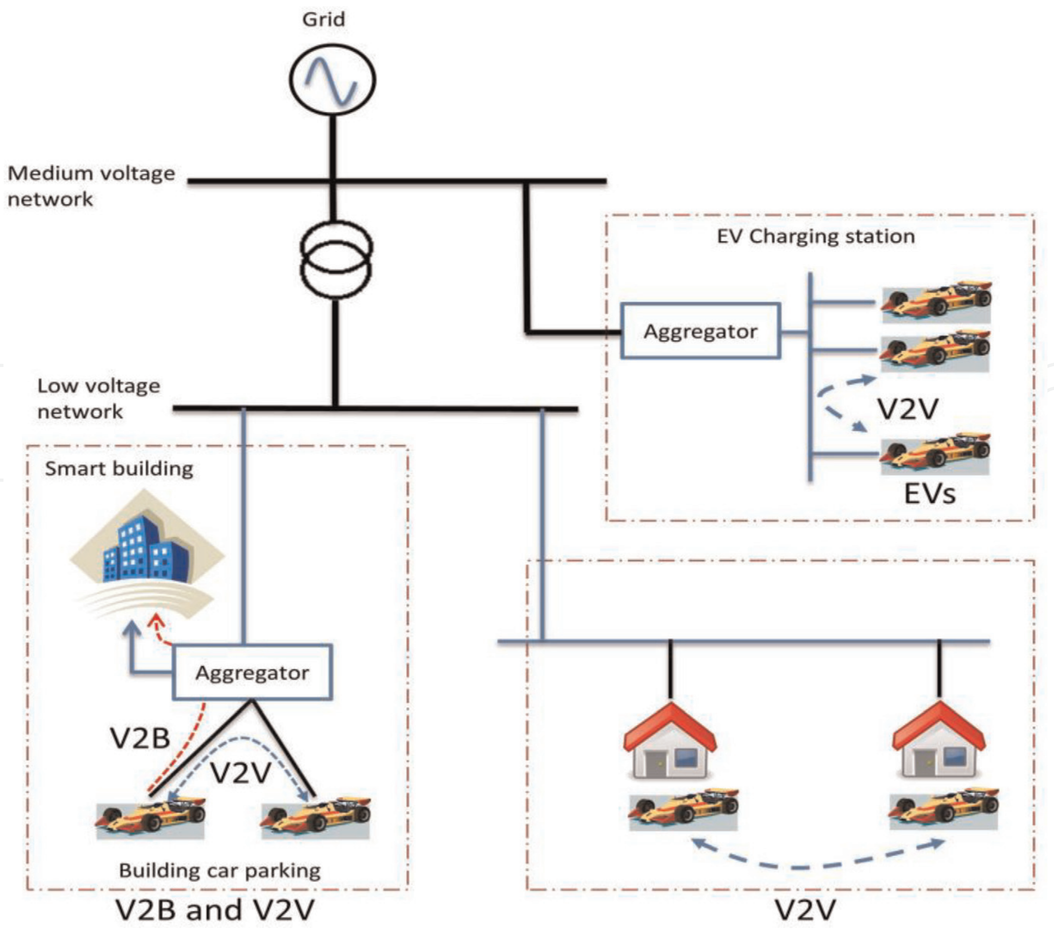

Figure 3.
Structure of V2V, V2B, and G2V at commercial locations.

- V2B/V2V can be coordinated with the RESs installed in the building or community houses and provide more reliable and secure energy supply for the consumer and in the end reduce stress to the grid.
- Since V2B/V2V is less complex but has access to large energy capacity, it can contribute significantly for implementing a smart grid.

4. Feedback regulation for V2X and ancillary services

The controller input for V2X varies according to particular ancillary services to the grid or home. The energy services can be ranged from under-frequency, over-frequency, and energy supplies to power smoothing provisions. However, EV battery SOC is the only parameter that defines the amount of energy capacity available for ancillary service regardless of the types of services. In V2H, mainly active power reference is used as feedback, whereas in V2B/V2G the reference could be extended to frequency, voltage, and other important parameters, as required by the grid operator.

4.1 Frequency-controlled EV regulation

Frequency regulation along with changing the load-generation situation with contingencies is crucial to control and maintain frequency balance and satisfy the grid requirements. A frequency feedback command to V2G controller regulates EV power output to respond to frequency variations for primary frequency control while maintaining EV owner preferred SOC limit [25]. The method can be used to regulate grid frequency by coordinating with the variation in RESs power output and minimize frequency oscillation [26]. In comparison to spinning reserves, frequency regulation is more frequent and is required for a short of time. A typical schematic of frequency feedback-controlled EV power regulation is shown in **Figure 4**. EV power output has regulated the deviation in frequency from the nominal value. The power-frequency (P-f) droop defines the specific EV power for the definite frequency deviation, and the droop gain adjusts the overall intensity of EV response. The set charging power of EV is denoted by P_{EV-set}^{Charge}. EV charging/discharging limit ensures that EV does not violate the maximum converter capacity. The output power reference at EV terminal (PEV/R) is executable when the defined SOC condition is satisfied, i.e., PEV/O has the absolute value of 1.

4.2 Voltage-controlled EV charging scheduling

With the increased roof-top solar penetration, grid voltage experiences spike especially during peak solar generation. Voltage-constrained EV charging plan can regulate the grid voltage considering variation in a solar generation as shown in **Figure 5** [27]. An energy pricing arrangement for voltage control in a fast charging

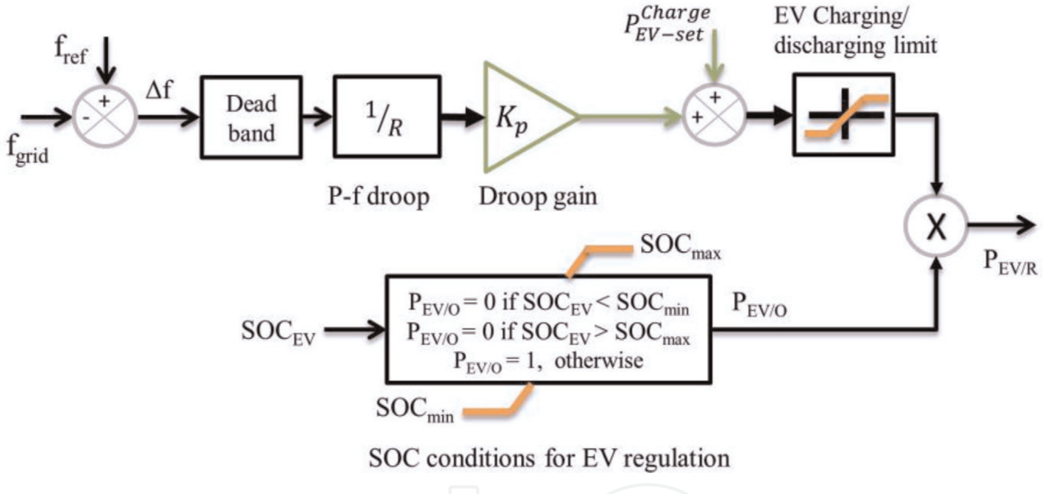

Figure 4.
Frequency-controlled EV regulation.

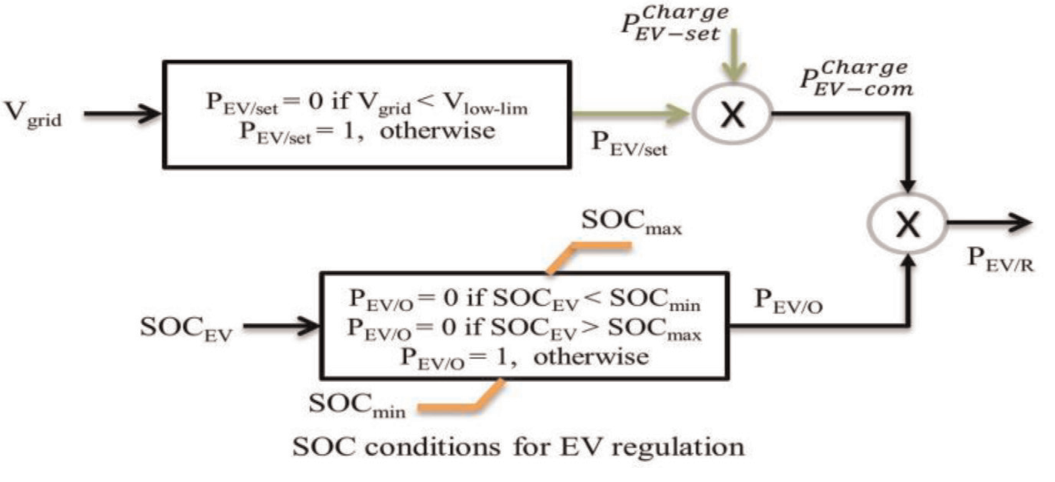

Figure 5.
Voltage-controlled EV charging scheduling.

station can also attract EV customer to charge the vehicle and participate in voltage control [28]. During peak solar generation in the daytime, EV charging will reduce the rising voltage distress from the peak generation by operating in charging mode. EV can be charged as long as the grid voltage is higher than the lower voltage limit, and hence the status of EV PEV/Set will be 1. EV charging command P_{EV-set}^{Charge} defines the power reference for EV charging to be executed, whereas PEV/O delineates the fulfillment of SOC conditions to maintain EV battery SOC during the charging/discharging process. EV can also be designed as V2G service provider (charge/discharge) during voltage transients as in frequency control using droop control method. EV can also participate in voltage feedback-controlled reactive power regulation of EV and enhance power quality issues in the grid and improve power quality of the grid by minimizing voltage sags with the discharge power from EV [29].

4.3 Power-controlled EV regulation

During peak shaving [30], in the case of load outage [31] or utilizing EV for mitigating power oscillation [32] resulted from RESs, the active power reference is taken as the feedback for V2G/V2H/V2B. The power output of EV is constrained by the converter capacity and SOC of EV battery. The active power output reference for EV can be written as in Eq. (1):

$$P_{ref-EV}(t) = P_{load\_e}(t) - P_{load\_a}(t) \tag{1}$$

where t is the time, $P_{ref\text{-}EV}(t)$ is the active power requirement at EV terminal to maintain power balance, $P_{load\_e}(t)$ is the estimated load demand, and $P_{load\_a}(t)$ is the actual load demand.

5. EV charge/discharge management (ECDM) and communication issues in smart grid

As mentioned in Section 4, the corresponding power equation of EV depends on the particular feedback signal. However, the calculation of SOC remains the same for any power equation of EV. The changes in battery energy during a charge/discharge process can be defined as in Eq. (2) [33]:

$$\Delta E_i = \int_0^t \eta P_t \, dt \tag{2}$$

Therefore, the actual SOC can be calculated from the SOC value at the previous stage and the percentage of the available energy capacity of EV battery in the following way as in Eq. (3):

$$SOC_t = SOC_{(t-1)} + \int_{t-1}^{t} \frac{\Delta E_i}{E_i} \, dt \tag{3}$$

where SOC_t is the SOC at time t, $SOC_{(t-1)}$ is the SOC at a time $(t-1)$, E_i is the battery capacity, η is the charging/discharging efficiency, and ΔE_i is the change in battery energy.

5.1 Modeling of ECDM in V2H and G2V

Since battery charger and battery are not 100% efficient, the amount of power available for discharging is less than the rated capacity, and the total intake power of EV during charging is higher than the rated capacity. Hence, the equation of EV power in V2H/G2V can be defined as in Eq. (4):

$$P_T(t) = P_D(t) + S(t) * \sum_{n=1}^{K} P_{EV,n}^{TC/TD}(t) \tag{4}$$

In V2H (discharge), the EV power output can be written as in Eq. (5):

$$P_{EV,n}^{TC/TD}(t) = -P_{EV,n}^{TD}(t) \tag{5}$$

In G2V (charge), the equation of EV power can be written as in Eq. (6):

$$P_{EV,n}^{TC/TD}(t) = P_{EV,n}^{TC}(t) \tag{6}$$

where $P_{EV,n}^{TC}(t) = \eta^C P_{EV,n}(t)$= total EV power in charging mode; $P_{EV,n}^{TD}(t) = \eta^D P_{EV,n}(t)$= total EV power in discharging mode; N = number of EVs connected to the home network; P_T = total home power demand; P_D = home load power demand without EV; S = EV position {at home and plugged-in (S = 1), outside/at home but unplugged (S = 0)}; $P_{EV,n}(t)$ = the power output of EV (positive (charging)/negative (discharging)); η^C = charging efficiency of EV charger and EV battery; η^D = discharging efficiency of EV charger and EV battery.

ECDM can be planned according to real-time pricing or randomly. However, unplanned charging will increase electricity costs of a home, which is the last thing an EV owner would wish for. Hence, an optimal charge/discharge plan needs to be adopted to minimize the cost of electricity in the home. The power calculation in V2H and G2V can be written as in Eq. (7):

$$P_{EV,n}^{TC/TD}(t) = \begin{cases} -P_{EV,n}^{TD}(t), & \begin{array}{c} if\ t = time_{on-peak}\ and\ P_{E\_on-peak}(t) > P_{E\_off-peak}(t) \\ \text{and } SOC(t) \geq SOC_{ODT} \text{ or } SOC(t) \geq SOC_{\min} \end{array} \\ P_{EV,n}^{TC}(t), & \begin{array}{c} if\ t = time_{off-peak}\ and/or\ P_{E\_off-peak}(t) < P_{E\_on-peak}(t) \\ \text{and } SOC(t) \leq SOC_{max} \end{array} \\ 0, & otherwise \end{cases} \tag{7}$$

where $P_{E\_on-peak}$= on-peak electricity price (per kWh); $P_{E\_off-peak}$ = off-peak electricity price (per kWh); SOC_{ODT} = EV owner defined SOC threshold (pu).

In the case of discharging EV during peak periods when electricity price is high and charging for the period of off-peak time with a lower price, the energy calculation can be represented as in Eq. (8):

$$\begin{aligned} \sum_{n=1}^{N} \sum_{0}^{t} P_{ET}(t) = & \sum_{off-peak_{min}}^{off-peak_{max}} \left\{ P_D(t) + S(t) * P_{EV,n}^{TC}(t) \right\} * P_{E\_off-peak}(t) \\ & + \sum_{peak_{min}}^{peak_{max}} \left\{ P_D(t) - S(t) * P_{EV,n}^{TD}(t) \right\} * P_{E\_on-peak}(t) \end{aligned} \tag{8}$$

where $P_{ET}(t)$= Total electricity price.

Without V2H (G2V only), total EV power in discharging mode is zero in Eq. (7), and hence the associated power reduction in Eq. (8) is zero.

5.2 Modeling of ECDM in V2G and G2V

The power equations of EV for V2G vary according to their installed location and the services it is providing. At home, EV must meet total home load demand, and then it can provide power to the grid. This is particularly applicable when a single connection point at home is available for the incoming and outgoing power. In V2G at home, the power equation can be written as in Eq. (9):

$$P_T(t) = P_D(t) - S(t) * \sum_{n=1}^{K} P_{EV,n}^{TD}(t) \tag{9}$$

where $\sum_{n=1}^{K} P_{EV,n}^{TD}(t) > P_D(t)$ and $P_T(t)$ is negative which indicates exporting power to the grid. The battery SOC conditions must be satisfied to secure customer preference and battery protection as in Eq. (10):

$$SOC(t) \geq SOC_{ODT} \text{ or } SOC(t) \geq SOC_{\min} \tag{10}$$

In view of selling energy to the grid when the price is high and recharging at off-peak periods with lower energy price, the calculation of energy pricing for V2G can be defined as in Eq. (11):

$$\begin{aligned}\sum_{n=1}^{N}\sum_{0}^{t} P_{ET}(t) = &\sum_{off-peak_{min}}^{off-peak_{max}} \left\{P_D(t) + S(t) * P_{EV,n}^{TC}(t)\right\} * P_{E\_off-peak}(t) \\ &+ \sum_{peak_{min}}^{peak_{\max}} \left\{P_D(t) - S(t) * P_{EV,n}^{TD}(t)\right\} * P_{SE\_on-peak}(t)\end{aligned} \tag{11}$$

where $P_{SE\_on-peak}$ = on-peak electricity selling price (per kWh).

At charging stations, V2G can be implemented as a power reference in the feedback loop of EV power regulation or frequency regulation through droop/inertia. In this case, the calculation of EV power can be defined as in Eq. (12):

$$P_{EV,n}^{TC/TD}(t) = \begin{cases} -P_{EV,n}^{TD}(t), & V2G \\ P_{EV,n}^{TC}(t), & G2V \\ 0, & otherwise \end{cases} \tag{12}$$

In the case of frequency regulation in the feedback loop, the droop-controlled equation can be defined as in Eq. (13):

$$P_{EV,n}^{TC/TD}(t) = \begin{cases} -P_{EV,f}^{TD}(t), & \mathrm{f}_{actual} < \mathrm{f}_{ref} \\ P_{EV,f}^{TC}(t), & \mathrm{f}_{actual} > \mathrm{f}_{ref} \text{ } or \text{ } SOC(t) < SOC_{\max} \\ P_{EV,r}^{TC}(t), & SOC(t) < SOC_{\min} \text{ } or \text{ } SOC(t) < SOC_{RTD} \text{ } or \text{ } SOC_{\max} \\ 0, & SOC(t) > SOC_{\min} \text{ } or \text{ } SOC_{ODT} \text{ } or \text{ } SOC_{\max} \end{cases} \tag{13}$$

where

$$P_{EV,f}^{TD}(t) = P_{EV,f}^{TC}(t) = \frac{\mathrm{f}_{actual} - \mathrm{f}_{ref}}{R} = \frac{\Delta f}{R}$$

$P_{EV,f}^{TD}(t)$ = EV discharge power in V2G for a frequency lower than the rated value; $P_{EV,f}^{TC}(t)$ = EV charge power in V2G for a frequency higher than the rated value; $P_{EV,r}^{TC}(t)$ = the rated EV charging power in (a) V2G when EV is inactive (frequency is within the allowed limit) in V2G priority mode or (b) in the recharging priority mode, when SOC is lower than the minimum SOC/required SOC threshold for driving/maximum SOC; Δf = frequency deviation; SOC_{RTD} = required SOC threshold for driving back to home from the workplace.

Hence, the available SOC for V2G service is as in Eq. (14):

$$SOC_{V2G} = SOC_{RTD} - SOC(t) \tag{14}$$

The inertia and droop control can be combined to obtain improved frequency response [34]. Thus, the power reference to reflect charge/discharge in frequency regulation can be expressed as in Eq. (15):

$$P_{EV,f}^{TD}(t) = P_{EV,f}^{TC}(t) = \frac{f_{actual} - f_{ref}}{R} + \frac{d}{dt}\Delta f\ G_{in} = \frac{\Delta f}{R} + \frac{d}{dt}\Delta f\ G_{in} \tag{15}$$

where G_{in} is the gain of the inertial controller.

5.3 Modeling of ECDM in V2B/V2V

The feedback loop for EV in V2B/V2V modeling can be the same as in V2G. The modeling depends on the purpose and control in building energy management system for V2B or simple energy exchange between two or more EVs. Hence, power regulation as in Eq. (12) or frequency regulation as in Eq. (13) can be picked out for V2B. In V2V, simple power regulation for exchanging energy can be selected as in Eq. (12). The exchanged energy of an EV in V2G at charging stations/building (V2B)/other vehicle (V2B) can be easily priced according to Eq. (16):

$$\sum_{0}^{t} P_{ET}(t) = P_{EV}^{TC}(t) * P_{charge}(t) - P_{EV}^{TD}(t) * P_{discharge}(t) \tag{16}$$

where P_{charge} is the energy price for charging (G2V) and $P_{discharge}$ is the energy price for discharging (V2G). The negative and positive prices indicate credit and debt, respectively, for EV owner.

5.4 Modeling of ECDM in V2D

The energy consumption in V2D depends on certain aspects related to the vehicle as well as weather and road conditions. The tractive effort (F_{te}) to propel the vehicle forward must overcome and accomplish the forces as in Eq. (17) [35]:

$$F_{te} = F_a + F_{rr} + F_{ad} + F_{gr} \tag{17}$$

where F_a = acceleration force, F_{rr} = rolling resistance force, F_{ad} = aerodynamic force, and F_{gr} = grade resistance force.

The acceleration force of EV can be derived from Newton's law as in Eq. (18):

$$F_a = ma \tag{18}$$

where m and a are vehicle mass (kg) and acceleration (m/s^2), respectively.

The rolling resistance is related to the frictions related to the vehicle tire on road, bearings, and gearing system. This is roughly invariable with vehicle speed and proportional to vehicle mass that can be derived as in Eq. (19):

$$F_{rr} = maC_{rr} \tag{19}$$

where C_{rr} is the coefficient of rolling resistance.

The aerodynamic force which is a function of the design of the car that represents the friction of EV in the air can be formulated as in (Eq. (20)):

$$F_{ad} = 0.5\rho AC_d V^2 \tag{20}$$

where ρ is the surrounding air density (kg/m^3); A is the front area of the car (m^2); C_d is the drag coefficient that depends on the design of the car, shape, and frontal area of the car; and V is the velocity.

The grade resistance force can be defined as vehicle weight that functions along the slope as in Eq. (21):

$$F_{gr} = ma \sin \phi \tag{21}$$

where ϕ is the slope angle.

Thus, the mechanical power of EV to overcome the aforementioned forces can be calculated as in Eq. (22):

$$P_{tm} = maV + maV \sin \phi + 0.5\rho AC_d V^3 + maC_{rr}V \tag{22}$$

5.5 EV SOC control in various operation modes

Regardless of different operation modes, EV SOC changes as it consumes or provides energy and therefore needs to be recharged for guaranteeing the availability of EV for the next service. As EV charger and battery are not 100% energy efficient, the total energy capacity of EV for V2X is not available and can be calculated according to the efficiency of battery and EV charger. Also, energy consumed by EV including the charger is slightly higher than the rated capacity. While V2B, V2G, and V2V are independent of distance, V2D is solely dependent on traveling distance and speed, in general.

As outlined in Section 5.4, EV SOC in V2D is subjected to certain variables that are specific to the vehicle such as vehicle mass, rolling resistance, vehicle aerodynamics, specific road conditions such as down/up slop, the number and behavior of passengers and the driver, air conditioner/heater on/off, and day/night time (headlight on/off). In addition to these, vehicle speed defines the change in energy capacity. In Australia, the average traveling distance is less than 20 km for 73% of the employed people traveling from their working place to their residing place [36]. Moreover, passenger vehicles in Victoria annually traveled 14,498 km on average [37]. Thus, an average daily distance by individual passenger vehicle is approximately 55 km in view of 260 working days. Therefore, the SOC calculation based on distance can be written as in Eq. (23):

$$SOC_{DT} = SOC_{(DT-1)} + \frac{\Delta E_{DT}}{E_i} \tag{23}$$

where SOC_{DT} is the SOC at present location (km), $SOC_{(\mathrm{DT-1})}$ is the SOC at previous location (km), and $\Delta \mathrm{E}_{\mathrm{DT}}$ is the amount of energy consumed for the traveled distance per km. In V2G/G2V/V2B/V2H, battery SOC is calculated by Eq. (3).

5.6 Communication issues of EV in smart grid

In a smart city environment, where centralized or dispersed energy generations and load systems are connected to the web through wireless or wired connections, communication issues and standards play an important role for the secure and reliable exchange of data and information between various entities. Therefore, scalable and efficient communication technologies are imperative for EV to be a part of the intelligent transportation system and electric grid [38]. There are multiple communication standards that are in use in existing studies such as ISO 15118 [39], IEEE 1609 WAVE, and IEC 61850 [40]. Nevertheless, the performance evaluation studies in [40, 41] demonstrated the superiority of IEC 61850 standards over the other. Hence, it can be said that standard communication technologies are the key to implement smart grid facility and attain maximum energy benefit of the integrated energy elements.

6. Case studies of EV in various operation modes

This section presents various cases of EV charge/discharge management in providing multiple services.

6.1 EV SOC in V2D, G2V, and V2H at home

When EV participates in different operation modes, the feedback control strategy as mentioned in Section 4 defines EV power regulation. In addition to the feedback control strategy, an energy pricing policy can also be included in the control approach for economic analysis and ensuring financial benefit for the EV owner for EV battery charging/discharging. The power exchange of an EV for a typical day in different EV operation modes is presented in **Figure 6**. EV discharging efficiency for V2X is considered as 98%. It is assumed that EV owner travels a distance of 55 km/day as mentioned in Section 5.5. The selected EV model is Nissan LEAF, and discharged power during V2D is collected from the reference [42]. EV needs to be charged to the maximum SOC (1.0pu) before the next morning, and considering economic aspect, EV is charged during off-peak periods only. The consuming and supplying of power are denoted by positive and negative values, respectively. The daily traveling time of the vehicle is 8–9 am in the morning and 5–6 pm in the afternoon. The vehicle speed is 80 km/h for 20 km, 90 km/h for 15 km, and 60 km/h for 20 km, and the associated EV power consumption is 152, 163, and 128 Wh/km, respectively [33]. The EV discharges 8.045 kWh of energy for

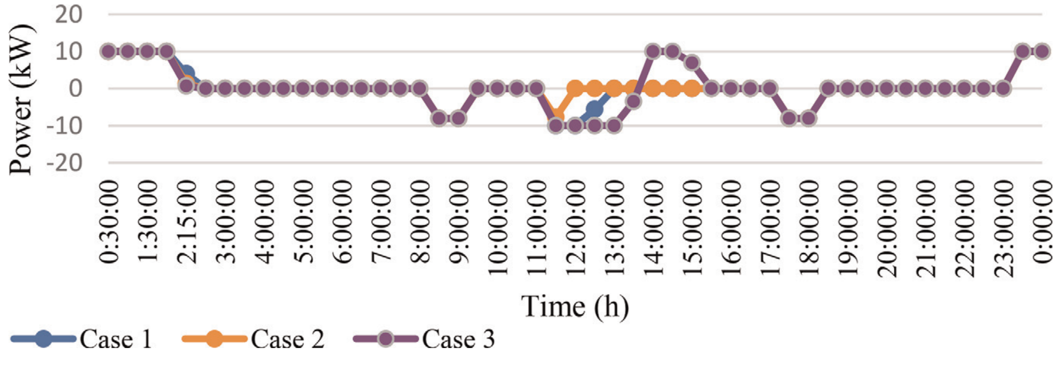

Figure 6.
The power exchange of an EV for a typical day in various operation modes.

one-way travel, and thus battery SOC reduces to 0.799 pu when EV arrives at the work place. The EV SOC reduces by 0.201 pu in the morning, and assuming similar distance and driving speed, the required battery energy capacity is the same to return back home. Hence, with the minimum SOC of 0.2 pu for safe battery discharge limit, the updated SOC value before the departure from office has to be greater or equal to 0.401 pu. It is assumed that V2G operation starts at 11 am and continues for multiple hours in accordance with the selected SOC constraints. There are three SOC constraints in the study, and they are as follows: (1) V2G (with V2V and V2B) and G2V, Case 1; (2) V2G (with V2V and V2B), V2H, and G2V, Case ; and (3) V2G (with V2V and V2B), V2H, and G2V (recharge), Case 3. EV is fully charged during overnight when the energy price is low. EV battery SOC status and constraints for three cases are outlined in **Table 1**.

Case 1 indicates that when EV is not participating in V2H, higher amount of energy is available for V2G/V2V/V2B services compared to Case 2 as shown in **Figure 6** and **Table 1**. However, this will drain out all the EV energy, i.e., EV battery SOC reaches to the lowest safe margin when EV arrives at home as shown in **Figure 7** and may not be accessible in the case of emergency driving. The less amount of energy is obtainable for V2G/V2V/V2B services in the event of Case 2 as EV is planned to be utilized for V2H. Therefore, EV battery SOC is higher than Case 1. This has multiple benefits, i.e., EV can be placed for V2H or can be accessible for emergency V2D in the evening. Nevertheless, available energy for V2G/V2V/V2B services reduces by nearly half than that of Case 1. EV SOC reduces gradually as EV discharges in V2H operation. Considering such contrasting environment of Case 1 and Case 2, a new charge/discharge plan is presented, i.e., Case 3. In the instance of Case 3, EV is discharged until battery SOC reaches to the minimum SOC level as shown in **Figure 7** and then recharged back to the expected value of 0.601pu before

Case	SOC on arrival at office	Plan for V2H and estimated SOC (pu) reserve for V2H	Expected SOC (pu) on arrival at home	SOC (pu) for traveling back to home	SOC (pu) before departure with minimum SOC 0.2pu	Energy (kWh) available for V2G/V2V/V2B
Case 1	0.799	No	0.2	0.201	0.401	15.592
Case 2	0.799	Yes/0.2	0.4	0.201	0.601	7.752
Case 3	0.799	Yes/0.2	0.4	0.201	0.601	23.476

Table 1.
EV SOC status and constraints at various operation modes.

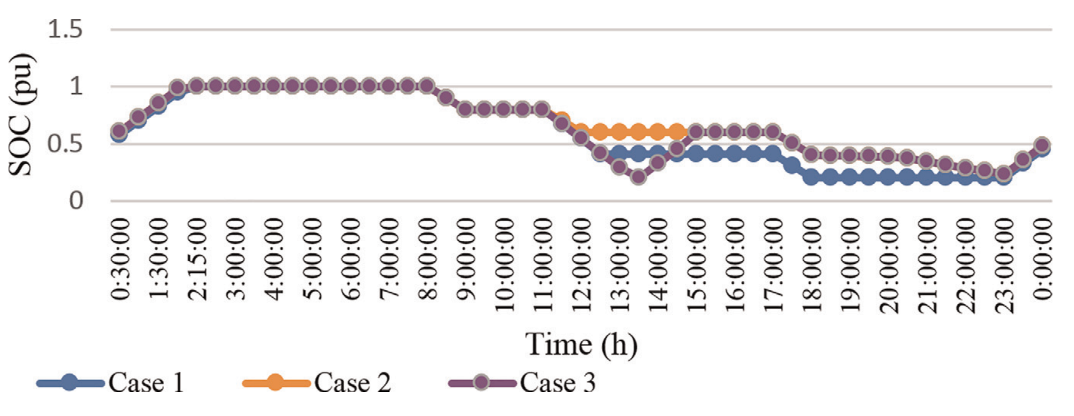

Figure 7.
EV SOC status for a typical day in various operation modes.

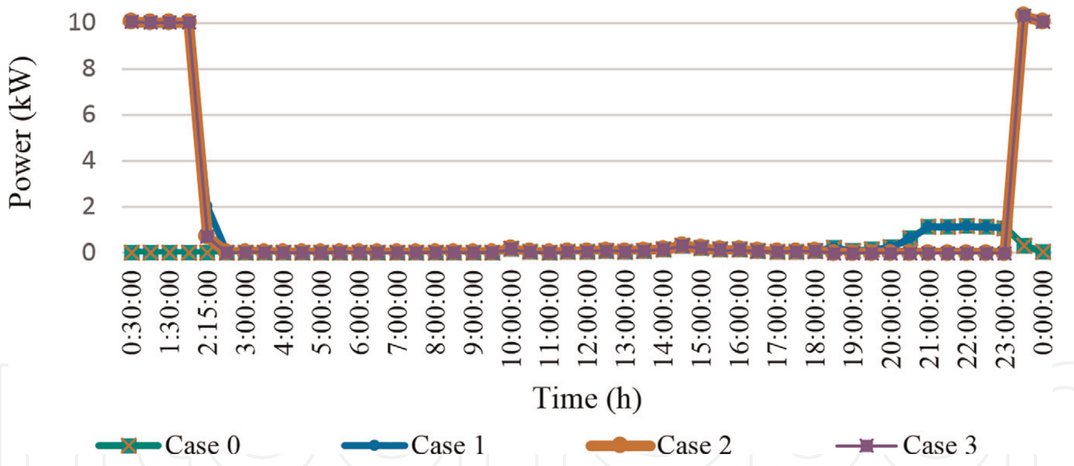

Figure 8.
EV power in V2H and G2V at home only.

the departure of EV in the afternoon. This ensures that higher amount of energy (23.476kWh) is available for V2G/V2V/V2B services, and also sufficient SOC is available when EV arrives at home for V2H or emergency V2D.

The amount of energy exchange at home in different EV operation modes is shown in **Figure 8** where Case 0 defines the event of energy exchange without an EV. For Cases 1, 2, and 3, the maximum charging power is 10 kW during off-peak time to reduce EV charging cost. The close-up view shown in **Figure 9** illustrates that total house energy demand between 18:00 and 23:00 h is met by EV, and hence the net cost of energy purchase from the grid is zero.

Hence, it is observed that EV can participate in various operation modes according to the planning and management of EV battery SOC. An effective SOC management such as Case 3 provides better resolution on battery SOC management and maximum utilization of EV battery capacity in a smart grid environment.

6.2 Aggregated EV for V2G services

In order to evaluate the performance and importance of EV in the power system for V2X services, an isolated MG is considered as shown in **Figure 9** with different level of EV penetration. A 5.1 MW PV farm is integrated at bus 3, and EVs are connected through an aggregator at bus 2. Two different case studies are simulated to demonstrate the contribution of EV in V2G. A 100% load growth is applied at bus 3 for the duration of 0–0.5 s for various scenarios, and the generator frequency responses are shown in **Figure 10**. **Figure 10** depicts that with integrated PV (dotted green line), the frequency of generator drops to 0.9874pu in comparison to 0.9925pu in the case of without any PV integration (solid blue line). The frequency

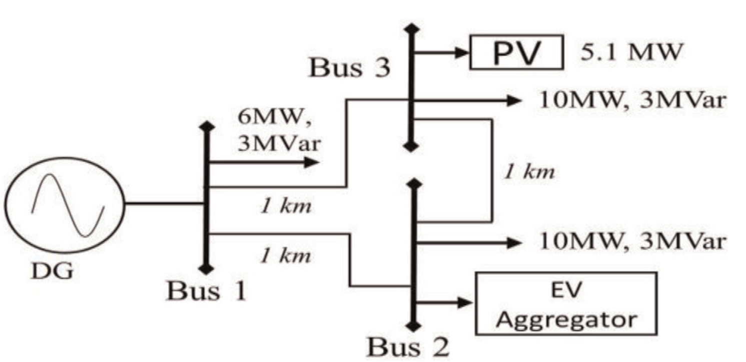

Figure 9.
Studied MG with PV and aggregated EV.

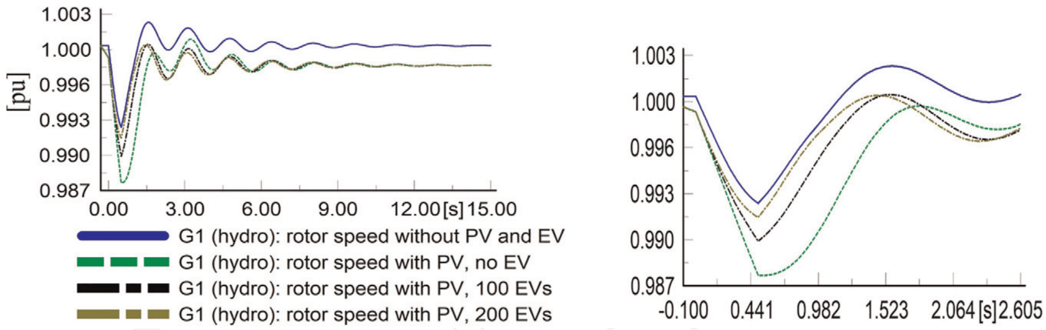

Figure 10.
The generator frequency response with 100% load growth at bus 3.

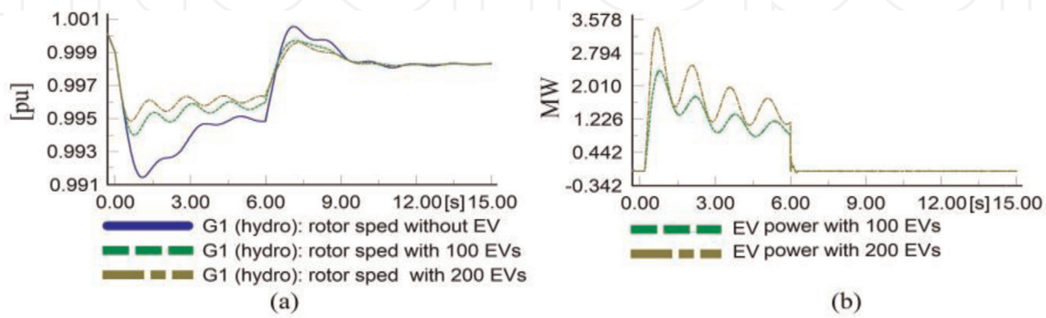

Figure 11.
The generator frequency response with temporary PV outage.

drops due to the fact of negative inertial contribution with increased PV penetration. On the contrary, the frequency drop reduces considerably with EV participation in V2G regulation. It can also be seen that with the increased number of EVs (100 vs. 200), frequency deviation reduces as EV aggregator provides more power with a higher amount of EVs. This implies better frequency regulation and energy management in a smart grid environment.

Another case study on the temporary outage of PV power output during t = 0–2 s due to cloudy weather condition is considered to further exhibit EV importance in V2G regulation. **Figure 11a** also illustrates an improved frequency performance, i.e., lower frequency deviation with the integrated EV (dotted green and dark yellow lines) than without an EV (solid blue line) while providing V2G services. The higher amount of power output of EV aggregator is visible in **Figure 11b** as the number of EV increases which justifies the improved frequency performance following the disturbance events.

7. Conclusion

With revolutionized transportation industry, numbers of EVs are expected to rise around the globe. However, the large volumes of EVs are a great concern for stable and reliable operation of grid due to the unpredictable moving nature of EV. Hence, it is essential to adopt suitable planning for the management of EV energy. V2X is one of the paramount means of improving power systems' stability and reliability, power quality, and maximizing the economic benefit of EV in the present-day and future electric grid. This chapter has thoroughly presented and discussed the structures of EV in various operation modes, feedback regulation, and the charge/discharge management strategy of EV for V2X services. Furthermore, a case study demonstrates the flexibility of EV charge/discharge planning and management at grid level and customer end in accordance with associated EV battery

SOC status and constraints. In addition, this study illustrates the ample opportunity of EV in V2X and G2V to minimize the technical challenges from the expected enormous penetration of EV in the coming years.

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Nomenclature

GHG	greenhouse gas
EV	electric vehicles
V2H	vehicle to home
V2G	vehicle to grid
V2V	vehicle to vehicle
V2B	vehicle to building
V2D	vehicle to drive
G2V	grid to vehicle
SOC	state of charge
MG	microgrid
ECDM	EV charge/discharge management
PCS	power conversion system
V2X	vehicle to everything

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