Chapter 11
Integrating Smart PHEVs in Future Smart Grid

F. R. Islam and H. R. Pota

Abstract In a smart power network, PHEVs can act as either loads or distributed sources of energy. The two terms most commonly used to describe the interconnection of a power network and electric vehicle are ‘Grid-to-Vehicle (G2V)’ and ‘Vehicle-to-Grid (V2G)’. When electric vehicles are connected into the grid to recharge their batteries or supply energy to it, they act as loads known as the G2V or V2G modes of operation respectively. This chapter reviews the impact of implementing the G2V mode, and the benefits and drawbacks of, and strategies for, the V2G interfacing of individual vehicles with a PHEV park. The performance of a power system network can be improved using V2G technology, which offers reactive power support, power regulation, load balancing, and harmonics filtering, which in turn, improve its quality, efficiency, reliability and stability. To implement V2G technology, a power network might require significant changes in its structure, components and controls, the issues for which include battery life, the need for concentrated communication between vehicles and the grid, the effects on distribution accessories, infrastructure changes, and social, political, cultural and technical concerns. As storage is essential for a power system, distributed electric vehicles can be an economical storage solution if it has a good plan for buying and selling its energy. Bidirectional power flow technologies of V2G systems need to be addressed and the economic benefits of V2G technologies depend on vehicle aggregation and G2V/V2G strategies. In the future, it is expected that their benefits will receive greater attention from grid operators and vehicle owners.

Keywords Smart Grid · Renewable energy · PHEV · V2G · G2V

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Table 11.1 Charging power levels

Power level	Description	Power level
Level 1	Opportunity charger (any available outlet)	1.4 kW (12 A) 1.9 kW (20 A)
Level 2	Primary dedicated charger	4 kW (17 A) 19.2 kW (80 A)
Level 3	Commercial fast charger	Up to 100 kW (12 A)

11.1 Introduction

Due to environmental and climate issues, along with the rising cost of petroleum, energy security and limited reserves of fossil fuels [1–3], PHEV technology has become of increasing interest. However, it is in an early stage of development and faces a few problems before it can be adopted worldwide, such as technical limitations, sociocultural obstacles and the fact that PHEVs currently cost more than conventional vehicles [4]. According to the EPRI, penetration of PHEVs into the USA's vehicle market will be 35 % by the year 2020 [5]. To attain a stable and versatile interfacing between a grid and PHEVs, standards and codes for system requirements are developed by various organizations, such as the automotive sector, the IEEE, the Society of Automotive Engineers (SAE) and the EPRI. In this dissertation, PHEVs are chosen for analysis as they have a few advantages over hybrid electric vehicle (HEV) and internal combustion engine (ICE) vehicles as they can act in the discharge mode as V2G devices and in the charging mode as G2V devices [6]. This chapter reviews V2G/G2V technologies on grids and customer requirements, cost analysis, challenges and policies for V2G interfaces of both individual PHEVs and vehicle fleets. To assess the impacts and utilization of PHEVs in utility distribution or transmission networks, their controls and usage prototypes need to be evaluated. The SAE has defined three levels of charger for PHEVs [7], as summarized in Table 11.1. A PHEV behaves as a load when it needs to recharge its battery in the G2V mode and as a generator when a utility grid takes power from its battery in the V2G mode of operation. Its recharging and discharging characteristics depend on a few factors, such as its geographical location, the number of PHEVs in that particular area, its charging levels (charging current and voltage), battery state and capacity, and the connection type used (unidirectional or bidirectional) [8, 9].

11.2 Impact of G2V on Grid

First-generation mass-market PHEVs, such as the Chevrolet Volt and Nissan Leaf [10, 11], connect to the grid for only battery charging, which is the most basic configuration. G2V includes conventional and fast battery charging systems, and the latter can stress a grid distribution network because its power is high, as a typical PHEV requires more than double an average household's load [25]. Charging practices in different locations also have an effect on the amount of power taken from an electric grid by a fleet of PHEVs; for example, charging at work in congested urban centres can lead to undesirable peak load [12], which could require significant investments in expensive peak generation. Injected harmonics and a low power factor can be serious problems if the charger does not employ a state-of-the-art conversion for charging PHEVs at night, which has minimal impact on the power grid given suitable choices for intelligent controls [5, 13–17]. The increasing exploitation of PHEVs is still a topical area of research. One of the foremost recent studies of smart-grid development with PHEVs is [18] that recognized the complexity of studying the impact of PHEVs on a smart grid, with the results depending on many factors (power level, timing, duration of PHEV connection to the grid) and possibly affecting several variables (capacity needs, emissions generated). As mentioned above, as a charging PHEV may present a load to an electrical grid twice the order of magnitude of that of a typical home, connecting it may create power quality problems, such as momentary voltage drops. An interesting point about the simulations in [19], which assumed no control over the charging of vehicles, is that they showed voltage drops between 5 and 10.3 % depending on the time of day and season. The simulation results showed how the voltage supplied to a house changed without and with PHEV charging where, for the latter, the drop in it increased from 1.7 to 4.3 % while, for the former, much more random behaviour was exhibited with average voltage drops of around 4 % (although this eventually reached a value close to 1.7 % once the PHEV was charged). These results point to a need to improve the quality of electrical energy delivery by utilizing smart technology to coordinate the charging of PHEVs. The study in [19] was based on simulations using residential power consumption profiles. The shorter period of AC power consumption became a switched load, with levels similar to what would be expected to be observed in PHEVs with Level 2 charging profiles, that is, the notion that the grid had not experienced high-magnitude loads with a random switching profile was not true. This switching high-power AC consumption profile was masked by its aggregated effect on the grid. One other important aspect when studying the effect of PHEVs on an electric grid is the grid's stability for which damping components will need to be introduced into future designs for controlling PHEV charging.

11.3 V2G Technology

V2G describes a system in which PHEVs communicate with the power grid to sell demand response services by delivering electricity into the grid or throttling their charging rate. PHEVs can serve as stored and distributed energy resources as well as reserves for unexpected outages when they have proper on-board power electronics, smart connections to the grid and inter-active charger hardware control [14, 20–23]. A bidirectional charging system is essential to support energy injection into the grid [24–27], as a unidirectional charger, although simple and easy to use in terms of control, can be used only for a G2V system.

A smart charging system and proper management can shift loads and avoid peaks while a proper controller can minimize the impact of PHEVs on the utility grid [16, 17, 28]. Smart metering, communication and control systems play important roles in the direct coordination of the V2G and G2V modes of operation. The real-time, nonlinear pricing of a utility bill is one of the important factors for obtaining higher returns from grid-connected PHEVs [29]. In the V2G mode, interconnection between the grid and vehicle is essential and an individual vehicle or even a fleet of PHEVs can take part as spinning reserves for the grid. A group of cars in a park is more convenient to manage as a load for the grid [30] and more helpful as it can work as a distributed energy resource when necessary [31]. The potential benefits and economic issues of V2G technology are of great concern for researchers nowadays [28–47]. Another current issue is the use of RESs in a power network as, due to their sporadic natures, they need storage devices for which a PHEV's battery can be a solution as it offers the opportunity to store wind and solar energy at times of excess generation and provide possible backup when necessary [6, 32–34]. The implementation of V2G technology has been explored in a number of ways through different research, such as for reactive power support [28], active power regulation, load balancing by valley filling [35, 36, 48], and peak load shaving [37, 38]. These systems can enable such ancillary services as frequency control and spinning reserves [6, 30, 39–42], improve grid efficiency, stability, reliability [43] and generation dispatch [44], and reduce utility operating costs and, potentially, even generate revenue [29]. In addition, PHEVs owners benefit when electricity is cheaper than fuel for equivalent distances. Researchers have estimated that potential net returns from V2G methods range from $90 to 4,000 per year per vehicle based on the power capacity of electrical connections, market value, PHEV penetration and the energy capacity of the PHEV battery [6, 19, 20, 45–47]. Besides the intrinsic benefits of PHEVs, emissions have been reduced [17, 49, 50], and it has been reported that V2G strategies have the potential to displace the equivalent of 6.5 million barrels of oil per day in the USA [37]. Peterson et al. estimated the annual net social welfare benefits from the grid to be $300–400 [51]. The design of a power system filter is one more option for using V2G technology, which in this dissertation, is described so that its implementation makes the grid smarter.

The expected increase in the number of electric vehicles produced could have a significant impact on the potential for utility-related energy storage as these vehicles can provide some of its benefits. Specifically, it may be cost-effective to charge electric vehicles when energy prices are low and then dispatch the power from them to support the grid, especially during grid emergencies. Using electric vehicles as distributed storage is an important complement to the expected increase in intermittently RESs, such as solar and wind power outputs, which are sometimes produced when the energy demand and price are low and can change rapidly [52]. If every suburb in Australia installed just one vehicle to a grid recharge point, Australia's V2G coverage would look like that in Fig. 11.1 [53].

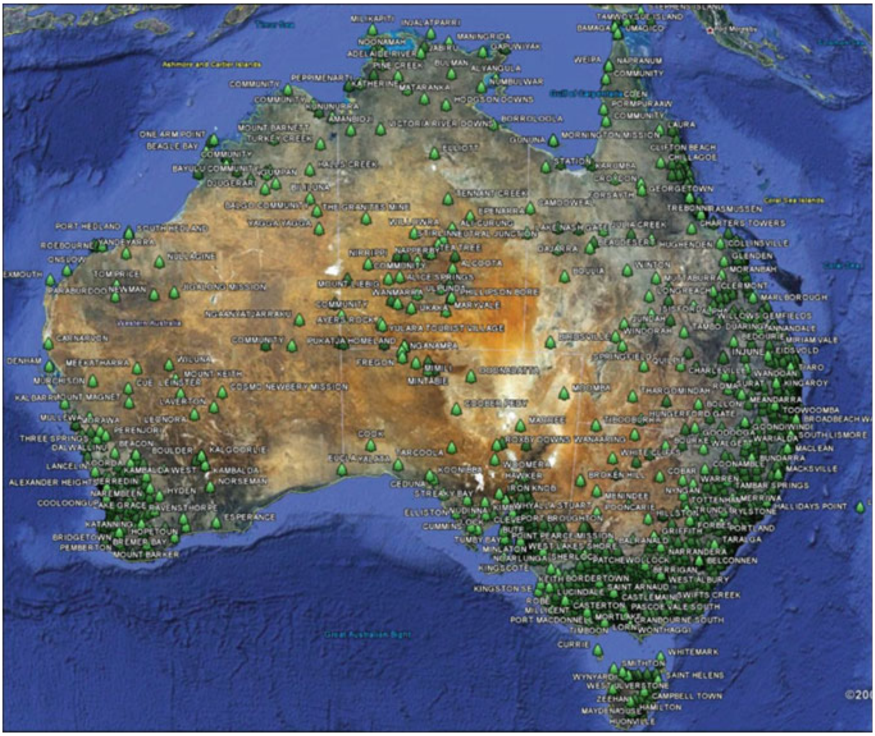

Fig. 11.1 Potential V2G coverage in Australia

11.4 A Simple Structure of V2G System

Pang et al. summarized the requirements for a simple V2G structure with energy resources and an electrical utility as being an independent system operator and aggregator, a charging infrastructure and locations, a bidirectional electrical energy flow and communication between each PHEV and the aggregator, on-board and off-board intelligent metering and control, and the PHEV's battery charger and management [54]. In short, a power connection with a grid, suitable metering and control with effective communication can build a V2G system [55]. Figure 11.2 [56] shows a simple V2G system structure and Fig. 11.3 the power flows within the charger. In general, although communications must be bidirectional to report a battery's status and receive control commands [57, 58], achieving intelligent metering and control that are aware of a battery's capacity and state-of-charge (SOC) is challenging [6, 59–61]. Both on-board and off-board smart meters have been proposed to support V2G methods [28, 48, 62], smart metering can make PHEVs into controllable loads to help combine them with renewable energy [63], GPS locators and on-board meters are useful [43, 62] while sensors and smart meters on charging stations can monitor and exchange in- formation with the

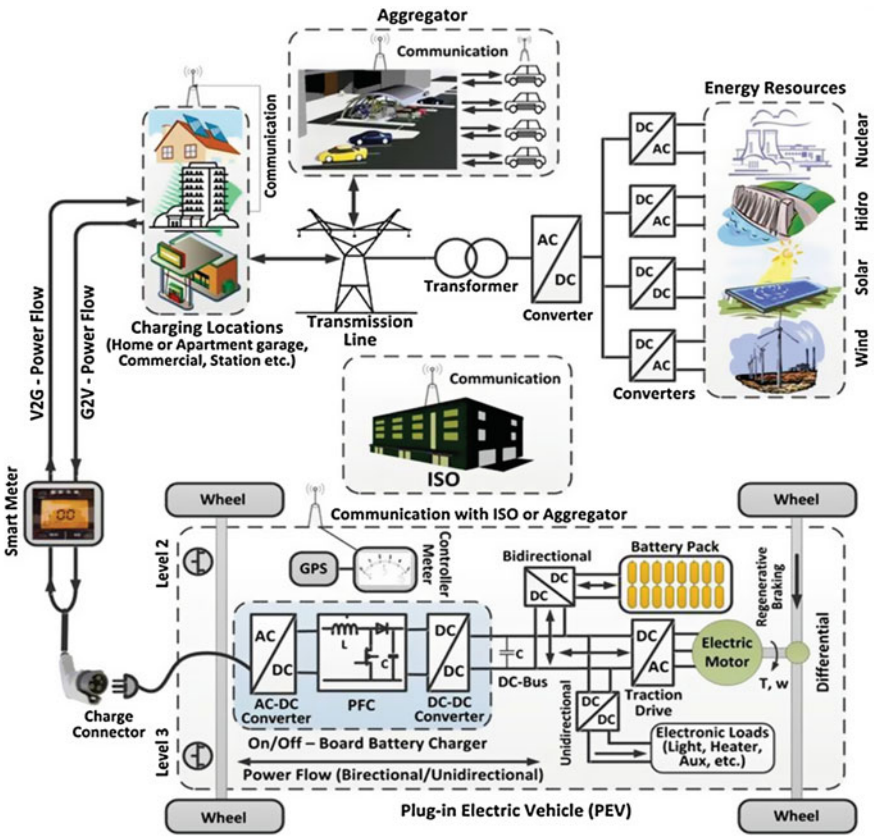

Fig. 11.2 The components and power flow of a V2G system

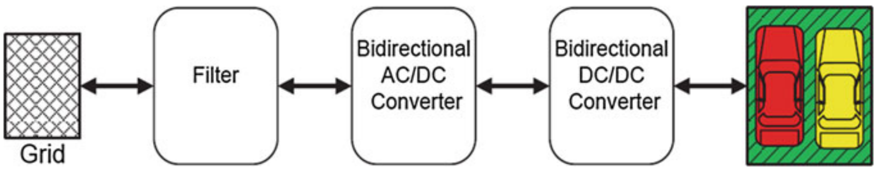

Fig. 11.3 General unidirectional and bidirectional power flow topology

relevant control centre through a field area network [55]. Also, control and communication are essential for services such as dynamic adjustments that track intermittent resources and alter charging rates to track power prices, frequency or power regulation, and spinning reserves [6, 64–67], for which a variety of protocols have been discussed, including Bluetooth, Home-Plug, Z-Wave and ZigBee, [68–72]. In US, the IEEE and SAE provide the necessary communications requirements and specification [73–75] while the National Electric Infrastructure

Working Council (IWC) has defined a communications standard to enable PHEVs to communicate with chargers [76, 77]. PHEV chargers without state-of-the-art power electronics can produce deleterious harmonic effects on a distribution system [78]. The IEEE-519 [79], IEEE-1547 [80], SAE-2894 [81] and International Electrotechnical Commission's IEC-1000-3-6 [79, 81] standards limit the allowable harmonic and DC current injections into the grid with which PHEV chargers are usually designed to full fill. Sophisticated active power converter technology has been developed to reduce harmonic currents and provide a high power factor [25, 82–85], while shock hazard risk reduction for PHEV charging is addressed in the standard for personnel protection systems for PHEV supply circuits [86].

11.5 PHEV as Source of Stored Energy for Distribution Networks

A single PHEV's battery storage capacity is small relative to that of the grid. However, the better coordination and reliability of a smart grid can be achieved by aggregating PHEVs as storage devices [23, 30, 87]. An aggregator can be a communication or controller device, or an algorithm that plays an effective role between PHEV owners, the electricity market and distribution and transmission system operators [88–90]. Both aggregated vehicles and the grid need to be properly controlled to maintain the stability of the grid [91]. Figure 11.2 shows an aggregator in a V2G system. One of its ma jor roles is to manage PHEVs to operate in the V2G mode whenever the grid needs power [92]. Each PHEV can be contracted for this service in a cost-effective way by an aggregator that understands its battery's SOC condition [43, 93, 94]. In an aggregated smart grid environment, vehicles can engage and disengage while performing ancillary services of the grid [64] and maintaining the maximum and minimum contract limits. Considering each vehicle as an individual decision maker and the aggregator as the coordinator, Wu et al. proposed a method of smart pricing and optimal frequency regulation [95]. Another optimal frequency regulation controller for a V2G aggregator was designed by Han et al. [96] while the western Danish power system was used for the long-term aggregation of PHEVs in [97]. In the industrial networks MOBIE [98] and Better Place [99], the aggregation concept was successfully implemented, and it was found that control and communication with individual vehicles was much difficult than with the aggregator [67].

11.6 Benefits of V2G System

PHEVs can support V2G mode of operation because on average, in the USA they travel on the road for only 4–5 % of the day while sitting in home garages or parks for the rest of the time [23, 62, 65]. Several services, such as voltage and frequency regulation [23, 30, 39, 40], spinning reserves, reactive power support, peak shaving, valley filling (charging when demand is low), load following and energy balance [28, 37, 48] could be provided by PHEVs. These services are sometimes essential for power system while using V2G system overall costs could be reduced and, thereby, prices to customers, and selling energy to the grid could improve load factors and reduce emissions [5], and possibly replacing large-scale energy storages.

11.6.1 Renewable Energy Supporting

The power quality of intermittent source of energy wind and solar can be improved using PHEVs as storage and filter devices [23, 33, 34, 97, 100–103]. The combination of PHEVs and renewable energy sources can make the grid more stable and reliable. The unpredictable nature of wind speed makes the wind energy sources strongly intermittent and leading to imbalances [33, 104]. Solar radiations are available during the day while the peak energy demand occurs in the evening which refers the excess solar energy generation at the time when exciting grid does not need it [66].

A number of studies have been done to combine PHEVs with renewable energy sources for different purposes such as using as battery energy storage system (BESS) and reactive power support system. To overcome the fluctuation of wind power Kepton and Tomic [23] investigated the possibility of using V2G technology while Guille and Gross [30] proposed a structure using model predictive control (MPC) to analyze the positive effect of PHEVs on wind generator. To improve the power quality of a renewable energy based power network, Ota et al. [105] design a control scheme of PHEVs as distributed spinning reserve. Wand et al. [106] have provided a combination of demand response and wind power integration while Goransson et al. [107] elicited different strategies for integrating PHEVs into a wind-thermal power system.

A higher level penetration of renewable energy sources make the grid unstable, PHEVs can improve the situation by charging and discharging their battery during the period of excess generation and the period of peak load demand respectively. It can help the generation and load scheduling by consuming and supply energy whenever necessary [66]. Thus, V2G increases the flexibility of the grid to better utilize intermittent renewable sources.

11.6.2 Environmental Benefits

PHEVs have emissions benefits over conventional vehicles, even when considering power generation emissions. CO_2 emissions would fall significantly if PHEVs replaced conventional ICE vehicles [99]. In V2G mode of operation,

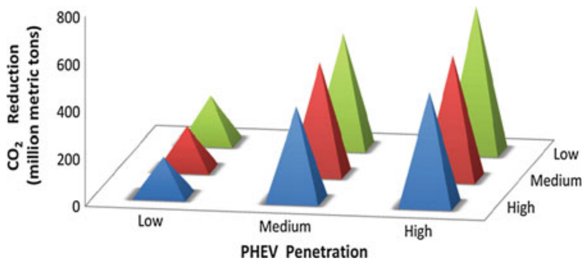

Fig. 11.4 Annual greenhouse emission reduction from PHEVs

PHEVs could offer more environmental benefits and reduce greenhouse-gas (GHG) emissions [16, 29]. CO_2 emissions are estimated to drop from about 6.2–4 tons per year from a single vehicle [33, 57] while GHG emissions linked to driving depend on the type of fuel used for electricity generation. When the electricity is produced from fossil fuels, the environmental benefits of PHEVs are reduced, for renewable energy sources the GHG emissions almost 0 g/km while for coal-based plants it increases up to 155 g/km [108], even then their emissions may be 7–21 % lower than those of HEVs [17, 109] and 25 % fewer GHG emissions than ICE vehicles [110]. The estimated reductions for PHEVs range from 15 to 65 % in another USA-based study that examined low-carbon electricity sources [5, 17]. Long-term GHG reductions depend on reducing a grid's carbon intensity [111, 112], and using PHEVs more than 33 % emission can be reduced in future smart grid [113]. However automotive and oil companies allege that EVs would have a net negative effect on the environment because of lead discharges from battery manufacturing facilities and battery disposal [4, 114].

EPRI predicted the GHG impact of PHEVs over the years from 2010 to 2050 [115], as shown in Fig. 11.4, in which three scenarios represent levels of both CO_2 and total GHG emissions intensity and another three scenarios represent penetration of PHEVs. Nine different outcomes are possible from these two sets of scenarios, which determine the potential long term impacts.

From the analysis, it is found that each of the nine scenario combinations reduced annual GHG emissions significantly while reaching a maximum reduction of 612 million metric tons in 2050 (High PHEV fleet penetration, Low CO_2 intensity case) and reductions from 2010 to 2050 can range from 3.4 to 10.3 billion metric tons.

11.6.3 Auxiliary Services

To maintaining stability, reliability, supply and load balancing and overall power quality, power system sometime needs auxiliary services from external and internal network devices. PHEVs with a bidirectional charger can provide higher quality ancillary services, such services are voltage and frequency regulation, load levelling and peak demand management. A few of them are described here in the light of literature. An aggregator can be the main part of the system by creating a larger and desirable load for the utility [30, 116].

11.6.3.1 Voltage and Frequency Regulation

Voltage and frequency regulation in power system is always essential for the better quality power supply to the end user, V2G technology can provide this service and it could be one of the best service from PHEVs due to their high market value and minimal stress on a vehicle power storage system [62, 117]. An expensive process of cycling large generator in the network [95] is used to regulate the frequency in present grid system to balance supply and demand for active power [118] and the reactive power demand is balanced by voltage regulation [118]. The charging and discharging of PHEVs can be an alternative way of frequency regulation [23].

A proper logic of charging and discharging of PHEVs can be implanted in the battery charger with a voltage control to compensate reactive power, which will select the current phase angle to operate in inductive or capacitive mode of charging [118]. With an appropriate voltage control a PHEV can able to decide when it will charge or discharge it's battery. As for example, when the grid voltage becomes too low, vehicle charging can stop and, when it becomes too high, charging can start [66]. Although penetration of large number of PHEV for charging batteries from the grid could be a reason of line over loading and voltage instability at a low voltage network [119], it can regulate the reactive power within the local network by V2G operation [19].

The Union for the Coordination of Transmission of Electricity (UCTE) defined three types of control for the frequency stability in the distribution network: primary, secondary and tertiary frequency control [120].

There are two regulation in power system: regulation up and down and separate prices are given for regulation down and regulation up capacity, depending on bids submitted during an auction. If a vehicle providing regulation submits a bid below the market clearing price, it is contracted for its available capacity. Over the course of the contracted hour, the vehicle will charge or discharge some percentage of its contracted capacity. When the vehicle charges for regulation up, the owner will be charged for the energy consumed, and when it discharges for regulation down, the owner will be reimbursed for the energy provided. For secondary and tertiary frequency control, activation is also based on bids. When demand for regulation up arises, the lowest bid is activated first. Because delivering regulation down means charging at a lower price, this can be profitable for PEVs [45]. In [121], primary control is expected to have the highest value for V2G.

V2G research group at the University of Delaware compared the potential profit of V2G with existing grid regulation system and found that a PHEV with 10–15 kW power regulation capacity can earn $3,777–4,000 per year [23, 62] and Brooks's calculation on California City's PHEVs shows the amount up to $5,038 for V2G application [122].

11.6.3.2 Load Shifting

By discharging during daily peaks and charging during low demand V2G can level the energy load. Local and global smart-charging control strategies could reduce the peak load [123]. Based on variation method an electricity pricing algorithm has been proposed for load levelling and identified an electricity price curve by Takagi et al. [36] that could realize an ideal bottom charge while PHEV owners could minimize their electricity bills. Sana showed that even 4 million PHEVs charging load could be accommodated with the existing grid of Californian [124] and for New York City it is observed that, up to 10 % of peak capacity could be safely contributed by PHEVs at penetration levels of around 50 %, which represented an economic benefit of $110 million per year [125]. Smart charger reduce peak load and shift energy demand [35, 126] while a little financial incentive for increased PHEV penetration when V2G is used for peak load reduction [51, 116].

11.7 Challenges to V2G Concept

V2G technology in a power distribution system may impact on its performance through overloading transformers and feeders, and in some cases this would reduce efficiency, produce voltage deviations and increase harmonics [127, 128]. The US Department of Energy reported [129] specific challenges and opportunities in terms of communication needs. Security issues are another challenge at public charging facilities [130]. Battery degradation, investment costs, energy losses, resistance of the automotive and oil sectors are also impediments and barriers to V2G systems.

Rapid charging and discharging of PHEV's battery for V2G concept may reduce the life of its battery. The rate of energy withdraws and cycling frequency determines the amount of battery degradation. Equivalent series resistance (ESR) and state of charge (SOC) are two major parameters proper controlling of which is a good way of slowing degradation [131–133].

According to Andersson [45], the investment cost of a battery is $300/kWh and a lifetime of 3,000 cycles at 80 % depth of charge (DOC), the degradation cost is $130/MWh. For a 16 kWh battery Peterson et al. [134] calculated the maximum net annual degradation cost of battery for V2G services, which is only $10–120.

Implementation of V2G technology in the present distribution network is likely to have a huge impact on equipment [135, 136]. Depending on the number and capacity of PHEV a distribution network could overload distribution transformers, increase voltage deviations, harmonic distortions and peak demand [137–142].

According to Dyke et al. [143], PHEVs penetration need a significant investment in electrical networks within the United Kingdom, while Fernandez et al. [144] presented the impacts of investments in distribution networks and incremental energy losses for different levels of PHEV penetration.

11.8 Scope of Research

From the above literature, there are several issues, which have not yet been taken into consideration by researchers. In this dissertation, some are discussed, with the main focus being on the following.

- Consideration of PHEV battery dynamics for load calculation and a cussed in the literature.
- Introduction of a novel ancillary service of PHEVs through designing a filter for a power system.
- Designs of virtual FACTS devices using PHEVs, which a few researchers have addressed.
- A complete power quality solution for a benchmark distribution network using V2G technology.

11.9 Chapter Summary

In this chapter, the impact of G2V and V2G technologies on power system and the benefits and challenges with the requirements and strategies for the interconnection between PHEVs and power system were reviewed. With the help of a bidirectional charger PHEVs can act like energy storage devices and serve the network whenever necessary. Unidirectional charger was the logical first step of the PHEV while the addition of on board bidirectional charger makes PHEV a smart part for the future smart grid with the opportunity of charging from any outlet of the grid and supports the network by injecting energy back to the grid. The economic benefits, CO_2 emissions, cost and the impact on the distribution system depend upon the cooperation between PHEV owner, aggregators and efficient strategy for grid operators.

Efficiency, stability, reliability and generation dispatch of a grid can be improved by using V2G operations. This mode of operation can offer active power regulation, reactive power support, power sources, current harmonic filtering, peak shaving and load balancing by valley filling for the grid. To improve the reliability of intermittent renewable energy sources PHEVs can provide possible backup as energy storage and as load at the time of excess generation. Several auxiliary supports can be provided by PHEVs to power system, such as voltage control, spinning reserves, reduce grid operating cost and generate revenue. Based on the power market value, the number of PHEVs and their battery energy capacities V2G mode of operation have the potential of net return between $90 and 4,000 per year per vehicle.

The V2G operation includes the cost of battery degradation, the need for smart communication between the vehicles and the grid, effects on the distribution system, the requirement for infrastructure changes, and political, social, technical and cultural issues. A number of proposed V2G technique have been discussed in this chapter, and it is shown that with a few disadvantage V2G technology is more economical and feasible from both owner and grid operator point of view. Political and environmental benefits can be ensured by the development of PHEVs. For the better interfacing of the PHEV and grid, the PHEV battery must have an extended life cycle with pre-determined standard of V2G and G2V connections.

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