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Stare-of-Art of V2X Mode of Operation of Electric Vehicles and its Future Perspectives

Shirazul Islam[a], Atif Iqbal[a], Mousa Marzband[b,c], Irfan Khan[d], Abdullah M.A.B. Al-Wahedi[e]

[a]*Department of Electrical Engineering, Qatar University, Doha, Qatar*
[b]*Northumbria University, Electrical Power and Control Systems Research Group, Ellison Place NE1 8ST, Newcastle upon Tyne, United Kingdom*
[c]*Center of Research Excellence in Renewable Energy and Power Systems, King Abdulaziz University, Jeddah 21589 Saudi Arabia*
[d]*Clean and Resilient Energy Systems (CARES) Lab, Texas A& M University,Galveston TX 77553, USA*
[e]*Doha, Qatar*

Abstract

The advanced mode of operation of electric vehicles (EVs) like vehicle-to-everything (V2X) mode is popularly used. In this mode of operation, the pool of battery energy storage created by large fleet of EVs is used to supply power to electric vehicles, smart homes, smart loads and main grid which enables other mode of operations of V2X system like vehicle-to-grid (V2G), vehicle-for-grid (V4G), vehicle-to-vehicle (V2V), vehicle-to-home (V2H) and vehicle-to-load (V2L). In addition to improvement in reliability of supply, the V2X mode of operation is used to provide various services like regulation of active power demand, reactive power compensation, shaving peaks and valleys in load demand, frequency and voltage regulation, compensation of harmonics in grid current, improvement in system stability to the utility. In this review paper, state of art of various modes and services provided by V2X functionality to the system are discussed. The comprehensive literature review related to control techniques used to achieve above mentioned objectives with their associated advantages and limitations is included in this paper. The associated challenges and future perspectives of the V2X system are also discussed in detail.

Keywords: Electric vehicle, V2X functionality, frequency deviation, hierarchical control.

Email address: `shiraz.ulislam@qu.edu.qa Corresponding author` (Shirazul Islam)

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1. Introduction

The burning of fossil fuels used for vehicular applications leads to emission of greenhouse gases which is responsible for global warming. From data analysis and scientific assessment carried out in recent years, it is concluded that the global warming is responsible for rapidly changing behavior of climate [1–3]. To overcome this problem, electric vehicles (EV)s are considered as the best option to replace internal combustion engines. The EVs reduces the carbon foot print, dependence of fossil fuels, noise levels and increases efficiency of conversion [4–6]. The EVs requires less number of components as compared to internal combustion engines [7]. Due to above mentioned advantage, a rapid expansion in the EV sector is being observed around the world. The sale of EVs around the globe has increased by 46% during the year 2018-2019 [8]. The net sale of 60% of EVs is being expected in UK by 2030 [9].

The EVs are charged with the help of chargers. Two types of techniques are widely used for charging EVs which are classified as wired and wireless charging. In wireless charging method, there is no direct connection between the EV and charging system. The charging energy is transferred through transmitter coil and received through receiver coil. The wireless charging techniques are convenient to use, provides galvanic isolation, enable charging of EVs whiling driving and reduce range anxiety [10–13]. Due to above mentioned advantages, the wireless charging method is considered as the potential solution for charging EVs in future [14]. However, wireless charging techniques offers low efficiency of conversion, low power density, higher cost, bigger size of setup and manufacturing complexity as compared to wired charging techniques. The efficiency of conversion is further affected by factors like geometry, distance, alignment and design of coil, compensation topology and frequency of energy conversion. The wireless charging techniques are under development and requires extensive research to replace existing wired chargers with wireless chargers [15, 16].

Due to above mentioned limitations associated with wireless chargers, the contact type chargers which include EVs directly connected to the charging system with the help of interconnecting cables or wires are used. As per the standard SAE J1772 [17], there are two types of battery chargers categorized as (a) off-board (stand-alone) (b) on-board (integrated) chargers. In case of off-board chargers, the charger is mounted on the charging station while in case of on-board chargers, the charger is mounted on the EV. In literature, various types of on-board [18–27] and off-board chargers [28–31] are discussed in details. Depending on output level of charging power supplied to the battery pack, the on-board chargers are classified as level-1, level-2 and level-3 chargers. The level-1 and level-2 chargers includes single phase supply, while level-3 includes three phase supply. Level-1 and level-2 are used for slow charging while level-3 may be used for slow and fast charging which depends on the size of battery pack and the time required to charge battery pack [14, 32, 33]. Single phase on-board chargers are discussed in [18–21] and three phase on-board chargers in [21–27]. On-board chargers provide the facility of charging EVs at any location [14, 34, 35]. However, due to continuous increment in battery capacity of EVs to alleviate range anxiety and to improve vehicle capability, on-board chargers suffers from the limitation of weight, size and cost constraints [14]. To overcome these limitations, off-board chargers are preferred. These are dc chargers and used for fast, super fast and ultra fast charging of EVs [30, 31, 35]. However, the operation of off-board chargers is location specific. Therefore, the emphasis is given on development of lightweight, high energy density, compact and efficient on-board chargers [14, 34, 36, 37].

To charge EVs, unidirectional and bidirectional on-board chargers are widely used [14, 32, 38, 39]. In general, grid-to-vehicle (G2V) functionality can be achieved through either unidirectional or bidirectional on-board chargers. However, utilization of energy storage pool created due to large penetration of EVs is becoming increasingly important [40]. However, the stored energy of EVs is distributed in nature. The vehicle-to-everything (V2X) functionality enables the easy utilization of this distributed energy pool to provide various services to the utility. To realize V2X mode of operation of EVs, bidirectional on-board converters are required. This mode of operation is utilized to provide various benefits to the system or utility. Due to various benefits imparted by V2X system, an extensive research effort is observed around the world. The broad objective of this research work is to develop efficient converter topologies with high power density and control techniques to make V2X system more smarter. The research related to V2X functionality is in early stage.

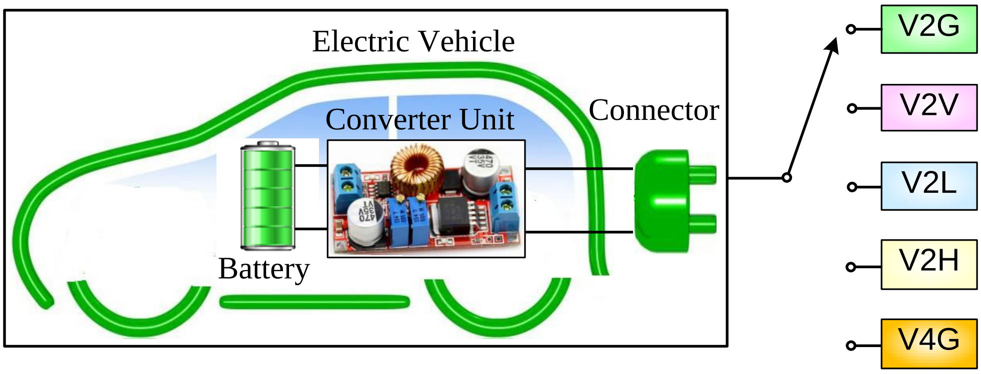

Figure 1: Schematic for various modes of V2X system

An extensive research is required in the domain of power density, power level, converter topologies and control techniques related to V2X system. Therefore, V2X systems are not much commercialized [37, 41–45]. In the last decade, reported work mainly deals with the development of fast chargers [46]. Therefore, the V2X system has large scope of research in future.

V2X system is used to supply power to electric vehicles, smart homes, smart loads and main grid which enable various mode of operations of V2X system. However, in this paper, the discussion is limited to vehicle-to-grid (V2G), vehicle-for-grid (V4G), vehicle-to-vehicle (V2V), vehicle-to-home (V2H) and vehicle-to-load (V2L) modes of operations as shown in Figure 1. In present scenario, the research work is dealing with mature development of these modes of operations [14, 37, 41–45]. Out of these modes of operations, V2G functionality of V2X system is the most important. In addition to improvement in reliability of supply, the V2G funtionality is used to provide various services like regulation of active power demand, reactive power compensation, shaving peaks and filling valleys in load demand, frequency and voltage regulation, compensation of harmonics in grid current, improvement in system reliability, stability and efficiency [14, 45, 47, 48].

One of the most important applications of V2G system is to provide the reactive power support to the main grid or utility. The various control techniques used to provide reactive power support by V2G system are discussed in [45, 49–56]. Reactive power is injected into the grid to regulate bus voltages and to minimize the difference in reactive power supplied by the source and demanded by load. The V2G functionality is preferred due to its fast dynamic response to voltage regulation. Inductive and capacitive reactive power can be compensated by controlling the magnitude of power factor angle. Each EV can is responsible for independent control of reactive power compensation. Further, the voltage profile can improved by charging the EVs during light load period and discharging during peak load period [48]. The permissible value of reactive power compensated by the V2G system depends on SOC of the battery [57]. Reactive power support provided V2G system does not affect the SOC of battery and battery life time [50]. Various controllers are suggested in literature to ensure reactive power compensation by V2G system. However, the performance of these controllers may affect due to external disturbances and variation in parameters of system.

In [58–60], the V2G system is used to shave peaks and filling of valleys in load demand. The philosophy of these techniques is to encourage V2G operation during peak load demand and V2G functionality during off-peak hours [61]. Smart charging of EVs plays an important role in leveling load curve [62]. The economic benefits provided by V2G system in leveling peaks in load demand are analyzed in [63]. However, during peak leveling, the active power support is provided by the V2G system. Therefore, battery life may reduce due to battery degradation.

In smart grid, the loads are connected to the ac system through power electronic converters which are called converter interfaced loads. Due to sensitive loads, the voltage across interfacing converter are regulated in a narrow range using voltage controller. Due to voltage controller action, these loads starts behaving as nonlinear loads and draw harmonics from main grid or utility. To improve power quality, the V2G functionality is used to compensate harmonics in grid current. To bring harmonic contents in the grid current within the defined limits prescribed in standard IEEE-519 [64], V2G system behaves as an active filter and provide harmonic compensation. Harmonic compensation techniques including V2G system are reported in [65–69]. However, a gap is observed between cost and efficacy of harmonic compensation techniques.

The output of renewable energy sources like photovoltaic (PV) sources, wind turbines is intermittent in nature and depends on the atmospheric conditions. The V2G functionality finds dominant application in minimizing the effect of uncertainty in generation of renewable energy sources. The V2G system acts a controllable load which can adjust its demanded/supplied power [70]. Due to this feature, the V2G system acts as energy buffer to compensate generation uncertainty of renewable energy sources and mitigate the impact of increased penetration of renewable energy sources. V2G functionality to minimize the impact of generation uncertainty of renewable energy sources is discussed in [70–75]. The cost benefits of V2G operation are discussed in literature. However, the battery degradation is not considered in this analysis. Further, there is need to study the impact of smart charging/ discharging to minimize the impact of battery degradation in a system including PV sources and wind turbines.

The imbalance between the active power power supplied by sources and active power demanded by loads may lead to frequency deviation between the nominal and actual value of frequency of main grid. The potential sources of this frequency deviation is stochastic nature of supply and load demand [76–78]. The frequency deviation in grid frequency may lead to black out, brownouts and voltage fluctuations. To minimize frequency deviation, a large amount of spinning reserve is required make operation uneconomical [79]. The dynamic response of conventional generator units used to regulate frequency of the grid is slow [77]. To resolve these issues, V2G condidate is considered as the best option to regulate frequency of the grid. V2G functionality enable the utilization of pool of energy storage created by fleet of EVs can be efficiently utilized to minimize frequency deviation by compensating active power imbalance in main grid in an economical fashion [80]. Also, the dynamic response of V2G system is fast as compared to conventional generator units [48]. Aggregator based hierarchical control schemes discussed in [77, 81–86] are widely used to regulate frequency of the main grid. The purpose of this scheme is to achieve various objectives like minimization of grid frequency deviations and proportional dispatch of regulation signals [84]. However, limited literature is reported which address the issues like maximal bidirectional active power support provided by V2G system and battery degradation effect induced due to frequent charging/ discharging cycles. An extensive research is required to fill this gap.

The V4G mode of operation is used for compensating the harmonics in line current and injecting reactive power for improvement in voltage profile of the system. This mode of operation is discussed in detail in [47, 87, 88]. In this mode of operation, the EV connected to grid is able to compensate harmonics and inject reactive power even when it is operating in G2V/ V2G mode of operation. V4G system acts as an active power filter in addition to G2V/ V2G functionality. This mode operation does not utilize the energy stored in the battery and prevent aging of battery. V4G mode of operation can be realized even when the EV charger is not operating in G2V/ V2G mode of operation. However, the remaining energy which is not utilized in G2V/ V2G modes of operation can only be utilized only for harmonic and reactive power compensation during V4G mode. In addition to reactive power support and harmonic compensation, V4G functionality can also be used for frequency regulation. However use of V4G system for providing other services mentioned above is not sufficiently discussed in literature.

In spite of development in charging infrastructure, there are chances that that EVs may not have accessibility to charging station. To resolve this issue, V2V mode of operation is preferred in which one EV provides the feasibility of providing charging point to another EV [89]. Using V2V mode, the EV owners can sell their surplus power to the other EVs. V2V functionality is also used for redistribution of battery charge among various EVs connected to smart homes and parking lots. This leads to reduction in power losses and overloading on main grid. After charge redistribution, overall energy required for charging is communicated to main grid. To coordinate overall operations, centralized controller called aggregator is used which communicate with EVs and grid and charge distribution [5]. The V2V functionality of EVs is reported in [5, 43, 89–92]. However, the existing literature lags the efficient converter topologies included in V2V system and more exploration of economic benefits imparted by V2V system [93].

The V2H mode of operation is similar to V2V mode of operation with a difference that V2H includes a single EVs connected to a smart home. It is able to provide the reactive power support and able to interact with V2V and V2G mode of operations. V2H mode of operation has very high efficiency and improve the effective utilization of renewable energy sources like PV sources installed in the premises of smart homes [5]. The V2H mode of operation of operation is discussed in [5, 47, 94–101]. However, the control schemes required to ensure smooth transition between V2H and G2V/ V2G modes are not sufficiently discussed in literature.

The V2L mode of operation is discussed in detail in [37, 102–104]. The V2L can be considered as special case of V2H and V2V modes of operation of EV chargers. The V2L mode of operation uses the framework which is used for V2H/ V2V modes. It is used to enhance the reliability of supply to critical loads like hospitals, military bases and data centres etc. in case of main grid failure [105]. However, use of V2L system for other services, its economic benefits and effect of battery degradation is not discussed in literature.

The Internet-of-Things (IoT) based EVs are considered as a good concept to implement the various above mentioned functionalities of V2X mode of operation and to impart various services to the utility. The ecosystem created by V2X system can be used as a asset to smart grid. It facilitates the selling and purchasing of energy by an individual owner of IoT based EV and enables the efficient utilization of renewable energy sources during critical time [106]. The interaction between different entities of IoT based V2X frame work to accomplish above mentioned objectives, communication of suitable bandwidth is required [107]. However, the data communication among different entities increases the vulnerability of the V2X system to cyber-physical attacks and instability caused due to time delay [108, 109]. To overcome these limitations, the primary objective is to design the V2X system which is resilient to cyber-physical attacks and time delays. However, by using techniques cyber-resilient techniques, authentication protocols and delay tolerant techniques, the resiliency of V2X system to cyber-physical attacks and time delays can be increased [106, 108].

The various mode of operation of V2X system reported in literature are listed. The services provided by the EVs in this mode to the system are clearly highlighted. This paper deals with extensive review of state of art approaches used in V2X mode and their advantages and limitations are clearly highlighted. This work may prove to be beneficial to readers dealing with applications of EVs in V2X mode. Following are the major contributions of this paper.

1. Detailed discussion related to various modes of operation used with system having

V2X functionality is included.

2. State-of-the-art review of various control techniques used in V2X mode.
3. Various services imparted by the V2X mode to the system are clearly highlighted.
4. Detailed discussion related to benefits and challenges of EVs in V2X mode is included and potential areas of future research are identified.
5. Future perspectives of EVs operating in V2X mode are highlighted.

This paper is organized as follows; Section 2 deals with operation of EVs operating in G2V mode used for charging. In Section 3, the various control techniques used to ensure V2X mode of operation of EVs are discussed. In Section 4, the future perspectives of V2X mode of operation are discussed. Section 5 discusses the challenges and blockades associated with V2X mode of operation and potential areas for future research are discussed. Section 6 concludes the paper.

2. Control of EVs in G2V Mode

To utilize the energy stored in the battery of EVs effectively, it is necessary to charge the battery upto rated capacity. EVs are operated in G2V mode to charge the battery. As discussed in previous section, the on-board chargers are preferred choice to charge the EVs. Various types of power level for charging EVs are defined for these on-board chargers [17]. These chargers can be of single stage or two stage type. Single stage type chargers are used in low power applications. However, the magnitude of ripples in output current of single stage converter is high. To ensure low magnitude ripples in output current and galvanic isolation required for double fault protection, two stage on-board chargers are preferred [32, 110–112].

2.1. Two stage on-board chargers

The schematic shown in Figure 2 shows the two-stage on-board charger generally used to operate EVs in G2V mode. The first stage converts ac to dc nearly at unity power factor (UPF). The front end ac-dc converter converter ac supply into regulated dc-link voltage supply. Various circuit topologies and control techniques are used for UPF operation of

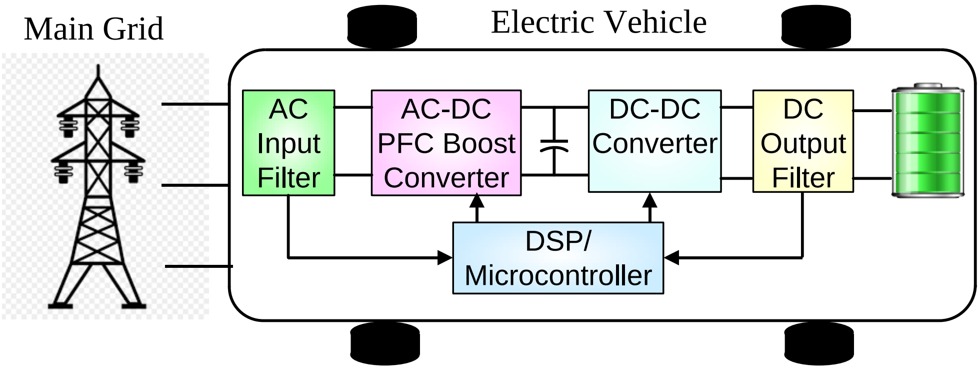

Figure 2: Schematic of two-stage on-board charger

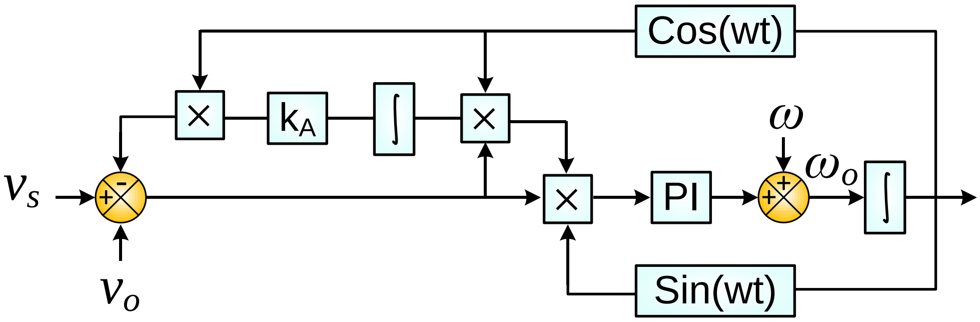

Figure 3: Block diagram of enhanced PLL

ac-dc converter. However, conventional bidirectional boost topology is the most popular topology used for ac to dc conversion.

The second stage of on-board charger is dc-dc converter which is used to control the battery charging voltage and current. It converts the dc-link voltage into regulated dc output voltage supply which is used to charge batteries of EVs. The controller of the dc-dc converter maintain voltage regulation across the output terminals of dc-dc converter within the specified limit and enhance the transient performance of converter. Conventional bidirectional dc-dc buck converter is widely used to charge the EVs [32, 110–112].

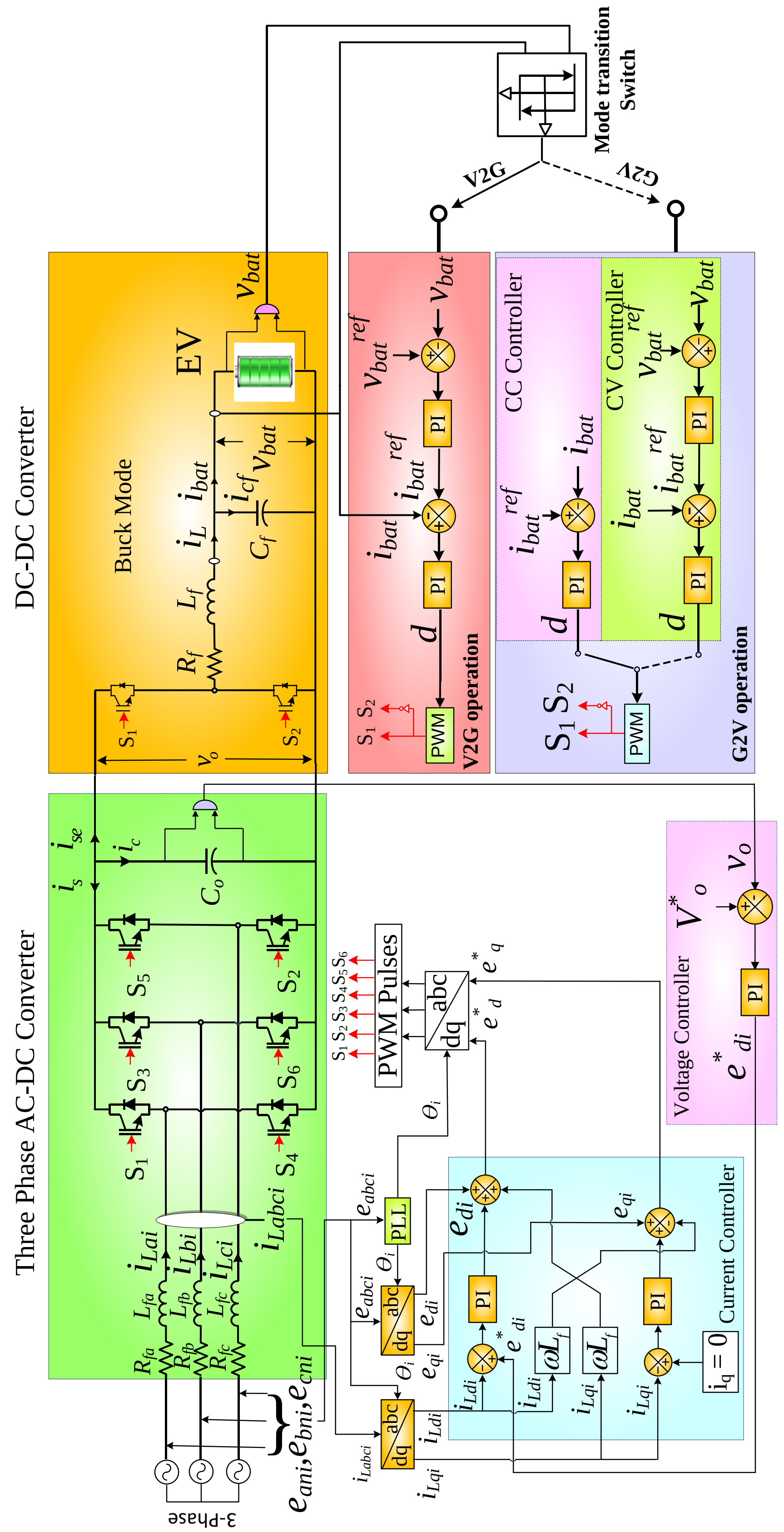

Figure 4: Control scheme of two stage on-board charger in G2V and V2G mode

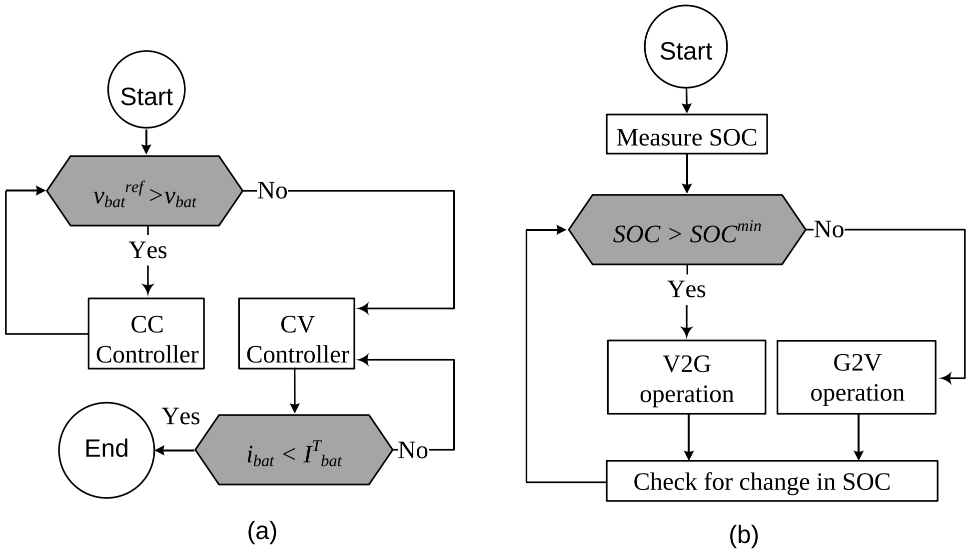

Figure 5: Flow chart (a) Used to control operation of G2V system with CC and CV charging. (b) Used to control switching between G2V and V2G mode.

2.2. G2V mode of operation of EVs

To ensure power flow from grid to EVs in G2V mode, it is important that ac-dc converter must be synchronized with the fundamental value of grid voltage. For this purpose, a emhancement type of Phase Locked Loop (PLL) is used as shown in Figure 3 [113]. It guarantees the phase synchronization of the signals and evaluates the fundamental component of grid voltage.

The control scheme of three unity power factor rectifier is shown in Figure 4. A three phase filter inductor, L_f is placed between the rectifier and source bus of main grid to prevent the flow of large inrush current during start up process of the converter. To reduce the harmonic contents in the currents drawn from the mains supply, the rectifier is operated at unity power factor. By maintaining the reference value, $i_q = 0$, unity power factor operation of active rectifier is realized. The inductor current is regulated using current controllers. The d-axis and q-axis currents, i_{Ldi} and i_{Lqi} are controlled using linear PI regulators. The dc-link voltage, v_{dc} is regulated in a narrow range using dc-link voltage regulator. The linear PI controller is used to minimize the error between actual value of dc-link voltage, v_{dc} and its reference value, V_{dc}^{*}. The voltage controller regulates v_{dc} by minimizing the mismatch between the active powers demanded by the EVs and supplied by main grid [114–117].

The dc-dc converter of second stage operates in buck mode (charging mode) to charge battery of EV in G2V mode of operation. Depending upon the state of charge (SOC) or terminal voltage of battery, dc-dc converter operates in either Constant Current (CC) or Constant Voltage (CV) charging mode. The control scheme of dc-dc buck converter including CC and CV mode is shown in Figure 4. Depending upon the battery voltage, the battery is charged first in CC mode. When battery voltage reaches near to its nominal value of battery voltage, the charging mode is switched to CV charging mode. The Figure 4 shows the control scheme of dc-dc buck converter including CC and CV controller. In CC mode, linear PI controllers are used to minimize difference between the reference value, i_{bat}^{ref} and actual value of battery current, i_{bat} so as to supply constant charging current to battery. During CV mode, linear PI controllers are used to minimize the difference between the refernce value, v_{bat}^{ref} and actual value of battery voltage, v_{bat} so as to maintain constant voltage across the battery during CV mode [54, 118, 119]. The flowchart used to control switching operation between CC and CV mode of battery charging of EVs is shown in Figure 5(a) [120]. The battery voltage is sampled and compared with its nominal value. If $v_{bat}^{ref} > v_{bat}$, the battery is charged in CC mode otherwise in CV mode. When the value of charging current, $i_{bat} < I_{bat}^{T}$, the charging of battery pack stops.

3. Control of EVs in V2X Mode

In this section, the V2X mode of operation of EVs is discussed in detail. This mode includes various modes of operation of like V2G, V4G, V2V, V2H and V2L to utilize the energy stored in the battery pack of EVs. In this section, a literature survey related to these modes of operations of EVs and the respective services imparted to the system by these modes will be discussed.

3.1. V2G mode of operation of EVs

In this mode, the energy stored in the battery of EVs is returned back to the grid with the help of back-end dc-dc converter and front end ac-dc converter. For V2G operation, the dc-link voltage, v_o has to be greater than peak value of grid voltage. Usualy battery voltage is less than dc-link voltage. Therefore, a dc-dc step-up converter is required [49]. In V2G functionality, the dc-dc operates in boost mode (discharging mode) and its control scheme is shown in Figure 4. The dc converter includes outer dc-link voltage control loop and inner battery current control loop. In voltage control loop, linear PI controller is used maintain the dc-link voltage, v_o equal to its reference value, v_o^{ref} so as to maintain constant value of dc-link voltage during discharging. To discharge the battery at constant current, the inductor current, i_L is regulated using PI controller in current control loop. This leads to an improvement in life of battery [54].

In V2G operation, the ac-dc converter operates as three phase full bridge inverter having controlled output current. In this mode, the active power is supplied back by the battery of EV to the grid. As the active power injected back to grid, the reference value of inductor current, i_L^{ref} is in phase opposition to the grid voltage. Due to limited capacity of battery of EVs, limiters are used to set an upper limit on active power injected by EVs [47]. During operation in V2G mode, the full bridge ac-dc converter must be synchronized to the grid which is realized using three phase PLL shown in Figure 3.

The control system of the dc-dc converter consists of two separate controllers, one for boost-mode operation and the other for buck-mode operation as shown in Figure 4. The selection of operation mode depends on hysteresis control of the DC-link voltage. The transition between G2V and V2G modes of operation is controlled using the algorithm shown in Figure 5(b) [121].

3.2. Services provided by EVs in V2G mode

The benefits imparted by EVs in V2G mode of operation are listed in literature. V2G mode of operation is used as a backup for renewable energy based sources like solar photovoltaic (PV) sources, wind turbines etc. It minimizes the effect of generation uncertainty in output of renewable energy sources due to variation in atmospheric conditions. It enables the regulation of active power, provide reactive power support and helps in shaving off peaks and filling valleys in load demand. It is able to compensate harmonics in grid currents within the defined limits. In addition to above mentioned services, V2G mode of operation is able to provide ancillary services like regulation of voltage and frequency, enhancement of spinning reserve, improvement in grid reliability, efficiency and stability. V2G systems reduces the operating cost of utility. Various advantages offered by V2G are elaborated in Figure 6. The state of art literature survey related to services provided by the V2G systems and their relative advantages and limitations are discussed in subsequent subsections.

(a) Reactive Power support

The reactive power support provided by the V2G system in case of single phase on-board charger used for EVs is discussed in [49]. The control scheme of ac-dc and dc-dc converter is shown in Figure 6(a) and 6(b). The active and reactive power to be supplied by the traction batteries in V2G mode is controlled by the components, i_α and i_β of reference value of grid current, i_g^*. The voltage controller is used to minimize the error between actual value of dc-link voltage, v_o and its reference value, V_o^* and its output is used as reference value of active power, P_{ac}^* to be supplied by V2G system. If S is the apparent power rating of battery charger, the reference value of reactive power, Q_{ac}^* that can be supplied by the EV is $Q_{ac}^* = \sqrt{S^2 - P_{ac}^*}$. The direct, pll_α and quadrature component, pll_β of grid voltage, v_s are calculated using single phase PLL. Using, pll_α, pll_β, P_{ac}^* and Q_{ac}^*, the control block diagram to calculate i_α, i_β and i_s^* is shown in Figure 6(a). The Figure 6(b) shows the control scheme of dc-dc boost converter. The reference value of battery current, i_{bat}^* is

$$i_{bat}^* = \frac{P_{ac}^*}{v_{bat}} \tag{1}$$

In [49], V2G system inject the reactive power into the grid and improve the voltage profile of main grid. However, the analysis for dynamic performance of controllers of ac-dc and dc-dc converters is not included.

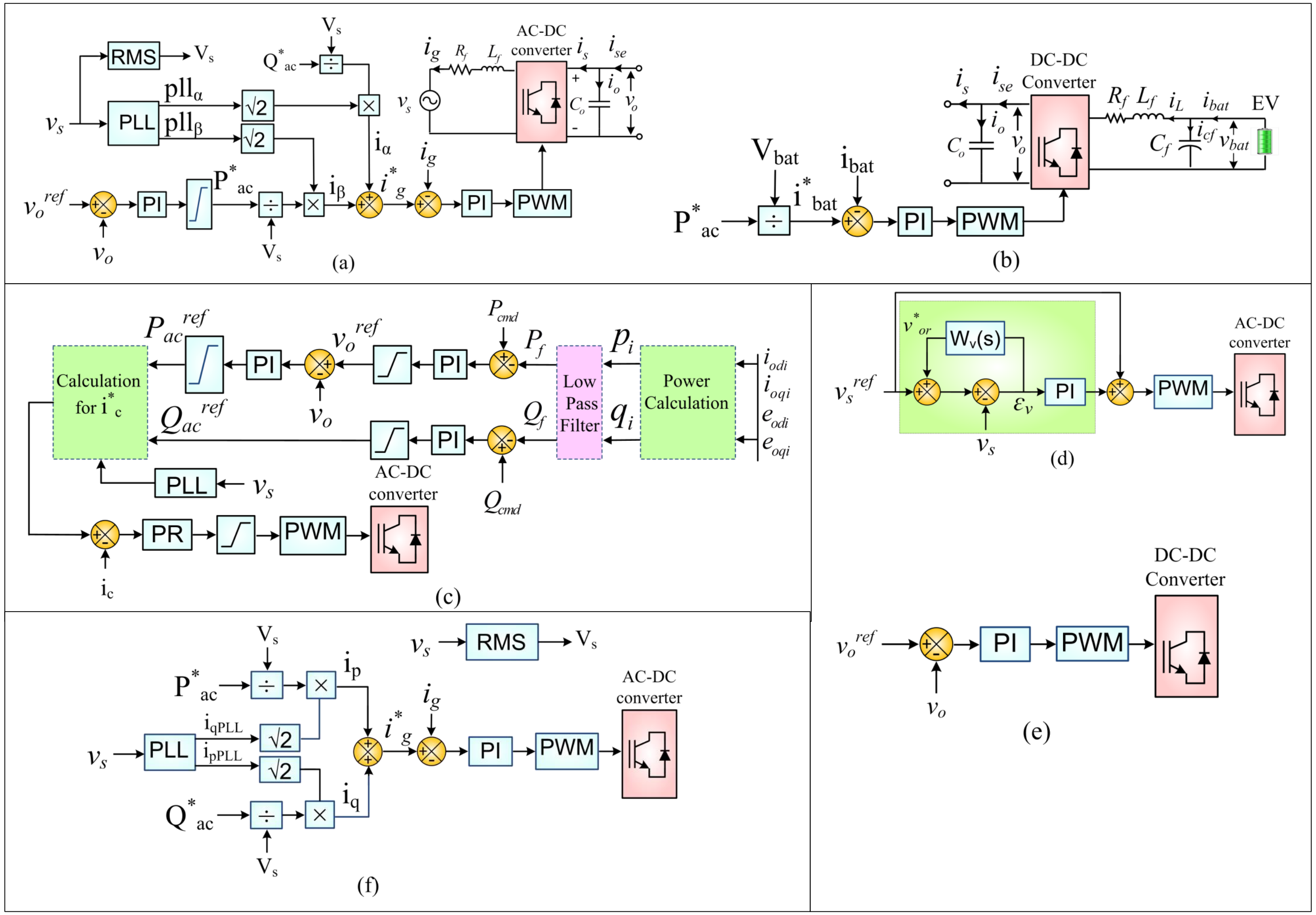

Figure 6: Control scheme of (a) ac-dc and (b) dc-dc converter used in [49]. (c) Control scheme of ac-dc converter suggested in [50]. Control scheme of (d) ac-dc and (e) dc-dc converter used in [45]. (f) Control scheme of ac-dc converter suggested in [54]

To improve the dynamic response of the V2G system, a unified controller is suggested in [50]. The V2G system includes a single-phase on-board plug-in electric vehicle (PEV) charger. The control schemes of the ac-dc and dc-dc converters used in this charger are shown in Figure 6(c). In unified controller, reference values of active, P_{cmd} and reactive power, Q_{cmd} are supplied by the utility grid. The active power loop $(P - loop)$ which includes PI controller minimizes the error between the actual value of active power P_f and its reference value, P_{cmd}. The output $(P - loop)$ generates the reference value of dc-link voltage, v_o^{ref} which supplied to inner dc voltage loop $(v - loop)$. By minimizing the mismatch between v_{dc} and v_o^{ref}, the reference value of active power, P_{ac}^* to be supplied by the EVs in V2G system can be controlled. Reactive power demanded by grid is regulated using outer reactive power loop $(Q - loop)$. The output of the $Q - loop$ generates the reference value of reactive power, Q_{ac}^* that the charger should supply in V2G mode. The reference value of line current, i_g is calculated using P_{ac}^* and Q_{ac}^*. The inner most loop $(i - loop)$ which includes a proportional plus resonant controller is used to generate PWM pulses for ac-dc converter. The control scheme of dc-dc converter is same as that shown in Figure 4 working in V2G mode.

The suggested controller is able to provide reactive power support along with excellent dynamic response and steady state performance. The V2G shows excellent performance during variation in power demand imposed by main grid.

In [49, 50], conventional PI and PR controllers are used for zero error tracking dc reference inputs and ac reference inputs, respectively. However, the performance of these controllers may be affected by the disturbances in signals and uncertainties in plant parameters. To enhance the robustness of the system against the disturbances and parameters variations, the PI controller is augmented with a voltage robust tracking error cancellation controller (VRECC) in [45]. The control scheme of ac-dc converter in V2G mode including robustness controller, W_v and linear PI controller is shown in Figure 6(d). The control scheme of dc-dc converter is shown in Figure 6(e). The suggested controller minimizes the impact of external disturbances in control signals and enhances the robustness of PI controllers against the variation in parameters of V2G system. However, the gain of PI controller is constant and may not be able accommodate the unknown disturbances during operation. To resolve this issue, Sliding Mode Controller (SMC) is used in [51] to regulate the dc-link voltage. However, the performance of the suggested SMC controller may deteriorate due to phenomenon of chattering which cannot be fully eliminated. Further the practical applicability of SMC controller in digital platforms like Digital Signal Processors is difficult. To overcome these limitations, hysteresis current controller is suggested in [53]. The suggested controller ensures fast dynamic response and simple to implement. However, the operation of three independent hysteresis current controllers used to control three phase AC-DC converter may lead to increased switching losses at high switching frequency and lower value of modulation index. The controllers suggested in [53] leads to excellent dynamic and steady state performance of the system and enhances robustness of V2G system against the external disturbances and uncertainties in system parameters. However, the performance of the suggested controller may become poor in harmonics in grid currents. In order to improve the performance of V2G system in case the grid voltage is distorted due to harmonics or unbalanced loading, an adaptive frequency-fixed second-order generalized integrator with dc offset rejection capability (AFF-SOGI-DRC) is suggested in [52]. The positive sequence voltages of grid evaluated using AFF-SOGI-DRC is used to calculated fundamental value of grid voltage. The grid voltage helps in evaluation of signal corresponding to reference value of active and reactive power to be supplied by the V2G system.

In [45, 49–53], single battery unit is considered in EVs. However, in actual practice an EVs includes various battery modules which are stacked together. A small difference in manufacturing tolerances, battery capacity, discharge profile, terminal voltages etc. may exist among different modules. Difference in charge/discharge profile may lead to charge imbalance among different modules after number of successive cycles. The charge imbalance decreases battery efficiency and degrades battery life. To overcomes this problem, a Charge Equalization Circuit (CEC) is considered in [54]. Depending upon the required active and reactive power demand imposed by the main grid in V2G mode, CE determines the minimum number of battery modules to obtain the minimum voltage. The discharge starts with minimum number of battery modules having highest SOC. If the SOC of a battery module reaches the SOC of bypassed battery modules, the bypassed battery is switched into the stack of battery modules used in V2G mode. The control scheme of ac-dc converter is shown in Figure 6(f). The control scheme of dc-dc converter is same as that shown in Figure 4 in V2G mode. However, the performance of V2G may become poor due to absence of battery management system.

To optimize the output of distributed energy sources and to ensure smooth control of active and reactive powers in G2V or V2G mode, Energy Management System (EMS) based energy box controller is suggested in [55]. The suggested controller ensures uniform charging/discharging profiles of battery modules, efficiently controls charge equalizer circuit and enhances reliability of system. However, the cost and complexity of system may increase due to inclusion of digital platforms required to implement energy box controller. In [56], droop control technique is used to control charge and discharge action of batteries in G2V and V2G mode of operations.In V2G mode of operation, droop controller ensures proportional sharing of load power among EVs. However, the performance of V2G system becomes poor in case of cables having unequal values of cable resistances used to connect EVs to the dc microgrid.

(b) Shaving of Peaks and filling of valleys in load demand

The V2G system used for peak load shaving is discussed in [58] while the system used for valley filling in load demand is discussed in [59]. In [58], control technique schedules the optimal dispatch of V2G system in with an objective to maximize system benefits and minimize customer costs. In [59], regional time shift control technique is used to charge the EVs during night time. The technique suggested in [59] may not be effective for a system having no flexibility for shift in charging time. The active power support is provided by the V2G system for leveling peak discussed in [58] may lead to degradation in battery life. In [60], a control technique is suggested for the system to shave peaks and fill valleys occurring in load curves due to variation in load demands. To take into account the profitability of V2G mode, the cost function associated with battery degradation is considered. Depending upon the of number of EVs available in V2G mode, their battery capacity and time of their availability, an objective function is formed to compensate peaks and valleys in load demand. However, the suggested technique is effective for limited number of EVs in the area.

(c) Compensation of harmonics in grid current

The V2G system enables active filtering and compensation of harmonics present in the grid currents. To improve the power factor and compensate harmonics in grid currents, a bidirectional harmonic modulation techniques are suggested in [65, 66]. The control schemes of dc-dc converter used for harmonic compensation during G2V/ V2G mode of operations are shown in Figs. 7(a) and 7(b). The suggested techniques ensures harmonics in line current within the specified limit and improve power factor of the system. However, the effectiveness of the proposed controller is observed for discontinuous conduction mode of operation of interleaved dc-dc converter. The performance of suggested techniques become poor for low value of input supply voltage and cost of interleaved converter is high. The harmonic compensation techniques based on injection of reactive power in V2G mode are discussed in [47, 49–55]. In [67], a three phase four system including virtual impedance technique is used to compensate harmonics in V2G mode of operation. However, the availability of neutral wire of connection may not feasible in certain systems. In [68], an external shunt converter is used for active filtering of harmonic currents of main grid. The shunt converter effectively and efficiently reduces Total Harmonic Distorsion (THD) in grid current. However, the suggested technique may is not economical due to extra cost of shunt converter.

There are chances that the charging of EVs may lead to harmonic distortion in line currents. The THD profile of various industrial EV chargers during G2V mode are discussed in [69]. The relationship between the SOC of batteries of EVs and among the THD caused due to chargers when operating in CC, CV and Multistage CC mode is studied in [69]. However, the practical transformer includes number of EVs. Therefore, it is necessary to show harmonic aggregation when several EVs are connected to the single distribution transformer.

(e) Minimization of generation uncertainty in renewable energy sources

In [73], the deterministic optimization technique is used to control the charging and discharging action of EVs to minimize the uncertainty in generation of PV sources and

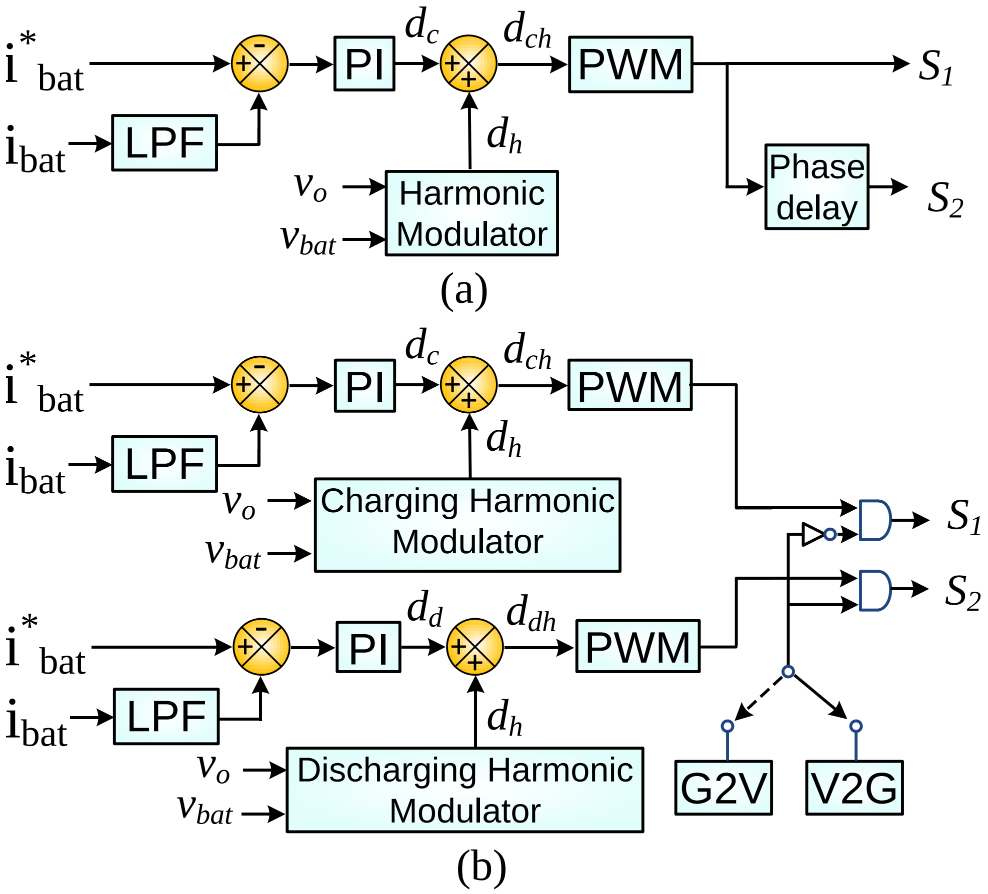

Figure 7: Control scheme of dc-dc converter used for harmonic compensation in (a) [65] and (b) [66] during G2V/ V2G mode.

wind turbine. However, the suggested technique requires prior information of daily forecast load curve and daily target load curve. In [74], dynamic demand control technique is used to control the charge/discharge action of EVs and to minimize the effect of generation uncertainty of wind turbine. However, the efficacy of suggested controller is explored for uncertainty in active power output. In [72], a charging controller is suggested to control charging and discharging action of battery of EV with an objective to minimize the impact of voltage rise and reverse power flow which takes place due to surplus power generated by PV source during midday. However, the implementation of V2G mode in case of PV requires financial assessment for a given system due to energy losses occurred in charging and discharging actions of batteries of EVs. Further, the uncertainties present in EV charging may affect the system reliability. To minimize the impact of uncertainties present in EV charging, aggregators are used in [75] to enable the participation of EVs into the load management. These aggregator ensures minimization of error in evaluation of power contributed by EV. The error arises due to uncertainties in EV charging such as punctuality, rounding of time, forecast error of daily energy consumption and charging failure. However, the V2G operation leads to battery degradation. The cost of battery degradation is not considered in [75]. To take into account the cost of battery degradation, the stochastic programming is used in [70, 71]. The charging schedule of EVs is decided by the stochastic output of renewable energy sources. In [70], the generation uncertainties present in output of wind turbine and PV sources are taken into account by the framework of stochastic programming. However, by using smart charging, the effect of battery degradation can be minimized which is not considered in [70]. To minimize the cost of battery degradation, smart charging is considered in [71]. In [71], probabilistic load flow analysis is carried out to handle the uncertainties caused due to charge/discharge action of PEVs and wind turbines. It is validated in [71] that by including a wind turbine, V2G functionality make the operation of system economical. However, the effect of PV source is not considered in this study.

(e) Minimization of frequency deviation

To minimize the frequency deviation caused mismatch between the supply and load demand using V2G system, various techniques are reported in literature. However, to enhance the flexibility of operation and to regulate the frequency efficiently, a high level of control called hierarchical control scheme is widely used. It is discussed in detail in [77, 81–86]. The block diagram of hierarchical control scheme is shown in Figure 11. It includes three levels of controllers name as primary, secondary and tertiary controllers which are discussed below.

(i) Primary control

The power imbalance between the supply and demand leads to frequency deviation appearing at the terminals of home outlet. To minimize the frequency deviation, primary control technique is used. In this technique, the V2G sources are operated as droop controlled sources. Droop controller adjusts the active power output of V2G source in such a way that the mismatch between the power supplied by source and demanded by load is minimized. The active power supplied by V2G source depends on the frequency deviation and SOC of batteries. This method is simple, easy to implement and ensures fast minimization of frequency deviation. It requires no communication among V2G sources as signals corresponding to frequency deviation are available at the output of V2G sources. In primary control, the SOC of battery is maintained using balance control of SOC. In balance control, the smart charging or one way charging (V1G) of EVs is used to satisfy charging preset of EV user [122]. The minimization of frequency deviation using V2G functionality is discussed in detail in [123, 124].

(ii) Secondary control

The performance of primary controller may become poor in case of system including large number of EVs. This may lead to lack of coordination among different EVs. In this scenario, it may be difficult to achieve a global optimum of frequency deviation and to predict stability of main grid. To overcome this problem, secondary controller for frequency regulation is used. In some literature, it is named as aggregator which is used to minimize the frequency deviation created due to primary controller. Secondary controller requires communication among V2G sources. Depending upon the control structure, secondary controllers are classified as (i) centralized and (ii) distributed secondary controllers. In case of centralized structure, a single aggregator is responsible charging and discharging action of the EVs to minimize frequency deviation [83]. However, the suggested scheme suffers from the limitation of low scalability. Distributed control schemes, the aggregators are supplied signals corresponding to the active power to be supplied by each V2G source. The active power contributed by each EV is decided by the participation factor [82, 84–86]. However, the performance of distributed secondary controllers may be affected due to time delay in communicated values.

(iii) Tertiary control

Tertiary control deals with economical dispatch of energy from V2G sources. To supply power from one microgrid or main grid to another microgrid or main grid, the secondary controller is contracted by the DSO/TSO. These operators performs the economic scheduling on timely basis and sets the optimum generation target to each aggregator used with V2G sources. The energy exchanged among various areas is decided by frequency deviation and market price set for trade of electricity. Tertiary controller enables an aggregator to act as a player in the electricity market which maximizes its profit. Tertiary control helps in huge revenue generation by utilizing V2G mode of operation [77, 81]. However, it may be difficult to set the tariffs for trade of energy exchange in diversified nature of power generation in power system.

3.3. V4G mode of operation of EVs

The V4G mode of operation is used for compensating the harmonics in line current and injecting reactive power for improvement in voltage profile of the system. This mode of operation is discussed in detail in [47, 87, 88]. The schematic of V4G system is shown in Figure 9. In [47], V4G mode of operation can be realized even when the EV charger is operating in G2V/ V2G mode of operation. However, the remaining energy which is not utilized in G2V/ V2G modes of operation can only be utilized only for harmonic and reactive power compensation. The control schemes used for reactive power support and harmonic compensation are not discussed. In [88], the V4G system provides the reactive power support (inductive and capacitive) and compensate the harmonics in grid for a smart car park with chargers having dc-bus and ac-bus topologies. These topologies are used for bidirectional power flow between the grid and EVs. The dynamic responses of the two systems are identical. The V4G system shows less values of THD, reduced magnitude of ripples in active and reactive powers and reduced value of execution time in case of dc-bus topology as compared to ac-bus topology. The coordination of V4G system with V2G and G2V system is also included. However, the effect of nonlinear and unbalanced load is not considered. The V4G system discussed in [87] deals with reactive power and harmonic compensation in case the line currents of main grid are unbalanced. The controller suggested in [87] for the front end ac-dc converter topology is able to maintain harmonics in grid currents within the specified limit. The V4G system specifically used for providing active, reactive power support and harmonic compensation is reported in literature. However, the cost of V4G system may increase due to requirement of three-phase four wire system. Further, use of V4G system for other services is not sufficiently discussed in literature.

3.4. V2V mode of operation of EVs

V2V mode of operation is discussed in detail in [5]. The V2V system includes the redistribution of energy among various EVs connected to smart homes and parking lots with an objective to reduce power losses which occurs due to transfer of energy in charging EVs by the main grid. To control V2V system, centralized controller called aggregator is used which communicate with EVs and grid operator and controls overall V2V mode of operation. The framework used for V2H mode of operation is fully utilized by V2V mode of operation. The reactive power becomes attractive in this mode of operation. The schematic of V2V system is shown in Figure 10.

V2V mode of operation is discussed in [43, 89–92]. A portable charger which is able to provide V2V charging of EVs is suggested in [90]. However, the charging device requires

Table 1: Comparison table of unidirectional EV charger topologies

Services Provided	**Modes of Operation**	**Contribution**	**Limitation**	**Reference**
Reactive Power Support	G2V, V2G	• Reconfigurable battery charger is suggested • Improves voltage profile of main grid	• Slower dynamic response of system	[49]
	G2V, V2G	• Unified controller is suggested for PEV • Fast dynamic response of system	• Poor performance in case of external disturbance and variation in parameters of V2X system	[50]
	G2V, V2G, V2H	• Robust controller included along with PI controller • Effect of external disturbance and variation in parameters is minimized	• Poor performance in case of unknown disturbances	[45]
	G2V, V2G, V2H	• Sliding mode controller used to regulate dc-link voltage • Effect of unknown disturbances is minimized	• Poor performance due to chattering • Difficult to implement	[51]

Continued on next page

Table 1 – continued from previous page

Services Provided	Modes of Operation	Contribution	Limitation	Reference
	G2V, V2G	• Hysteresis current controller used to control AC-DC converter • Good dynamic response and easy to implement	• Poor performance due to high switching frequency and harmonics in grid current	[53]
	G2V, V2G	• Adaptive frequency-fixed second-order generalized integrator used • Good performance in case of harmonics in grid currents	• Poor performance in case of multiple battery modules	[52]
	G2V, V2G	• Charge equalization circuit suggested to minimize charge imbalance • Good performance for a system having multiple battery modules	• Poor performance in absence of battery management system.	[54]
	G2V, V2G	• Energy box controller is suggested to ensure battery energy management • Suggested controller ensures uniform charging and discharging profile	• Cost and complexity of system increases	[55]

Continued on next page

Table 1 – continued from previous page

Services Provided	**Modes of Operation**	**Contribution**	**Limitation**	**Reference**
	G2V, V2G	• Droop controller used to control charging and discharge action of batteries of EVs connected in dc microgrid	• Poor performance in case cables of unequal cable resistances are used to connected EVs to dc microgrid	[56]
Shaving off peaks and filling of valleys	G2V, V2G	• Optimal scheduling algorithm is considered for V2G system • Shaving off peaks in load demand using V2G system considered	• Battery degradation not considered	[58]
	G2V, V2G	• Load balancing by filling of valleys in load demand • Charging schedule is suggested to charge the EVs	• Effective only for V2G system having flexibility for shift in load demand	[59]
	G2V, V2G	• Load balancing by shaving off peaks and filling of valleys in load demand • Battery degradation is considered	• Performance of suggested technique deteriorate with increase in number of EVs in the area	[60]

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Table 1 – continued from previous page

Services Provided	**Modes of Operation**	**Contribution**	**Limitation**	**Reference**
Compensation of harmonics in grid current	G2V, V2G	• Bidirectional harmonic modulation technique used • Harmonics in grid currents are limited within specified limit	• Poor performance in case of low value of input voltage	[65, 66]
	G2V, V2G, V2L	• Virtual impedance method used • Various harmonics in grid currents are compensated	• High Cost of system due to requirement of neutral wire	[67]
	G2V, V2G	• A shunt active filter used for harmonic compensation	• High Cost of system due to requirement of extra converter	[68]
Minimization of uncertainty in generation of renewable energy sources	G2V, V2G	• Deterministic optimization technique is used	• Requires prior information of daily forecast load curve and daily target load curve	[73]
	G2V, V2G	• Dynamic demand control technique used to minimize impact of generation uncertainty of wind turbine	• Uncertainty in reactive power output not considered	[74]

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Table 1 – continued from previous page

Services Provided	**Modes of Operation**	**Contribution**	**Limitation**	**Reference**
	V2G	• Charging controller is suggested • Minimize the impact of voltage rise and reverse power flow caused due to PV source	• Implementation of suggested controller requires financial assessment	[72]
	V2G	• Aggregators used to minimize impact of uncertainties in EV charging	• Battery degradation not considered	[75]
	G2V, V2G	• Stochastic programming is considered to evaluate the cost of battery degradation	• Smart charging of battery not considered	[70]
	G2V, V2G	• Stochastic programming is considered to minimize impact of battery degradation	• Effect of PV source not considered	[71]
Minimization of frequency deviation	G2V, V2G	• Primary controller is used to minimize frequency deviation	• Performance becomes poor in case of system including large number of EVs	[122–124]
	V2G	• Centralized secondary controller is used to minimize frequency deviation caused due to primary controller	• Low scalability to the addition of new EVs.	[83]

Continued on next page

Table 1 – continued from previous page

Services Provided	Modes of Operation	Contribution	Limitation	Reference
	V2G	• Distributed secondary controller is used to minimize frequency deviation	• Performance becomes poor due to time delay in communicated values	[82, 84–86]
	V2G	• Tertiary controller used to ensure economical dispatch of energy from V2G sources.	• To set the tariffs for trade of energy exchange becomes difficult	[77, 81]

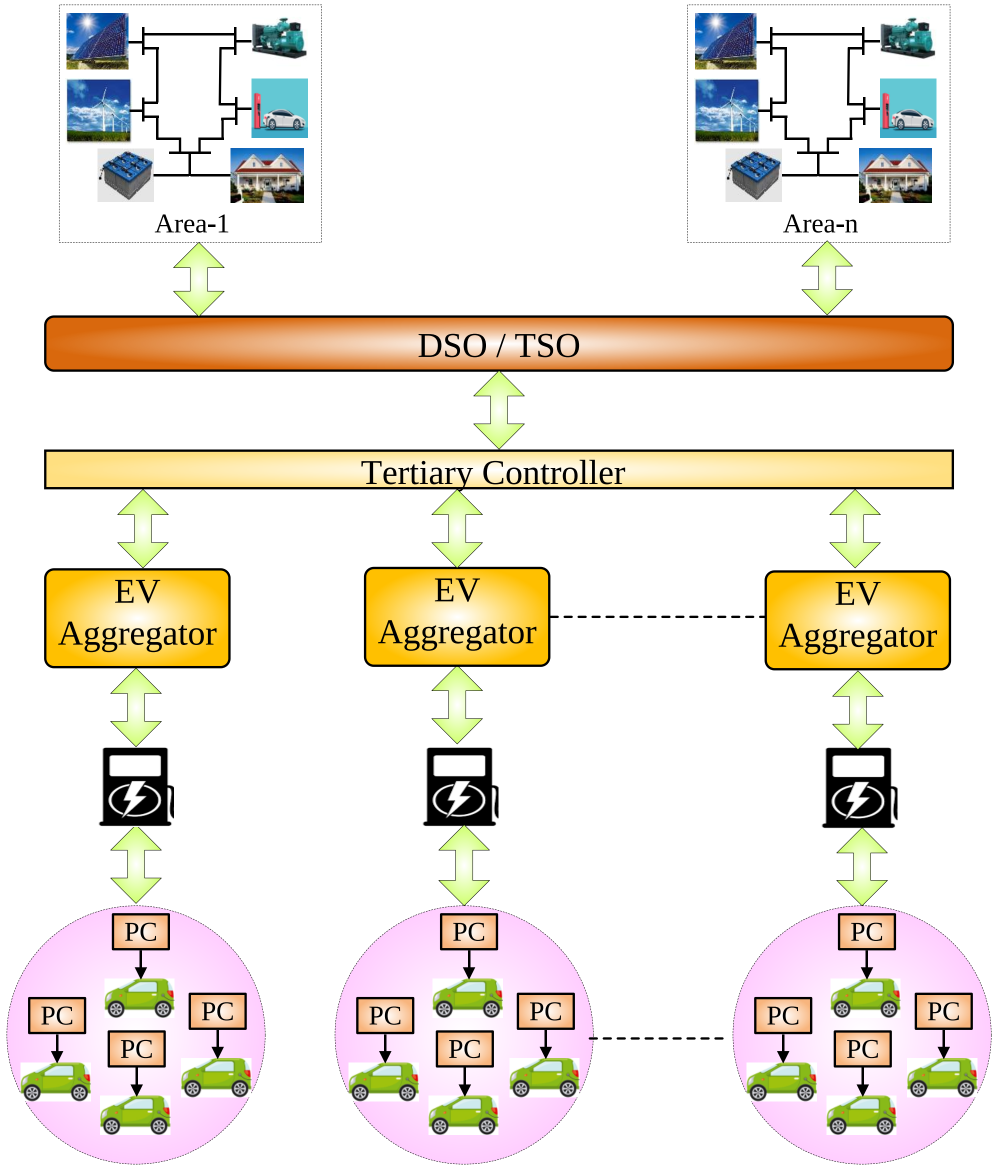

Figure 8: Hierarchical control scheme of V2G sources.

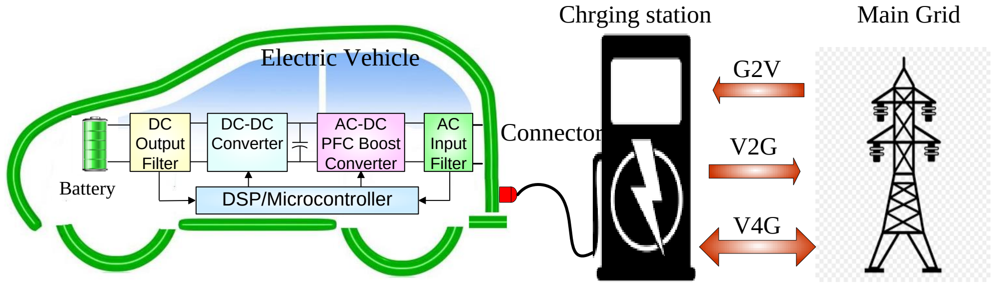

Figure 9: Schematic of V4G mode of operation of system.

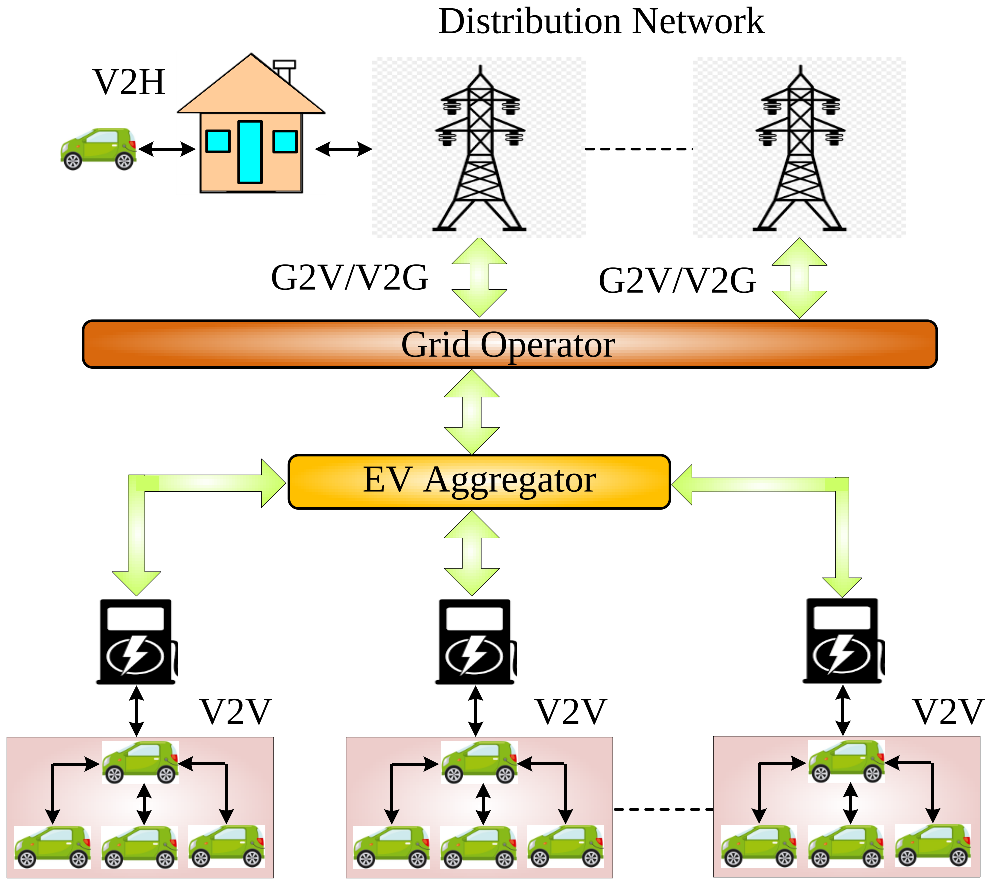

Figure 10: Schematic of V2V mode of operation of system.

an extra off-board charging device and charging power is limited (up to 325 W) during V2V mode of operation. To overcome this problem, an advanced EVs charger is suggested in [89]. The suggested charger is able to provide charging power which depends on maximum power ratio of EV and does not require additional charger. The suggested charger is able to provide reactive power support and harmonic compensation. However, the performance of the system may become poor in case of V2V system including multiple EVs. In [91], V2V system including tactical military vehicles which are stopped and not in operation are connected in radial configuration to form a dc microgrid. The droop control technique is used for proportional sharing of load demand (vehicle hotel loads and off-board loads) among EVs. However, the performance of droop controllers becomes poor in case of dc microgrid in which tactical military vehicles are connected to dc-bus through cables of unequal values of cable impedances. The efficiency of V2V operation in usually low. The efficiency evaluation of V2V system including on board converter is discussed in [92]. A universal power connector which support V2V mode of operation and having high efficiency is suggested in [43]. The suggested controller provides the facility of galvanic isolation. By using V2V mode of operation, the EV owner can trade their stored energy independently among themselves. However, a limited literature is available on economic benefits imparted by V2V system [93].

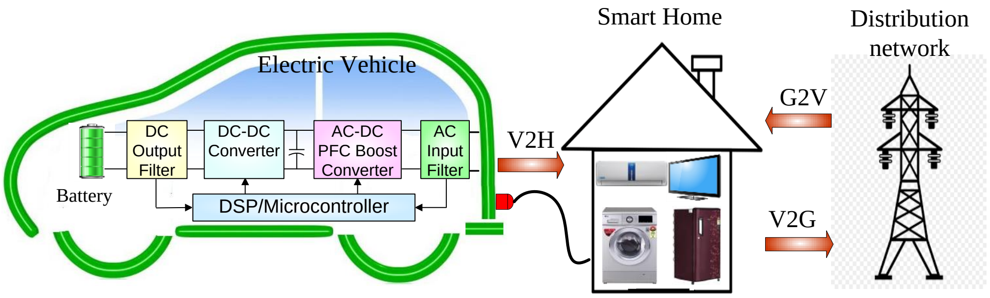

Figure 11: Schematic of V2H mode of operation of system.

Table 2: Literature Survey of published articles related to V2X mode of operation

Services Provided	**Modes of Operation**	**Contribution**	**Limitation**	**Reference**
Reactive power support and harmonic compensation	G2V,V2G, V4G	• V4G system provides reactive power support • V4G system compensates harmonics in grid current	• The control scheme used for reactive power support is not discussed • Control scheme used for harmonic compensation is not discussed	[47]
	G2V, V2G, V4G	• V4G system provides reactive power support in case of unbalancing in supply voltage • V4G system compensates harmonics in case of unbalancing in supply voltage	• Control scheme require three phase four wire system which increases cost	[87]
	G2V, V2G, V4G	• Performance of dc and ac system compared with reference to V4G functionality • dc system gives good performance as compared to ac system	• Effect of nonlinear loads is not considered	[88]
Active power support	V2V	• EV is used to charge another EVs	• Requires extra off-board charging device	[90]

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Table 2 – continued from previous page

Services Provided	**Modes of Operation**	**Contribution**	**Limitation**	**Reference**
Active, reactive power support and harmonic compensation	G2V, V2G, V2V	• EV is used to charge another EVs • No extra charger required	• Performance becomes poor in case of multiple EVs	[89]
Active power support	V2G, V2V	• Standing EVs are used to form DC microgrid to supply power to EVs	• Poor performance due to interconnecting cables of unequal resistances	[91]
Active power support	G2V, V2G, V2H	• EV used to supply power to smart home	• Performance of V2H system validated only for linear loads	[94, 95]
	G2V, V2G, V2H	• EV used to supply power to smart homes having smart loads	• Performance of V2H system may deteriorate during mode transition	[47]
	G2V, V2G, V2H	• Soft transition is ensured during mode transition	• Performance of V2H system may deteriorate during step variation in load demand	[97]
Shaving off peaks	V2G, V2H	• V2H system minimizes the mismatch between the supply and load demand	• Effect of battery degradation not considered	[100]
	V2H	• Smart charging used to minimize the effect of battery degradation	• Cost of battery degradation is not considered	[99]

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Table 2 – continued from previous page

Services Provided	**Modes of Operation**	**Contribution**	**Limitation**	**Reference**
	V2G, V2H	• Cost benefits of V2H system are studied	• Study limited to a battery included in EV of a single make	[101]
Active power support	V2L	• Dual active bridge based converter typologies are suggested for V2L mode of operation	• Economic benefits of V2L operation are not discussed	[102–104]

3.5. V2H mode of operation of EVs

The V2H mode of operation is similar to V2V mode of operation with a difference that V2H includes a single EVs connected to a smart home as shown in Fig 11. It is able to provide the reactive power support and able to interact with V2V and V2G mode of operations. V2H mode of operation has very high efficiency and improve the effective utilization of renewable energy sources like PV sources installed in the premises of smart homes [5]. The V2H mode of operation of operation is discussed in [94, 95]. However, the efficacy of V2H mode of operation is validated for linear loads. The smart home includes various appliances which acts as constant power loads and are dominantly nonlinear in nature. To fill this gap, the nonlinear loads are considered in [47] for V2H mode of operation of EV charger. During grid connected mode, V2H system operates as offline UPS and able to interact with G2V/ V2G modes of operation. In islanded mode, V2H system operates as voltage source converter [47]. During transition among these modes of operations, the switching of control structure may take place which may deteriorate the transient performance of the system [94, 96]. To ensure seamless or soft transition between G2V/ V2G and V2H mode of operations, a modified controller for ac-dc converter is suggested in [97] as shown in Figure 12. The suggested controller of ac-dc converter rather than dc-dc converter only takes control action to ensure this soft transition as shown in Figure 13(a) and 13(b). The step variation in load demand in case of V2H system may affect the transient performance of system. Effect of connection and disconnection of smart home appliances on the performance of V2H system is discussed in [98].

The V2H can also be used for shaving off peaks present in load demand which is discussed in [99, 100]. Similar to V2G mode, V2H mode of operation leads to battery degradation which is not discussed in [100]. To fill this gap, effect of V2H operation on battery degradation is considered in [99].Smart charging scheme including energy management system is used to minimize the effect of battery degradation. However, the cost of battery degradation is not considered in [99]. The cost of battery degradation is considered in in [101]. The cost benefits imparted by V2H operation to the system are discussed in detail.However, the above mentioned study is carried out for a battery included in an EV of a particular company. Further, the control schemes required to ensure smooth transition between V2H and G2V/ V2G modes of operations are not sufficiently discussed in literature.

3.6. V2L mode of operation of EVs

The V2L mode of operation is discussed in detail in [37, 102–104]. The V2L can be considered as special case of V2H and V2V modes of operation of EV chargers. The V2L mode of operation uses the framework which is used for V2H/ V2V modes. It is used to enhance the reliability of supply to critical load in case of main grid failure. V2L system is popularly used to supply power to critical loads such as hospitals, military bases and data centres [105]. In addition to these applications, the ability of V2L functionality to operate in islanded mode, makes it a reliable and efficient solution for remote electrification. The Figure 14 shows the schematic of V2L system used to cater power to sensitive loads. The V2L system in power system is popularly used to provide active and reactive power support. However, use of V2L system for other services, its economic benefits and its effect of battery degradation is not discussed in literature.

3.7. Interaction among various modes of V2X system

The various modes of operation of V2X system are discussed in various research articles. The services provided these operating modes to the utility or system are also discussed in literature. To summarize these articles, the modes of operations, services provided, contribution and limitations of existing approaches are listed in table I. The table mainly takes into account the literature related to G2V and V2G modes of operations. The table II deals with the literature survey of V2X system operating in V4G, V2V, V2H and V2L modes of operations.

After going through above mentioned literature survey, the interaction among different operating modes of operations like V2H, V2G, V4G, V2V and V2L can be predicted. Based on the discussion available in previous sections, a transition diagram is drawn which shows possible interaction among various modes of V2X system. The Figure 15 shows the interactions among V2H, V2G, V4G, V2V and V2L modes of operation of system. The V2G mode is very important and is able to interact with G2V, V4G, V2H and V2V modes. However,

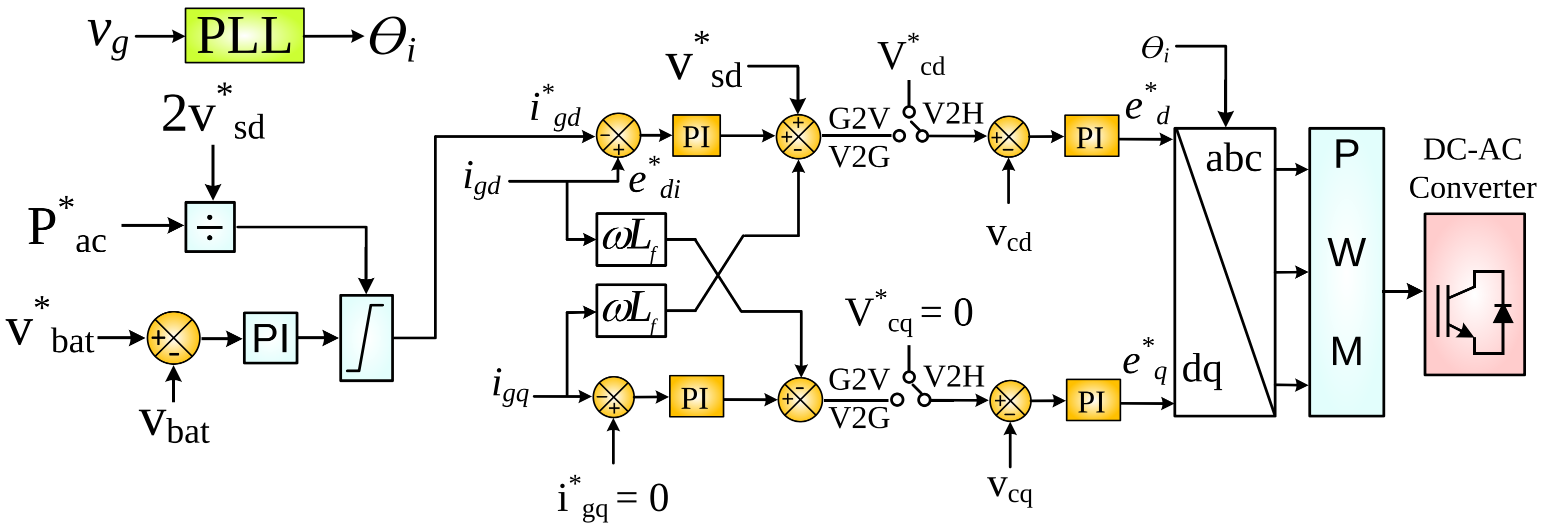

Figure 12: Control scheme of ac-dc converter suggested in [97].

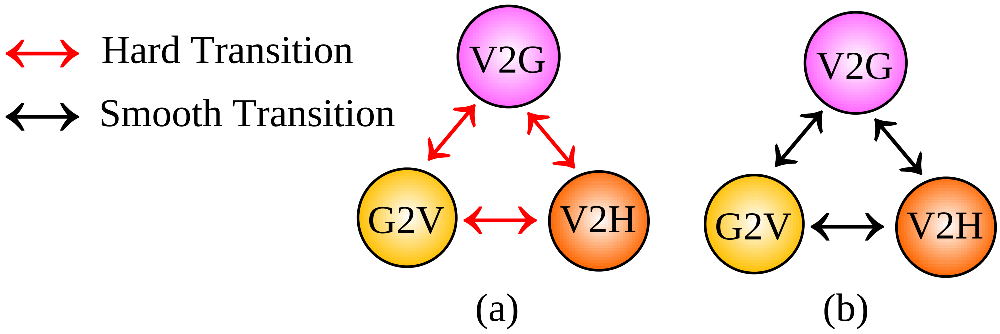

Figure 13: Schematic of (a) Hard transition (b) Smooth transition among G2V/ V2G and V2H modes of operation.

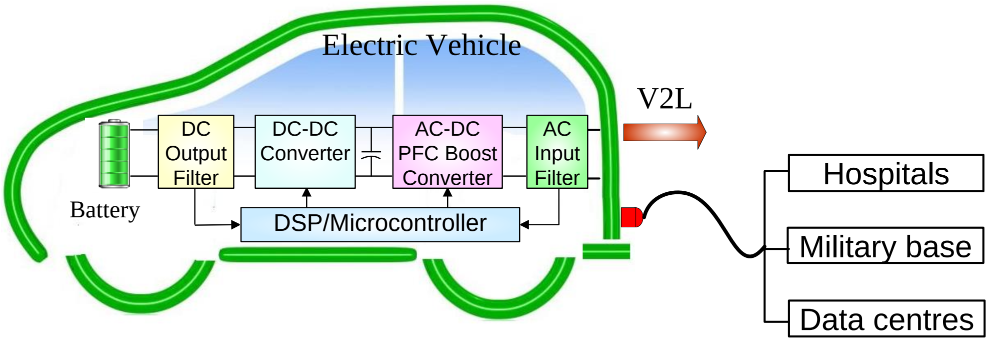

Figure 14: Schematic of V2L mode of operation of system.

V2L mode is operational only when grid is main grid is absent and interacts with V2H and V2V modes.

4. Challenges to V2X Mode

The operation of system in V2X offers various advantages and services to the system which are discussed in previous section. However, the V2X mode of operation suffers from various limitations, challenges and blockades to the system which are related to the reliability, stability, efficiency and privacy of system. These issues are discussed in this section.

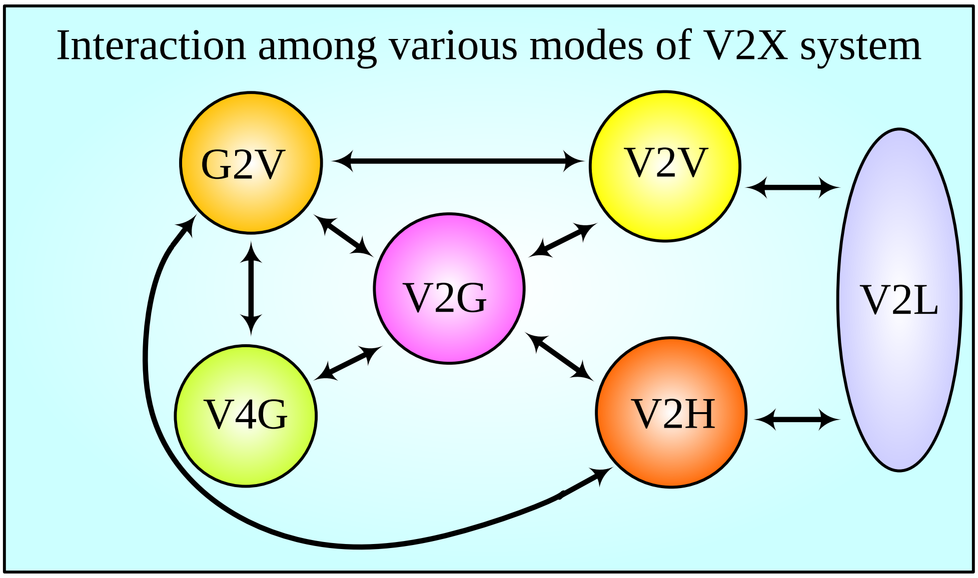

Figure 15: Interaction among various operating modes of EVs.

4.0.1. Battery degradation

Dominant application of pool of energy storage of EVs is for providing ancillary service like frequency regulation at the demand side by utilizing V2G mode of operation which is discussed in detail in previous section. The charge and discharge action of batteries of EVs due to bidirectional active power injection so as to minimize frequency deviation may result in battery degradation. Since the cost of battery more than half of EV price, therefore, it is necessary to carry out economic asessment of battery dergation, to predict battery life to device methods which slow down battery degradation process. The techniques for economic assessment of battery degradation in V2G operation is discussed in detail in [125, 126]. In these studies, the cost of depreciation of battery depends on the energy supplied and the level of SOC. Similarly the life of battery is predicted by estimating the internal resistance of battery and SOC retaining capability of battery after a given number of charge/discharge cycles.

Various techniques used to slow down the battery degradation are discussed in literature. In [85], mixed integer linear programming (MILP) based optimization technique is used to schedule the optimal charging and discharging policy of EVs. In [85], multiobjective primal problem (MOPP) which includes multiple constraints based optimization techniques is discussed. Interior point technique is used to solve this optimization problem. A multilevel online V2G (MLOV) algorithm is used in [86] for hierarchical scheduling. The suggested optimization approach requires no forecasting information on regulation signals. In [83], a centralized secondary controller is suggested to minimize the effect of charging/discharging action on battery degradation.

4.0.2. Cyber attacks

The battery management system (BMS) of on-board chargers is responsible for charging/discharge action of EVs which in turn control the V2X mode of operation of EVs. To accomplish V2X mode of operation, it acquires the information corresponding to terminal cell voltage, charging current, state of charge (SOC), state of health (SOH), cell temperature etc. of the battery. After processing this information, the BMS comes up with desired charging and discharging profile of EV and communicates with controllers of on-board chargers [109]. Similarly, aggregators are used to regulate the frequency of main by providing active power injection during V2G mode of operation. In case of V2V mode of operation, aggregators are used to achieve uniform distrubution of SOC level among various EVs connected in a group. To accomplish above mentioned task, aggregator require communication with main grid and on-board chargers of vehicles. However, these communication channels are vulnerable to cyber attacks. If the attack gets a physical access to the communication channel, the specific data between various subsystem can altered and corrupted which may hamper normal functioning of the controller and may cause serious damage to the integrity of EV charger and main grid. Due to rapid advancement in Internat of Things (IoT), advance communication protocols, cloud computing enabled applications used in EVs, the power electronic based system becoming more vulnerable to cyber physical threats. To enhance the resiliency of EVs system against the cyber attacks, it is necessary to identify the type of cyber attack and to use approaches both on software and hardware levels which make EV charging infrastructure a cyber resilient one [109, 127, 128].

The cyber threats related to V2X mode of operation of on-board chargers is classified into four major catergories which are denial of service (DOS) attacks, replay attacks, false data injection attacks, interception attack and stealthy data injection attacks as shown in Figure 16. In DOS attack, the attacker inject a high frequency data into communication channel to cause data congestion which hampers the normal functioning of controllers of EV chargers. In replay attack, the attacker supplies the stored data corresponding to the healthy condition of EVs chargers to the controllers during the condition of fault or external disturbance. The system fails to take control action so as to safe guard on-board chargers. In false data injection technique, the malicious data is injected into the communication channel which corrupt the useful information corresponding to various control signals. The controller is no longer able to track the right value of control signal. In case of interception attack, the attacker completely takes complete control of the system by accessing password information of the operator. The information of the operator no longer remains confidential. The wiretapping, keystroke logging, fibber taping, etc. are the common examples of interception threats. In case of stealthy data injection technique, the attacker has complete information of the system and can inject the data without being detected [109, 128].

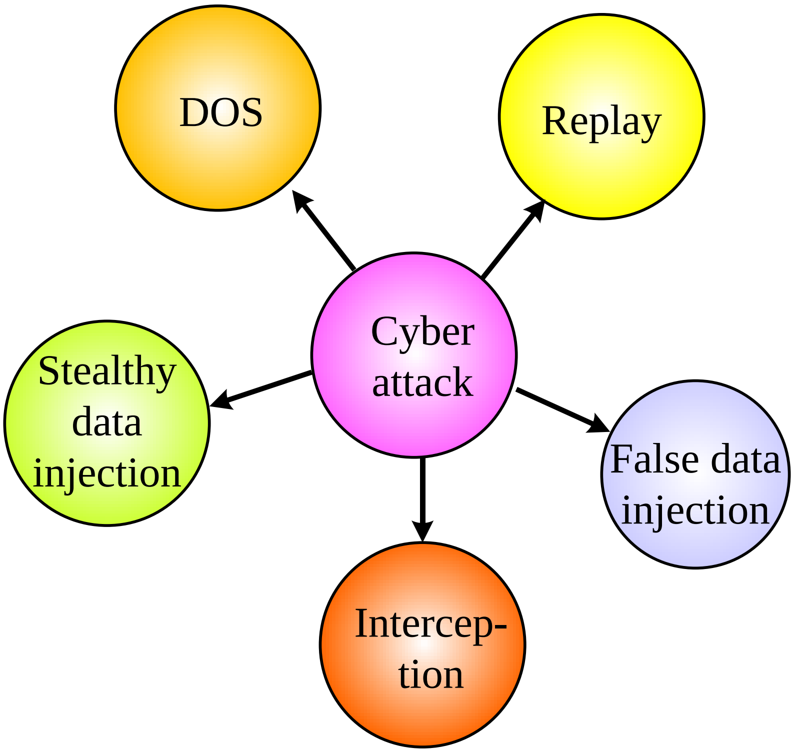

Figure 16: Various cyber physical attacks on V2X system

4.0.3. Time Delay

The time delay encountered by communicates values in case of aggregated EVs reduces the stability margin. The increased penetration of aggregated EVs may further increase the magnitude of time delay encountered due to cyber physical system. In case, the time delay is more than the delay margin of the aggregated V2X system, it may lead to unstable operation of V2X system. To evaluate the delay margin of the V2X system, it is necessary to model the time delay of the cyber physical system and carry out the stability analysis. Various methods are reported in the literature to evaluate delay margin. By using delay tolerant techniques, the adverse effect of time delay of cyber physical system on the stability of V2X system can be minimized [129].

4.0.4. Stability issues

Due to large penetration of EVs as well as renewable energy sources on the existing system or utility, there are chances that the existing system might not able to handle large penetration of EVs and renewable energy sources. This may lead to drop in system voltage and frequency deviation between the actual and nominal value of frequency. However, minute deviation of frequency is more severe than voltage difference among the source buses. The V2X system is able to handle these issues. However, sufficiency of V2X system to tackle these issues may not be guaranteed. This may lead to unstable operation of V2X system [130, 131]. Further, the effect of external disturbances and variation in parameters of V2X system may lead to unstable operation of V2X system [45, 132–134].

5. Future Perspectives of V2X System

There are various blackouts reported in literature in the last few years which results in heavy loss of revenue and takes a lot of time and manpower to bring the system to its normal operating condition [135]. Main source of blackout are frequency deviation which occurs due to active power mismatch between the supply and demand. To resolve this issue, a large spinning reserve is required. However, to maintain such a large spinning reserve is uneconomical affair. External battery storage devices are used to enhance the spinning reserve. However, this requires extra cost in purchasing large capacity battery storage devices. To resolve this issue effectively, distributed pool of energy storage created by V2X system is considered as the potential solution in future to improve spinning reserve [83, 85, 86]. To reduce the carbon foot print, most of the power is being generated using renewable energy sources. The growth of power generation from solar PV and WTs are 32% and 10%, respectively, whereas that from renewable energy sources is 8.3%. Further, it is expected that the global renewable energy production could be doubled by 2030, in which major contribution will be from solar and wind energy [136]. Recent technological advancements in the field of low capacity sources, power electronic converters and energy storage devices have motivated to generate power from distributed energy sources. The power generation from the distributed energy resources is referred to as distributed generation and includes both renewable and nonrenewable based energy sources like micro turbines, internal combustion engines, fuel cells, solar PV, wind power and energy storage units [137, 138]. However, the distributed generation based sources suffers from the limitation of generation uncertainty due to variation in atmospheric conditions. The increased penetration of distributed generation based sources into the existing utility grid may lead to voltage rise, variation in operating frequency and protection issues [139]. The connection of renewable energy sources based distributed generation sources with main grid may lead to unstable operation of system [140].

Again, the battery storage devices discussed above are considered as best solution to minimize the effect of generation uncertainty. But, it requires heavy initial investment to purchase battery storage devices. However, storage created by V2X system can minimize the effect of uncertainty in generation of distributed energy resources. The effective utilization of V2X system will encourage more penetration of renewable energy resources. To enhance the robustness of the system against external disturbances and parameters variation of V2X system, robust controllers are considered as best candidates to handle stability issues in V2X system [45, 132–134].

To minimize the frequency deviation, V2X utilize the aggregated EVs. These aggregators require communication among various charging stations connected in an area. The time delay caused due to communication may lead to unstable operation of V2X system. However, using large bandwidth communication channels like LAN, WAN networks, the effect of these dealys may be reduced. Hence aggregated V2X system can be efficiently utilized in future.

Cyber physical attacks is most dominant threat to V2X system. To safeguard the V2X system from these threats, it is necessary to keep the privacy of he network intact. Also, there is a need to adopt the techniques which enhances the resiliency of V2X system against cyber physical attacks. By using these strategies, the V2X system can be the potential solution to resolve above mentioned issues.

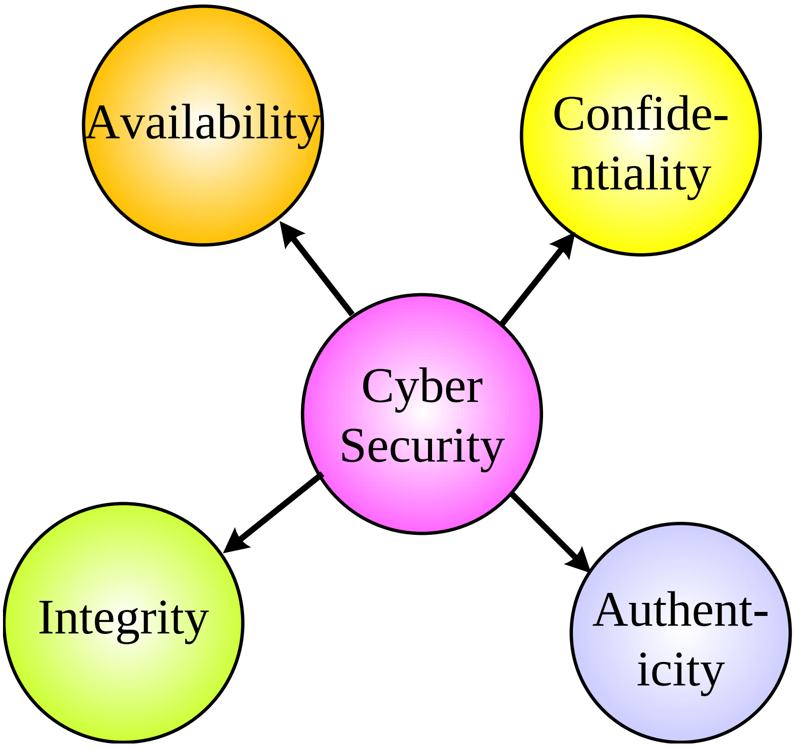

Figure 17: Objectives of cyber physical security of V2X system.

In recent years, several security standards are drafted by the automotive industry like Society of Automotive Engineers (SAE), International Organization for Standardization (ISO) etc. which are discussed in [141–143]. These standards are framed with an objective to satisfy the requirement of confidentiality, authenticity, integrity and availability to the V2X system as shown in Figure 17. Confidentiality ensures that the data exchanged between the V2X operator and EV user should be confidential. For confidential data transfer, the authenticity of the V2X operator and the EV user should be customized. The data integrity ensures that data exchanged between the V2X operator and EV user will not be modified by the attacker. Availability of communication of suitable bandwidth is important to as ensure seamless data transfer between the V2X operator and EV user.

Due to large penetration of fleet of EVs, the issues like accidents, pileup crashes, vehicle platooning or traffic jams will increase. However, modification in the existing infrastructure to accommodate this large pool of EVs requires huge investment. However, these issues can be resolved by using various applications based on Internet of Things (IoT) and Intelligent Transportation Systems (ITS) [91]. These applications are developed in recent years. To enhance the driving safety and comfort of users, communication among EVs is required [144]. IoT and ITS based applications require V2V and V2I communication models [145]. However, big players in EV market like Audi (Germany), General Motors (U.S.), BMW (Germany), Volvo Cars (Sweden), Daimler AG (Germany), Toyota Motor Corporation (Japan), Qualcomm Technologies, Inc. (U.S.), Volkswagen (Germany) and AutoTalks Ltd. (Israel) are developing and actively participating in funding applications that support V2V communication [144]. Due to this advancement in EVs market, the revenue generated by global V2V communication market is expected to be 24 billion (USD) by 2023 [91].

6. Conclusion

This paper deals with state-of-art literature survey of articles related to V2X functionality. The various modes of operations of V2X system including bidirectional on-board chargers are clearly elaborated and discussed in detail. The services provided by V2X system like regulation of active power demand, reactive power compensation, shaving peaks and valleys in load demand, frequency and voltage regulation, compensation of harmonics in grid current, improvement in system stability to the grid or system are studied in detail. The control techniques used to impart these services to the system in various modes are discussed and their benefits and limitations are highlighted. The potential benefits imparted by V2X functionality imparted to the system are also discussed.

The existing threats and challenges like cyber-physical attacks, time delay in communication, battery degradation and stability issues which may affect the normal operation of V2X system are discussed. The techniques which enhances the resiliency of V2X system against these threats are included. The dominant areas which have sufficient scope of future research are also explored. From this study, it can be concluded that to encourage penetration of renewable energy sources in the exiting power system, to enhance stability margin of system, to increase existing spinning reserve of the system required to minimize frequency deviation in emergency conditions and to realize intelligent smart transportation system, V2X system is the most effective and economical solution.

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