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Impacts of grid integration of solar PV and electric vehicle on grid stability, power quality and energy economics: a review

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Abstract: Grid integration of solar photovoltaic (PV) systems and electric vehicles (EVs) has been increasing in recent years, mainly with two motivations: reducing energy cost, and reducing emission. Several research studies focuses on the individual impact of grid integration of PVs and EVs. However, it is worth noting that with the increasing penetration of PVs and EVs, the power grid will be experiencing the combined impact of PV–EV integration. To present a thorough understanding, this study first presents a detailed study on the impact of grid integration of PVs and EVs individually, followed by combined impact of PV and EV, on the aspects of grid stability, power quality and energy economics. It has been identified from the literature review that individually PVs and EVs can negatively affect the grid stability and power quality due to the intermittent nature of PV energy and uncertainty of EV load. However, several research works have reported that coordinated operation of the PVs and EVs can negate the issues arising due to individual integration of PVs and EVs. Furthermore, large-scale penetration of PVs and EVs are expected in future energy market, and coordinated operation of them can potentially help lowering energy costs and carbon footprint.

1 Introduction

The quest for cleaner energy and reduction in the fossil-fuel reserve has triggered a transition of the traditional power grid towards a renewable energy (RE)-based power system. All over the world, there has been a revolution in adopting RE sources instead of conventional fossil-fuel-based energy sources, as fossil fuels are touted as one of the main contributors of greenhouse gas (GHG) emission and global warming [1]. Almost all the countries in the world are emphasising on the reduction of GHG emission. Following the GHG emission reduction target, most of the countries are defining RE target to offset the equivalent generation from conventional fossil-fuel based power plants [2–5]. In order to meet the RE target, different types of RE sources are now integrating into the power network. Among the available RE sources, the most popular RE sources are wind and solar PV. Due to the easy accessibility, simpler implementation and noiseless operation, solar PV is the most explored RE source, which is mostly integrated into the distribution network of the power grid [6–9]. Due to the intermittent nature of solar PV systems, the power injection of this energy source into the grid will also be intermittent. It will be dependent on the availability of solar irradiance. The generation from solar PV cannot be regulated based on the load demand. In contrast, conventional energy sources can adjust their generation as per the load demand. This new behaviour on the energy generation side is new to the existing power network, and therefore with large-scale integration of solar PV sources can pose significant challenges on the power system operation.

Besides fossil-fuel-based power generators, the transportation sector is another major source of GHG emission in developed and developing countries. The transport sector is the second-largest producer of greenhouse gas in Victoria state in Australia, which is currently accounting for 22% of the total emission of the state [10]. In order to minimise the GHG emission from the transportation sector, the latest development of vehicles is moving towards electric vehicles (EVs) with electric motor and battery storage [11, 12]. The development of battery technology and the reduction in battery price makes the EVs more affordable than before. Also, the running capacity with a single charge is now comparable with the conventional internal combustion engine (ICE) vehicles; for example Tesla 3 can run 345 km with a single charge [13]. The demand for EV is increasing as it is becoming more affordable in terms of total life cycle cost. High penetration of RE sources in the power grid and adaptation of EVs are essential to ensure sustainable energy infrastructure and decarbonised environment for the future [14]. EVs are growing very fast in the car market, and it is predicted to take a significant market share shortly. Fig. 1 shows the expected growth in EV sales in the coming years. On the other hand, solar energy is anticipated to become the world's largest source of electricity by 2050 [15] with rapid improvements in relevant technologies and reduction in the cost of solar PV systems. Expected global growth in the uptake of solar is shown in Fig. 2.

The power grid is expected to experience a higher degree of intermittency and uncertainty both in generation and demand sides due to increasing uptake of solar PVs and EVs, which may result in overloading of the distribution network, and affect the grid stability, as well as the power quality [18–23]. However, the coordinated operation of solar PV and EV charging can be complementary to each other. It can overcome the grid stability and power quality issues that may arise due to individual integration of these devices. Moreover, with high penetration, PVs and EVs are likely to emerge as new players in the energy market operation and can potentially play a significant role in redefining the market [24–29]. Several research works have investigated and reported the individual impact of EV charging and PV system on the grid operation, for instance [30–37]. However, a very few studies have been reported in the literature that investigates the combined impacts of PVs and EVs on grid stability, power quality and energy economics. To thoroughly investigate both the individual and combined impacts of EVs and PVs, on the light of existing literature, this paper first investigates the individual impacts of high penetration of PVs and EVs; followed by a thorough study on the collective impacts of high penetration of PVs and EVs on the power grid operation, from the aspects of grid stability, power quality and energy economics.

The remaining of the paper is organised as follows. In Section 2, first, a brief overview of EV technologies, followed by the impacts of grid integration of EVs on grid stability (voltage,

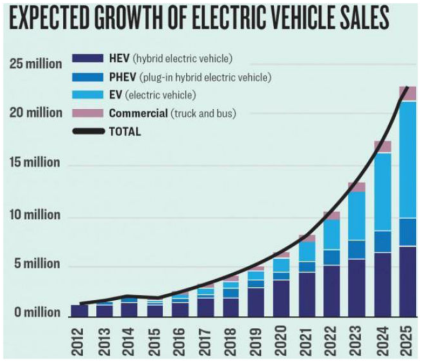

Fig. 1 *Expected growth of EV sales in the coming years [16]*

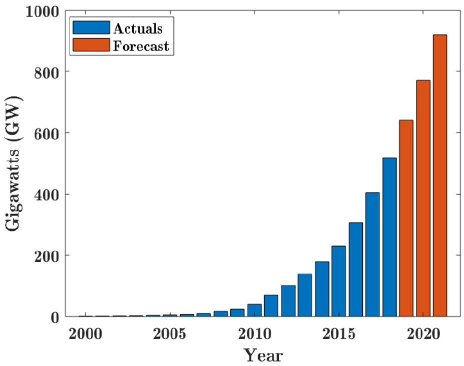

Fig. 2 *Global growth in solar installations [17]*

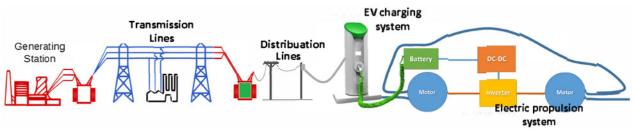

Fig. 3 *Electric propulsion system and EV charging system*

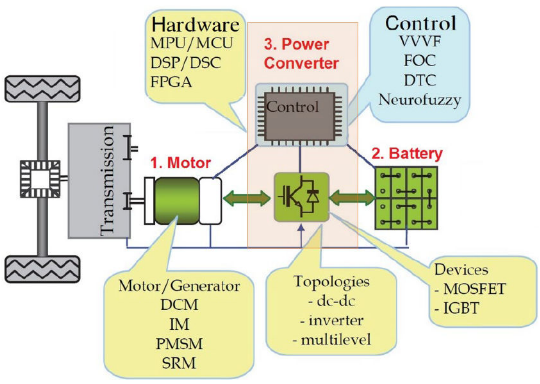

Fig. 4 *Electric propulsion systems of an EV*

frequency and oscillatory stability), power quality and energy market have been presented. A brief overview of PV system technology, including PV structure and grid code requirements, have been presented in Section 3.1. This is followed by a detailed study of the impacts of large-scale grid integration of PVs in Section 3.2. In Section 4, combined impacts of grid integration of PV and EV on the power grid operation have been presented. Finally, a conclusion is drawn in Section 5.

2 EV integration to the grid

This section briefly describes blackEV technology followed by a detailed investigation of the impacts of grid integration of EV. The EV technology about the power grid is the EV charging/discharging system that interfaces the EV battery storage to the grid [29, 38]. Technologies such as vehicle-to-grid (V2G) or grid-to-vehicle (G2V) refer to the mechanisms that control battery charging and discharging operations in a power grid. Charging and discharging of EVs from and to the grid can significantly affect the power quality, grid stability and energy economics. In the following sections, first, a brief overview of existing EV technologies has been presented, followed by a discussion on the issues related to grid integration of EV.

2.1 Brief overview of EV technologies

EV technologies can be segmented into two main components, such as electric propulsion system and EV charging system, as shown in Fig. 3. The electric propulsion system in an EV system provides the required energy for the EV motor while driving. On the other hand, the EV charging system provides energy for the EV battery while parked and connected to the grid. The electric propulsion system of EVs consists of electric machines, power converters, battery pack, and controllers as major components as shown in Fig. 4 [39].

The EV charging technology interfaces an EV system with the grid, which may be categorised into AC and DC in three levels, as shown in Table 1. A number of work-groups have been established for EV charging standards such as Society for Automobile Engineers (SAE), International Electromechanical Commission (IEC) and CHAdeMO standards [18]. Table 1 shows the categories of the EV charger based on the SAE standard. The AC level 1 and 2 EV chargers can be utilised for home-based charging, while DC chargers can be used for commercial fast charging [18]. Fast charging stations can be compared with the petrol stations, and with high penetration of EVs with fast charging, a significant power will be drawn from the grid, which can significantly affect the grid operation.

EVs can also be used to export stored energy to the grid, and the EV owners can be active players in the electricity market [40, 41]. V2G and G2V technologies are mechanisms that control discharging and charging of EVs to and from the grid, and can control EVs as ancillary service providers to the grid [42, 43]. In unidirectional V2G, the EV battery is considered as a dispatchable load to balance power in the grid. The battery of an individual EV is too small to affect the grid. An EV aggregator, including a large number of EVs act as an intermediary between individual EVs and market operator (MO). EVs can connect to a third-party aggregator individually or as a fleet operator (a parking lot) within a city or whole area, as shown in Fig. 5 [43]. An EV aggregator can decrease the volume of communication signals to the MO. Therefore, EV aggregator can reduce market operator complexity and improve the risk of cyber-security [44].

2.2 Impact of grid integration of EV

With the ever-increasing uptake of EV, several efforts have been made to study the impact of grid integration of EV. The reported studies widely investigate impacts of grid integration of EV on the aspects of power quality issues such as voltage profile, harmonic and power losses [30], as well as the stability issues of the power grid. Moreover, with high penetration of EV in the electric grid, electricity price will be significantly impacted. Several studies have been reported in the literature on the aspect of energy economics. In the following, impacts of grid integration on the aspects of grid stability, power quality and energy economics are explained.

2.2.1 Impacts of EV integration on grid stability: Power system stability means the ability of a power system to regain its steady-state operating condition after facing a disturbance [45]. Many blackouts have been reported due to the power system instability show the importance of stability studies. Since EVs, while charging from the grid appear as non-linear loads with different characteristics from usual loads, they can impose stress on the power system. Moreover, uncertainties in EV connection points, time and period of charging cause challenges to predict the behaviour of this new load. Therefore, a large number of EV charging might cause concerns about power system stability [18]. In the past, stability studies were subjected to only the transmission part of the power system. However, with high penetration of EVs

Table 1 EV charging categories based on SAE standard

Type	AC			DC		
Charging speed	Slow	Semi-fast	Fast	Fast charging		
Level	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
voltage	120 VAC	240 VAC	—	200–500 VDC	200–500 VDC	200–600 VDC
max current	12 A	16 A	—	80 A	200 A	400 A
max power	2 kW	20 kW	>20 kW	40 kW	100 kW	240 kW
on/off board	on-board	on-board	—	off-board	off-board	off-board
connection to grid	1-phase	1- or 3-phase	—	3-phase	3-phase	3-phase
charging time	17 h	1.2 h	—	1.2 h	20 min	less 10 min
connectors	J 1772	J 1772	to be determined	J 1772 Combo	J 1772 Combo	J 1772 Combo

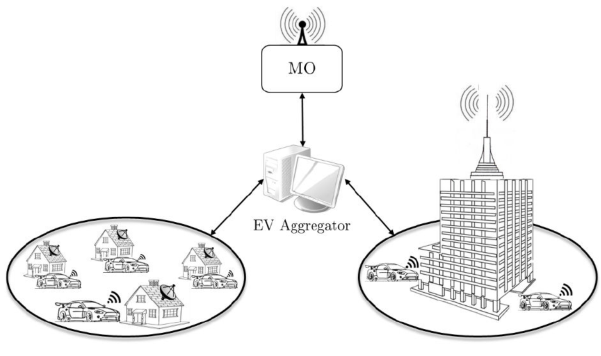

Fig. 5 *V2G connections*

Table 2 EV load model parameters with varying lead resistance [18]

Lead resistance, R	a	α	b	Load model
0.01	0.046	−2.3	0.95	Exp 1
0.02	0.072	−3.1	0.93	Exp 2
0.03	0.073	−5.2	0.93	Exp 3

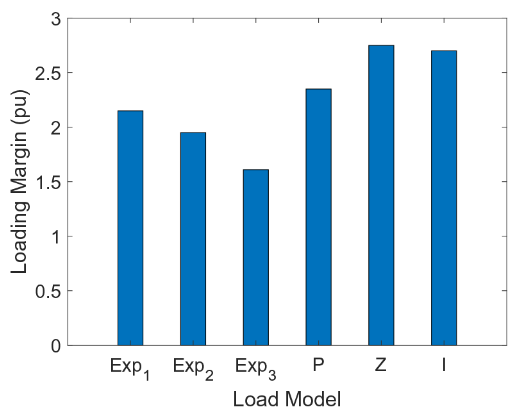

Fig. 6 *Loading margin of the weakest bus in IEEE 48-bus system with grid-integrated EV charging station [18]*

into the distribution network, the power industry is also focusing on the stability studies of AC and DC distribution networks [31, 46].

Since characteristics of load can significantly impact power system stability, an accurate EV load modelling is necessary to study the system stability [18]. The different types of EV load models have been considered in various research studies, for example a constant power load (P) model of EV independent of voltage level and a constant impedance load (Z) model with a constant ratio of input voltage to current have been presented in [47]. In contrast, a constant current load (I) model of EV has been presented in [33]. In [18, 48], a static load model for EV fast charging with an AC–DC rectifier and a DC–DC converter has been developed to study grid stability.

It has been reported in many studies that, grid integration of EV can significantly impact the grid stability. Onar and Khaligh [49] investigated the impact of the integration of EVs on distribution network stability because of current harmonic injections and reactive power consumption. The results showed the system stability is deteriorated due to EV connections and recovery time to reach steady-state conditions is increased. Wu *et al.* [50] proposed an application of the superconducting magnetic energy storage (SMES) alongside EVs to enhance the transient stability of the grid. Also, Tabari and Yazdani [51] proposed a non-linear control approach that can coordinate EVs in a DC distribution network so that the stability of the distribution network is enhanced. Pham *et al.* [52] indicated that EV integration could enhance the stabilisation of load fluctuations. In the following, the impact of grid integration of EV on different types of power system stability such as voltage stability, frequency stability and oscillatory stability are explained.

Impacts on voltage stability: The term voltage stability refers to the ability of a power grid to retain voltages at an allowable voltage level in all buses after any disturbances [45]. It is a well-known fact that variation in load demand and load characteristics can significantly impact the grid voltage stability. Since the EV load characteristics vary considerably from the conventional load models (ZIP models), the accurate load model is essential to study and analyse the accurate impact of EV integration on grid voltage stability. However, most of the existing studies in the literature represented the EVs as conventional ZIP load models [33, 47, 49, 53]. A more accurate EV load model has been presented in [18, 54], which modelled EV load behaviour as a combination of a constant power component and a voltage-dependent negative exponential component as shown in (1). The variation in load model due to varying lead resistance that interfaces an EV system with the grid is shown in Table 2. It has been shown in [55] that the negative value of alpha in the load model may lead the power system more towards instability following a contingency in the system. In order to study the impact of EV penetration on power system voltage stability, in [18], a thorough analysis has been carried out on IEEE 43-bus test distribution network with interconnected EV charging stations. Fig. 6 shows that with the integrated EV charging station, represented by the model shown in (1) and model parameters in Table 2, the loading margin of the weakest bus in the IEEE 43-bus test distribution network decreases significantly. With the increased number of EV integration, the loading margin of the weakest bus further decreases, as shown in Fig. 7. It has been also shown in [18] that the location of the EV charging station affects the voltage stability of the power grid

$$\frac{P}{P_0} = a\left(\frac{V}{V_0}\right)^{\alpha} + b \tag{1}$$

de Hoog *et al.* [31] focused on the impact of EVs on voltage stability in the residential networks in Australia. The results showed that voltage stability indices of the distribution network are affected significantly by the location of integration and the size of the EV load. Similar conclusion on the detrimental impacts of EV integration on the power grid voltage stability has been drawn in [54], which recommended the grid operator to carry out a detailed study on the grid voltage stability including accurate EV model while planning for the capacity and location of an EV charging station.

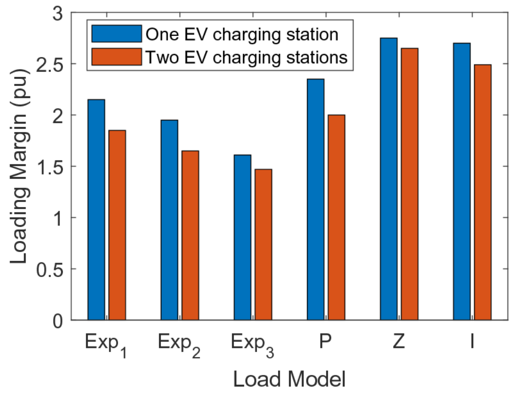

Fig. 7 *Loading margin of the weakest bus in IEEE 48-bus system deteriorates with an increased number of grid-integrated EV charging stations [18]*

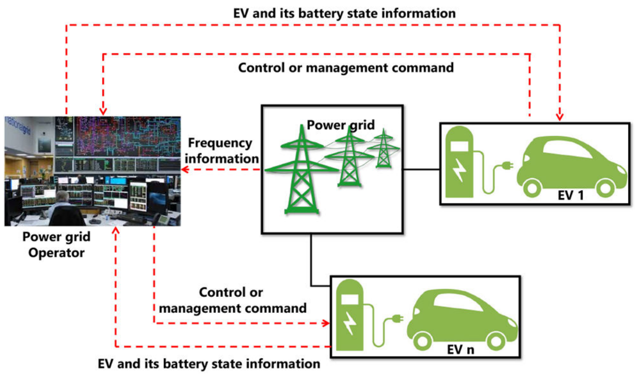

Fig. 8 *Structure of distributed dispatch system for EVs participating in grid frequency regulation [59]*

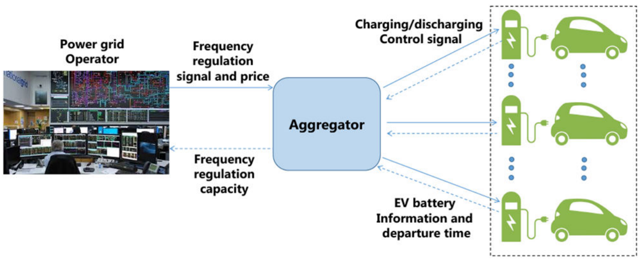

Fig. 9 *Structure of centralised dispatch system for EVs participating in grid frequency regulation [59]*

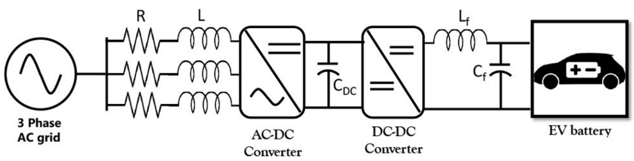

Fig. 10 *Schematic diagram of an EV charger*

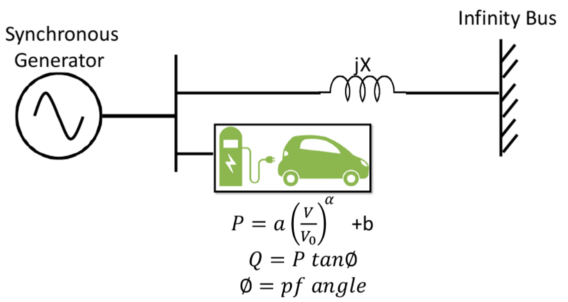

Fig. 11 *SMIB system with EV load*

Impacts on frequency stability: Any imbalance between generation and load demand in a power grid may cause the frequency to deviate from its permissible value. The term frequency stability in the context of a power system refers to the ability of the power system to retain its permissible frequency after the occurrence of a grid disturbance [45]. With high penetration of EVs, while charging the load demand in the grid will increase dramatically, and in order to meet the increased load demand, power generation is required to be increased to maintain the grid frequency in the permissible limit [42]. Moreover, uncertainties in the number of EV connections, and the period of connection and disconnection is likely to impose an increased level of uncertainty on the load demand [24].

By regulating the time and rate of charging or discharging, EVs can be operated as controllable loads. Recognising this attribute, recent studies such as [42, 56–58] have demonstrated that EVs can be utilised to balance load demand and power generation in the grid, and in turn, they can be used to regulate the grid frequency. The EVs may participate in the grid frequency regulation either using distributed dispatch system or centralised dispatch system. In distributed dispatch system the participating EVs are integrated at distributed locations in the grid. Each of the participating EVs communicates with the grid operator to supply power to the grid, as shown in Fig. 8. On the other hand, in centralised dispatch mode, through an aggregator, EVs located in a charging station or in a parking lot or in a community participate in frequency regulation, as shown in Fig. 9. The power grid operator communicates with the aggregator regarding required power to be dispatched to regulate the grid frequency, while the aggregator manages the power dispatch from the EVs.

Recent studies, for example [24, 42, 60] have demonstrated the potentiality of EV aggregators participation in ancillary service markets, as EVs possess faster ramp rate as compared to that of conventional gas turbines. Pahasa and Ngamroo [61] considered EVs charging/discharging and SoC control to improve the frequency stability of a microgrid using a multiple model predictive control. In similar work [62], EVs have been investigated as secondary and primary frequency controller to maintain the grid frequency under load fluctuations using a dynamic output feedback H_∞ controller with multiple time delays in the control input.

Impacts on oscillatory stability: The term oscillatory stability in power system commonly refers to the ability of the synchronous generators in a power grid to remain in synchronism after the occurrence of a disturbance, which depends on the ability of each synchronous machine in the system to maintain/restore equilibrium between electromagnetic torque and mechanical torque [45]. Large-scale penetration of EV into the power grid is expected to impact the oscillatory stability of the grid. However, since the EV load characteristics are significantly different from the conventional constant impedance, current and power (ZIP) loads, it is essential to model EV loads in detail to analyse their impacts on grid oscillatory stability. In [48, 54], load model of EV charger, including AC–DC converter, DC–DC converter, filter and associated control devices (Fig. 10), has been developed, which represents the EV charging system load model as a combination of constant power component and voltage-dependent negative exponential component, as shown in (1). Using the EV charging load model in (1), a linearised state-space model of a single-machine infinite-bus (SMIB) system (Fig. 11) has been developed in [63] to analyse the oscillatory stability of power grids with EV load. The state-space model is then used to calculate the damping ratio of the oscillatory modes of the SMIB system by varying a and α of the load model in (1), as shown in Fig. 12. The damping ratio is a measure describing how oscillation in a system will decay following a disturbance. It has been shown in [18] that the α parameter to be negative in the EV load model (1), which can be attributed to the filter resistance, converter switches and cables in the EV charging system. It can be seen from Fig. 12 that the damping ratio for the SMIB system decreases, as a α parameter in the load model (1) becomes negative. Therefore, the integration of EV loads in the grid reduces the damping ratio of the oscillatory modes of the power grid, which implies that the oscillatory stability of the power grid deteriorates due to integration of EVs.

A brief summary of the impact of EV penetration on grid stability has been tabulated in Table 3.

2.2.2 Impacts of EV integration on power quality: Grid integration of EVs can affect the power quality of the power system. Impact of EV integration on the power quality parameters such as voltage profile, voltage unbalance, power-losses and harmonics are mainly studied in the existing literature. The impact of grid integration of EVs on the power quality depends on the characteristic of EV charging, network features, and the number of EVs [19, 30]. Table 4 summarises and categorises the challenges of EV integration on power quality issues. Table 5 classifies and summarises the approaches to mitigate the impact of EV integration on power quality.

2.2.3 Impacts of EV integration on the electricity market: This section investigates the impact of grid integration of EVs on the electricity market operation. With the increase in the penetration level of EVs, the investment in generation, demand, prices, and emissions are bound to increase. Several studies have covered the economic impacts of integrating EVs on electricity markets [84, 85]. In the following, the impacts of EV integration on the aspects of load profile, energy price, operational cost and ancillary service have been presented.

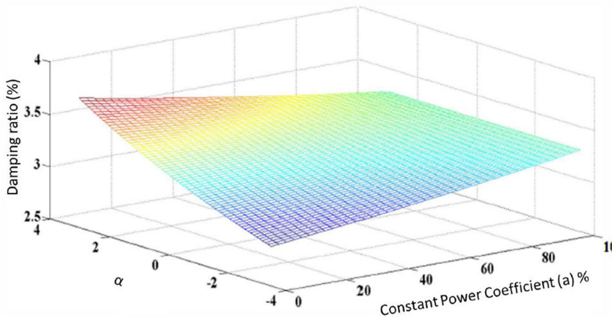

Fig. 12 *Damping ratio for different values of a and α in load model (1) [63]*

Table 3 Summary on the impact of EV integration on grid stability

	Impact of EV integration	Reference
Voltage stability	EV charging presents different load characteristics as compared to conventional loads. Integration of EVs can negatively affect voltage stability of the grid, which depends on the location, penetration level, EV charging time.	[18, 54, 55]
Frequency stability	Uncertainty of EV connection point, level of penetration, and the period of connection and disconnection cause increased level of load demand. This may have a detrimental impact on the frequency stability of the grid. However, EV can be operated as controlled load and with faster ramp rate can participate in grid frequency regulation.	[24, 42, 56]
Oscillatory stability	Characteristics of EV load are significantly different from conventional loads. The negative exponential EV load characteristics have more impact on the power system oscillatory stability compared to conventional system loads.	[48, 63]

Table 4 Challenges of EV integration about the power quality

Challenges	Remarks
Fluctuation in voltage	Impact on voltage fluctuation depends on the integration level and charging rate of EVs. As the penetration and charging rate increases the impact increases [19, 30, 64].
Voltage unbalance	Impact on voltage unbalance increases with the increased EV single-phase charging [65].
Losses	Power loss increases with a high number of uncontrolled and single-phase EV charging systems [20, 65, 66]. Overloading and losses in distribution transformer increase with high penetration of EVs [31, 67].
Harmonic	Impact on harmonics due to EV penetration varies with the penetration level, the impact increases as the penetration level and charging rate increase [68, 69]. Also, as shown in [70], the harmonics increases with random unregulated EV charging.

Table 5 Approaches to mitigate the impact of EV on the power quality

Approaches to mitigate the impact of EV on voltage profile	Remarks
Traditional voltage regulators	Use of devices such as capacitor banks and tap changes [71, 72].
Charging management of EVs	Adopting smart load management by coordinating EV charging [73].
Control strategies for active and reactive power	Charging and discharging of EVs can be controlled optimally and in a coordinated manner to regulated network voltage [64, 74].

Approaches to mitigate the impact of EV on voltage unbalance	Remarks
Voltage regulators	Energy storage units, feeder capacitor bank, dSTATCOMs, and so on can be used to reduce voltage unbalance [71, 72].
EV charging/discharging management	Optimisation of EV charging/discharging rate can reduce voltage unbalance [75].
Phase reconfiguration approach	Phase reconfiguration method, for example time of use (ToU) tariff [76] can be adopted to reduce voltage unbalance.

Approaches to mitigate the impact of EV on power loss	Remarks
Coordinating EV charging/discharging	Optimal coordinated operation of EVs can be used for peak shaving and minimising power loss [77, 78]. By scheduling EV charging in the LV distribution network, power loss can be minimised [79].
Coordinating with distributed generators	EV charging demand can be coordinated with distributed and RE sources to reduce power loss [24, 65, 80].

Approaches to mitigate the impact of EV on harmonics	Remarks
Traditional filters	Use of power factor correction devices and active filters for EV charging stations to mitigate harmonics distortions [81–83].
Absorbing or injecting harmonic currents	EVs can participate in ancillary services for harmonics and reactive power.
Coordinating with wind generators	EV loads can be coordinated with wind generators to consume the harmonics produced by a wind generator.

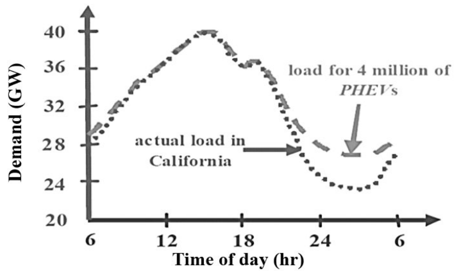

Fig. 13 *California load profile with EVs in a typical summer day [87]*

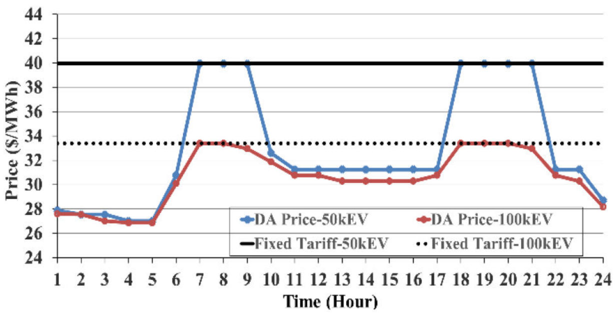

Fig. 14 *Impact of the fixed-rate tariff and the number of EVs on day-ahead prices [93]*

Impacts on load profile: The high penetration of EV can impose the additional load on the power system because of EV charging demands. Hadley and Tsvetkova [86] showed that the current network infrastructure could accommodate increased demand by shifting the EVs demand to off-peak hours. For example, Guille and Gross [87] show that a 25% EV penetration can be accommodated by the current network disregarding the need for new generation sources, as shown in Fig. 13. Foley *et al.* [88] investigated the effects of 213,561 EV in the peak and off-peak duration on the wholesale electricity market in Ireland. The results showed that off-peak charging is more helpful than peak charging and charging with the RE source also helps in emission reduction. Furthermore, stochastic modelling of aggregated EVs and their impact on the optimal load profile of the power system is presented in [56], which show that optimal scheduling of V2G energy and ancillary services has the potential to offer financial benefits to the EV owner and system benefits to the utilities.

Impacts on electricity price and EV charging tariff: With high penetration of EVs, in future EVs can play an important role and can impact on the electricity prices in the electricity market. Olivella-Rosell *et al.* [89] indicated that EVs significantly increase the price on Iberian day-ahead market, depending on the EV numbers and charging characteristic. The results in [90] illustrated that a large number of EV charging could increase the electricity prices above 17% by 2020. However, the growth in price can be negotiated by devising efficient charging strategies. As presented in [40], the EV aggregator has the potential to emerge as one of the key market players, who can coordinate V2G operations and mitigate the volatility of energy price due to integration of stochastic energy systems. However, EVs will have to compete with other established players in the ancillary service market [91]. Therefore, EV aggregators must offer attractive tariffs to EV owners and develop an efficient strategy to maximise the profit of the aggregator and attract new customers [92]. In [93], the authors compared the day-ahead (DA) prices with 50,000 and 100,000 EVs for the fixed-rate tariff, as shown in Fig. 14. As can be seen from the figure, the fixed-rate tariff with the high number of EVs (100,000 EVs) causes a reduction in the electricity price and EV charging tariff in a competitive market.

Impacts on operational cost: Energy market operator supervises generation sources and the load demand to manage operational costs. The day-ahead and real-time market managements cause equilibrium in supply–demand and to integrate renewable generations and energy storage system appropriately. EV integration can impact the operational costs through intelligent charging and discharging [94]. Many researchers have shown the benefits of coordination between renewable power generators and EVs charging in the power system, the impact of EV integration in a wind-thermal power system on emissions and cost is investigated in [95]. In [96, 97], a stochastic model is developed for wind-thermal power system scheduling under EVs charging pattern scenarios to minimise the operational costs of a power network. Unidirectional V2G services for energy trading have been presented in [40]; the proposed approach can maximise profit and minimise the risk of energy trading in day-ahead electricity markets.

Impacts on ancillary services market: The ancillary services are necessary to balance sudden changes in loads and generations. Ancillary service providers in a power grid are required to provide a fast response to any mismatch in the grid power demand, and balance generation and demand. Since EV possesses the fast ramping capability, it can be regarded as a good candidate for ancillary services [42]. For example, in [24], the authors explained how the EV load aggregator participates as a dispatchable load in the energy and ancillary service markets by submitting energy bids and regulation offers. It is assumed that the EV aggregator can deviate from day-ahead power-drawn (or POP) to amend wind imbalance energy by reducing or increasing their charging rate with consideration of EV aggregator energy constraints. When real-time wind energy is more than the forecasted day-ahead wind energy, the EV load aggregator regulates down with more charging, and vice versa, as shown in Fig. 15.

In order to enable ancillary services using dispatchable EV loads, a mechanism or platform is required for grid integration of EVs. The V2G mechanism provides a platform for EVs to communicate with the grid to provide ancillary services by either

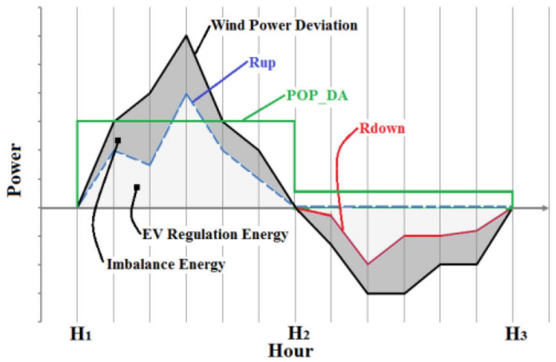

Fig. 15 *Coordination between EV demand and wind power deviation in energy and regulation market [24]*

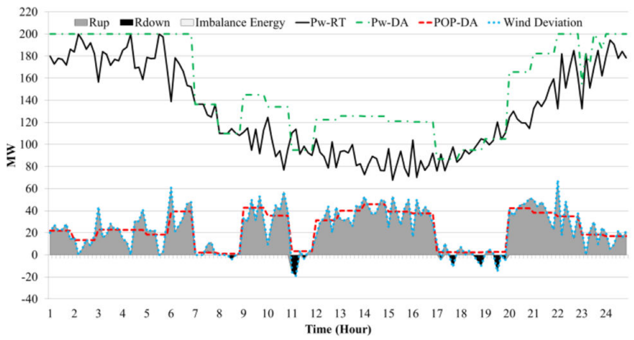

Fig. 16 *Wind power generation and EV demand schedule [24]*

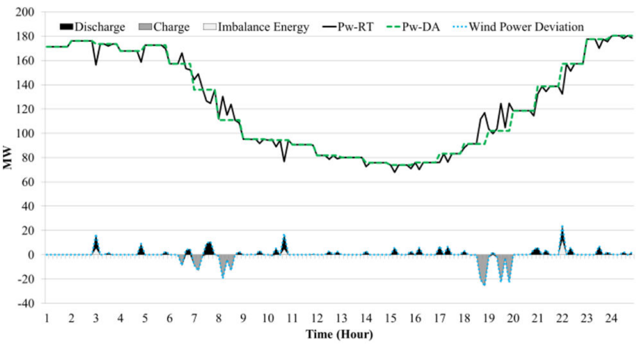

Fig. 17 *Wind power generation schedule, and BES profile [24]*

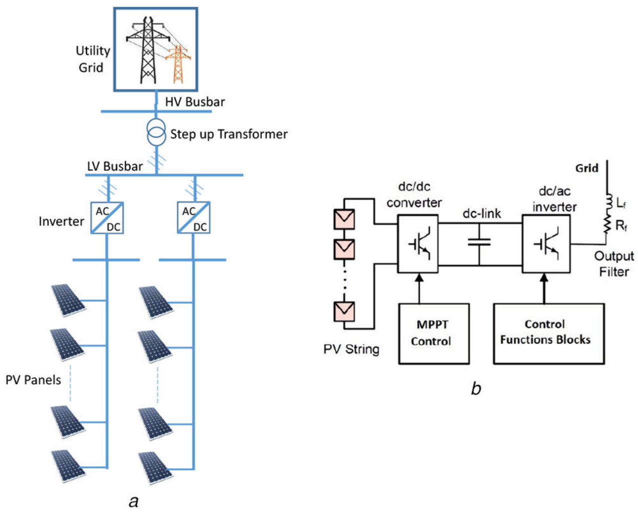

Fig. 18 *Structure of*
(a) PV system connected to grid, ***(b)*** PV control [100]

selling energy to the grid or by throttling their charging rates [26, 43, 98]. The authors in [41, 56] investigated the EV participation in the energy and regulation markets through EV smart charging. The results demonstrated that EVs could provide fast responses for ancillary service to compensate for uncertainties and intermittency of wind and solar powers [60]. In [24], the authors presented an energy exchange strategy between a wind generating company and EV aggregator, which offers flexibility in selecting between the energy demand balancing, regulation services, and/or ESS for a wind generator company to compensate for wind power deviations. Comparing the results presented in [24], Figs. 16 and 17 show the total EV load aggregators contributions are more than the battery storage system in the ancillary services. It could be because of the discharging cost of the battery storage system while EV load aggregators can only turn on/off the EV battery charging in the ancillary services. These figures demonstrate day-ahead wind power (Pw-DA), real-time wind power (Pw-RT), wind power deviation (ΔPw), day-ahead EV charging schedule (POP-DA), EV regulation up/down, and energy imbalance provided by the balancing market (P-imb). Moreover, research studies, for example [26, 84], have shown that participation of EVs in the ancillary service market can generate a significant revenue for the EV owners. This will encourage an increase in investment in EVs and their adoption.

From the extensive literature survey, it can be summarised that a large number of EVs integration into the distribution grid have impacts on the power quality, system stability and on the electricity market areas. These impacts are mainly due to the direct relation of a large number of EVs charging on the load profile, voltage fluctuation, harmonics, power losses and voltage, frequency and oscillatory stability conditions. These impacts can be managed by applying feeder capacitor bank, tap changing transformer, energy storage, dSTATCOM, filter for charging station, coordinated charging, using a distributed generator, applying time of use (ToU) tariff, and so on.

In this section, the impacts of grid integration of EVs have been studied in detail. Apart from EVs, grid integration of solar PV systems is gaining immense popularity. In the following section, a brief overview of PV systems followed by the impacts of grid integration of solar PV system has been presented.

3 Solar PV integration to the grid

In recent years, the uptake of solar PV systems has increased significantly. PV systems can either operate in grid-connected mode or in stand-alone mode. The stand-alone system is more applicable for remote areas, islands, or marine applications. The stand-alone systems are usually supported by the energy storage systems and/or diesel generators. The grid-connected PV system is connected to the distribution or transmission networks as a large-scale power plant or small-scale rooftop PV systems [99].

3.1 Brief overview of PV system technology

3.1.1 Solar PV structure: A typical PV system comprises PV panels, a DC/DC converter, DC link, DC/AC inverter, filter, and control blocks. Fig. 18 displays the overall structure of the PV system. The large-scale PV systems are usually connected to medium-voltage radial feeders by step-up transformers. The inverters connected to PV systems inject low short-circuit current into grids with no mechanical inertia [100]. The DC/DC converter in a PV system is driven by a maximum power point tracking (MPPT) controller to gain the maximum power from PV panels [101]. In contrast, the DC/AC converter controller operates depending on the mode of operation of the PV system. If the PV system is operating in grid-connected mode, the aim of the DC/AC converter controller is to dispatch the maximum possible solar power harvested by the PV system to the grid. On the other hand, in an islanded mode of operation, this controller coordinates with other accompanying sources such as diesel generator and/or storage devices to regulate the voltage and frequency of the isolated power network.

3.1.2 Grid codes for PV: The grid codes to improve the system reliability have been developed for integrating PV into the grid in a few countries, including South Africa, China, Germany, and the

Table 6 Categorisation of PV integration into grid [106]

Category	Voltage level	Power range (P)	Networks
X1	LV	$0<P\leq 13.8$ kVA	LV distribution system
X2		13.8 kVA$<P<$100 kVA	LV distribution system
X3		100 kVA$\leq P<$1 MVA	LV distribution system
Y	MV and HV	1 MVA$\leq P<$20 MVA	MV distribution and HV transmission systems
Z	HV	$P\geq$20 MVA	HV transmission system

Table 7 Control functions required for PV integration into grid

Control functions	X1	X2	X3	Y	Z
frequency control	—	—	—	—	yes
voltage control	—	—	—	yes	yes
Q control	—	—	—	yes	yes
power factor control	—	—	—	yes	yes
delta production constraint	—	—	—	—	yes
absolute production constraint	—	—	yes	yes	yes
power gradient constraint	—	—	yes	yes	yes

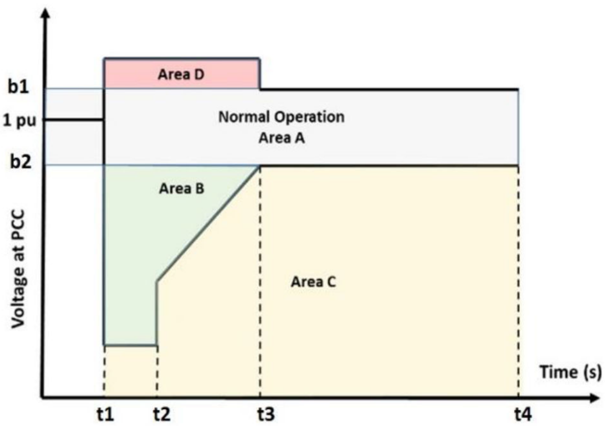

Fig. 19 *Voltage ride-through capability [106]*

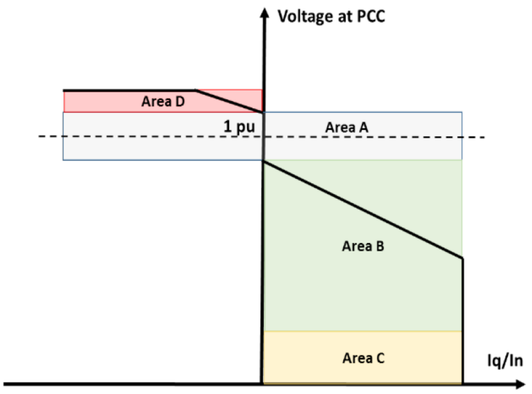

Fig. 20 *Requirements for reactive power support during voltage sag and voltage swell [106]*

US. The differences and comparisons among the grid codes of different countries have been indicated by the authors in [34, 99, 102–105]. To analyse and evaluate the PV integration into the grid, the connected voltage level, power rate, and connection points of the PV system are important. Table 6 shows a categorisation of PV integration based on voltage level, power range, and network according to the South Africa Grid Code [106]. According to grid codes, the PV system is equipped with the control functions to control and monitor the PV generation. Table 7 shows the control function selections based on Table 6 categories such as voltage level, power rate, and connection points of the PV system according to the grid code in [106].

A network connected to a PV system is required to deal with some challenges because of the variable characteristics of the solar output. These challenges are related to the control of voltage, frequency, active and reactive powers, and fault conditions. The grid codes provide technical requirements for PV integration as categorised below:

(i) *Fault ride-through (FRT) requirements:* In the event of the fault in the power grid, the PV system experiences a voltage sag or voltage swell conditions at the connection point [103]. This disturbance may cause disconnection of the PV system from the grid to maintain grid stability. The grid codes require the PV system to remain connected with the grid under faults conditions [102, 103]. The basic voltage-time profile for voltage ride-through capability under the voltage sag and voltage swell is shown in Fig. 19 [106]. The values of time and voltage at the connection point are different for categories based on the voltage level, power rate, and connection type of PV system. Also, the PV system can support the system voltage stability during fault conditions through injecting/absorbing reactive power, as shown in Fig. 20 [106]. The definitions of the areas for FRT capability curves are listed in Table 8.

(ii) *PV active power constraints:* The active power control of a PV plant should comply with the solar intermittency and grid requirements [102, 106]. According to the South African grid code in [106], the active power control of a PV plant should abide by the following power constraints: (a) absolute production (power curtailment), which is the active power value defined by the grid operator that a PV plant is required to provide to the grid, (b) delta production, which defines the active power reserve that helps to have a future control of the PV plant when a grid disturbance occurs, (c) power gradient which limits the rate at which power generation of a PV plant has to step up or down. The aforementioned constraints are illustrated in Fig. 21 [106].

(iii) *Participation in frequency regulation:* Large-scale PV plants (20 MVA or above) are required to possess the capability to contribute to grid frequency regulation by supplying the active power to the grid following the *P–f* characteristics as shown in Fig. 22 [102, 103, 106]. There are two droops with two different slopes for the primary frequency control and critical frequency control [106].

(iv) *Reactive power and voltage control:* Large-scale PV plants are required to possess the capability of controlling the reactive power supply to the grid. There are three methods to control reactive power, such as (a) voltage regulation, (b) power factor regulation, and (c) reactive power control. The voltage regulation is based on a droop function, as shown in Fig. 23 [106]. The power factor regulation control reactive power about active power, as shown in Fig. 24.

Table 8 Definitions of areas in FRT capability curves

Area	Mode	Reactive support
A	PV system operates continuously with normal voltage profile.	Normal production.
B	PV system has to stay connected to the network for a period of time.	Supplying a controlled amount of reactive power to ensure system stability.
C	PV system can be disconnected from the network.	—
D	PV system has to stay connected to the network for a period of time.	Absorbing a controlled amount of reactive current to ensure system stability.

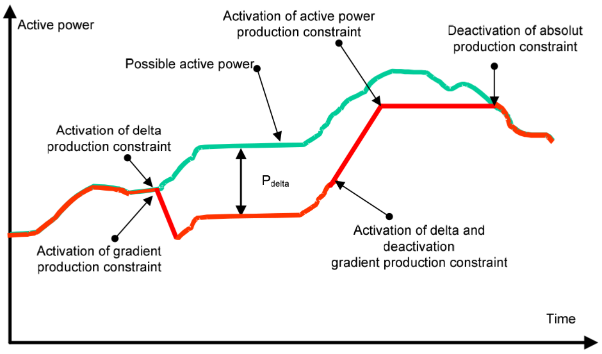

Fig. 21 *Active power control functions for a Renewable Power Plant according to South African Grid code [106]*

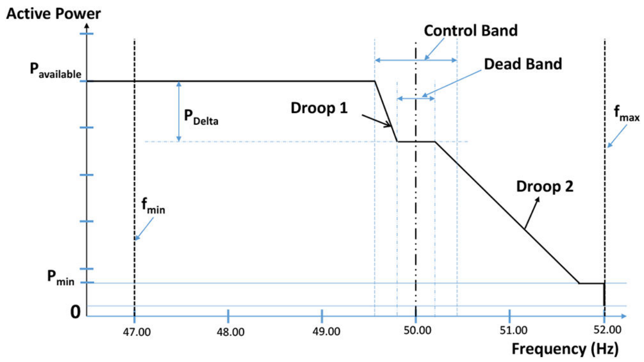

Fig. 22 *Frequency response requirements for large-size power plants [106]*

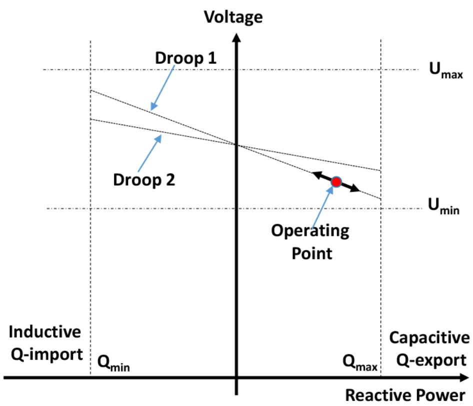

Fig. 23 *Voltage regulation of large-scale PV plants [106]*

3.2 Impacts of grid integration of PV

With the increasing amount of grid integration of PVs, the impact of this intermittent energy source on the grid is becoming more significant. In the following, the impact of grid integration of PV system from the aspects of grid stability, power quality and energy economics has been presented.

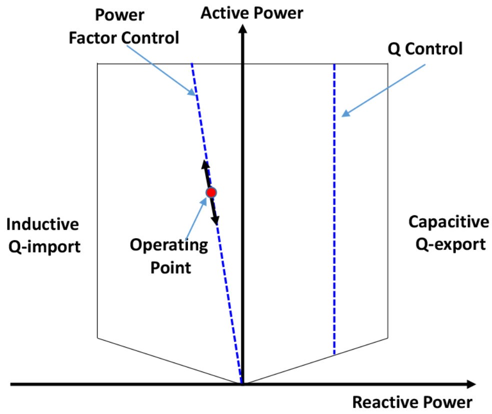

Fig. 24 *Power factor regulation of large-scale PV plants [106]*

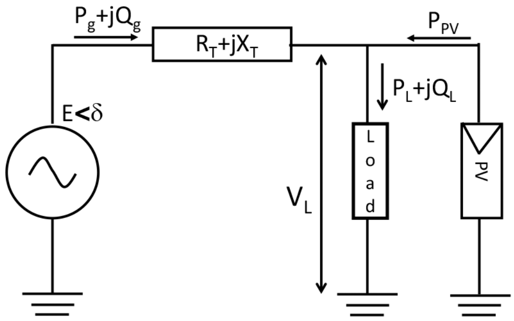

Fig. 25 *Simplified two bus representation of a PV system connected to the electrical network [21]*

3.2.1 Impacts of PV integration on grid stability: High penetration of PV systems can significantly impact on power system stability due to the characteristics of solar irradiance. With high penetration of PV in the power grid, lack of reactive power support and system inertia can impose significant challenges on grid stability [21]. Several studies have been carried out over the years to study the impact of high penetration of PV system on grid stability [21, 35, 101, 107, 108]. In the following, a brief overview of grid integration of PV system on the aspects of voltage, small-signal, transient and frequency stability has been presented.

Impacts on voltage stability: With the increased penetration of PV systems into the power grid, a several studies carried out over the years to investigate the grid voltage stability in both distribution system and transmission networks [21, 109–112]. For example, in [21], in order to analytically study the impact of PV penetration in transmission network on grid voltage stability, a two bus representation of PV connected to electric power network has been considered as shown in Fig. 25 to formulate a quadratic characteristic of load voltage V_L in terms of PV power generation, P_{PV}, as shown in (2), where $k = \tan\theta$, θ is the load power factor angle

$$\begin{aligned} &|V_L|^4 + (P_{PV} - P_L)^2(R_T^2 + X_T^2) - k^2P_L^2(R_T^2 + X_T^2) \\ &-2|V_T|^2R_T(P_{PV} - P_L) + 2kP_LX_T|V_T|^2 - |V_T|^2E^2 = 0 \end{aligned} \quad (2)$$

The solution of (2) is presented in Fig. 26, which shows that the load voltage varies quadratically with variation in PV penetration for a given load demand. Similar conclusion regarding the impact of PV integration on grid voltage has been drawn through simulation studies carried on a large-scale power system representing the entire Western Electricity Coordinating Council (WECC) with transmission voltage levels ranging from 34.5 and 69 kV, to 345 and 500 kV as shown in Fig. 27. On the other hand, in [109], a thorough study on the impact of PV penetration on the distribution network voltage profile has been presented, which

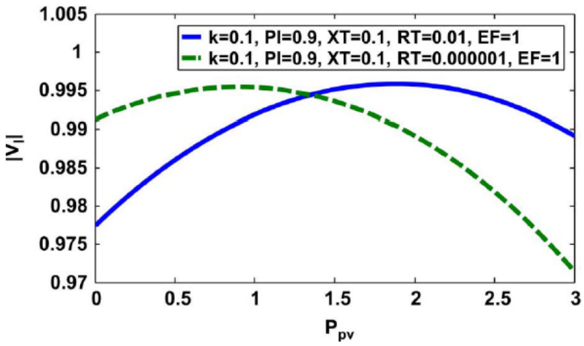

Fig. 26 *Variations of the load voltage versus the amount of solar generation for a two-bus system (Fig. 25) [21]*

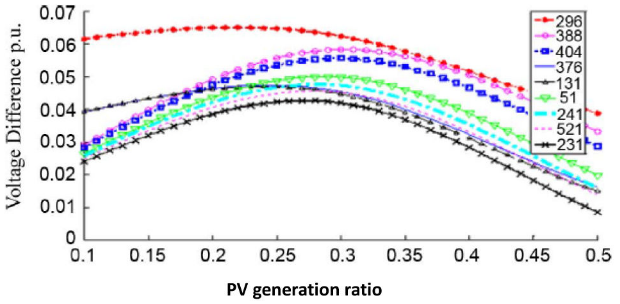

Fig. 27 *Steady-state bus voltage deviation of the WECC system with varying PV penetration levels [21]*

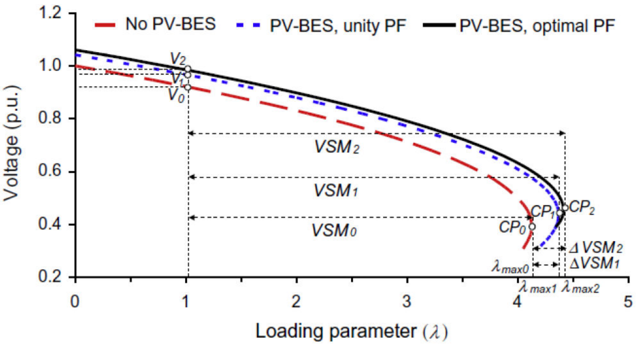

Fig. 28 *BES can enhance maximum loadability and voltage stability margin of the power grid with high penetration of PV system [118]*

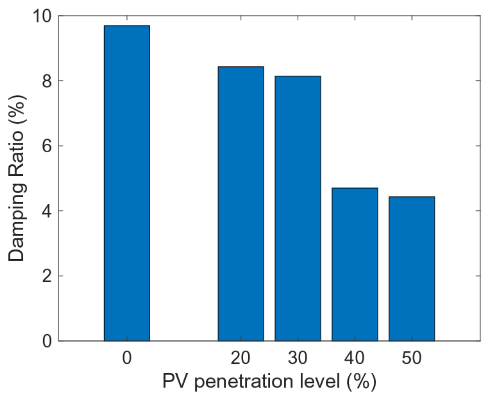

Fig. 29 *Damping ratio of the critical modes of the power system is detrimentally affected by high penetration of PV system [21]*

shows that the intermittency of a PV system can result in voltage rise and fluctuations, which turns worse as the integration of PV system increases. This effect is more prominent when a large-scale PV system is connected near the end of long, lightly loaded feeders. Similar studies in [113–117] also show that intermittency in PV power generation can cause voltage fluctuation in the low-voltage distribution network and affect the voltage stability of the distribution network. Especially during fault conditions, the intermittency in PV power generation can cause short-term voltage instability in the distribution system. As countermeasures, in [109, 111, 118] use of power compensation devices such as STATCOM, energy storage devices, and so on have been recommended. For example, in [118], it has been shown that the use of battery energy storage (BES) alongside PV systems can negate the intermittency associated with the PV generation and enhance voltage stability margin (VSM) of the system, as presented in Fig. 28. The study in [110] proposed excess power capacity for inverters to inject/absorb reactive power for voltage regulation. Another study in [112] has proposed the inverters to possess dynamic voltage support capability to inject active and reactive power to prevent short-term voltage stability.

Impacts on transient stability: With the increasing level of PV penetration into the grid, its impact on transient stability is becoming more significant. In order to analyse the impact of PV integration on grid transient stability in [35], a power grid including integrated PV systems has been simulated using dynamic simulation software PSS/E. The results in [35] show that the power system vulnerability rises with the high penetration of PV. In another study [21], extensive fault studies on high-voltage transmission network of the WECC power system, with or without high penetration of PVs have been carried out to understand the impact of PV integration on the transient stability. Simulation results demonstrate that integration of PV systems may pose both negative and positive impacts on the power grid operation depending on the PV penetration level, system topology, location of PV integration, type and location of the disturbance (fault or loss of generator) experienced by the grid. In order to better utilise the benefits of solar energy and ensure the seamless participation of PV systems in grid frequency regulation, Remon *et al.* [119] proposed synchronous power controllers (SPCs) which ensure harmonious interaction of PV system with the grid. The results of the study demonstrate that the SPCs can limit frequency deviations, improve the oscillation damping, and reduce the stress of other generating units, following a grid disturbance.

Impacts on small-signal stability: Since the PV systems do not have inertia as like the conventional synchronous generators, with the high penetration of PV systems overall inertia of the grid will be reduced. Also, PV systems are interfaced with the grid through power electronic interfaces, and their interaction with the grid is determined by the control of these power electronic interfaces. Therefore, it is important to investigate the impacts of large-scale penetration of PV systems on the dynamic behaviour of the grid. It has been shown in studies [22, 23, 119] that the impact of high penetration of PV systems on the small-signal stability depends on PV integration locations and penetration level. In [22], an eigenvalue analysis on the linearised WECC test power system with different levels of PV penetration has been carried out to investigate the effect of increased PV penetration on the critical modes of the power grid. It has been found from the eigenvalue analysis that with high penetration of PV system, the system inertia is decreased due to retirement of conventional synchronous generators, which cause a detrimental impact on the damping ratio of the critical modes of the system, as shown in Fig. 29. The outcome of the eigenvalue analysis has been further validated through time-domain simulation three-phase short-circuit faults with different levels of PV penetration at a location that excites the affected critical mode of the system (determined through simulation studies). Simulation results show that after clearance of the fault the speed of the generator close to the fault location experiences more oscillation as the PV penetration level increases (Fig. 30), which aligns with the conclusion drawn from eigenvalue analysis, i.e. reduction of system-critical mode damping ratio due to the high penetration of PV systems. On the other hand in [101], small-signal stability analysis of a power system with high penetration of PV has been carried out, which shows that the DC-link capacitor, inverter and the controllers can impact on oscillatory modes in a sub-synchronous range of frequencies and the damping of the sensitive modes. It has been recommended in [23] since high penetration of PV may adversely affect the small-signal stability of the grid, critical synchronous generators are required to be kept on-

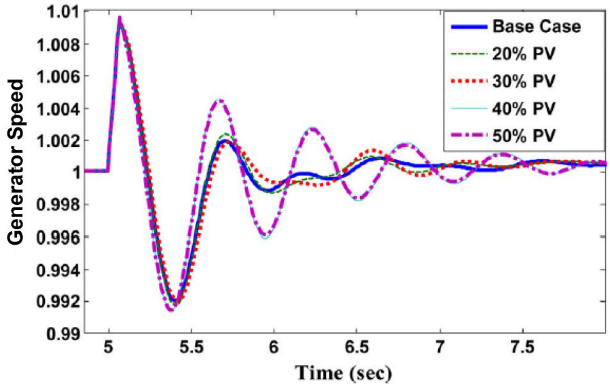

Fig. 30 *Generator speed becomes more oscillatory following a three-phase fault as PV penetration increases [21]*

Table 9 Summary on the impact of PV integration on grid stability

	Impact of EV integration	Reference
Voltage stability	Intermittency of a PV system can result in voltage rise and fluctuations, which turns worse as the integration of PV system increases. This effect is more prominent when a large scale PV system is connected near the end of long, lightly loaded feeders.	[109, 113–117]
Transient stability	Integration of PV systems may pose both negative and positive impacts on the power grid transient stability depending on the PV penetration level, system topology, location of PV integration, type, and location of the disturbance (fault or loss of generator) experienced by the grid.	[21, 35, 119]
Small-signal stability	As the PV penetration into the power grid increases, grid inertia decreases due to the retirement of conventional synchronous generators, which cause a detrimental impact on the damping ratio of the critical modes of the system. Consequently, the system response becomes oscillatory following a grid disturbance.	[22, 23, 119]
Frequency stability	With the increased PV penetration into the power grid, the conventional synchronous generators undergo retirement and consequently, the grid inertia decreases. The reduction in system inertia makes the grid highly sensitive to grid disturbances; and the RoCoF becomes very high, which may significantly increase the risk of grid frequency instability.	[120–122]

line, or other countermeasures such as static VAR compensator (SVC) are required to maintain sufficient damping of low-frequency oscillation.

Impacts on frequency stability: Large-scale grid integration of PV systems can potentially impact the grid frequency stability. As the PV integration is increasing, and that is expected to only increase in coming years, it is important to study the impact of PV integration on grid frequency stability. It should be noted that with the increased PV penetration into the power grid, the conventional synchronous generators undergo retirement. Consequently, the grid inertia decreases and the reduction in system inertia makes the grid highly sensitive to grid disturbances such as faults, sudden change in load demand and/or generation [120–122]; and the rate of change of frequency (RoCoF) becomes very high. This can significantly increase the risk of grid frequency instability, due to violating the permissible operating frequency boundary. In the worst case, this may lead to cascading failures and blackouts. Battery storages with appropriate control can be used to emulate the synthetic inertia to negate the arising frequency stability issues due to the high penetration of PV system into the power grid [123–125]. In another study [126], the authors investigated the frequency stability of the islanded hybrid PV–battery–hydropower plants. This paper proposed a hierarchical controller for the frequency stability in a hybrid PV-battery-hydropower microgrid.

A brief summary of the impact of PV penetration on grid stability has been tabulated in Table 9.

3.2.2 Impacts of PV integration on power quality: Power quality is regarded as one of the major concerns while integrating inverter interfaced RE sources. With high penetration of PV system in the grid, power quality issues are going to be prominent. To investigate the power quality issues regarding PV integration, two important impacts are considered in the reported literature. First, the impact of power quality challenges caused by the PV system on the power system. Second, the impact of the power quality challenges caused by power system disturbances on the PV system. According to IEEE Standard 929-2000, voltage, and power fluctuations and harmonic distortions are main power quality parameters regarding PV integration [127]. With the high penetration of PV system in the grid, any disturbances from PV systems can impact the power system adversely [128]. Many studies have been conducted to evaluate the impacts of high PV deployment on power quality issues. The impacts are categorised as follows:

(i) *Impacts on network voltage:* Grid integration of PV systems can cause voltage fluctuation that may potentially impact the lifetime of the network equipment. Studies show that grid integration of PV impacts the following aspects of grid voltage [128, 129]: (a) voltage unbalance, (b) voltage rise, (c) voltage sag and swell, and (d) flicker. Several studies in the literature have indicated that high penetration of single-phase rooftop PV integration can cause the voltage to unbalance in the distribution network. It has been identified through simulation studies in [130], as presented in Fig. 31, that the unbalance voltage due to single-phase rooftop PV installations has a relationship with PV size, PV connection point, and load amount. Voltage rise has been identified as another impact resulting due to reverse power flow occurring as a result of grid integration of PV systems [131]. Tonkoski *et al.* [132] revealed that the high impedance between the PV and LV transformer causes a voltage rise in the distribution network. Another study in [128] has identified that as rooftop PV installations are connected to different phases of a distribution network, the voltage unbalance, and voltage rise might exceed the standard boundary. Voltage flicker (variation in voltage peaks) is another problem caused by PV power fluctuation due to fast changes (up to 15% per second) in irradiance and clouds. Whitaker *et al.* [133] recommended developing fast inverters and controllers technologies in coordination with voltage regulations to provide rapid voltage regulation for the mitigation of flicker. Lim and Tang [134] developed dynamic load controllers to mitigate the voltage fluctuations and flickers.

(ii) *Impacts on network power:* Due to irradiance and temperature variability output power of a PV system fluctuates. This fluctuating nature of PV output can cause grid frequency fluctuation with high penetration of PV systems [128]. Singh *et al.* [135] showed that superconducting magnetic energy storage (SMES) with PV system could potentially improve frequency fluctuations, although SMES is inapplicable for high power rates. Different approaches that have been investigated for mitigating power and voltage fluctuations due to PV integration are shown in Table 10.

(iii) *Impacts on network harmonics:* PV systems are sources of harmonics because of semiconductor switches in the inverter. The total harmonic distortion is dependent on the inverter technology, solar irradiation, temperature, and network characteristics [147]. The current harmonics in an LV network with high impedance can result in significant voltage distortions [148]. The current harmonics reduce when the PV is operating at the nominal voltage level [149]. Many approaches have been proposed to mitigate the impact of harmonics produced by PV systems. The passive and active filters are the traditional solutions to eliminate the harmonics in the system. However, the power system requires additional compensators [148]. Another method is to apply control strategies for inverters to compensate harmonics [100]. Different approaches to eliminate the harmonics are shown in Table 11.

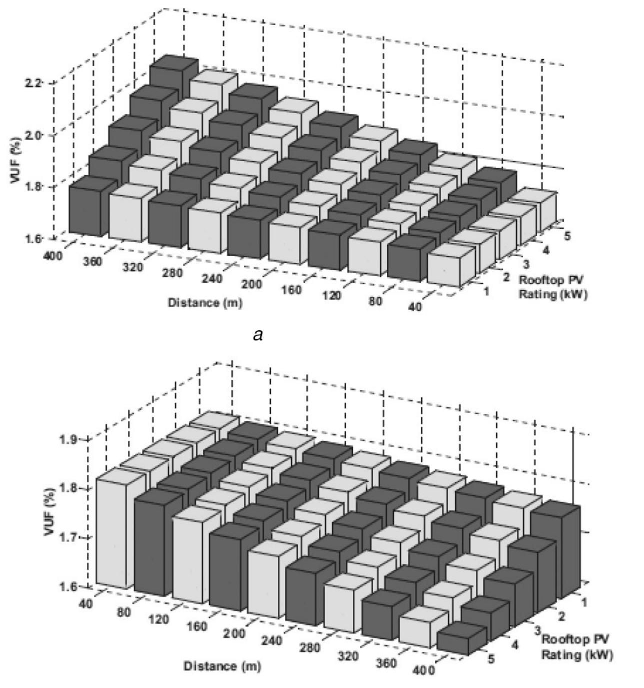

Fig. 31 *Voltage imbalance in low-voltage distribution network depends on PV penetration level and connection point*
(a) Lightly loaded phase, ***(b)*** Heavily loaded phase [130]

3.2.3 Impacts of PV integration on power economy: As PV systems result in higher uncertainty and intermittency in electricity generation, high penetration of PV system may cause fluctuations in energy price. Hence, the role of ESS and ancillary services such as demand response becomes important. It has been investigated that increasing uptake of PV generations motivates to invest in the technologies related to ESS, V2G and ancillary services. Hartner and Permoser [154] investigated the impact of PV generations on electricity prices. It has been reported through case studies on Germany and Austrian energy network in [154] that the energy price follows the pattern of PV injected power to the grid during a day, as shown in Fig. 32. It can be further seen from the figure that low PV penetration level causes a flatter price curve and the peak energy prices around noon are significantly reduced as compared to the energy price without any PV penetration. Also, with higher PV penetration, energy price drops significantly around noon, which is usually lower than the energy price at night times.

Grid integration of PV systems is increasing in various sizes from small-scale rooftop PV to large-scale solar PV farm. Detail study on the integration of PV systems shows that it may have both the positives and negatives. Some investigations conclude that integration of PV systems can potentially improve the voltage condition at the far end of the distribution system and can support the local load. On the other hand, some studies show that large-scale integration may potentially cause detrimental impacts on grid stability, power quality and energy economics. On the other hand, a few studies highlighted that uncontrolled installation of small-scale PV could make the overall network unbalanced.

So far, the impacts of grid integration of EV and PV have been studied individually. However, several research studies show that the simultaneous deployment of PV and EV, as well as their coordinated control, can benefit the grid from various aspects. In the following, the combined impact of grid integration of PV and EV is studied in detail.

Table 10 Approaches for mitigating the voltage and power problems of PV integration

Approach	Remarks	Reference
Adjusting transformer tap changer	Major problem of this approach is that the tap cannot be altered many times if it is needed to regulate the voltage.	[136]
Upgrading the conductors	Expensive.	[136]
Reducing transformers short circuit resistance and feeder impedance.	Expensive.	[136]
Capacitor bank	Simple and inexpensive. In distribution networks with $R > X$, voltages are less responsive to reactive power. Also, higher power loses and current can be consequences of reactive power control. This method cannot improve the voltage rise.	[136, 137]
Dump load	Simple and inexpensive. This method cannot improve the voltage drop. Also, higher power losses and current can be consequences of this method.	[137]
dSTATCOM	This method can decrease the maintenance cost of the transformer. The large size of dSTATCOM significantly reduces the voltage violation, although it can be expensive.	[138]
Dynamic voltage regulator	Mitigating voltage sag or swell through active power injection or reactive power absorption.	[139]
unified power quality conditioner (UPQC)	Mitigating voltage sag and swell issue.	[140]
Battery storage units	Expensive. Two storage units: (i) a large slow unit for energy shifting, and (ii) a small fast charging unit for smoothing.	[141, 142]
Reactive power control of the PV inverters	Apparent power (capacity) of the inverters might have to be increased.	[143]
Active power control of the PV inverters (the active power curtailment)	Control of PV inverters requires excessive communication, computation, and complicated control algorithms.	[141]
Power management system	Control of PV inverters in coordination with diesel generators and ESS in a microgrid.	[144]
Virtual-impedance control	Virtual-impedance-control method can be applied for FRT requirements.	[145, 146]

Table 11 Approaches for eliminating the harmonics of PV integration

Approach	Remarks	Reference
Passive power filters	LCL filters	[148]
dSTATCOM	Solar-dSTATCOM reduced current and voltage THD to 0.7 and 0.5%, respectively, which meet the standard.	[150]
UPQC	Solar-shunt active filter reduced the current THD 30.39–3.11%.	[151]
Battery storage units (BSS)	Current harmonics are reduced to less than 5%.	[152]
Multifunctional grid-tied inverter (MFGTI)	Advanced MFGTI integrates PV system into the power grid and improves the power quality of the grid as an auxiliary service.	[153]
Virtual-impedance-control method	Optimal virtual impedance design and robust implementation are an important factor to use this method.	[152]

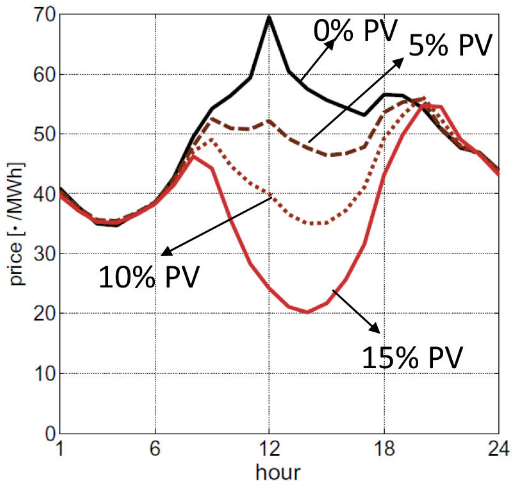

Fig. 32 *Impact of PV penetration on electricity price [154]*

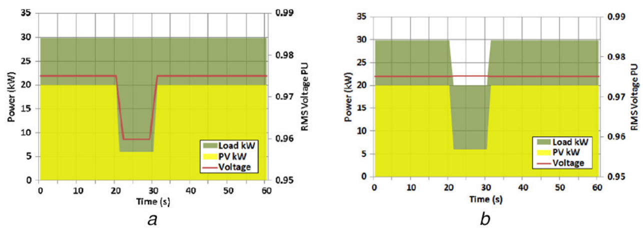

Fig. 33 *Feeder voltage under PV output power fluctuation*
(a) Without EV, ***(b)*** With EV

4 PV–EV integration to the grid

The PV and EV both are connected to the power network and based on their connection and operating time, the combined effect can be different than that we have discussed in previous sections. There are different configurations to integrate the PV and EV into the grid, and the connection point of PV and EV in the grid depends on the voltage level of the connection point. Large-scale PV power plant and EV load aggregators are commonly connected to MV distribution and HV transmission systems. In the distribution grid, there are increasing uptakes of rooftop PVs in households, as well as in small and medium scale commercial buildings. Also, with the increase of adoption of personal EVs, while charging, these EVs are connected to the distribution network. Several studies on the grid integration of PVs and EVs have highlighted the prospective combined effects on power quality, grid stability and energy economics, which are discussed in the following subsections.

4.1 Potential power quality issues of integrating PV and EV

This section reviews the grid power quality issues when the EVs are charging, and PVs are connected to the grid. The power quality improvement for power regulation, harmonics minimisation, voltage regulation, and frequency control at AC mains is achieved by using PVs with smart inverters connected to the grid [155]. The EVs and PVs together to grids can offer reactive and active power regulations, power and load balancing, voltage ride-through requirements, and efficiency and reliability of the grid [156].

4.1.1 Voltage and frequency regulation: One of the major problems experienced in the LV network due to the integration of PV is the voltage rise. The coordination between EV loads and PV system can solve the voltage rise problem [157]. Alam *et al.* [158] tested the coordination strategy on an Australian distribution system based on real PV and EV data, which show that optimised and controlled charging/discharging pattern of EV can potentially mitigate the adverse impacts of PV, such as voltage rise during midday or to support the evening load peak. Akhtar *et al.* [159] proposed that regulation of smart loads that include heaters, lighting (especially, passive LED lighting systems), and small motors with no stalling problems (e.g. fans, ovens, dishwashers, dryers, etc.) can effectively mitigate the voltage issues caused by PV integration and EV charging in low-voltage distribution networks. The fast-charging station comprising PV system, a Li-ion BES system (BESS) with a decentralised energy management system (EMS) was studied in [160] to control the voltage with a decentralised control method disregarding the communication interface. Also, Torreglosa *et al.* [161] investigated a decentralised energy management system (EMS) of a charging station composed of PV solar energy and batteries as energy storage system using a model predictive controller (MPC) to regulate the bus voltage. Weckx and Driesen [162] showed that the coordinated three-phase PV inverters and EV chargers could balance the phases through transferring power from high loaded phase to low loaded phase. And in turn, more balanced grid operation can be ensured. A similar study in [163] proposed global EMS for PVs and EVs to mitigate grid phase unbalance issues. Bayat *et al.* [164] evaluated the role of end-user devices such as EVs and PVs for grid voltage and frequency support. Rogers *et al.* [60] showed that EVs can be used as an energy storage system accompanying PVs and may provide frequency regulation, spinning reserves and ancillary services in the power grid. Rana *et al.* [165] investigated a modified droop controller including EV aggregators, wind and solar units, and diesel generators to control the frequency of a microgrid.

4.1.2 Voltage ride-through: When coordinated between each other, PVs and EVs are capable of injecting both active and reactive power to support the grid during voltage ride-through conditions. EV and PV system can be connected to the grid via either separate inverters or an identical inverter. In either connection, the DC-link capacitor must be large enough to inject reactive power to the grid. Also, during PV transients, EVs can reduce the transient tension on the grid by injecting active power. Falahi *et al.* [155] showed that the EV perfectly supports the reactive and active power regulations during fault ride-through conditions. Foster *et al.* [166] showed that by regulating the charging of EVs, the voltage transients arising due to PV output power fluctuation while cloud covering can be mitigated, as shown in Fig. 33 (a) (only PV, no EV) and (b) (both PV and EV).

4.1.3 Power regulation: The mitigation of PV power fluctuations is a crucial concern from the grid perspective. Traube *et al.* [167] investigated using a bidirectional DC-to-DC EV charger that is connected to the DC link of a PV inverter. The experimental results indicated that this approach reduces the ramp rate of the PV power as well as provide fast EV battery charging from the PV system [167]. It has been studied in several research that the DC distribution system is suitable for industrial and commercial buildings with integrating PVs and EVs [168, 169] due to power loss reduction and no reactive power problem. Wi *et al.* [168]

proposed an EMS of the DC network in buildings, which determines optimal schedules for EV charging depending on the forecasted PV output and electricity consumption. Abdelsamad *et al.* [170] show that high penetration of EV charging loads can cause overloading of distribution transformer and their loss of life. Abdelsamad *et al.* [170] further show through Monte Carlo (MC) simulation that if EVs are deployed with PVs, this adverse impact of EV on the distribution transformer can be reduced. The results showed that if the PV and EV are coordinated the stress on the transformer can be reduced, and its life can be extended [170].

4.1.4 Voltage fluctuation and harmonics: The non-linear power electronic switches within EV chargers and PV inverters can increase the voltage and current harmonics. Tovilović and Rajaković [171] investigated the combined impacts of PVs and EVs on voltage profiles and harmonic distortions on a distribution network. The results showed that PVs and EVs could reduce voltage fluctuation, although PVs and EVs increase the total harmonic distortion of voltage [171]. However, EVs and PVs can reduce current harmonics through absorbing or injecting harmonic currents from or to the network [172].

4.2 Potential grid stability benefits of integrating PV and EV

It has been already discussed in previous sections that individually PVs and EVs can have detrimental impacts on grid stability. This is mainly due to the intermittent nature of PV energy and the uncertain load characteristics of EVs due to unpredictable EV connection point, time, rate and period of EV charging. However, studies show that if PVs and EVs are coordinated together properly, they can be used to improve grid stability. Pahasa and Ngamroo [61] considered EVs charging/discharging and SoC control to improve the frequency stability of AC microgrid, including PV system via a multiple model predictive control. In similar work, Pham *et al.* [62] investigated EVs as secondary and primary frequency controllers to maintain the system frequency stabilisation of load fluctuations using a dynamic output feedback H_∞ controller with multiple time delays in the control input. In DC grids, PVs and EVs easily integrate into the system. The stability studies in the DC grid due to load and generation changes are important. Iovine *et al.* [173] investigated a non-linear control of a DC grid for the integration of PV and EV. The simulation results indicated that the proposed control method is robust under the transient-state and steady-state operation modes.

4.3 Economic benefits of integrating PV and EV

PVs and EVs with high penetration are considered as new players in the electricity market. Vithayasrichareon *et al.* [174] used an MC-based portfolio modelling to investigate the costs and CO_2 emissions of future generation portfolios with increased PVs and EVs growth. The Australian National Electricity Market (NEM) case study results show that EV charging management in coordination with a PV system can minimise cost and CO_2 emissions. The carbon tax is another important factor to maximise the benefit of PV and EV integration. In another study in [166], the coordination policy for EV charging based on forecasted energy prices and PV output generation was investigated. The results demonstrated that the average annual charging cost of an EV system could be reduced through the day-ahead market data [56]. Moreover, with high penetration of EVs with fast charging rates, the grid might not support the high power demand from EV charging. Badawy and Sozer [175] showed the benefits of a hybrid grid-tied system of PV–battery for fast EVs charging stations. In another work in [176], a two-stage problem was investigated for a PV powered charging station considering PV uncertainty and uncertain EV parking behaviours to maximise the total profit at the real-time operation. Tushar *et al.* [177] classified EV owners for a PV powered charging station into three categories: (a) premium; (b) conservative; and (c) green. An optimisation problem was formulated to minimise the energy trading cost for the EV charging station solved by a mixed-integer programming (MIP) technique. With the reduced price of rooftop PV and increase in EV penetration in end-user houses or building, a revolution has occurred in the structure and management of the home electricity system. Paterakis *et al.* [178] considered several smart households with V2H, V2G, and PV technologies in a neighbourhood zone to minimise power peaks on the LV transformer and energy procurement cost through bidirectional power flow. Romo and Micheloud [179] calculated the cost of a household load with 1000 kWh/month and single EV. The results showed that the user might make benefit from the installation of PV panels with the payback period of 2 years.

4.4 Application of PVs and EVs for ancillary services

The PV powered EV charging station can participate in ancillary service markets such as reactive power, real-time EMS, and harmonic ancillary service markets. Islam *et al.* [27] developed an algorithm to calculate the optimal size of PV panels, transformers, and BSS for a PV powered charging station participating in ancillary services. Chen *et al.* [180] showed the applicability of PV powered EV charging stations participation in ancillary services for real-time EMS. A similar study in [181] concluded that EV charging station with PV energy sources has the potential of profitably participating in day-ahead energy, spinning reserve and energy regulation markets.

4.5 Coordinated control of PV and EV

From the discussions in aforementioned sections, it is evident that with the increased penetration of PV and EV the power grid is expected to experience a higher degree of uncertainty and intermittency both in the generation and load, which may negatively impact the grid stability and power quality. However, coordinated and combined control/management of PVs and EVs may enhance grid stability, power quality and participate in ancillary services. Several recent studies have been reported in the literature that present control approach to coordinate PVs and EVs operation to utilise them to enhance grid stability, power quality, economic benefits, etc. EV charging stations are recommended to be assisted with PV energy sources to negate the uncertainties associated with EV charging and participate in grid operations such as stability and power quality assessment, participate in ancillary service market [180, 182–185]. For example in [180], a solid-state transformer-based PV-assisted charging station (PVCS) for EVs has been introduced with a rule-based energy management strategy to participate in the ancillary service market. In another study [186], a coordinate control strategy for integration of large-scale PV assisted EV charging station into the MV distribution network have been presented, where the EV load pattern has been forecasted using a probabilistic approach, which is coordinated with PV generated power to participate in grid stability and power factor improvement. Coordinated control of IoT enables EV charging station to neutralise the sudden dip and rise in load demand in the PV penetrated distribution network and enhance the reliability of the power grid [187]. In [188], an approach for management of EV charging management and optimum pricing based on Starkelberg game for PVCS has been presented. In order to best utilise the potential of EVs, the concept of EV aggregator has been deployed to act as a middleman between a power grid operator and EV owners. From the grid operator's perspective, the aggregator operates as a large generation source, which may participate in the day-ahead energy market and ancillary services [189]. In [190], optimised bidding approaches for an EV aggregator to participate in the energy market have been presented. In another study [191], a coordinated droop charging control strategy for EV aggregators to participate in frequency regulation of microgrid with high penetration of PV systems in order to enhance power system stability.

5 Conclusion

There has been a tremendous increase in grid integration of PV energy sources and EVs in recent years, which is expected to only grow in the coming years. This paper first presented a thorough review of the impacts of grid integration of PVs and EVs separately from the aspects of grid stability, power quality and energy economics. This is followed by the study of the combined impact of PV and EV integration on grid stability, power quality and energy economics. From this review, it is evident that high penetration of PV systems and EVs individually can negatively impact on the grid stability and power quality due to the intermittent nature of PV energy sources and uncertain load characteristics of EVs. However, coordinated or combined operational strategies of PV systems and EVs can mitigate these negative impacts on the power quality and grid stability. Also, in terms of the energy economy, with high penetration, the large-scale EV load aggregators and PV systems are regarded as strategic players in the future energy market, who can potentially affect the price and outcome of the wholesale energy market in the future smart grid.

As the power grid is going through a transition from the conventional power grid with traditional synchronous generators and loads towards a modern power grid with high penetration of non-synchronous RE sources (such as PV systems) and controllable loads (EVs), grid operators are required to re-evaluate and re-investigate this transition. In order to cope with the emergence of these non-synchronous RE sources (PVs) and controllable loads (EVs), and mitigate the intermittencies and uncertainties associated with such sources and loads, the modern power grid needs efficient and sufficient ancillary services to maintain the grid reliability, and harmonics supports to ensure power quality. Deployment of conventional compensator and limiters, including synchronous condensers, STATCOM, SVCs, etc. might increase the CAPEX (capital expense) and OPEX (operational expense) complexity and cost. However, an extensive review of recent research studies on PVs and EVs show that, if the grid integrated PVs and EVs are coordinated among themselves they can participate in grid voltage, frequency and FRT support. Also they can provide ancillary services. Investments in the roll-out of PVs and EVs, as well as their coordinated operation, can bring long term benefits for both the operators and consumers. The benefits include a reduction in energy price, reduced reliance on fossil-fuel-based energy sources and less GHG emission. Also, they can be optimally regulated and coordinated among themselves to participate in the enhancement of grid stability (voltage and frequency) and power quality.

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