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Review Article

Power quality improvement in smart grids using electric vehicles: a review

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Abstract: The global warming problem together with the environmental issues has already pushed the governments to replace the conventional fossil-fuel vehicles with electric vehicles (EVs) having less emission. This replacement has led to adding a huge number of EVs with the capability of connecting to the grid. It is noted that the presence of such vehicles may introduce several challenges to the electrical grid due to their grid-to-vehicle and vehicle-to-grid capabilities. In between, the power quality issues would be the main items in electrical grids highly impacted by such vehicles. Thus, this study is devoted to investigating and reviewing the challenges brought to the electrical networks by EVs. In this regard, the current and future conditions of EVs along with the recent research works made into the issue of EVs have been discussed in this study. Accordingly, the problems due to the connection of EVs to the electrical grid have been discussed, and some solutions have been proposed to deal with these challenges.

1 Introduction

An electrical grid consisting of a wide range of electrical devices such as smart appliances, smart meters, and renewable energy resources, can be defined as a smart grid. The definition of the smart grid was officially introduced by the Energy Independence and Security Act of 2007 (EISA-2007) in January 2007 and approved by the US. This definition includes ten characteristics for the smart grid as follows:

The United States established a supportive policy to modernise the national electricity transmission and distribution systems to have a secure and reliable electricity infrastructure to meet the future demand growth and to achieve the following items characterising a smart grid:

(i) Increased application and implementation of control technology and digital information to enhance the security, efficiency and reliability of the electrical grid; (ii) dynamic optimisation of resources and grid operation while considering full cybersecurity requirements; (iii) integration and deployment of distributed generation (DGs) and resources, including renewable energy sources (RESs); (iv) incorporation and development of demand response (DR) programmes, energy-efficiency resources and demand-side resources; (v) implementing smart technologies (automated, real-time and interactive technologies which optimise the operation of consumer devices and appliances) for communication and metering purposes considering the grid status and operation, and for distribution automation; (vi) integration of smart consumer devices appliances; (vii) integration and deployment of peak-shaving technologies and high-tech electricity storage, including hybrid electric vehicles (HEVs) and plug-in HEVs (PHEVs) as well as thermal storage systems; (viii) providing the control options and timely information for consumers; (ix) development of standards for interoperability and communication of equipment and appliances connected to the electrical power grid including the infrastructure serving the electrical grid; (x) identification and reduction of unnecessary or unreasonable barriers to adoption of smart grid practices, technologies and services' [1].

There are some common elements in most of the definitions of smart girds including smart devices and digital communications. The works that have been going on in electric systems modernisation, especially distribution automation and substation, are now unified in the general concept of the smart grid. There are many technologies that can be included in smart grids while one of the most recent ones is the electric vehicle (EV) which comes in different types such as HEVs, PHEVs, and battery EVs (BEVs) [2].

EVs first appeared in the mid-19th century when the electricity became a suitable type of energy for motor vehicle propulsion systems, providing the opportunity for good operation compared to other technologies of that time. Despite the advances in the modern internal combustion engines over recent years, introducing EVs has revolutionised the motor vehicle industry. Thanks to the technological development and the high attention to RESs, EVs experienced a resurgence of interest in power industries. This technology offered numerous benefits to the power grids, such as peak-load shaving, spinning reserve, power grid regulation and reactive power compensation [3]. However, the negative impacts of EVs in terms of power quality (PQ) need to be investigated to get more benefits of this green technology [4].

The term 'power quality' refers to providing the near sinusoidal voltage and current waveforms for the power system at the rated magnitude and frequency [5]. PQ can be affected by several factors such as voltage and frequency variations, imbalance, interruption, flicker, and harmonics [6–8]. Accordingly, PQ is one of the important considerations in the secure and reliable operation of smart grids and it is likely to be impacted by the demand growth for EVs shortly [7]. Therefore, it is of great significance to investigate the PQ issues in smart grids while considering EVs [9–11].

Over the last decade, it has been great attention to the PQ issues caused by EVs in the technical literature. However, no attempt has been made heretofore to compile all these works into a comprehensive review paper. Therefore, this paper aims to review and discuss the impacts of EVs on smart grids. The paper focuses on the following subjects:

- PQ issues in traditional and modern power networks.
- Overview of EVs.
- PQ in conventional networks using EVs.
- PQ improvement in smart grids using EVs.

The paper is organised as follows. Section 2 provides the highly cited papers and highly used keywords, and Section 3 includes the overview of PQ issues in both traditional and modern power systems. Section 4 presents a review of different types of EVs. The PQ issues in the presence of EVs in conventional and smart grids have been investigated in Sections 5 and 6, respectively. The future roles of EVs have been discussed in Section 7, and Section 8 draws some relevant conclusions.

2 Highly used keywords and highly cited papers

This section aims to present the highly cited papers and highly used keywords in the area of the PQ and EVs in the published documents. To this end, the terms of ‘PQ’ and ‘EVs’ have been searched in the SCOPUS database.

Table 1 Ten most commonly used keywords

Id	Keywords	Occurrences
1	electric vehicles	484
2	power quality	438
3	charging (batteries)	184
4	vehicles	147
5	EV	127
6	electric power transmission networks	98
7	secondary batteries	94
8	smart power grids	89
9	hybrid vehicles	89
10	power electronics	76

Table 1 presents the ten most commonly used keywords in the area. EVs, PQ, charging (batteries), vehicles, EV, electric power transmission networks, secondary batteries, smart power grids, hybrid vehicles, and power electronics are the most used keywords. Table 2 presents the top 20 highly cited documents published between 2014 and 2018. The next section presents an overview of PQ issues in the electric power systems.

3 Overview of PQ in traditional and modern electrical networks

3.1 Review of PQ issues, associated causes, and effects

This section is devoted to introducing the main PQ issues that a modern power system may confront. Besides, the associated origins and impacts of these issues are summarised. The main classification of the PQ issues is represented in Fig. 1 [32–35].

The transient-based PQ problems can be categorised using their peak magnitude, frequency component and also according to the rise time and the signal duration. Short-duration and long-duration issues are determined based on their durations and classified in terms of the magnitude variations. Total harmonic distortion (THD) and harmonic spectrum analyses are dominant identifiers of the power system waveform distortion. Intermittency is a technical index through which, the voltage fluctuations can be effectively detected [32–35].

To evaluate the causes and effects of the PQ issues, the characteristics of the most frequent phenomena are concisely explained as listed in Table 3.

3.2 PQ issues in conventional power systems

Generally, in the conventional power systems with large centralised generating units, overhead transmission/distribution lines, and passive consumers, any non-linearity in the loads or even system dominant apparatuses are the leading causes promoting the associated PQ problems [32]. PQ problems may cause motor overheating, transformer saturation, system resonance, capacitor overloading, protection malfunction, light intensity change, damage to the generator and turbine shafts, loss of production and even human health, irritation and headaches [32, 33].

3.3 PQ issues in modern power systems

Over the recent decades, with the ever-increasing trend in the widespread utilisation of distributed energy resources (DERs), the tendency towards using the power electronic based interfaces has

Table 2 Highly cited documents

ID	Authors	Reference	Year	Journal/Conference	Citations
1	El-hawary	[12]	2014	Electric Power Components and Systems	106
2	Gray and Morsi	[13]	2015	IEEE Transactions on Power Systems	57
3	Jiang *et al.*	[14]	2014	IEEE Transactions on Power Delivery	53
4	Farhadi and Mohammed	[15]	2016	IEEE Transactions on Industry Applications	52
5	Sbordone *et al.*	[16]	2015	Electric Power Systems Research	45
6	Rangaraju *et al.*	[17]	2015	Applied Energy	43
7	Yang *et al.*	[18]	2015	Renewable And Sustainable Energy Reviews	41
8	Weckx and Driesen	[19]	2015	IEEE Transactions on Sustainable Energy	41
9	Tan and Wang	[20]	2014	IEEE Transactions on Smart Grid	39
10	Pinto *et al.*	[21]	2014	IEEE Transactions on Vehicular Technology	37
11	Benyahia *et al.*	[22]	2014	International Journal of Hydrogen Energy	31
12	Mozafar *et al.*	[23]	2017	Sustainable Cities and Society	29
13	Wang *et al.*	[24]	2015	IEEE Transactions on Smart Grid	26
14	Hajforoosh *et al.*	[25]	2015	Electric Power Systems Research	26
15	Javadi and Al-Haddad	[26]	2015	IEEE Transactions on Industrial Electronics	26
16	Mocci *et al.*	[27]	2015	Electric Power Systems Research	24
17	Esmaili and Rajabi	[28]	2014	IET Generation, Transmission & Distribution	22
18	Moradi *et al.*	[29]	2015	International Journal of Electrical Power & Energy Systems	21
19	Soares *et al.*	[30]	2016	Applied Energy	20
20	Lucas *et al.*	[31]	2015	Electric Power Systems Research	20

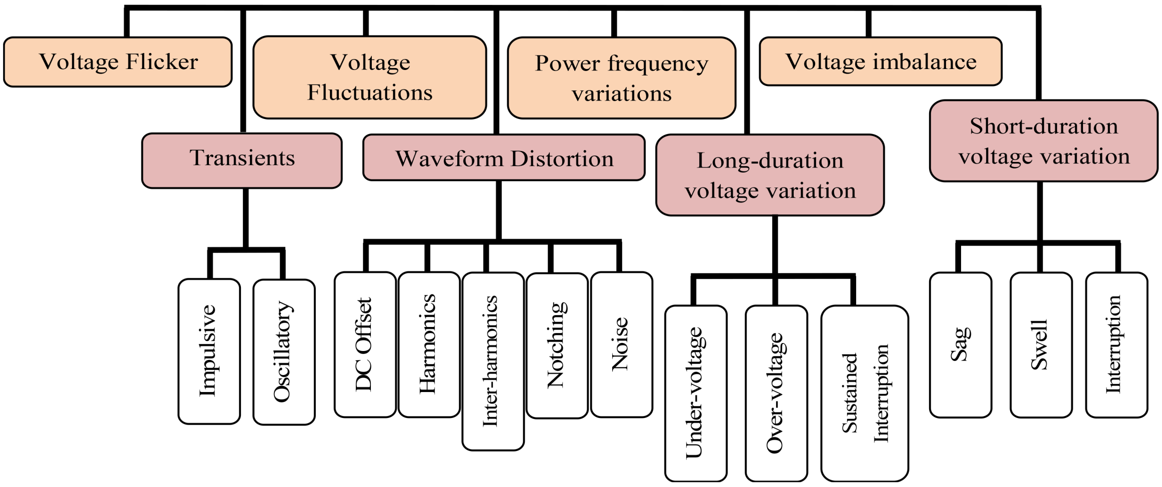

Fig. 1 *PQ issues classification [32–35]*

Table 3 Most frequent PQ issue characterisations [32–35]

PQ issue	Characteristics	Causes	Effects
voltage sag	magnitude: (0.1–0.9) V_{rms}frequency: power frequencyduration: 0.5 cycles to 1 min	motor startingsingle line to ground faultsconnection of heavy loads, EV*s*	protection malfunctionloss of productionmalfunction of some controllers
voltage swell	magnitude: greater than 1.1 V_{rms}frequency: power frequencyduration: 1 cycle to few seconds	capacitor switchinglarge load switchingfaults, EVsbadly regulated transformer	protection malfunctionstress on computers and home appliances
short interruptions	duration: few milliseconds to two seconds	temporary faults	loss of productionmalfunction of fire alarms
long interruptions	duration: greater than two seconds	faultsfailure of protection devices	loss of production
voltage imbalance	difference in three phase amplitude and/or phase angles	single phase loadsingle phasing	heating of induction motors
harmonics	frequency: multiple of power frequency	adjustable speed to driversnonlinear loads, LEDsArc furnaces, EVs, inverter-based DGs	increased lossespoor power factorelectromagnetic interfaces

also been increased. Despite the conventional power systems, power electronic devices as rigid non-linear loads have also been operated; their dispersion is not as much as modern power systems [34]. Along with DERs, the worldwide move towards decreasing the pollutant emissions invigorates the idea of the electrified vehicle in the context of EVs. Thus, it can be stated that besides the generation technology innovation, the nature of the electrical loads has also been altered. It seems that modern power systems are experiencing more non-linearity both from generation and demand sides. The electronic smart home appliances are strengthening factors which lead the system operators to be more concerned regarding the PQ issues. Adjustable Speed Drives (ASDs) and LED lamps are new alternatives which negatively impact PQ indices. HVDC lines, increased power line communications, and ever-increasing trend in replacing overhead lines with underground cables change the nature of the conventional power systems. The economic losses also become a critical restriction intensifying the importance of the research on the nature, causes and techno-economic and even environmental outcomes of the PQ issues [33, 34]. The unintended and probably novel impacts of the PQ issues stemmed from modern system innovations still require more research. However, some of them can be adopted based on the conventional system deteriorations as those listed in Table 3 [34].

4 Overview of EVs

In 1828, the first effort was made to utilise an electric motor to move a vehicle in 1834 while Thomas Davenport utilised an electrotherapy machine on the light rail [36]. In 1835, Prof. Sybrandvs and Christopher invented non-rechargeable batteries [37] for the propulsion system of a vehicle. In 1859, the acid battery was imagined by French physicist and opened the path for the rechargeable batteries [36, 37].

Until 1920, due to the innovation of the exhaust of an internal combustion engine, the EVs production almost ended. Moreover, the development of the electric starter and the revelation of oil field made internal combustion engines more popular compared to EVs [38]. Besides, low speed and also the need for battery replacement over short periods were other influencing factors for EVs in exacerbating this issue.

In 1996, 1117 EVs were manufactured by General Motors. However, they were just accessible to the states of California, Arizona, and Georgia, which there was an acceptable demand. In 2000, Prius was manufactured by TOYOTA in Japan and several years later it was distributed throughout the world [38]. Tesla presented a vehicle (Roadster) in 2011 which has a speed of 386 km/h, while, the price was set for >$100,000 [38].

After the accomplishment in the early 20th century, EVs slowly retook their previous position in the vehicle market contrasted with a different vehicle. Additionally, the Organization of the Petroleum Exporting Countries (OPEC) oil ban in 1973 [38] caused fuel costs to increase to a confounding rate and accordingly, the eagerness of organisations to observe contrasting options to be included.

In 2010, Nissan's BEV, i.e. Nissan Leaf was introduced in the United States, which it's driving range was around 160 km with a single charge while the price was $ 30,000. In 2017, Tesla designed the concept car as a vehicle for the mass market named ‘model 3’.

During the past few years, manufacturing EVs have been increasing steadily. All vehicle manufacturers have HEVs and PHEVs in their program, exceptionally the PHEVs and BEVs deals will drastically increase in 2018 [39].

The progress of the hybrid car market has changed the structure of traditional car manufacturing systems. In general, all vehicles that are linked to the integration of two or more power transmission systems directly or indirectly depend upon the transmission system.

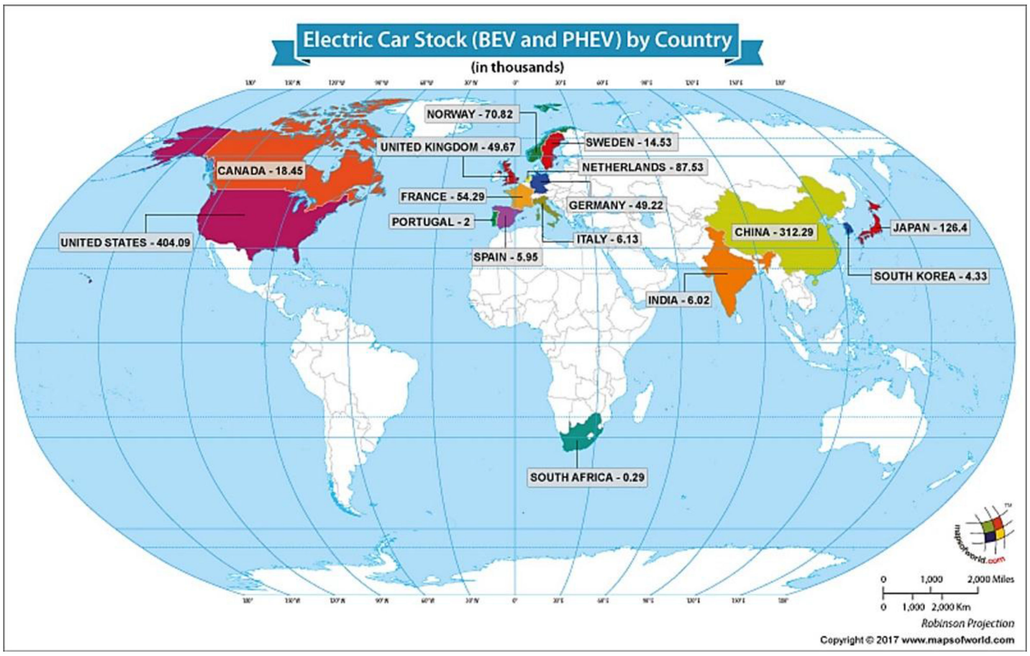

Fig. 2 *Rate of 2014 overall EVs activity countries [41]*

HEVs are usually a combination of internal combustion engines and an electric motor.

The research projected by the International Energy Agency (IEA) revealed that the total number of BEVs and PHEVs was 477,000 in 2015 while the target markets were China, the Netherlands, Norway, and USA [40]. The government of China had a target of putting 500,000 BEVs and PHEVs out on the town before the end of 2016, and 5 million by 2020.

Moreover, China has the best task force of battery-electric bicycles with >150 million in the organisation, and 36 million manufactured each year so that electric transports from 29,500 in 2014 increased to >170,000 in 2015 [40].

There were 1.45 million EVs' power supply outlets at the end of 2015 which around 162,000 of those were straightforwardly available direct outlets and 28,000 unreservedly open snappy outlets (China owned 44% at the end of 2015). Fig. 2 shows the rate of overall EV activity of countries in 2014 [41].

5 PQ in the conventional electrical networks using EVs

EVs as new components connected to conventional electrical networks can impact the PQ. The PQ of an electrical network is usually investigated in terms of voltage and frequency fluctuations, power losses, phase unbalance, and harmonics. In this section, the impacts of EVs on PQ issues are reviewed regarding the challenges and approaches as follows.

5.1 Voltage profile

EVs' charging can impact the network voltage problems such as voltage drop and voltage fluctuations. Many researchers have studied the impacts of EVs' charging on the system voltage. The Monte Carlo simulation technique was applied to investigate the impact of EVs' charging on the system voltage due to uncertainties in EVs' availability [42]. These influences can be significant [43] or insignificant [44] depending upon the number of EVs, network characteristics, and EVs' charging features. The study in [44] showed that the impacts of the charging power of such vehicles on an urban distribution network are minor with low penetration of EVs. Unlike [44], the research study in [43] concluded that with 50% penetration of EVs, network voltage deviations go beyond the standard level. In [45], the results indicated that six EVs with fast charging technology cause the standard voltage level of the network to violate.

The voltage regulation devices and strategies have been used in numerous research works to maintain the voltage of networks within the standard interval. The traditional methods including optimal capacitor bank installation and tap changer can be applied to mitigate the voltage deviation in the network [46, 47].

Charging management of EVs is another approach to improve the voltage profile of a network. Masoum *et al.* [48] investigated a smart load management control strategy through coordinating EVs' charging [48]. The results showed that the EVs' charging coordination with a feasible tariff and a time zone priority scheme successfully regulates the voltages in the system [48].

Also, the decoupled active and reactive power control strategy for EV chargers can be used to regulate the network voltage. The active power control adjusts the operation of EV charging, and the reactive power control can inject reactive power into the grid to support the network voltage [45]. Yong *et al.* [45] modelled a bidirectional DC fast-charging station which is capable of regulating the bus voltage through injecting reactive power. Yong *et al.* [49] designed and implemented a three-phase off-board EV charger prototype which can maintain a constant DC-link voltage as well as regulating the network voltage within the permitted range through injecting reactive power without negatively affecting the charging process.

Nowadays, EV charging control for voltage profile regulation can be taken into account as an approach for the distribution and transmission service providers.

- *LV distribution networks*: The main problems are the voltage drop in the peak load and the voltage rise due to the PV active power injection. Marra *et al.* [50] proposed the coordination between EV loads and the PV system to solve the voltage rise through simulating a home with rooftop PV and an EV. The results through simulating a home with rooftop PV and an EV show the applicability of this method [50]. Also, the study in [51] tested the coordination strategy on an Australian distribution system based on real PV and EV data. However, the study in [52] proposed the smart loads with back-to-back converters to mitigate the voltage problem due to EVs and PVs in LV networks. The results show the smart loads with back-to-back converters can regulate the bus voltage, although two converters are required [52].
- *MV-level networks*: García-Triviño *et al.* [53] studied the voltage regulation using a fast charging station with a decentralised Energy Management System (EMS). The results indicated the feasibility of the proposed technology to control the voltage with a decentralised control method disregarding a communication

interface [53] — also, Torreglosa *et al.* [54] investigated a decentralised EMS of a charging station using model predictive control (MPC) to regulate the bus voltage.

- *Transmission network:* Bayat *et al.* [55] evaluated the role of end-user devices such as EVs for the voltage control of the grid. In this study, an active support group is considered to regulate the frequency and reactive support group to control the voltage of the transmission bus. Rana *et al.* [56] investigated a modified droop control method including EV aggregators, wind and solar units, and diesel generators to control the frequency of a microgrid. To track the set point, EV aggregator can change the charging and discharging rates concerning EVs and State of Charge (SoC) limits [56]. EV converters can inject active and reactive power to support the grid during voltage ride-through conditions. During renewable energy transients, EVs can reduce the transient tension on the grid through injecting active power. Falahi *et al.*[57] showed that EVs perfectly supports the reactive and active power regulation during the ride-through conditions. The study in [58] showed the EVs' voltage support for the grid during PV transients as depicted in Fig. 3.

5.2 Phase unbalance

The EV single-phase charging in electrical grids can cause unbalanced operation of the system which can increase the power losses and violate the voltage limits in the system. In [59], the impact of EVs' charging/discharging on the voltage unbalance in a residential low voltage (LV) distribution grid has been evaluated using the Monte Carlo simulation method because of the uncertainties in EV charging rates and connection points. The results indicated that EVs insignificantly impact the voltage balance at the beginning of the feeder, although it can increase the voltage unbalance factor at the end of the feeder [59].

Voltage regulators can be used to minimise the unbalance index in a network. The energy storage units, feeder capacitors, and D-STATCOM are used to improve the PQ regarding the voltage unbalance and variations [46, 47].

Another method to improve the voltage unbalance factor is a phase reconfiguration approach. In [53], the economic aspects of a phase reconfiguration to mitigate the EVs' unbalance impacts on an LV distribution system has been assessed. The results obtained in [60] verified that a phase reconfiguration approach could reduce the EVs' unbalance impact through using the time-of-use tariff.

Moreover, EV charging/discharging management can decrease the phase unbalance problem. An optimal decision on the status of charging/discharging, connection points (phases *a*, *b* or *c*), and charging/discharging power rates can balance the voltage of a system. The study in [61] demonstrated that coordinating EVs' charging/discharging can significantly enhance the voltage unbalance factor.

5.3 Harmonic

Non-linear power electronic devices such as rectifiers in EV chargers cause injecting the voltage and current harmonics to the network [62]. Kim *et al.* [63] showed that the low penetration of EVs and slow charging rate insignificantly impact the network PQ regarding the harmonic distortion. However, the high penetration of EVs and fast charging rates may result in considerable voltage and current harmonic distortion [31, 64]. Furthermore, Deilami *et al.* [65] found that random EVs' charging could violate the standard level of the voltage harmonic.

There are conventional approaches to mitigate or eliminate harmonics caused by EV chargers [66]. Power factor correction in EV chargers or installing shunt active power filter for charging stations were investigated in [67, 68]. However, using a shunt active power filter probably causes current harmonic amplification [66].

Other research works like [69] considered EVs as harmonic compensators through absorbing or injecting harmonic currents from/to the network. EVs can also participate in harmonic and reactive power ancillary service markets [69].

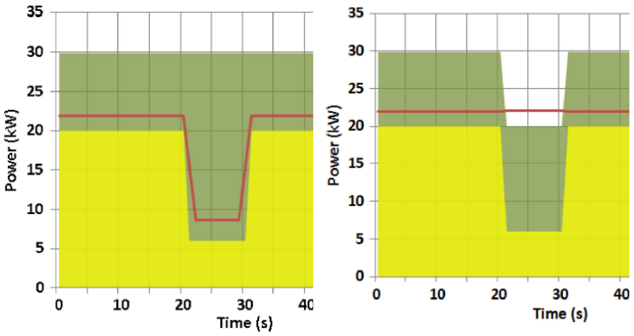

Fig. 3 *Feeder voltage under PV transients without EV and with EVs [58]*

Misra and Paudyal [70] indicated that low EV penetration could remarkably affect the current THD while wind generators as harmonic current sources can supply the common harmonic of EVs.

5.4 Power loss

Integration of EVs into the electrical grid influences power flow in the network. The increasing power flow results in more power losses throughout the power system and power components. There are numerous research works regarding the influence of EVs integration on power losses [71]. The authors of [72, 73] showed that the high penetration of EVs with uncontrolled EV charging could negatively affect the power losses in distribution systems. Masoum *et al.* [74] indicated that integrating EVs can increase the power losses of a distribution transformer up to three times for a large number of EVs.

Coordinating EV charging/discharging is considered as a solution to mitigate the negative impact of EVs' integration on the power losses in a network. In [75], the coordinated charging/discharging of EVs is proposed in a domestic area for peak-load shaving and system losses minimisation. Clement-Nyns *et al.* [76] used an optimal coordinated charging pattern to minimise the power losses through a stochastic programming technique. Also, according to [72], managing EVs' load can result in decreasing the power losses by 10%.

Luo and Chan [77] discussed a real-time scheduling method for EVs' charging to minimise either power losses or voltage drop in LV residential distribution systems based on the EVs availability [77].

Utilising another approach, EVs' load demand can be supplied with adjacent DGs to reduce the power losses in the network [71]. The EVs' charging demand can also be fully supplied only through renewable sources. The stochastic nature of EVs can be coordinated with the stochastic nature of renewable sources [78]. The optimal power losses can be obtained for the residential distribution networks by managing EVs' charging in coordination with renewable sources [79].

5.5 Frequency

In electric power systems, generation and load have to be equal in the real-time; otherwise, the grid frequency deviates from the standard value. If a high charging load from EVs is imposed on the grid, more power generation would be required to maintain the grid frequency within the permitted range [80]. Also, the departure and arrival times of EVs are associated with uncertainties. Therefore, power systems are likely to face increasing uncertainty from the demand side [78].

Load curtailment or Demand-Side Management (DSM) programs can be taken into account to balance load and generation in the grid. The coordinated control of EVs helps balance the power in the power system [80, 81]. EVs' aggregators can participate in a sizeable number in the energy and ancillary service markets. EVs have a much faster ramping capability than gas turbines, while it is a cheaper approach compared to conventional energy storage systems [78, 80, 82, 83].

There is sufficient literature regarding the impact of EV integration on the power system quality [44, 56]. Table 4

Table 4 Challenges of EV integration in relation to the PQ

Challenges	Remarks
voltage fluctuation	• Low impact with low penetration of EVs [43]. • High impact with 50% penetration of EVs [45]. • High impact with few EVs equipped with fast charging technology [72].
voltage unbalance	• High impact with a large number of EV single-phase charging's [73].
power losses	• High impact with a large number of EVs and uncontrolled charging system [74, 84]. • High impact with a large number of EV single-phase charging [73]. • High impact on the distribution transformers' power rates and power losses with a high penetration [31, 63].
harmonic	• Low impact with a low EV penetration and slow charging rate [65]. • High impact with a high EV penetration and fast charging rate [46]. • High impact with random EV charging [47].

Table 5 Methods to mitigate the impact of EV integration on the PQ

Impacts	Method	Remarks
impacts of EV integration on voltage profile	traditional voltage regulators	voltage regulation by [48, 49]: • Feeder capacitor bank. • Tap changer.
	charging management of EVs	A smart load management control by [61]: • Coordinating EV charging.
	decoupled active and reactive power control strategy	The active power control by EV charging, and the reactive power control by injecting reactive power into the grid to regulate the network voltage [60, 72].
impacts of EV integration on voltage unbalance	voltage regulators	To mitigate voltage unbalance by [48, 49]: • Energy storage units. • Feeder capacitor bank. • dSTATCOM
	EV charging/discharging management	To balance network voltage at connection points (phases *a*, *b* or *c*) by [75]: • Optimal charging/discharging status • Optimal charging/discharging power rates
	a phase reconfiguration approach	A phase reconfiguration method by using [76]: • The time of use tariff.
impacts of EV integration on power loss	coordinating EV charging/ discharging	To decrease power losses by: • Optimal coordinated charging/discharging EVs for peak shaving and losses minimisation [77]. • Optimal coordinated charging through a stochastic approach [78]. • A real-time scheduling method for EV charging in LV residential distribution system [79].
	coordinating with DGs	• Coordinating EV charging demands with DGs and RESs [56, 66, 67].
impacts of EV integration on harmonic	the traditional filters	To mitigate harmonic distortions by [68, 69, 73]: • A power factor correction in EV chargers. • A shunt APF for charging stations. However, using shunt APF could increase the current harmonic distortions.
	absorbing or injecting harmonic currents	Participating in harmonic and reactive power ancillary service markets [70].
	coordinating with wind generators	Consuming harmonic current components from wind generators by EV loads [85].

summarises and categorises the challenges of EVs integration regarding the PQ issues. Moreover, there are many research works regarding the mitigation of the impact of EVs on the PQ issues. Table 5 classifies and summarises the approaches to reduce the impact of EVs integration on the PQ.

6 PQ improvement in the smart grid using EVs

Previous chapters presented challenges in conventional grids' customer services such as active and reactive power issues. This section focuses on improvements in the grid services which can be achieved by using additional capabilities of modern grid components such as EVs. V2G capability of EVs can be utilised to enhance the PQ and grid service reliability.

One of the main conventional techniques to improve the grid's capability to provide a clean and stable supply to the end-users is to adopt Volt-VAR components. These components include transformers with on-load tap changers (OLTCs), voltage regulators (VRs), capacitor banks (CBs), as well as other industrial Volt-VAR control components in distribution grids [86].

Recently, a larger penetration of dispatchable resources in customer side including EVs has caused new challenges and at the

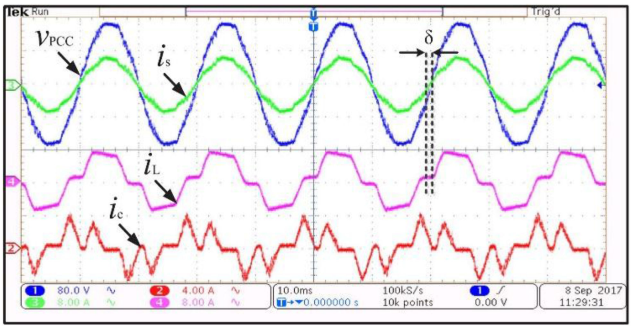

Fig. 4 *Experimental results indicating STATCOM and APF performance of EV chargers for PQ improvements [98]*

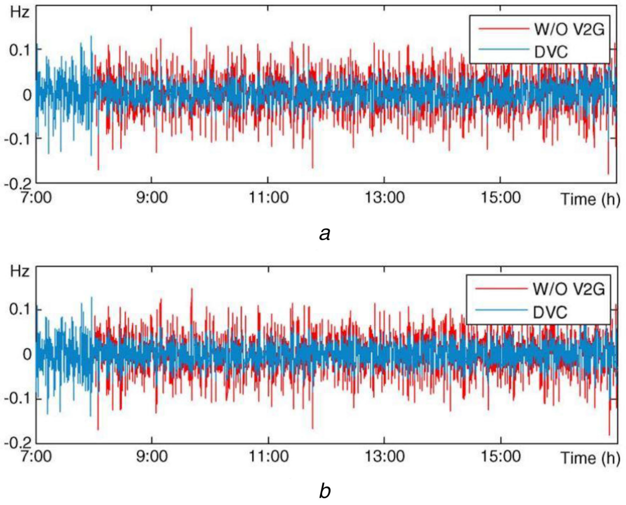

Fig. 5 *Frequency deviation in*
(a) EVs integrated into area A, ***(b)*** EVs integrated into area B [97]

same time has provided the distribution network operators with new opportunities. Although some system operators try to develop new algorithms and operational solutions to minimise the load impacts of the customer-side resources, others try to take the dispatchable resources, provided by customers, as new potential sources to develop new strategies to optimise the distribution grids to deliver new services to the end-users. This potential can be realised together with the recent evolutions in technologies, communication systems, and Information Technology (IT). Advanced Metering Infrastructure (AMI) using new meters provides Supervisory Control and Data Acquisition (SCADA) systems with extensive network data in a desirable format and resolution [87].

Various research works have investigated the effects of EVs on distribution grids with a concentration on grid-to-vehicle (G2V) massive loading impacts on the network [88–90]. Other studies have proposed coordinated EV charging algorithms to minimise the active power losses in the grid [91–93]. To improve the PQ in modern grids utilising services such as vehicle-to-grid (V2G), previous works have indicated that new multi-functional EV inverter technologies would enable the reactive power injection to the grid [94–97]. Therefore, shortly, a group of EVs in V2G operating mode can be utilised as reliable reactive power sources to remove issues caused by active and/or reactive power losses in the grid.

Specific PQ improvements, which are achieved by ancillary functions of the designed EV chargers from multiple studies, are (a) reduction of THD, (b) voltage regulation, and (c) reactive power compensation [87, 98].

For instance, a unified multi-functional on-board EV charger, which connects to a LV household network and improves PQ is designed and tested in [98]. The proposed EV charger in these work functions as a four-quadrant STATCOM and an active power filter (APF) during charging (V2G) or discharging (G2V) operations. The main advantage of such an on-board charger is the simultaneous improvements in all three areas mentioned above (contributions from (a) to (c)).

The experimental results from the implementation of such a multi-functional EV charger being displayed in Fig. 4. The green curve in this figure shows the improved grid-side current in an LV residential network. The PQ improvement in this work is achieved by injection of i_c to i_L by the proposed EV charger. The purple curve in Fig. 4 (i_L) shows the LV load curve before any PQ improvements with high harmonic distortions. The designed EV charger has reduced the harmonics of the grid-side current (i_S) by its APF functionality. Furthermore, this charger supports the reactive power demanded by inductive/capacitive loads as it could be observed in Fig. 4. This figure shows that the designed charger injects reactive power to the grid and as a consequence, i_S and $V_{\rm PCC}$ are synchronised (no phase shift is observed after reactive power injection). Hence, the designed charger shows multiple functionalities at the same time.

Apart from the harmonic reduction, voltage regulation, and reactive power compensation, other works have indicated that the frequency regulation could be achieved by utilising EV chargers, as well. In [97], V2G capability of EVs is utilised to provide primary (decentralised) frequency control services to the grid. A decentralised V2G control (DVC) method is proposed in the mentioned paper to achieve an adaptive frequency droop control.

A smart charging method, which simultaneously considers the frequency regulation, is developed in this study. Simulation results in a two-area (areas A and B) interconnected power system with wind power integration show the effectiveness of the charging scheduling method in that paper. Fig. 5 displays the grid frequency fluctuations in each area of the studied system. The red line represents the frequency fluctuations without utilising the V2G and the blue line indicates the frequency deviation in case of using the proposed charging schedule considering primary control (DVC). Based on the statistics reported in this paper, the maximum, minimum, and RMS frequency in area A before using the V2G capability are 0.1480, −0.1703, and 0.0369 Hz, respectively. After EV integration the values above are 0.0693, −0.0929, and 0.0216 Hz, respectively. It could be observed that the grid frequency deviation in the case of using V2G has been significantly reduced. This work is enhanced by the authors in [97] to bring a large number of EVs into a centralised Supplementary Frequency Regulation (SFR). The same interconnected power system in [98] is subject to a higher penetration of EVs in the latter paper. An EV aggregator unit is proposed in the improved work, which coordinates EVs and the power system control centre for centralised frequency regulation.

Fig. 6 illustrates different operating modes of AC/DC inverters in EV chargers. There are four operating states indicated in this figure. Quadrants I and IV represent charging in the inductive and capacitive operations, respectively. The most popular EV operating case is the border between these two quadrants, where $P > 0$, $Q = 0$. In this case, the EV consumes only the active power. Quadrant IV is the charging mode where the EV inverter consumes active power, and at the same time, it injects reactive power to the network. This feature of the aforementioned operating mode leads to boosting the capacity of the distribution grid, improvement in voltage profile, and reduction in reactive power losses [86]. Quadrants II and III refer to the discharging modes of the inverter in the inductive and capacitive modes, respectively. Discharging modes (V2G) are considered as a modern capability of EVs which can be used for enhancing the reliability and stability of the electrical grid where there is an urgent need for active/reactive power.

Some research works like [99, 100], showed that the required changes to the topology of the traditional EV chargers to make them bidirectional, are minimal. Experimental results in these studies proved that the ripple of the current in the DC-link capacitor in single-phase inverters is strong enough to operate in the capacitive mode. Yang *et al.* [99] proved that although the total losses of the EV chargers are slightly augmented in case of reactive power injection (compared to the normal operation), the EV battery and the input inductor current are not affected at all. In other words, the reactive power injection would not impact the lifetime

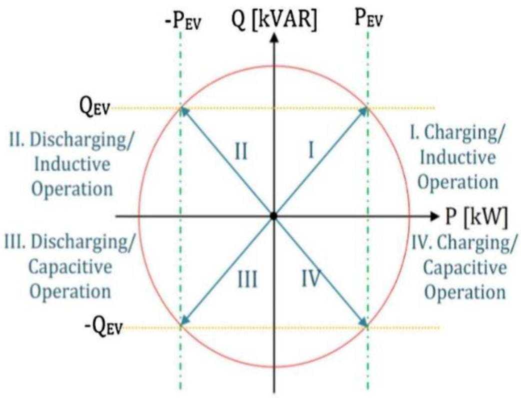

Fig. 6 *Different operating modes of an EV inverter [86]*

of the EV's batteries. Furthermore, considering the new generation of the multi-functional EV chargers, no harmonic mitigation measures are required [16, 99]. As depicted in Fig. 7, modern EV chargers for medium/large EV charging stations are capable of detecting the order of the harmonic current that exceeds the standards and filters them out to avoid EV harmonic effects. Harmonic detection and reactive power compensation are considered additional functionalities in a new generation of multi-functional EV chargers.

Apart from the research mentioned above, some research activities focus on the role of EVs in the V2G mode to enhance the power system operation in terms of reliability and demand recovery. In this context, dispatchable EVs are considered the reserve capacity to be used in case of outages in the system. For instance, results achieved in [100, 101] show the scenario when an outage occurs in the system, and local EVs are utilised to recover the demand during the outage as illustrated in Fig. 8. This can lead to a significant enhancement in the reliability of the grid and it is shown by calculating the widely accepted reliability indices such as System Average Interruption Duration Index (SAIDI) and Average Energy Not Supplied (AENS) as indicated in Table 6.

Fig. 8 indicates that the reserve capacity (reversible energy) by EVs reaches its maximum at night (around 24:00) when most of the EVs are connected and have enough SoC, while the minimum reserve capacity occurs in the morning (around 9:00 AM) where the majority of EVs are on the road.

Table 4 illustrates SAIDI and AENS calculation results in three different scenarios as listed below:

Case 1: a typical distribution network without DERs or parking lots.
Case 2: a typical distribution network with DERs, but without V2G.
Case 3: The same as Case II, with the addition of a parking lot with EVs participation ratio of 10% (30 EVs of a parking lot participating in case of emergency).

It could be observed from Table 6 that in case of using EVs during the outage in the studied distribution network (case 3), SAIDI and AENS, which represent the average number of the minutes of interruption and the energy not served per customer per year, respectively, have significantly dropped.

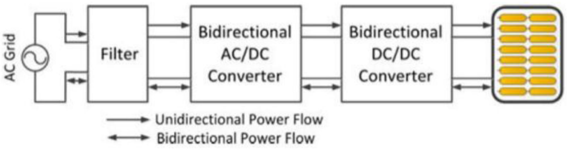

Fig. 7 *General unidirectional and bidirectional power flow topology [99]*

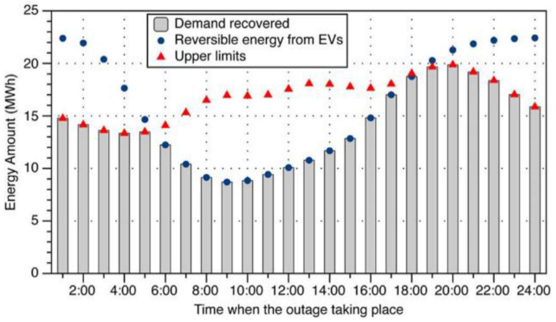

Fig. 8 *Demand recovered by local V2G with centralised EV charging [100]*

Table 6 Using EVs to enhance grid reliability [99]

Case	1	2	3
SAIDI, h/customer year	15.17	8.998	6.335
AENS, kWh/customer year	26.41	16.411	11.253

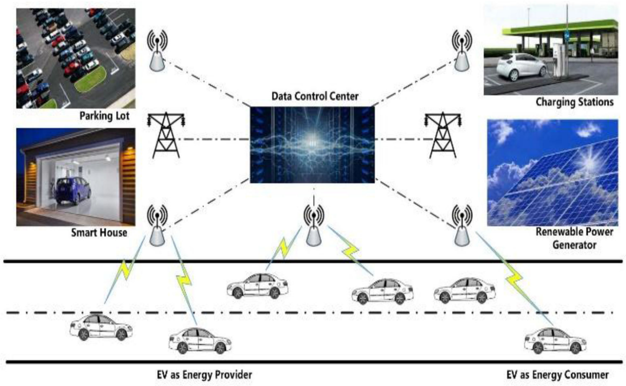

Fig. 9 *IoT-based V2V cooperative charging platform [105]*

Another aspect of PQ improvement is the coordination between EV chargers, which requires V2V communications. Internet of Things (IoT) platforms are developed in [102–104] to implement the cooperative V2V charging. For instance, Fig. 9 illustrates an IoT platform that facilitates the cooperative V2V charging. The key components of the platform are smart houses, EV chargers, charging stations, and communication/power infrastructure. In the proposed platform, each EV charger is equipped with a programmable board capable of bidirectional communications using the 5G technology while it can perform charging and discharging behaviour. Data control centre as the brain of the system, connects to all components above and collects information to process. After running the EV charging/discharging scheduling algorithm, the results would be sent back to the EVs. Direct EV-to-EV power transfer is considered in this work as an additional method of power transfer to the V2G and G2V operations. Hence, EVs can operate as energy consumers and energy providers in this work.

Also, other works have investigated the optimal energy utilisation for V2V charging strategies. In [104], the Lagrange duality optimisation method is utilised within a semi-distributed price-based V2V charging scheme to achieve low-cost energy transactions. The main components of the heterogeneous wireless network-enhanced architecture are shown in Fig. 10. Vehicle-to-road side units (RSUs) communicate with the base station (BS) of the cellular network to receive the charging/discharging decision for each specific time interval. Real-time information from each EV and the price control signals are frequently uploaded to the BS. The performance evaluation section of this research study proves that the proposed architecture can maximise the discharging revenues and minimise the charging costs for the V2V energy transfer applications.

There are pilot projects to investigate real-world trials on PQ improvements by EVs. European Commission Joint Research Center (JRC) has investigated fast charging impact on the THD due to the phase cancellation effects by on-field experiments. Harmonic histogram from a set of four types of fast chargers is reported in [107]. Full charging cycles are measured four times per charger

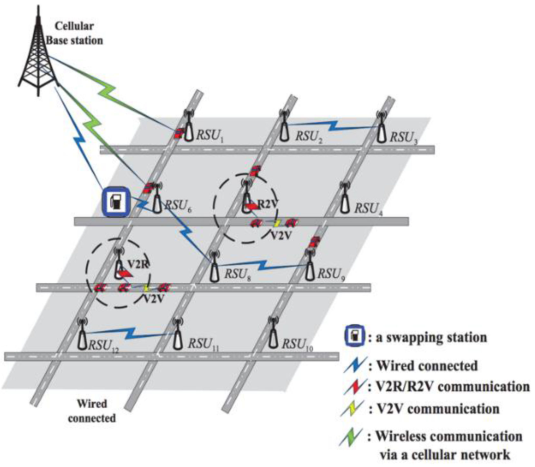

Fig. 10 *V2V charging architecture [106]*

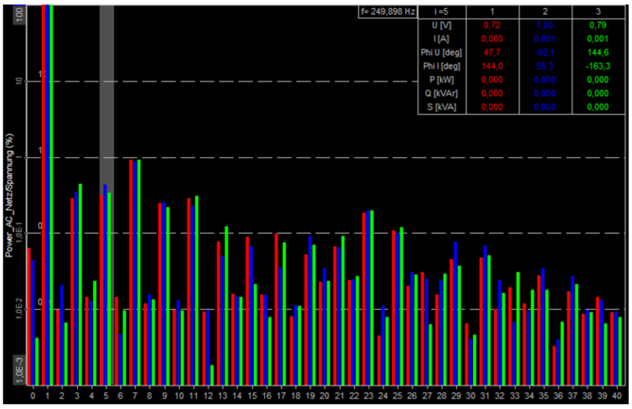

Fig. 11 *Harmonics of Nissan iMiev charging with 14A [108]*

and the THD for voltage and current are recorded and visualised in this technical report. It could be observed from the results that two of the chargers fail to comply with the standards and the harmonics are out of the limit of 4.5% for the 11th and 13th harmonics.

In another trial project, European Research Infrastructure supporting smart grid systems (ERIGrid) has presented an analysis of PQ through smart EV charging processes [108]. Renault Zoe, Tesla P90D, Nissan iMiev, and BMWi3 are tested to extract the constant current-constant voltage behaviour of EVs. This report displays the harmonic order of the real Nissan iMiev car charging at different levels as follows:

Fig. 11 shows that the highest harmonics are in the order 3, 5, 7, and 11 over the range of charging current between 0 A until 14 A. Based on this behaviour, smart chargers with harmonic detection algorithms are presented by this research institute.

Similar to the latter project, the electric power engineering division of the Chalmers University of Technology in Sweden has presented PQ issues for a fully-electric public transport system in Gothenburg city [109]. Instantaneous voltage and current waveforms during the charging at the highest level are recorded and exhibited in this work. The results of this article indicate the grid-side harmonic issues caused by a passive diode rectifier in the front end of the charger. This work recommends active rectification utilising power electronic switches as a solution to enhance the quality of the charger waveforms.

Overall, this section has presented the improvements in grid services to the end-customers to resolve issues in traditional services using new capabilities offered by EVs in the grid. EVs may bring new challenges into conventional optimisation algorithms running in the utilities for a long time, but on the other hand, they provide opportunities to enhance the stability, reliability, and voltage profile of the power system. To conclude this section, the PQ improvements offered by EVs can be categorised into two main classes:

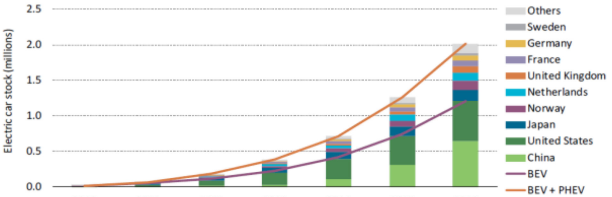

Fig. 12 *Global electric car stock evolution from 2010 to 2016 [110]*

i. *System-level improvements*: These improvements are achieved by using the aggregation of EVs. The V2G operation of groups of EVs can be used to enhance the reliability (demand recoverability) of the power grids as indicated by the results of multiple studies. These studies showed by the active power dispatch of aggregation of EVs, reliability indices such as SAIDI and AENS can be improved.
ii. *End-user level improvements*: These studies are related to individual improvements at each node of the grid (end-user side). As indicated by multiple studies, the new generation of EV chargers is capable of multiple functionalities such as harmonic detection, active power filtering, and reactive power injection. These additional functionalities significantly improve the voltage profile at every single node of the grid as displayed in the results of the studied articles.

7 Future trend

The past decade has seen the rapid development of EVs in many industrialised countries, as they can provide low-emission future and high power quality for power distribution systems. EVs are also appropriate to support synergies with different RESs. The global electric car stock evolution from 2010 to 2016 is depicted in Fig. 12 [108]. As can be observed, electric car stock exceeded two million units in 2016, and the highest electric car market belonged to Norway (29%) in 2016. Nevertheless, to attain a stable and secure operation, some technical and regulatory issues have to be settled before EVs can become commonplace.

Such developments in the field of EVs with over 750,000 sales worldwide in 2016 have led to the transition to electric road transport technologies [111]. The issue of wireless charging of vehicles has also received considerable attention in recent years. Even though this is not still viable, a key policy priority should be planned for the future as the situation may change. Moreover, vehicles such as trucks can get their required power from overhead lines like trains or trams [112]. To sum up, the electrification of the transport industry is undoubtedly one of the long-term ambitions in the field of EVs.

It is becoming increasingly difficult to ignore the role of smart-grids in the future of modern electric power systems. As mentioned before, V2G technologies allow power exchange between the EV and the utility grid. V2Gs are the link between smart grids as the future of conventional power systems and EVs as the future of vehicles [113]. Nonetheless, currently, there is not any proper infrastructure for integrating V2Gs in existing conventional utility grids. V2Gs can provide numerous services to the power grid such as ancillary services, peak load shaving, and DSM. Therefore, more research needs to be carried out on optimisation techniques, objectives, and constraints for the V2G implementation for the future V2G deployment. For example, congestion caused by the high V2G charging demand during particular periods of the day is one of the vital impacts of high penetration of EVs on the power system. Therefore, the government and power utilities must guarantee identical opportunities for all network users. Power and urban air quality, noise mitigation and greenhouse gas (GHG) reductions are also the main environmental benefits of using V2Gs in the power system. However, the accomplishment of the V2G technology requires the active participation and collaboration of the government, power utilities, and the EV owner.

Private and publicly accessible charging infrastructure is among the significant components in the EVs development path. There has been a sharp increase in the number of publicly accessible charging points with a 72% growth since 2015 [110]. The number of publicly accessible charging points peaked in 2016 with 320,000 units [108]. However, more attempts are required to be made by governments to implement new policies aimed at fully reaping the merits of EVs. Purchase subsidies, measures supporting EVs deployment, and fuel economy standards are some key tools that can be employed by policy makers [111]. Assessment of country targets shows that the electric car stock will range between 9 and 20 million by 2020 and between 40 and 70 million by 2025 [112, 114]. In other words, the EV market will change to the mass market adoption in the next 10–20 years.

As the number of EVs rises, charging and discharging of batteries can have a considerable impact on the capacity needed by the power grid at certain times and locations [113]. To make EVs more attractive, the current charging technologies must be enhanced. The reduction of battery charging time to make EVs more flexible and the provision of grid communication for chargers to facilitate smart metering and bidirectional charging are key aspects of EVs development in the future [114].

More policy adjustments are also needed for the transition from early deployment to the mass market adoption for electric cars [111]. EVs will become growingly cost competitive as a consequence of battery pack cost reduction. In a big EV market with enormous sales volumes, subsidies for EV will not be economically sustainable. Growing EV sale also leads to the reduction of revenues collected from conventional fuel taxes [110]. The decline will be significant in the countries with the highest fuel taxes. Tax based on distance travelled by the vehicle rather than the consumed fuel is one of the most suitable alternatives for moving beyond early market developments [110].

The demand for commodities required for battery manufacturing, like lithium and cobalt needed for future battery technologies will also be stimulated by large sales volumes [111]. Thus, better batteries with higher power density, lower cost and weight and larger capacities are essential for the future EVs deployment. Hence, most of the researchers are likely to go on emphasising better battery technologies, ultracapacitors, fuel cells, flywheels, and other individual and hybrid configurations. To put the EV market on an economic and environmentally sustainable trajectory, the price and availability of these resources must be controlled and checked. Battery reuse and material recycling will also play key roles in minimising the environmental impacts of their extraction and processing. Overall, the future trends in the integration of EVs in the power system are essentially related to

i. More research on the electrification of transport industry needs to be undertaken.
ii. Future studies on PQ improvements in smart-grids such as solutions for renewable energy intermittency issues using V2G technologies are also recommended.
iii. The accomplishment of the EV technology requires the active participation and collaboration of government, power utilities, and EV owners.
iv. More attempts are also needed to be made by governments to implement new policies with the aim of providing private and publicly accessible charging infrastructure and more policy adjustments to transit from early deployment to the mass market adoption for electric cars.
v. The optimisation methods are needed for the V2G energy management as it has to cater to the complex power system constraints and to achieve various objectives.
vi. Better batteries with higher power density, less cost and weight and larger capacities are essential for the future EVs deployment.
vii. One of the main future challenges regarding the PQ improvements using EVs is to design cost-effective on-board EV chargers that can offer provisions for ancillary services. These services include voltage regulation, reactive power compensation, and harmonic reduction while the EV operates in either V2G or G2V mode. This requires additional current measurement sensors which must be considered in the next generation of the EV chargers.
viii. Future research can be conducted on the design and implementation of the EV chargers offering the aforementioned ancillary services while simultaneously considering the lifetime of the EV battery.
ix. Technical feasibility of the DSM needs to be assessed.

8 Conclusions

As stated in the last paragraph of Section 6, challenges regarding the PQ improvements could be studied in system level and end-user level. Consequently, a multi-layer communication-enhanced infrastructure is required to realise the coordination between the key players. The first layer handles the coordination between the system operator and the EV aggregators for dispatching active/reactive power by sending charging/discharging commands (system level improvements). The second layer manages the coordination between end-users (EV owners) and the EV aggregator units (end-user improvements) for PQ improvements in LV networks. As discussed in Section 6, both modern and conventional communication systems are required to connect different aforementioned layers. The main challenge in PQ improvement is to develop EV chargers that operate as multifunctional four-quadrant STATCOM and an APF to simultaneously cover active/reactive power injection and harmonic reduction.

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