

Review

Review of Positive and Negative Impacts of Electric Vehicles Charging on Electric Power Systems

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Received: 23 July 2020; Accepted: 4 September 2020; Published: 8 September 2020



Abstract: There is a continuous and fast increase in electric vehicles (EVs) adoption in many countries due to the reduction of EVs prices, governments' incentives and subsidies on EVs, the need for energy independence, and environmental issues. It is expected that EVs will dominate the private cars market in the coming years. These EVs charge their batteries from the power grid and may cause severe effects if not managed properly. On the other hand, they can provide many benefits to the power grid and get revenues for EV owners if managed properly. The main contribution of the article is to provide a review of potential negative impacts of EVs charging on electric power systems mainly due to uncontrolled charging and how through controlled charging and discharging those impacts can be reduced and become even positive impacts. The impacts of uncontrolled EVs charging on the increase of peak demand, voltage deviation from the acceptable limits, phase unbalance due to the single-phase chargers, harmonics distortion, overloading of the power system equipment, and increase of power losses are presented. Furthermore, a review of the positive impacts of controlled EVs charging and discharging, and the electrical services that it can provide like frequency regulation, voltage regulation and reactive power compensation, congestion management, and improving power quality are presented. Moreover, a few promising research topics that need more investigation in future research are briefly discussed. Furthermore, the concepts and general background of EVs, EVs market, EV charging technology, the charging methods are presented.

Keywords: electric vehicles; uncontrolled charging; delayed charging; controlled charging; V2G; V2B; V2H; peak shaving; valley filling; congestion management; renewable energy sources

1. Introduction

Greenhouse gases (GHGs) emissions, global warming, and climate change are getting significant attention worldwide [1]. Countries aim to diminish the use of fossil fuel which is the main reason behind these issues. Most of fossil fuel consumption is in electricity generation and transportation sectors [2]. In 2014, 35% of the total energy consumption was by the transportation sector [3]. Electricity generation can cut fossil fuel usage by moving to renewable energy sources (RESs) instead of traditional nonrenewable generation and transportation sector can cut fossil fuel usage by moving to electrified transportation. With this transformation in the transportation sector, carbon dioxide (CO₂) emissions can be reduced [4,5]. The advancement in EV technology can lower the reliance on fossil fuels and leads to emission reduction [5]. Charging the EVs from a power grid with high share of RESs generation contributes more to decreasing pollutant emissions [6].

Electrified transportation like metros, electric trains, trolleybuses, trams, etc., are widely used in many countries public transportation and is considered a mature technology, but private electrified transportation like private EVs have not had large adoption in the past due to limitations in battery technology in terms of heavy weight, high price, short life, and long charging duration. Due to the breakthroughs and recent developments in battery technology, EVs are proposed as a competitor to traditional vehicles driven by gasoline due to the fast decline of EV prices [7]. Moreover, EVs produce no pollution (locally) and have a very high energy conversion efficiency compared to traditional vehicles because the internal combustion engine (ICE) is less efficient than the electric motor (EM). Furthermore, several countries already initiated governmental programs to increase EVs market share by financial subsidies and tax exemptions to motivate people to buy EVs. Additionally, many car manufacturers produce various types of EVs that have different specifications and prices. This gives the buyer a lot of options to choose from depending on his budget and car usage (i.e., long distance or short distance).

These EVs can be charged from large charging stations, street chargers, workplace chargers, and private home chargers [8], which will be supplied from the distribution network. It is expected that this new load which draws a large amount of electric energy from the power system in a short time will have harmful effects on the distribution network if not managed optimally and will foster the need for large infrastructure upgrades, which are an economic burden for utility companies. Therefore, comprehensive studies should be executed to understand and assess the characteristics of EVs load and probable effects they may have on the electric power system, especially the distribution networks [9], and consider this new load in the design, operation, and planning processes. Additionally, techniques to minimize and alleviate these negative effects and for optimal integration of EVs into the power grid should be developed [10].

A large number of research studies have investigated and assessed the impacts of uncontrolled EV charging on distribution networks due to uncertainties related to these studies. Many uncertainties should be considered like charging start time, the charger power rating, the charging location, EVs battery capacity, EVs battery state of charge (SoC) [11] when started charging, penetration level, and distribution network status. The studies assessed the impacts of uncontrolled EVs charging on distribution networks total power demand [12], transformer loading and life [13], cable loading [14], voltage profile [15], power losses [16], voltage and current unbalance [17], and harmonics distortion [18]. Moreover, various studies proposed solutions for optimal integration of EVs by delayed charging, smart charging, vehicle to grid (V2G) technology, vehicle to building (V2B) technology, and vehicle to home (V2H) technology, and how it can provide electrical services like frequency regulation, voltage regulation and reactive power compensation, peak shaving and valley filling, integration of RESs, spinning reserves, and improving power quality [19,20].

This paper is organized as follows: Section 2 presents a general background of EVs, EVs market, EVs types, the benefits and challenges of EVs, and EV charging technology. Section 3 presents the charging and discharging methods; for instance, uncontrolled charging, delayed charging, controlled charging, V2G technology, V2B technology, and V2H technology. Section 4 presents the negative impacts of uncontrolled EVs charging on electric power systems. Section 5 presents the positive impacts of controlled charging and discharging of EVs on electric power systems. Section 6 presents a few promising research topics that need more investigation in future research. Finally, conclusions are presented in Section 7.

2. Electric Vehicles Technology

An EV is a vehicle that is powered or driven, at least in part by electricity such as trams, metros, electric cars, electric trains, trolleybuses, etc. Most of the mentioned technologies are mature and widely used, except the private EVs (i.e., electric cars), but they are getting huge attention in the last years. EV technology is not new as it appeared in the 19th century powered by lead–acid batteries and it was not used a lot because the fuel-powered cars, i.e., internal combustion engine vehicles (ICEVs),

showed better performance at that time because the energy density of fuel was better than lead–acid batteries. Usually, EV terminology is widely used to refer to private electric cars and not to other electrified transportation methods like trams, metros, etc.

2.1. Electric Vehicles Market

Based on the 2019 global EV outlook report of the International Energy Agency (IEA) [7], there is a very rapid growth of EVs market. The report shows that the EVs stock crossed 3 million in 2017 and exceeded 5 million in 2018. China represents the largest EVs market, then Europe and the United States after that. Norway achieved the highest deployment of EVs with a market share of 46% followed by Iceland 17% and Sweden 8%. It is expected that the number of EVs will increase significantly in the coming years. The forecasts for EVs number at 2030 between 130 and 250 million. There are many EVs in the market now from several manufacturers (BMW, Chevrolet, Ford, Hyundai, Kia, Mercedes-Benz, Mitsubishi, Nissan, Tesla, Renault, Volkswagen, etc.) with different specifications (battery technology, battery capacity, electric motor power, electric range, and onboard charger power rating,) which gives a wide range of options for people interested in buying an EV. Although the fast increase in the EV market, it still represents a small percentage of the global passenger light-duty vehicles market currently. This means that EVs have a long way until they become capable of making a significance in GHGs emissions and oil demands.

It should be mentioned that large scale adoption of EVs will have economic impacts and they should be viewed from two points of view, the EV owners' point of view and the power grid point of view [21]. From the power grid point of view, a high-power load represented in EVs will be introduced, which means additional expenses in fuel and generation capacity [22]. The grid power losses will rise, although they can be reduced by the use of controlled charging approaches [23]. Several studies showed that the electric power system will have a significant power loss due to EVs charging with different penetration levels. The lifespan of transformers and cables in the distribution grid may decrease due to excessive uncontrolled charging. A study in [24] showed that controlled charging of EVs results in reducing the peak demand and 60% saving in the system cost. Therefore, the improvement in EVs charging infrastructure and charging strategies need attention to enhance the power grid economic aspects. From EV owners' point of view, various benefits can be achieved like reducing the operating costs due to lower electricity prices compared with fuel and higher efficiency of EMs used in EVs compared with ICEs used in ICEVs [25]. On the other hand, the high initial cost of EVs due to the expensive batteries used compared with ICEVs represents a considerable challenge. Mass production of EVs, advancement in battery technology, new charging infrastructure and smart charging strategies, and providing rewards and incentives to EVs owners may control the high initial cost of EVs [26–28].

2.2. Types of Electric Vehicles

There are many types of EVs categorized according to the energy converter (i.e., ICE or EM) used to propel the vehicle, the power source (i.e., battery, fuel cell, or gasoline), and if it charges from an external source (i.e., charging station or home charger) [4]. A brief explanation of those types is presented in the following subsections. The basic structure of different EVs types is shown in Figure 1.

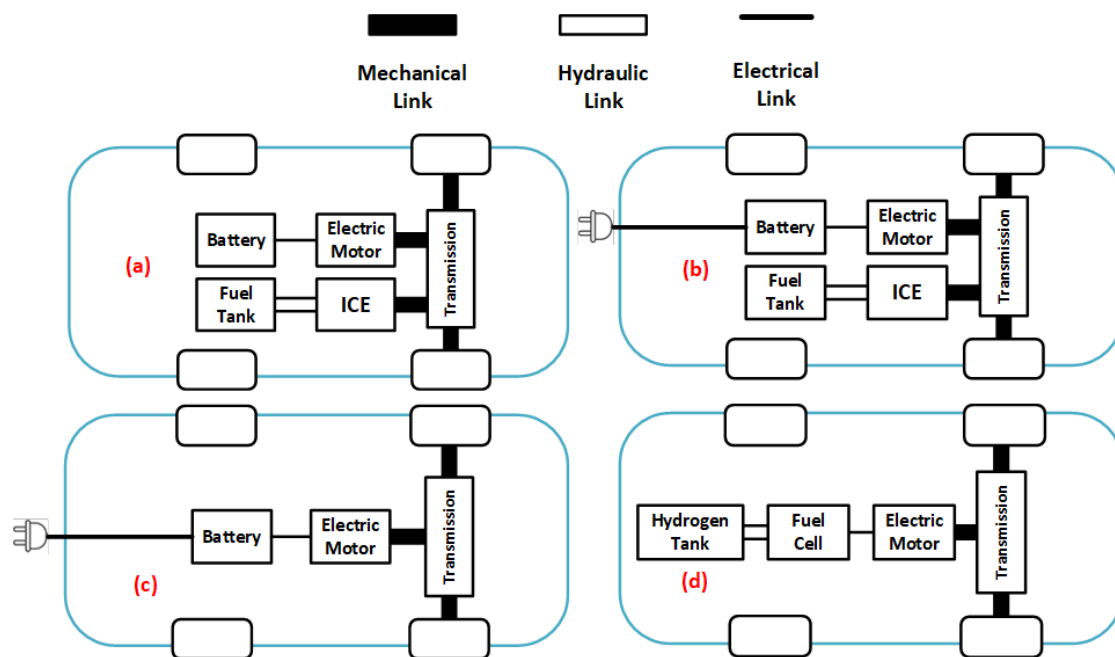


Figure 1. Basic structure of different electric vehicles (EVs) types. (a) Hybrid Electric Vehicle (HEV); (b) Plug-in Hybrid Electric Vehicle (PHEV); (c) Battery Electric Vehicle (BEV); and (d) Fuel Cell Electric Vehicle (FCEV).

2.2.1. Hybrid Electric Vehicle (HEV)

HEV is similar to ICEV but with oversized EM and battery. The battery can be charged by regenerative braking and by the ICE at light loads. Usually, battery and EM drive the vehicle at lower speeds and the ICE drives the vehicle at higher speeds. Furthermore, EM can assist the ICE at high load and enhance vehicle performance and efficiency. HEV has lower GHGs emissions and fuel consumption than ICEVs. In this type, no charging from distribution network by EV charger is used [29,30]. Therefore, it does not result any negative impacts on the power system due to battery charging and cannot provide any electrical services. There are different structures of this type [29]: series, parallel, series/parallel, mild, and complex HEVs, in addition to series/parallel plug-in hybrid electric vehicle (PHEV) which is explained in the next subsection. The basic configuration for parallel HEV is shown in Figure 1a.

2.2.2. Plug-in Hybrid Electric Vehicle (PHEV)

This is a HEV, but its battery can be charged by regenerative braking, by ICE, and EV charger supplied from distribution network as well. It is characterized by larger EM power, smaller ICE, and larger battery capacity compared with HEV in order to extend the electric range. It can operate in all-electric mode and use EM only which results in zero GHGs emissions. The capacity of the battery specifies the range of electric operation [29,30]. This type usually has a small battery capacity. Therefore, it is expected that it has a limited negative impact on electric power system. Moreover, its ability to provide electrical services is limited. PHEV can be in any hybrid configuration. The basic configuration for parallel PHEV is shown in Figure 1b.

2.2.3. Battery Electric Vehicle (BEV)

BEV is expected to dominate the EVs market with future advancements in battery technology and price reduction. BEV contains only EM which is powered by a battery and does not contain ICE. The electric driving range depends on battery capacity. The main advantage of this type is that it produces no emissions locally, which is very crucial in big cities. There are many configurations of

this type [29] depending on different companies' designs but the basic configuration and principal components are shown in Figure 1c. The battery is charged from the distribution network by different kinds of EV chargers. Moreover, during deceleration and braking of EV the motor operates as a generator and produces electric energy that charges the battery. This is called regenerative braking which is used in other public electrified transportation like metros and trams too. To enable regenerative braking bidirectional DC/AC converter is used. It allows electric energy to flow from battery to AC motor in the driving mode and from the AC motor to the battery in braking mode [29,30]. The main challenge for BEV is the long charging period and limitation of public charging infrastructure. This issue will be tackled in the near future with the advancement in battery technology which will extend the electric range that the EV can drive before the need to be recharged. Furthermore, the large-scale deployment of public fast charging stations will reduce EV owners range anxiety. Moreover, in the future, BEV manufacturers may enable battery swapping. This means replacing the empty battery with a fully charged one in battery swapping station which needs a very short time. More details about battery swapping are given in Section 2.4.3. This type of EVs has the largest battery capacity and its charging can result in a severe negative impact on the power system if not managed properly. Additionally, its ability to provide electrical services is higher than other EV types.

2.2.4. Fuel Cell Electric Vehicle (FCEV)

FCEV is powered by EM like BEV, but it uses a fuel cell instead of a battery. The vehicle is refueled with hydrogen and the fuel cell converts hydrogen gas chemical energy to electric energy which powers EV motor. Hydrogen can be produced from fossil fuels like natural gas or water electrolysis. FCEV has short refueling time like ICEVs [29,30]. The basic configuration of FCEV is shown in Figure 1d. It can also work with a combination of battery and supercapacitors. If no battery is used, this vehicle type will have no impact on the power system because it does not need electric charging from distribution system.

2.3. Benefits and Challenges of Electric Vehicles

It is essential to introduce the advantages and disadvantages of conventional vehicles which are dominant in the market now. Table 1 shows the advantages and disadvantages of ICEVs. The disadvantages of ICEVs might be a big problem in the future of the transportation sector. This was the reason to look for some alternatives. EVs appeared as a promising solution to some of these disadvantages.

Table 1. Advantages and disadvantages of internal combustion engine vehicles (ICEVs).

Advantages	Disadvantages
Long range	Low efficiency (15 to 35%)
Fast refueling	No regenerative braking
Low cost per unit of power	Pollution due to exhaust gases
	Noise

EVs show many benefits compared with ICEVs but few challenges must be faced to increase EVs adoption. Table 2 shows both the benefits and challenges of EVs [29,31]. Because both traditional vehicles and EVs have their strengths and weaknesses, hybrid vehicles (i.e., HEVs and PHEVs) with several configurations appeared, which try to combine the strengths of both types and avoid weaknesses.

Table 2. Benefits and challenges of EVs.

Benefits	Challenges
Emissions are localized at power stations and not in cities which improves citizens' health	Limited electric range
High efficiency because of high electric motor efficiency	Limited number of charging stations and long charging (refueling) time
Low (for PHEV) or no emissions (for BEV)	Negative impacts on the power grid if uncontrolled charging is used
Fuel or energy independence from countries which produce fuel	Consumer acceptance
Simple transmission, fewer moving parts and low maintenance	High prices
Less noise pollution	Battery low energy density
Provide electrical services to the power system and helps the RESs integration.	Expensive battery and needs replacement after few years

2.4. Electric Vehicles Charging Technologies

EVs charging can be classified into three main technologies: conductive charging, wireless (i.e., contactless) charging (WC), and battery swapping. Conductive charging is the simplest and the currently used charging method. For conductive charging, there is physical contact (i.e., cable) between the power supply and battery but for WC there is no physical contact. WC and battery swapping are not widely used like conductive charging and still under study and development. The following subsections will provide more details about these technologies. Figure 2 presents classification of different charging technologies.

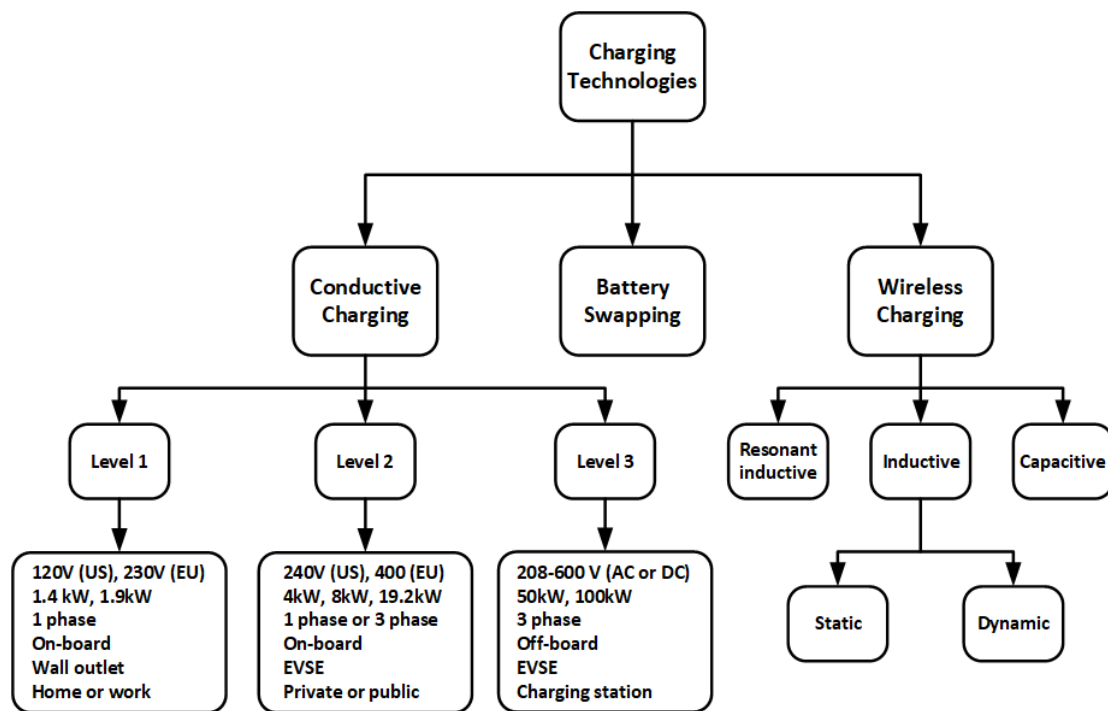


Figure 2. Classification of EVs charging technologies.

2.4.1. Conductive Charging

EV battery chargers have a significant responsibility in the advancement of EVs because the EVs adoption and social acceptance depends on the effortless access to charging stations or street chargers. Several topologies were presented for single phase and three phase EV chargers [32,33]. It consists of AC/DC converter, power factor correction elements, and DC/DC converter as shown in Figure 3. Charger systems are classified to on-board (i.e., inside vehicle for slow charging) and off-board (i.e., outside vehicle for fast charging). Moreover, they can be classified to unidirectional or

bidirectional chargers [34]. Unidirectional charging has simple charging hardware and allows power flow from grid to EV only. Bidirectional charging allows power flow from the grid to EV and can inject power from the EV battery to the grid, building, or home.

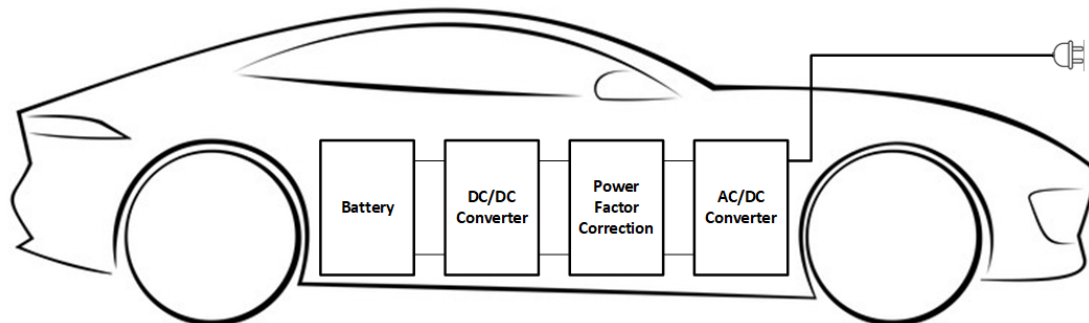


Figure 3. Onboard EV charger components.

Availability and advancement of EV charging infrastructure can decrease the required onboard energy storage and decrease the range anxiety of EV owners. According to the Society of Automotive Engineers (SAE) Standard J1772 [35], there are three charging levels. Most of the EV owners are expected to charge at home overnight according to the Electric Power Research Institute (EPRI) so Level 1 and Level 2 chargers will be the primary option [36], while level 3 will be used for commercial charging stations.

- **Level 1 Charging**

This is the slowest charging way and the simplest because no additional infrastructure is needed, and any wall outlet can be used. In the US, a standard 120 V/15 A wall outlet is used for Level 1. It is available only as an on-board charger. Although its cost is less than other charging levels, the EV needs a long time to be fully charged. Due to its low power rating, this charging level has the lowest impacts on distribution systems.

- **Level 2 Charging**

Level 2 charging uses 208 V or 240 V at currents up to 80 A, and 19.2 kW charging power. EV owners prefer Level 2 compared with Level 1 because of its shorter charging time. It may need dedicated electric vehicle supply equipment (EVSE) installation for public or home charging. Some EVs like Nissan Leaf have an on-board charger of this charging level.

- **Level 3 Charging**

Level 3 is for fast charging and it operates as a commercial refueling station (i.e., less than 1-h charging time) similar to the conventional gas station which can be installed at city main roads and highways. It is supplied from a three phase circuit with 480V or higher voltages. It is available only as an off-board charger because the charging power is high and may exceed 100 kW. It is clear that level 3 charging is not suitable for home charging. It has a high installation cost, and this represents a potential issue. It is expected that public chargers will use Level 2 or Level 3 for fast charging in shopping centers, parking lots, restaurants, hotels, theaters, etc. High charging power represents an advantage from charging time point of view, but it may generate a peak demand and overload the distribution network equipment in addition high installation cost.

2.4.2. Wireless Charging (WC)

WC enables EVs charging without physical contact or cable between the power supply and battery. Advancement of WC will reduce the required onboard battery capacity which will decrease EVs price and mass, which will result in reduction of EVs energy consumption. WC may become a future alternative for traditional conductive charging. WC has a potential to be used for charging electric bus batteries [37]. It can operate at different voltages (level 1, 2, and 3). The highest efficiency recorded for WC is 90% [38]. There are three main technologies of WCS: inductive, resonant inductive, and capacitive WC [39,40].

Inductive wireless charging (IWC) will be explained to provide the basic idea of this technology. The IWC contains AC/DC converter that converts AC power supplied from electricity grid to DC. Then, it is converted again to AC power with high frequency fed to transmitting (i.e., primary) coil. All these components are in the street underground. The EV contains receiving (i.e., secondary) coil that receives power from transmitting coil by electromagnetic induction through the air gap. Then the AC power is converted to DC by AC/DC converter and charge the battery [41]. A simplified diagram of IWC that explains the main concept is shown in Figure 4. IWC can be classified into static inductive charging and dynamic inductive charging. For static inductive charging, EV must be stationary during charging. However, dynamic inductive charging allows WC while EV is moving [42].

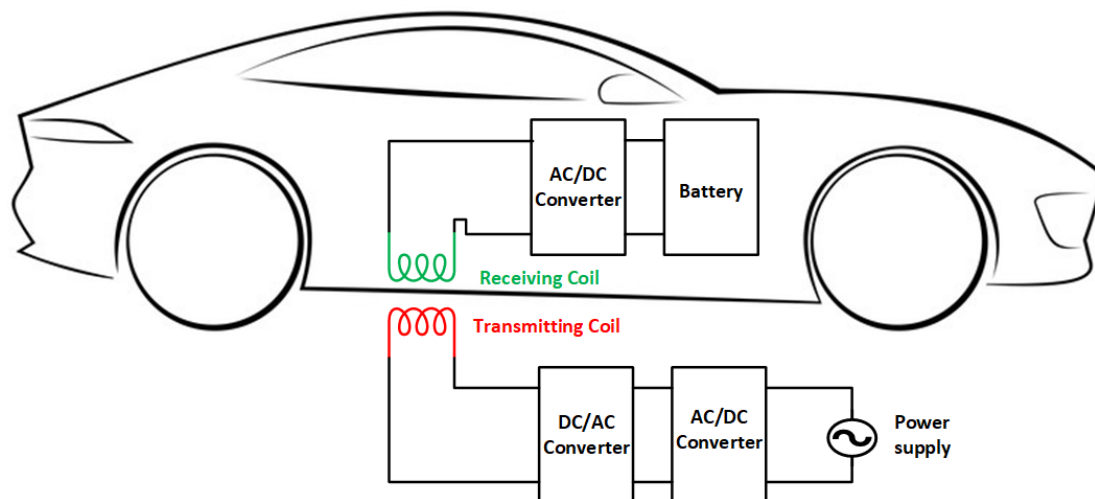


Figure 4. A simplified diagram of inductive charging.

Current WC is designed for unidirectional power flow from grid to vehicle, but future development of this technology is to enable EVs to discharge power to the grid wirelessly to provide electrical services. The advantages of this technology are electrical safety, no cables needed, and user convenience. The challenges of this technology are the high infrastructure cost compared to conductive charging, and low power transfer efficiency between coils [40].

2.4.3. Battery Swapping

Battery swapping station (BSS) is a charging station at which the empty EV battery will be replaced by a fully charged battery in few minutes [43]. Battery swapping may be used with electric buses that have a high capacity battery which will take a long time to be charged by traditional conductive charging. This technology requires a large stock of batteries owned by the BSS or a third party and rented to EV owner. BSS contains a distribution transformer, AC/DC converters to charge the batteries, batteries, and battery swapping equipment [44,45]. Some studies considered that BSS can use bidirectional chargers to provide electrical services by V2G mode [46,47]. The challenges of this technology are battery standardization, high infrastructure cost, and large space for BSS. In 2013, Tesla company revealed a battery swapping system that can swap the battery in 90 s [48].

3. Charging and Discharging Methods

Charging methods can be classified into two main categories, unidirectional and bidirectional charging. In unidirectional charging the energy flow is only from the grid to EV (i.e., uncontrolled charging, delayed charging, and controlled charging). In bidirectional charging, energy can flow from the grid to EV and from EV to the grid or loads as buildings, or homes (i.e., V2G, V2B, and V2H). Figure 5 presents the classification of different charging and discharging methods. Figure 6 shows how the total power demand profile of distribution system will change with different EV charging or discharging methods [10].

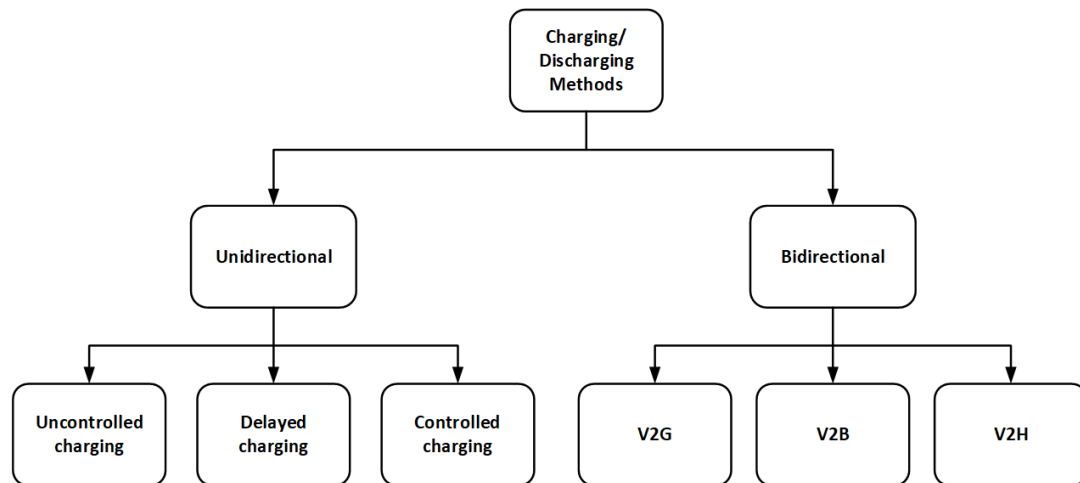


Figure 5. Classification of different charging and discharging methods.

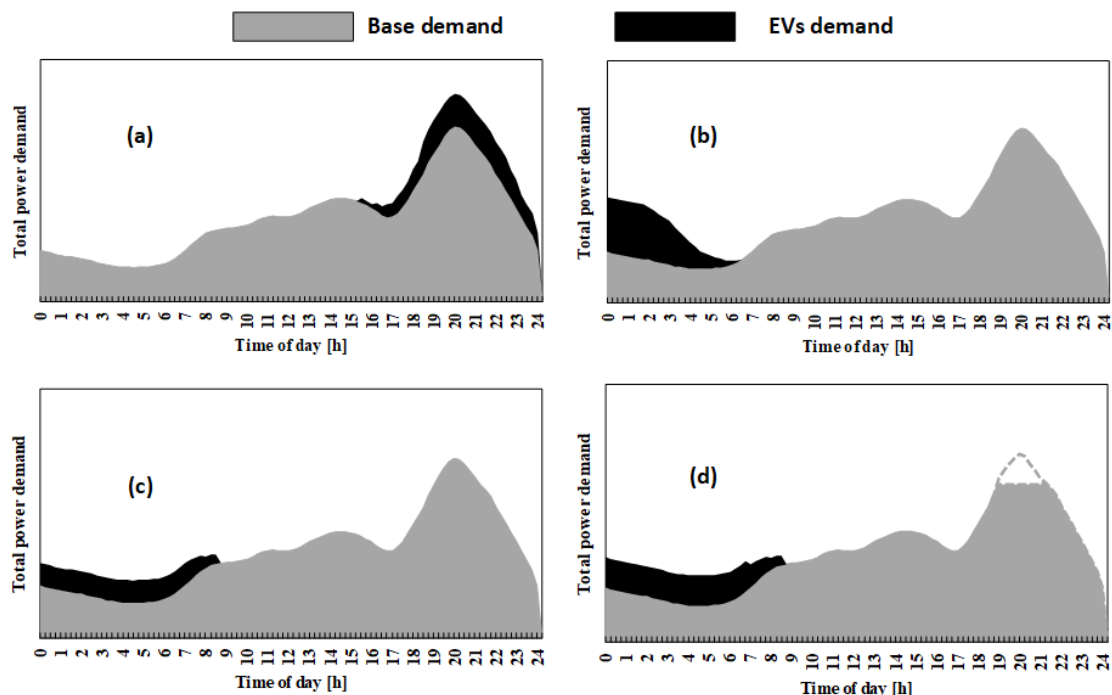


Figure 6. Total power demand profile with different charging and discharging methods. (a) Uncontrolled charging; (b) Delayed Charging; (c) Controlled Charging; and (d) V2G, V2B, and V2H.

3.1. Uncontrolled Charging

This is the simplest method to charge EVs and the current used way. The EV is plugged in for charging at the maximum power rating of EV charger until the EV battery is fully charged (i.e., state

of charge (SoC) is 100%), similar to any electric device with a battery (i.e., laptop, smart phone, etc.). Several studies concluded that uncontrolled charging of EVs may result in severe negative impacts on distribution networks such as increase in peak load demand, overloading of transformers and cables and shorten their life, increase voltage drop, increase system unbalance due to single phase chargers, increase power losses, and increase harmonic distortion [49,50]. Moreover, this type of charging limits the EVs acceptable penetration level, because EV owners charge their vehicles when arriving home from work, which usually coincides with peak hours as shown in Figure 6a. The figure shows the total power demand of residential consumers during the day [51] before connecting EVs (in grey) and how the total power demand will change when EVs are connected to the distribution network for charging. Furthermore, it will accelerate the need for infrastructure upgrade. This charging method is also known as dumb charging, uncoordinated charging, and unregulated charging.

3.2. Delayed Charging

The severe impacts of uncontrolled charging can be alleviated with the use of delayed charging. In this case, the utility has different electricity prices during the day with low price at off peak time (i.e., time utility wants EV owners to charge at) and high price at peak time (i.e., time utility does not want EV owners to charge at). This method controls the charging time and not the charging power (i.e., EV charge at charger maximum power rating). With the optimal design of electricity tariff prices during the day, it can work as an incentive for EV owners to charge their vehicles on low price times which maximize both utility (i.e., distribution system operator (DSO) or distribution company) and EV owners benefit and result in valley filling as shown in Figure 6b. Although this method is a very simple technique to flatten the load profile and shift the load to off peak time, non-optimal design of electricity price, can incentivize a large number of EV owners to charge at off peak times, which may result in a second peak especially at the beginning of off peak time. Moreover, this method ignores EV owners' preferences and needs to charge their EVs at different times during the day. This charging method is also known as off peak charging, and indirect controlled charging with time of use pricing [52,53].

3.3. Controlled Charging

Although delayed charging has less impacts on distribution networks than uncontrolled charging, it has limitations. These limitations can be surpassed using controlled charging. This method controls the charging time and charging power of EV depending on some distribution network parameters like total power demand, transformer loading, voltage stability, power losses, etc., or to minimize the charging cost. In this technique, EV acts as a controllable load. Various studies proposed controlled charging algorithms for maximizing EV owner benefit by charging cost reduction and maximize utility benefit by distribution network stress and losses reduction, enhancement of power quality, and shifting the EV load to off peak hours which result in valley filling [54,55] as shown in Figure 6c. This charging method is also known as coordinated charging and smart charging.

Controlled charging can be classified as centralized, decentralized, and autonomous control architecture [56]. In centralized control, a central controller collects data such as electricity prices, system loading condition, EVs status, and owner preferences; based on this data the controller determines the set points of controlled EVs. Although centralized charging control usually results in optimal use of the system and enables EVs to participate in many electrical services, it has few disadvantages. There are privacy issues because all users data can be accessed by the central controller, the need for expensive two way communication infrastructure, large data amount must be processed, which is a high computational burden, any problem in the central controller or loss of communication can lead to severe consequences, and a large number of messages should be communicated in a short period which can result in communication issues. Moreover, most of the utility companies do not use real time pricing, which makes this method inapplicable currently [56].

In decentralized charging control, the control entity (i.e., DSO or aggregator) sends signals to EVs like electricity prices to incentivize them to take a specific action such as reducing their charging power or stop charging at peak hours. In this case no need to send EVs private information to the control entity. Although decentralized control methods need a cheaper processing and communication infrastructure compared with centralized control methods, they have few disadvantages. The optimal utilization of the system is not ensured, their ability to participate in ancillary service markets is limited and they are vulnerable to variations in customers behavior [56].

In autonomous charging control, the charging power is regulated based on local inputs such as voltage and battery SoC without any communication between EVs and control entity [57,58]. Usually, autonomous charging control is classified as decentralized control with no communication. Although this control architecture is the single option for distribution systems with no communication facilities and it can enable the integration of a larger number of EVs to the power grid in its current status, it has few disadvantages. Their ability to participate in ancillary service markets is limited, they are vulnerable to variations in customers behavior and the system cannot be operated optimally [56].

3.4. Vehicle to Grid (V2G)

This refers to the capability of EVs to supply power to the distribution network and operate as distributed energy storage devices. Bidirectional EV chargers are used to enable the electric power to flow in both directions from grid to vehicle (i.e., charging) and from vehicle to grid (i.e., discharging). When there is surplus electric energy (off-peak times) EVs will charge, which is called grid to vehicle (G2V) mode, and when there is a deficit in electric energy and consumption is higher than generation, EVs will supply power to the distribution network and this enhances the system reliability and efficiency [59]. So EVs can be seen by utilities as load and source. Because EV power and energy are limited and approximately have no effect on the power system, usually an aggregator is the responsible for aggregating EVs power or energy, which are located in geographical area to participate in electrical services.

The interaction in this case is between EV and power system management organization like DSO, which has to operate the power system in a reliable way. V2G can provide many grid services such as frequency regulation, spinning reserve, enabling the integration of more RESs, and peak load shaving and valley filling [60] as shown in Figure 6d. Other benefits of V2G is generating revenues for EV owners, and decrease emission and operating cost if grid services were provided by traditional nonrenewable generation [60]. Although this is a very promising technology regarding providing electrical services to the power system, it has many challenges and barriers. This technology is very complex and needs many infrastructure changes because it needs bidirectional chargers and continuous two-way communication between EVs and system operator or aggregator. Moreover, it is expected that continuous charge and discharge of EV battery may lead to battery degradation and shortening its life. In contrast, new studies concluded that EV can participate in V2G without battery degradation [61].

3.5. Vehicle to Building (V2B)

V2B is similar to V2G but in V2B there is no communication between the vehicle and the grid, and it only communicates with the building so the energy stored in the EV battery can be used to supply the building loads only. The use of V2B mode can be very effective during peak load times and outage conditions. EVs are used as an energy storage device and operates in two modes: G2V and V2B. It operates in a G2V mode to charge the battery at low cost when the grid is lightly loaded and there is surplus electric power generation. It operates in a V2B mode to supply the building loads when the electricity price is high at peak hours [62]. By doing this V2B is providing peak shaving and valley filling which is utility benefit and reduce building expenses by discharge at periods with high electricity prices and reduce building demand from the grid. This method is simpler than V2G as it operates behind the building meter, but it provides less electrical services to the power system. V2B involves one building (i.e., many homes) and many EVs.

3.6. Vehicle to Home (V2H)

This is very similar to V2B but in this case, only one home is involved and not a whole building as in V2B and only one EV. Normally EV absorbs power from home and can supply power to home when needed. It needs a simple architecture compared to V2G and V2B and can provide less electrical services to the power system compared to them. It can flatten the house daily load profile and reduce house consumption during peak hours with high electricity prices. Local energy production from photovoltaic (PV) or small wind generation can be effectively used by storing the excess generation in EV battery and use it when needed [63,64].

4. Negative Impacts of Electric Vehicles on Electric Power Systems

Uncontrolled charging of EVs with high penetration levels is expected to introduce unwanted negative impacts on the power system. The possible negative impacts are the impact due to increase of peak demand, voltage deviation from the acceptable limits, phase unbalance due to the single-phase chargers, harmonics injection, overloading of the power system equipment, and increase of power system power losses [65]. A large number of studies have investigated these impacts because the estimation of EVs charging impacts is based on several conditions [65] and have many uncertainties that must be considered and modeled properly in the study to accurately estimate the impact of EVs charging on the power systems, the main key variables are [66,67]:

- **EV battery charger**

Depending on the charging infrastructure and the EV model single phase or three phase chargers may be used for charging. Moreover, there are many power ratings for EVs chargers operating at different voltage levels. So, the fast chargers are expected to increase the peak demand in a larger value compared with slow chargers.

- **Time**

The time of connecting the EVs for charging is not certain so it is unknown how many EVs may be charging at the same time and the probability that the EV charging time interferes with the peak demand time of the distribution networks. Some studies assume the charging start time of EVs, and other studies make surveys in a geographical area or a city to know the home arriving time of vehicles and model it as probability distribution.

- **Location**

The place at which an EV charge is random. EV owner may charge at home, friend's home, street charger, or charging station. It may be different from distribution network to another where are the charging locations and what are the EV charger type (i.e., private or commercial chargers).

- **Battery capacity**

There are a wide range of EV batteries capacity. PHEV usually contains a small battery capacity while BEV contains higher battery capacity. EVs with high battery capacity will draw a larger amount of energy from the power grid.

- **Battery SoC**

The battery SoC at the plug-in instant is stochastic. Many studies assume the SoC and others consider it as a probability distribution.

- **Penetration level**

EVs still have a very small market share which will increase quickly for few countries like Norway and slowly for many other countries. Therefore, many studies considered different EVs penetration levels ranging from 10% to 100%.

- **Distribution system status**

There are many differences between distribution systems in terms of structure (i.e., radial or ring), equipment loading condition before connecting EVs, voltage level (i.e., medium voltage or low voltage), voltage profile, daily load profile of loads, etc.

Therefore, numerous studies were executed to assess the impacts of EVs charging on the power system. Most of the studies focus on the distribution network at which EVs charging occurs, because the most severe impacts are expected to occur at the distribution level. Classification of positive and negative impacts of EVs charging/discharging on electric power system can be seen in Figure 7 and they are explained in the following sections.

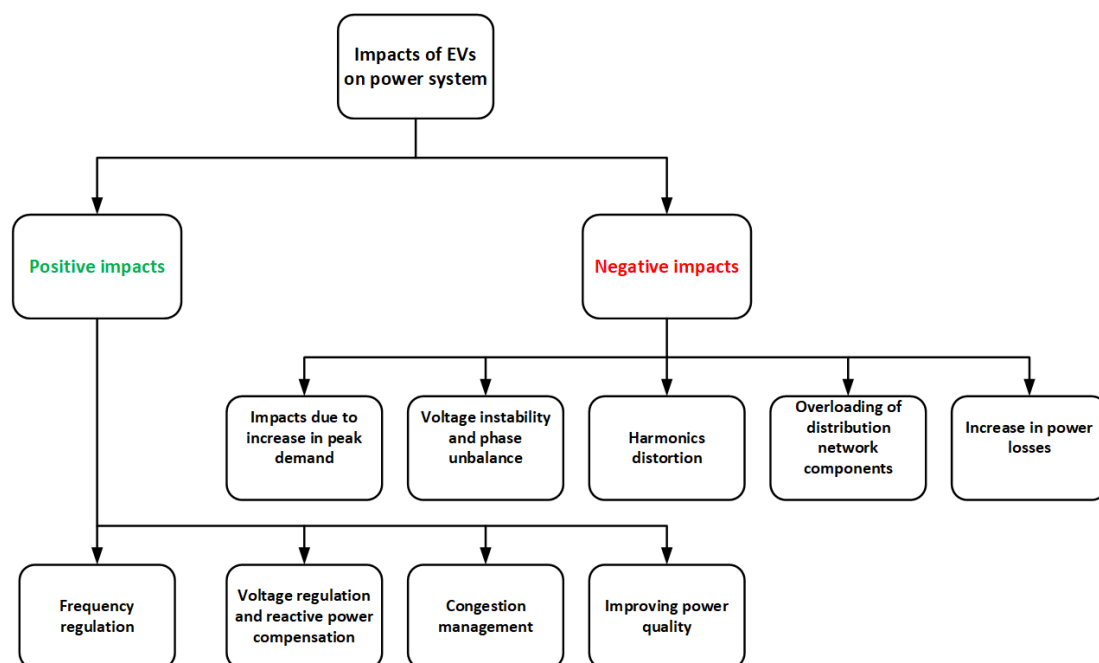


Figure 7. Classification of EVs charging impacts on electric power systems.

4.1. Impacts Due to Increase in Peak Demand

Various studies have been performed for assessment of EVs charging impact on the peak demand and load profile on distribution systems. Many distribution networks in different countries and with different topologies and characteristics were chosen to conduct these studies. In [68], the peak demand increased by 53% when uncontrolled EVs charging was used with 30% penetration level. In another study [69], with only 10% penetration level of uncontrolled EVs charging in residential network, the peak demand increased significantly. In [70], the effect of charging light duty vehicles up to 100% penetration level on system peak demand was investigated. For 100% penetration level, uncontrolled charging resulted in a high increase in peak demand, which must be minimized by delayed charging. In [71], it was found that EV rapid charging at peak hours will result in a significant rise in peak demand and equipment limits were exceeded even with very small penetration levels. However, by the use of slow charging at off peak hours, distribution network could integrate up to 50% penetration level without violating equipment limits.

In [72], the impact of uncontrolled charging of EVs on total power demand for three distribution networks (i.e., urban, suburban, and rural) with different capacities were evaluated. The study considered penetration levels up to 25%. For the highest penetration level, the peak demand increased by 9% for both urban and rural networks and 11% for suburban network. This increase made the rural network exceed the maximum capacity limit while urban and suburban did not exceed the capacity limit. In [73], it was found that uncontrolled charging increased the peak demand. The study proposed a demand response method to control EVs demand and other flexible home devices. This method enabled the integration of EVs without increase in peak demand from the base case (i.e., without EVs).

In a recent study [74], the impacts of uncontrolled EVs charging on Great Britain power system was investigated. The study also considered how controlled charging can mitigate these impacts. For a 100% penetration level, it was found that the peak demand will increase by 8 GW at generation and transmission level. Moreover, the results showed that controlled charging can significantly reduce the increase in peak demand and eliminate the need for new generation infrastructure. At the distribution level 100% penetration level will require 28% upgrades at distribution network. Controlled charging can reduce the distribution network upgrade requirements to only 9%. Another interesting conclusion in this study is that load profile at distribution level and load profile at transmission level cannot be flattened at the same time using controlled charging. For instance, flattening the load at transmission level (i.e., national demand) will require 19% upgrades at the distribution level. Moreover, flattening the load at distribution level will result in 6 GW increase in national demand.

In [75,76], it was concluded that the increase in peak demand can be crucially mitigated by the use of optimized charging and time of use (ToU) charging. A study on the Estonian grid [77] with 30% penetration level of the passenger' cars available was conducted and the results showed an increase in the peak load with 5% for uncontrolled charging and 4% increase for controlled charging. Section 5.3 gives more details on how controlled charging can flatten the load profile and how controlled charging/discharging can cut the peak demand (i.e., peak shaving).

From the previous studies, it is clear that large integration of EVs charging in uncontrolled manner may lead to a significant increase in peak demand. This increase in peak demand will result in higher operation costs because expensive generation must be operated at peak hours for short duration to supply peak load. In addition, infrastructure upgrade is required if the peak demand is higher than components capacity at generation, transmission, or distribution levels. Moreover, the use of delayed charging and controlled charging is effective in minimizing peak demand increase due to EVs demand and the accompanied negative impacts; this can enable higher EVs penetration.

4.2. Voltage Instability and Phase Unbalance

Voltage instability represents a challenging issue and can result in system disruptions [78]. The reason for that is the operation at high load demand and near the stability limit. The grid voltage stability is crucially affected by the characteristics of the load. EVs load characteristics are different from the conventional loads (i.e., residential, industrial, and commercial) characteristics and the earlier estimation of its power and energy demands are difficult. In addition, the EVs consume more power in a short time to fully charge the battery. Furthermore, single phase EVs chargers may increase phase unbalance at distribution network. Phase unbalance results in unwanted negative effects at distribution network operation and connected loads and should remain in the acceptable limits.

Numerous studies have been executed to evaluate the impacts of EVs charging on voltage instability, voltage deviation, and phase unbalance. In [79], the voltage stability was investigated in a study implemented in the Institute of Electrical and Electronics Engineers (IEEE) 43 bus distribution system. The results showed that voltage stability of distribution network is highly reduced by EVs fast charging. The impact of uncontrolled charging on voltage deviation at different daily durations was assessed in [80]. Obtained results showed a large increase in voltage deviation which was close to exceeding the acceptable limits especially if EVs were charging at peak period. The study proposed stochastic programming strategies to minimize voltage deviation. In [72], the impact of uncontrolled

charging of EVs on voltage drop for three distribution networks (i.e., urban, suburban, and rural) was estimated. The study considered penetration levels up to 25%. For rural network which has long feeders, higher voltage drop was recorded due to EVs charging which fosters the need for voltage regulation devices. The impact of uncontrolled charging of EVs on voltage deviation in primary and secondary distribution systems was examined in [81]. The study considered different penetration levels (i.e., 30% and 50%), different EVs types (i.e., BEV and PHEV), and different charging levels (i.e., level 1 and level 2). Results showed no voltage limits violation at any node of primary distribution system. However, voltage limits violations were recorded in the secondary system. Moreover, it showed that BEV caused more voltage drop than PHEV due to its higher battery capacity and level 2 charging caused more voltage drop than level 1. In another work [82], the effect of large-scale integration of EVs with high power charging in IEEE 39 bus distribution system and how the distribution network reliability was improved by optimal charging of EVs was investigated. Another method for reducing the voltage instability was proposed in [83]; the method is based on voltage control by the tap-changing transformer.

In [84], the impact on voltage unbalance due to uneven EVs distribution on the three phases was investigated. The study considered two scenarios for EVs distribution on phases. For scenario A, 50% of EVs are connected to phase a, 30% to phase b, and 20% to phase c. For scenario B, 80% of EVs were connected to phase a, 20% to phase b, and 0% to phase c. For scenario A, the voltage unbalance factor (VUF) did not violate the limits until 50% penetration level. However, for scenario B, the VUF reached the limits at 25% penetration level. Another study [85] investigated the impact of single phase EVs charging (i.e., G2V) and discharging (i.e., V2G) on voltage unbalance of low voltage distribution network. The study considered many cases and results showed that in some cases VUF exceeded the limit for both charging and discharging modes. In [86] a significant phase unbalance occurs due to the EVs charging with single phase chargers at level 1 at the residential network which results from the unequal distribution of EVs chargers in the three phases. However, a small impact on voltage and current unbalance was observed due to EVs charging in [87]. It should be mentioned that by using controlled charging and discharging of EVs with considering VUF minimization, the voltage unbalance at distribution network can be minimized. More details are provided in Section 5.4.

Previous studies showed that usually low EVs penetration levels can have a small impact on voltage values even if uncontrolled charging was used. However, high EVs penetration levels can cause high voltage drop, and voltage value may exceed the acceptable limits especially at the end of long feeders (i.e., rural network), which will require the installation of voltage regulation devices. Studies showed that secondary distribution networks have a higher probability of exceeding voltage limits than primary distribution networks. Moreover, phase unbalance represents a challenging issue since most EVs are expected to be charged by single phase private chargers. Very small EVs penetration levels can cause small phase unbalance. However, high EVs penetration levels and high uneven distribution of chargers on the three phases may result in VUF higher than acceptable limits.

4.3. Harmonics Distortion

Power quality problems may arise due to EVs charging. Because power electronic devices are used in EV chargers, so high EVs integration can affect the power network's power quality. Harmonics injected by EV chargers into the power grid will lead to negative effects on electric power system components which are designed to be supplied by pure sinusoidal waveform and increase system losses. Few studies found that EV chargers had a non-significant effect on harmonic distortion. For instance, in [88], a comprehensive harmonic study was implemented using the Monte Carlo method and the results showed a minor impact of harmonics in the distribution network. Another study [89], found that commercial EV chargers resulted in a small increase in the total harmonic distortion of voltage (THDv), and it was less than 0.8%.

In contrast, many studies concluded that EVs charging had a large impact on the distribution system. In [90], the THD_v increased to 11.4% due to uncontrolled rapid charging and this value exceeded the limit of 8% based on EN 50,160 standard and a solution to the harmonic problem was proposed by using the control of PV inverter as an active filter. In [91], the impact of EVs charging with slow and fast charger on total harmonic distortion (THD) was assessed for different EVs models. A high total harmonic distortion of current (THD_i) was recorded for fast charging between 12% to 24%. In [92], the impact of traditional EV charger on the quality of system voltage and drawn current was evaluated. Traditional charger caused very high THD. The authors proposed a smart charger that draws sinusoidal current and has a unity power factor. The smart charger significantly reduced THD compared with traditional charger. The negative effects of EV home chargers on distribution network power quality and transformer life were studied in [93]. The study found a quadratic relation between THD_i and life consumption of the transformer. Moreover, the study concluded that THD_i should not be more than 25 to 30% to have acceptable increase in life consumption of the transformer. In [94], the impact of EV chargers' current harmonics on distribution system capacity was studied. Results showed that the 10 kV cable was overloaded at 27.25% penetration level when current harmonics due to EV chargers was considered. However, the cable was overloaded at 30.74% penetration level when current harmonics due to EV chargers was neglected. For harmonics reduction from EVs integration, filters must be added to the EV chargers.

Only a few studies found that EV chargers harmonics result in a minor impact in the distribution network. Most of the studies showed that traditional EV chargers can cause unacceptable harmonics values. These high harmonics will result in decreasing the life cycle of distribution network components (i.e., transformers and cables). However, by proper design of EV charger circuits, control strategy, and filters integrated into the charger circuit, the charger harmonics can be alleviated significantly. More details can be found in Section 5.4.

4.4. Overloading of Distribution Network Components

The high EVs energy demand requires a large amount of electric energy to be transmitted from the generation stations to the distribution networks. The distribution networks' equipment such as transformers and cables may get overloaded due to the new EVs load and this will lead to stress these components and reduce their lifespan and foster the need for infrastructure upgrade. Several researches were executed to analyze the impacts of EVs charging on distribution system components. In [95], the distribution transformer aging due to uncontrolled charging of EVs with level 1 and 2 charging power was investigated. The results showed that level 2 charging has a higher aging impact on the transformer in comparison with level 1 charging. The impacts of EVs charging on transformer and underground cable were assessed in [96] for low and high penetration levels (i.e., 12.5% and 70%). The transformer and cable were overloaded in both penetration levels. The impact of uncontrolled charging of EVs on distribution transformers with 25 kVA and 50 kVA power rating was examined in [81]. The study considered different penetration levels (i.e., 30% and 50%), different EVs types (i.e., BEV and PHEV), and different charging levels (i.e., level 1 and level 2). Results showed that 50% penetration level resulted in overloading 50% of the 25 kVA transformers and 35% of the 50 kVA transformers. Furthermore, BEV with level 2 charging caused 10% increase in the number of overloaded transformers compared with PHEV with level 1 charging.

In [72], the impact of uncontrolled charging of EVs on the loading of secondary transformers installed in three distribution networks (i.e., urban, suburban, and rural) with different capacities was executed. The study considered penetration levels up to 25%. The study counted the number of transformers overloaded above 20%. EVs charging resulted in increasing the number of transformers overloaded above 20% for suburban area, while urban and rural areas did not have high overloading percentages. The impact of uncontrolled charging on distribution networks transformers and cables was investigated in [97]. Results showed a large increase in the number of overloaded transformers and cables. The number of overloaded transformers and cables decreased by 25% and 8%, respectively,

when controlled charging was used. In [98], it was found that the presence of EVs will lead to reducing life duration of distribution transformer. In [99], it was concluded that the uncontrolled charging of EVs will lead to aging of 25 kVA distribution transformer. Moreover, it was found that transformer aging can be reduced using controlled charging strategies.

Another study [100], concluded that uncontrolled level 1 EVs charging has insignificant impact on transformer life but the massive penetration of EVs may have a severe effect on transformer lifespan. The transformer lifespan can be enhanced by using off-peak EV charging and load management [95,100,101]. In [102] the cable loading was examined for EVs peak charging hours. The results demonstrate that the cable can handle up to 25% penetration level for slow charging and up to 15% penetration level for fast charging and cannot handle massive EVs penetration easily.

The high energy demand of EVs will increase the loading at different parts of the power system (i.e., generation, transmission, and distribution). Distribution level is highly affected by EVs charging compared to transmission and generation levels, and most of the studies focused on the impacts of EVs charging on distribution network components. The studies showed that the acceptable EVs penetration level before overloading of network components varies depending on the network components' capacity and their loading condition before connecting EVs. Studies concluded that the uncontrolled charging of EVs result in overloading of many transformers and cables at the distribution network and can result in reducing their lifespan and requires components upgrade which represents economical challenge to electric utilities. Results showed that many distribution networks can only allow 10% penetration level before overloading if level 2 charging was used. The network can handle higher penetration levels if level 1 slow charging was used. Using proper charging and discharging methods (i.e., delayed charging, controlled charging, V2G, V2B, and V2H), distribution networks can integrate higher EVs penetration levels before they reach their capacity limits. More details can be found in Section 5.3.

4.5. Increase in Power Losses

Extra power demand represented in EVs charging will lead to higher currents flowing and extra power losses in different system components, such as generators, transformers, and cables, which is the main concern for utilities. Various studies were performed to examine the EVs charging impact on system losses. In [103], the impact of uncontrolled charging of EVs on two large scale distribution system was executed under three penetration levels (i.e., 35%, 51%, and 62%). Uncontrolled charging resulted in a large increase in energy losses and required investment cost. Losses and investment costs reduced when delayed charging or controlled charging were used. The impact of uncontrolled charging on power losses at different daily durations was assessed in [80]. Obtained results showed a large increase in power losses especially if EVs were charging at peak period. The study proposed stochastic programming strategies to minimize power losses. In [104], a study examined the EV charging impact on a Danish distribution network. The obtained results showed that for uncontrolled charging with 50% penetration level the grid losses increased by 40% and increased only 10% for controlled charging.

In [105], the impact of EVs charging on distribution transformer power losses was investigated. It was found that for penetration levels ranging from 2% to 40%, the transformer losses increased to more than 300% mainly due to windings copper losses increase. The increase in power losses at the IEEE 33 bus distribution system due to EVs fast charging station was evaluated in [106]. The study investigated many cases by changing the charging station bus and the charging station power consumption. It was found that installing charging stations at weak buses (i.e., far from the main transformer) increased system power losses. Moreover, the power losses could be reduced by distributing charging station load at two buses instead of one bus. In [107], the increase in energy losses of a distribution network due to EVs charging was examined. The distribution network supplies residential and commercial loads and located on a Korean island. The results showed that daily energy losses increased by 66% for 40% penetration level.

Previous studies focused on assessing the impact of uncontrolled EVs charging on the power losses at distribution networks. The studies concluded that uncontrolled EVs charging resulted in a high increase in distribution network power losses. Using proper charging and discharging methods (i.e., delayed charging, controlled charging, V2G, V2B, and V2H), power losses due to EVs charging can be reduced significantly. Additionally, the installation of distributed generation (DG) near the charging location can decrease the energy supplied from the grid, and hence reduce the power losses.

5. Positive Impacts of Electric Vehicles on Electric Power Systems

EVs are parked for most of the daytime [108], and they are connected to the charger for a longer duration than required recharging duration. Therefore, EV battery can be used to provide grid services and gain revenues for EV owners by injecting power to the grid to keep demand–supply balance or by controlling the charging time and power to reduce the charging cost and electricity bill. Many studies showed that controlled EVs charging can improve power system efficiency, reduce operation cost, and minimize RESs curtailment. Moreover, EVs controlled discharging can provide additional benefits and electrical services [109]. EVs can provide short time scale electrical services due to the fast response of battery chargers such as primary frequency control (PFC), medium time scale electrical services, such as secondary frequency control and long time scale electrical services, such as congestion management and minimization of power losses due to the high battery capacity [110]. The focus in reviewing the literature will be in operational aspects and services provided by EVs and not in the optimization algorithms and control methods used due to the broad spectrum of approaches used in these studies [111].

5.1. Frequency Regulation

Power system frequency should be maintained at nominal value (i.e., 50 or 60 Hz) for normal operation. It is considered an important indicator of active power supply–demand balance. In normal operation, the power imbalance occurs due to continuous load variation or fluctuation of RESs generation that depend on weather conditions. In emergency conditions, the power imbalance occurs due to sudden outages of loads, transmission lines, or generating units. Failing to maintain frequency in the specified limits will result in load shedding in case of under frequency or disconnection of generating units in case of over frequency. In traditional power system, frequency regulation is achieved by synchronous generators in large power plants (e.g., hydro and thermal power plants) [112]. In future power systems, controllable loads like heat pumps and EVs will have a significant role in frequency control [113]. EV batteries have a faster response compared to traditional generation units due to the fast response of EV power electronic interface (i.e., EV charger). Therefore, controlled charging and discharging of EVs can be an effective option for frequency regulation. Moreover, frequency regulation is becoming more challenging due to the reduction of system inertia and increase of fluctuation due to the increasing share of RESs with power electronic interface [114–116].

The ability of available commercial EVs (i.e., Nissan Leaf) to provide PFC by only changing the charging power and with no V2G capability was tested experimentally in [117]. A small isolated power system with renewable generation was used as a test system. The results proved the technical feasibility of EVs to provide PFC with fast response time. In [118], the authors studied how EVs can participate in PFC in two ways. The first is to switch off EVs charging and the second way is to inject power to the grid in V2G mode. Another study [119] proposed a control method to provide PFC in three area power system by coordinating EVs charging and discharging while minimizing battery degradation cost. The effectiveness of EVs to provide primary frequency regulation was tested in [120] for a small isolated power system containing wind turbines, diesel generators, and hydro generators. The study verified that EVs were very effective in reducing frequency oscillation with a small change of EVs consumed energy and negligible variation of the required charging time. It also showed that EVs can enable more wind energy share while keeping normal operation.

In [121], the authors studied two modes of EVs charging control for frequency regulation while considering EV owner driving behavior. The first mode only controls the charging power and the second mode controls charging and discharging power. Results showed that EVs were effective in reducing frequency fluctuation. A coordinated control strategy between EV operating in V2G mode and traditional generation for load frequency control (LFC) was proposed in [122]. The proposed control strategy was tested on the Great Britain power system. The results showed the effectiveness of the proposed strategy in improving frequency regulation and reduction of power mismatch. Moreover, due to EV participation, the traditional power generation output variations were reduced. The EVs ability to participate in LFC in a microgrid operating in isolated mode was investigated in [123]. The microgrid contains both renewable and nonrenewable generation. The studies proved that EVs can enhance frequency stability in addition to reducing emissions from nonrenewable generation and increase microgrid operator profit. In [124], EVs operating at V2G mode were used to provide LFC in a multi-area power system containing traditional nonrenewable generation (i.e., thermal, hydro, and gas turbines).

Previous studies results proved the feasibility of using EVs to provide frequency regulation due to its fast response. Results showed that the use of EVs can achieve rapid control action in balancing the generated power and the power demand during load and source variations and the system frequency perturbation controlled by EVs is much lower than the other generation units. EVs can provide frequency control either by regulating charging power with no V2G capability or by regulating charging and discharging power (i.e., V2G capability). In the first approach, frequency regulation can be achieved by only change the EVs charging power. This approach is simple, requires simple infrastructure, and have a limited effect on battery degradation. In the second approach, frequency regulation is provided by controlling both charging and discharging power. This approach is more effective than the first approach. However, this approach is more complex, requires infrastructure upgrade (i.e., ICT and bidirectional chargers), and affect battery life cycle due to continuous charging and discharging. The studies showed that EVs are effective in providing frequency regulation at traditional power systems containing only nonrenewable generation. It resulted in reducing frequency fluctuation and reducing the variation of generation units output power. Furthermore, it is effective when there is a renewable generation installed in traditional power systems. It can reduce fluctuations due to intermittent renewable generation, enable the integration of more renewable generation, and reduce curtailment of renewable generation production. Moreover, EVs proved their effectiveness in providing frequency regulation in microgrids with a high share of renewable generation. It can reduce frequency fluctuation, increase microgrid profit, reduce curtailment from renewable generation, and enable integrating high share of intermittent renewable generation while operating in acceptable limits.

5.2. Voltage Regulation and Reactive Power Compensation

The voltage at any point of the power system must be maintained within acceptable limits. Voltage is an indicator of the loading status of distribution system. Voltage is high if the network is lightly loaded and low if the network is highly loaded. Although the common problem in distribution system is exceeding the lower limit, excessive DG may cause voltage rise and exceeding the voltage upper limit. Keeping the voltage within normal values at distribution level, which usually has a radial structure, is a challenge especially for long feeders and may require voltage regulation devices. Violation of these limits will result in improper operation or damage to the connected loads and may lead to voltage instability. Voltage control can be achieved by active or reactive power control. Active power can be controlled by DGs, energy storage technologies, and controllable devices like EVs and heat pumps. Likewise, reactive power can be controlled by transformers on-load tap changer (OLTC), capacitors, and static var compensators.

Many researchers studied voltage regulation by EVs active power control. An online controlled charging method was tested in [125]. The objective was to maximize EV owners satisfaction while considering distribution network limits. The algorithm minimized voltage deviation,

transformer loading, and power losses. In [126], a decentralized/autonomous controlled charging method was proposed. It regulates the charging power based on the local voltage and battery SoC. It charges at a high charging power if the voltage is normal and decrease the charging power or stop charging if the voltage is low. EVs with low SoC have a charging priority. The proposed method reduced the voltage drop and improved the voltage profile compared to uncontrolled charging. In [127], an optimization algorithm was developed to provide peak shaving and valley filling in addition to improving voltage profile by controlling the charging and discharging of EVs. In [128], a controlled EVs charging technique was used to solve the voltage rise issue resulted from excessive PV generation at distribution system.

Another option for EVs based voltage regulation is by using capacitors in the DC link of the EV bidirectional chargers to supply reactive power. EV charger can do this even if the EV is not connected for charging. The ability of level 1 EV bidirectional charger to provide reactive power support was tested in [129]. The study showed that the DC link capacitor can provide reactive power support with no effect on battery degradation. In [130] a direct voltage control method was used to enable EV charger at DC fast charging station to inject reactive power to the grid to regulate bus voltage and reduce system power losses. In [131], a strategy for voltage regulation at distribution network was proposed. It is based on the coordination of DG, OLTC, and EVs providing reactive power support by operating at V2G mode. The proposed algorithm was effective in voltage regulation, minimizing OLTC operation times, and reduce the active power curtailment of DG. A limited number of studies investigated the use of EV chargers for reactive power compensation, which makes it a promising research area to be investigated in future research studies.

From studies results, it can be concluded that uncontrolled charging of EVs can result in a higher voltage drop at distribution networks and voltage values exceeding the acceptable limits, especially in long feeders, and will require infrastructure upgrade by installing voltage regulation devices. However, using controlled charging and discharging methods the voltage at all parts of the distribution network can be kept within acceptable limits and daily voltage profile can be improved without voltage regulation devices. Moreover, studies showed that the EV charger DC link capacitor is effective in providing reactive power support and voltage regulation.

5.3. Congestion Management

Load demand varies during the day and usually have peak hours in the evening. During peak hours expensive generators should be turned on for few hours for supply–demand balance. Uncontrolled charging of EVs will result in enlarging the peak power demand, which results in operating expensive power generation in addition to transmission and distribution networks stress. If the installed generation capacity is less than the required demand at peak period, new power plants must be constructed. This issue can be eliminated or alleviated by using delayed charging, controlled charging, V2G, V2B, and V2H. Using delayed charging and controlled charging can shift EV charging to off peak hours, which results in valley filling as shown in Figure 6b,c. Using V2G, V2B, and V2H technology enables injecting power to the grid, building, or home at peak hours which results in peak shaving and charge at off peak hours which results in valley filling as shown in Figure 6d. The process of peak shaving and valley filling is called load flattening or load leveling, which means reducing the difference between the maximum demand and the minimum demand during the day. By doing this congestion at the power system can be handled (i.e., congestion management).

Delayed charging was proposed in [132], and compared to uncontrolled charging. The results indicated that delayed charging is effective in reducing the stress of distribution system components, reducing voltage drop and power losses compared to uncontrolled charging. A decentralized controlled charging method for valley filling was proposed in [133]. This method needs simple unidirectional communication between the system operator and EV to broadcast day-ahead electricity prices. Based on the price, EV can autonomously control the charging behavior and charge at off peak period to reduce charging costs. This resulted in valley filling and reduction in generation cost by

28% compared to uncontrolled charging. The impact of uncontrolled EVs charging on total power demand was investigated in [134]. Results showed that uncontrolled charging will increase peak demand. Delayed charging and controlled charging were proposed for alleviating the impact of uncontrolled charging. The results showed that the proposed methods were very efficient in shifting the EVs charging from peak period and postponing any network upgrade.

Another study showed that the German transmission system cannot handle large scale uncontrolled EV charging even with future expansion plans [135]. It also showed that V2G technology is effective in reducing transmission system congestion and enhance grid stability. The effectiveness of V2G in providing peak shaving and valley filling was proved in [136]. By allowing some of the EVs to inject power back to the grid at peak period resulted in reducing the original peak demand (i.e., peak shaving). By allowing EVs to charge at off peak period only resulted in valley filling. In [137], the integration of EVs in a weak isolated grid in a Spanish island was studied. The study proposed a strategy for coordinated charging and discharging of EVs. Results proved the effectiveness of EVs in the efficient management of the grid, in addition to filling the valley and shaving the peak demand.

In [138], V2B was used in a building-integrated microgrid which contains EVs, battery storage, and PV. The objective was to reduce the peak load, which will decrease subscribed power rating and reducing the building electricity bill. The study showed that V2B can enable peak load shaving. By encouraging more buildings to have a similar management system it can reduce the peak load demand in the distribution system or even the whole grid. The effectiveness of V2H in reducing home peak demand was tested in [64]. Results showed that V2H was very effective in minimizing home peak demand and home electricity bills.

Previous studies' results showed that uncontrolled charging of EVs will result in an increase of peak demand at different levels of the power system (i.e., generation, transmission, and distribution) and can overload many network components and will require components upgrade which represents high investment costs for system operators. A more cost-effective solution to these issues is using proper charging methods. The studies proved that simple charging method like delayed charging, which only depends on variable electricity prices during the day, can shift most of the EVs load to off-peak hours by motivating EV owners to decrease the charging costs. Delayed charging can lead to reducing the increase in peak demand, reduce the number of overloaded components, postpone infrastructure upgrades, and valley filling. A more advanced charging method is controlled charging, where EVs can change their charging time and power depending on many variables such as electricity prices, load demand, components loading, grid constraints, etc., depending on the proposed control strategy. Controlled charging can lead to reduced charging costs, reduced increase in peak demand, reduction in the number of overloaded components, delay in network components upgrade, and valley filling. Moreover, the use of V2G, V2B, and V2H can provide more benefits to the grid and EV owners. By injecting stored energy in EV batteries to the grid, the peak demand can be shaved (i.e., peak shaving) and reduce power system operation costs by shutting down generation units with high operating costs. Furthermore, they can defer the need for infrastructure upgrades, gain revenue for EV owners by charging when the electricity price is low and discharge when the electricity price is high (i.e., energy arbitrage), and reduce home or building electricity bills.

5.4. Improving Power Quality

Although single phase uncontrolled charging of EVs may cause a severe effect on system unbalance, controlled charging methods can decrease system unbalance. In [139], the reduction of voltage unbalance by controlling EVs charging current was tested experimentally. The proposed control method is autonomous and depends only on local voltage measurement without the need for infrastructure upgrade and expensive communication infrastructure. The results proved that the proposed EVs controlled charging method can reduce voltage unbalance and minimize voltage drop. In another study, a method based on PV and EVs interaction for voltage unbalance minimization was tested in [140]. In [141], an optimization algorithm was used to control the charging and discharging

of EVs to minimize VUF. An unbalanced distribution network with 1.93% VUF was used to test the proposed strategy. Uncontrolled charging of EVs increased the VUF significantly to 7.7%. The controlled charging of EVs declined the VUF to 0.71%. Controlled charging and discharging of EVs dropped the VUF to 0.5%. To control the voltage unbalance, the number of EVs connected at each phase was optimized using a genetic algorithm in [142]. The authors of [143] proposed a hybrid method combining centralized controlled charging of EVs and decentralized controlled discharging of reactive power for voltage unbalance minimization. The proposed strategy was effective in reducing VUF compared to uncontrolled charging case.

It was presented in Section 4.3 that EV chargers can result in significant harmonic distortion. However, the proper design of charger power electronics circuits and control methods can minimize or eliminate this issue. Few studies proposed EV chargers that cause no harmonic distortion or can provide harmonic filtering. A novel control strategy applied to onboard bidirectional three phase EV charger was proposed in [144]. The proposed method enabled the charger to draw or inject sinusoidal current with no harmonics regardless of the power quality of the grid. Another study [144] proposed EV charger that can operate as active filter and eliminate the harmonics caused by other loads at the charger connection point in addition to providing reactive power compensation. In [145], the EV charging station was used to eliminate the harmonics in distribution network by acting as active filter.

The high penetration of PV generation at distribution network can cause power quality issues due to its intermittent nature and dependence on weather conditions. The variation of weather conditions (i.e., clouds) results in fluctuation of PV power output which can cause voltage fluctuation and light flicker. Therefore, DSOs need to develop mechanisms to mitigate power quality issues caused by the fluctuation of PV output. Several studies proposed controlled charging of EVs as a possible solution to alleviate the fluctuations caused by PV generation [146–148]. For instance, reference [148] assessed the impacts of rapid variation of PV output on voltage fluctuation at low voltage distribution network for three scenarios. The study proposed a controlled charging of EVs to mitigate voltage fluctuations. The results proved the effectiveness of the proposed strategy in reducing voltage fluctuations and accompanied light flicker.

The previous sections demonstrated that EVs can provide many benefits and services to electric power systems. A very important secondary benefit that EVs can provide is helping the integration of RESs. It is well known that to face environmental challenges and depletion of fossil fuel, large capacities of RESs are being installed worldwide. Most of RESs installations are PV and wind due to the technology advancement and fast drop in their prices. Electricity generation from RESs like PV and wind are variable and intermittent depending on environmental conditions (i.e., sun and wind) and hard to predict or forecast. This increases fluctuation and uncertainty in power system besides load fluctuation [149]. Moreover, they are non-dispatchable generation and they cannot change the generated power following demand variations like traditional power plants, which increase the need for more flexibility in the power system which cannot be provided by central power plants only. More flexibility in the power system can be achieved from distribution systems by demand response (i.e., controllable or dispatchable loads) and energy storage.

Till now there is no economical utility-scale energy storage technology. EVs can act as controllable loads by controlled charging and as energy storage by V2G, V2B, and V2H. Several studies investigated how EVs can enable integrating more RESs [150]. EVs can absorb excess RESs generation and deliver it to the grid when needed. In [151], it was concluded that EVs and heat pumps can reduce the cost of integrating RESs, such as required balancing cost and required back-up generation cost. In [152], based on the German 2030 scenario of RESs penetration, it was found that by controlling EVs charging more RESs can be integrated into the power system. In [153], two case studies were considered for Germany and California 2030 scenario with a high share of EVs and RESs. It concluded that the smart charging of EVs can mitigate RESs fluctuation.

Reference [154], investigated the impact of V2G on two power systems and with different penetration of wind generation, from 0% to 100%. It was found that V2G can enable a higher share of wind power generation in the power system. An optimization strategy was tested in [155] to schedule the charging of EVs which were connected to microgrid with PV and wind generation. The proposed strategy achieved load leveling in addition to reducing microgrid operating costs and EVs charging costs. The impact of EVs operating at controlled charging mode or V2G mode on the operation of a power system with high share of RESs was examined in [156]. Results showed that controlled EVs charging and discharging reduced deployed reserves usage, better usage of renewable generation by reducing wind spillage, and reduced operation cost. In [157], it was found that controlled charging and discharging of EVs can reduce operation costs and reduce emissions, besides maximizing RESs utilization. In [158], an optimization algorithm was used to manage EVs charging and discharging to increase the penetration of RESs. The proposed strategy was able to increase PV penetration up to 50%.

6. Discussions and Future Research Directions

The main contribution of this article is to provide a review of potential negative impacts of EVs charging on electric power systems mainly due to uncontrolled charging, and how through proper charging and discharging methods, those impacts can be reduced and become even positive impacts as discussed in Sections 4 and 5. For each potential negative impact or positive impact of EVs, the findings and conclusions of a few research papers were discussed as examples of the research done at each point to clarify it. Figure 8 provides a summary of the negative impacts of uncontrolled EVs charging on the electric power system and how these impacts can be mitigated or even become positive impacts using suitable charging and discharging methods.

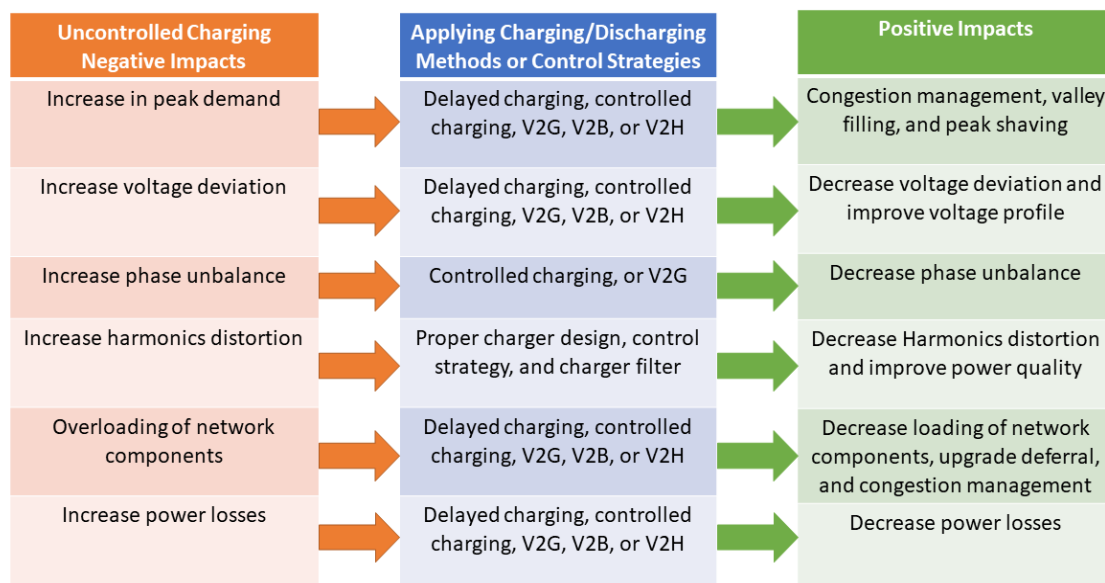


Figure 8. Uncontrolled charging negative impacts on the power system and how it can be mitigated and become positive impact using the proper charging/discharging method.

As described in previous sections, there is a lot of ongoing research on the integration of EVs to electric power system, focusing on accurate evaluation of the negative impacts of uncontrolled EV charging or the services and benefits EVs may provide if other smart charging and discharging methods are used. Other research areas that are being investigated by researchers are:

- **Cost-benefit analysis of different charging and discharging methods**

Most of the studies that investigate the benefits that smart charging and discharging methods can provide focus on the technical feasibility and charging cost. However, there is a need to assess

the cost of providing these services on EV batteries degradation, because EV battery is a very expensive component in EVs. After that, the economic feasibility of different charging and discharging methods can be accurately estimated. Reference [159] executed a cost–benefit analysis of controlled charging and V2G implementation considering EV batteries degradation cost. The results showed that controlled charging is economical. Moreover, the study concluded that V2G implementation is not economical without wind generation presence, while it is economical in the presence of wind generation. This area requires more studies to evaluate the economic feasibility of different EV smart charging and discharging methods on different case studies and different scenarios. The different scenarios can consider the economic feasibility of using EVs to provide various services (i.e., frequency regulation, voltage regulation, congestion management, etc.; or consider different power systems with different characteristics (i.e., presence of different types of RESs, different penetration levels of RESs, types of power plants, etc.).

- **Coordination between transmission system operator (TSO) and distribution system operator (DSO) for providing EV services**

As explained in previous sections, EVs can provide many local and system-wide power and energy services. Figure 9 summarizes the services provided to different power system parties (i.e., transmission system operator (TSO), DSO, and loads such as buildings or homes) [160]. It is worth mentioning that the provision of system-wide services by EVs may result in issues at distribution system at which EVs are connected which may result in conflict of interests between TSO and DSO. For instance, the use of EVs to provide a TSO service such as frequency regulation which requires continuous change at charging and discharging power may cause negative impacts at the distribution system managed by DSO such as overloading of distribution network components, phase unbalance, etc. Therefore, there is a need for coordination between TSO and DSO to guarantee reliable and cost-efficient EVs based services [161,162]. This topic is rarely investigated in the literature and there many open questions that require study. Therefore, it requires more attention in future research.

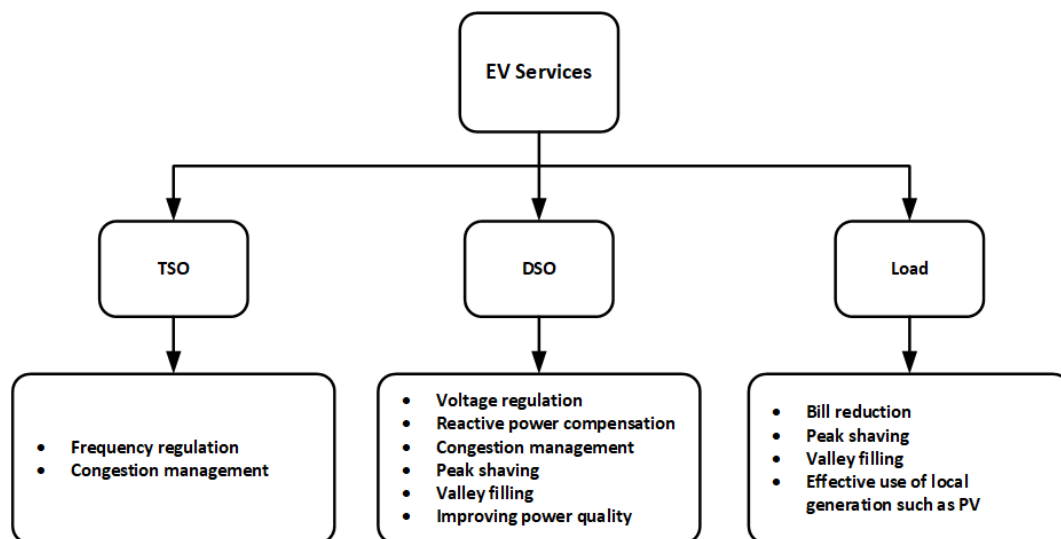


Figure 9. EV services provided to different power system parties.

- **Planning of public charging Infrastructure**

With the large-scale adoption of EVs in the near future, many public EV charging stations will be deployed in streets, highways, workplaces, shopping centers, etc. One of the main challenges for EVs acceptance is its limited range compared to ICEVs and driver range anxiety. Therefore, the EV chargers deployment must be planned accurately and efficiently to achieve both transportation and power system

objectives and needs. Many studies investigated the planning of future EV charging infrastructure. The studies considered the optimal location and capacity of EV chargers [163]. Some studies considered the transportation network only without considering power system conditions. Other studies considered the power system only without considering transportation networks. These studies consider power system economic and operation constraints while reducing investments required for power system infrastructure upgrade. It is worth mentioning that EV charging stations couple both transportation network and power system; therefore, both must be taken into account at EV charging infrastructure planning. Few studies considered both transportation network and power system at the planning of EV chargers [164], because EV infrastructure planning studies require real data for both the transportation sector and power system, which varies between countries. There is a room for more research in this area considering different case studies.

7. Conclusions

The paper presented EVs technology and the current need for it as well as its benefits compared to traditional vehicles in addition to challenges it must tackle to achieve high adoption and social acceptance. Furthermore, it presented the current EVs market and future predictions. Different charging technologies were presented such as conductive charging, which is the current charging method and other charging methods such as wireless charging and battery swapping which may have future potential. A review of the negative impacts that EV may cause on electric power systems if uncontrolled EV charging is used was presented. Conclusions of many studies that assessed these impacts were discussed. All the studies showed that uncontrolled EV charging will result in unwanted negative impacts on the power system especially the distribution networks and it will foster the need for infrastructure upgrade. The severity of these impacts varies between different studies due to many uncertainties in EV charging impacts studies (e.g., distribution system status, EV battery capacity, EV battery SoC, time and location of charging, EV charger power rating, and EV penetration level).

The paper also showed that these impacts can be mitigated using delayed charging and controlled charging methods, which can benefit both the power system and EV owner. More benefits and electrical services can be obtained from EVs with advanced charging control methods like V2G, V2B, and V2H. Different electrical services that can be provided with controlled charging/discharging of EVs were presented and discussed. This review article briefly discussed the main research areas that are being investigated for the integration of EVs to sustainable future power system, which can be helpful for engineers and researchers. It further discussed a few interesting research topics that need more study in future research.

Author Contributions: M.N. wrote the manuscript first draft. J.P.C.-Á., G.M., and Á.S.-M. reviewed, edited, and suggested modifications to the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

List of abbreviations used in this paper.

AC	Alternating Current
BEV	Battery Electric Vehicles
BSS	Battery Swapping Stations
CO ₂	Carbon Dioxide
DC	Direct Current
DG	Distributed Generation
DSO	Distribution System Operator

EM	Electric Motor
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FCEV	Fuel Cell Electric Vehicle
G2V	Grid to Vehicle
GHGs	Greenhouse gases
h	Hour
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IWC	Inductive Wireless Charging
km	Kilometer
kVA	Kilo volt ampere
kW	Kilowatt
kWh	Kilowatt hour
LFC	Load Frequency Control
Li-ion	Lithium-ion
OLTC	On-Load Tap Changer
PFC	Primary Frequency Control
PHEV	Plug-in Hybrid Electric Vehicles
PLDV	passenger light-duty vehicles
PV	Photovoltaic
RES	Renewable Energy Source
SoC	State of Charge
THD	Total Harmonic Distortion
THDi	Total Harmonic Distortion of current
THDv	Total Harmonic Distortion of Voltage
ToU	Time of Use
TSO	Transmission System Operator
V2B	Vehicle to Building
V2G	Vehicle to Grid
V2H	Vehicle to Home
VUF	Voltage Unbalance Factor
WC	Wireless Charging

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