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Impacts of Electric Vehicles on Distribution System Planning and Operation

T. Al-Abri[1] and M. Albadi[*,1,2]

[1] Sultan Qaboos University, PO Box 33, Muscat 123, Oman
e-mail: s67735@student.squ.edu.om; mbadi@squ.edu.om

[2] Arab Open University-Oman, PO Box 1596, Muscat 130, Oman.
e-mail: m.badi@aou.edu.om
* corresponding author

Abstract. Nowadays, the use of electric vehicles (EVs) is becoming more popular due to technological improvements. Along with their ancillary services to the grid as a storage element, the integration of EVs into distribution systems (DSs) will definitely have impacts on the DS security and power quality in both vehicle to grid (V2G) and grid to vehicle (G2V) modes of operation. Hence, DSs' planners and operators should regulate the integration of EVs and address relevant challenges for a reliable and efficient system. This paper surveys recent literature on the impacts of EVs on DSs considering the presence of renewable-based distributed generation (Re-DG). The paper summarizes potential services provided by EVs and identifies the potential impacts.

Keywords. Electric vehicle, distribution system, power planning and operation, renewable energy, distributed generation, power quality, V2G, G2V

1. Introduction

EVs' usage has grown rapidly in the last decade given an upward trend toward a fast replacement of fossil fuel in the transportation sector. Around 2.9 million EVs were sold in 2020, with an availability of more than 1.3 million public charging stations according to the Global Status Report [1]. The report also recorded that around 80 V2G pilot projects were initiated in some countries. It is expected that the worldwide EV penetration will increase dramatically in the coming few years. Consequently, the integration of a large fleet of EVs into the DSs will introduce new operational and planning technical challenges [2]. In addition, the network infrastructure needs methodical DS network reinforcement to comply with the EV integration requirement.

The research community has paid great attention to different technical impacts that EVs have in the DS, as discussed in [3]. However, many studies address these challenges in different aspects based on network parameters that are affected by this technology [1]. These parameters are related to the power quality issues, such as voltage drops, harmonic distortion, power losses, and equipment overload. In addition, numerous articles have investigated the impact of combining renewable energy sources (RES), such as photovoltaics, with EVs in the DSs [2], [4], [5]. Other researchers have extended the assessment to cover the impacts of EVs' charging stability and reliability [6]. In [7], the authors highlight the effects of EVs' charging and discharging behaviors on load forecasting. [8] investigates the existing methodologies of scheduling, clustering, and furcating strategies to highlight the key issues and challenges in controlling EV charging. Moreover, to achieve high financial and operational performance, various classes of controlled charging schemes are investigated and addressed in [9] and [10], where each class gives a unique control action. These schemes should be strongly supported by the advanced communication capabilities of the smart grid in order to build a database for the current load and demand states which is the backbone of EVs' control decisions.

An interesting part of distribution planning is to demonstrate the financial and economic framework of both charging/discharging time and allocation of the charging stations in the DS. To study such impacts, the stochastic behavior of EVs should be modeled and studied and included among other characteristics, such as traveled distance, mobility patterns, and profiles of EV owners, in order to have a comprehensive model that yields more accurate results [6]. This can be considered as one of the main gaps that still needs more study.

This paper surveys the influence of integrated EVs in distribution system planning and operation.

After this introduction, section II presents a classification of EVs' services in the power system. Section III discusses the impacts of EVs' integration in DSs. Future research areas are identified in Section IV. Finally, the main conclusions are summarized in Section V.

2. Classification of EV Services in the Power System

Different power system entities may benefit from the presence of EVs differently. In addition, power system structure and the local electricity market structure will

have an impact on the potential ancillary services that EVs can provide. For example, at the transmission system level, EVs can provide ancillary services to support network security and stability. At the distribution system level, EVs can provide ancillary services related to local operational issues, such as facilitating the integration of RES into the local DSs. It is worth noting that there is no standard classification for EVs' ancillary services. Instead, researchers have defined them based on their own preferences [3]. Moreover, the classification can be different from market to market and from requirement of each country's regulations.
The authors in [3] present their classification in three categories as shown in Table I: active/real power support, reactive/imaginary power support, and RES integration support. The real power is considered as the main revenue of the DSs operators, while the reactive power maintains the voltage. Both of them should be controlled efficiently to overcome operation challenges such as over/under-voltages, power losses, and equipment overload.

Table I: A Classification of Potential EV Ancillary Services

Category	Ancillary service
Active power support	Congestion management
	Loss minimization
	Load shifting
	Peak shaving–Valley filling
	Voltage control by active power
Reactive power support	Reactive power compensation
	Voltage control by reactive power
Renewable energy source integration support	EV + PV
	EV + Wind

It is noticeable that the frequency regulation was excluded from the above classification because it is mainly a part of the transmission system operator requirement. The service of the active power support is under the concept of demand-side management (DSM). DSM is defined as the methodology to distribute the demand uniformly and efficiently during the planning [11]. DSM aims to reduce the cost of energy by applying methods such like peak shaving, load shifting, and valley filling. It should induce a lower power consumption corresponding to changes in both the pattern of demand and the price of electricity [11]. Figure 1 illustrates the methods applied in DSM. In fact, DSM can be a tool for the demand response (DR), which is defined as changing the end user's electricity consumption behaviors in response to the electricity price changes over time [12]. The benefits associated with both of them can be considered under the customers' usage behaviors, reliability, and market performance [11], [12].
Regarding the active power support, the services can have similar objectives. Most of them deal with peak conditions and prevent overloading of the power network directly or indirectly—for example, moving the load from peak times to valley times to achieve shaving and valley tasks under the load shifting process.

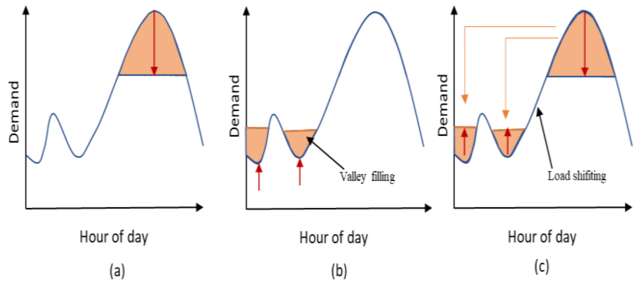

Fig. 1. a) Peak shaving b) Valley filling c) Load shifting

Reactive power compensation and voltage control are the main services in the reactive power support. Voltage control can be also available in the active power support. Renewable energy source integration support service is available when EVs are charging/discharging along with the PVs and wind energy.

3. Overview of the Impacts

The impacts of EVs on the grid depend on their charging/discharging characteristics. Charging mode and the timing of EVs' access with different patterns and scales should be considered while analyzing these impacts.

A. Load Profile Losses

The load profile summarizes the consumption pattern of a utility. V2G and G2V modes of operation have different impacts on the system load profile. In G2V mode, the EVs draw power and hence increase the total amount of demand. Therefore, G2V might increase the system peak depending on the timing and the amount of EVs' power consumption. On the other hand, in the V2G mode, EVs work as DGs; therefore, they may reduce or change the system peak.
The study in [13] used DIgSILENT Power Factory as a simulation tool to model the 22 kV network of the Thailand Provincial Electricity Authority and then applied different EV charging scenarios by changing the EVs' penetration level and timing of operation. The authors concluded that utility peak time was shifted and new peak values were created. Therefore, the high EV penetration level with uncontrolled discharging mode may lead to more network losses due to equipment overloading.

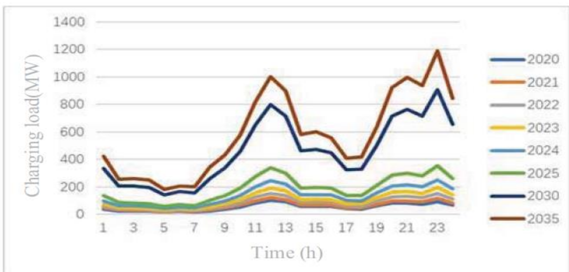

Fig. 2. Forecast Results of Charging Load [14]

Figure 2 shows the forecast charging load from 2020 to 2035, as provided in [14]. The highest peak occurs at midnight, and there is a concentrated load at noon and in the early morning.

B. Voltage

Connecting a large number of EVs in the DSs might cause a voltage rise/drop. The influence of charging EVs (G2V) on the voltage level was studied in [15], where a DS was modeled using MATLAB Simulink tool. The simulation results demonstrate that the charging locations and magnitude have a direct impact on the voltage drop. Increasing EVs' charging load will increase the voltage drop. Similarly, placing the charging stations in the middle of the DS lines will decrease the voltage magnitude both at the charging point and at the end of the feeder. Similar results were reported in [2] and [13].

In addition, the voltage flicker level is expected to increase due to the increased rapid voltage variations. This result is due to the fact that switching between EVs' modes of operation, charging and discharging, causes step changes in the voltage at the point of common coupling (PCC). If the power changes associated with switching can be made gentler, then such voltage steps can be minimized, at least during planned switching operations.

C. Harmonics

EVs depend on power electronics converters such as DC/AC, AC/DC, and DC/DC. These converters emit current harmonics into local grids and distort the voltage signal. Harmonics increase losses in both transformers and cables [16]. It was reported that increasing the penetration level of EVs from 50% to 70% can increase the harmonics to 40% [16]. A similar conclusion was reported in [13]. The case study in [16] modeled a single charging station connected to a DS without a filter using MATLAB (Simulink). Simulation results demonstrated that the total harmonic distortion (THD) reached 154%. However, the implementation of a proper harmonic filter can reduce the THD to within the standard limit.

D. System with Renewable Energy

One of the main challenges related to renewable energy is its intermittency. EVs with their storage feature can be used to facilitate the wide deployment of intermittent renewable energy sources in power systems [17]. This can be achieved using proper charging/discharging control methodologies. EVs can provide a flexible resource to system operators and hence facilitate the wide deployment of intermittent renewable energy in power systems. However, all uncertainties related to the driving path, EVs charging time, power quality issues, the availability of other DGs should be considered [2].

For example, the intermittency of PV systems can be mitigated using EVs' batteries as storage. Surplus energy can be stored and then used when required. This will also improve the financial feasibility of PV projects.

E. Unbalanced Three-Phase Loading

EVs are mostly single-phase load. Therefore, the wide deployment of EVs in distribution systems might cause voltage unbalance. Consequently, the distribution of charging stations in different phases is required to prevent the negative impacts of unbalanced distribution systems [4].

F. Cost Impact

Plugging EVs into the system without coordination can seriously affect the system voltage and power losses, as mentioned previously. In addition, distribution infrastructure loading is also an aspect that has a direct effect. Generally speaking, the technical issues caused by integrating EVs into the network coincide with an economic issue [18]. Utilizing EVs' charging points might have other financial implications as follows:

1) *Cost related to the power losses: As the number of EVs increases, power losses will increase; therefore, the associated cost will increase.*
2) *Cost of infrastructural upgrade: The cost that is needed to upgrade the network infrastructure in order to accommodate the growth of the EV and non-EV loads.*
3) *Cost of energy supply to EVs: The DS operator must consider the cost that is associated with meeting the increased demand for charging the EVs.*

Figure 3 is a diagram of a DS that has different EVs integrated in different nodes and supported with a communication interface.

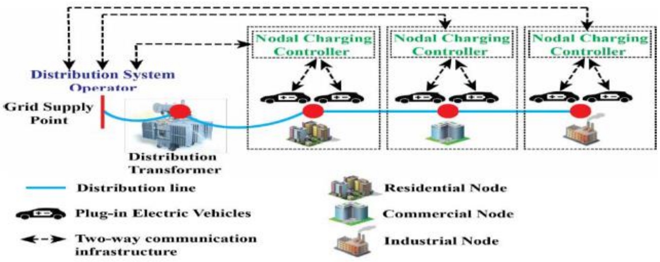

Fig. 3. DS with EVs Representative [18]

G. Protection Coordination

In case of V2G mode, EVs act as DGs. Hence, the short-circuit analysis should be evaluated to adjust the relay setting. It can be noticed that the charging point is an inverter, based on which the short circuit depends on the design of the control strategy.

The ancillary services provided by EVs work to provide more stable operation, which leads to less operation of protection relays. Sequentially, their characteristics act in short-term high-value power flow to balance the constant fluctuance on the load side and to have the ability to adapt to any unexpected equipment failures [19].

H. Reactive Power Compensation

Bidirectional EV chargers, besides their function of providing energy to the battery, are also designed to inject reactive power into the grid. Hence, the voltage and power factor correction will be maintained accordingly [3]. However, a reactive power control should be used to keep both the voltage and the power factor within the accepted limits.

4. Future Research Suggestions

Based on what has been explained, it can be noticed how many issues, solutions, and suggestions there are for integrating EVs into the grid. Therefore, it becomes necessary to assess the implementability and stackability of EVs' services in real applications [3]. Implementability refers to how easily EVs can be used in real life on different time horizons (see Figure 4). Stackability is how possible it is to combine EVs' services.

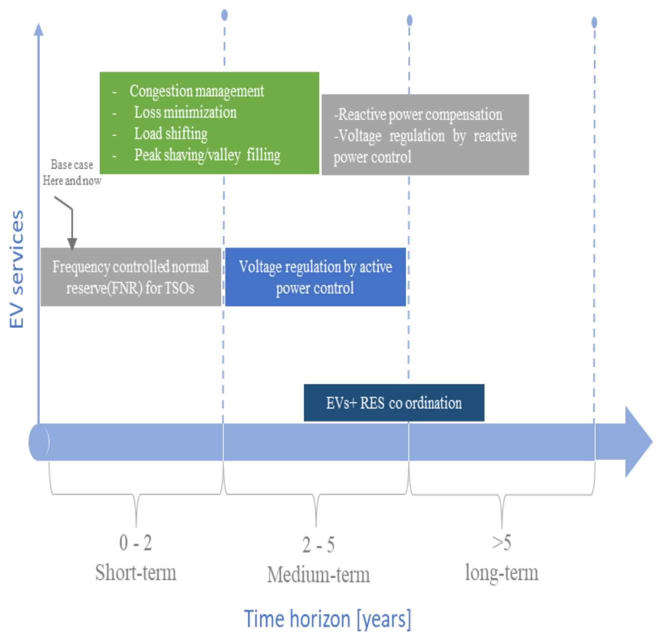

Fig. 4. EV Implementability [3]

Plug-in EVs have a strong ability to define a new market framework for reactive power support in peak shaving, valley filling, and load shifting [3]. At present, the market design of the EVs has great potential for future study. Another interesting research topic for EVs is the economic aspects that are related to benefits analysis, including stockholders' benefit, service providers' regulation framework, the billing process, and ways of minimizing the EV charging/discharging cost. However, the recent studies seem to focus more on providing solutions in terms of developing algorithms, strategies, and methodologies without economic consideration [3].

The uncertainty of EVs' exchange behaviors and the different types of charging rates may have a negative impact on battery degradation. This degradation affects the battery lifespan and hence creates an interesting topic to be tackled in future research [3].

5. Conclusion

This paper presents an overview of potential services and impacts of EVs on DS planning and operation. The ancillary services can be divided into three categories: active power support, reactive power support, and renewable energy integration support. The impacts of EVs on distribution systems include the voltage profile, losses, power quality issues, and system protection. To minimize the negative impacts, selecting the optimal sizing and location of EVs' charging points is vital to maintain the system power quality and reliability. Assessment studies should include the behavior of the EVs' owners/drivers. As research gaps, the authors suggest to further investigate the potential impacts of EVs on reactive power market frameworks and the economy.

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