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Electric Vehicles: From Charging Infrastructure to Impacts on Utility Grid

Rania A. Ibrahim [a1] and Ibrahim M. Gaber [a]
[a] *Electrical and Control Engineering Department,*
Arab Academy for Science, Technology and Maritime Transport,
Alexandria 1029, Egypt

Abstract. Electric vehicles (EVs) are penetrating rapidly into the transport sector, profoundly impacting the electricity and energy sectors. While EVs bring many benefits, they present challenges to utility grid operators, particularly during charging their batteries. Uncoordinated charging stands out as a critical charging strategy requiring attention to mitigate potential adverse effects on power grids. Smart charging and vehicle-to-grid (V2G) technologies enable intelligent and bidirectional power transfer between the EV and the grid taking into account network conditions and requirements. However, the widespread adoption of these technologies depends on the formulation of effective infrastructure and regulatory frameworks. This paper presents the effects of unmanaged charging of EVs on the utility grid power quality such as voltage violations, utility assets overloading and harmonic distortion. The paper also sheds light on some mitigation strategies incorporated in literature to reduce the adverse effects of EV integration.

Keywords. Electric vehicle impacts, V2G, utility grid, power quality, uncoordinated and coordinated charging.

1. Introduction

The reliance of the transportation sector on fossil fuels presents a significant challenge, contributing substantially to both climate change through the release of greenhouse gases, especially within urban areas. Presently, transportation stands as one of the largest consumers of global energy, prompting serious movement toward electrified transportation with the aim to substitute conventional internal combustion vehicles with EVs. The transition to electrified transportation thus decreases dependence on traditional energy sources while integrating reliable and cost-effective solutions.

Over the past decade, there has been a notable surge in the demand for EVs. Projections indicate that by 2040, approximately 54% of global vehicle sales are expected to be comprised of EVs. Despite the fast-growing segment, inadequate charging infrastructure still exists which brings up challenges for EV users regarding the EV range of usage. Consequently, overcoming consumer fear is a key obstacle to the widespread acceptance of EVs, and large-scale deployment is impossible without the availability of sufficient and efficient charging infrastructure.

[1] Corresponding Author, Rania A. Ibrahim, Electrical and Control Engineering Department, Arab Academy for Science, Technology and Maritime Transport, Alexandria 1029, Egypt; E-mail: rania_assem@aast.edu.

The focus on efficient and convenient charging solutions has been a topic of research in many literatures. EVs can be equipped with a unidirectional charger that absorbs energy from the power grid without injecting energy, or a bidirectional charger through which it may absorb or inject energy from/to the utility grid [1]. Consequently, two prominent categories of EV charging technologies, coordinated and uncoordinated charging, have emerged to address the evolving needs of EV users and the power demands placed on utility grids [2].

EVs have positive economic and environmental impacts, but their large volume may limit grid functionality due to uncoordinated charging, voltage fluctuations, supply shortages, and increased operating and maintenance costs. On the contrary, during the off-peak charging times when there is not sufficient demand, the unused and excess-generated power will be rendered useless. Introducing new concepts such as vehicle-to-grid (V2G) and vehicle-to-vehicle (V2V) can in fact address these challenges and solve the current obstacles and problems in the power grid [3].

This paper summarizes an overview of contemporary EV engines technologies, chargers and charging strategies. The main aim is to provide an in-depth insight of the major challenges faced by the utility grids amidst the rapid adoption of EV charging infrastructures. Concurrently, the work highlights the existing mitigating solutions that have been implemented or proposed in literature to address these challenges, in an attempt to provide a holistic perspective on the EV adoption and its impact.

2. EV Engines Technology

EVs engine technologies are continuously advancing to provide customers with a much wider selection. To accurately evaluate the impact of EVs on power systems, it is crucial to understand their charging profile. Currently, engines are categorized concurring to the energy converter utilized to propel the vehicle (i.e., internal combustion motor (ICE) or electric motor (EM)), the power source (i.e., battery, fuel cell, or gasoline)) [4]. EVs can be classified based on their powertrain design and engine settings into four types named as: Battery Electric Vehicle (BEV), Hybrid Electric Vehicle (HEV), Plug- in Hybrid Electric Vehicle (PHEV), and Fuel Cell Electric Vehicle (FCEV) [5]. Table 1 compares all type of existing EV technologies.

2.1 Battery Electric Vehicle (BEV)

BEVs, powered by battery-powered electric drives, are ideal for urban environments due to their low emissions and rechargeable battery banks, consisting of an electric motor, inverter, battery, control module, and drive trainv [22]. The battery pack converts AC power to electric motor, controlling speed and propelling wheels through a cog. During braking, motor functions as an alternator, generating power to recharge battery.

2.2 Hybrid Electric Vehicle (HEV)

HEVs have an internal combustion engine (ICE) and an electric motor, resulting in lower gas emissions and fuel consumption. They consist of an engine, electric motor, battery pack, controller, inverter, fuel tank, and controlling module, and do not require grid-charged charging [6]. Therefore, battery charging has no adverse effect on the power system and cannot provide electrical service.

2.3 Plug-in Hybrid Electric Vehicle (PHEV)

A PHEV is a hybrid electric vehicle (HEV) powered by regenerative braking, ICE, and an EV charger. It can operate in all-electric mode or hybrid mode, with the main components being the EM, engine, inverter, battery, fuel tank, control module, and battery charger [6], [7]. PHEV type usually utilizes a small battery capacity, thus less negative impact is expected on the power system.

2.4 Fuel Cell Electric Vehicle (FCEV)

FCEVs, also known as Zero-Emission Vehicles, employs 'fuel cell technology' to generate the electricity required to run the vehicle. FCEV has short refueling time like ICEs [6], [7] and its main components are: EM, fuel-cell stack, hydrogen storage tank, battery with converter and controller. The FCEV uses a combination of batteries and supercapacitors to generate electricity, eliminating the need for grid charging and affecting the electricity network.

Items of emissions, BEV and FCEV encounter the least, while HEV account for the highest as demonstrated in Table 1. However, BEVs have the longest charging time, and thus fewer charging stations. FCEV on the other hand is totally fuel independent, yet exhibit the highest cost due to fuel cell cost.

Table 1. EV engine technologies

	BEV	HEV	PHEV	FCEV
Mechanism	Powered by electric motor + battery that are charged by plugging into electric outlet	Powered by a conventional engine + electric motor + battery that is charged by regenerative braking	Powered by a conventional engine + electric motor + batteries that can be plugged into an electric outlet	Powered by electric motor + fuel cell + battery + supercapacitor
Engine	AC induction / Synchronous	AC Synchronous	AC Synchronous	AC synchronous
Power supply	Battery + electric motor	ICE + Electric motor	ICE + Electric motor	Fuel Cells + electric motor
Fuel	Electric	Petrol/diesel as main fuel	Gasoline and electricity as fuel sources	Hydrogen gas
Advantages	High Efficiency Low noise	High efficiency Several fueling stations	High efficiency Several fueling stations	Zero emission or ultra low emission Independence on crude oils
Disadvantages	Long charging time Few charging stations	Oil dependent Engine noise Complex architecture	Complex architecture Few charging stations	Fuel cell cost Hydrogen infrastructure
CO2 Emission	Very low emissions	Relatively high	Moderate	Very low emissions
Power grid Impact	High	None	Minor impact	none

3. Power Flow Through Electric Vehicles

Lack of EV charging stations may impede EV development, and range anxiety is aggravated by insufficient charging stations and lengthy charging times. Recently, many literatures on the study of the stand-alone and grid connected (and grid support) operating modes in EV integration exist. Accordingly, several categories exist as depicted in Figure 1: vehicle-to-home (V2H), building-to-vehicle-to-building ($V2B^2$), vehicle-to-external load (V2L), and vehicle-to-vehicle (V2V) for standalone connection [8]. As for grid connected and support modes, Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), and Vehicle-for-Grid (V4G).

- Vehicle-to-Home (V2H): In case of power outages when emergency power is required then EV batteries can be used as offline UPS
- Building-to-Vehicle-to-Building ($V2B^2$): Introduces the idea that utilizes EVs as an energy storage device to exchange energy among buildings with the main intention to promote the zero-energy building aim
- Vehicle-to-external Load (V2L): This concept permits electrical loads feeding in stand-alone mode.
- Vehicle-to-Vehicle (V2V): Allows energy sharing between vehicles thus eliminates the need for a charging station and reduces range anxiety in parallel.
- Grid-to-Vehicle (G2V): In the G2V mode, power flow is from the grid to the charger and then to the EV battery. This mode is used to charge batteries.
- Vehicle-to-Grid (V2G): When there is a requirement for power in the grid, the battery has to supply power to the grid. In this mode, power flows in the reverse direction from the battery to the grid via the controller and the control during the mode will be taken care of by the power grid manager.
- Vehicle-for-Grid (V4G): When EV is non-operating in G2V mode and V2G modes it can be used for reactive power compensation acting as an active power filter.

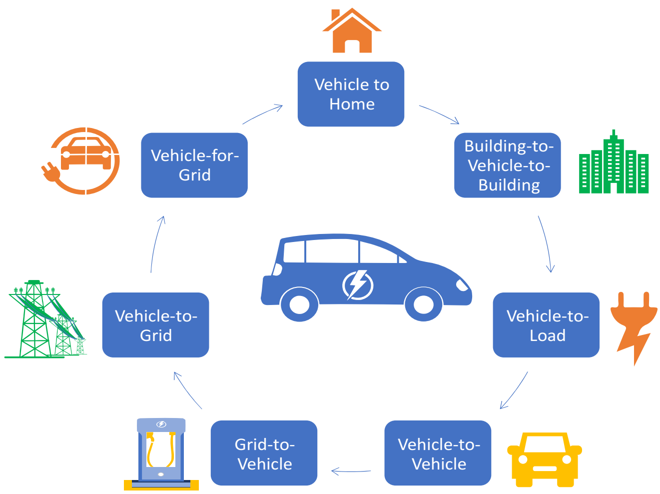

Figure 1. EV modes of operation.

4. EV Battery Charging and Levels

Charging devices offer the link between the EV and the utility grid by converting AC power into DC power, which in turn is used to charge the EV battery system. Figure 2 summarizes the classification of different charging technologies. EVs charging technologies can be classified into three main technologies: conductive charging, wireless (i.e., contactless) charging (WC), and battery swapping [9]. Conductive charging is the simplest and currently the most common charging method. Conductive charging has a physical contact (such as a wire) between the power source and the battery, whereas a WC has no physical contact. WC and battery swapping are not widely used like conductive charging and still under study and development [10]. There are two strategies utilized in EV charging stations for conductive charging, a) on-board chargers (for AC slow chargers), and b) off-board chargers (for AC and DC fast chargers) [11], [12]. Conductive charging can be further subdivided into Level 1, Level 2, Level 3, and Level 4 charging as depicted in Figure 2, with Level 4 as the fastest option.

5. Strategies for Charging and Discharging EVs

The power flow transfer between EV and grid can typically occur in two modes of operation: unidirectional and bidirectional. In addition, EV's charging management is classified into coordinated and uncoordinated categories.

5.1 Un-coordinated Charging

In uncontrolled charging, EVs are charged upon plug-in without any attempt to pre-schedule the charging process. In this approach, the grid operator does not receive any user information, potentially giving rise to problems with grid stability, power quality, and battery state-of-charge (SOC). Uncoordinated charging is economically attractive and less complex due to the absence of communication requirements and thus less privacy concerns. Research on uncontrolled charging has been concentrated on examining the effects of EV on the electrical grid which is the prime focus of this work [13].

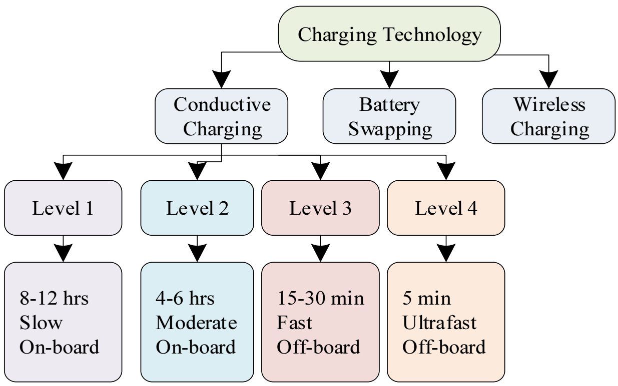

Figure 2. EV charging technologies.

5.2 Delayed Charging and Discharging

With delayed charging, some consequences of uncontrolled charging may be mitigated. The utility sets daytime electricity rates according to off-peak and on-peak hours such that EV owners are encouraged to charge their vehicles during off-peak times. This method benefits both utility companies and EV owners. However, non-optimal pricing may lead EV users to excessively charge during off-peak hours, creating an unavoidable second peak.

5.3 Coordinated Charging

In coordinated charging, the whole operation is controlled directly by a third-party controller or aggregator [14]. Henceforth, the EV users and private and public charging station operators are involved in charging management by selling or buying electric power [15]. Therefore, the power flow between the EV and grid can occur in indirect controlled, smart controlled, and bi-directional modes as demonstrated.

5.4 Indirect Controlled Charging

Consumer behavior and decisions are considered when indirect control is applied. As the name suggests, indirectly controlled charging does not affect the charging parameters in a direct way. However, it may control other parameters that can affect the charging parameters. For instance, the energy cost can be managed as part of the charging mechanism that will influence users to charge at required times throughout the day. Consequently, charging rates may be defined to avoid congestion, voltage violations, and overloading of electrical network equipment, therefore, the charging parameters are controlled indirectly [16].

5.5 Smart Charging

As the name implies, smart or intelligent charging/ discharging refers to a system whereby a data connection is shared between an EV and a charging station, and the charging station is connected to a transmission/distribution system operator. In order to maximize energy consumption, intelligent charging enables the charging station operator to monitor, regulate, and restrict the remote usage of their devices. This is accomplished by controlling a set of parameters to coordinate the charging process in order to achieve certain objectives, such as minimizing power loss, limiting charging costs, and maximizing the operator's profit.

5.6 Bi-directional Charging

Bi-directional charging differs from smart charging/ discharging in that it promotes the V2G concept, which enables EVs to inject power into the power grid. This is practically convenient especially when EVs are usually parked for a long time. Additionally, this type pf charging strategy reduces the negative impacts imposed on the utility grid which takes place during the charging–discharging action.

6. Impact of EV on the Utility Grid Power Quality

Power flow modes permit both unidirectional and bi-directional energy flow between the grid and EV which not only can reduce the grid effects of EV charging but also can offer grid assistance if needed. As mentioned earlier, incorporating EVs offers numerous benefits and operational versatility such as power regulation, reactive power support, energy losses minimization, and load balancing. However, the rapid integration of EVs into grid networks has given rise to other significant challenges which must be addressed to optimize the integration of EVs into grids. For these reasons, the following section will discuss the pros and cons of integrating EVs into the power grid supported mitigation strategies adopted in recent publications as per Table 2.

6.1. Voltage Magnitude Variation

Voltage magnitude variation refers to the fluctuations in the average voltage values over a time period and bandwidth. Voltage sag is a common power quality issue where sudden load variations can result in a drop in line voltage magnitude creating a voltage sag, or a rise in voltage magnitude causing a voltage swell. Heavy traffic, vehicle colliding with the utility pole which tends the wire to touch, concentration of charging points are all causes of voltage sags from an EV equipment. It is worth mentioning that reactive power compensation is fundamental in maintaining nodal voltages. For this reason, several work have revolved around exploring the capabilities of EVs to offer voltage and reactive power support when operating in V2G mode [17][20][28].

Table 2. Power quality mitigation approaches

	Parameter	Approach	Diligence
[17]	Voltage profile improvement	Charging control	Valley-filling approach to meet charging demands and nodal voltage
[18]	Voltage unbalance	RES and energy storage with optimal scheduling	Optimal scheduling uing energy storage batteries
[19]	Voltage unbalance and reactive power	Energy Storage	Studying the economic aspects of using energy storage systems compensators
[20]	Voltage profile regulation	Compensation Devices	Optimally allocating EV charging capacity and decentralized compensation algorithm
[21]	Voltage unbalance, stability and power loss reduction	Network reconfiguration	Optimizing static var compensator location and size with an optimization algorithm
[22]	Voltage unbalance	Network reconfiguration with DG	Optimal sizing and siting of DG with network reconfiguration
[23]	Voltage unbalance	Active Compensation Devices	Negative, zero and a positive-sequence reactive current compensator
[24]	Load, losses and stability	Demand response	Utilizing fuzzy logic controllers to alleviate transformers loading
[25]	Network losses and voltage profile	Demand response and load shaping	Charged scheduling taking charging decisions considering grid and customer
[26]	Harmonics	Converter control	Proportional quasi resonant controller to block the path of the DC bus voltage ripple
[27]	Voltage stability, reliability, and power losses	Optimal placement of charging stations	Novel approach for charger citing that takes into account cost, accessibility index, and voltage stability reliability power loss index
[28]	Voltage profile improvement	Renewable resources utilization	Integration of EVs and PV along with an optimal power flow algorithm

[29]	Voltage unbalance	Intelligent charging strategies	Hierarchical control to address voltage unbalance by incorporating central and local controls
[30]	Stability and frequency regulation	Power Converter	Partial power control to aid the injection of required current
[31]	Disturbance rejection and stability	FACT compensation	D-STATCOM and disturbance rejection control for anti-interference
[32]	Harmonics and interference immunity	Power converter	Modified 3-phase buck rectifier to improve input current total harmonic distortion
[33]	Reliability	Optimal placement of charging stations	Charger placement considering voltage stability, reliability, and cost
[34]	Reliability	Smart charging	Impact of dynamic wireless charging of electric buses
[35]	Stability and frequency regulation	Power Converter	Single staged control model based on virtual synchronous machine
[36]	Stability and reactive power support	Filter based Control	Hystresis filter-based approach for circulating current reduction
[37]	Mitigating transformer overloads	Demand response and load shaping	Scheduling EV utilizing a priority-driven charging approach
[38]	Overloading on utility equipment	Demand response	Power management through coordinated charging based on state of charge
[39]	Voltage drop and active power losses	Renewable resources utilization	Network reconfiguration determining the sizing and distribution of charging load
[40]	Power fluctuations, sag and harmonics	Superconducting magnetic energy storage	Unified-power-quality-conditioner to unify the multiple V2G functions
[41]	Voltage unbalance	Intelligent charging strategies	Droop control to generate charging rates for individual EV chargers
[42]	Reduction of peak load	Demand response and load shaping	Dynamic pricing model for demand management

6.2. Stability of Utility Grid

Grid stability refers to the system's capacity to handle sudden changes in frequency, current, or voltage disruptions within a permissible range of ±5% from standard values [24][27]. Nonetheless, the connection of multiple high- fast charging stations to the grid makes it challenging to maintain regulated frequency and voltage at the point of common coupling [30][31]. Grid instability can have a profound impact on customer service, existing infrastructure, as well as the charging stations in a network [35][36].

6.3. Overloading on Utility Assets

The extensive integration of EVs when multiple EV owners simultaneously charge their vehicles. This action can strain different distribution network components such as transformers and cables, leading to potential overload situations that stress these elements, reduce their lifetime, and necessitate upgrades to the infrastructure [21][37][38][42].

6.4. Voltage Unbalance

Large loads, like EVs, induce three-phase voltage unbalanced during charging and discharging of their batteries [18][19]. This may lead to elevated network congestion, increased peak load, harmonic distortions, and may also lead to disrupted protective relays operation [22][23]. Additionally, these imbalances contribute to higher power losses, overheating in neutral lines, which leads to further elevated operational and maintenance expenses within the power system [29][41].

6.5. Power and Frequency Regulation

Regulating power system frequency serves as a crucial indicator for balancing active power supply and demand. Extended frequency deviation limits could result in load shedding during under-frequency events or the disconnection of generation units in cases of over-frequency occurrences. Thus for maintaining system frequency, managing the charging and discharging of EV batteries presents is essential [30][35][40].

6.6. Harmonics Distortion

High harmonic currents are associated with converting the voltage of an AC power system to the DC voltage of an EV battery. Life expectancy is shortened, and losses are increased in distribution components due to harmonic currents. In addition, harmonic currents introduced in the distribution network also create harmonic. These distorted voltages can affect the power system's loads and therefore must be maintained within specific standards [26][32].

Table 2 summarizes several methodologies adopted in literature to lessen the power quality impacts. Utility companies may implement advanced monitoring strategies to provide real-time insight into the grid's performance. In addition, some issues may require power electronic solutions, utilizing complex control. Optimization algorithms driven by demand response can play a vital role in managing charging dynamics and ensure efficient distribution of resources. Grid infrastructure upgrades and addition of equipment can increase grid's resilience towards higher EV penetration. Furthermore, integrating renewables and energy storage systems can smooth out peaks and contribute to grid stability. Moreover, collaborative efforts between utilities and regulatory frameworks are essential in developing strategies and standards to ensure seamless EV adoption while maintaining the network power quality limits.

7. Conclusion

The popularity of EVs is expected to grow significantly in the coming future, which necessitates the adoption of more advanced technologies, specifically smart charging and vehicle-to-everything connection. The deployment of these technologies becomes imperative to establish a reliable infrastructure aiming to minimize the charging impacts on the utility grid while fulfilling the expectations of EV owners. This paper presented a comprehensive overview of present EV engine technologies, chargers and charging strategies to realize the current state of EV and grid integration research. Through this work, a thorough understanding of potential challenges confronting grid operators is investigated. The work also highlights potential solutions drawn from existing literature for different power quality issues.

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