

Review

# An Insight into Practical Solutions for Electric Vehicle Charging in Smart Grid

Sara Deilami <sup>1,\*</sup> and S. M. Mueen <sup>2</sup> <sup>1</sup> School of Engineering, Macquarie University, Sydney, NSW 2113, Australia<sup>2</sup> School of Electrical Engineering, Computing and Mathematical Sciences, Curtin University, Perth, WA 6102, Australia; sm.mueen@curtin.edu.au

\* Correspondence: Sara.deilami@mq.edu.au; Tel.: +61 2-9850-2296

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**Abstract:** The electrification of transportation has been developed to support energy efficiency and CO<sub>2</sub> reduction. As a result, electric vehicles (EVs) have become more popular in the current transport system to create more efficient energy. In recent years, this increase in EVs as well as renewable energy resources (RERs) has led to a major issue for power system networks. This paper studies electrical vehicles (EVs) and their applications in the smart grid and provides practical solutions for EV charging strategies in a smart power system to overcome the issues associated with large-scale EV penetrations. The research first reviews the EV battery infrastructure and charging strategies and introduces the main impacts of uncontrolled charging on the power grid. Then, it provides a practical overview of the existing and future solutions to manage the large-scale integration of EVs into the network. The simulation results for two controlled strategies of maximum sensitivity selection (MSS) and genetic algorithm (GA) optimization are presented and reviewed. A comparative analysis was performed to prove the application and validity of the solution approaches. This also helps researchers with the application of the optimization approaches on EV charging strategies. These two algorithms were implemented on a modified IEEE 23 kV medium voltage distribution system with switched shunt capacitors (SSCs) and a low voltage residential network, including EVs and nonlinear EV battery chargers.

**Keywords:** EV charging; uncontrolled charging; online coordinated charging; battery charger harmonics

## 1. Introduction

Over the past decade, smart grid technology has been significantly developed by the introduction of electric vehicles (EVs) as well as distributed energy resources (DERs). This smarter grid requires a two-way communication network to enable bi-directional flow between new electric appliances, online control of assets, real-time monitoring, and protection of the power network. This brings opportunities and innovations in the distribution network and grid performance by integrating DERs as well as EVs [1]. A smart grid not only covers energy storage and load balancing but also overcomes the issues associated with voltage variations caused by DERs and EVs.

EV manufacturers, such as Toyota, Ford, TESLA, Mercedes Benz, Chevrolets, and Nissan Leaf, have been trying to introduce their own new EVs with up-to-date technology and smart applications. This trend continues to introduce the latest and modern EV generation that represents a constant improvement. This is to overcome the issues and current limitations, and tackle the requirements. A large growth of EVs by up to “approximately 50 million [is expected] by 2025 and 125 million by 2030” [2–4]. This is likely to affect the grid and its performance. This growth can increase the peak demand, power consumption, and complexity of the network [2,3]. In other words, EVs in large-scale

penetration can have a detrimental impact on the power quality, performance, reliability, and stability of the grid, especially with the integration of DERs.

To deal with the undesirable impacts of uncontrolled EV charging on a power network, controlled centralized and decentralized practices have been introduced in many recent research investigations [4–7]. For example, in [5], the conventional centralized algorithm and its challenges were discussed and decentralized controlled algorithms in a smart grid were introduced. A study [6] introduced another technique for controlled EV charging of multiple stations in distribution systems. Many researchers have explored EV charging activities and their impacts on residential and distribution networks. The effectiveness of controlled EV charging strategies versus uncontrolled EV charging and different approaches have been analyzed and implemented, respectively, to overcome the issues related to the power quality and performance of the grid [8]. Additionally, studies aimed at improving the performance, reliability, stability, and power quality of grid by implementing different approaches and strategies, such as demand side management (DSM), controlling the active/reactive power flow, and including load tap changers (LTCs) or switched shunt capacitors (SSCs) to the network [9–16], have been performed. In [10], a smart efficient pricing was proposed as part of a demand-side management mechanism. The researchers in [11] investigated demand-side management to mitigate the impact of EV fast charging in residential buildings with the integration of renewable energy. However, there are still gaps in the research on the smart application of EV charging activities as well as their impact on uncontrolled charging behaviors on the power quality and stability of the grid.

It is important to consider the severe impacts of the injected current harmonics caused by nonlinear loads on the power grid. The nonlinear loads can be industrial/commercial loads, such as variable speed drives and pumps, or residential customers, such as EVs [17–21]. The harmonic distortions caused by nonlinear loads can directly contribute to the power system's concerns, such as voltage variations, power system losses and harmonic resonances, and many other grid-related issues [18–21]. Recently, different approaches have been developed and introduced in the literature to overcome the issues with the grid power quality and performance. Some studies [18–20] investigated the impacts of EV battery chargers and harmonics caused by EV chargers on the power quality of distribution systems. The authors of [17] particularly focused on the grid performance as well as power quality of the power system. The focus of this paper was to satisfy customers' desire to fully charge their vehicles and have their vehicles ready for their next trip early in the morning while mitigating harmonics [17].

This paper provides a practical insight into EV charging strategies and a review and analysis on different approaches. The review first introduces the EV infrastructure and EV charging strategies. The review also investigates the challenges and presents solutions. This is to resolve the existing issues and overcome those challenges and provide further future directions and research opportunities. Table 1 presents a list of the reviewed papers with a brief explanation about the area of the work. The organization of the paper is as follows. It starts with an introduction in Section 1.

Section 2 is dedicated to EV battery charging strategies and infrastructure and Section 3 explains EV charging strategies with the subsections outlining the impact of uncoordinated charging. These two sections are the continuation of the introduction section. In Section 4, controlled charging approaches are analyzed and compared. Section 5 is a comparison analysis of two practical approaches and includes the results and discussion of two optimization algorithms. This section helps readers with the application of optimization algorithms on EV charging strategies. Section 6 is the conclusion and future directions.

**Table 1.** List of reviewed publications and contributions.

Publications	Detailed Description/Contribution
[1–8]	Smart grid, Grid modernization, Integration of EVs, EV chargers, and infrastructure—Centralized and decentralized controlled algorithm, Challenge, Load control through smart metering
[9–11]	Demand side management, Three steps- approach (offline/online optimization), online learning, EVs and integration of renewable energy
[12–16]	Optimal scheduling of LTC and SSC, Real time coordination of EV charging, EV charging impacts, charging schemes and strategies, Smart Load Management, EVs and integration of renewable energy
[17–21]	Power quality concerns, Impact of EV battery chargers on residential networks, Harmonics.
[22–25]	EV charging impacts, charging schemes and strategies, EV Standard SAE 2010-2017
[26–31]	Smart grid- Integration of EVs, survey and analysis, Fast charging, Dynamic charging EV charging impacts and mitigation,
[32]	Power quality, Harmonics in power systems
[33,34]	EV charging fact sheets online datasheet- BWMi3, Idaho national laboratory
[35–43]	EV charging impacts, charging schemes and strategies, Electric vehicle infrastructure, Fast charging technology, Reliability of power system
[44–54]	Optimal scheduling of LTC and SSC, Capacitor sizing, EV charging, Volt/Var control. nonlinear loads in Residential and distribution networks Fuzzy and GA optimization, sensitivity analysis and MSS optimization, EV charging fact sheets online datasheet- Nissan Leaf
[55,56]	Price List Standard Fees and charges, IEEE standard 519.

## 2. EV Battery Charging Strategies and Infrastructure

Electric cars may be different based on their charging infrastructure and how they connect to the power grid to get charged. Some manufacturers designed EV cars with fast charging facilities, and some provided their cars with sockets for charging. This can be either DC fast charging or AC charging [22–27]. The connections between the EV battery chargers and the charging stations as well as their communications depends on the type of battery charger (every manufacturer has its own specifications) and EV infrastructure [23]. The classification of the battery chargers as well as their connectors are thoroughly specified and presented in [24]. Generally, there are three important EV charging levels. Level 1 charging (slow chargers), level 2 charging (medium chargers), and level 3 charging (fast chargers) according to SAEJ1772 standards [25–27]. Table 2 refers to the EV charging levels' characteristics, their power levels, and expected charging rate [24,25].

**Table 2.** EV battery charger characteristics and power level [24,25].

EV Type	Input Voltage	Input Current	Typical Use	Charging Time
Level 1- AC	120 single phase)	15 A–1.9 kW	House or office	10–13 h
Level 2- AC	208–240 Three phase)	40 A–20 kW	Private or Commercial	1–3 h
Level 3- DC Fast charging	200–500 (Three phase)	80 A–40 kW	Public	0.5–1.44 h

EVs can be charged overnight after plugging them into an outlet at home and charged overnight (slow charging). The second charging method is level 2 charging, which is known as primary charging, with a required outlet range of 208 to 240 V. Compared to level 1 charging, it is more costly. Level 3 (DC fast charging) is normally used for commercial/public use and it is more costly than level 1 and level 2 charging [25,26]. Besides the EV charger characteristics, EV chargers' manufacturers tend to consider the harmonic currents and voltage spectrums and the total harmonic distortion in the voltage (THDv) and in the current (THDi) level.

### 3. EV Charging Strategies

The integration of EVs as well as renewable energy resources (RERs) into the power grid may lead to detrimental issues on the power quality, performance, and efficiency of the grid. The EV control strategies need to be properly studied and investigated. The two most common strategies in EV charging are the random/uncontrolled strategy and coordinated/controlled charging strategy [28,29].

It is well-known that moderate and high EV penetrations in random strategies may lead to severe grid power quality and grid performance conditions and unacceptable voltage variations, especially during peak hours. Further, research studies have introduced new controlled schemes/charging strategies to resolve the abovementioned issues even with high EV penetrations [28–31].

#### 3.1. Impact of Uncoordinated Charging—High EV Penetrations

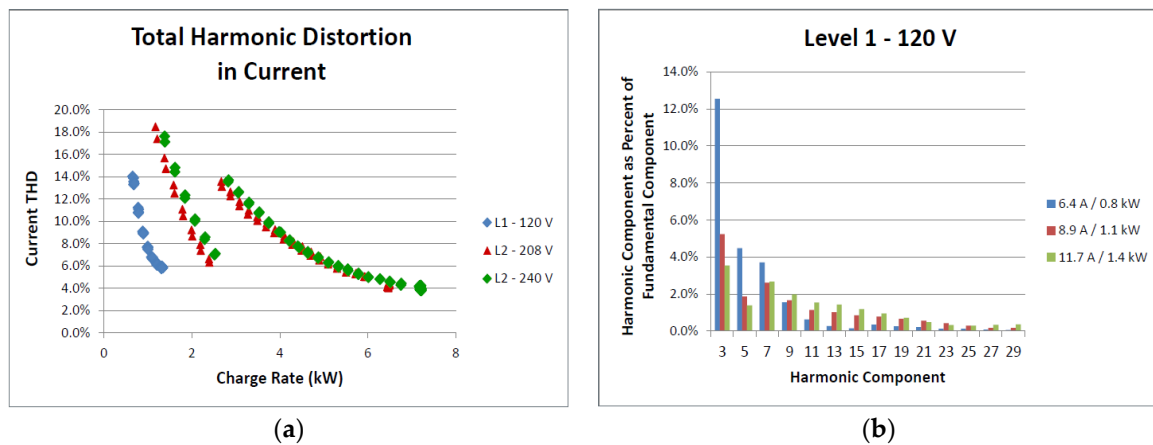
The impact of uncontrolled EV battery charging on the distribution and residential network is unavoidable. As shown in many research studies, the main parameters of the power network listed below may be affected by the randomized EV charging.

##### 3.1.1. Power Quality

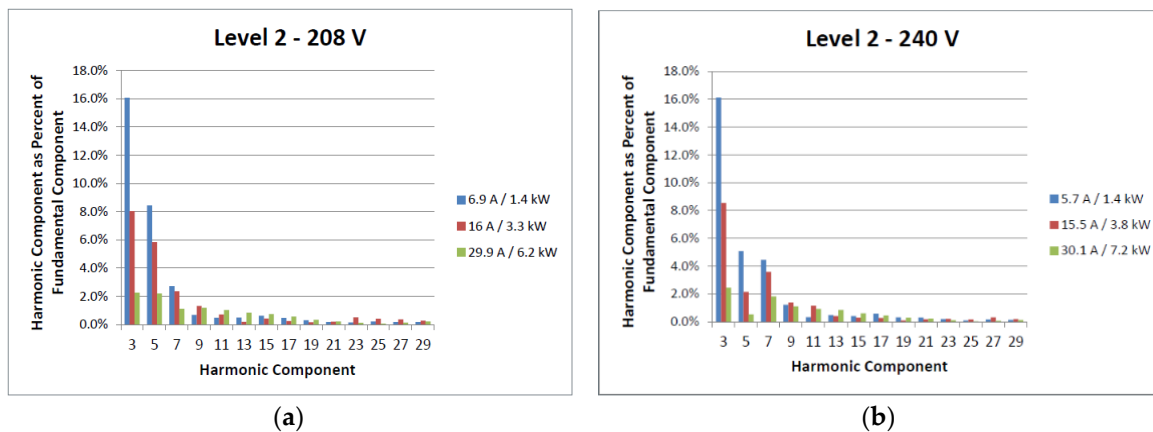
The power quality is one of the main factors of the power distribution grid [17–32]. The injected current harmonics caused by EV battery chargers may lead to severe consequences, such as power quality issues, voltage sag, increasing distortion, and power losses, especially with the growth in EV demand. The researchers of [18–21] also investigated the impact of EV battery chargers on the power quality of the distribution network.

During the charging time, the connection of the EV charger to the charging stations can create harmonic distortion. The harmonic distortion depends upon the specific harmonic spectrums, which have been thoroughly studied and investigated for many types of EV battery chargers with different charging power levels [33,34]. Manufacturers have specifically been testing and investigating the harmonic distortion and individual harmonic orders for different vehicles. The harmonic status of EV battery chargers for different charging levels is different. However, in all cases, the third harmonic is dominant and has a negative impact on the power quality of the electrical grid.

Figure 1a shows the results of THDi. Figures 1b and 2a,b present the harmonic components for BMW i3 for different levels of charging [33]. A test was done in Idaho National Laboratory (INL) [34] to measure the power quality and efficiency of this type of EV [33]. The vehicle was considered to be steady state for 120 V level 1 charging rate, 240 V level 2 charging, and 208 V level 2 charging. The charging rate is defined as the level at which the battery is charged with respect to its capacity. The charge rate in this study was calculated by multiplying the voltage (V, in volts) by the current (I, in amps) divided by 1000 (P, kW). According to [33], the maximum charging rate differs for each level of charging. For example, the maximum charging rates for level 1 charging and level 2 (208 V) charging are 1.33 and 6.47 kW, respectively. Additionally, as shown in Figure 1, the charging rate for level 2 (240 V) charging is 7.22 kW (green graph). As the vehicle charge rate decreases, the efficiency decreases, and the total harmonic distortion increases. As shown in Figures 1b and 2a,b, the third harmonic component is dominant in all scenarios. The blue, red, and green colors in the figures refer to the minimum, medium, and maximum charging rate selected for each test, respectively [33].



**Figure 1.** (a) THDi of EV for level 1 (120 V), level 2 (208 V), and level 2 (240 V) for BMW i3 (18.8 kWh). (b) Harmonic components of EV for level 1 charging (120 V) for BMW i3 (18.8 kWh) [33,34].



**Figure 2.** Harmonic components of EV charging for BMW i3 (18.8 kWh) for (a) level 2 charging rate (208 V), (b) for level 2 charging rate (240 V) [33,34].

### 3.1.2. Voltage Stability

Another important parameter is the voltage stability of the networks. Voltage stability is the ability of the power network to maintain an adequate and acceptable voltage at all buses in the system under normal conditions and after being exposed to a disturbance. EV charging may lead to a sudden increase in the loads and cause grid stability issues such as voltage instability [35–38]. As discussed in [36,37], voltage stability can be calculated from the PV curve (changes of the active power with respect to the increase of the voltage profile). The simulation results for the case of voltage instability were tested in [37]. In [37], the authors showed the voltage sensitivity factor and bus stability factor required for the voltage stability index.

### 3.1.3. Peak Demand

The increase in EV penetration also leads to a significant rise in peak demand levels as well as transformer performance. It can also reshape the electricity load curve. During peak hours, people tend to plug in their cars into charge after they return from work and increase the power demand. This can have a negative impact on residential EV hotspots or the points of EV charging stations. EV hotspots are the areas in the grid with a greater concentration of EVs charging or charging stations, and therefore, a capacity constraint might occur depending on the transformer and feeder sizes and levels [35,38].

Table 3 shows a good example of locations with EV hotspot issues depending on the EV battery charger sizes/rates and capacity. Therefore, the load demand needs to be managed and controlled carefully to avoid any issues for utilities [35].

**Table 3.** Hierarchical levels and capacity requirements/sizes of EV charging [35].

Network Level	Typical Size	Charger	10 EV Charging	100 EVs Charging
<b>Transformers</b>	50–250 kVA	7.4 kW/22 kW	30%–150%/Exceed capacity	Exceed capacity/Exceed capacity
<b>Feeders</b>	5–10 MVA	7.4 kW/22 kW	0.7%–1.5%/2%–4%	7%–15%/22%–44%
<b>Zone Substations</b>	30–60 MVA	7.4 kW/22 kW	0.1%–0.2%/0.4%–0.7%	1.2%–2.5%/4%–7%

### 3.1.4. Reliability

Another important factor to consider is reliability. This factor is usually analyzed separately and widely as an important matter for a power system. In a power system, a reliable system satisfactorily operates for a period of time under certain operating conditions [35–43]. The reliability of a power system refers to “the reliability of generation, transmission, distribution” and closely relates to customer satisfaction. The authors of [37] performed a comprehensive overview of the reliability of the power system and introduced the importance of reliability indices: “System average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), and customer average interruption duration index (CAIDI)”. Table 4 shows the definition and significance of the indices for the reliability of the power system [37].

**Table 4.** Definitions of reliability indices in the power system [37].

Index	Definition	Significance
<b>SAIFI</b>	Units of interruptions over a certain time period per customer	Condition of the system, units of interruption per customer.
<b>SAIDI</b>	Average interruption during per customer served	Shows the duration of interruption as the condition of the system.
<b>CAIDI</b>	Average interruption time for those customers interrupted over a year	Offers the average outage duration that any given customer would experience.
<b>ENS</b>	The total energy not supplied by the system	An indicator of Energy deficiency of the system
<b>AENS</b>	Average system load curtailment index	Represent how much energy is not served over a certain time.

## 4. EV Coordinated Charging Approach

Many studies have investigated the capacity problems and negative impact of uncoordinated EV charging on the residential and distribution power system. The main approaches are summarized below [35]:

- Introducing the infrastructure, such as large-scale batteries, vehicle-to-grid (V2G) opportunities, or increased network capacity [35].
- Control chargers installed in the car: Many EV manufacturers have developed their own controlled device to control their charging and prevent any high peak prices, such as Nissan Leaf. Controlling the charging device can also be done remotely by sending signals to the charger.
- EV Coordination: Controlling/introducing a different tariff for peak hours and off-peak hours to the customers and encouraging people to charge their vehicle when required during off-peak hours. This can be done dynamically/statically or by smart charging, where the active control of the EV charging can be handled by the utilities or EV charging provider. Smart charging is centralized or decentralized.



- EV coordination (load sifting with the integration of RERs) is another possible solution that has been constantly proposed and discussed. There have been many studies in EV controlled charging strategies with the integration of wind generation or RERs.
- Intelligent/smart controlling scheme is another approach. Load shedding and load shaving have been discussed and investigated as possible solutions.

There are different optimization strategies to cover the controlled/coordinated EV charging. The online coordinated charging approach is one type of smart charging strategy, with the aim of reducing the cost of generation, losses, and electricity bills as well as increasing customer satisfaction and system performance with the help of different optimization techniques [17,38,44]. In the optimization process, an objective function along with few operating conditions are defined and implemented to attain the optimal solution.

Online EV coordination has been widely developed, modified, and proposed by different optimization techniques, such as particle swarm optimization (PSO), maximum sensitivity selections (MSSs), and genetic algorithms (GAs), aiming at slightly different objectives due to their applications. These optimization algorithms have been modified/improved to address different barriers and major issues in the power grid.

#### 4.1. Online MSS Optimization with EV Battery Chargers

This practical approach is a fast and precise optimization technique to solve the objective function based on computing the sensitivity of the EV charging loads at each time intervals [8,17]. This optimization is defined based on the Jacobian matrices and uses power mismatch equations [45]. The applications for this optimization are in the control of reactive power and voltage stability in a large power distribution network.

The existing solution for online controlled EV charging is the sensitivity of the system losses to the number of EVs that can be extracted from the entries of the Jacobian matrix [17]:

$$MSS_{t,i} = \partial P_{t,loss} / \partial P_{EV,i}, i = 1, \dots, i_m, \quad (1)$$

where  $MSS_{t,i}$  is defined as the sensitivity of power losses to the EV charging at node  $i$  at time interval  $t$  and  $i_m$  represents the number of EVs. In this formula,  $P_{EV,i}$  is the total consumption of the EV connected to node  $i$ . Entries of the MSS vector are derived from the Jacobian matrix of decoupled harmonic power flow (DHPF) [17]. The DHPF algorithm is usually used for harmonic power flow calculations to model the smart power system under non-sinusoidal operating conditions with nonlinear loads. In this model, the nonlinear loads are modeled as current sources. These current sources inject harmonic current into the system [45,46].

It is further discussed that the sensitivity of reactive power to the bus voltage is included in the optimization algorithm [45,46]. The partial derivatives are available from the Jacobian matrix [17]. The authors of [17] show the modified online optimization approach to not only coordinate the EV charging but also to include the nonlinearities (the harmonics) of EV battery chargers. This is due to the negative impact of the injected current harmonics on the performance, power quality of the grid, and customer satisfaction. Therefore, this method is a combined MSS, DHPF, and optimal dispatch of SSC optimization [46].

#### 4.2. Online GA Optimization with EV Battery Chargers

GA is also another optimization algorithm that has been widely used in many research publications and previous investigations [47–52]. This algorithm is a near optimal solution and an iterative approach. This algorithm begins with an initial arbitrary population consisting of individuals called chromosomes. A new generation is then created from chromosomes after going through an iterative process. GA optimization improves the initial population through different repetitive steps of mutation, crossover, inversion, and selection operator [47]. The nonlinear online GA optimization shows controlled EV

charging considering the EV battery charger to improve the efficiency, performance, and power quality of the grid.

#### 4.3. Application of SSC and Optimal Dispatch in Online EV MSS Optimization

The inclusion of EVs and battery chargers and integration of RERs into the smart grid have created concerns about their deployment, application, customer satisfaction, and utility requirements. Their inclusion into the grid also raises more concerns about their impact on the efficiency, reliability, and stability of the smart power grid. To control the nonlinearity of smart appliances, such as EV battery chargers, or the peak demand and over loading, LTCs and SSCs are a good choice to improve the voltage variations, harmonic distortions and power quality, efficiency, and performance of the smart power system.

The optimal dispatch of SSC in optimization algorithms helps to improve the harmonic distortion and power quality of the power grid considering the nonlinearities of EV battery chargers [46–52]. A previous study [46] demonstrates a good application of SSCs in the online EV controlled strategy with MSS optimization considering EV battery chargers. In this program, a day-ahead/online SSCs dispatch program was added to the algorithm to improve the performance and power quality as well as the customer satisfaction.

#### 4.4. Problem Formulation of the Objective Function Optimization Problems

The objective functions are usually defined differently due to their applications. For many online EV controlled charging optimizations, the objective functions are defined to reduce the losses or cost of losses and generation of energy. Depending on the optimization approach, objective functions are formulated to calculate the fundamental and harmonic losses of the power system. The objective functions are also formulated to consider the EV power consumption both at the fundamental frequency and the harmonic frequencies considering the EV battery chargers and harmonic injections. The following objective function was defined to reduce the cost associated with the losses and generation [17]. This formulation was modified to include the harmonic currents injected by EV battery chargers:

$$\text{Min } F_{\text{cost}} = \sum_t K_E P_{t,\text{loss}} + \sum_t K_{t,G} D_{t,\text{total}}, \quad (2)$$

where

$$P_{t,\text{loss}} = \sum_{k=0}^{n-1} R_{k,k+1} \left( |V_{k+1} - V_k| |y_{k,k+1}| \right)^2, \quad t = \Delta t, 2\Delta t, \dots, 24 \text{ h}, \quad (3)$$

where  $F_{\text{cost}}$  is defined as the cost consisting of the cost of the total system losses and the cost of system generation.  $\Delta t$  refers to the time interval and it depends on the optimization approach.  $K_E$  and  $K_{t,G}$  are the cost per MWh of losses and the cost per MWh of generation, respectively. Additionally,  $k$  and  $n$  refer to the node number and total number of nodes, respectively.

### 5. Comparative Analysis

For motivation and proof of this study, two MSS and GA optimization algorithm were performed and tested on the modified IEEE 31 node 100 kV distribution test system of [53]. The modified system includes 22 LV (415V) 19 nodes residential network [8,17,46], which are populated with different EV penetration levels based on real system data in Western Australia [17]. The Western Australia tariff in 2018 is available in [54]. The proposed online MSS strategy for EV coordination with SSC scheduling and the complete simulation results are available in [46].

The EV battery charger is a real model of the Nissan Leaf, with a rated battery capacity of 24 kWh and a charging rate of 6kW and level 2 charging (208 V/16 A). The efficiency and the SOC of the EV are 88%. The harmonic spectrum for these types of chargers is shown in Table 5 [46,47,53].



**Table 5.** Harmonic current spectrum of EV chargers and industry nonlinear loads [46,47,53].

Harmonic Order	EV		Six-Pulse VFD		PWM-ASD	
	Mag. [%]	Phase [deg]	Mag. [%]	Phase [deg]	Mag. [%]	Phase [deg]
1	100	0	100	0	100	0
5	2	−67	23.52	111	23.52	111
7	2	−67	6.08	109	6.08	109
9	1.5	−46	4.57	−158	4.57	−158
11	1.8	−46	4.20	−178	4.20	−178
THDi	18.9%		25.2%		7.1%	

For the calculation of the objective function in this study, the cost per MWh of the system losses were assumed as  $K_{t,G} = 50\$/\text{MWh}$  [17,48], and the cost per MWh of generation ( $K_{t,G}$ ) was taken from [17,46].

The results for uncontrolled EV charging, nonlinear MSS online EV charging, and GA online EV charging are presented and compared in Table 6.

**Table 6.** Definitions of the reliability indices in the power system.

EV Charging Approach	EV Penetration (%)	Voltage Deviations (%)	THDv at Worst Bus (%)	Number of EVs Left Uncharged
Uncontrolled	32	8.27	6.3	0
	47	13.2	11.3	0
	63	16.1	15.4	0
GA- Approach	32	0.99	5.5	0
	47	0.99	5.4	0
	63	1.12	5.6	12
MSS- Approach	32	0.97	5.1	0
	47	0.97	5.3	0
	63	0.98	5.3	0

Table 6 shows three different scenarios of charging strategies for EV charging considering the battery chargers' harmonics. The aim was to first present the impact of the uncontrolled EV charging approach on the power grid, especially with high penetration as a benchmark, and compare the results with two online controlled strategies of the MSS and GA approaches [46], and then to investigate the impacts of EV battery chargers and nonlinear load harmonics on these controlled strategies. In the first row (the uncontrolled charging with different penetrations), EVs arrive randomly at any time and charge as soon as they get home. Therefore, the THDv level is very high.

The second scenario is the online GA optimization with SSC scheduling that includes the EV charger harmonics. The results prove the effectiveness of this approach to improve the power quality and performance of the grid. As shown in Table 6, although the GA approach could successfully improve the THDv level (5.4% for EV 47% penetration) and grid performance, it failed to fully charge the EVs with a penetration of 63% (12 EVs left uncharged) and therefore cannot satisfy the EV owners' desire to have their vehicles ready before their next trip in the morning.

The third scenario shows nonlinear online MSS optimization with SSC scheduling considering the EV battery charger harmonics. This approach has already been proposed and presented in [46]. The results in Table 6 show the effectiveness of this online controlled strategy even for high EV penetrations. All vehicles are charged by 0800h in the morning and are ready for the next day's trip. This is without transformer overloading and exceeding the THDv standard limits of 5% [55].

Comparing both the MSS and GA optimizations, the MSS approach is a better option for online controlled charging, especially considering the customer satisfaction and faster computation time.

The conclusion of the results is listed below based on the comparison between the two case studies with the application of on online MSS optimization with EV battery chargers [46] and online GA optimization with EV battery chargers (Table 6):

- The uncontrolled EV approach leads to high THDv and voltage deviations beyond the acceptable standard limits, especially with high EV penetration. In this controlled strategy, EV owners can easily charge their vehicles at any time.
- The online GA optimization with EV battery chargers: This approach was tested and implemented on the modified system. As shown in Table 6, GA optimization is not able to fully charge the EVs till 8am in the morning and therefore all EVs will not be ready for their trip in the morning. The computational time of this approach is slower than the MSS optimization strategy. However, this approach is still able to satisfy the grid power quality and grid performance requirement even for high EV penetrations.
- The online MSS optimization with EV battery chargers [46]: This controlled strategy is the most effective and practical approach. The computational time for the MSS approach is quicker than the GA algorithm. This optimization was implemented and tested in [46].

## 6. Conclusions and Future Directions

This paper reviewed EV battery infrastructure and charging strategies and investigated the main impacts of uncontrolled/uncoordinated EV charging on the power system. The study included the relevant recent research on uncontrolled charging strategies to recognize the main parameters affected by the uncontrolled charging method and provided a practical insight into the existing and future solutions to achieve high penetration of EVs into the network. In the second part, the research provided a practical overview of the existing and future solutions to manage the large-scale integration of EVs into the network. In the last section, the study also included a practical showcase of recent solution approaches to highlight the effectiveness and correctness of the proposed methods provided in the recent studies. The main contributions are:

- The review analysis on EV battery infrastructure and charging technologies presents the basics of the EV structure, EV industry, and connection to the power grid. The study also explored the existing challenges and opportunities associated with uncontrolled EV charging methods.
- The uncontrolled charging of EV batteries can lead to severe impacts on the performance, power quality, and stability of the power network. The paper studied the important issues associated with uncontrolled EV charging and the main grid factors affected by this EV charging method.
- To address the existing issues and number of priority problems, the research provided an overview of practical solution approaches and enables the readers to determine the relevant research works and their own practices.
- The suitability and validity of the solution approaches were discussed and compared in a practical case study.

Based on this review, the researchers can follow the recent studies and attempts in the field of EV charging, especially in EV industry and market. This research also identified the major research gaps and provided future directions, such as combined voltage and frequency control by an EV charging schedule and a complete analysis of controlled EV charging strategies on reliability indices.

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