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# Power Quality of Electric Vehicle Charging Stations and Optimal Placement in the Distribution Network

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***Abstract-*** *Due to the presence of power electronic converters in electric vehicle battery chargers, the electrical power drawn from the distribution system has severe distortions which pose many problems to the power quality. Herein, the impact of chargers in terms of indicators, e.g., penetration level, battery state of charge, type of charging stations, the time of connection of chargers to the network, and the location of charging stations was comprehensively studied on a sample distribution network. The effect of these chargers was investigated based on power quality parameters, e.g., total harmonic distortion (THD) and voltage profile, and the effect of each indicator on these parameters was determined. To minimize the effects of the chargers, an IEEE 33-bus distribution sample network was optimized with the objective functions of voltage drop and THD. Based on this optimization algorithm, the installation placement and the power capacity of the charging stations were obtained to achieve the lowest voltage drop and THD.*

***Keyword:*** Electric Vehicle, EV charging station, Distribution network, Power quality.

## 1. INTRODUCTION

The entry of electric vehicles (EVs) into power grids and their battery charging pose many problems in the power grid. Success in the use of EVs in large volumes depends on the quality of power and reliability of the electrical network and vehicle charging. To meet the requirements of EV operators, chargers must have high power quality and be reliable and cost-effective. To this end, manufacturers of EVs and related equipment must have sufficient information about the specifications of the electrical network to which the charger is connected, as well as the effects that the charger can have on the network and the quality of service [1]. The most important issues that may arise in this regard include voltage drop in the network and overload in feeders and transformers [1-3]. In addition, the power quality of the network can be impacted by the connection of vehicles to the network [4-5]. Regarding power quality, network problems occur when charging large power batteries. Since EV batteries usually receive a relatively high current from the network for charging, they are considered medium and large batteries and can be the source of serious problems related to the power quality of the network.

Generally, because the battery operates at the DC level, a rectifier (AC-to-DC converter) is required [6-8]. For this purpose, it is necessary to convert the AC to the DC signal, and also to another DC voltage level by a DC-to-DC converter. Both of these processes produce harmonic perturbations [8, 9]. To study the effects of EVs on the power quality of power grids, many studies have been conducted in the form of articles and standards [10]. In these studies, the effects of harmonic distortions have been discussed on electrical network equipment, including transformers, power cables, capacitors, measuring devices, relays, and electrical panels. Harmonic distortions also affect adjacent loads, especially power electronic devices and motors [11, 12]. Fast charging of electric vehicles is characterized by high charging power, concentrated load demand in the charging station, charging during the day and busy hours, and being pulsed due to the short charging time with high power [13]. Because of these features, fast chargers cause power quality issues, including voltage fluctuations, harmonic stability, and harmonic propagation [14-15]. The impact of adding EV chargers to the existing low-voltage distribution network should be analyzed by considering various criteria, e.g., the impact on the network with different EV chargers, mobile EV charge, power quality, voltage profile, and peak load demand [16, 17]. Besides negative effects, electric vehicles confer some advanced technologies,

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thanks to which their optimal use can enhance network efficiency. For example, electric vehicles can be utilized as energy storage in emergencies [18]. EVs can provide frequency control services to improve power system operation [19]. It is also possible to alleviate the negative impacts of EVs via different methods, e.g., reducing the THD of the input current by using AC/DC rectifiers with the control method via a virtual resistor [20]. To solve the problem of locating and allocating EV charging stations' capacity, mathematical programming models have been primarily adopted in the literature. However, for such models, the computational complexity increases as the number of constraints and/or decision variables rises, thereby making it challenging to find an optimal solution. On the other hand, metaheuristic algorithms are used to find a universal (almost optimal) solution with less computational effort. References [21, 22] defined an optimization problem as an indefinite hard time (NP-Hard) polynomial problem. To solve the NP-Hard problem, the total area was divided into small square cells. The optimization problem was solved using the genetic algorithm (GA). In addition to GA, swarm intelligence metaphorical algorithms have also been used in several studies [23, 24], which utilized the gravitational search algorithm (GSA) and particle swarm optimization (PSO) to implement the CS infrastructure due to energy costs and limited battery capacity [25, 26].

In this paper, the impact of EV chargers is investigated on the power grid from various aspects, e.g., the location of charging stations, penetration level, the number of charging stations, charging time, and the type of charging stations. Moreover, based on the PSO algorithm, the capacity and placement of the EV chargers are obtained with objective functions of voltage drop and THD. In Section 2, the effect of EV chargers on power quality parameters is studied. In Section 3, the impact of EV chargers on a sample IEEE 33-bus network is examined in various aspects. Finally, in Section 4, the results of this article and solutions to prevent negative impacts of EV charging are presented.

## 2. THE EFFECT OF EV CHARGERS ON THE POWER QUALITY OF NETWORK

In this section, the effect of chargers on the power quality of network is examined based on the battery state of charge (SOC), the penetration level of the EV and the charging level. Also, the impact of various types of EVs and high power chargers on the network is investigated.

### 2.1. The effect of SOC on THD

Reference [27] provides a method to predict the connection time of EVs to the network as well as their SOC, which leads to a better utilization of the network, and also improves the power quality. Generally, the amount of harmonic injection into the network by the EV chargers depends on factors such as charging method, EV battery energy level, the number of cars connected to the network at the same time, and etc. [27]. Fig. 1 shows the current waveform of an EV charger in the two different SOCs [27]. According to Fig. 1, for the completely discharged battery, the percent of THD is equal to 20%, and for the battery with the SOC of 88%, THD is equal to 67%, which shows the effect of SOC on the amount of harmonics produced in the network. The charger examined in this case has the power characteristic shown in Fig. 2. According to the maximum power of the charger in Fig. 2, which is approximately 7.5 kW, the above-mentioned charger is a level 2 charger.

### 2.2. The effect of EV penetration level on THD

Reference [28] examines the presence of EVs in the network for low-load and high-load times of the network. It is concluded that much more power can be transferred to the EVs without reducing the power quality of the network in the low-load times. In other words, it is shown that the penetration level of the EVs has a significant effect on the THD [28]. Fig. 3 shows the amount of THD in the different busbars of a sample network for the different penetration of EVs [28]. In Fig. 3, three penetration levels of 30%, 50% and 80% are considered and the level 1 charger with the harmonic specifications presented in SAE J1772 standard is used. It is clear that as the penetration level of EVs in the network increases, the amount of THD generated for all three phases increases, and according to the relevant standards, the penetration level must be limited. So that the THD does not exceed the allowable value.

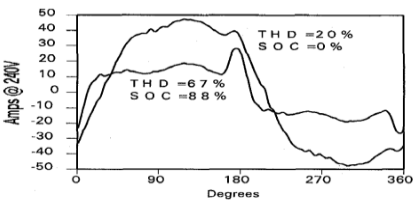



**Fig. 1. Current waveform of charger in two different SOC [28]**

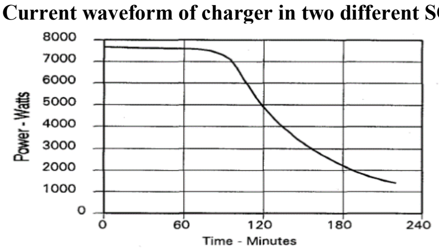
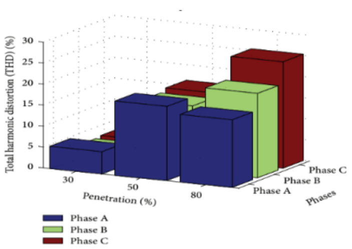
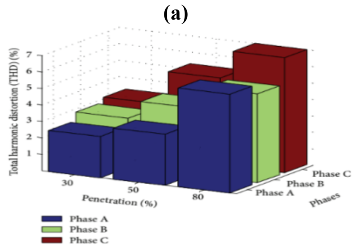



**Fig. 2. Power characteristic of a typical charger [28]**




**(a)**




**(b)**

**Fig. 3. THD in two busses in a sample grid for the penetration levels of 30%, 50% and 80% [28]**

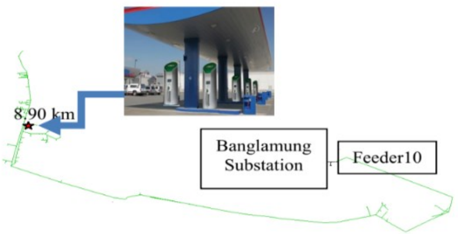



**Fig. 4. Real network and charging station installation location [29]**

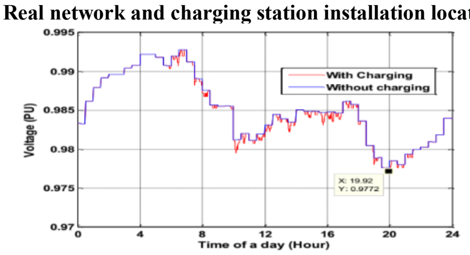



**Fig. 5. Network voltage profile in the presence of 500 EVs [29]**

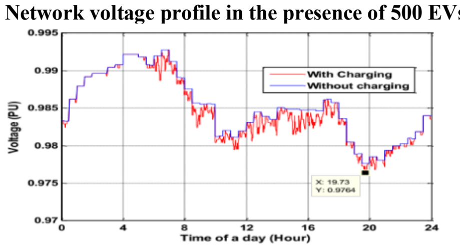



**Fig. 6. Network voltage profile in the presence of 2500 EVs [29]**

## 2.3. The effect of fast chargers on network voltage

Due to the importance of charging time, many measures have been taken to develop the fast chargers and along with them, many studies have been conducted to investigate the impact of fast chargers on the power grid. In [29], the effect of fast chargers on the voltage profile of the power grid is investigated. In this reference, using a real network (Fig. 4) and installing a charging station, various scenarios have been investigated. Examining Fig. 5 and Fig. 6, it is clear that the presence of EVs and fast charging stations has a great impact on the network voltage profile, and causes sudden voltage changes that are harmful to the sensitive network loads. Also, according to the above figures, it is clear that the increase in the number of vehicles has caused more changes in the network voltage and has led to more voltage drops.

## 2.4. The effect of high power fast chargers on THD

To investigate the effect of high power fast chargers in the power grid, a 10 kV distribution network as shown in Fig. 7 is investigated. In the desired network, two power levels of charging station (1000 kVA and 3000kVA) are considered, the results of which are presented in Table 1 and Table 2. By examining the above-mentioned tables, the following results are extracted:

- Feeder 1 has the highest harmonic, followed by feeders 2 and 3, and the lowest harmonic is related to feeders 4 and 5. Therefore, the harmonics will be higher in the busses near the charging station.
- Current THD increases as the capacity of the charging station increases, so that by increasing the capacity of the charging station to 3000kVA, the amount of THD in the feeder 1 is out of range, and if the capacity of the charging station is increased again, the THD in other feeders will exceed the allowable value.

**Table 1. Network feeder's harmonic with a capacity of 1000 KVA for fast charging station**

| 19th (A)/ Allowed amount | 17th (A)/ Allowed amount | 5th (A)/ Allowed amount | THD (%) | current (A) | feeder |
|---|---|---|---|---|---|
| 0.64/0.92 | 0.41/1.02 | 0.7/3.4 | 1.88 | 58.2 | 1 |
| 0.29/2.9 | 0.17/3.22 | 0.64/10.74 | 1.41 | 58.3 | 2 |
| 0.29/2.9 | 0.17/3.22 | 0.64/10.74 | 1.41 | 58.3 | 3 |
| 0.23/3.27 | 0.34/3.64 | 0.52/12.2 | 1.42 | 58.4 | 4 |
| 0.23/3.27 | 0.34/3.64 | 0.64/10.74 | 1.42 | 58.4 | 5 |
| 0.64/2.9 | 0.52/3.22 | 0.58/10.74 | 1.98 | 58.3 | 6 |

**Table 2. Harmonic network feeders with 3000 KVA capacity for fast charging station**

| 19th (A)/ Allowed amount | 17th (A)/ Allowed amount | 5th (A)/ Allowed amount | THD (%) | current (A) | feeder |
|---|---|---|---|---|---|
| 2.07/0.92 | 1.27/1.02 | 2.25/3.4 | 6.15 | 58.2 | 1 |
| 0.87/2.9 | 0.46/2.9 | 2.02/10.74 | 4.51 | 58.3 | 2 |
| 0.87/2.9 | 0.46/2.9 | 2.02/10.74 | 4.51 | 58.3 | 3 |
| 1.34/3.27 | 1.10/3.64 | 1.74/12.12 | 4.52 | 58.4 | 4 |
| 1.34/3.27 | 1.1/3.64 | 1.74/12.12 | 4.52 | 58.4 | 5 |
| 2.27/2.9 | 1.63/2.9 | 1.80/10.74 | 6.32 | 58.3 | 6 |

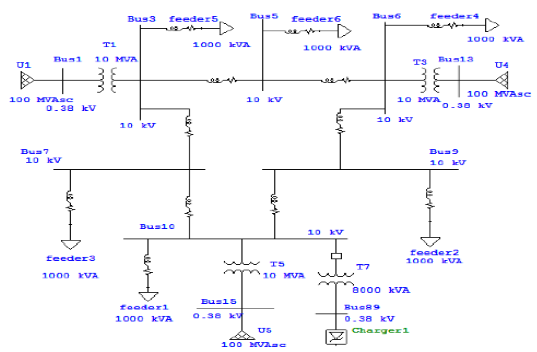


**Fig. 7. 10-bus distribution network**

## 3. DISTRIBUTION NETWORK POWER QUALITY ANALISIS

In this section, the impact of EVs on the power quality of network is examined from the different aspects of: location of charging stations, penetration level, number of charging stations, charging time, and type of charging stations. To achieve the mentioned goal, different scenarios are considered and a sample network is used to examine the scenarios. The sample network in this section is the 33-bus IEEE network, the single-line diagram of which is shown in Fig. 8. The amount of active and reactive power consumed in this network is 3745 kW and 242 kW, respectively. Complete information of the 33-bus network is also provided in the reference [30].

### 3.1. The effect of EV charging stations number

In order to evaluate the effect of the number of EV chargers, the voltage level and the capacity of each charger must first be determined. According to SAE J1772 standard, the capacities of the different types of chargers are presented in Table 3. In this section, three scenarios are considered. **Scenario 1:** In this scenario, level 1 chargers are used in the network. Given that, level 1 chargers have a low capacity and perform the charging operation by connecting the charger mounted on the EV directly to the network. It is assumed that the level 1 chargers are connected in the all network busbars and three modes of these chargers are checked in this scenario. The first case is 300 chargers, the second case is 800 chargers and in the third case, 2000 level 1 chargers are considered in the network. **Scenario 2:** In this scenario, level 2 chargers are used in the network. Because onboard chargers are connected to the network and are used in public centers, there are fewer level 1 chargers in the network. Hence, it is assumed that 10 busbars of the network are under study and three modes of the level 2 chargers are considered. In the first case, 40 chargers, in the second case, 100 chargers, and in the third case, 200 level 2 chargers are considered in the network. **Scenario 3:** In this scenario, level 3 chargers are used in the network. Due to the fact that level 3 chargers have a high capacity and charge outside the car in public centers such as shopping malls, gas stations, and etc., the number of them is smaller than level 1 and 2 chargers, which have been studied in the three network busbars (Fig. 8). In this regard, three modes are considered for them, in the first case, there are 5 stations, in the second case, there are 12 stations, and in the third case, there are 25 level 3 charging stations are in the network.

The results of the above scenarios are presented in Table 4. In this table, the numbers 300, 800 and 2000 for level 1 chargers correspond to the powers of 432, 1152 and 2880 kW, which is considered according to the total network consumption (3745 kV). In fact, the number of chargers is considered in such a way that approximately 10, 30 and 60% of the power consumption in the network is the capacity of network charging stations.

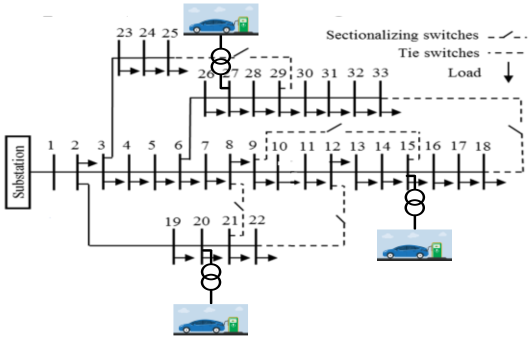



**Fig. 8. Location of Level 3 charging stations on the 33-bus distribution network**

**Table 3. Specifications of EV chargers in the SAE j1772 standard**

| Maximum power (kW) | Input voltage (V) | Charger type |
|---|---|---|
| 1.44 | 120 | Level 1 |
| 11.5 | 208-240 | Level 2 |
| 96 | 208-240 | Level 3 |

**Table 4. Network THD value for the different number of chargers in EV charging stations**

| Level 3 | | | Level 2 | | | Level 1 | | | Charger | |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | Number of stations | parameter |
| 25 | 12 | 5 | 200 | 100 | 40 | 2000 | 800 | 300 | Number of chargers | |
| 16.7 | 7.35 | 2.93 | 17.06 | 7.97 | 3.08 | 24.1 | 8.9 | 3.17 | Maximum network THD(%) | Harmonic |
| 0.07 | 0.038 | 0.016 | 0.09 | 0.045 | 0.017 | 0.14 | 0.05 | 0.02 | Minimum network THD(%) | |
| 6.22 | 2.85 | 1.15 | 7.5 | 3.61 | 1.15 | 11.08 | 4.1 | 1.5 | Average network THD(%) | |
| 0.81 | 0.86 | 0.89 | 0.83 | 0.87 | 0.89 | 0.81 | 0.87 | 0.9 | Minimum voltage (pu) | Voltage |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | Maximum voltage (pu) | |

### 3.2. The effect of charging stations placement

In order to investigate the effect of charging station location on the network power quality, the following three modes are considered for the location of EV charging stations.

- **Case 1:** the charging station is located at the beginning of the main network feeder
- **Case 2:** the charging station is located in the middle of the main network feeder.
- **Case 3:** the charging station is located at the end of the main network feeder.

This section also examines the level 3 chargers, and for all three of the above cases, the harmonic modeling of charging stations is used. The results of all cases are summarized in Fig. 9 and Fig. 10. According to the results of these figures, it is clear that the farther the charging station is installed from the main feeder, the higher the THD and voltage drop.

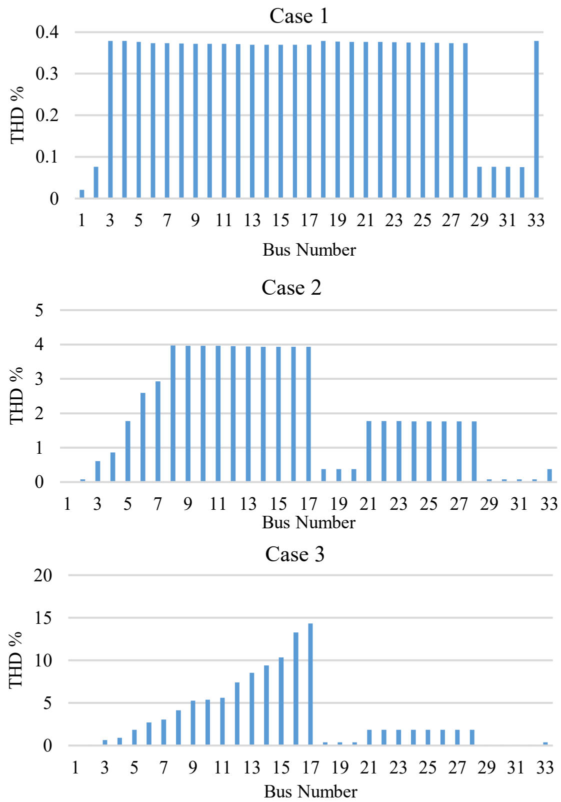



**Fig. 9. THD effect of charging stations placment**

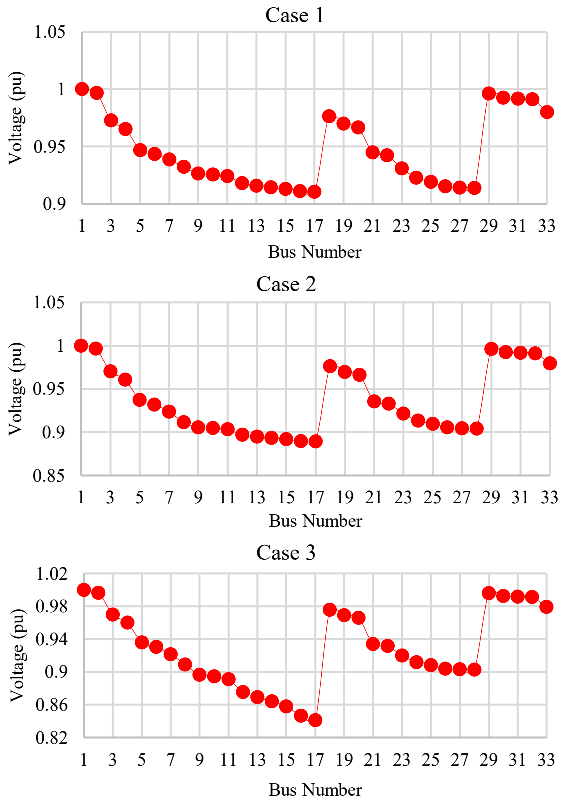



**Fig. 10. Voltage effect of charging stations placment**

**Table 5. Power quality index comparison for level 3 charger**

| Power quality analysis for level 3 charger | | | |
|---|---|---|---|
| Index | State | Maximum THD % | Minimum Voltage pu |
| The Effect of EV Charging Stations Number | 5 stations | 2.93 | 0.89 |
| | 12 stations | 7.35 | 0.86 |
| | 25 stations | 16.7 | 0.81 |
| The Effect of Charging Stations Placement | Case 1 | 0.38 | 0.91 |
| | Case 2 | 3.96 | 0.89 |
| | Case 3 | 14.3 | 0.84 |
| The Effect of Charging Time | 8 o'clock | 7.7 | 0.88 |
| | 14 o'clock | 7.5 | 0.84 |
| | 22 o'clock | 7.5 | 0.83 |

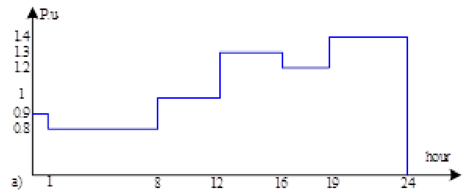



**Fig. 11. Load variation curve [17]**

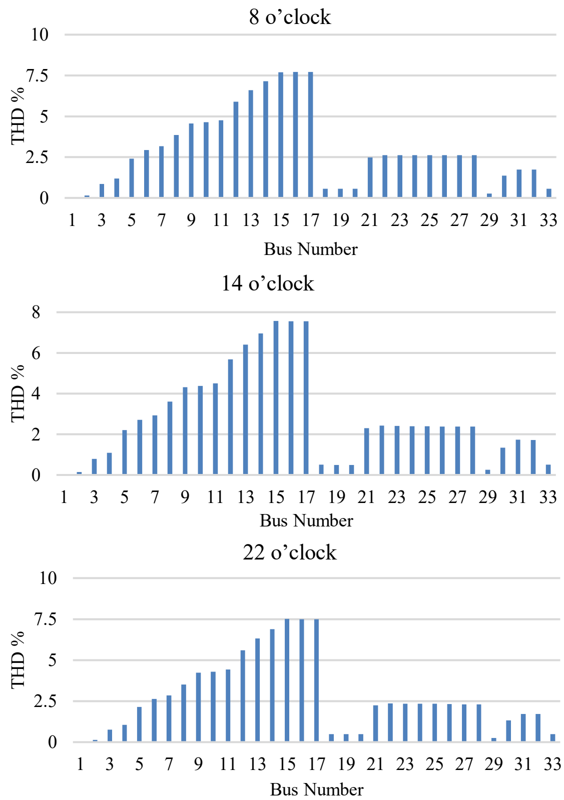



**Fig. 12. THD effect of charging time**

### 3.3. The effect of charging time

In order to investigate the effect of charging time on the network power quality, the daily load change curve in Fig. 11 is used [31]. In this section, to investigate the effect of charging time of EVs on the power quality of network, according to Fig. 11, three specific hours are examined. According to this figure, at 8 o'clock, the network load is 0.8 times the base load, at 14 o'clock, the network load is 1.3 times the base load, and at 22 o'clock, the network load is 1.4 times the base load. Therefore, in this part, the simulation is performed at 8, 14 and 22 o'clock, which different loading occurs in the network. In addition, because the charging level in this section does not make a difference in the results analysis, the simulation is performed only for the level 3 chargers. According to the results, as shown in Fig. 12 and Fig. 13, it is clear that during low-load hours, less voltage drop occurs in the network, but the amount of THD produced in the network decreases during high-load hours. In fact, because the power drawn from the network to charge the cars is constant in every three hours studied, more harmonic injected to the network in low-load hours.

In order to summarize the results of the analyses performed for the power quality issues (for the worst case-level 3 charger) and compare them, Table 5 is given. According to this table, for the number of chargers index, the higher the number of chargers, the higher the maximum THD and the lower the minimum voltage. Based on the location of the charging stations, the more charging stations are installed at the end of the main feeder, the worse it is in terms of power quality issues. Based on the charging time during the day, during the busy hours of power consumption, the condition is worse in terms of minimum voltage, but on the contrary, better condition prevails for maximum THD. In this table, the worst cases are highlighted.

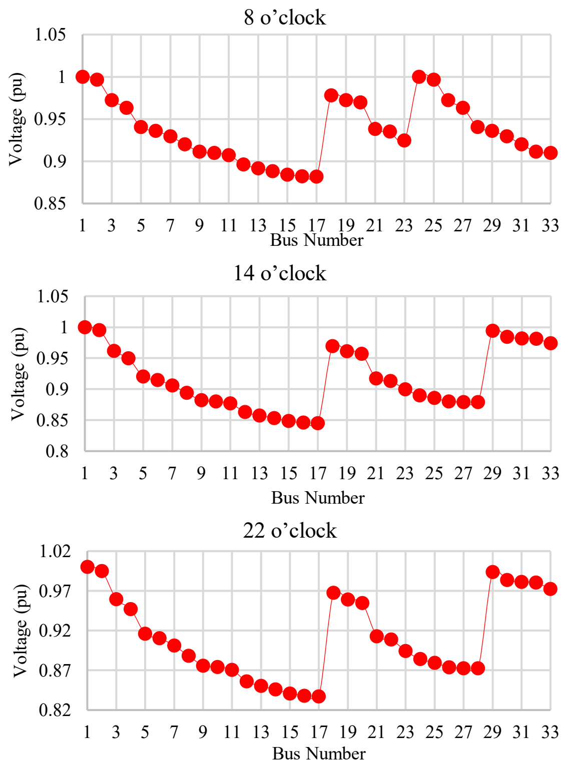



**Fig. 13. Voltage effect of charging time**

## 4. OPTIMIZATION ALGORITHM

Each system or engineering element is represented by a set of committees, some of which appear as a set of variables in the design process called design or decision variables. Here a control vector should be defined to include the placement of the charging station and the number of chargers in each station. The desired control vector, X, is defined as follows:

$$\mathbf{X}=[x_{s,1},x_{s,2},\dots,x_{s,Ns},x_{ch,1},x_{ch,2},\dots,x_{ch,Ns}]_{2\times N_S} \quad (1)$$

Where, $x_{s,i}$, $x_{ch,i}$ and $N_S$ are the location of *i*-th charging station in the network (bus number to which the station is connected), the number of chargers available at the *i*-th charging station, and number of charging stations in the network, respectively.

In this paper, two important objective functions in the power quality problem of the power grid are used, which are the total harmonic distortion (THD) and the voltage drop of the network bus. By calculating the harmonic voltage for different network buses, the voltage THD of the network buses based on the normal voltage of different busbars can be calculated by the following equation [32]:

$$\%THD_V=\frac{1}{V_1}\sqrt{\sum_{h=2}^{\infty}V_h^2}\times 100=\left(\sqrt{\left(\frac{V_{rms}}{V_{1rms}}\right)^2-1}\right)\times 100 \quad (2)$$

Similarly, the current THD can be calculated as follows:

$$\%THD_I=\frac{1}{I_1}\sqrt{\sum_{h=2}^{\infty}I_h^2}\times 100=\left(\sqrt{\left(\frac{I_{rms}}{I_{1rms}}\right)^2-1}\right)\times 100 \quad (3)$$

The formulation of the objective function of THD is as follows [24]:

$$\min\ f_1(X)$$

$$f_1(X)=THD_{total}=\sum_{i=1}^{N_{bus}}THD_{bus_i}\Big/N_{bus} \quad (4)$$

Where, $THD_{total}$, and $THD_{bus_i}$ are the total network THD and the *i*-th bus THD.

Minimizing the amount of bus voltage drop $d_{voltage}(\mathbf{X})$ from the nominal value is one of the most important issues in distribution networks, which is considered with the aim of minimizing the defined objective function (as secondary objectives) and modifying the voltage profile and safe operation in the distribution network. The following equation is used to minimize bus voltage drop:

$$f_2(\mathbf{X})=d_{voltage}(\mathbf{X})=\max\left[|1-V_{\min}| \quad and \quad |1-V_{\max}|\right] \quad (4)$$

Where, $V_{\min}$, and $V_{\max}$ are minimum and maximum bus voltage, respectively.

The second step in defining an optimization problem is to specify the constraints of the problem. Due to the limited capacity of power transmission through the lines, the restriction on the power through the lines must be observed in any issue related to the power network, including the operation of charging stations. The above constraint, which is an unequal constraint, is expressed as follows:

$$\left|P_{ij}^{Line}\right| < P_{ij,\max}^{Line} \tag{6}$$

Where, $P_{ij}^{Line}$ , and $P_{ij,max}^{Line}$ are active power and maximum active power through the lines.

Active and reactive transmission powers in the lines depend on the magnitude and angle of the voltages at the start and end of the line and the impedance of the path that are obtained from the following equation. This is an equal condition that must be observed at every stage of the problem solving.

$$P_{ij} = \sum_{i=1}^{N_{bus}} V_i V_j Y_{ij} \cos(\theta_{ij} - \delta_i - \delta_j) \tag{7}$$

$$Q_{ij} = \sum_{i=1}^{N_{bus}} V_i V_j Y_{ij} \sin(\theta_{ij} - \delta_i - \delta_j) \tag{8}$$

In above equation, $P_{ij}$ , and $Q_{ij}$ are active and reactive powers injected by the *i*-th bus to *j*-th bus. Also, $V_i$ , $V_j$ , $Y_{ij}$ , and $\theta_{ij}$ are the voltage magnitude of *i*-th bus, the voltage magnitude of *j*-th bus, the admittance and admittance angle of the branch between two buses *i* and *j*, respectively. Furthermore, $\delta_i$ , and $\delta_j$ are bus voltage angles for *i*-th and *j*-th buses.

To control the amplitude of the current passing through the transformers, the following unequal constraint must be established.

$$\left|I_{t,i}\right| \le I_{t,i}^{max} \qquad i = 1, 2, \ldots, N_t \tag{9}$$

In the above equation, $\left|I_{t,i}\right|$, $I_{t,i}^{max}$ , and $N_t$ are the transform current magnitude, the maximum *i*-th transform current, and the number of transformers, respectively.

The next step in the optimization is to choose a suitable method to solve the problem. In this paper, the particle swarm optimization (PSO) algorithm is used to solve the problem [33]. The advantages of this method include simple concept, easy implementation, computational efficiency and robustness to control parameters compared to the mathematical algorithms and other heuristic optimization methods. Particle swarm optimization (PSO) method is one of the types of evolutionary methods that was first used by Eberhart and Kennedy to solve optimization problems and its ability to be used in optimization problems with continuous functions has been proven [33]. In this method, the movement towards the optimal point of the function is based on the information of the best point obtained from each of the factors in the initial population and also the best point found by neighboring points. According to Fig. 14, the basis of the particle group optimization algorithm can be explained.

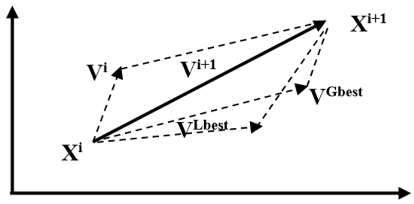



**Fig. 14. Basics operation of PSO**

First, a number of points are selected as the initial population in the search space:

$$\mathbf{X}_i = \left[x_{i,1}, x_{i,2}, \ldots, x_{i,n}\right]$$
$$V_i = \left[v_{i,1}, v_{i,2}, \ldots, v_{i,n}\right] \tag{10}$$

The value of the function is calculated for each factors in the search space. In each category, the minimum and the maximum point of the objective function are determined. In this way, the best point in each category is determined. On the other hand, with the availability of the past information of each factor, it is possible to determine the best point that has been discovered so far. In this way, the optimal point information of each category and each factor is determined. The first data corresponds to the global optimal point ($G_{best}$) in each group and the second data corresponds to the local optimal point ($P_{best,i}$ ). With this information, each factor moves in the direction of the vector $V_i^{k+1}$ .

$$V_i^{k+1} = \omega \times V_i^k + c_1 \times rand(.) \times (P_{best,i} - \mathbf{X}_i^k) + c_2 \times rand(.) \times (G_{best} - \mathbf{X}_i^k) \tag{11}$$

$$P_{best,i} = \left[p_{best,i,1}, p_{best,i,2}, \ldots, p_{best,i,n}\right]$$
$$G_{best} = \left[g_{best,1}, g_{best,2}, \ldots, g_{best,n}\right] \tag{12}$$

$$\mathbf{X}_i^{k+1} = V_i^{k+1} + \mathbf{X}_i^k \tag{13}$$

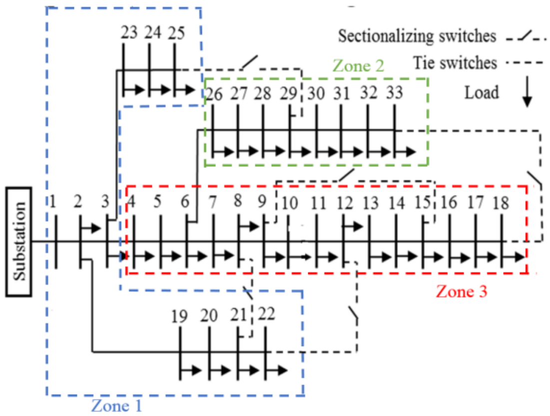


Fig. 15. IEEE 33-bus distribution network zoning for charging stations

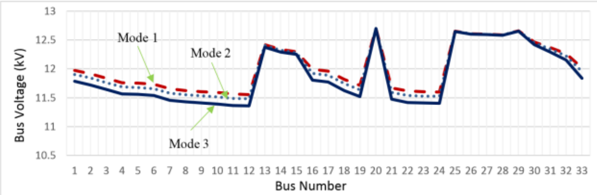


Fig. 16. Network voltage profiles for the three different charge modes

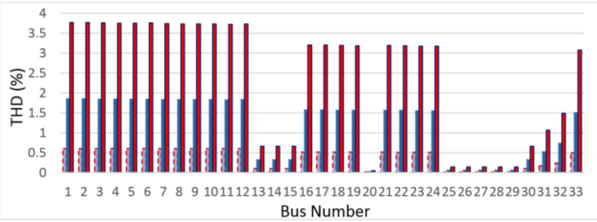


Fig. 17. THD in network buses for three different charge mode

Where, $c_1$ and $c_2$ are coefficients of random values. In this way, the PSO algorithm is able to find the optimal global point of the desired function in successive iterations.

The sample distribution network on which the results of the algorithm are tested in this section is the IEEE 33-bus network. In this section, electric vehicle charging stations are located in the network and their capacity is determined with the aim of improving the power quality. To implement the proposed algorithm on the sample network, the network is divided into three zones according to Fig. 15. In fact, this zoning has been done to prevent charging stations from being located in the same place or close to each other. According to Fig. 14, a level 3 charging station is placed in each zone.

### 4.1. Solving the problem with the objective function of voltage drop

In this section, the objective function of the problem is only to minimize the voltage changes of the buses. The problem solving results are presented in Table 6. Since charging stations are connected to the grid as consumers, the higher their capacity, the greater the voltage drop across the grid. So, the optimization algorithm moves the responses in a direction that minimize the capacity of the stations. In the first row of Table 6, the simulation results are presented by considering the location and capacity of charging stations as the control variables. It can be seen that the capacity of the stations is minimal and their location is suggested at the beginning of the lines. In this case, the value of network THD is 0.56%, which is a small amount. The reason for the low THD is the low capacity of charging stations.

In rows two and three of Table 6, in order to check the higher capacity of charging stations, the minimum capacity of each station are considered $3\times96\ kW$ (three chargers from level 3 type) and $6\times96kW$ (six chargers from level 3 type). In these cases, the connection point of the stations was obtained as expected at the beginning of the buses, but the THD level of the network increased due to the increase in the capacity of the charging stations. Fig. 16 shows the voltage of the main bus after installing the charging stations for the three modes in Table 6. According to this figure, the maximum voltage drop is related to the bus 12.

Table 6. Results of connecting charging stations to the IEEE 33-bus network with the aim of minimizing voltage drop

| Mode | Charging station connection bus | Stations Power (kW) | Grid average THD (%) | Grid lowest voltage |
|---|---|---|---|---|
| 1 | Bus 2, Bus 11, Bus 19 | 96 | 0.56 | 11.5 |
| 2 | Bus 1, Bus 11, Bus 19 | 288 | 1.2 | 11.48 |
| 3 | Bus 1, Bus 11, Bus 19 | 576 | 2.4 | 11.36 |

Table 7. Results of connecting charging stations to the IEEE 33-bus network with the aim of minimizing THD

| Mode | Charging station connection bus | Stations Power (kW) | Grid average THD (%) | Grid lowest voltage |
|---|---|---|---|---|
| 1 | Bus 1, Bus 11, Bus 19 | 96 | 0.39 | 11.56 |
| 2 | Bus 1, Bus 11, Bus 19 | 288 | 1.18 | 11.48 |
| 3 | Bus 1, Bus 11, Bus 19 | 576 | 2.4 | 11.36 |

Table 8. Results of connecting charging stations to the IEEE 33-bus network with the objectives of the lowest THD and the lowest voltage changes

| Mode | Charging station connection bus | Stations Power (kW) | Grid average THD (%) | Grid lowest voltage |
|---|---|---|---|---|
| 3 | Bus 1, Bus 11, Bus 19 | 576 | 2.4 | 11.36 |

### 4.2. Solving the problem with the objective function of THD

In this section, the objective function is to minimize the network THD. The problem solving results are presented in Table 7. In fact, if charging stations are installed at the end of lines, the current and voltage THD are increased. Their current also becomes harmonious and thus the THD level of the network increases. In Table 7, the optimization results are considered for the three modes. In the first case, the minimum number of chargers in each station is 1, in the second case is 3, and in the third case is 6. Fig. 17 shows the THD levels of network busses for the three modes. As shown in this figure, as the charging level of the stations increases, the amount of THD in the whole network increases.

### 4.3. Solving the problem with the target functions of voltage drop and THD simultaneously

In Table 8, the results of the problem optimization are presented simultaneously by considering the target functions of voltage changes and THD. The answer obtained in this section is similar to the best answer in the previous two sections. The similarity in the results obtained with the two different objective functions is due to the fact that the THD and the voltage drop have the same behavior. In other words, by optimizing one of these two objective functions, the other function is also optimized and the results obtained is the same.

The IEEE network examined in this section is a radial network fed on one side. In radial networks with one-way power supply, the closer the load is to the power supply, the lower the voltage drop and the lower the THD in the network. Therefore, in the simulations performed, the charging station locations were located at the beginning of the network lines. However, It should be noted that the distribution networks are now more complex due to the multi-point power supply (via ballast networks or distributed generation), and it cannot be said that the best place to install the charging stations is the beginning of the lines and feeders. In these networks, the importance of using the algorithm presented in this report becomes clearer. With the increase in the use of electric vehicles and their charging from the electricity network, the demand of the electricity network increases. With the increasing penetration of electric vehicles and fast chargers in the future, there is a need to increase the capacity of transmission and distribution lines. However, it is possible to manage the charging of electric vehicles with the capacity of the existing distribution lines by using the intelligent charging methods, the optimal placement of charging stations, and using the energy storage devices next to the charging stations. The use of renewable energy in the charging stations also contributes to this issue.

## 5. CONCLUSIONS

This paper examined the effects of different EV charging scenarios on the power quality of the electrical distribution network based on THD indices and voltage drop. Depending on the number of charging stations, the higher the number of charging stations with the highest power level, the higher the THD and the voltage drop, such that it is out of range in some cases. Therefore, it is essential to compensate for appropriate instruments such as energy storage devices and power filters to prevent these negative effects. Based on the installation location of charging stations in the distribution network, by examining the three installation modes at the beginning, middle, and end of the main feeder, it was concluded that the farther the charging stations from the main power supply, the higher the THD and voltage drop. Therefore, an optimal location is essential for the installation of charging stations. Furthermore, by examining the charging time of EVs, it was concluded that THD is lower during peak hours and higher during off-peak hours. There is also less voltage drop during off-peak hours than during peak hours. Consequently, intelligent scheduling of charging time for EVs should be performed. Herein, by implementing the PSO algorithm for objective functions of voltage drop and THD, the optimal location and capacity of the EV chargers were obtained. The optimal locations were buses number 1, 2, 11, and 19, and the optimal capacity of the EV chargers was $96\,kW$, $3\times96\,kW$, and $6\times96\,kW$.

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