A Review of Electric Vehicle Charging Impact on Power Grid

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***Abstract*—In view of increasing popularization of electric vehicles (EVs) in transportation system, it is necessary to conduct a comprehensive review of EVs charging impact on the power system along with its positive impact in terms of cost-benefit and environment. Voltage drop, unbalance and harmonic distortion have been among the main power quality concerns due to large-scale penetration of electric vehicles the system and therefore, these has been formulated and analyzed in this paper. A cost-benefit analysis is carried out under EVs penetration for assessment of cost for charging infrastructure and external factors such as health and climate benefits. Additionally, a substantial focus is given to compute the overloading of transformer, cable, and increased energy losses that appear after integration of single phase electric vehicle charging load in a distribution network and the obtained results may serve as a guiding parameters for network reinforcements.**

***Index Terms*—Electric vehicles, voltage drop, voltage unbalance, harmonic distortion, energy losses**

I. Introduction

Popularization of EVs is becoming high rather than discussing their negative impact on electrical distribution system and it is assumed that the distribution system is capable enough to support EVs' load [1], and it is not true in real. As the most likely point for charging an EV is home, so it indicates most probable addition of heavy single phase loads in the residential low voltage (LV) distribution network. Nonetheless, a large-scale penetration of EVs may overburden the present power infrastructure with a rise of power quality issues which may be detrimental to a sustainable power infrastructure. However, recently, some considerations have been made to discuss limitations of distribution network capacity for EV charging [2], [3]. Several studies have been carried out to assess EVs´ impact on the power grid [4], [5] and other studies about EVs´ impact on the power distribution system are described in [6], [7]. Large-scale integration of EVs is likely to put certain impact on the power system infrastructure, mainly on LV power distribution system [8]. As EV load is directly interfaced with the distribution network so it may affect the power system multifariously. Impact of EV charging load on the operation of power distribution system can be broadly considered in terms of technical concerns and economic issues. In the technical context, mostly loads connected to the system need an appropriate level of power quality and such loads may fail to function properly in case of variations in the fundamental parameters of power system i.e. voltage, frequency and or current and consequently, some of components e.g. transformers, motors and may face reduced lifespan. Quantity of power quality indices is restricted by a number of relevant standards. Generally, a specific system is considered and studied, for evaluation of any power quality index, that is aimed at identifying potential problems and causes of the issues in the system because power quality depends on various factors ranging from power generation site to the point of ultimate consumption and the elements connected to it. Thus, envisaged EVs´ impact on power distribution system include increased power flow in power cables, distribution lines, transformer overloading, harmonic distortion, voltage drop, voltage unbalance and etc [9]. Additionally, EVs are characterized as a single phase load in a three phase distribution system and it is well known fact that presence of large single phase loads and their uneven distribution on each phase causes voltage unbalance in the system.

On the other hand, conventional vehicles produce a lot of carbon emissions that are ejected into our natural atmosphere, leaving us vulnerable to things like pollution and greenhouse gases. In order to help positively the environment we live in, an electric car is a great step forward. Electric vehicles, for being environment friendly, can overshadow the negative technical impacts.

This paper is organized as follows: technical and economic impact of EVs is explained in Sec. II, vulnerability of distribution network is described in Sec. III. Formulation of voltage drop, voltage unbalance and harmonic distortion is presented in Sec. IV. A business of of EVs charging is briefed in Sec. V. Transformer and Cable overloading is detailed in Sec. VI, and Sec. VII contains energy losses. The paper is concluded in Sec. VIII.

II. Technical and Economic Impact of EVs

Large-scale integration of EVs put certain impact on the power system infrastructure, mainly on LV power distribution system. As EV load is directly interfaced with the distribution network for former´s charging. EVs may affect the power system multifariously that can broadly be classified into technical and economic concerns as illustrated in 1.

A. Economic Concerns

EV battery chargers are equipped with power electronic components for recharging EVs and former are characterized

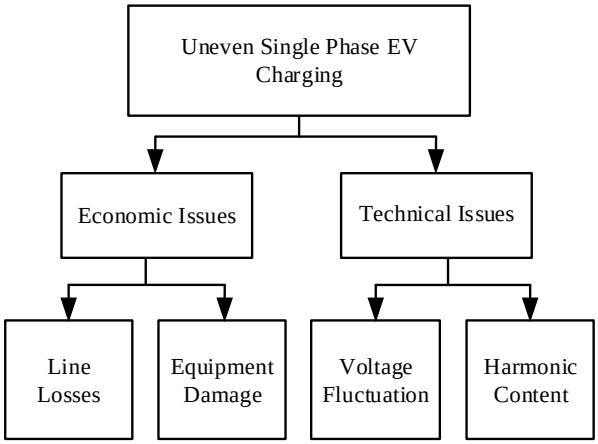


Figure 1. Concerns related to EV charging load

as non-linear loads or distorting loads which introduce harmonics in the system. Importantly, presence of voltage unbalance in the system induces non-characteristic triplet current harmonics e.g. 3rd and 9th harmonics adding them with characteristic harmonics of power converters. In power electronic interfaced loads, a small increase in voltage unbalance may cause input current to become significantly unbalanced that causes change its waveform into single-pulse waveform from a double-pulse waveform due to asymmetrical conduction of power electronic elements. Excessive flow of phase currents in a three phase system due to the voltage unbalance may circuits of overload-protection to trip [64]. As harmonic injection in the system causes an increase in phase currents so it leads to increased lines losses and overloading of cables. Harmonic contamination induced by VU in the distribution network alters reactive power circulation abnormally and voltage regulation problems that badly affects working efficiency of distribution transformer and results in the decreased life of machines. Where, increased line losses, de-rating of induction machines, decreased efficiency and reduced life of power equipment are described as an economic concern for DSOs. Thus VU caused by uneven single phase load of EVs is quite harmful to economy of a distribution network.

B. Technical Concerns

In the technical context, a power quality problem can be defined as, manifestation of any problem in voltage, current or frequency of the power system that results in malfunctioning of equipment,. Since a decade, power quality has been gaining due attention because of to its effects on components in the power system. Mostly, loads connected to the system need an appropriate level of power quality and such loads may fail to function properly in case of variations in the fundamental parameters of power system i.e. voltage, frequency and or current and consequently, some of components e.g. transformers, motors and may face reduced lifespan. Thus, it is quite important to assess power quality index. There are different power quality indices to be quantified including, voltage unbalances, harmonic contents, frequency variations, voltage drop and etc. Quantity of power quality indices is restricted by a number of relevant standards. Generally, a specific system is considered and studied, for evaluation of any power quality index, that is aimed at identifying potential problems and causes of the issue in the system because power quality depends on various factors ranging from power generation site to the point of ultimate consumption and the elements connected to it throughout.

III. Vulnerability of Distribution Network

The impact of connection of EV charging load on low voltage distribution system is of great concern because of latter's specific characteristics. As an LV distribution system is characterized with varying loads, unbalanced phase voltages, higher value of resistances on its branches, low reactance values, i.e. small ratio of X/R with radial structure as compared to medium voltage (MV) networks so it exhibits power quality problems. As a fact of matter low voltage networks are termed as the weaker portion of electrical power system. It implies that in case of even small variation in demand and supply could arouse worse effects in the power distribution system and it can be explained in view of the fact that the LV distribution lines have limited capacity of the connected equipment with impedance from HV/MV lines which results in problematic power supply with large impedance.

Taking this into account, the LV distribution system is expected to suffer a significant impact following a future scenario with large scale EV integration, which can affect system performance. In this context, an EV impact analysis for LV distribution grids is required in order to identify the impacts of EV connection to the network while providing with the means to deal with them. For analysis of the impacts of EV connection on the operation of LV distribution grids, a steady-state tool should be used. The tool should be able to take into account the specific characteristics of LV distribution systems with EV integration, especially the fact that LV grids are generally unbalanced and, more importantly, it must be able to model and implement the EV demand for different scenarios. For this reason, a specific tool is adopted in order to perform the following required tasks:

- Define EV demand, charging method and mobility
- Run an LV three-phase power flow routine
- Verify the main technical constraints of the system (such as system losses, voltage profiles)
- Provide supply quality and system performance parameters and indexes calculation (namely voltage imbalances and load imbalances)
- Compile the results from different scenarios.

The entire process is shown in the flow chart in 2 and the description is explained below.

A power flow routine was developed in order to be capable of dealing with the specificity of LV distribution networks, mainly the existence of three unbalanced phases plus a neutral conductor and lines with a low X/R ratio. This routine will enable the analysis of the steady-state behavior of a LV

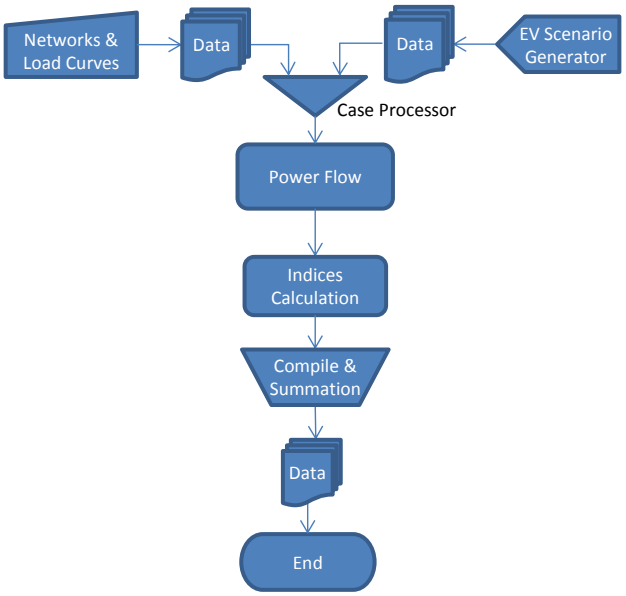


Figure 2. Flow-Chart: EV impact analysis on LV grid

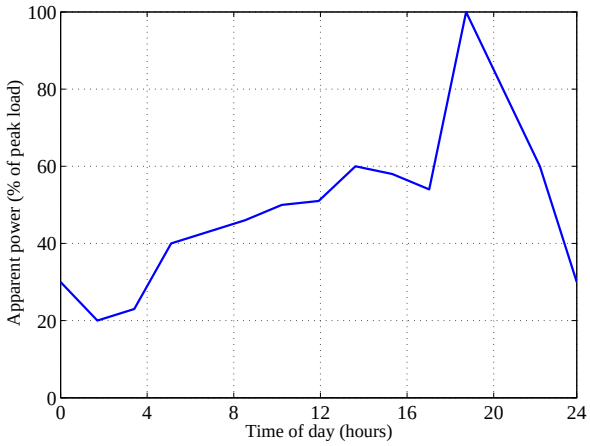


Figure 3. Daily loading on a distribution network ([12])

network and dealing with single-phase loads and different micro-generation technologies. A first version of the algorithm was developed in [10] as a microgrid analysis tool, and extended to four-wire systems in [11] being used for three-phase, four-wire and radial distribution networks. Moreover, although designed for radial distribution networks, it may be adapted for weakly meshed networks. However, this is no obstacle since the test-networks to be used are typical LV distribution grids and therefore with a radial structure.

IV. Formulation of Voltage Drop, Unbalance and Harmonic Distortion

Definition of voltage drop given by EN 50160 is: "decrease in voltage due to load variation". Voltage drop is one of the most likely problems that may be observed in case of large scale EV penetration in the distribution network. When a light load is connected, the system could feed a large amount of additional load within its allowed limits. Thus, a particular amount of EV load could be connected to a distribution system without being subjected to the power quality problem.

To investigate the voltage drop in the distribution system, peak load hours of the feeder are considered. During this period, at the possible occurrence of maximum load on the feeder, a severe voltage drop is expected to occur. A load curve on daily basis taken from [12] shows the fraction/percentage of maximum power demand as an apparent power demand of the power system as shown in 3. The curve shows that the load is around 30 % of the peak load demand during midnight to 6 am.

Voltage drop ΔV_D from point R_k to the end of distribution feeder can be expressed as in Eq. (1)

$$\Delta V_D = R_k \left(n - R_k + 1\right) \frac{\sqrt{P^2 + Q^2} z_1}{V_{nom}} \tag{1}$$

where, z_1 is the impedance of line segments between two nodes, n is the number of nodes, P and Q represent active and reactive power and V_{nom} is the fundamental value of voltage.

A. Voltage Unbalance

Definition of voltage unbalance in this paper is taken as a ratio of the negative sequence voltage component to the positive sequence voltage component present in a three phase power circuit". Mathematically it is given in Eq. (2).

$$Voltage\,Unbalance\,Factor(\%) = \frac{V_2}{V_1} * 100 \approx \sqrt{\frac{1 - \sqrt{3 - 6\beta}}{1 + \sqrt{3 - 6\beta}}} \tag{2}$$

where, $\beta = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{\left(V_{ab}^2 + V_{bc}^2 + V_{ca}^2\right)^2}$

Where, V_1 and V_2 are positive and negative sequence voltage components.

B. Harmonics Evaluation

Generally, harmonics originate from power electronic interfaced loads. Harmonic in the power system may cause significant problems in the form of excessive heating of AC electric machines, transformers and occurrence of resonance in the system, thus posing technical as well as economic concerns [13]. As electric vehicles are connected to the distribution system though power electronic interface so these represent an addition of non-linear load in the system. A harmonic pattern provided by any non-linear load means a specific harmonic content and its quantitative amount is expressed as total harmonic distortion (THD).

Total current and voltage harmonic distortion $(THD)_i$ $(THD)_v$ can be expressed as given in Eq. (3) and 4.

$$THD_i = \frac{\sqrt{\sum_{h=2}^{H} \left(I_k^h\right)^2}}{I_k^1} \tag{3}$$

$$THD_v = \frac{\sqrt{\sum_{h=2}^{H} \left(V_k^h\right)^2}}{V_k^1} \quad (4)$$

where h represents harmonic order, H is the highest number of harmonic, I_h is the RMS value of the h harmonic component and I_1 is the fundamental frequency component. Typically, an EV charging is done via power converters and there has been rapid evolution of robust topologies and control schemes of power converters for the same purpose [14], [15].

C. Relevant Standards

The standards EN 56160 and IEC 61000 are considered to be the most relevant for assessment of voltage variations. EN 50160 defines that the voltage variations in a public distribution networks at consumer's terminal should not be any beyond 10% of the nominal voltage specificity. Generally, it requires that the supply voltage must not violate the limit of ±10 of the nominal value [16] and standard IEC 61000 also limits voltage drop up to 10% [17]. In that division, LV feeder, MV/LV transformer and cable connections are assigned voltage variations of 4%, 2.5%, and 1.5% respectively. An overall allowable limit of 9% is considered in the simulation setup instead of exactly 10%.

In view of EV integration in the system and the related harmonics effect include current harmonic content that is injected into the power grid and voltage harmonics caused by distorted current into the system. Quantitative amount of current harmonics into the power grid are defined by a number of standards.

According to this standard, values of the voltage unbalance should not be more than 2 % under normal operating conditions. However, in some cases the content of voltage unbalance may reach up to 3 %. EN 50160 defines the limit in terms of negative to positive sequence voltage components only, as these components are truly relevant there is turbulence on the load connected to the distribution system. In case of unbalanced supply voltage another standard EN 61000 defined by EMC, for low voltage characteristics, sets the limit to 2 % only [18]. IEEE Recommended Practice for Electric Power Systems in Commercial Buildings allows VU of 2 or 2.5 % for some electronic equipment [13]. IEC restricts the voltage unbalance up to 1 %, otherwise motor should be derated. European norms, EN 50160 and IEC 61000 are considered the most relevant standards for EV requirements [19], [16].

V. Business Model of EVs Charging

A sustainable expansion of EVs in the transportation sector requires substantial charging facilities, up-gradation of distribution network, and aggregated control strategies for market integration. Installation costs for charging facilities and equipment depend on the required charging mode and physical location. According to the information given in [20], [21], let's assume a scenario of EV charging at public lot only and estimates the figures of the total cost of the charging stations including installation cost equipment, electrical connections, connection with the grid, maintenance and administrative costs. The considered public lot has following characteristics; it can serve an EV charging on both slow and fast modes, charging time ranges from 15 min to 12h depending on the employed charging mode (whether slow or fast charging method) and the charging facility is available 24 hours with V2G property. Its cost is 2130 € for a slow charging station of maximum power of 3.5 kW at a public lot and the cost will be 44692 € for a fast charging station of power up to 10 kW. Generally, aggregators offer EV charging facilities to EV users through public charging stations. The aggregators act as retailers; they purchase energy from the spot market, and sell it to the ultimate customers.

a) Cost Estimation: The cost for deployment of EV charging infrastructure (EV_{DCI}) can be estimated (in €) as given in Eq. (5):

$$EV_{DCI} = EV_{PL}.T_{CV}.(C_{pp} + C_{RU} + C_{CMS} + C_{Eq.} + C_{DNE}) \quad (5)$$

Where, EV_{PL} is EV penetration level, T_{CV} represents the total cost of conventional vehicles, $C_{pp}$and C_{RU} stand for cost of charging stations at public parking lots and cost of charging stations at single residential units. C_{CMS} is the cost of control and management software, $C_{Eq.}$stands for the cost of equipment and C_{DNE} represents the cost of expansion distribution network.

The cost of ambient factors in € can be calculated as expressed in Eq. (6):

$$C_{AF} = AL_{EV}\left(TC_{Em.} + TC_{cc} + TC_N\right) \quad (6)$$

TC_{AF} is the total cost of ambient factors, AL_{EV} stands for average life of an EV, $TC_{Em.}$is the total cost of emission, TC_{cc} represents the cost of climate change, TC_N stands for the noise cost.

VI. Transformer, Cable Overloading and Energy Losses

This section describes and illustrates the transformer, cable loading and increased energy losses that appear after integration of single phase electric vehicle charging load. As the power demand increases due to additional load of EVs, it causes to raise the current flow, so it provokes energy losses to increase. In order to evaluate the increased energy losses, a base case as a reference point is taken to quantify the impact of EV penetration levels. The reference point is taken as the network condition which supplies energy to the actual consumers within the allowed limits of voltage unbalance content, before connection of EVs in the system. It is observed that active power losses increase after connection of EVs in the system, particularly at a certain level of penetration of EVs when voltage unbalance is detected beyond its standard limit. As a matter of fact, in case of voltage unbalance, presence of negative sequence voltage components leads to large amount of rise in the current unbalance of the order of 6-10 times of voltage unbalance percent and thus, it results in high energy losses.

Table I
ACTUAL LOADING AND THE CURRENT CARRYING CAPACITY OF CABLES OF URBAN DISTRIBUTION SYSTEM WITH EV PENETRATION OF 45 %

Node from	Node to	Cable name	Current capacity (A)	Current PL: 45 %
R1	R2	G1	395	383.5
R9	R10	G1	395	92.3
R3	R11	G3	58	46
R12	R13	G4	157	96.8
R6	R16	G3	157	148.1
R10	R18	G3	157	101.4

Table II
ACTUAL LOADING AND THE CURRENT CARRYING CAPACITY OF CABLES OF RURAL DISTRIBUTION SYSTEM WITH EV PENETRATION OF 25 %

Node from	Node to	Cable name	Current capacity (A)	Current PL: 25%
C2	C3	L1	270	171.2
C11	C12	L1	270	91.6
C4	C13	L2	145	73
C14	C15	L2	145	46.7
C20	C22	L3	110	103.5
C12	C24	L4	110	23.8

Besides voltage drop and voltage unbalance, it may also be important to see affect of EVs addition in the system in terms of loading of transformer and power cables. In this section, transformer and cable loading are considered and assessed. In case of urban distribution system, current carrying capacity of the power cables according to [12] before addition of EVs and thereafter, current flow in each segment of the cable with the above mentioned penetration levels and scenarios are given in I. The feeder transformer rated current and actual amount of load on the transformer for the corresponding scenarios are 433 A and 389 A respectively. Likelihood of the overloading conditions are also mentioned. The values of all lines segments are not specified but some of them are summarized here for simplicity and demonstration of the problem.

The given values in I indicate that the cable and transformer loading remain within the allowed capacity at EV penetration levels of 45 %. However, the actual flow of current could violate the capacity in case of higher penetration level. The system load corresponds to the excessive voltage drop on some nodes of the distribution system which are found near the built-in capacity. It shows that the transformer and cables operate closed to the current limits and these segments are likely to be overload with higher degree of load.

In case of the rural distribution network, current carrying capacity of the overhead power cables, before addition of EV and load and after addition of EV load are mentioned in II, where flowing current at additional load of EV penetration level of 25 % is compared with the rated current of the line segments. Regarding transformer load, there is rated current of 216.5 A and the actual flowing current is 183.4 A.

It could be observed from the recorded values, the current does not approach the rated limit under the studied case, despite the voltage drop reaches its maximum permissible limits. Thus the voltage drop stands as a dominant factor for the additional load of EV charging in the rural area. In the urban distribution network under considered scenarios, results show that the voltage drop in the system approaches its limits before overloading of conductors and transformers. Though, the cables nearer to the distribution feeder and MV/LV transformer are heavily loaded and that may face overloading with a little addition of load on the feeder. The overloading may happen explicitly of voltage loss in the system, it may occur when additional heavy load is concentrated closer to the transformer. In case of rural network, the voltage loss appears much before cable of transformer overloading are observed and it is justified with the fairly long power cables in the rural area. It is noted that the obtained results might not be applicable for all urban or rural areas. For instance, the situation may differ with diverse topologies of distribution system and cable lengths of the power lines. Thus the carried out study be considered an example for investigating the voltage drop issue the power distribution network. Additionally, this section describes and illustrates increased energy losses due to integration of single phase electric vehicle charging load. As the power demand increases due to additional load of EVs, it causes to raise the current flow, so it provokes energy losses to increase. In order to evaluate the increased energy losses, a base case as a reference point is taken to quantify the impact of EV penetration levels. The reference point is taken as the network condition which supplies energy to the actual consumers within the allowed limits of voltage unbalance content, before connection of EVs in the system as mentioned in table III. It is observed that active power losses increase after connection of EVs in the system, particularly at a certain level of penetration of EVs when voltage unbalance is detected beyond its standard limit. As a matter of fact, in case of voltage unbalance, presence of negative sequence voltage components leads to large amount of rise in the current unbalance of the order of 6-10 times of voltage unbalance percent and thus, it results in high energy losses.

VII. RESULTS

Percentage of increase in the energy losses is recorded with the different EV penetration levels. The increment in the losses is found to be a bit higher in case of uncontrolled EV charging. Whereas, adoption of tariff based charging scheme makes it possible to decrease power losses in the urban distribution system. Thus, uncontrolled charging of EVs shows worst results as it leads to high peak loads and in turn that causes higher power losses in the LV distribution system. In this study, EVs are replicated as a single phase electrical loads at a particular node. It shows its impact as an additional load on the current at a specific node. The power flow algorithm is based on the iterative process presented in [11], through which node current, voltage and overloaded line segments are identified and total power losses are computed in the LV network. The result related to increased energy losses (%) due to integration of single phase electric vehicle charging load is shown simulation section.

Table III
LOADING ON THE URBAN DISTRIBUTION NETWORK

Node	No. of households	Max. Load (kVA)
R11	9	16
R15	25	33
R16	48	68
R17	09	14
R18	21	45

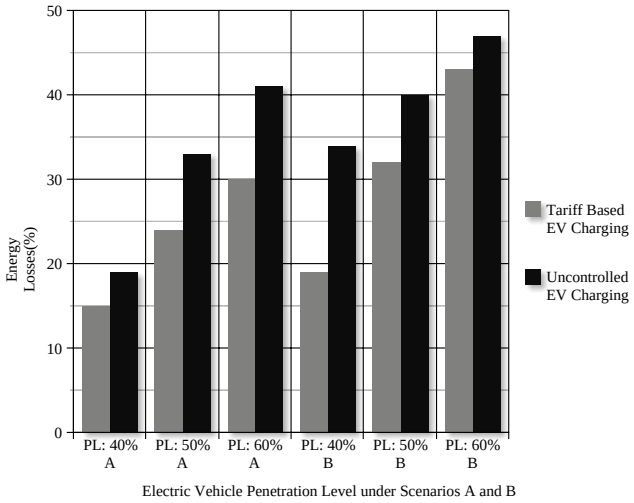


Figure 4. Increased Energy Losses

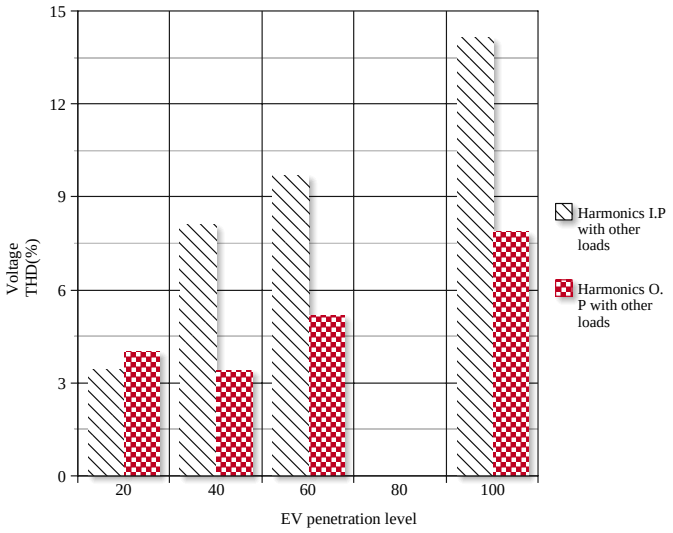


Figure 6. Voltage harmonic caused by EV charging with current THD of 17.4%

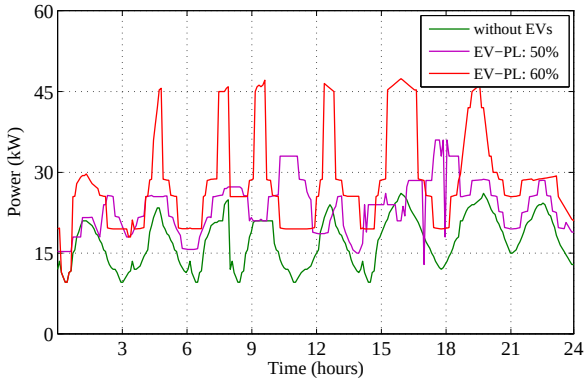


Figure 5. Rise in power consumption

The result shown in Fig. 6 illustrates that the appeared voltage THD, recorded at different EV penetration levels, in the distribution system violates the permissible limit of 8 % in many cases. Thus, for this level of THD, it could be seen that EVs may contaminate the system by harmonic injection. For the worst scenario, the voltage harmonic distortion can reach the limits when EV penetration level is higher than 45 %. Additionally, rise in power consumption for a period of 24 hours is illustrated in 5 for 50 % and 60 % EV penetration level. It is observed that with 60 % EVs in the system, there is nearly 109 % increase in power consumption, as it changes from 23 kW to 49 kW. In view of obtained results, it could be noted that the network experiences a significant rise in peak load and it most likely to lead to excessive voltage drop and then voltage unbalance in the system.

VIII. CONCLUSION

It becomes a visible fact that a massive adoption of electromobility will significantly alter the existing power system operations and practices. Several important power quality parameters including voltage drop, unbalance, harmonic distortion, cable and transformer overloading, and increased energy losses due to additional load of EVs are formulated and quantified in this paper. It is suggested that the reinforcement of network for connection of EVs may be designed based on the presented violating figures of power quality indices. It is important to consider that there may be a condition when the power distribution network is no longer able to support further EV charging load because of system parameters' violation in the operation of network. Therefore, certain measures and upgradation requirements must be considered before addition of large number of EVs in the system.

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