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Harmonic Analysis of Different Types of EV Chargers on Residential Distribution Systems

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Abstract

Pollution levels in major cities in India are increasing exponentially. According to Air Visual, 22 of the world's 30 most polluted cities are in India. Therefore, there is a need to find an alternative way to operate the conventional vehicles. Recently, the National Electric Mobility Mission Plan 2020 was notified by the Government of India (GoI) to address the environmental challenges posed by conventional motor vehicles and boost the production of reliable, affordable and efficient Electric Vehicles (EVs). Without a charging infrastructure, electric vehicles are supposed to charge the battery in the home. The EV charger is required to charge the batteries. The charger is basically a non-linear device. This paper analyses harmonics generated by electric vehicles and the determination of the total harmonic distortion (THD) at different nodes of the residential distribution network. Decoupled Harmonic Power Flow (DHPF) was developed for residential distribution system to assess the harmonic effects of EV loads.

Keywords: Harmonics, THD, Electric vehicle, EV chargers, Harmonic Power flow

1. Introduction

Nowadays, due to the heavy reliance on imported fossil fuels and rising oil prices, finding alternatives to the traditional passenger transportation system mainly supported by road vehicles is imperative. The alternatives should also limit greenhouse gases such as CO_2 to reduce global warming [1]. Electric vehicles are expected to reduce CO_2 emissions by 1 gigatonne in India by 2030, according to government think tank NITI AAYOG [2].

The important components of electric Vehicles are the electric battery system, motor control, electric motor, regenerative braking, propulsion system. A battery is a device made up of one or more cells that convert chemical energy into electrical energy. EV is powered by the battery, which replaces the fuel in fuel-powered vehicles. This battery is charged by the charging system. EV owners typically prefer to charge their EVs at home. The availability of EV charging at home is closely related to population density, the number of dwellings with a garage or parking space, and the local proportion of EVs. In order to charge a vehicle at home, you need a suitable EV charger. If an electric vehicle is being charged at home, this indicates the most likely addition of heavy single-phase loads on distribution network. Nonetheless, due to their high electrical energy demand, widespread adoption of electric vehicles can adversely affect the distribution grid in a variety of ways, leading to undesirable spikes in power consumption and consequent power quality issues, including increased current flow in power cables, transformer overload, voltage sag, harmonic pollution, etc. [3-4].

The impact of EV charging on distribution grids (DSN) is influenced by a variety of parameters, including the number of EVs charged at the same time, charging patterns, coordination, location of EV chargers, charging rate, and charging timing [5]. The impact of E-bus integration on the power grid has been studied in [6], and voltage regulation, harmonic distortion levels, unbalance, additional losses and transformer lifetime losses are all issues to consider when analyzing the impact of EV charging on the distribution networks. Due to the fact that a distributed system entails a more horizontally structured network in terms of power quality, it has become important to study the effects of harmonics [7]. The influence of electric vehicles on network quality has been described in various ways in the literature[11-15]. The authors in [8] proposed a new method to study the operational status of EV charging stations, considering the random output factor, electricity price, waiting time and analyzing the characteristics of harmonics from the charging station. The authors in [9] give theoretical support for the future development of charging stations in a fast and efficient direction and have some practical significance in the art.

The authors in [10] analysed the harmonics generated by EV chargers using the measured data. The main disadvantage of measurement methods is that the analysis of the harmonics takes a long time. In this paper, the simplified harmonic power flow method is proposed to analyse the harmonics generated by the EV chargers in residential distribution systems.

2.Methodology

The harmonic power flow is expected to assess the harmonic distortion of residential distribution systems in the presence of EV chargers. It is proposed to use the decoupled harmonic power flow (DHPF) method to study the impact of EV charging on power quality due to its computational efficiency

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and strong convergence. Harmonic power flow (HPF) calculations can commonly be classified into coupled and decoupled techniques. The coupled approach treats all harmonic orders simultaneously. This approach has good accuracy but introduces more computational effort as the problem becomes quite complicated. On the other hand, the decoupled approach assumes that the coupling between harmonic orders can be rationally neglected and consequently the calculation can be performed for each harmonic order separately. Therefore, this approach requires less computational effort.

Furthermore, non-linear loads like EV chargers are modeled with harmonic current, it is very easy to include them in the calculations using measured non-sinusoidal current and/or voltage waveforms. Although the decoupled approach is not as accurate as the coupled technique, it offers a compromise between computational complexity and result accuracy. To assess the harmonic effects of EV chargers on the distribution system, decoupled harmonic power flow (DHPF) is used and simulated in MATLAB. First the distribution system load and admittances of all lines at the fundamental frequency were calculated and then the system admittance matrix is constructed at the fundamental frequency. Using the system admittance matrix Y_{bus}, fundamental voltages at various nodes of the distribution system and the injected current matrix I_{bus} are calculated. Once base voltages at different nodes are known, the base load currents at different nodes of the system can be estimated. Then, using the current magnitude at the fundamental frequency and data describing the parameters of the load harmonics distribution, the current harmonics generated by the load can be estimated for each harmonic order. The decoupled harmonic power flow method is shown as a flow chart in Figure 1.

All data required to simulate the test system must be at the fundamental frequency. Parameters such as harmonic (h), maximum harmonic number (H) and penetration level, etc. are considered required data. The EV Penetration Level (PL) is the important parameter that will affect the residential network. It determines the number of electric vehicles that have to be charged in the distribution network. Penetration rate refers to the ratio of EVs to all vehicles in a given residential area. As more electric vehicles enter the market, the impact of adding large numbers of electric vehicle chargers to the grid is becoming increasingly prevalent. So, the degree of penetration (PL) of electric vehicles will definitely have a harmonic impact on the distribution system of homes. The MATLAB code is first run for the power flow at the fundamental frequency, resulting in the fundamental voltages at various nodes. Then it is performed for different harmonic frequencies. In the end, the program is run for different degrees of penetration to evaluate the voltage THD at different nodes of the considered distribution system.

The following algorithm is used to determine the total harmonic distortion (THD) at various nodes of the distribution system.

Algorithm: Decoupled harmonic power flow

Step 1: Enter the system data, Penetration level and highest order harmonic (H)
Step 2: Construct system admittance matrix Y_{bus} at the fundamental frequency
Step 3: Determine fundamental voltages at various nodes of the distribution systems
Step 4: formulate the harmonic admittance matrix $[Y_h]$.
Step 5: Determine the harmonic current matrix $[I_h]$
Step 6: Check for maximum harmonic number (H), if achieved stop running the loop
Step 7: Calculate the Total harmonic distortion (THD) at all five nodes

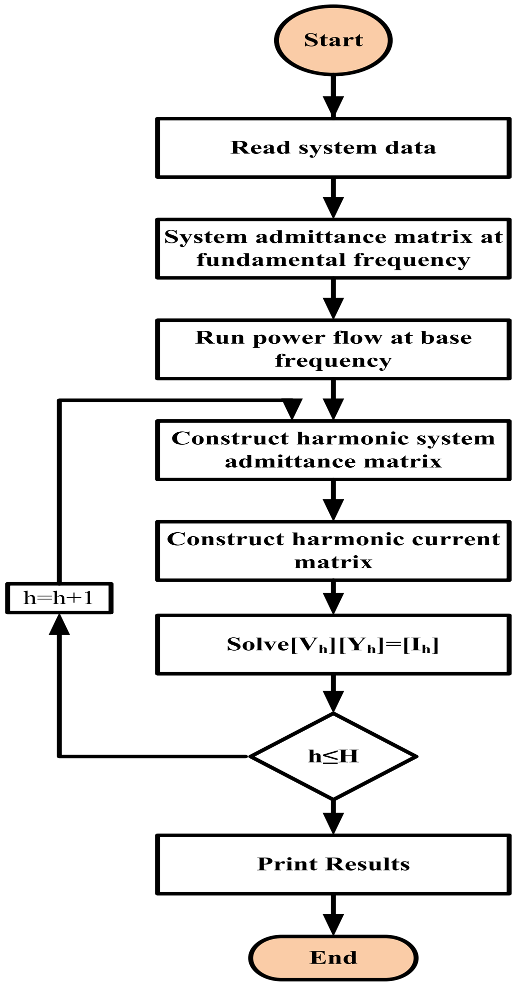


Fig. 1. Flowchart for decoupled the harmonic power flow

3. System description

To study the harmonic effects of EV chargers, the radial distribution system shown in the figure 2 is simulated with and without EV chargers. A harmonic model was developed for the distribution system. To study the harmonic effects of EV chargers, the radial distribution system shown in the figure 2 is simulated with and without EV chargers. A harmonic model was developed for the distribution system.

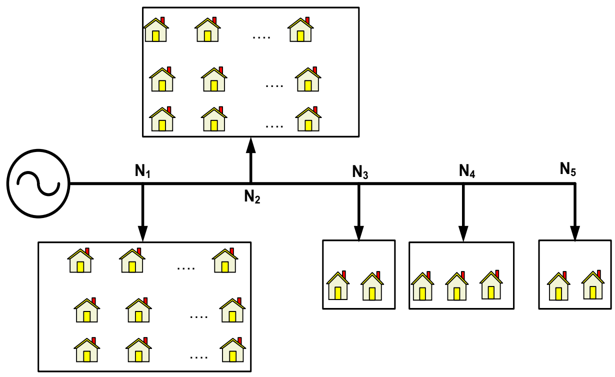


Fig. 2. Residential distribution

4.Mathematical modelling

(a)System modelling at the fundamental frequency

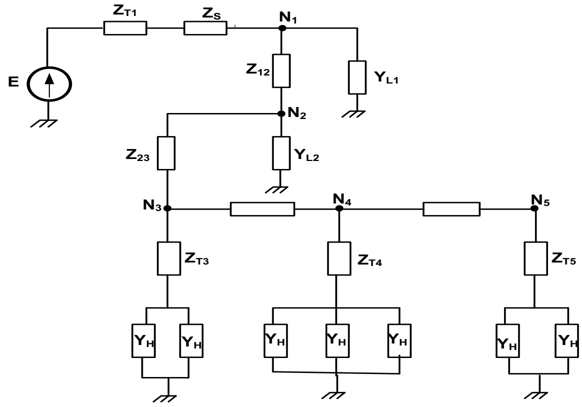


Fig. 3. Circuit representation of distribution system

Figure 3 is the equivalent circuit diagram of a typical residential distribution system under consideration. Suppose the distribution system is supplied with an infinite bus. Voltage and frequency are constant and loads are shared equally on each phase. This assumption is made here to reduce the computational effort. Major elements present in residential distribution systems are transformers, distribution lines, and residential buildings. Transformers and lines were modeled as impedance elements. Point loads at nodes N1 and N2 are represented as entry elements, and also each house at nodes N3, N4, N5 is replaced by entry elements. Figure 3 is further simplified as a five-node system as shown in figure 3.Substation transformer is symbolized by a voltage source in series with impedance and all other elements represented by conventional circuit elements. Y_{L1} and Y_{L2} represent the lumped loads at node N_1 as well as N_2.

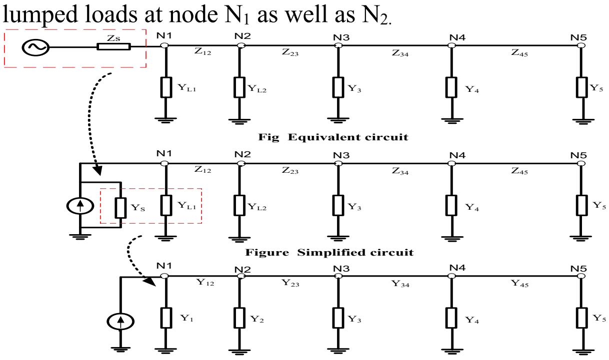


Fig. 4. Circuit reduction of distribution system

To perform the nodal analysis, Norton equivalent circuit is required. Equivalent admittances of Y_s and Y_{L1} is Y_1 which is placed at node N_1. First, the system load and line admittances are calculated at the fundamental frequency and then the system admittance matrix is formed. Z_{12},Z_{23},Z_{34},Z_{45} are line impedances as shown in the figure 4. Line admittances of various lines can be computed using the equation (1) to (4).

$$Y_{12} = \frac{1}{Z_{12}} \tag{1}$$

$$Y_{23} = \frac{1}{Z_{23}} \tag{2}$$

$$Y_{34} = \frac{1}{Z_{34}} \tag{3}$$

$$Y_{45} = \frac{1}{Z_{45}} \tag{4}$$

System admittance matrix is constructed for figure 3. Number of nodes exist in the distribution systems is 5. The size of the system admittance matrix is 5x5.It is containing diagonal elements and off diagonal elements. Eq. (5). Nodal analysis is performed using the system admittance matrix Y_{bus} and current injection matrix I_{bus} to obtain fundamental voltage.

$$\mathbf{V}_{bus} = Y_{bus}{}^{-1}\,\mathbf{I}_{bus} \tag{5}$$

(b) Harmonic modelling

(i) Electric vehicle Load:

The EV charger is connected between grid and battery. EV charger is a non-linear device. Non-sinusoidal current is drawn from the supply. The non-sinusoidal current waveform consists of harmonic frequencies. EV chargers are considered the main source of harmonics. The inductance of elements changes due to harmonics. Let R be the resistance and X the reactance at the fundamental frequency. The resistance value is independent of the harmonic number, but the reactance value depends on the harmonic number (h).The load impedance at harmonic frequencies can be represented by R+jhX. Current harmonics generated by the EV charger are represented by a current source. Figure 5 shows the stress plot at harmonic frequencies. Harmonic current source I_h and load impedance at harmonic frequencies are connected in parallel.

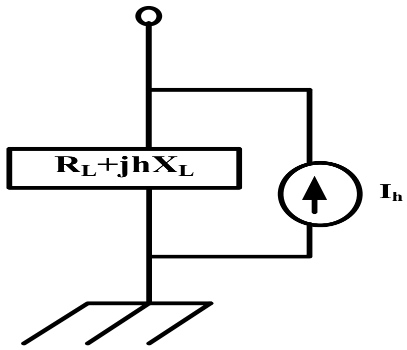


Fig. 5. Representation of the load in a harmonic environment

The RMS value of the harmonic current I_h generated by the load can be found using the equation

$$I_h = C\frac{\mathrm{I}}{\mathrm{h}^{\alpha}} \tag{6}$$

where 'I' is the fundamental load current. Constants 'C' and 'α' describe the distribution of harmonic current produced by the load. The constant 'C' can be computed by the equation.

$$C = \frac{d_i}{\sqrt{\sum_{h\in N}\frac{1}{h^{2\alpha}}}} \tag{7}$$

where 'd_i' is the coefficient of harmonic current whose value is 0.12. The term α represents the summation exponent and its typical value is 1.5. A detailed explanation of the summation principle and the summation exponent values for different harmonic orders are presented in [16]. The term 'N' is to represent set of harmonics (3, 5, 7, 9, 11), and the highest order harmonic is H=11. Hence the value of 'C' is

$$C = \frac{0.12}{\sqrt{\frac{1}{3^3}+\frac{1}{5^3}+\frac{1}{7^3}+\frac{1}{9^3}+\frac{1}{11^3}}} = 0.54. \tag{8}$$

Impedance of various elements present in network will change due to the presence of harmonics.

(b).Transformer

Let Transformer impedance at base frequency is $Z_T^1 = R_T + jX_T$. Impedance of Transformer at harmonic frequencies is givenby

$$Z_T^h = R_T + j * h * X_T \tag{9}$$

(c). Lumped loads

Admittance of Lumped load at node N1 is Y_{L1}. Impedance of the lumped load at node N1 can be computed using equation (10)

$$Z_{L1}^h = R_{L1} + j * h * X_{L1} = Re(\frac{1}{Y_{L1}}) + j * h * Im(\frac{1}{Y_{L1}}) \tag{10}$$

In Equation(10), Re means real part and Im means imaginary part. Harmonic current produced by lumped load at node N1 is given by Equation (11)

$$I_{L1}^h = C\frac{I_{L1}}{h^\alpha} \tag{11}$$

Admittance of Lumped load at node N2 is Y_{L2}.
Impedance of the lumped load At node N2 can be computed using equation (12)

$$Z_{L2}^h = R_{L2} + j * h * X_{L2} = Re(\frac{1}{Y_{L2}}) + j * h * im(\frac{1}{Y_{L2}}) \tag{12}$$

Harmonic current produced by lumped load at node N2 is given by Eq(13)

$$I_{L2}^h = C\frac{I_{L2}}{h^\alpha} \tag{13}$$

(d). Residential house parameters

Admittance of all residential houses are equal in magnitude. Equation (14) is used to compute the impedance of each residential house

$$Z_R^h = R_R + j * h * X_R = Re(\frac{1}{Y_R}) + j * h * im(\frac{1}{Y_R}) \tag{14}$$

Harmonic current produced by each residential house is given by Equation (15)

$$I_R^h = C\frac{I_R}{h^\alpha} \tag{15}$$

(e)Distribution line: Let Z_{12} is the line impedance at base frequency between node N1 and N2. Impedance of same line at h^{th} harmonic can be find using the

$$Z_{12}^h = R_{12} + j * h * X_{12} \tag{16}$$

Now formulate the system admittance matrix at harmonic frequencies. The harmonic analysis involves solving for the nodal voltages at each harmonic using the network equation (17)

$$\begin{bmatrix} Y_{11}(h) & -Y_{12}(h) & -Y_{13}(h) & -Y_{14}(h) & -Y_{15}(h) \\ -Y_{21}(h) & Y_{22}(h) & -Y_{23}(h) & -Y_{24}(h) & -Y_{25}(h) \\ -Y_{31}(h) & -Y_{32}(h) & Y_{33}(h) & Y_{34}(h) & Y_{35}(h) \\ -Y_{41}(h) & -Y_{42}(h) & -Y_{43}(h) & Y_{44}(h) & -Y_{45}(h) \\ -Y_{51}(h) & -Y_{52}(h) & -Y_{53}(h) & -Y_{54}(h) & Y_{55}(h) \end{bmatrix} \begin{bmatrix} V_1(h) \\ V_2(h) \\ V_3(h) \\ V_4(h) \\ V_5(h) \end{bmatrix} = \begin{bmatrix} I_1(h) \\ I_2(h) \\ I_3(h) \\ I_4(h) \\ I_5(h) \end{bmatrix} \tag{17}$$

$V_1(h), V_2(h), V_3(h), V_4(h), V_5(h)$ are nodal voltages at harmonic h. Values of system Admittance matrix vary with harmonic order.$I_1(h), I_2(h), I_3(h), I_4(h), I_5(h)$ are nodal currents at harmonic h. Harmonic voltages can be computed using equation (17). Total harmonic distortion (THD) is calculated at various nodes of the distribution system using the Equation (17)

$$THD_V = \frac{\sqrt{\sum_{h>1}^{h_{max}} |V_h|^2}}{V_1} \qquad h = 2,3, \dots\dots\dots h_{max} \tag{18}$$

V_1 is the fundamental voltage of particular node.V_h is the harmonic voltage at that Node. Suppose fundamental voltage of node N1 is V_1 and harmonic voltages are V_3 ,V_5,V_7,V_9,V_{11} at node N1.Total harmonic distortion(THD) at nodeN1 can be computed using Equation (19)

$$THD_V = \frac{\sqrt{V_3^2 + V_5^2 + V_7^2 + V_9^2 + V_{11}^2}}{V_1} \tag{19}$$

Similarly, THD values at various node can be computed.

5.Results and Discussion

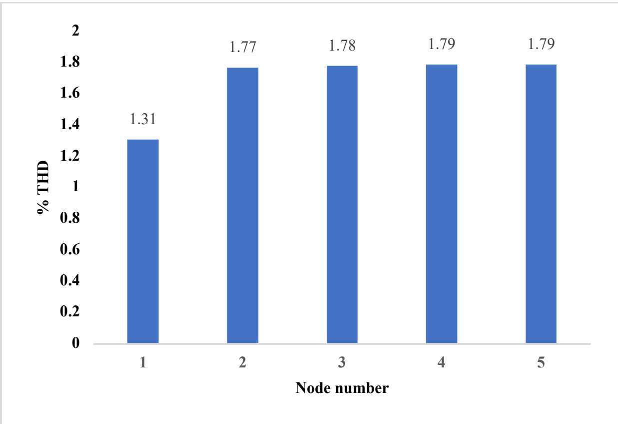
The harmonic impact of EV charger on the distribution network can be studied by setting the values for an average baseload of individual houses, type of charger used for charging the battery, and distribution systems parameters. Different types of electric appliances are required for performing different activities in the residential house like washing machine, greaser, electric heater, air conditioner, fans, and electric lamps, etc. The baseload of each house is 6 KW . Assume that baseload produces less amount of harmonic distortion. EV charger is a new kind of load to existing systems. Different kinds of EV chargers are available to charge electric vehicles. The Nissan leaf EV charger is the most popularly used EV charger to charge the EV battery in residential houses. Parameters of EV charger used in the simulation are 3.3 kW, 15A, 220 volts, and 6.6, 30A, 220 volts. EV penetration is another important parameter to determine the harmonic impact. The EV penetration level shows the quantity of EVs in contrast with the number of household vehicles in the residential area. System is simulated with different penetration levels from 10% to 100% and harmonic impact is evaluated. There exist various metrics to calculate the power quality of a distribution system. The mainly used procedure is to find the deviation of voltage and current wave shapes from their ideal sinusoidal shape. This deviation is due to the presence of harmonic components, hence it is required to find harmonics exist in the voltage and current. The overall power quality of the distribution system is decided by the combination of all the existing harmonics. Total harmonic distortion (THD) is a parameter to find the extent to which the sinusoidal grid voltage or current is distorted by the harmonic components with respect to the fundamental frequency component. THD is defined as the root mean square (RMS) averages, i.e., the square root of the sum of the individual harmonic orders (h) magnitudes squared, divided by the fundamental (I_1 or V_1). Equivalent Distribution systems parameter used in the simulation are presented in Table 1. The MATLAB code was developed for the flow of decoupled harmonic power (DHP) to calculate the harmonic voltages on different parts of the distribution system. First, the distribution system is simulated with base load without considering the EV chargers, and then the same distribution system is simulated with different penetration levels of EV chargers.

Table 1. System data

Parameter	Per unit value
Grid voltage	1
Impedance of substation transformer	j 0.023
Transformer impedance at N_3 and N_4	1.7+ j 17
Transformer impedance at N_5	0.82+ j 8.2
Lumped load admittance at N_1 and N_2	0.035- j 0.02
Z_{12}	0.050+ j 0.22
Z_{23}	0.083+ j 0.24
Z_{34}	0.018+ j 0.011
Z_{45}	0.042+ j 0.025

(i) Without integration of Electric vehicles

Distribution system is simulated without integration of EV loads and results are presented in figure 6. It is clear that the values of fundamental voltages and THDs at all five nodes are within the limits. Small amount of harmonic distortion is produced at all nodes. This is because of the normal loads used in house like fluorescent lighting ballast produces the small amount of distortion.



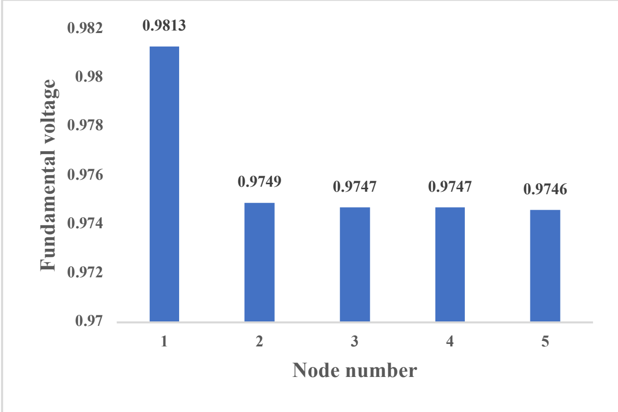


Fig. 6. %THD values and fundamental voltages at different nodes of systems without EV integration.

(ii) With integration of electric vehicles

The distribution system is simulated with different penetration levels of electric vehicles and the results have been presented and the harmonic effects on different nodes of the distribution system are analyzed. The distribution system is simulated first with 3.3 EV chargers and then with 6.6 EV chargers. Accepting all EV chargers of the same type is practically impossible. There are many types of level 2 chargers available. The distribution system is simulated with the combination of 80% 3.3 kW EV charger and 20% 6.6 kW EV charger. These three cases are explained in the following subsections

Case1:3.3 kW EV chargers

The distribution system is simulated with different penetration levels of 3.3 kW EV chargers and the results were presented. The harmonic impact on different nodes of the distribution system is analyzed. The analysis was carried out for different degrees of penetration from 10% to 100%. Fundamental voltage (V1), harmonic voltages (V3, V5, V7, V9, V11) and %THD values are displayed for each PL. Fundamental voltages (V1) and %THD values at all five nodes corresponding to different PL are presented. Magnitudes of V1,V3,V5,V7,V9,V11 and THD values of various nodes corresponding to penetration levels are given in the table 2. All the voltages are expressed in per unit (p.u) and total harmonic distortion (THD) at various nodes are expressed in percentage.

The following notations are used for analysis.

V_1 : Fundamental voltage in per unit ; V_3 : 3rd harmonic voltage in per unit; V_5: 5th harmonic voltage in per unit; V_7: 7th harmonic voltage in per unit; V_9 : 9th harmonic voltage in per unit; V_{11}: 11th harmonic voltage in per unit; PL : Penetration level.

Summary of results for 3.3 kW chargers is presented in table 2. it is observed that harmonic Distortion produced by 3.3 kW chargers on distribution systems is acceptable below the 60% of penetration level.

Table 2. Summary of results for 3.3 kW chargers

% PL	Node N1		Node N2		Node N3		Node N4		Node N5	
	V_1	% THD	V_1	% THD	V_1	% THD	V_1	% THD	V_1	% THD
10	0.9797	2.6096	0.9729	3.4981	0.9729	3.501	0.9728	3.5011	0.9728	3.5012
20	0.9777	2.8458	0.9703	3.8104	0.9703	3.8161	0.9703	3.8163	0.9703	3.8165
30	0.9758	3.0792	0.9678	4.1191	0.9677	4.1277	0.9677	4.128	0.9677	4.1282
40	0.9738	3.3099	0.9652	4.4244	0.9651	4.4358	0.9651	4.4362	0.9651	4.4366
50	0.9719	3.5379	0.9627	4.7264	0.9626	4.7406	0.9626	4.7411	0.9626	4.7415
60	0.9699	3.7632	0.9602	5.0251	0.96	5.042	0.96	5.0426	0.96	5.0431
70	0.968	3.9859	0.9577	5.3206	0.9575	5.3402	0.9575	5.3409	0.9575	5.3415
80	0.9661	4.2061	0.9551	5.6128	0.9549	5.6351	0.9549	5.6359	0.9549	5.6366
90	0.9641	4.4237	0.9526	5.902	0.9524	5.9269	0.9524	5.9278	0.9524	5.9286

100	0.9622	4.6389	0.9501	6.188	0.9499	6.2155	0.9499	6.2165	0.9498	6.2174

Case2: 6.6 kW EV chargers
A summary of the results for 6.6 kW chargers is shown in Table 3. It is observed that the harmonic distortion generated by 6.6 kW chargers in distribution systems is acceptable below the 40% penetration level.

Table 3. Summary of results for 6.6 chargers

% PL	Node N1		Node N2		Node N3		Node N4		Node N5	
	V_1	% THD	V_1	% THD	V_1	% THD	V_1	% THD	V_1	% THD
10	0.9782	2.7939	0.9709	3.7405	0.9709	3.7434	0.9709	3.7435	0.9709	3.7436
20	0.9747	3.2083	0.9664	4.2877	0.9663	4.2934	0.9663	4.2936	0.9663	4.2938
30	0.9712	3.6143	0.9619	4.8243	0.9618	4.8328	0.9618	4.8331	0.9618	4.8334
40	0.9678	4.0119	0.9574	5.3506	0.9573	5.3618	0.9573	5.3622	0.9573	5.3626
50	0.9644	4.4015	0.9529	5.8669	0.9528	5.8808	0.9528	5.8813	0.9528	5.8818
60	0.9609	4.7833	0.9485	6.3735	0.9484	6.3901	0.9483	6.3907	0.9483	6.3912
70	0.9575	5.1575	0.9441	6.8706	0.9439	6.8898	0.9439	6.8905	0.9439	6.8912
80	0.9541	5.5242	0.9397	7.3585	0.9395	7.3803	0.9395	7.3811	0.9395	7.3819
90	0.9507	5.8838	0.9353	7.8375	0.9351	7.8619	0.9351	7.8628	0.9351	7.8636
100	0.9474	6.2364	0.931	8.3078	0.9307	8.3347	0.9307	8.3357	0.9307	8.3366

Case 3: Combination of 3.3 kW and 6.6 kW Chargers
The distribution system is simulated with a combination of 80% 3.3 kW chargers and 20% 6.6 kW chargers. The analysis was performed for different degrees of penetration, starting from 10% to 100%, similar to the previous cases

Table 4. Summary of results for combination of EV chargers

% PL	Node N1		Node N2		Node N3		Node N4		Node N5	
	V_1	% THD	V_1	% THD	V_1	% THD	V_1	% THD	V_1	% THD
10	0.9795	2.6371	0.9726	3.5343	0.9726	3.5372	0.9726	3.5373	0.9726	3.5374
20	0.9773	2.9002	0.9697	3.8819	0.9697	3.8876	0.9697	3.8878	0.9697	3.888
30	0.9751	3.1598	0.9669	4.2252	0.9668	4.2337	0.9668	4.234	0.9668	4.2343
40	0.9729	3.416	0.9641	4.5642	0.964	4.5756	0.964	4.5759	0.964	4.5763
50	0.9708	3.6689	0.9708	4.8991	0.9611	4.9132	0.9611	4.9137	0.9611	4.9142
60	0.9686	3.9185	0.9584	5.23	0.9583	5.2468	0.9583	5.2474	0.9583	5.248
70	0.9664	4.1649	0.9556	5.5569	0.9555	5.5764	0.9554	5.5771	0.9554	5.5777
80	0.9643	4.4082	0.9528	5.8799	0.9526	5.9021	0.9526	5.9028	0.9526	5.9036
90	0.9621	4.6484	0.9524	6.199	0.9498	6.2238	0.9498	6.2247	0.9498	6.2255
100	0.9612	4.8856	0.9473	6.5143	0.947	6.5418	0.947	6.5427	0.947	6.5437

The harmonic impact of EV chargers depends on the type of charger used to charge the EV battery. In a given residential area, all chargers may not be created equal. A combination of different types of EV chargers exists in a real distribution system. A summary of the results for the combination of EV chargers is shown in Table 4. It is observed that harmonic distortion generated by a combination of EV chargers in distribution systems is acceptable below 60% penetration level.

6. Conclusions and future scope

This paper thoroughly estimates the impact of EV charging on the residential distribution system at different EV penetration levels and presents the results. The results show that when the system is simulated with an EV with 3.3 kW charging power, the THD is below the allowed limits around 60% EV penetration for all buses. With 100% EV penetration, the voltage THD will not increase much when the EVs are connected to residential distribution systems. If the same distribution system is simulated with EVs with a charging capacity of 6.6 kW, the THD at most nodes is below 5% for an EV penetration of around 30%. In the end, the same distribution systems are simulated with the combination of 80% 3.3 kW EV chargers and 20% 6.6 kW EV chargers. The results show that at around 50% EV penetration, the THD is below 5% on most nodes.

This work does not consider the effects of harmonics in the presence of renewable energy sources.it is possible to simulate the residential distribution systems with renewable energy sources and EVs. As an extension of the present work, an optimal charging and discharging of electric vehicles based on cloud computing could be carried out.

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