Investigation of THD Analysis in Residential Distribution Systems with Different Penetration Levels of Electric Vehicles

Case Study

Jayababu Badugu
Department of Electrical and Electronics Engineering,
VLITS, Guntur, Andhra Pradesh, India
Jayababu.badugu@gmail.com

Y.P. Obulesu
School of Electrical Engineering,
VIT Deemed to be University, Vellore, Tamilnadu, India
yp.obulesu@vit.ac.in

Ch. Sai Babu
Electrical and Electronics Engineering Department,
JNTUK, Kakinada, Andhra Pradesh, India
chs_eee@yahoo.co.in

Abstract – *Electric Vehicles (EVs) are becoming a viable transportation option because they are environmentally friendly and provide solutions to high oil prices. This paper investigates the impacts of electric vehicles on harmonic distortions in urban radial residential distribution systems. The accomplishment of EV innovation relies on the accessibility of EV charging stations. To meet the power demand of growing EVs, utilities are introducing EV charging stations in private and public areas; this led to a change in the residential distribution system infrastructure. In this paper, an urban radial residential distribution system with the integration of an electric vehicle charging facility is considered for investigation. An impact of different EV penetration levels on voltage distortion is analysed. Different penetration levels of EVs into the residential distribution system are considered. Simulation results are presented to validate the work carried out in this paper. An attempt has been made to establish the relationship between the level of penetration of the EVs and voltage distortion in terms of THD (Total Harmonic Distortion).*

Keywords – *Electric vehicles, total harmonic distortion, charging stations, penetration levels, distribution systems*

1. INTRODUCTION

The energy crisis has been a significant issue in the last few decades. The scarcity of fossil fuels is becoming a matter. There is an estimate that oil production left in the landscape can only be used for less than 50 years [1]. Conventional fuel based vehicles deliver a huge amount of air contamination in each and every single year [2-3]. Electric vehicle technology is used to reduce the usage of fuel for conventional internal combustion vehicles and air pollution [4]. However, the realisation of EV technology depends on the availability of EV charging stations. To meet this requirement, utilities may introduce EV charging stations at residential and commercial locations [6]. Large-scale EV charging causes many problems in the distribution network, increases load demand, losses and voltage drop [9-10]. The charging of EVs produces considerable additional power electronic load which can generate harmonics, and results in associated power quality issues in residential networks. A Level 2 EV charger used at home can use power levels 3.3 KW [11]. Integration of an EV charger may have an adverse effect on the distribution network if the penetration is not planned carefully and systematically. Harmonics can cause unusual activity, for example, temperature rise, diminished effectiveness of a transformer, and untimely protection and winding disappointments. Therefore, it is important to analyse the harmonic impact of EV chargers in the distribution system. Considerable progress has been made in the development of correct apparatus to monitor the harmonic behaviour of power systems. Measurements may not be economic. In such situations, computer simulations based on mathematical modelling provide a workable alternative to physical measurements.

The main objective of this paper is to investigate harmonic distortion in an urban radial residential distribution network with different penetration levels of electric vehicles into the system. In order to evaluate the performance of the residential distribution network, this has been carried out without EV chargers and with EV chargers for different levels of penetration of EVs. Finally, THD is presented for different penetration levels of EVs. The proposed work has been carried out by using MATLAB software.

2. DESCRIPTION OF TEST SYSTEM AND MATHEMATICAL MODELLING

An urban radial residential distribution system in Andhra Pradesh, India, is chosen to examine the effects of EV battery chargers on residential distribution systems as shown in Figure 1. This substation supplies power to residential consumers located in three different areas. Three-phase laterals serve large areas. Few residential loads are connected to a single-phase lateral. The total number of consumers in the selected area is 837. 450 consumers are connected to node1 and three 380 consumers are connected to node2. The loads connected to node1 and node 2 are considered as lumped loads. Single-phase transformers are located at node3, node4, and node5, respectively, and each single-phase transformer supplies power to two or three homes. The selected distribution system has 4 transformers which are located at node1, node3, node4, and node5, respectively. Assume that lumped loads are equally distributed in the three-phase system. This assumption reduces the calculation burden.

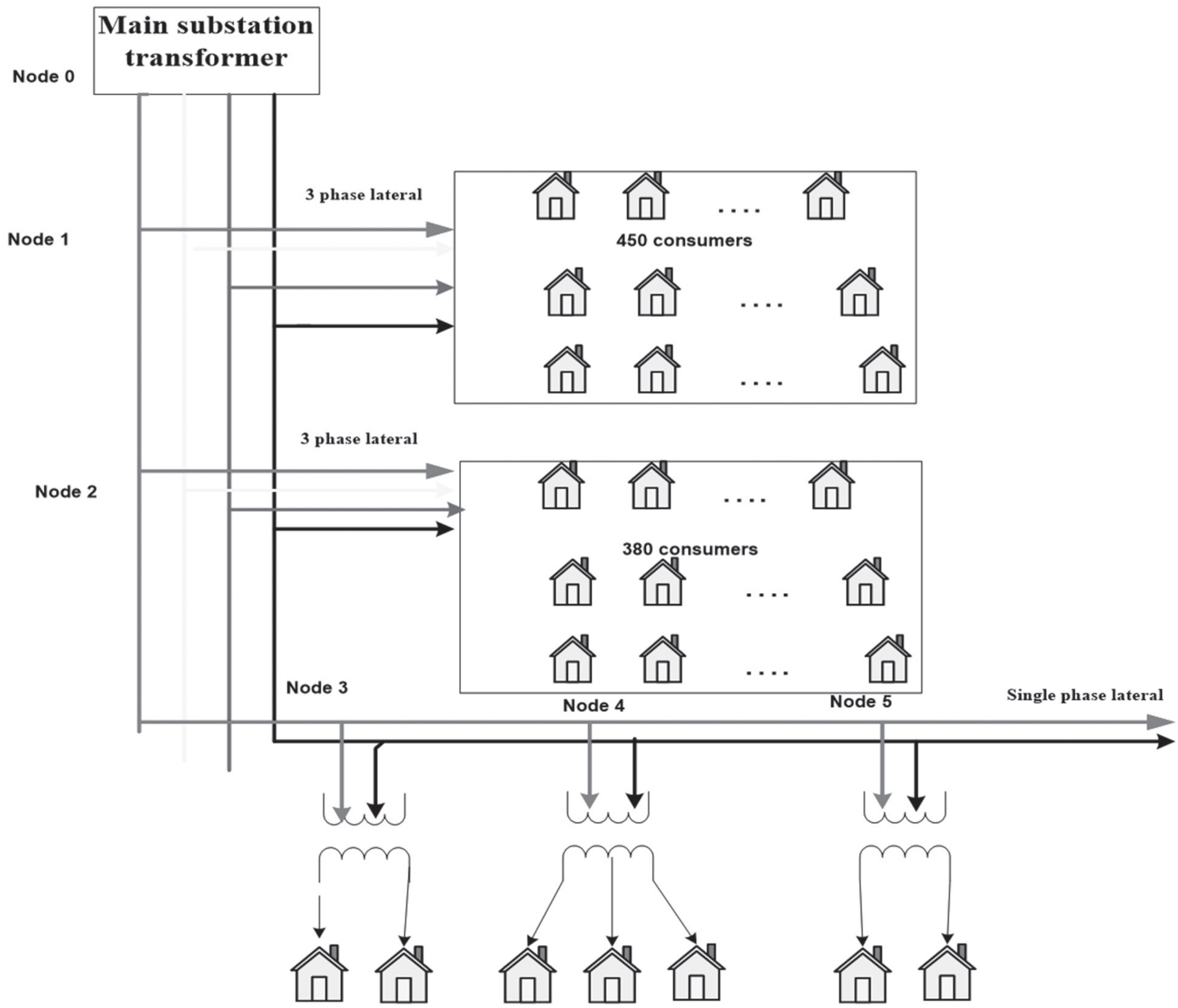

Fig. 1. Configuration of the residential distribution system studied

Consumers connected to this feeder are expected to use electric vehicles. In this paper, we are trying to analyse the harmonic effect of an electric vehicle with different penetration levels. To simulate the test system with EVs, first we have to collect load of each house, system data, and EV charger ratings. Typical loads used in-house are listed in Table 1. The baseload of each house is calculated as 6,000 W. So, each house requires 6 KW of power. Different types of EV chargers are available in the market. The Nissan leaf EV charger level-2 is the most preferred charger. The Nissan leaf charger rating is presented in Table 2.

Table 1. A typical load profile of a residential house

No	Appliance	Power rating (watts)	No of appliances
1	Ceiling fan	80	3
2	CFL	30	3
3	LED lamps	10	2
4	Microwave oven	1,100	1
5	Refrigerator	1,200	1
6	Iron box	1,200	1
7	Laptop	50	1
8	Air conditioner	1,000	2
9	Incandescent lamp	100	2
10	Coffee maker	900	1
11	Flat screen TV	100	1
	Total power	6,000	

Table 2. Nissan leaf charger parameters

No	Parameter	
1	Charging power	3.3 KW
2	Battery size	12 kWh
3	Charging hours	8 hours
4	Per hour charge	14 km
5	Voltage	240 volts

In general, voltage harmonic issues happen in a group of single-phase loads connected to the same node. This framework has centred on a couple of homes associated with residential transformers on a solitary stage to watch the impacts of every individual consumer. Other single-phase loads are considered as lumped loads. Lumped loads and the equivalent circuit of the system are shown in Figure 2 and Figure 3, respectively.

In Figure 3, at node1 lumped load, the transformer, and the distribution line were all combined into one node admittance in parallel with a current source which is Norton equivalent. Homes and transformers connected at each node were combined into one node admittance. A simplified admittance model circuit is shown in Figure 4.

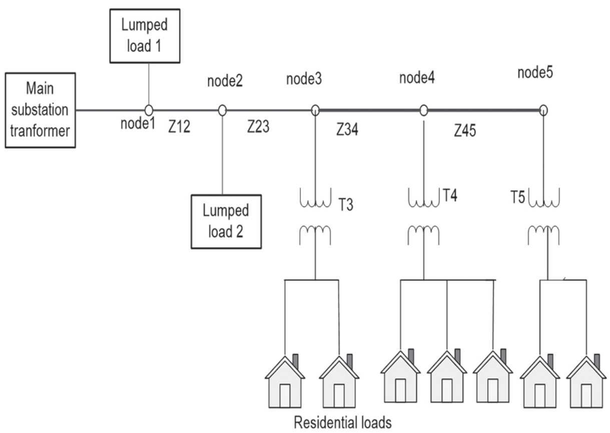

Fig. 2. Residential distribution system

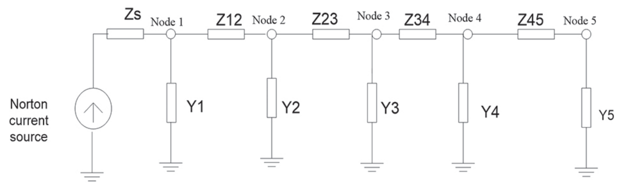

Fig. 3. Equivalent circuit

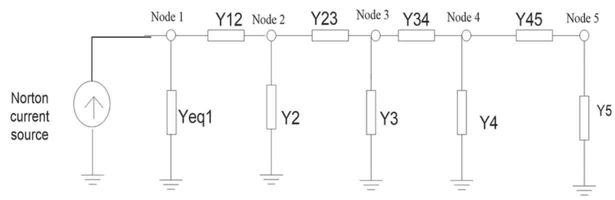

Fig. 4. Simplified circuit of the system

Line and load admittances have been computed at the fundamental frequency. This is used to form the system admittance matrix at the fundamental frequency. In order to calculate voltage and current at the fundamental frequency nodal analysis has been performed. Current harmonics produced by the loads for different harmonic frequencies are figured by utilizing fundamental values and a few information depicting load harmonic distributions. Nodal analysis has been rehashed for every harmonic order to acquire the RMS values of the voltage h ascertaining total harmonic distortion (THD). In the proposed system, all loads are assumed to be equally dispersed in each phase. Lumped load1 and the main transformer can be represented by admittance in parallel with the Norton current source. Homes and transformers associated with every node are joined to be a single admittance element. All impedances have been converted into corresponding admittances to establish a system admittance matrix. Table 3 shows per unit values of the system under consideration.

Table 3. System parameters per unit

Grid voltage	1
Main transformer impedance	j0.023
Impedance of the transformer at node3 and node4	1.7+j 17
Impedance of the transformer at node5	0.82+j8.2
Admittance of lumped load at node1 and node2	0.035-j0.02
Distribution line z12	0.050+j0.22
Distribution line z 23	0.083+j0.24
Distribution line z34	0.018+j0.011
Distribution line z 45	0.042+j0.025

Figure 5 shows the main component of the EV charger. A DC power supply is needed to charge the battery. The purpose of an AC-DC converter is to convert AC voltage into DC voltage. A DC-DC converter is used to modulate the battery DC voltage and the battery charging current.

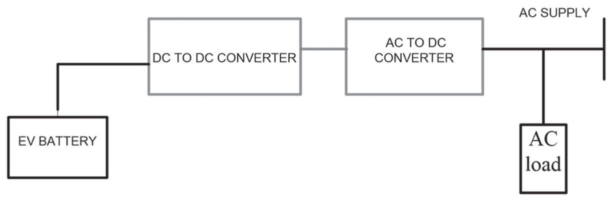

Fig. 5. Basic circuit of the EV charger

An old version of EV chargers was based on full-wave rectification using diodes. The thyristors were used in later versions. Because of nonlinear elements in the EV charger unwanted harmonics in current waveform will be generated. Harmonic frequencies are integer multiples of the fundamental frequency. The EV charger takes a symmetrical distorted current from the supply. Due to the symmetry of positive and negative half-cycles, even harmonics (2, 4, 6, 8, 10, 12, etc.) have insignificant amplitudes. Odd harmonics (3, 5, 7, and 11) have significant amplitudes. This paper is focused on up to the 11^{th} harmonic which is normally the highest order harmonic generated by EV battery chargers. We have neglected even harmonics. A single-phase load generates odd harmonics. The circuit shown in Figure 6 represents a harmonic source at harmonic frequencies.

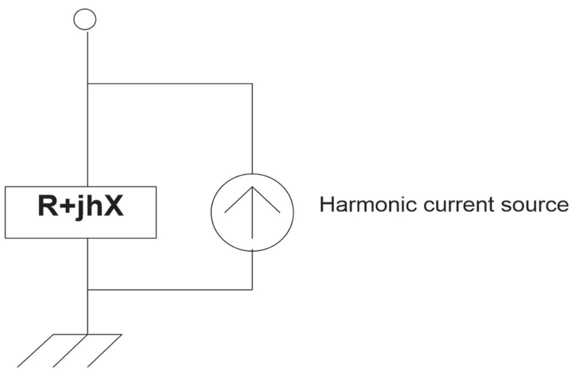

Figure 6. Representation of a harmonic source

I_h is a harmonic current source connected parallel with the load impedance. The RMS value of the harmonic current generated by the load is given by the following equation:

$$I_h = C\frac{I}{h^{\alpha}} , \qquad (1)$$

where 'I' denotes the fundamental current of the load, and 'C' and 'α' are constants which describe harmonic current distribution generated by each load. Constant 'C' can be calculated by the following equation:

$$C = \frac{d_i}{\sqrt{\sum_{h\in N}\frac{1}{h^{2\alpha}}}} , \qquad (2)$$

where 'd_i' is the coefficient of harmonic current taken as 0.12. α is the summation exponent. The typical value of 'α' is 1.5. In [13], the principle of summation is explained and the summation exponent values is given for different harmonic order. 'N' is the set of harmonics (3, 5, 7, 9, 11). The highest harmonic number is H=11. 'C' can be calculated as follows:

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

3. METHODOLOGY

The admittance matrix [Y_{bus}] method is used to determine harmonic voltages. System parameters at the fundamental frequency are given in Table 3. We have to calculate these parameters at harmonic frequencies. Let resistance R and inductive reactance X be calculated at the fundamental frequency. 'h' is the harmonic number (3, 5, 7, 9, 11). Resistance is independent of frequency. But, inductive reactance at the harmonic frequency is 'h' times inductive reactance at the fundamental frequency. Suppose inductive reactance between node1 and node2 is X_{12} at the fundamental frequency. Inductive reactance at the 3^{rd} harmonic is $3X_{12}$. Now we can calculate inductive reactance at any harmonic number h as hX_{12}. The voltage distortion matrix can be calculated by means of the harmonic current matrix [I_h] and the harmonic admittance matrix [Y_h]. This method is widely used in commercial software because of its computational efficiency. The admittance matrix equation for the h_{th} harmonic is given by:

$$[I_h] = [Y_h]\,[V_h] \qquad (3)$$

Voltage distortion values at every node can be calculated by using equation (3). The proposed distribution system has five nodes. The size of the admittance matrix is 5X5. The admittance matrix can be calculated by using equation (4).

$$Y_{bus} = \begin{bmatrix} Y_1+Y_{12} & -Y_{12} & 0 & 0 & 0 \\ -Y_{12} & Y_2+Y_{12}+.Y_{23} & -Y_{23} & 0 & 0 \\ 0 & -Y_{23} & Y_3+Y_{23}.+.Y_{34} & -Y_{34} & 0 \\ 0 & 0 & -Y_{34} & Y_4+Y_{34}.+Y_{45} & -Y_{45} \\ 0 & 0 & 0 & -Y_{45} & Y_5+.Y_{45} \end{bmatrix} \qquad (4)$$

Total harmonic distortion (THD) at each node can be calculated from equation (5).

$$THD = \frac{\sqrt{V_3^2+V_5^2+V_7^2+V_9^2+V_{11}^2}}{V_1} \qquad (5)$$

V_3, V_5, V_7, V_9, and V_{11} are the 3_{rd}, 5_{th}, 7_{th}, 9_{th}, and 11_{th} harmonic voltages at each node, respectively, and V_1 is the fundamental voltage at each node.

A flow chart of the harmonic power flow method is shown in Figure 7.

Input data required to simulate the test system are system data at the fundamental frequency, harmonics number (h), maximum harmonic number (H), and penetration level. This computer program first runs power flow at the fundamental frequency which gives fundamental voltages at various nodes. Later it will be run for harmonic frequencies and for different penetration levels to estimate the voltage total harmonic distortion at various nodes of the residential distribution system under consideration.

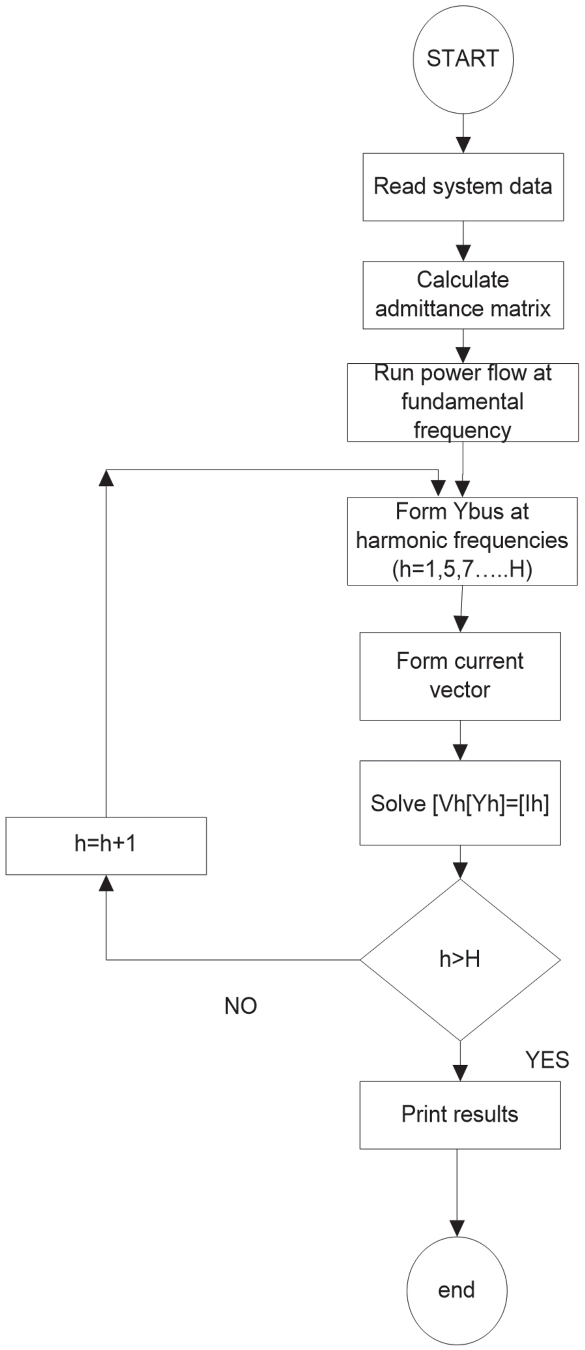

Fig. 7. Flowchart of the harmonic power flow

Input data required to simulate the test system are system data at the fundamental frequency, harmonics number (h), maximum harmonic number (H), and penetration level. This computer program first runs power flow at the fundamental frequency which gives fundamental voltages at various nodes. Later it will be run for harmonic frequencies and for different penetration levels to estimate the voltage total harmonic distortion at various nodes of the residential distribution system under consideration.

4. RESULTS AND DISCUSSION

Simulation results are presented for the residential distribution system with and without EV chargers and analysis has been done for different penetration levels starting from 20% to 100%. 20% penetration means that only 20% of homes will have one battery charger attached to the distribution system.

Case 1: Analysis of the distribution system with typical loads (without an EV charger)

The distribution system under consideration is simulated without an EV charger and results are presented in Table 4. From Table 4, it is observed that fundamental voltage magnitudes of various nodes are close to unity and THD at various buses is also within limits.

Table 4. Performance of the test system without EVs

Bus No	1	2	3	4	5
Voltage magnitude in pu	0.9813	0.9749	0.9747	0.9747	0.9746
THD	1.31	1.77	1.78	1.79	1.79

THD is less than 5% and it means that the system offers THD within acceptable limits of the IEEE 519-2000 standard. Figure 8 shows the graphical output of the system without an EV charger.

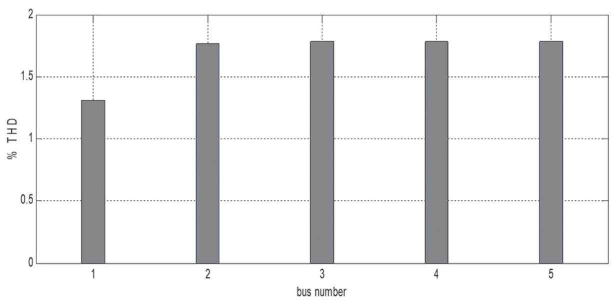

Fig. 8. Graphical representation of THD values at various buses

Case 2: Analysis of the distribution system with EV chargers

The performance of the residential distribution system with typical loads and with an EV charger has been analysed in this case. The EV parameters presented in Table 2 are used in simulation. The EV load has been modelled as an additional 3.3 kW load per home in addition to the initial load of 6 kW per home. Distortion coefficients of power system loads and EV chargers have been assumed to be orthogonal meaning that the angle between distortion coefficients of power system loads and EV chargers are 90 degree, i.e. the principle of summation [13]. The new distortion coefficient of the combined load is the phasor sum of distortion coefficients of power system loads and EV chargers. Simulations have been performed for different penetration levels and voltage distortion and voltage magnitude at various nodes have been presented in Table 5. Harmonic distortion in terms of THD against the level of penetration is shown in Figure 9 through Figure 13 for different nodes.

Table 5. Performance of the test system with EV for different penetration levels

% penetration	Bus No 1		2		3		4		5	
	Voltage magnitude in pu	THD	Voltage magnitude in pu	THD	Voltage magnitude in pu	THD	Voltage magnitude in pu	THD	Voltage magnitude in pu	THD
20	0.9777	2.85	0.9703	3.81	0.9703	3.82	0.9703	3.82	0.9703	3.82
40	0.9738	3.31	0.9652	4.42	0.9651	4.44	0.9651	4.44	0.9651	4.44
50	0.9719	3.54	0.9627	4.73	0.9626	4.74	0.9626	4.74	0.9626	4.74
60	0.9699	3.76	0.9602	5.03	0.9600	5.04	0.9600	5.04	0.9600	5.04
70	0.9680	3.99	0.9577	5.32	0.9575	5.34	0.9575	5.34	0.9575	5.34
100	0.9622	4.64	0.9502	6.19	0.9499	6.22	0.9499	6.22	0.9498	6.22

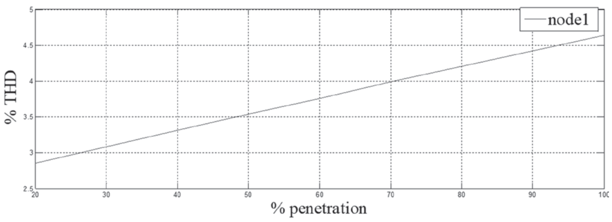

Fig. 9. THD against % penetration level at node1

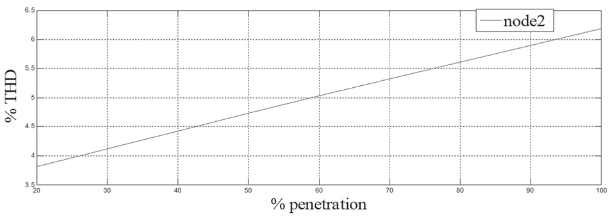

Fig. 10. THD against % penetration level at node2

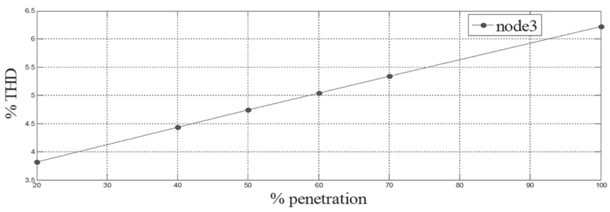

Fig. 11. THD against % penetration level at node3

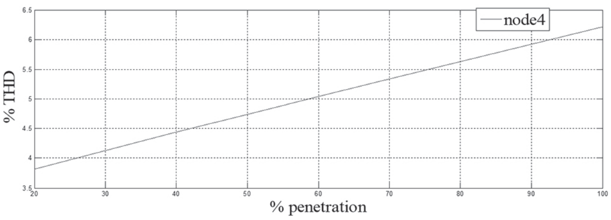

Fig. 12. THD against % penetration level at node4

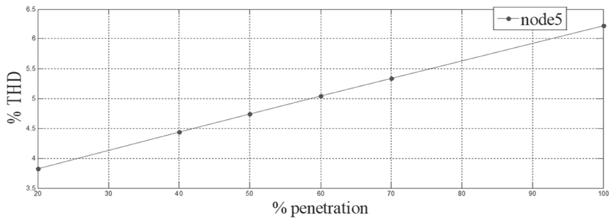

Fig. 13. THD against % penetration at node5

It is observed that the variation of THD against the percentage of the penetration level is linear. This linear relation is valid for the system under consideration as we considered residential loads only. If loads are other than residential loads, we may or may not get a linear relationship. The performance of the system with typical loads and different percentage penetration levels of EV chargers has been investigated. In this study, five buses are considered for voltage magnitude and THD has been obtained for different buses. From Table 5, it is observed that voltage magnitude remains constant at buses, but THD at bus 1 is about 3.54 % and it keeps on increasing from bus 1 to bus 5. Similarly, THD at bus 1 without the charger is 1.31% and it is 62.9% with 50% EV chargers.

Simulation results showed that voltage magnitude at various nodes will not get affected by even100% EV penetration, which means that the voltage profile will not be affected. But, voltage distortion increases when the penetration level exceeds 60%. It is also noticed that voltage THD is around 6% at buses 2 to 5, which is slightly greater than the maximum allowable limit of 5%, except for bus 1.

5. CONCLUSIONS

This paper comprehensively assesses the impacts of residential EV battery charging on distribution system voltages. Different EV penetration levels are considered for the purpose of the study and results have been presented. Simulation results showed that THD is below acceptable limits at all buses when EV penetration is below 60%. When EV penetration is above 60%, THD values at most of the buses are above 5% which is beyond acceptable limits. With 100% EV penetration voltage, THD did not increase much when electric vehicles are connected to this residential distribution system. This work can be extended further in terms of the following aspects:

- Develop smart load management and demand side management algorithms to minimize losses and overloading in the distribution system,
- Investigate PV systems integration with the distribution system and cost minimization, and
- Investigate discharging (V2G) technology and optimal charging and discharging of electric vehicles to obtain optimal charging costs.

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