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Research Article

Harmonic Impact of Plug-In Hybrid Electric Vehicle on Electric Distribution System

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This paper presents the harmonic effects of plug-in hybrid electric vehicles (PHEV) on the IEEE 37-bus distribution system at different PHEV penetration levels considering a practical daily residential load shape. The PHEV is modeled as a current harmonic source by using the Open-Source Distribution System Simulator (OpenDSS) and DSSimpc software. Time series harmonic simulation was conducted to investigate the harmonic impact of PHEV on the system by using harmonic data obtained from a real electric vehicle. Harmonic effects on the system voltage profile and circuit power losses are also investigated by using OpenDSS and MATLAB software. Current/voltage total harmonic distortion (THD) produced from the large scale of PHEV is investigated. Test results show that the voltage and current THDs are increased up to 9.5% and 50%, respectively, due to high PHEV penetrations and these THD values are significantly larger than the limits prescribed by the IEEE standards.

1. Introduction

Currently, there has been a considerable growth of plug-in hybrid electric vehicles (PHEV) integrated in electric power distribution systems. PHEV which are randomly injected into a distribution system would introduce many challenges and impacts on the system. The uncontrolled connection and disconnection of PHEV into a power distribution system will increase harmonic voltage and current distortions [1, 2]. From the power system operation perspective, the large scale integration of PHEV into the grid poses a real challenge. As most of the electric vehicles are fully or partially charged by electricity, it makes them connected to the distribution grid for considerable time duration [1]. Large scale connection of PHEV will cause uncertainty in power system operation. Some studies have shown that without any kind of mitigation the charging of PHEV incurs the electricity grid with additional loads which results in increment of aggregated load during peak hours and hence impacts the overall reliability of the grid [2]. High penetration of PHEV load can give rise to operating conditions which do not arise in traditional power systems and one of the potential issues that need to be addressed involves impact on power quality which includes interruption of service, variation in voltage magnitude, and harmonic distortion in voltage and current [3]. Thus, integration of PHEV may have adverse effect on the distribution network if the penetration is not carefully and systematically planned due to the nonlinear nature of PHEV that generate harmonics which can cause abnormal operation such as increased losses, reduced efficiency, temperature rise, and premature insulation and winding failures. Harmonic currents generated by large number of single phase electronic loads present in a distribution system can cause appreciable harmonic distortion in the grid voltage [4, 5]. The presence of nonlinear electronic loads will cause increasing spectral injectors of low order harmonic currents into the grid [4].

Many studies have been conducted related to the impact of PHEV on the grid during normal charging behavior and also concern the uncoordinated charging behavior of PHEV when connected randomly in the distribution system [6–8]. Previous studies that investigate the impact of PHEV integration on harmonics consider area residential load curve. In the proposed study on impact of PHEV, harmonic effects on a practical residential load shape have been exerted considering two cases: on-peak and off-peak hours during rapid charging. In addition, the impacts of PHEV on other

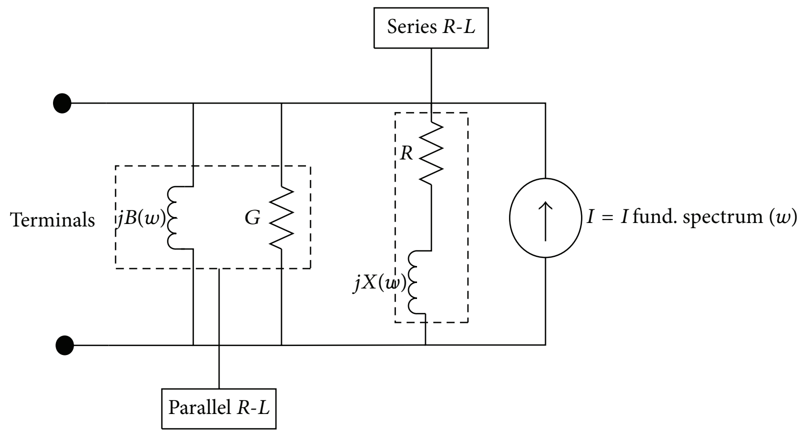

Figure 1: PHEV model in harmonic analysis.

power quality issues like voltage variation and circuit losses are also studied considering the daily load.

The aim of this study is to investigate the impact of PHEV on voltage and current harmonic distortion by performing harmonic analysis on a test system using the OpenDSS software. Harmonic power flow was executed at each harmonic frequency at the given harmonic spectrum associated with the PHEV. Due to the propagation of harmonic currents, the harmonic voltages at all nodes in the system were then captured. In this study, the baseband harmonics are confined to well below the 15th harmonic of the fundamental frequency of 50 Hz (850 Hz). The reason for confinement of the harmonic voltages and currents is based on several factors including the limited bandwidth of the distribution system and also the limited harmonic content of typical distribution system loads.

2. System Modeling

PHEV has been modeled as loads at separate individual phases to take into account the unbalanced three-phase loads and also single phase loads are very common in distribution feeders. For other loads in the distribution system, constant power loads are considered.

2.1. Line Model. For each of the series elements, a set of equations based on the *ABCD* parameters have been used. These parameters relate the sending end three-phase voltages and currents to the receiving end three-phase voltages and currents for each harmonic, which are given by

$$\begin{bmatrix} V_{l,s}^h \\ I_{l,s}^h \end{bmatrix} = \begin{bmatrix} A^h & B^h \\ C^h & D^h \end{bmatrix} \begin{bmatrix} V_{l,r}^h \\ I_{l,r}^h \end{bmatrix}. \quad (1)$$

The *ABCD* parameters of all the elements except the load tap changers (LTCs) are constant. In case of LTCs, these parameters depend on the tap position during the time of operation. The following equations are used to represent the *A* and *D* matrices for each LTC:

$$A_t^h = \begin{bmatrix} 1 + \Delta S_t \mathrm{tap}_{a,t} & 0 & 0 \\ 0 & 1 + \Delta S_t \mathrm{tap}_{b,t} & 0 \\ 0 & 0 & 1 + \Delta S_t \mathrm{tap}_{c,t} \end{bmatrix}$$
$$D_t^h = A_t^{-h}, \quad (2)$$

where Δ represents the change of time operation and $\mathrm{tap}_{a,t}$, $\mathrm{tap}_{b,t}$, and $\mathrm{tap}_{c,t}$ are the tap variables with integer values.

2.2. Constant Power Load. The wye-connected constant power loads on a per-phase basis are given as follows [7]:

$$\left| I_{p,L}^h \right| \left(\angle V_{p,L}^h - \angle I_{p,L}^h \right) = \left| I_{p,L}^h \right| \angle \theta_{p,L}^h. \quad (3)$$

For the delta-connected loads and capacitor banks, line-to-line voltages and currents are required. The equations for voltages and currents which relate line-to-line variables to phase variables are given as follows:

$$\begin{bmatrix} V_{a,b}^h \\ V_{b,c}^h \\ V_{c,a}^h \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_a^h \\ V_b^h \\ V_c^h \end{bmatrix}$$
$$\begin{bmatrix} I_a^h \\ I_b^h \\ I_c^h \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_{a,c}^h \\ I_{b,a}^h \\ I_{c,a}^h \end{bmatrix}. \quad (4)$$

2.3. Modeling of PHEV Load. In this study, PHEV is represented as injected current harmonic source. For harmonic analysis considering current injection method, PHEV load is modeled as a Norton equivalent circuit where the current source represents the harmonic currents injected by nonlinear portion of the load. Figure 1 shows a Norton equivalent

Table 1: Line current harmonic content of PHEV charger [9].

Harmonic order	Magnitude (%)	Angle (deg)
1.00	100.00	305.00
3.00	9.20	120.00
5.00	62.20	255.00
7.00	41.80	332.00
9.00	1.48	357.00
11.00	7.08	358.00
13.00	3.12	284.00
15.00	0.48	69.00

Table 2: Line current harmonic content of Nissan Leaf charger.

Harmonic order	Magnitude (%)	Angle (deg)
1.00	100.00	−26.00
3.00	25.00	−94.00
5.00	17.00	−96.00
7.00	14.20	−72.00
9.00	9.69	−68.00
11.00	5.04	−49.00
13.00	1.80	−49.00
15.00	0.37	−46.00

model of a load element in OpenDSS with a combination of series *R-L* and parallel *R-L* and the shunt admittance represents the linear load. The linear portion of the load provides a damping element to harmonic propagation. The current source is set to the value of fundamental current times the multiplier defined in the "spectrum" object associated with the load for the frequency being solved. The equivalent shunt admittance can be adjusted by stating the percentage of linear load that is connected as series *R-L* and parallel *R-L* where B and X are frequency dependent.

The typical line harmonic current content of PHEV obtained from [8] is shown in Table 1. Another harmonic content acquired from the Nissan Leaf vehicle real charger is shown in Table 2.

3. Harmonic Power Flow

The harmonic study involves solving for the node voltages at each harmonic using the network equation given by:

$$[I_h] = [Y_h][V_h] \quad h = 1, 2, \ldots, N, \tag{5}$$

where I_h is the vector of source currents, Y_h is the nodal admittance matrix, V_h is the vector of bus voltages, and h is the harmonic order.

The nonlinear load is modeled as a decoupled harmonic source that injects harmonic currents into the system. These currents are initialized to proper magnitudes and phase angles based on the fundamental power flow solution and harmonic spectrum associated with them. The harmonic current magnitude is assumed to be a percentage of the fundamental load current. The phase relationship between the fundamental current and nonlinear element current used to calculate the harmonic phase angle is given by

$$\theta_h = \theta_{h\text{spectrum}} + h\left(\theta_1 - \theta_{1\text{spectrum}}\right), \tag{6}$$

where h is the harmonic number, θ_h is the phase angle of current injected at harmonic h, $\theta_{h\text{spectrum}}$ is the phase angle specified in the harmonic spectrum at harmonic h, θ_1 is the fundamental current phase angle, and $\theta_{1\text{spectrum}}$ is the phase angle displacement at fundamental frequency given in the spectrum.

For the harmonic power flow calculation, the decoupled harmonic power flow in OpenDSS is used. At harmonic frequencies, the distribution system is modeled in the presence of passive elements and harmonic current sources. The related admittance matrix is modified in terms of harmonic frequency. Due to harmonic current injections into the system, the nonlinear loads are modeled as current sources. Modeling of the fundamental and the hth harmonic current of nonlinear load connected at node n is given by the following equations:

$$\begin{aligned} \ln_n^1 &= \left[\frac{P_n + jQ_n}{V_n^1}\right] \\ I_n^1 &= C(h)\, I_n^1. \end{aligned} \tag{7}$$

The voltage total harmonic distortion of voltage (THD_v) and current total harmonic distortion (THD_i) are defined as [10]

$$\begin{aligned} \text{THD}_v &= \left[\frac{\left(\sum_{h=2}^{13}\left|V_n^h\right|^2\right)^{1/2}}{\left|V_n^1\right|}\right] \times 100\% \\ \text{THD}_i &= \left[\frac{\left(\sum_{h=2}^{13}\left|I_n^h\right|^2\right)^{1/2}}{\left|I_n^1\right|}\right] \times 100\%. \end{aligned} \tag{8}$$

For THD_v and THD_i, the applicable limit to be considered in the study is up to 15th harmonic; the harmonic orders that come after the 15th harmonic order are negligible.

Once the conventional power flow converges, harmonic power flow mode is initialized. OpenDSS implements a decoupled harmonic power flow algorithm, where it builds the linear admittance matrix at each of the frequencies specified in the program and uses a direct solution to solve for voltages and currents throughout the system at all the specified frequencies [8].

4. Methodology

It can be said that PHEV will draw constant energy throughout the charging process. Considering this important piece of information in studying the impact of PHEV on a distribution system, PHEV can be represented by a harmonic source load and that harmonic analysis can be performed using time series analysis. OpenDSS and DSSimpc software are used to perform the power flow and time series harmonic analysis,

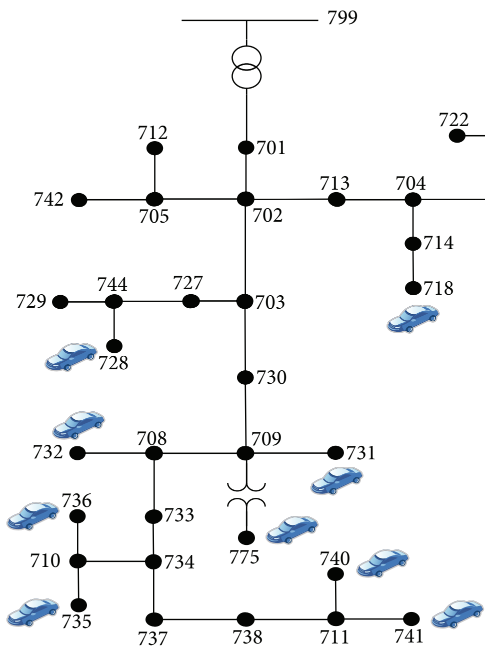

Figure 2: IEEE 37 node test feeder.

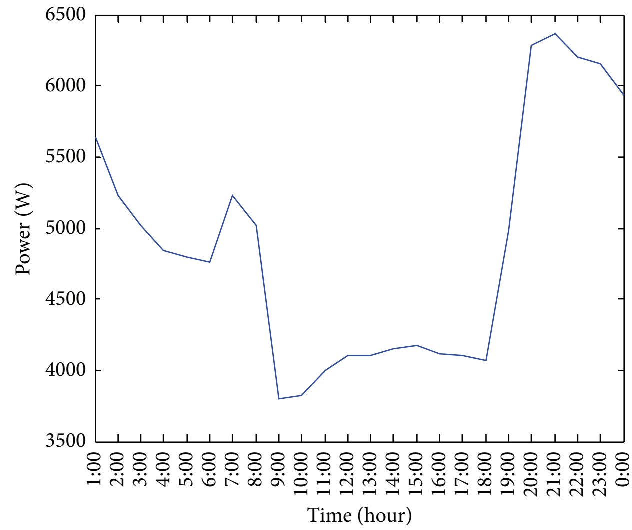

Figure 3: Residential daily load of Malaysia [6].

Table 3: Limits of acceptable THD_v at different voltage levels.

Voltage level	THD_v
33 KV	3.0%
11 KV	4.0%
0.4 KV	5.0%

respectively. The MATLAB software is also used to control the penetration of PHEV and distribute the PHEV to the nodes in a distribution system.

4.1. Test System Description. The IEEE37 test distribution system is modeled by using both OpenDSS and DSSimpc software as shown in Figure 2. Both software types are used to run the system power flow and analyze the PHEV harmonic impact and other power quality impact. The studied system voltage is 4.8 kV and the residential network voltage is 220 V.

4.2. Daily Residential Load. A typical residential power load shape in Malaysia was used in this study as shown in Figure 3. The load profiles for a period of 24 hours with the instantaneous power consumption given on an hourly basis are shown in the figure. The off-peak time starts from 9 am to 6 pm where most of the people are not at home at that time as depicted in the load shape, and then a sudden increase takes place after 6 pm and reaches a maximum at 8 pm and after that gradually decreases at midnight. Since Malaysia is considered as a hot country where consumers usually use air conditioners till late night hours, high demand continues until midnight.

4.3. Vehicle Charging Time. If there is no control in charging time, most of PHEV will be charged directly when arriving at the location where the chargers are located. Most likely when PHEV arrives at home, it will be plugged in immediately and start charging [10]. In this case, additional load from PHEV coincides with residential load peaks. This would exacerbate local peak load condition, forcing upgrading to be done on the infrastructures. Even though additional load is still within the capacity of the infrastructure in particular transformer, this situation will decrease transformer lifetime due to temperature-induced insulation aging. In this study, the penetration time of the PHEV to be charged is during on-peak hours which start from 6 pm to 12 pm and gradually decrease from 1 am to 8 am in the morning as shown in Figure 3.

For the practical distribution system, the voltage total harmonic distortion (THD_v) for MV is limited to 3% at 33 kV, 4% at 11 kV, and 5% at 0.4 kV and below, as shown in Table 3.

5. Results and Discussion

The effect of harmonic current spectrum of PHEV on a practical distribution system power quality considering the residential daily load shape of Malaysia is investigated. The penetration level of the PHEV is gradually increased in the system from 30% to 80% during the on-peak hours of residential load. The different power quality issues that have been studied are in terms of (i) voltage profile, (ii) system loss, and (iii) THD.

5.1. Voltage Profile. The distribution system is subjected to 30%, 50%, and 80% injection of the PHEV and the voltage profiles are plotted as shown in Figures 4 and 5. From the figures, the y-axis shows the magnitude of voltages per unit whereas the x-axis shows the distance from the substation to each bus and line, in kilometers. The voltage profile at 30% penetration is still within the accepted voltage values between 0.95 and 1.05 p.u. as shown in Figure 4. In contrast, at 80% penetration, the voltage profile is out of the accepted voltages as shown in Figure 5. It is clear that the heavy

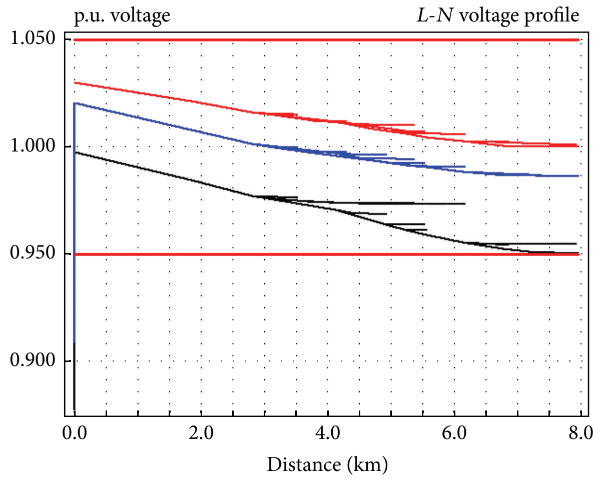

Figure 4: Voltage profile with 30% penetration.

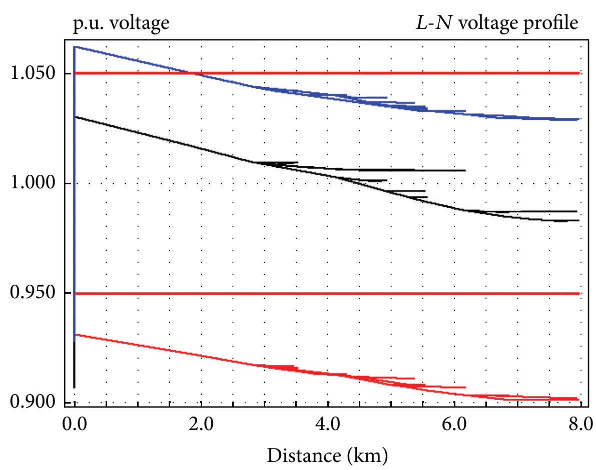

Figure 5: Voltage profile with 80% penetration.

injection of these vehicles would affect the performance of the distribution system voltage and would definitely introduce a new peak load in the system.

5.2. System Loss. At different penetration levels, the tested distribution percentage losses are analyzed. The total power losses collected from the line and transformer losses of the test system are considered as circuit losses as shown in Figure 6. The circuit power losses in percentages are calculated over 24 hours with no PHEV penetration as shown in Figure 7. From the figure, it is noted that the circuit power loss percentage ranges from 4.8% to 8.9%. The PHEV penetration is gradually increased with 30% integration of PHEV in the system and the circuit losses percentage is within 5.5% to 10% as shown in Figure 8. By further increasing the PHEV penetration to 80%, the power losses increase in the range of 7.8% to 11.8% as shown in Figure 9. Thus, the total circuit power loss is directly affected by the increase of PHEV penetration into the distribution system.

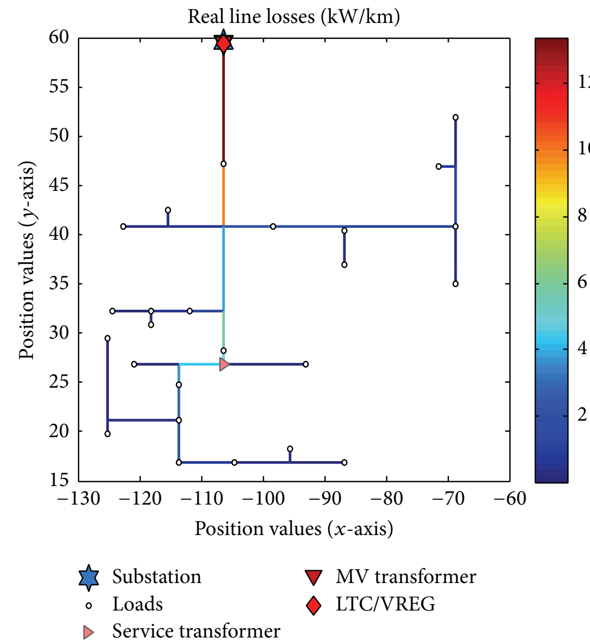

Figure 6: Circuit real power losses.

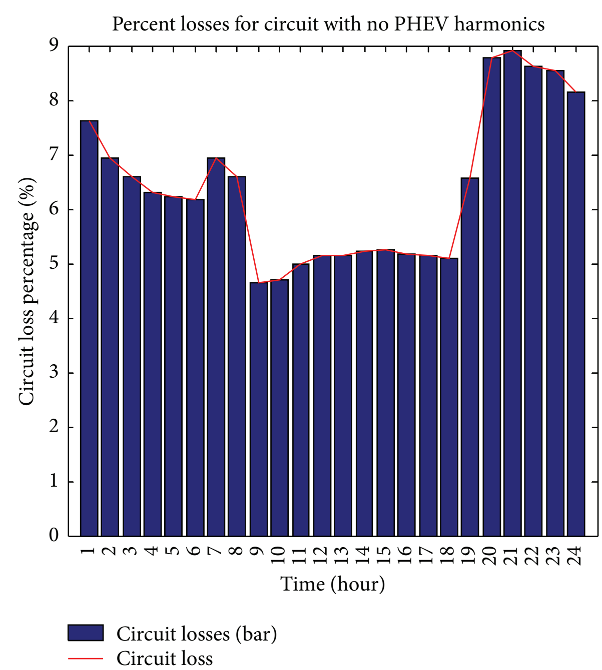

Figure 7: Total circuit power loss without PHEV penetration.

Figure 10 shows a comparison of the four levels of PHEV penetration ranging from 0% to 80%. The figure clearly indicates that the system losses increase due to PHEV harmonics with percentage increment of losses within 9% to 10.2%. The losses in the system are due to the effect of current and voltage harmonic distortions.

5.3. Total Harmonic Distortion. In this case, the impact of THD is investigated by considering 30% harmonic injection

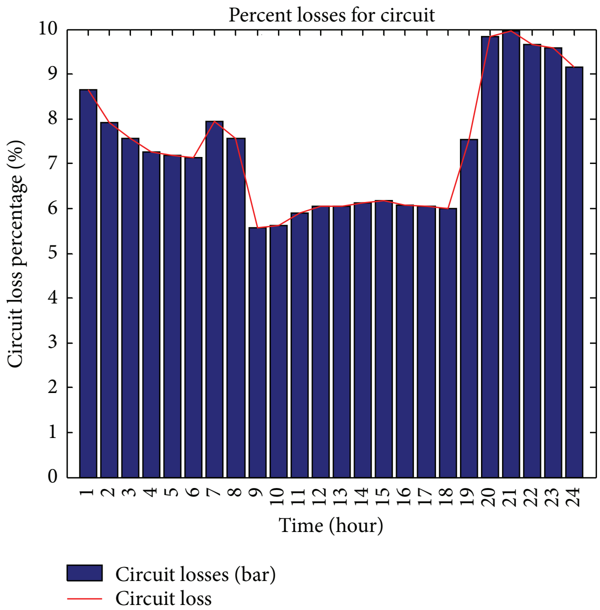

Figure 8: Total circuit power loss with 30% PHEV penetration.

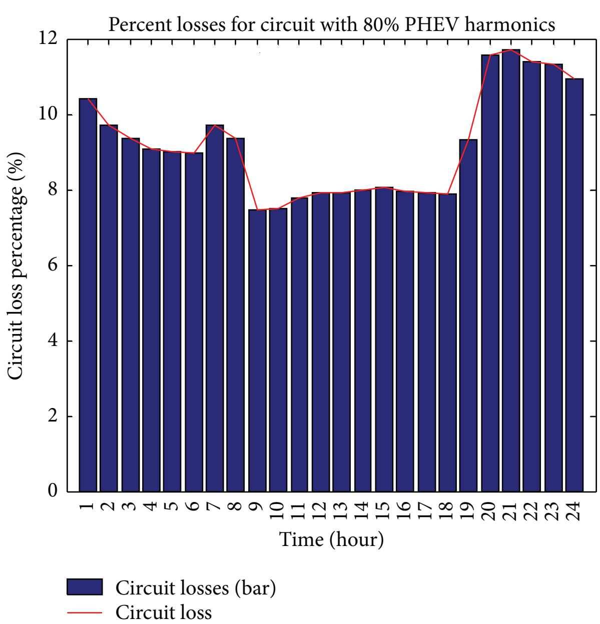

Figure 9: Total circuit power loss with 80% PHEV penetration.

at different nodes in the test system. The simulation was done considering 24-hour load profile with 15-minute time interval so as to capture the harmonic effects. Figure 11 shows the harmonics gradually increase with respect to the increase of frequency when it is assigned to the load in the system, with maximum harmonic distortion of 17.8% at 850 frequency. Figures 12 and 13 show THD_i at two different nodes 775 and 740, respectively, when the PHEV are connected at off-peak hours and on-peak hours. Three different PHEV penetrations have been considered: 30%, 50%, and 80%. From Figure 12, the maximum THD_i value is at phase C and at 80%

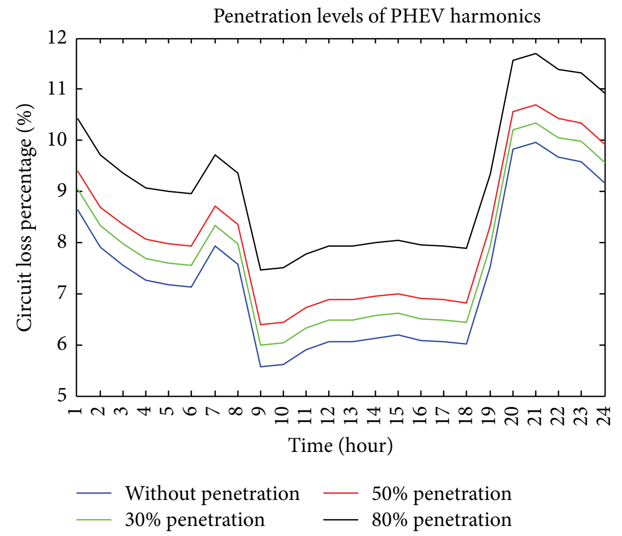

Figure 10: Percentage circuit power losses at different PHEV penetration levels.

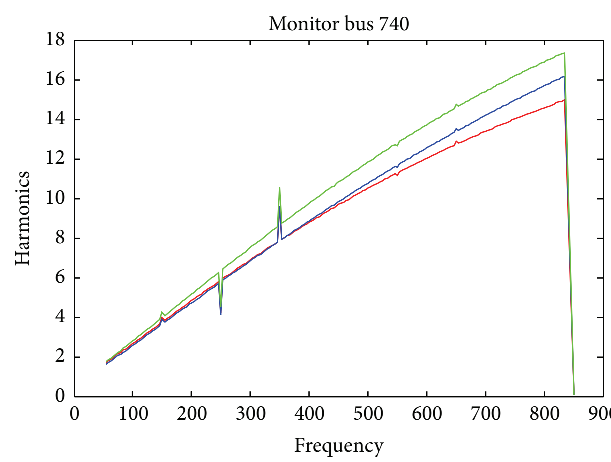

Figure 11: Harmonics versus frequency.

PHEV penetration level. Considering the harmonic limits specified in the IEEE Harmonic Standard, the effect of THD_i during off-peak time is acceptable when the level of PHEV penetration is 50%. However, above 50% penetration level, the THD_i values exceed the IEEE harmonic limit. Figure 13 shows significant increase of THD_i reaching 15% and 25% when the PHEV penetrations are 50% and 80%, respectively. The result shows that the maximum PHEV penetration to be adopted is 30%, in which above that value unacceptable harmonic distortions will be injected into the system.

6. Conclusion

The PHEV model required for harmonic power flow studies has been developed considering a practical residential load shape with on-peak and off-peak periods. Using the PHEV model, the impact of PHEV on current/voltage harmonics has been studied considering varying levels of penetration. Other power quality issues such as total circuit power losses

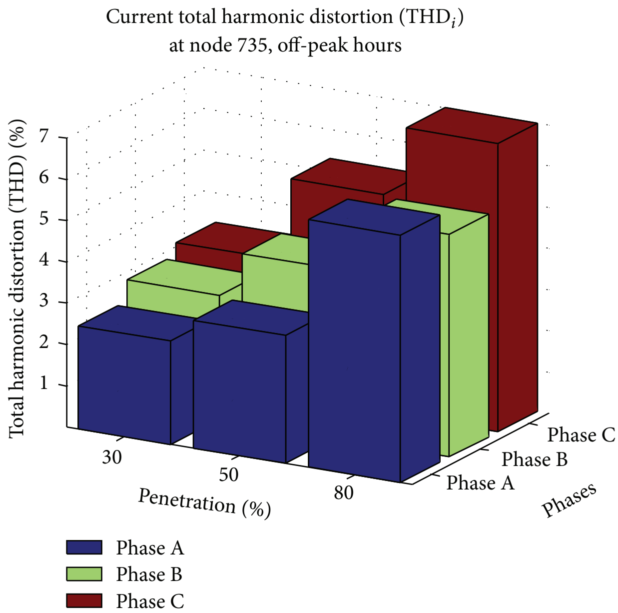

Figure 12: THD_i at node 775, with different PHEV penetrations.

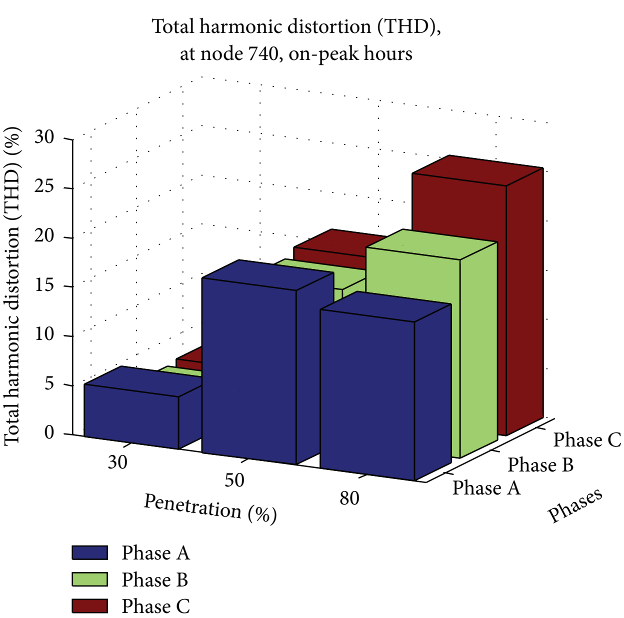

Figure 13: THD_i at node 740 with different PHEV penetrations.

and voltage profile have been investigated, by increasing the PHEV penetration in the distribution system. It has been observed that during off-peak time, 50% of PHEV penetration into the system is considered acceptable with no harmonic limits violated, whereas during on-peak time period, the acceptable PHEV penetration is 30%.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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