POWER QUALITY ANALYSIS OF DISTRIBUTION SYSTEMS INCORPORATING HIGH PENETRATION LEVEL OF EV BATTERY CHARGERS

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Abstract:

Harmonic pollution has an increased interest in recent years because of the increase in non-linear loads. As an effort to combat carbon emissions, governments around the world are taking initiatives to promote the use of electric/ hybrid electric vehicles (EVs/ HEVs) and a lot of research and development is also going on in the field to exploit the potential of such vehicles. This implies the induction of EV battery chargers in the power systems at a mass scale in future. However, the market penetration of electric vehicle battery chargers is a potential power quality threat due to the fact that the associated battery chargers are power electronic circuits, which produce deleterious harmonic effects on the electrical distribution system. In this research, the experimentally recorded harmonic model of a battery charger is employed to perform the harmonic analysis of a typical UK electrical distribution system in Electrical Transient Analysis Program (ETAP) considering different scenarios and penetration levels of EVs. The experimental and simulation results show an increasing trend in the harmonic distortion level with the potential increasing penetration level of EVs. The results also indicate the strong correlation between harmonic levels and the charging routines. The harmonic distortion in both current and voltage is found to be violating standard limits.

INTRODUCTION

With the ever increasing interest in the electrical power, newer technologies like Electric Vehicles (EVs) are being introduced into the power system. One major factor dictating the introduction of such advanced technologies is the growing concern about the climate control [1]. Moreover, increased demand for energy is another factor which has to be accounted for [2]. Research and development work, backed by different proposals made by several governments, is currently being conducted [3]. In addition to coping with carbon emissions, EVs are also much more efficient as compared to their internal combustion counterparts. [4].

This entails the introduction of EV battery chargers in the electrical distribution systems at a massive scale in near future. Certainly it will give rise to various power quality issues. However, considering the non-linear nature of battery chargers, this research work is focused on the harmonic distortion. Harmonic distortion in sine wave is caused by the generation of sinusoidal components which have their frequencies as integer multiples of the fundamental frequency [5]. Harmonic distortion is usually quantified in terms of Total Harmonic Distortion (THD) [6] which is defined as "The ratio of the rms of the harmonic content to the rms value of the fundamental quantity, expressed as a percentage of the fundamental". The equation for calculating THD is shown as below.

$$(\%)\ THD = \{[\sqrt{(\sum_{h=2}^{\infty} M^2_{h,rms})}] / M_{1,rms}\} \times 100\% \qquad (1)$$

where $M_{1,rms}$ and $M_{h,rms}$ give the rms value of fundamental and h^{th} harmonic constituent of voltage/current.

Efforts have been made, with contrasting results, to analyse the harmonic distortion caused by EV battery chargers in the power systems [7, 8]. However, these studies do not give a consideration to a large number of EVs predicted in future.

This research work is aimed at performing the harmonic analysis of a domestic distribution system considering large scale penetration levels of EV battery chargers. The study is also extended to investigate the impact of time of the day, when charging is started, on harmonic pollution levels. Both practical measurements and simulation results are presented in this paper.

EXPERIMENTAL ARRANGEMENT

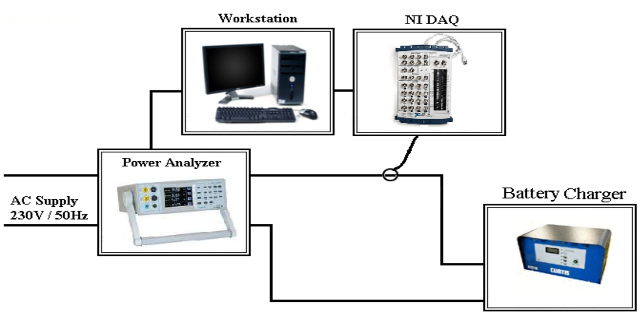

Fig. 1 Experimental Setup

The experimental arrangement set up for the harmonic analysis of the battery charger is shown in Figure 1. The Voltech PM1000+ power analyser; interfaced to a workstation for data acquisition using LabView; not only measures the real power and true power factor (PF_{true}) but also gives the amplitude and phase spectrum of the current waveform. National Instruments data acquisition (NI DAQ) module, aided by LabView and a current probe, is used to capture the current waveform drawn by the battery charger.

EXPERIMENTAL RESULTS

Measurements were taken while a battery charger was used to charge a battery pack with an initial state of charge (SOC) equals to 30%. It was observed that total harmonic distortion in current (THD_i) for a battery charger kept on increasing, from 44% to 55.3%, with the charging process which can be attributed to a gradual increase in the individual harmonic distortion in current (IHD_i) for third harmonic as shown in Figure 2.

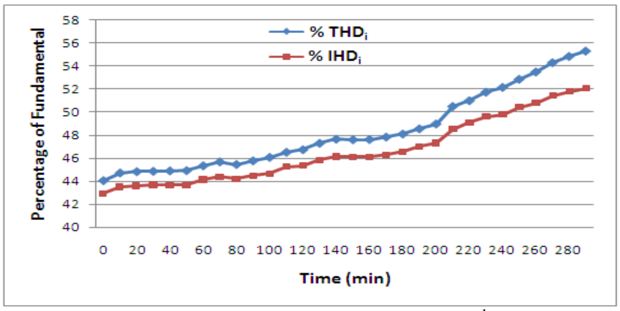

Fig. 2 Increasing Trend in THD_i & IHD_i for 3rd Harmonic

A similar increasing trend for other harmonics was also noticed. The amplitude spectrum of the current waveform drawn by the battery charger; having THD_i equal to 44.93% at an SOC of 40%; is shown in figure 3.

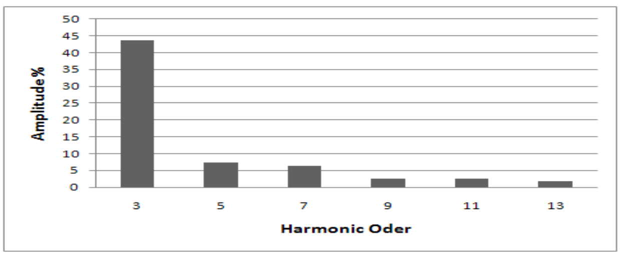

Fig. 3. Amplitude Spectrum of current drawn by a charger

The real power drawn by the charger to charge a pack of two batteries was 423.56 W, with a PF_{true} equal to 0.82, which makes the power required to charge a 144V pack of batteries equal to 2.72 kW. Similarly, harmonic models were developed for 30% and 60% SOC.

DISTRIBUTION SYSTEM UNDER STUDY

A typical UK residential distribution system, having a 500 kVA transformer supplying 100 homes, as shown in Figure 4 was implemented in ETAP for the simulation purposes.

HARMONIC ANALYSIS

Harmonic analysis was performed to obtain the current and voltage waveforms, at bus bar 8 supplying 53 homes and representing point of common coupling (PCC), i.e. a point where another consumer can be supplied, under different scenarios to analyse the impact of penetration level of battery chargers and time of the day used for charging on the harmonic distortion levels. For voltage level up to 69 kV, individual harmonic distortion in voltage (IHD_v) and total harmonic distortion in voltage (THD_v) have an allowable limit up to 3% and 5% respectively as per IEEE recommended practices. For the same voltage level and a short circuit ratio (I_{sc}/I_L) between 50 and 100, the limit of IHD_i for harmonics of order less than 11 is equal to 10% [9].

Impact of Penetration Level on THD

As per UK national statistics, percentage of households in the UK with at least one car/ van is 75% [10] making 75 homes of the considered distribution system to have a car. Keeping in view the anticipated future, different hypothetical scenarios are being considered for simulation with different penetration level of EVs into households. 30% penetration level means that 30% of the homes, out of 75 homes which have a car, are assumed to own an EV. The system loading under different penetration levels is given in Table 1. The highest probability of initial SOC lies between 20% and 80% SOC with the peak occurring at 40% SOC [11]. So, it is assumed that 60% of the total EV chargers are connected at 40% SOC. 20% of EV chargers are connected at 30% SOC and 20% of them are connected at

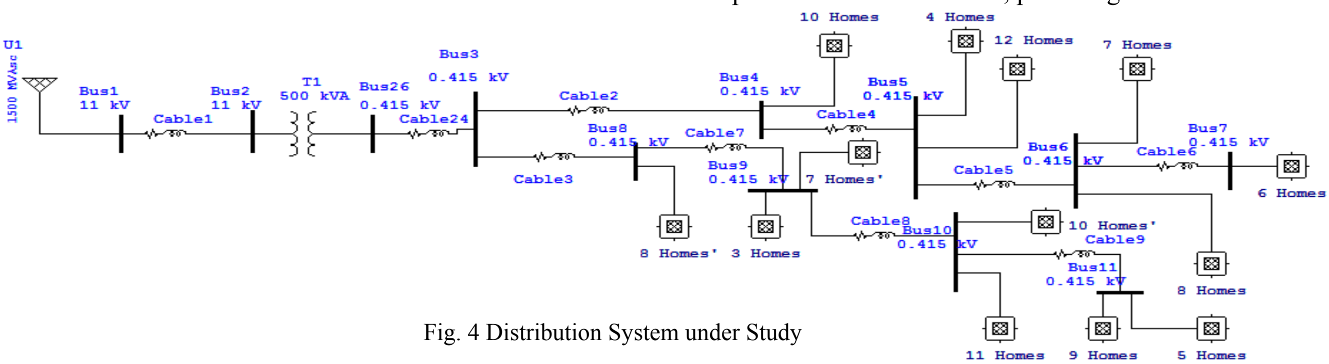

Fig. 4 Distribution System under Study

60% SOC.

Table 1 Loading details

EV Penetration Level	Total Load (kW)	Charging Load (kW)
30%	117.18	57.18
80%	223.3	163.3

At 30% Penetration Level

Current waveform at PCC is shown in Figure 5. The waveform is distorted because the 3rd harmonic having an IHD_i of 33.48%, higher than the recommended limits, is giving rise to a THD_i of 34.26%.

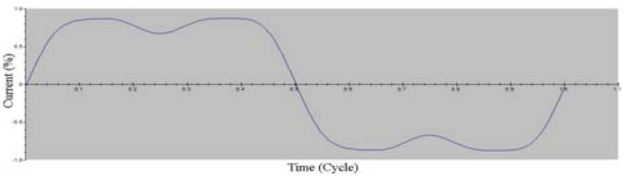

Fig. 5 Current Waveform at PCC at 30 % EV penetration

Voltage waveform is also distorted. However, THD_v being equal to 2.62% is within the standard limits.

At 80% Penetration Level

For a very much likely future scenario with the EV penetration level of 80%, the current waveform at PCC is shown in Figure 6. Current waveform is highly distorted with THD_i equal to 55.34%. The 3rd harmonic having an IHD_i equal to 54.09%, much higher than the standard value, dominates the distortion.

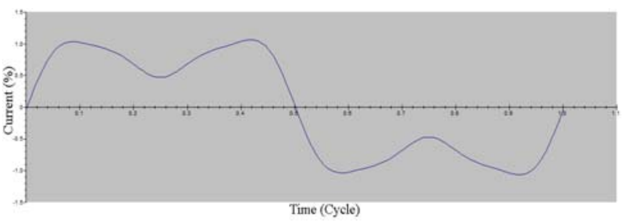

Fig. 6 Current Waveform at PCC at 80 % EV penetration

The highly distorted current significantly distorts the voltage waveform as well upon passing through the system impedance. The voltage waveform at PCC is shown in Figure 7 and its amplitude spectrum is presented in Figure 8. In addition to THD_v being equal to 7.56%, the 3rd harmonic with an IHD_v equal to 7.09% is also beyond the standard limits.

Discussion

Results indicate that the penetration level of EVs have a strong impact on the total harmonic distortion level in the distribution system. Appropriate solutions should be identified to mitigate the harmonic distortion produced by EV battery chargers before introduction of EVs is made at a large scale.

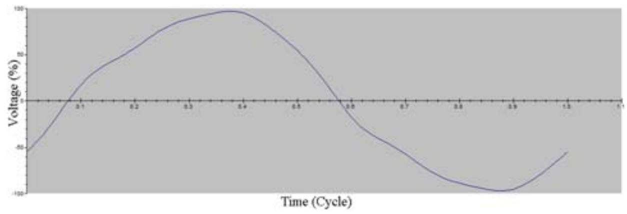

Fig. 7 Voltage Waveform at PCC at 80 % EV penetration

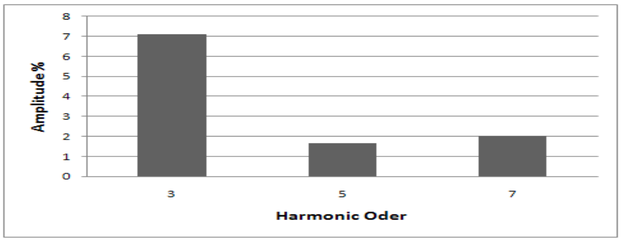

Fig. 8 Amplitude Spectrum of Voltage Waveform at PCC at 80 % EV penetration

Impact of Time of the Day

In order to focus on the impacts of time frame on charging, typical 50% penetration level of EVs is considered. Simulations are being carried out at different times of the day representing off-peak loading and peak loading as given in Table 2.

Table 2 Loading Scenarios

Time of Charging	Total Load (kW)	Charging Load (kW)
Off-Peak	110.3	95.3
On-Peak	295.3	95.3

Charging at Off-Peak Load Time

The current waveform at PCC is shown in Figure 9.

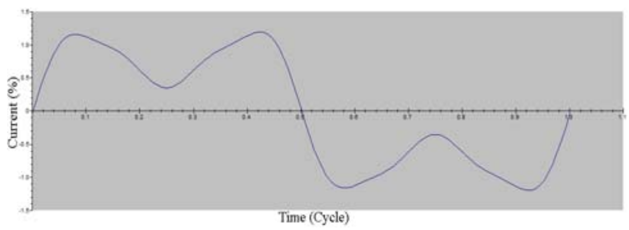

Fig. 9 Current Waveform at PCC at Off-Peak Load

It is a highly distorted waveform with a THD_i equal to 68.13% and 3rd harmonic with an IHD_i of 66.56% which is far beyond the standard limits.

Charging at the Peak Load Time

However, the harmonic distortion is much under the control as shown in Figure 10 if the charging is done at peak load time. The THD_i has a much smaller value equal to 20.72% with the third harmonic having an IHD_i of 20.27%.

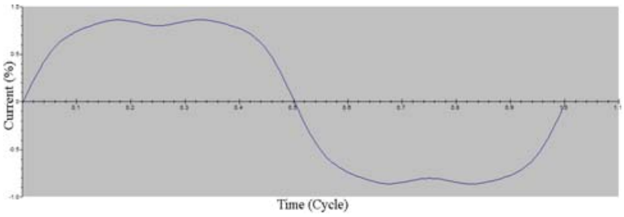

Fig. 10 Current Waveform at PCC at Peak Load

Discussion

Even though based upon results drawn in [12], it would be recommended by the demand side management (DSM) engineers to do the charging at off-peak load times to avoid the high load peaks and have a smooth load profile but at the same time, the results given above show that, to reduce the harmonic pollution levels it would be recommended to do the charging at peak load times. So a compromise has to be reached to find an optimum time of the day for charging.

CONCLUSIONS

The experimental results combined with the simulation results show the high levels of harmonic pollution in future power systems with a high penetration of EVs. The situation is bound to worsen if the varying nature of THD_i of battery chargers over the charging cycle and interaction of EV battery chargers with the other household appliances, which for this case study were assumed to be linear, will be considered. It was also found that to reduce harmonic distortion; it would be recommended to do the charging at peak load times. However, this contradicts with the recommendation of demand side management engineers who expect consumers to do the charging at off-peak load times to smooth off the load profile. Therefore, efforts are required to find out the best time of the day to do the charging which is acceptable to both DSM engineers and power quality experts. Moreover, an in depth study is required to analyse the interaction between EV battery chargers and other non-linear home appliances so that appropriate solutions could be identified to mitigate future harmonic distortion threats. This will enable the electrical engineers to fully utilise the potential of electric vehicles for a greener future.

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