The Interactive Effects of Multiple EV Chargers within a Distribution Network

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Abstract—**Power Quality (PQ) issues are increasingly important owing to the widespread use of power electronic devices, such as switch mode power supply, Electric Vehicle (EV) charging systems, etc. Non linear devices used in EV chargers draw non sinusoidal current and distort the input current from the grid resulting in the injection of Harmonic currents. This paper considers the PQ effects of a number of types of EV charging systems, and examines the effects of multiple instances of such chargers on a simulated network. Some designs will tend to cancel certain harmonics produced by others, and others may magnify the levels of particular harmonics. In addition, the paper explores the ability of the PWM charging system to produce harmonic currents at a chosen phase angle allowing cancellation of particular harmonics.**

Keywords-component; Distribution networks, Electic Vehicles, smart grids, Power Quality, Harmonic Distortion.

I. INTRODUCTION

With the current concerns about levels of Carbon Dioxide emissions, and the rapid diminution of reserves of coal and oil, the concept of Electric Vehicle (EV) is rapidly approaching. Developments in Drivetrain efficiency and battery energy storage density already allow current EVs to take the place of conventional petrol and Diesel powered vehicles for many applications. EVs can of course be charged from renewable sources of energy, so they have a double advantage in that whilst being low emission vehicles themselves,their adoption facilitates large scale use of renewable sources of electricity since the EV can be arranged to charge when there is surplus energy from renewable sources, and the energy stored in the EV batteries can then be available for load equalization of the power system [1].

Despite the advantages offered by the EV, there are drawbacks that need to be carefully considered. At present the major one is cost, since the price of an EV with acceptable performance and range is far in excess of that of a conventional equivalent. However, once the EV is mass produced, it seems likely that economies of scale can be found, much as was the case when petrol powered cars were introduced in the early 20th century. A further drawback of the EV is that it is capable of polluting the power grid, even if not the physical environment. Present charging systems postulate the drawing of mains power from the grid, typically at either 230V (single-phase) or 400 V (3-phase) and using a converter producing DC to charge the vehicle battery, which typically stores power at 300-400V. The production of the DC current from AC mains involves the use of non linear electronic components, such as Diodes, Thyristors and Transistors. Passage of current through these produces harmonics of the 50 Hz mains frequency which are injected into the power grid, causing operating problems for other users of the grid. Many loads are sensitive to harmonic distortion in the mains voltage supply, such as personal computers. Other problems caused by harmonic disturbances include shortening of equipment life and interference with communication and control equipment [2]. It can adversely affect meter readings and even contribute to system instability [3].

In this paper a comparison is made of the relative harmonic distortion levels produced by four different types of EV charger: Pulse Width Modulated (PWM), Square Wave, basic single-phase Bridge Rectifier, and 3-phase Bridge Rectifier. It is felt that these types represent typical EV charger configurations, as suggested by manufacturers' literature. In references [4] and [5], the authors noted the fact that under some circumstances EV chargers can interact so that a plurality of chargers connected to a system may produce a lower level of harmonic distortion than will a single charger. However, in [6] the authors noted that the introduction of EV chargers can increase the Total harmonic Distortion (THD) resulting from the operation of other domestic appliances. As a result of these findings, this paper examines the interactive effects of locating a plurality of each type of charger onto a power system in order to find the effects on the magnitude of each harmonic, whether diminished or augmented, as the number of such chargers is increased.

II NETWORK MODEL

A typical distribution network model, shown in the Appendix, is used for this study. The model includes a distribution network from the primary voltage level (33 kV)

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down to the low voltage level (400/230 V). The 33/11 kV substation has six 11 kV outgoing feeders, each supplying eight 11/0.4 kV substations. The 11/0.4 kV substation consists of four 400 V outgoing radial feeders. To simplify the analysis, only one 400 V feeder together with its connected loads and EV was modelled in detail. The other feeders together with their connected loads (and EV, if any) were represented as an individual lumped load connected to the main substation. The model assumed that each 400 V feeder supplies the equivalent of 100 individual domestic customers. The model is assumed to be at full load.

III TYPES OF CHARGER

A The PWM ConverterThe full-bridge converter (shown in Fig. 1) generates a rapidly switched (typically 10-50 kHz) DC voltage across the inductor varying between 0 and +400V for one half cycle and then between 0 and -400V for the next half cycle. The 'modulation index' (0-1) determines what proportion of the time the bridge conducts for each half cycle. The fundamental component of the resulting square wave is a 50 Hz sine wave whose phase may be adjusted to either lead or lag the mains phase angle. In a PWM converter, the real input power exchanged with the grid is a function of the phase angle between the mains waveform and the 50Hz fundamental component of the converter square wave; the greater the latter lags/leads the former, the greater is the real power transfer from/to the grid. It is possible in principle to use the PWM configuration to produce harmonic currents at specified phase angles, allowing cancellation of particular harmonics in the supply. This possibility is investigated and will be presented later in this paper. Fig. 2a shows the output current waveform (upper traces) and the rapidly switched square wave across the inductor (bottom trace) at a switching frequency of 3 kHz. Fig. 2b shows the harmonics in the output current. Fig. 3a shows the same signals but at a switching frequency of 30 kHz, with the resulting improvement in current waveform shown in Fig. 3b. Note that only certain odd harmonics are generated.

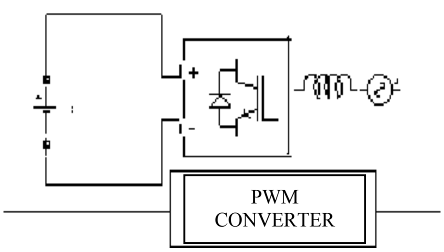
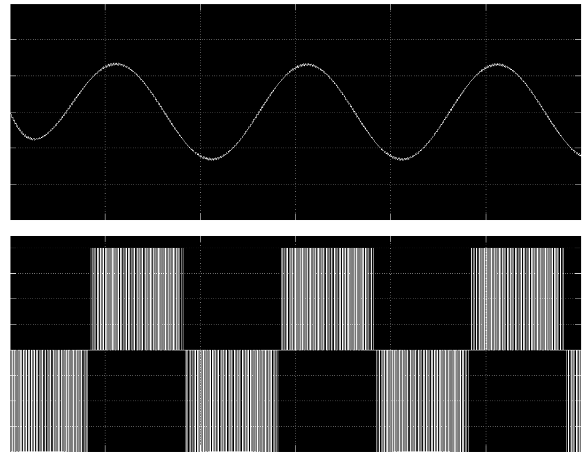
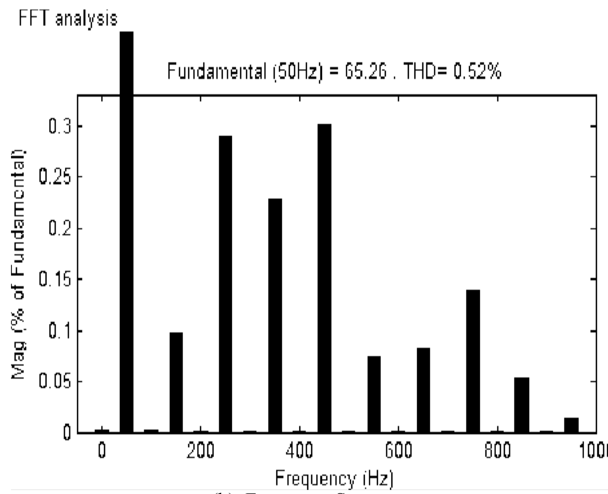


Fig. 1: Basic configuration of the PWM converter

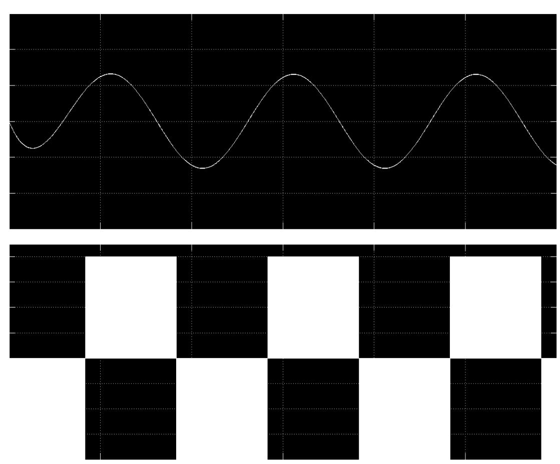


(a) Output current and voltage waveforms

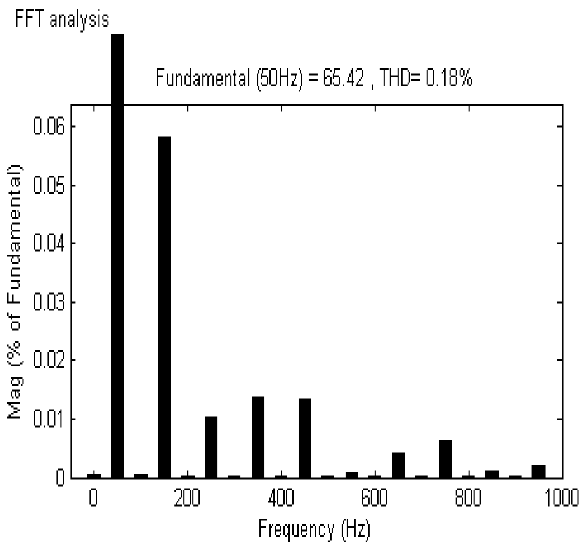


(b) Frequency Spectrum

Fig. 2



(a) Output current and voltage waveforms



(b) Frequency Spectrum

Fig. 3

B The Square-Wave Charger

This method is to power a dc converter from the mains input to provide a constant charging current to the battery until the incoming voltage reaches the battery voltage. On the downward part of the cycle, the charging current is switched off once the mains voltage falls below the battery voltage. The resulting duty cycle varies with battery voltage and the result is a square current waveform. Fig. 4 shows the circuit configuration, and Fig. 5 shows the harmonic spectrum of the input current for this application, showing the wide spread of harmonics at high level (duty cycle 40%). The THD increases markedly with increasing battery voltage, with its concurrent reduction in duty cycle.

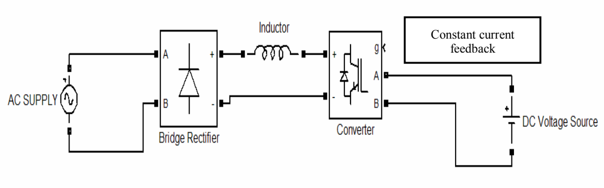


Fig. 4 Basic structure of the Square-Wave Charger

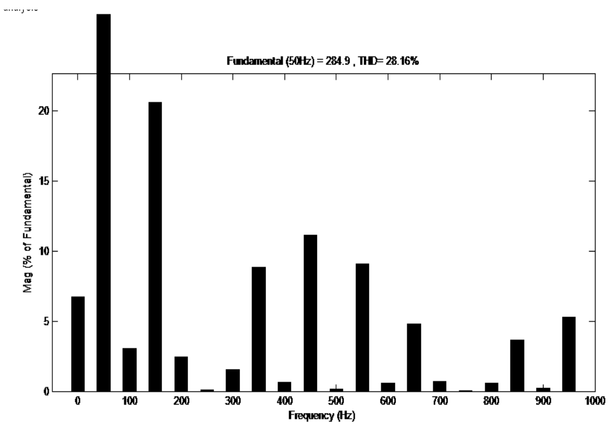


Fig. 5 Frequency Spectrum

C Basic Single-Phase Bridge Rectifier

This is the traditional circuit for charging lead acid batteries. A transformer is used to step down the voltage to supply the bridge rectifier, as shown in Fig 6. Fig. 7 shows typical harmonic spectrum produced. Note the high level of distortion comprising odd harmonics only.

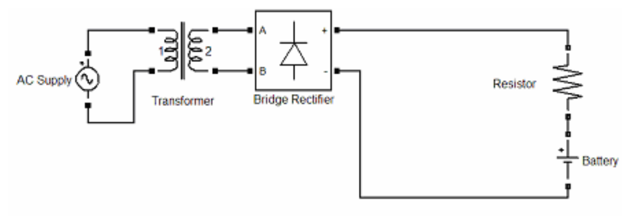


Fig. 6 Basic structure of the 1-ph bridge rectifier

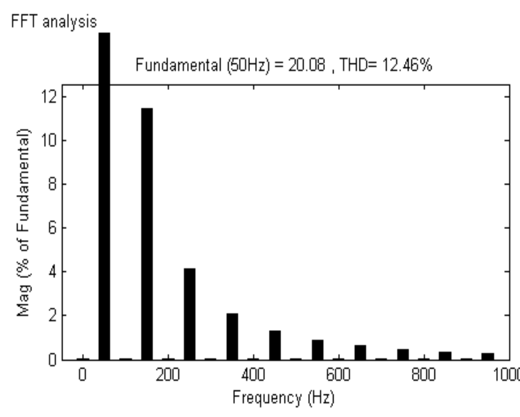


Fig. 7 Frequency Spectrum

D 3-Phase Bridge Rectifier

Fig. 8 shows a 3-phase bridge rectifier charging system The harmonic spectrum of the input current shown in Fig. 9 shows low level of distortion as compared to the basic 1-ph bridge rectifier arrangement

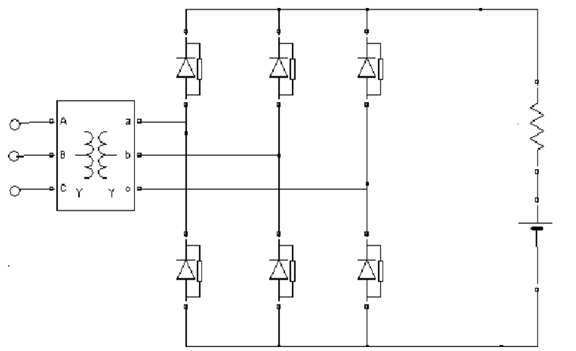


Fig. 8 Basic structure of the 3-ph bridge rectifier

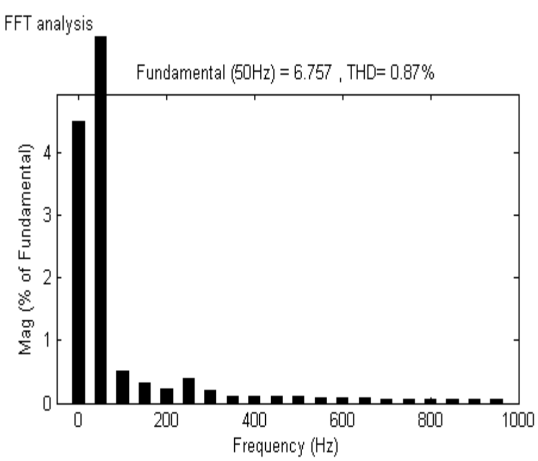


Fig. 9 Frequency Spectrum

IV EFFECTS OF MULTIPLE CHARGERS

In order to examine the effects of applying a multiplicity of chargers to the system, it was evident that the most pronounce effects would be measured where the system was weakest, i.e. at one of the points furthest from the 11kV/400V distribution transformer. Initially, using MATLAB/SIMULINK a single instance of each charger model was applied to the appropriate point in the system model, and the current harmonic distortion measured via FFT analysis at the input to the relevant bus in each case. Then a second, third and fouth example of an identical model of the charger was applied in parallel to the first, and in each case the THD was measured. In each case the THD was found to rise in proportion to the number of chargers applied at the bus. Then the effects of diversity were investigated. As will be seen the effects of diversity were well demonstrated with 4 chargers.

A PWM Charger

For the PWM based charger, the battery voltage, modulation index and converter phase angle were held constant, to give a constant charging current. Variation of converter frequency over a limited range does not affect the output current, and so a range of converter frequencies was examined between 9000Hz and 10000Hz and a value in the middle of the range was chosen for one charger. Then a second charger was applied, taking in turn the available frequencies, and the THD was measured for each in turn. It was found that a particular pair of converter frequencies gave the lowest THD, and this pair was then used as a fixed basis for examining the addition of a third charger, whose frequency was again varied to find the minimum value. This combination of three chargers was used as a basis for adding a fourth charger, whose frequency was varied as before. Fig. 10 shows the reduction in THD due to the mutual harmonic cancellation taking place.

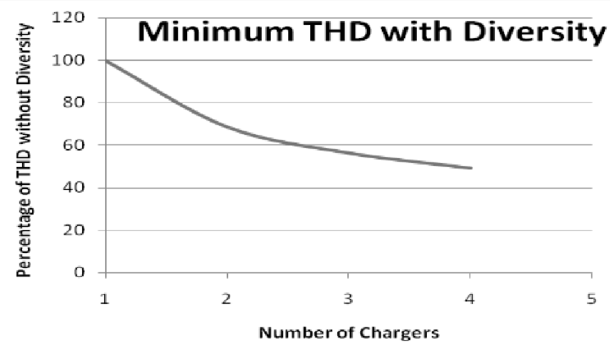


Fig. 10 THD for PWM chargers

B Square-wave Charger

In this charger, the battery voltage determines the duty cycle of the charger, and variation of the duty cycle alters THD and the phase angles of the various harmonics produced [3]. In order to simulate the effects of diversity, the battery voltage was varied between chargers, with the result that the duty cycle also varied. The same method was adpoted as before, with a mid range voltage used for the first charger, and experiments carried out to determine the minimum THD combinations of 2, 3 and 4 chargers. The results are given in Fig 11.

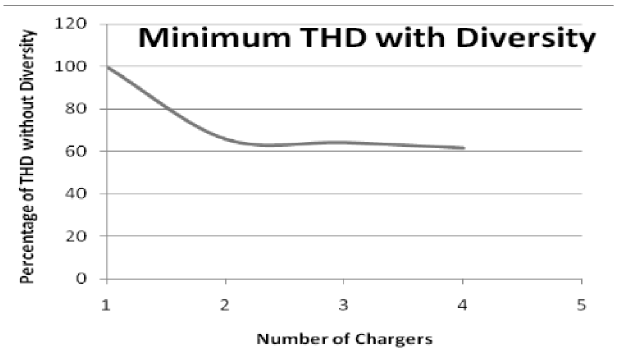


Fig. 11 THD for square-wave charger

C Basic single-phase Bridge Rectifier

In this charger, again the battery voltage determines the duty cycle of the charger, and variation of the duty cycle alters the THD and the phase angles of the various harmonics produced [3]. In order to simulate the effects of diversity, the battery voltage was again varied between chargers, with the result that the duty cycle also varied. The same method was adpoted as before, with a mid range voltage used for the first charger, and experiments, involving variation of the other battery voltages, were carried out to determine the minimum THD combinations of 2, 3 and 4 chargers. The results are given in Fig. 12.

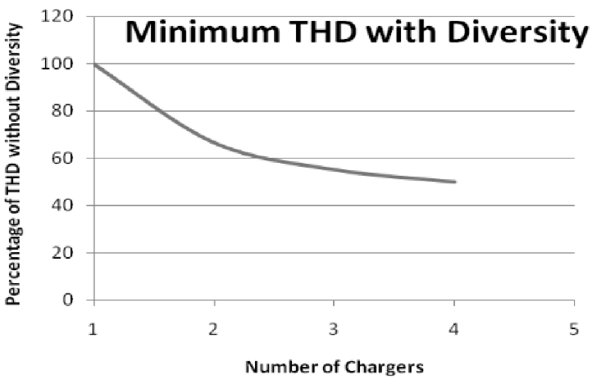


Fig. 12 THD for 1-ph bridge rectifier

D Three-Phase Bridge Rectifier

In this charger, once again the battery voltage determines the duty cycle of the charger, and variation of the duty cycle alters THD and the phase angles of the various harmonics produced [3]. In order to simulate the effects of diversity, the battery voltage was again varied between chargers, with the result that the duty cycle varied. The same method was adpoted as before, with a mid range voltage used for the first charger, and experiments carried out to vary the battery voltage in order to determine the minimum THD combinations of 2, 3 and 4 chargers. The results are given in Fig. 13.

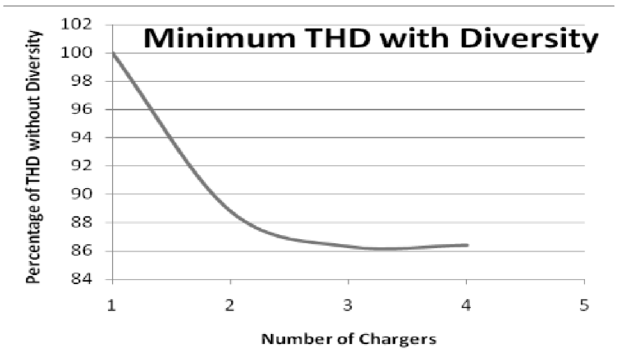


Fig. 13 THD for 3-ph bridge rectifier

V CANCELLATION OF HARMONICS

The Fourier series of a leading-edge PWM signal can be obtained as follows [7] :

$$F_{L(t)} = k + \frac{M}{2}\cos(\omega_s t) - \sum_{m=1}^{\infty}\left\{\frac{1}{m\pi}\sin(m\omega_c t) + \frac{J_0(m\pi M)}{m\pi}\sin(m\omega_c t + 2m\pi k)\right\}$$

$$+\sum_{m-1}^{\infty}\sum_{n=\pm 1}^{\pm\infty}\frac{J_n(m\pi M)}{m\pi}\sin\left(m\omega_c t + n\omega_s t + 2m\pi k + \frac{n\pi}{2}\right)$$

Where:

J_n = Bessel function of the first kind with integer order n .

k = zero-input duty-cycle of the pulsewidth modulated (PWM) signal.

m = carrier harmonic index.

M = modulation index ($0 \le M \le 1$) or equivalently, the value of the signal level normalized to the maximum signal level.

n = signal harmonic index.

ω_s = angular frequency of the modulating signal in rad/s.

ω_c = angular frequency of the carrier in rad/s.

It is thus feasible to establish a PWM operating regime which will produce any given harmonic at a pre determined amplitude and phase. This property can be used to reduce or remove unwanted harmonics from a system, and an EV charger could be configured to operate in such a way as to automatically minimise the THD of the supply to which it is connected, by operating to minimise the sum of selected harmonics.

VI CONCLUSIONS

The various types of EV charger in common use have been compared, and the effects of divesity in varying their harmonic contribution examined. It is clear that the PWM charger, in view of its flexibility, will be the charger of choice for EV operation where economics permit.

The results obtained show that if EV chargers are apprortaitely controlled, harmonic cancellation due to the effects of diversity can be achieved. This can be used as an effective means to reduce harmonic pollution due to EV chargers in future power distribution networks.

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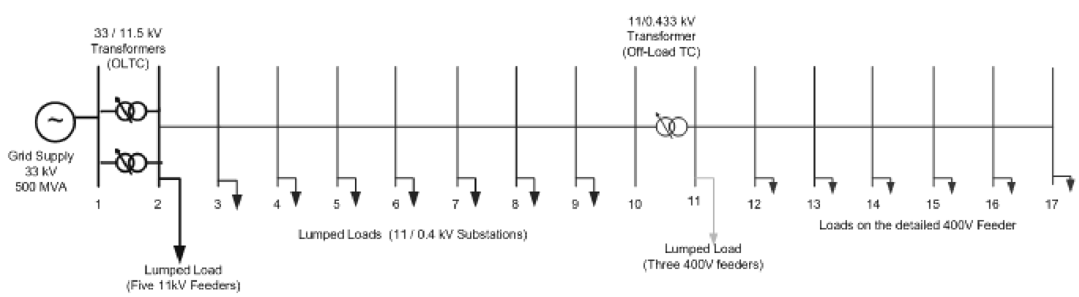
APPENDIX



Typical Distribution Network Model