

Design and Development of Three Phase Shunt Active Filter with Balanced and Unbalanced Supply

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Abstract

This paper presents a new and simple control strategy to determine reference compensation currents, under balanced and unbalanced source voltages which using the voltage source inverter for harmonic filtering of a three phase shunt active filter. The proposed control system is able to compensate the harmonics and reactive power of the non linear loads. The proposed approach is compared with a renowned shunt APF reference compensation strategy. The simulation of the system is done using MATLAB-SIMULINK and the results show that the proposed method is more effective than the existing one. In addition, the new approach demonstrates the substantial improvements in the filter performance during unbalanced supply and during load transients. The proposed control system is also very simple and robust. Moreover, it is very easy to implement this algorithm in a digital signal processor and testing results on an experimental shunt active power filter are presented to validate the proposed algorithm.

Keywords: Active Power Filter, Harmonics, Shunt Active Filter, Total Harmonic Distortion, Voltage Source Inverter.

Introduction

With the development of power electronics, the converters are widely used in the power supply devices and control application. These Non-linear loads draw currents that are non-sinusoidal and thus create voltage drops in distribution conductors. Typical non-linear loads based on solid-state converters are like UPS, SMPS etc.

Transformers and reactors may also (Sasaki et al., 1971; 1972) exhibit non-linear behavior in a power system during over voltage at saturated condition. Harmonics create many concerns for the utilities and customers alike. Typical phenomenons include neutral circuit overloading, metering inaccuracies and control system malfunction. This makes the authorities to impose standards for the power system (Duffey et al., 1989). In order to reduce the harmonics within the standards many methods for single phase (Costa-Castello et al., 2005; Kimihiko Sato et al., 2008) and three phase system have been produced. In three phase systems, series (Filipe Ferreira et al., 2009) and shunt active configurations are used.

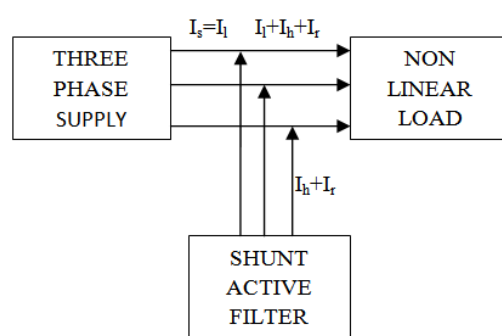


Figure 1: The Simple Shunt Active Filter

The objective is to achieve effective utilization of DC bus voltage and harmonic reduction in shunt active filter based system (Sasaki et al., 1971; 1972; Bhattacharya et al., 1995; Akagi, 1996; Singh et al., 1997; Akagi, 2006). In olden days magnetic Flux compensation method was used for harmonic compensation (Sasaki et al., 1971; Bhattacharya et al., 1995) and Transient Analysis were also performed (Sasaki et al., 1972). Nowadays active power filters are used for harmonic compensation (Bhattacharya et al., 1995; Saetio et al., 1995; Akagi, 1996; Gelan Zhu et al., 2009). PQ theory is one of the control techniques for APF that already exists (Akagi, 1996; Akagi, 2006) but has lot of disadvantages like the need to low pass filter to separate the average and oscillating parts of instantaneous powers. This factor introduces time delays and therefore, the dynamic performance of active filter is not guaranteed and demand more calculation, since they need the use of Clark transformation, and are not suitable for hardware implementation (Akagi, 2006). Apart from PQ theory there are other methods like sliding mode control method (Saetio et al., 1995; Singh et al., 1997; Gelan Zhu et al., 2009), Sinusoidal method, DQ theory etc., All these methods require various transformations like Park and Clark transformations. Various switching techniques also used for producing the pulses (Chelladurai et al., 2008). The intelligent techniques like neural networks (Vazquez et al., 2003), fuzzy logic control (Sharmeela et al., 2006) and genetic algorithms (Koteswara et al., 2009) also used for implementing the above said algorithms.

Initially this paper discusses the proposed control algorithm concepts, including the design of the power circuit and the controller. The design of the power circuit and

control circuit is also presented. The typical waveforms are given to demonstrate the operation of the active filter and support the discussion of its spectral performance. Hysteresis current controller was used to generate gate signals (Chelladurai et al., 2008). The simulations were carried out by MATLAB-SIMULINK.

Basic Configuration of Shunt Active Filter

One of the most popular active filters used for compensating reactive power and harmonics is the shunt active filter that is shown in figure 1. The simple shunt active filter arrangement with non-linear load is considered. The system comprises balanced three-phase voltage source feeding, a three-phase diode bridge rectifier with resistance and inductance load. The shunt active filter is connected to the three-phase line through the inductor (Ali Ajami et al., 2006; Fabio Carastro et al., 2008; Maurício Aredes et al., 2009; Bhim singh et al., 2009). Shunt Active Filter comprises of an IGBT based VSI, connected in parallel with the load. The VSI injects an appropriate current into the system to compensate for the undesired components of load current that are responsible for low power factor. The harmonic compensation performance of an active filter depends mainly on the technique used to compute the reference current, the design of inverter and the control method used to inject the desired compensation current into the line.

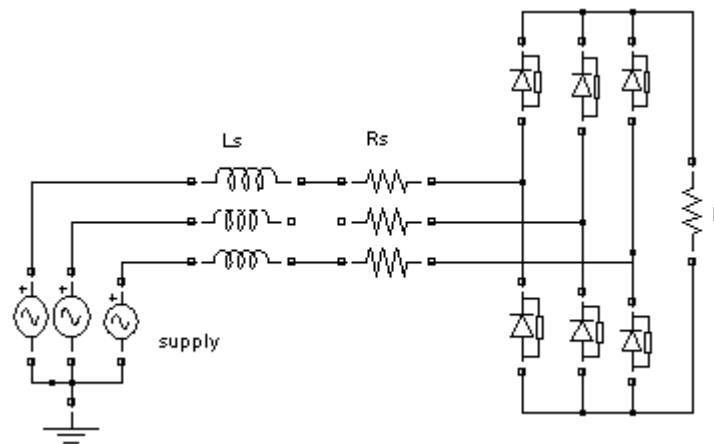


Figure 2: Basic Configuration of Shunt Active Filter

The DC side of the converter is connected to a capacitor, whose voltage can be raised or lowered by controlling the converter.

Proposed Control Method

The proposed control system of shunt active filter is concise, requires less computational efforts than many others found in the literature and is formed by a DC

voltage regulator and reference current calculation. In addition, Hysteresis controller is used for generating switching signals for SAF to force the desired current into the system. The compensating currents of active filter are calculated by sensing the load currents, DC bus voltage, and peak voltage of ac source. The Flow Chart for the proposed algorithm is shown below.

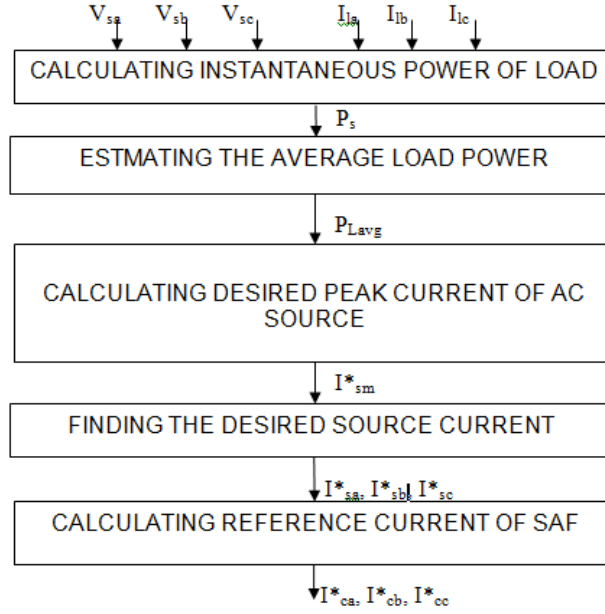


Figure 3: Flow Chart of the Proposed Algorithm

The instantaneous voltage of AC source is represented as;

$$\begin{aligned}
 V_{sa(t)} &= V_{sm} \times \sin(\omega t) \\
 V_{sb(t)} &= V_{sm} \times \sin(\omega t - 120) \\
 V_{sc(t)} &= V_{sm} \times \sin(\omega t - 240)
 \end{aligned} \tag{1}$$

The basic function of the proposed shunt active filter is to eliminate harmonics and compensate the reactive power of the load. After compensating, the AC source feeds the fundamental active power component of the load current and losses of the inverter for regulating the DC capacitor voltage. The peak of source reference current (I_{sm}^*) has two components. The first component corresponds to the average load active power (I_{smp}^*). The second component of AC source current (I_{smd}^*) is obtained from the DC capacitor voltage regulator. Instantaneous power of load (at K^{th} sample) is represented as;

$$P_{load}(k) = V_{sa(k)} I_{la(k)} + V_{sb(k)} I_{lb(k)} + V_{sc(k)} I_{lc(k)} \tag{2}$$

The average power of load (P_{Lavg}) is obtained by passing $P_{load}(k)$ to low pass filter. In order to compensate the current harmonics and reactive power of load the

average active power of AC source must be equal with P_{Lavg} . Considering the unity power factor for AC source side currents the average active power of AC source is represented as;

$$P_s = 3/2 V_{sm} I_{smp}^* = P_{Lavg} \quad (3)$$

From this equation the first component of AC side current is represented in equation 4 and named I_{smp}^*

$$I_{smp}^* = 2/3 P_{Lavg} / V_{sm} \quad (4)$$

The second component of AC source current (I_{smd}^*) is obtained from DC capacitor voltage regulator is represented as;

$$V_{cdc}^* = V_{dcref} - V_{cdc} \quad (5)$$

Capacitor is connected in APF for to give constant DC voltage to filter. DC capacitor design is represented as;

$$C = 2\Delta E / V_{ref}^2 - V_{min}^2 \quad (6)$$

Where

$$V_{ref} = V_{max} + V_{min}/2 \quad (7)$$

$$\Delta E = 1/2 C V_{ref}^2 - 1/2 \quad (8)$$

This (V_{cdc}^*) will be given to PI controller to obtain I_{smd}^* . The desired peak current of AC source is represented as;

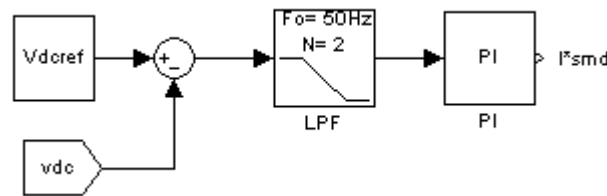


Figure 4: PI controller and low pass filter

$$I_{sm}^* = I_{smp}^* + I_{smd}^* \quad (9)$$

The AC source current must be sinusoidal and in phase with the source voltages. The desired currents of AC source can be calculated with multiplying peak source current to a unity sinusoidal signal that these unity signals are represented as;

$$\begin{aligned} U_a &= V_{sa} / V_{sm} \\ U_b &= V_{sb} / V_{sm} \\ U_c &= V_{sc} / V_{sm} \end{aligned} \quad (10)$$

The desired source side current is represented as;

$$\begin{aligned} I_{sa}^* &= I_{sm}^* \times U_a \\ I_{sb}^* &= I_{sm}^* \times U_b \\ I_{sc}^* &= I_{sm}^* \times U_c \end{aligned} \quad (11)$$

Then, the reference currents of AF can be obtained by subtracting the load current from the reference source current and it is shown as follows;

$$\begin{aligned} I_{ca}^* &= I_{sa}^* - I_{la} \\ I_{cb}^* &= I_{sb}^* - I_{lb} \\ I_{cc}^* &= I_{sc}^* - I_{lc} \end{aligned} \quad (12)$$

Switching Strategy of Converter

Hysteresis current control is a method of generating the required triggering pulses by comparing the error signal with that of the hysteresis band and it is used for controlling the voltage source inverter so that the output current is generated from the filter will follow the reference current waveform. This method controls the switches of the voltage source inverter asynchronously to ramp the current through the inductor up and down, so that it follows the reference current. Hysteresis current control is the easiest control method to implement in the real time.

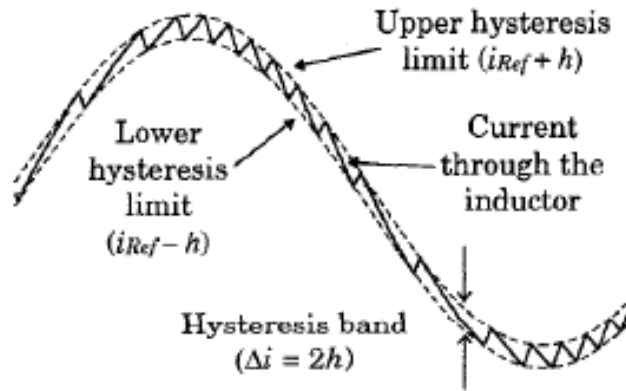


Figure 5: Hysteresis band

Hysteresis band is shown in Figure 5. If $I_{ca} < (I_{ca}^* - h_b)$ upper switch is OFF and lower switch is ON in first-leg.

If $I_{ca} > (I_{ca}^* + h_b)$ upper switch is ON and lower switch is OFF in the second-leg.

Similarly the switching logic of other two phases (b and c) of the SAF is formulated, using h_b the width of hysteresis band.

Simulation Results

In order to verify the results, the simulation is done in a MATLAB/SIMULINK environment. The model of proposed method is shown in Figure 6 and corresponding waveforms are obtained. The system parameters are given below. The System parameters are same as that of a renowned method (Ambrish Chandra et al., 2000) selected in order to compare the results. In this simulation nonlinear load considered is a 3-phase full uncontrolled rectifier with resistor and inductor.

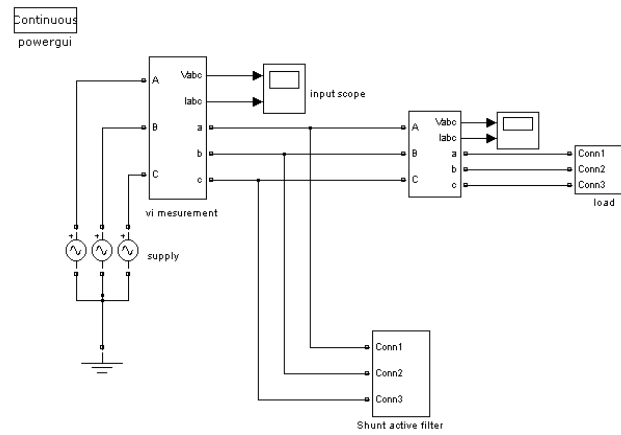


Figure 6: System with APF

Table 1: System Parameters

Supply Peak Voltage	56 V
Supply Frequency	50 Hz
V_{dc}	300 mF
L_f	3 mH
R_f	0.1 Ω
K_p, K_i	0.001, 0.1
R_s	0.25 Ω
L_s	2.5mH
R_l	10 Ω & 5 Ω
L_l	5 mH
Switching Frequency of Hysteresis controller	20 kHz

The various waveforms for the proposed method are shown in Figure 9 -15. Figure 8 shows ideal AC source voltage, while Figure 9 shows the load voltage and current waveforms and the frequency spectrum of the load current is shown in Figure 10. The THD of the source current which is the same as that of the load current when there is no compensation is, 20.75%, which is well above the IEEE 519 standards. In order to reduce the harmonic level in the system, within the IEEE 519 standard, the proposed algorithm based SAF is introduced in the system. Figure11 shows the

reference currents produced by the algorithm for the filtering purpose and the actual filter current is shown in the Figure 12. By injecting the required amount of current to the system the source current become sinusoidal as shown in Figure 13. With the proposed control algorithm the source current improves with the THD of 1.27% which is well within the standard. The frequency spectrum of the compensated source current is shown in Figure 15. In order to perform the above task the capacitor voltage should have to be maintained, and must be regulated by the algorithm. The proposed algorithm can properly regulate the capacitor voltage as shown in Figure 14.

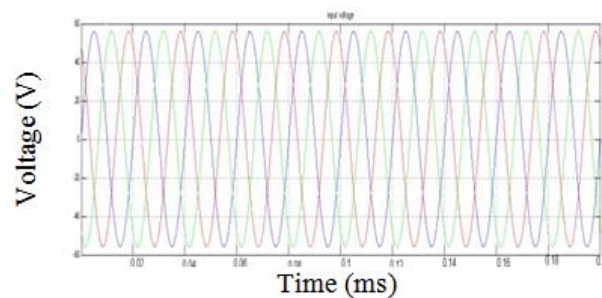


Figure 8: Source voltage waveform (a,b, c)

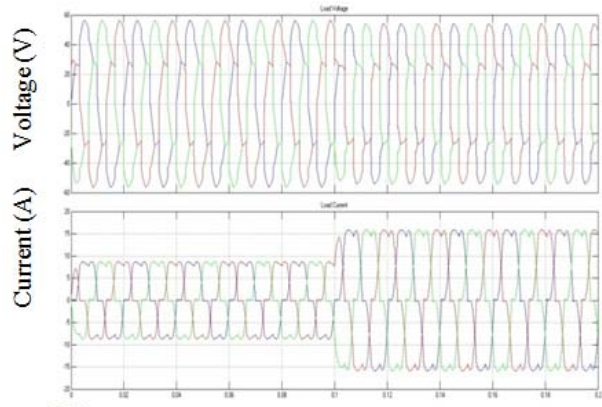


Figure 9: Load voltage and current waveform (a,b,c)

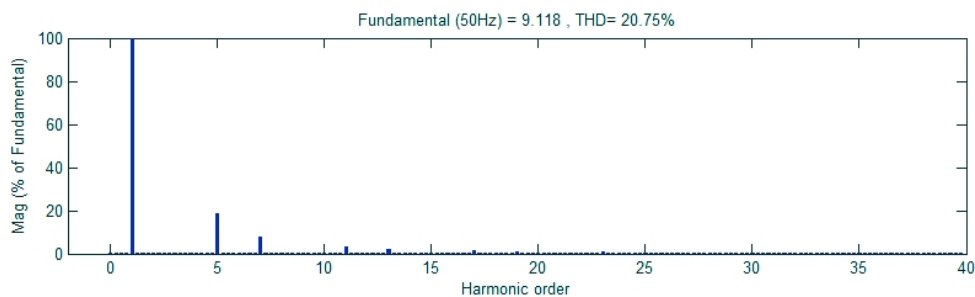


Figure 10: Frequency Spectrum of System without Filter

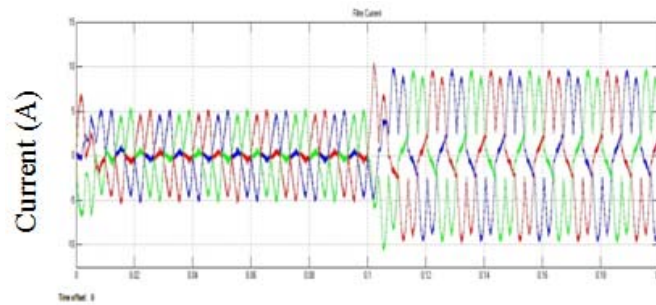


Figure 12: Filter current (a,b,c)

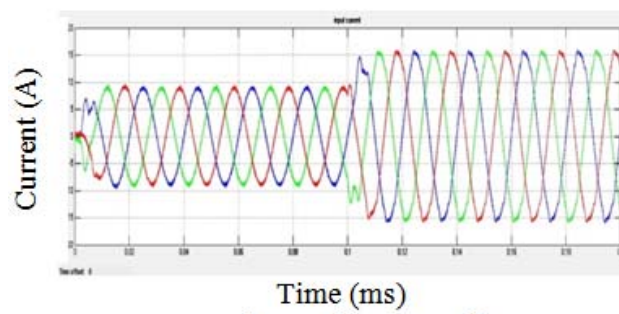


Figure 13: Source current with filter (a,b,c)

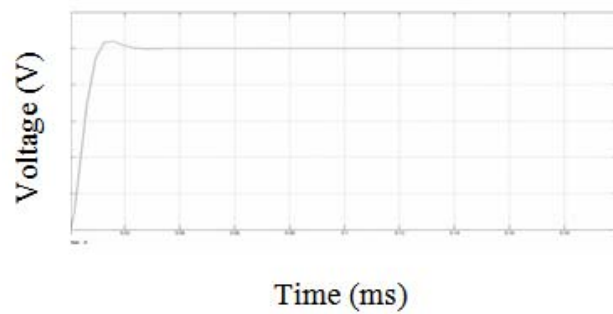


Figure 14: capacitor voltage waveform

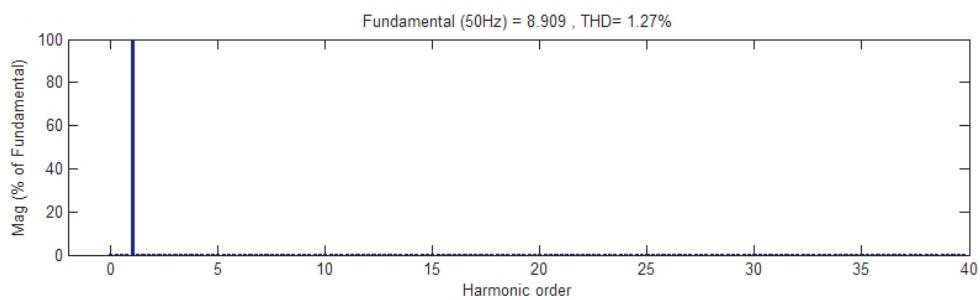


Figure 15: Frequency Spectrum of System with Filter

These results show that source always remains sinusoidal and lower than the load currents. It is evident from Figure 9 that even if the load resistor is been changed from $10\ \Omega$ to $5\ \Omega$ at 0.1msec, the proposed algorithm is capable of coping with the change in the load and the transient performance of the Active filter with the scheme is very good. In order to validate the performance of the proposed algorithm it is compared with an existing method (Ambrish Chandra et al., 2000). The THD of the existing method is 4.2% and the proposed method is only 1.27%.

The credibility of the proposed algorithm is checked by introducing another condition. A source voltage unbalance of 20% is introduced in the C phase. The source voltage is shown in Figure 16. The corresponding load voltage and load current waveforms are given below. The THD of the load current with this unbalance is 24.1%. The proposed algorithm is able to handle the unbalanced source voltage and still produces pure sinusoidal waveform.

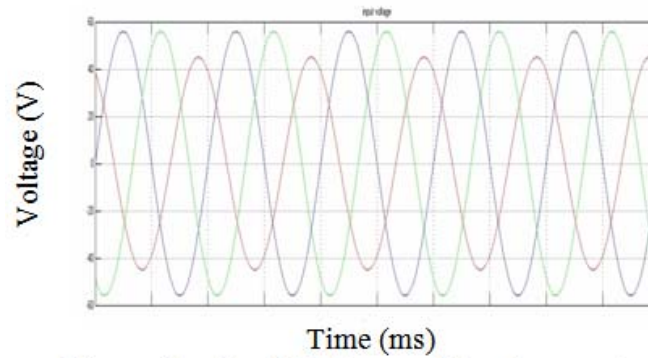


Figure 16: Source Voltage with 20% unbalance in the C phase

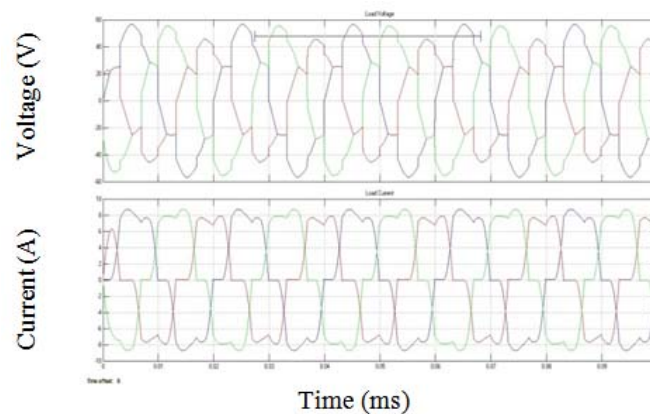


Figure 17: Load Voltage and Load current with 20% unbalance in the C phase

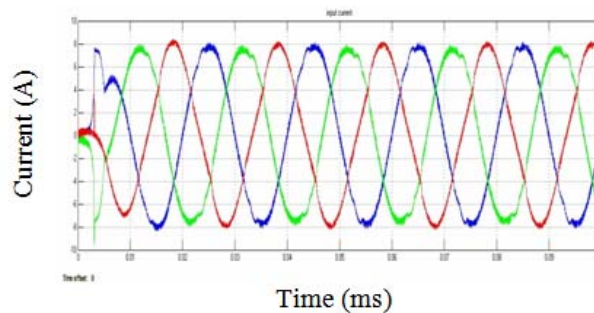


Figure 18: Source Current with 20% unbalance in the C phase

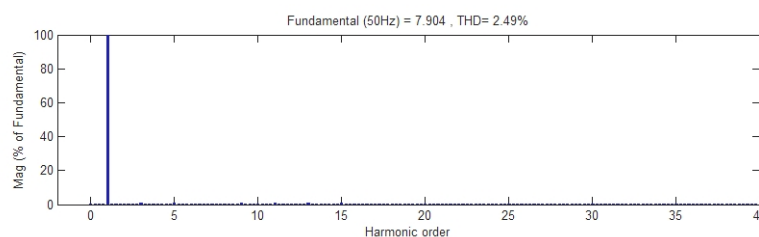


Figure 19: Frequency Spectrum of System With Filter with 20% unbalance in the C phase

It is observed that the THD of the given system reduces from 24.1% to 2.49%. It can also be observed from the harmonic spectrum of currents that, the proposed algorithm is effective to meet IEEE519 standard recommendations on harmonic level in both ideal voltage source and unbalanced voltage source conditions, as well as during load variation conditions. The proposed algorithm also compensates the reactive power requirements of the load and it improves the power factor of the system.

Experimental Verifications

An experimental system is constructed in order to demonstrate the operation of the proposed algorithm. Figure 20 shows the configuration of the experimental system. The objectives are to show that the proposed algorithm has better performance than the conventional algorithm (Ambrish Chandra et al., 2000) and can be implemented well in real time. A 2 kVA SAPF is developed for a three phase full bridge six pulse rectifier with a resistive load. The current detection algorithm proposed in this paper is adopted in the SAPF and complemented by DSP – TMS320LF2407 by which the precision of the calculations can be ensured. The supply voltages (V_{sa} , V_{sb} , V_{sc}) and load currents (I_{la} , I_{lb} , I_{lc}) are sensed using LEM sensors and given to the DSP through the inbuilt 10 bit A/D converter with the sampling frequency of 6.4 kHz with 128 samples per cycle. The computed reference compensating current components for the three phases are obtained at the inbuilt D/A converters output.

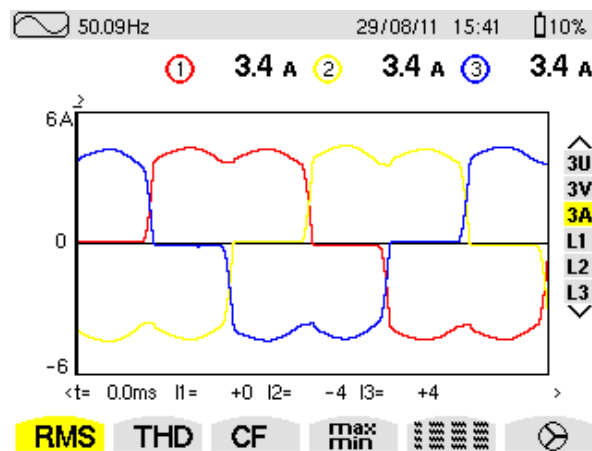


Figure 22: Experimental waveforms of 3 phase Source current

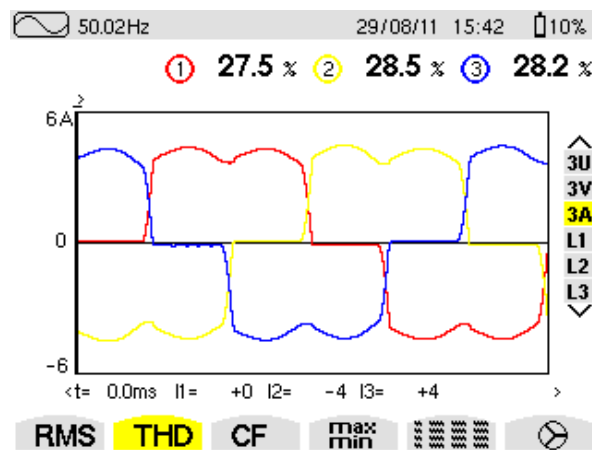


Figure 23: %THD of 3 phase Source current

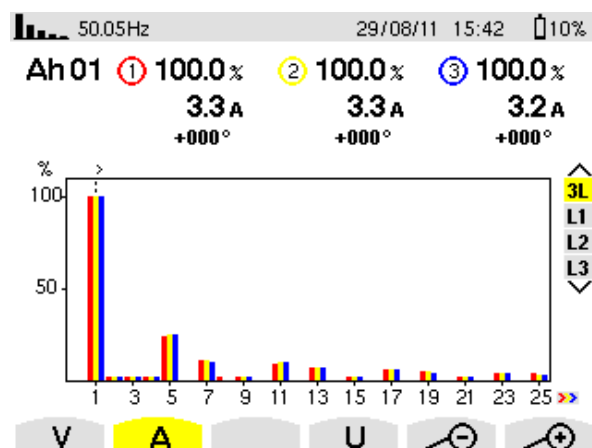


Figure 24: Frequency spectrum of the source current before compensation

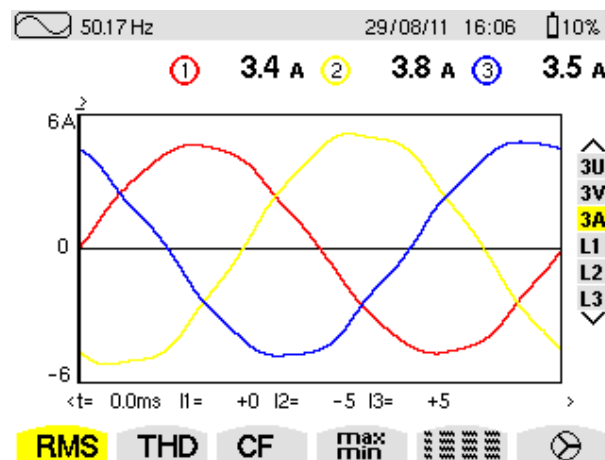


Figure 25: Experimental waveforms of 3 phase Source current after compensation

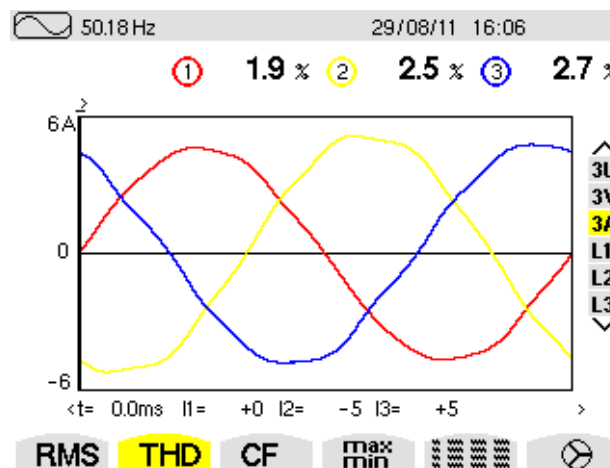


Figure 26: %THD of 3 phase Source current after compensation

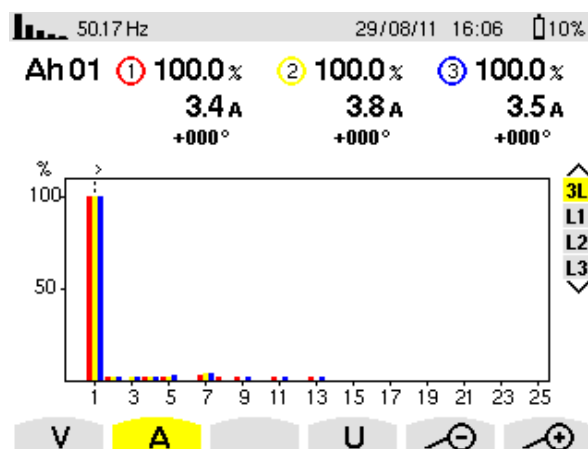


Figure 27: Frequency spectrum of source current after compensation

From the results shown in figures 21-27, it is clear that the 3 phase source current waveforms are nearly sinusoidal and the steady state performance of the SAF adopting the proposed algorithm is perfect. There is some deviation in the waveforms of the compensated load currents which are due to certain practical limitations such as the unbalance in the supply voltage itself and it is not because of the proposed scheme and the unbalance produced in the results also with the prescribed limit.

Conclusions

This paper demonstrates the validation of the proposed method for a parallel active filter application. From the simulation and analysis, it is evident that the proposed control system requires less number of equations, since it does not use any transformation, such as Park or Clark transformation. It is very flexible, rapid, and accurate also it is very suitable for hardware implementation. On this basis, a 2 kVA SAPF is developed using DSP TMS320F2407 and the results from simulation and hardware are compared. From the results it is found that the proposed control system is capable of reducing the harmonics to the limits of IEEE 519 in steady state, as well as in the transient period. This control algorithm works well when there is an unbalance in the supply, and it also compensates the reactive power requirements and also improves the power factor.

List of Symbols/Abbreviations

V_{sa}, V_{sb}, V_{sc}	– Source Voltages in Volts
I_{sa}, I_{sb}, I_{sc}	– Source Currents in Amps
I_{la}, I_{lb}, I_{lc}	– Load Currents in Amps
P_s	– Instantaneous Power
P_{Lavg}	– Average Load Power
I_{sm}^*	– Desired Peak Current of the source in Amps.
I_{smd}^*	– DC component of the Desired Peak Current in Amps.
I_{smp}^*	– AC component of the Desired Peak Current in Amps.
$I_{sa}^*, I_{sb}^*, I_{sc}^*$	– Desired Source Current in Amps
$I_{ca}^*, I_{cb}^*, I_{cc}^*$	– Reference Current in Amps
h_b	– Hysteresis band
V_{sm}	– Maximum Value of the Source Voltage in Volts
V_{cdc}	– Voltage across the Capacitor in Volts
V_{dcref}	– DC Reference Voltage in Volts
V_{cdc}^*	– Error Voltage between the reference and actual capacitor voltage in Volts
VSI	– Voltage Source Inverter

IGBT	– Insulated Gate Bipolar Transistor
SAF	– Shunt Active Filter
THD	– Total Harmonic Distortion

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