Simulation and Experimental Verification of Transformationless Control of Series Active Filter for Mitigating Load Voltage Harmonics

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Abstract—**This paper presents the performance analysis of Series Active Filter (SeAF) employing a transformation less control approach based on Sinusoidal Pulse Width Modulation (SPWM) switching. The percentage total harmonic distortion of the compensated load voltage has been considered as a measure for assessing the performance. The results obtained in MATLAB simulation and laboratory experimentation confirm that the performance of SeAF with transformation less control is successful in maintaining the load voltage harmonics within the limits recommended by IEEE-519 standards.**

Keywords- *Power Quality, Voltage Quality, Series Active Filter (SeAF), Voltage Source Inverter (VSI), Sinusoidal Pulse Width Modulation (SPWM), MATLAB/Simulink, TMS320LF2407A DSP Controller.*

NOMENCLATURE

- V_s Supply voltage / phase, V
- V_{inj} Injected voltage from SeAF / phase, V
- V_L Load terminal voltage / phase, V
- V_{pcc} Voltage at PCC / phase, V
- Z_L Line impedance/phase (R_L+jX_L), Ω
- R_L Line resistance, Ω
- X_L Line reactance, Ω
- L_f Filter inductance, mH
- C_f Filter capacitance, μF

I. INTRODUCTION

POWER quality in the distribution system becomes a critical issue because of the tremendous increase in the use of non linear loads. The poor power quality has a significant influence on the functioning of sophisticated sensitive equipment. Power quality problems include voltage sag, swell, unbalance, transient, interruption and distortion in the sinusoidal waveform. The harmonics present in the current drawn by the non linear loads from the sinusoidal supply results in distortion in the voltage at the Point of Common Coupling (PCC). Both distorted voltage and current may lead to failure or maloperation of sensitive loads connected at the common coupling point [1, 2].

Traditionally, passive filters are used to eliminate harmonics generated by large industrial loads due to their simplicity, low cost and high efficiency. The supply impedance strongly influences the compensation characteristics of the passive filters and they are highly susceptible to series and parallel resonance with the supply. Moreover, passive filters can eliminate the harmonics very selectively. With the vast development in the field of power electronics, active filters are introduced as custom power devices for mitigating the power quality problems. Shunt Active Filters are usually employed for current harmonic elimination and Series Active Filters are employed for voltage harmonic elimination [3-5].

II. SERIES ACTIVE FILTER

A. Principle of Operation

The Series Active Filter (SeAF) shown in Fig. 1 is a voltage controlled Voltage Source Inverter (VSI), which is connected in series with the load. It is controlled in such a way to inject a voltage, which is in phase opposition to the harmonic component of the non-sinusoidal voltage and thereby making the load voltage sinusoidal. Thus the voltage distortion problem at the point of common coupling could be avoided.

A three phase SeAF typically consists of three single phase voltage source inverters or a single three phase voltage source inverter as shown in Fig. 1. All the three inverters are connected to a common dc storage capacitor. Each VSI is connected to the distribution system through an injection transformer and required filters to eliminate high frequency switching components [6-8].

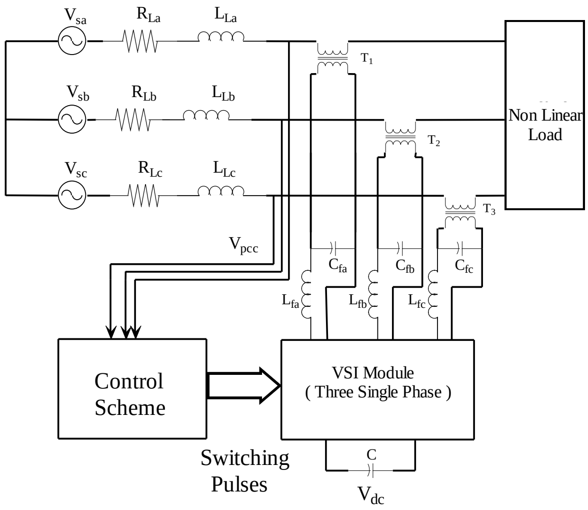

Fig. 1 Schematic diagram of SeAF

Several control methods such as instantaneous active and reactive power method or so called *'p-q' method, 'id-iq' method*, etc., [9] were proposed in the literature for elimination of voltage harmonics using series active filters. Different switching schemes for VSI like Sinusoidal Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM), hysteresis PWM, etc., were also attempted in the literature [10-11].

In this paper an attempt is made to analyze the performance of SeAF employing a transformation less control approach [12] based on SPWM switching for VSI. The effectiveness of SeAF with this control approach in mitigating the voltage harmonics is verified by MATLAB simulation and laboratory experimentation and the results are discussed.

B. Compensation Technique

The objective of the compensation technique is to guarantee balanced and sinusoidal voltage at the load terminals. The control algorithm derives the reference of the compensation voltage to be injected by the series active filter. Different approaches involved in deriving the reference of the compensation voltage from the measured distorted quantities can be grouped into two classes: frequency-domain approach and time-domain approach.

The frequency-domain approach implies the use of the Fourier Transform and its analysis, which leads to huge amount of calculations and thus making the control approach complex. In the time-domain approach, the traditional concepts of circuit analysis and algebraic transformations associated with changing of reference frames like instantaneous p-q theory, synchronous d-q reference frame theory, etc., are used. Sometimes, suitable analog or digital filters are employed for separating the successive harmonic components, which simplifies the control task.

The choice of the control algorithm therefore decides the accuracy and response time of the series active filter. The calculation steps involved in the control technique have to be minimal to obtain faster response.

C. Transformationless Control Approach

As discussed already, the objective of SeAF is to maintain the load terminal voltage sinusoidal at fundamental frequency and desired fixed magnitude. The control approach employed in the present study is the time domain-transformation less scheme based on unit vector template generation.

Initially, the supply voltage (assuming a pure sinusoidal source) is sensed and divided by V_{sm}, where V_{sm} represents the peak value of supply voltage under consideration. This gives a unity source voltage profile.

$$v_s = V_{sm}\, sin(\ \ t) \qquad (1)$$

$$u = sin(\omega t) \qquad (2)$$

For a given load, the desired load voltage is a fixed quantity. Let V_{Lm} represents the peak amplitude of desired load voltage. The unit vector template is multiplied with V_{Lm} to generate the profile of the desired load voltage.

$$v_{Ldes} = V_{Lm}\, x\, u = V_{Lm} sin(wt) \qquad (3)$$

The reference load voltage is compared with actual load voltage to derive the reference wave for carrying out the sinusoidal pulse width modulation switching of VSI to generate the compensation voltage to be injected by SeAF.

D. SPWM Switching

In this type of switching the triangular carrier wave (V_c) is compared with a sinusoidal reference wave (V_r) of desired frequency and the relative level of the two waves is used to produce the switching pulses for the devices in each phase of the inverter .

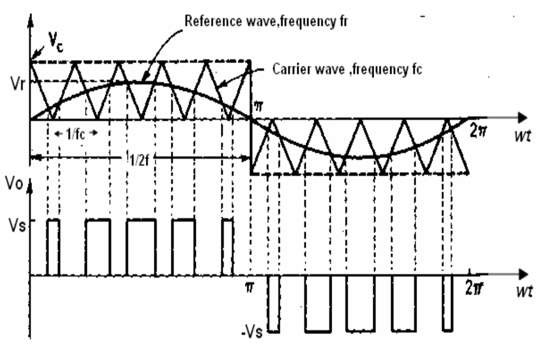

Fig. 2 Sinusoidal pulse width modulation

As shown in Fig.2, the switching pulses are determined as follows:

$$\text{If } V_r > V_c \qquad V_o = \text{High} \qquad (4)$$
$$V_r < V_c \qquad V_o = \text{Low} \qquad (5)$$

Number of pulses per half cycle is

$$N = f_c/2f \qquad (6)$$

The ratio of V_r/V_c is called Modulation Index (MI) and it controls the harmonic content of the output voltage waveform. The magnitude of fundamental component of output voltage is proportional to MI thus the output voltage is controlled by varying MI.

For MI less than one, largest harmonic amplitudes in the output voltage are associated with harmonics of order $f_c / f \pm 1$ or $2N \pm 1$, where N is the number of pulses per half cycle. Thus, by increasing number of pulses per half cycle, the order of dominant harmonic frequency can be raised, which can then be filtered out easily.

It is clear that as *N* is increased, the order of significant harmonic increases and the filtering requirements are accordingly minimized. But higher value of *N* entitles higher switching frequency of IGBT. This amounts to more switching losses and therefore impaired inverter efficiency. Thus a compromise between the filtering requirements and the switching requirements has to be arrived to decide the value of *N*. In the present work, 10 kHz is selected as the frequency of carrier wave.

III. SIMULATION OF SERIES ACTIVE FILTER

A simulation study for the analysis of performance of SeAF with the transformation less control approach is carried out using MATLAB/SIMULINK. The simulink model of the considered system shown in Fig. 1 is presented in Fig. 3. The system parameters are furnished in Table I. The results of simulation study are presented in Fig. 8(a) - Fig. 12(a) and discussed in Section V.

TABLE 1 SYSTEM PARAMETERS

Details	Parameters/ Phase	Data
Source	Input r.m.s. supply Phase-Neutral (*Vs*)	75 V, 50Hz
Line	Resistance (R_L), Inductance (L_L)	20 Ω, 1 mH
Load	R Load with diode bridge rectifier. Resistance of the load	65 Ω
Series Injection transformer	Three single phase transformers	1.5 kVA, 75 / 75V
Voltage Source Inverter	DC link Voltage (V_{dc}) Filter inductor (L_f) Filter Capacitance(C_f)	75 V 1mH 20 µF

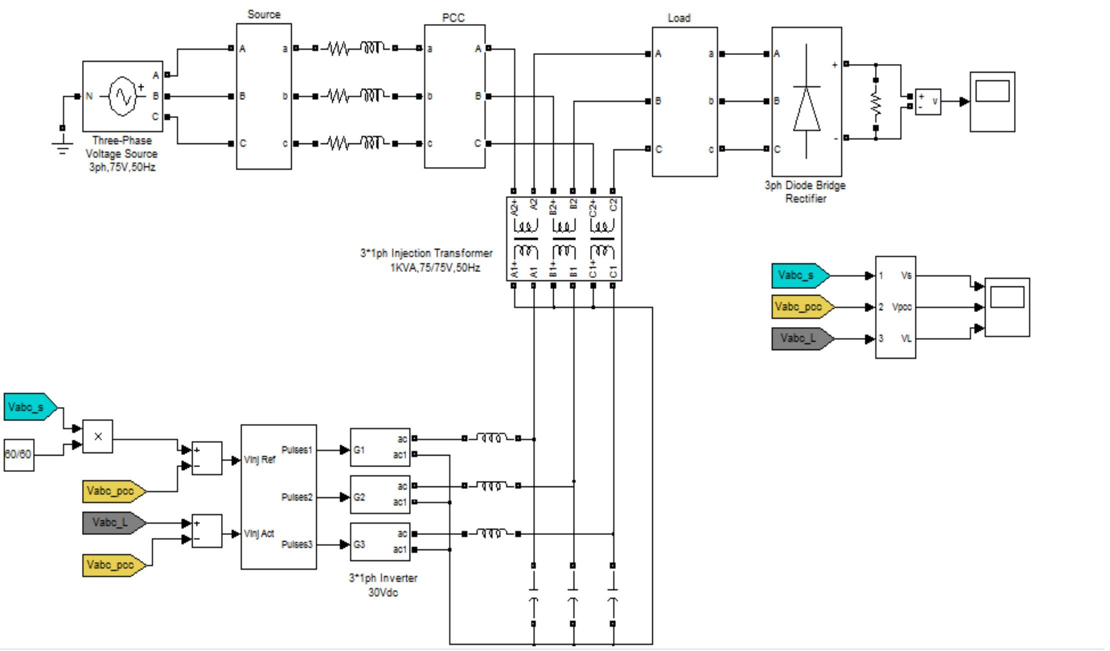

Fig. 3. SIMULINK model of the distribution network with Series Active Filter

IV. HARDWARE IMPLEMENTATION

A. Control Algorithm Implementation

The digital implementation of control algorithm discussed in section II has been carried out using TMS320LF 2407 EVM DSP controller. The flow of data and computation in the DSP controller is presented in Fig. 4. SPWM pulses are generated and taken out though the PWM pins available in the LF 2407 DSP EVM board.

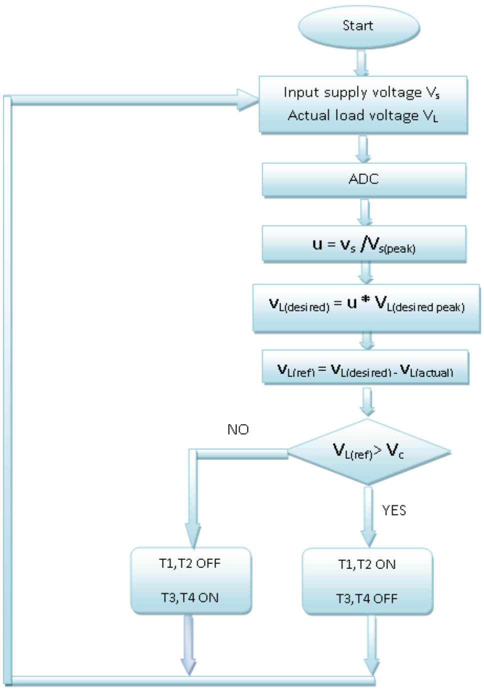

Fig. 4 Digital implementation in TMS320LF 2407A

The input supply voltage and actual load voltage are sensed using voltage sensors. LV 20 hall effect sensors as shown in Fig. 5 are used for sensing the voltage. These voltage sensors located at various points of power circuit step down the level of voltages to a value which is within the maximum input voltage limit specified for the DSP board (i.e. 0-3.3 V). This is achieved by suitable design of primary and secondary resistances while maintaining the current levels in primary and secondary within the specified limits.

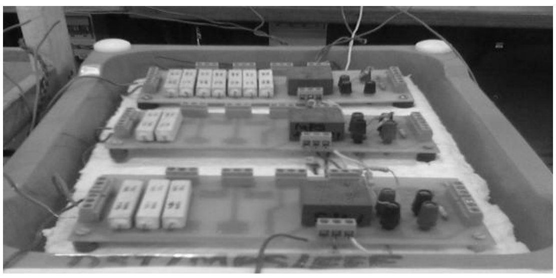

Fig 5. Photograph of voltage sensor circuit fabricated in the laboratory

The outputs of the voltage sensors with required offset are fed to the Analog to Digital Convertor channels available in the EVM board. The digital equivalent of sensed supply voltage is divided by its peak value inside the DSP using assembly language instructions to generate unit vector template. This is then multiplied with peak value of desired load voltage to obtain the digital equivalent of the desired load voltage profile. The digital equivalent of actual sensed load voltage is compared with digital equivalent of desired load voltage to generate the reference wave for SPWM operation. The associated SPWM pulses are obtained at the (T1-T3) PWM pins of the DSP EVM board.

The amplitude of SPWM pulses generated from the DSP controller will usually be 3.3V. Gate pulses at this voltage level is insufficient to trigger IGBT switches in the SEMIKRON built voltage source inverters used in the experimental setup; which requires gates pulse at 15V. Moreover the SPWM pulses generated using DSP (T1-T3) have to be inverted to get the pulses for other IGBTs in the respective legs of the inverter. A transistor amplifier circuit shown in Fig. 6 has been designed and fabricated to realise this operation.

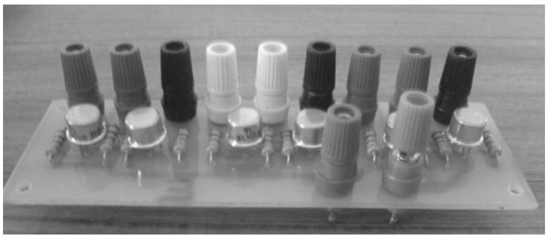

Fig. 6 Photograph of transistor amplifier circuit

The complete hardware setup for the implementation of the considered distribution network along with SeAF is shown in Fig. 7. The experimental results are presented in Fig. 8(b) - Fig. 12(b) and discussed in Section V.

V. SIMULATION AND EXPERIMENTAL RESULTS

The distribution network is supplied with a source voltage of 75 V. The simulated and experimental waveforms of the source voltage are shown in Figs. 8(a) and 8(b). The three phase rectifier fed R load draws a non sinusoidal current from the source resulting in a non sinusoidal voltage drop across the line resistance and inductance. This makes the load voltage also non sinusoidal as shown in Figs. 9(a) and 9(b). The harmonic spectrum of the load voltage before compensation is shown in Figs. 10(a) and 10(b). It is observed that the THD of load voltage is 11.60% in simulation and 12.2% in experimental study. When the SeAF is connected in the circuit, the load voltage improves as shown in Figs. 11(a) and 11(b). The injected compensation voltage makes the load voltage sinusoidal and harmonic free.

The harmonic spectrum of the load voltage after compensation obtained from simulation and experimentation are shown in Figs. 12(a) and 12(b) respectively. The THD of the load voltage has improved from 11.60% to 4.52% in simulation and 12.2% to 4.6% in hardware, which is within the limit recommended by IEEE 519 standards. The consequent improvement in the source current waveform before and after compensation can be observed from Fig. 13(a) and 13(b).

VI. CONCLUSION

The simulation and laboratory implementation of three phase series active filter have been carried out in the present work. A transformation less voltage control based on SPWM switching is employed to control the voltage source inverter of SeAF for harmonic elimination in load voltage. TMS320LF2407A DSP controller is utilized in the laboratory to implement the control approach and generate the firing pulses of SeAF. The MATLAB simulation result shows that the performance of SeAF is satisfactory in elimination of load voltage harmonics. The experimental result also confirms the simulation findings. The performance of SeAF with transformation less control is found to be successful in meeting out the standard IEEE-519 recommendations on harmonic levels in load voltage.

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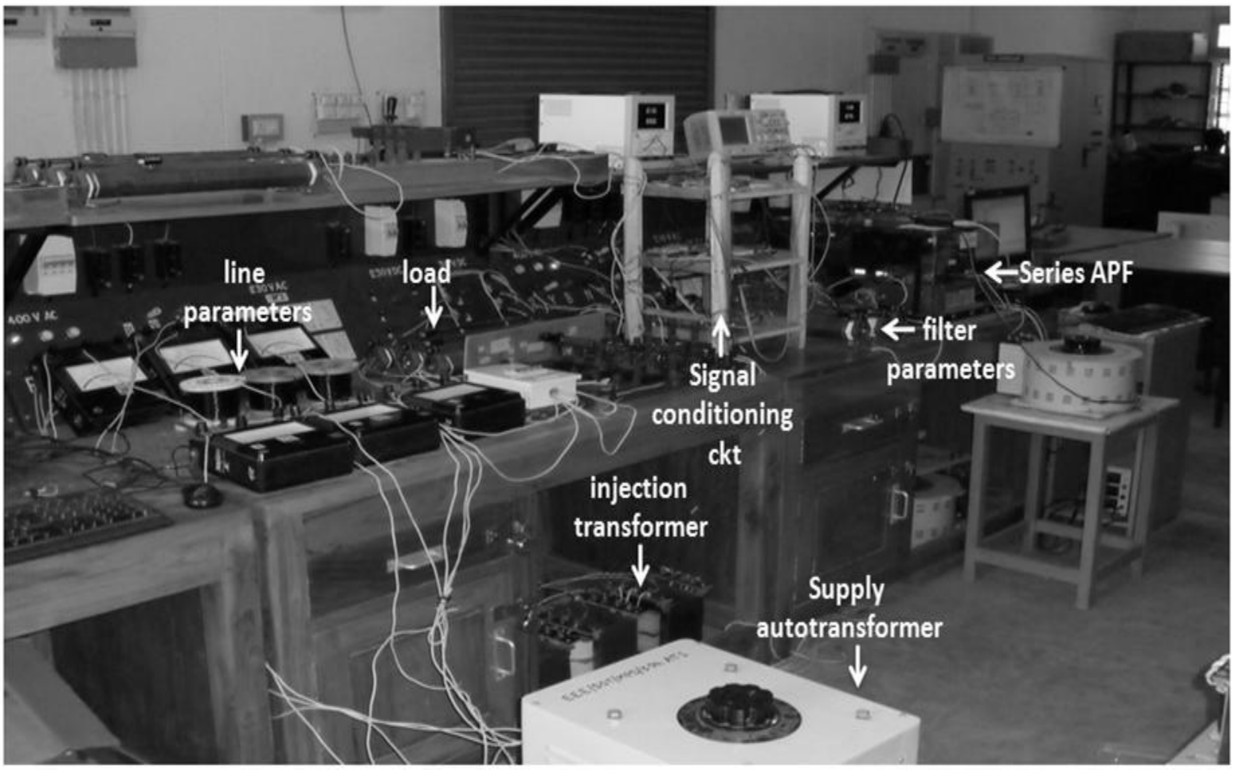

Fig. 7 Photograph of complete hardware setup for experimental verification of SeAF

SIMULATION RESULTS | **EXPERIMENTAL RESULTS**

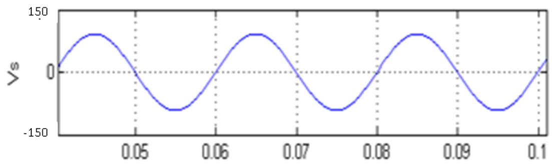

Fig.8(a) Source voltage, V_s (V)

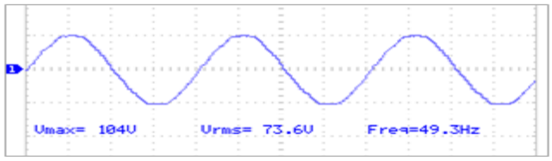

Fig. 8(b) Source voltage, V_s (V)

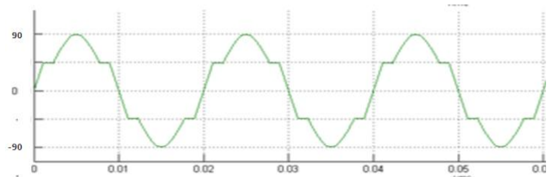

Fig.9(a) Load voltage before compensation ,V_L (V)

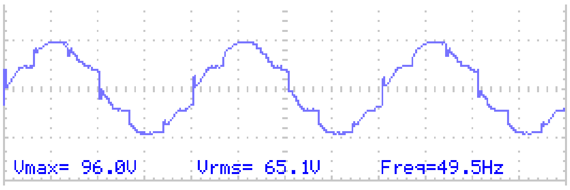

Fig.9(b) Load voltage before compensation ,V_L (V)

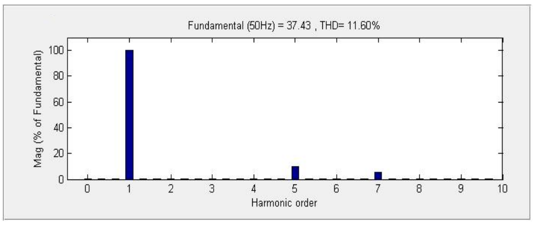

Fig.10(a) Harmonic spectrum of Load voltage before compensation

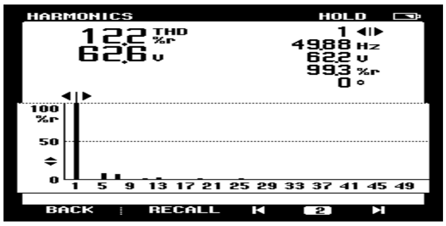

Fig 10(b) Harmonic spectrum of Load voltage before compensation

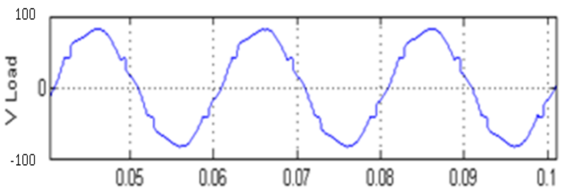

Fig.11(a) Load voltage after compensation ,V_L (V)

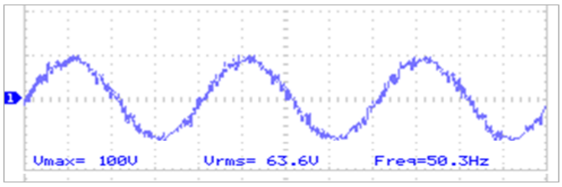

Fig.11(b) Load voltage after compensation ,V_L (V)

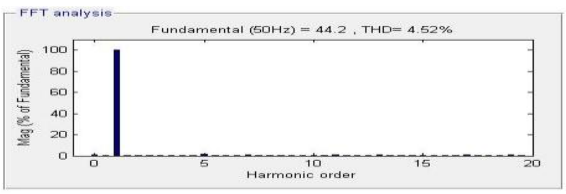

Fig.12 (a) Harmonic spectrum of Load voltage after compensation

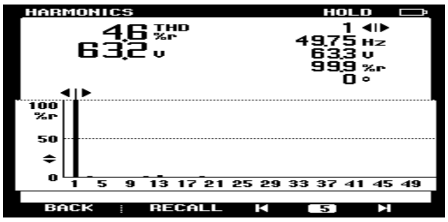

Fig.12 (b) Harmonic spectrum of Load voltage after compensation

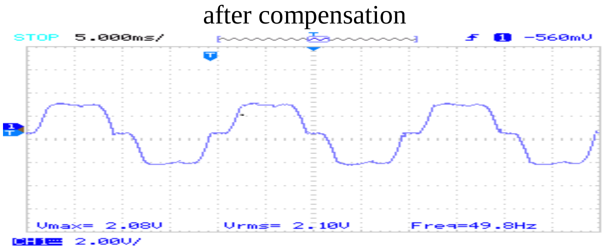

Fig.13 (a) Source Current before compensation

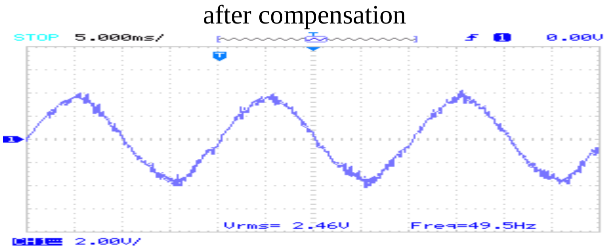

Fig.13 (b) Source Current after compensation