Mitigation of Harmonics in Distribution System using Shunt Active Power Filter by Fuzzy Logic Controller

Mrs.B.Kiruthiga[1] Dr.Narmatha Banu[2] Dinesh Kumar G[3] Ashok Kumar J.A[4] Ajay Lal S.H[5]
[1]Assistant Professor [2]Professor [3,4,5]UG Student
[1,2,3,4,5]Department of Electrical & Electronics Engineering
[1,2,3,4,5]Velammal College of Engineering and Technology, Madurai, India

Abstract— Three-phase, four-wire systems are prone to various power quality (PQ) problems such as load unbalancing, low power factor, harmonics and problem of neutral current. A distribution system using Shunt Active Power Filter with thyristor controlled rectifier using Fuzzy Logic is proposed to mitigate various PQ problems in four-wire distribution systems. The mitigation of power quality issues is quite complex, so it is modified to obtain various control technique. Fuzzy logic provides a simple way to arrive at a definite conclusion based upon vague, ambiguous and missing input information. The proposed algorithm is developed using MATLAB/Simulink environment and tested for mitigation of various PQ problems. Thereafter, a hardware prototype for shunt active power filter (SAPF) is developed along with various sensors, control circuits using space digital signal processor. Gating circuits provide proper gating pulses to control SAPF as per the algorithm. Results with linear and non-linear loads have been tested under a variety of loading conditions and thoroughly analysed for its performance.

Key words: Shunt Active Power Filter, Fuzzy Logic Controller, Harmonics

I. Introduction

Now a day's power electronic based equipment is used in industrial and domestic purposes. This equipment has significant impact on the quality of supplied voltage and they increased the harmonic current pollution of the distribution system. They have many negative effects on power system equipment and customer, such as additional losses in overhead lines and underground cables, transformers and rotating electric machines, problem in the operation of the protection systems, over voltage and shunt capacitor, error of measuring instruments, and many function of low efficiency of customer sensitive loads. Passive filter have been used traditionally for mitigating the distortion due to harmonic current in industrial power systems. But they have many drawbacks such as resonance problem, dependency of their performance on the system impedance, absorption of harmonic current of nonlinear load, which could lead to further harmonic propagation through the power system.

In this work, a new combination of a shunt hybrid power filter (SHPF) and a TCR (SHPF-TCR compensator) is proposed to suppress current harmonics and compensate the reactive power generated from the load. The hybrid filter consists of a series connection of a small-rated active filter and a fifth-tuned *LC* passive filter. In the proposed topology, the major part of the compensation is supported by the passive filter and the TCR while the APF is meant to improve the filtering characteristics and damps the resonance, which can occur between the passive filter, the TCR, and the source impedance. The shunt APF when used alone suffers from the high kilovolt ampere rating of the inverter, which requires a lot of energy stored at high dc-link voltage. On the other hand, as published by some authors, the standard hybrid power filter is unable to compensate the reactive power because of the behaviour of the passive filter. Hence, the proposed combination of SHPF and TCR compensates for unwanted reactive power and harmonic currents. In addition, it reduces significantly the volt-ampere rating of the APF part. The control method of the combined compensator is presented. A control technique is proposed to improve the dynamic response and decrease the steady-state error of the TCR. It consists of a PI controller and a lookup table to extract the required firing angle to compensate a reactive power consumed by the load. A nonlinear control of SHPF is developed for current tracking and voltage regulation purposes. It is based on a decoupled control strategy, which considers that the controlled system may be divided into an inner fast loop and an outer slow one. The currents injected by the SHPF are controlled in the synchronous orthogonal *dq* frame using a decoupled feedback linearization control method. The dc bus voltage is regulated using an output feedback linearization control. The SHPF can maintain the low level of dc bus voltage at a stable value below 50 V. The proposed nonlinear control scheme has been simulated and validated experimentally to compute the performance of the proposed SHPF-TCR compensator with harmonic and reactive power compensation and analysis through the total harmonic distortion (THD) of the source and the load current. The proposed methodology is tested for a wide range of loads as discussed further. Simulation and experimental results show that the proposed topology is suitable for harmonic suppression and reactive compensation.

The presence of harmonics up to 19th order, poor power factor, phase unbalancing, voltage regulation and large neutral current etc. are some of the prevalent power quality (PQ) issues in three-phase, four-wire distribution systems. In the presence of inductive load, the power factor of system may be very poor. This may lead to high loading of lines in comparison to the case when power factor is close to unity. Harmonics problem is related largely due to the presence of non-linear loads in our distribution systems. Harmonic currents flowing through the distribution lines lead to distorted voltage at user terminals. Moreover, neutral cable may get excessively loaded, at times due to the condition of phase unbalancing.

Mitigation of above-mentioned PQ problems requires designing and installing a compensator for improved performance. Harmonics in three-phase, four-wire systems may be eliminated with the help of passive filters. However, passive filters have their own limitations and active filters are getting popular due to their lower size, faster response and ability to generate/absorb reactive volts ampere reactive (VARs). In, different configurations of distributed static compensator (DSTATCOM) are explained. The performance of DSTATCOM has been shown for different systems and different types of load. It is also cost effective. In, dual DSTATCOM topology is discussed using simple control algorithm. In, unified power quality compensator (UPQC) is installed in distribution system to mitigate PQ problems. It works satisfactorily but installing UPQC is not financially feasible.

It uses zigzag transformer in three-phase, four-wire system mainly. Zigzag transformer can be used to compensate for neutral current which flows when unbalanced load or fault in the system is present. Zigzag transformer is an effective and low-cost solution to limit neutral current in distribution system. It presents the suppression of neutral current in three-phase, four-wire systems.

Least mean square (LMS) techniques are getting very popular and several modified variants of LMS are reported in the literature. The LMS technique works recursively on the principle of reducing the square of error between the reference and actual signal. It presents different fixed step as well as variable step LMS techniques. The main problem associated with LMS algorithms are that their convergence rate depends on selection of proper learning rate; else the performance deteriorates. Fixed step LMS is simple in approach, yet these algorithms may diverge if proper learning rate is not selected.

It discusses Gauss–Newton methods and their simplified versions. However, the literature review suggests that none of these methods has been applied for compensation of PQ problems in three-phase, three/four-wire systems. This work presents an improved and simplified control algorithm based on Gauss–Newton algorithm. Also, application of modified recursive Gauss–Newton (MRGN) to mitigate PQ problems in three-phase, four-wire system incorporating linear as well as non-linear load is presented. The main advantages of MRGN are fast, accurate and simplified technique capable of providing quick response under dynamics. In this paper, the evolution of Gauss–Newton methods and the mathematical formulation of modified G–N in the form of MRGN is discussed. Extensive performance studies showing simulation results are verified on prototype hardware system. The steady-state waveforms as well as dynamic performance results are presented for mitigation of PQ problems for different load conditions.

II. DESIGN OF CONTROL ALGORITHM USING MRGNTECHNIQUE

Fig. 3.1*b* shows the control algorithm block diagram for MRGN algorithm. The working of the proposed control algorithm is explained in the following subsection.

A. Generation of fundamental reference magnitude of current

Based on (3.1)–(3.28), peak fundamental reference current magnitude of each phase is calculated, i.e. *M∧a*, *M∧b* and *M∧c*. For the reference current generation, all the fundamental magnitudes are averaged so as to obtain the effective fundamental magnitude *M*∧avg, which corresponds to the active power requirement of the system from the grid.

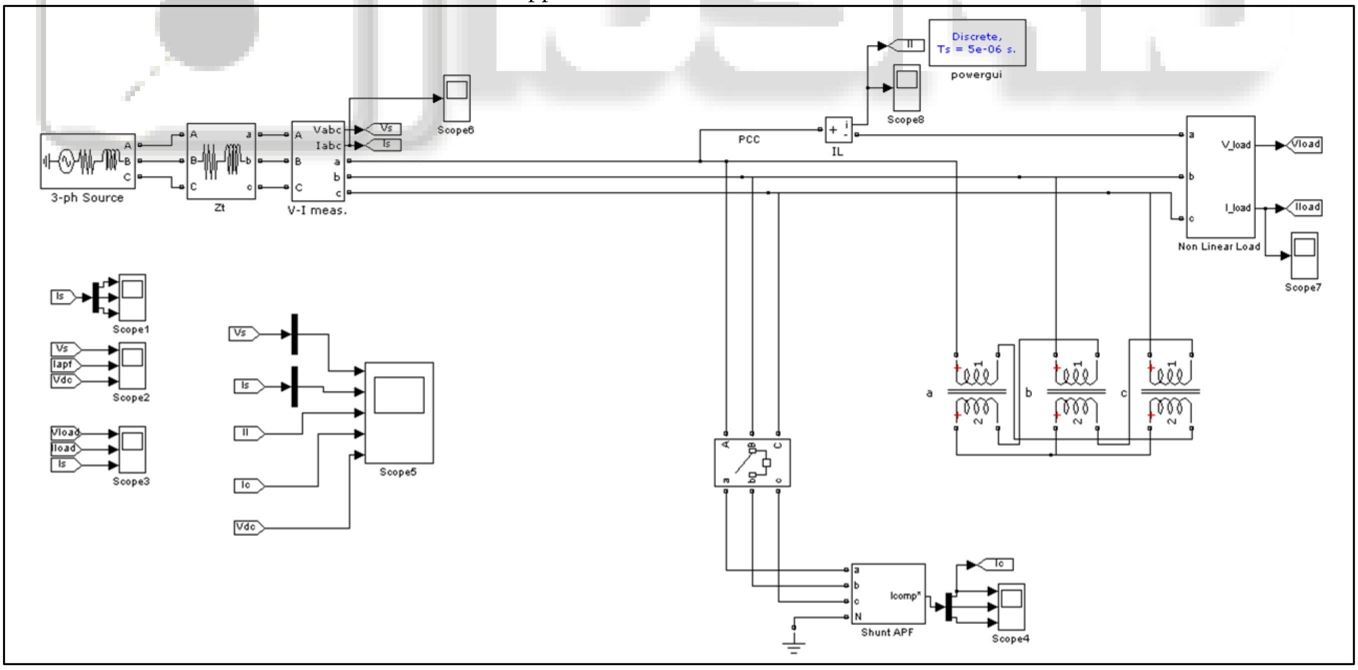


Fig. 3.1: Block Diagram of compensation of harmonics distortion using shunt active filter

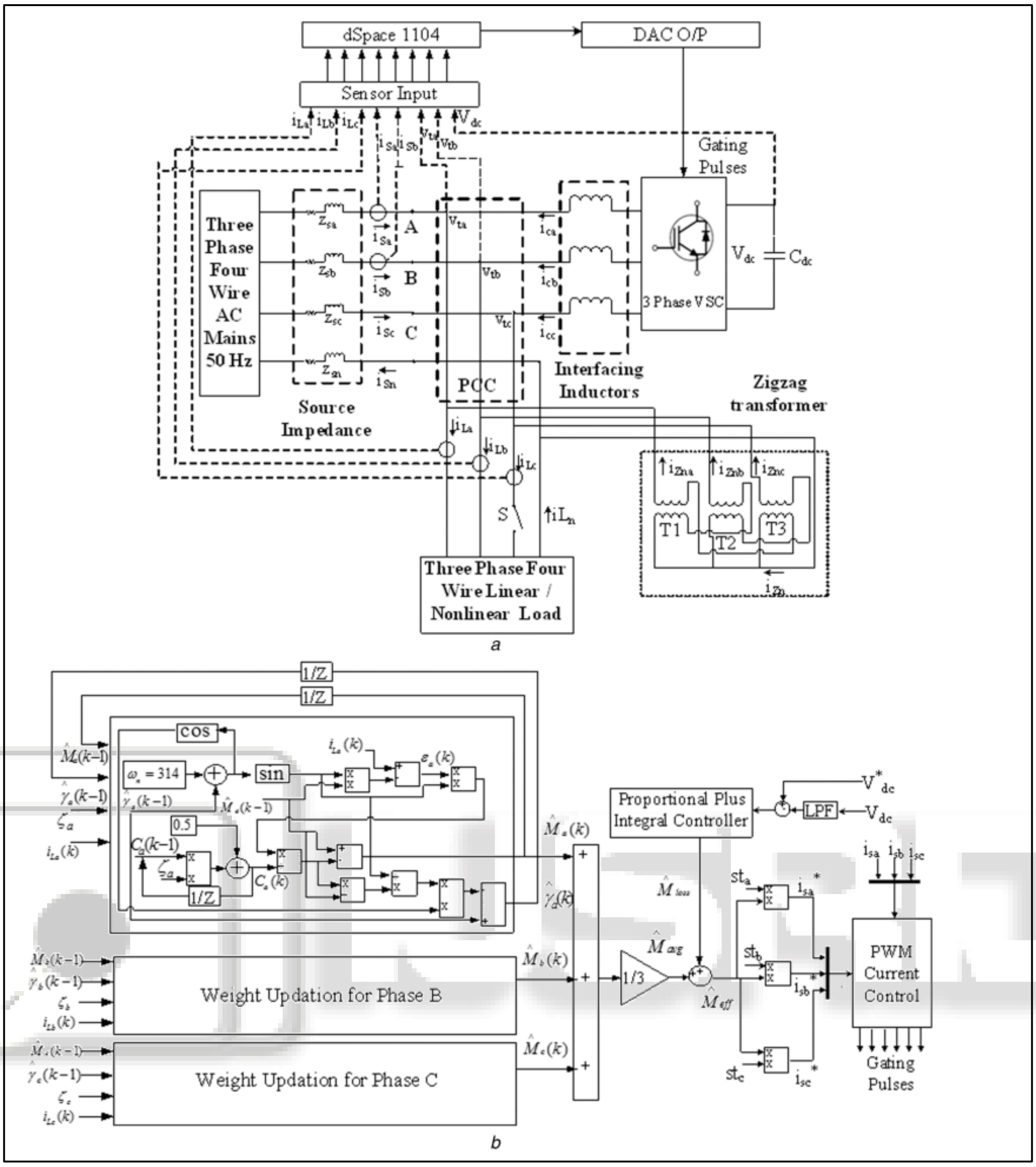


Fig. 3.2: Three *phase four wire system incorporating MRGN control algorithm (a)* Schematic of the proposed system, *(b)* Control block of proposed MRGN technique

III. COMPUTATION OF SWITCHING LOSSES

Since SAPF has active switching losses; hence, it is necessary to account for this switching loss *M*∧ loss. The control algorithm is designed so as to meet these losses from the grid itself. To calculate ∧*M* loss, actual dc link voltage *V*dc is subtracted from reference dc link voltage *V*dc∗ and the output is passed through PI controller to obtain

$$\hat{M}_{\text{loss}}(k) = \hat{M}_{\text{loss}}(k-1) + K_p\{E_{dc}(k) - E_{dc}(k-1)\} + K_i E_{dc}(k) \quad (3.29)$$

where dc(*k*) = *V*dc∗ (*k*) − *V*dc(*k*) and *K*p, *K*i are the proportional and integral gains of the PI controller.

The fundamental magnitude for reference current generation to be met by the grid is given as

$$\hat{M}_{\text{eff}} = \hat{M}_{\text{avg}} + \hat{M}_{\text{loss}} \quad (3.30)$$

IV. GENERATION OF SWITCHING PULSES FOR SAPF

A phase locked loop-less synchronisation technique is adopted for the grid current regulation. The *M*∧eff obtained from (3.30) is multiplied by in phase synchronising templates *sta*, *stb* and *stc*, to generate reference currents required for pulse-width modulation (PWM) current control of SAPF. In phase synchronising templates are calculated from the instantaneous and r.m.s. voltage at the PCC terminals as

$$st_a = \frac{v_{sa}}{V_m}, \quad st_b = \frac{v_{sb}}{V_m}, \quad st_c = \frac{v_{sc}}{V_m} \quad (3.31)$$

Where *vsa*, *vsb* and *vsc* are instantaneous three-phase supply voltages, and V*m*= 2/3(*v*s 2*a* + *v*s 2*b* + *v*s 2*c*) The three-phase reference currents are generated by multiplying synchronising templates to fundamental magnitude *M* ^ eff

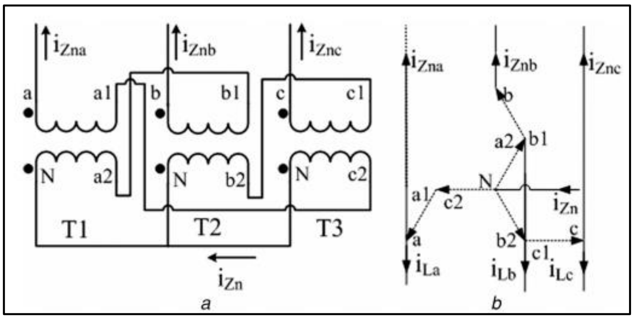


Fig. 3.3: *Configuration of Zigzag transformer (a)* Zigzag connections, *(b)* Phasor diagram

$$is_a^* = st_a \times \hat{M}_{\text{eff}}, \quad is_b^* = st_b \times \hat{M}_{\text{eff}}, \quad is_c^* = st_c \times \hat{M}_{\text{eff}}$$

The reference currents calculated above are compared with the sensed grid currents using PWM current control and necessary gating pulses for SAPF are generated. For the three-phase, four wire system considered in the paper, only a three-leg compensator is connected in shunt configuration. Three single phase loads are connected in the four-wire distribution system and under load unbalancing, a possibility of high neutral current results. A zigzag transformer has been designed and connected for neutral current compensation and is discussed in the next section. The use of zigzag transformer also allows only a three-leg compensator to be used for load compensation. This is beneficial in terms of lower rating and cost aspects.

V. Design of Zigzag Transformer

Zigzag transformer is used to provide a low impedance path for neutral current in three-phase four-wire system in case of load unbalancing. Three single-phase transformers (T1, T2 and T3) are utilised to form a zigzag transformer. The zigzag transformer has two identical windings per phase connected in series phase opposition as shown in Fig. 2*a*. The a1 terminal of T1 is connected in phase opposition to c2 terminal of T3. Similarly, b1 terminal of T2 is connected in phase opposition to a2 terminal of T1 and c1 terminal of T3 is connected in phase opposition to b2 terminal of T2. The phasor diagram of voltages across all three winding of zigzag transformer is shown in Fig. 2*b*. Each transformer is rated as 2.5 kVA, 110/110 V, i.e. turns ratio of primary and secondary is same and three such transformers are used in zigzag operation. The kVA rating of each transformer is selected based on the consideration of safe current limit. During the unbalanced load operation, load neutral current (*i*Ln) passes through the zigzag neutral (*i*zn) and the supply neutral current, *i*sn remains close to zero. Zigzag transformer provides three currents *i*zna, *i*znb and *i*znc, which are in same phase and equal magnitude. The output currents are injected at the PCC to their respective phases. The zigzag transformer effectively compensates high load neutral current effectively making the grid supply neutral current close to zero. Thus, zigzag transformer helps to overcome the PQ problem of neutral compensation and a lower rating, size SAPF with lesser devices can be used for compensation in three phases, four-wire distribution system.

VI. Operating Principle of TCR & FC-TCR

This Work will attempts with an overview of the problems encountered with Shunt compensator (FC-TCR). Fixed Capacitor Thyristor Controlled Reactor is a shunt type FACTS device which is used to improve the quality of power for the purpose of voltage and reactive power control. A basic diagram of single phase Thyristor controlled reactor (TCR) is shown in Fig.4.3 which consists of a fixed reactor of inductance L and a two anti-parallel Thyristors.

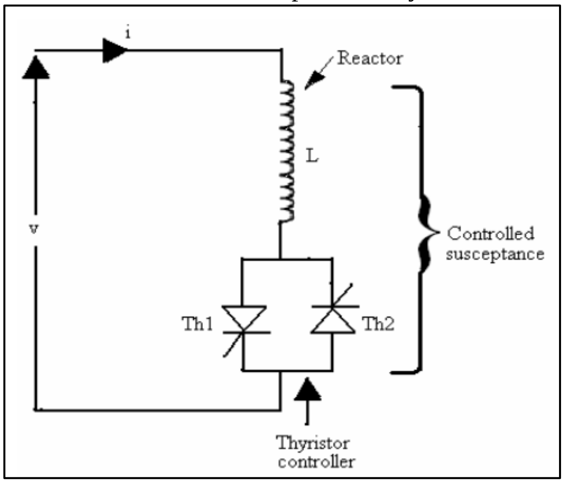


Fig. 4.3: Thyristor Controlled Reactor

The system carried out into conduction and simultaneous application of gate pulses to Thyristors of the similar polarity. Additionally, it may automatically block instantly after the alternating current crosses zero, until the gate pulses is applied again. The current in the reactor can be controlled from maximum (Thyristor closed) to zero (Thyristor open) by the phenomenon of triggering delay angle control. The Thyristor conduction delays with respect to the peak of the supplied voltage in each half-cycle, and hence the time interval of the current conduction duration is controlled. This phenomenon of current control is illustrated individually for the positive and negative current cycles in Fig.6 where the reactor current iL(α) at zero delay angle (valve fully closed) and at an α delay angle are shown.

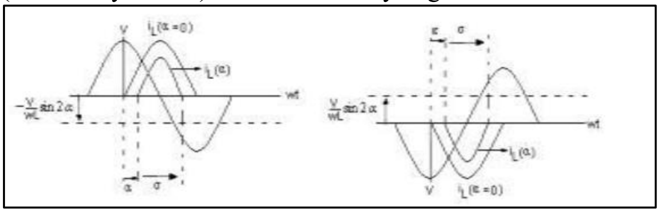


Fig. 4.4: Firing Delay Angle

When α=0 the valve closes at crest of the supplied voltage and clearly the resulting current in the reactor will be the same. When the gating of the switch is delayed by an angle α(0 ≤ α ≤ π /2) with respect to the crest of the voltage, the current can be expressed as:

$$V(t) = V \cos \omega t \tag{4.8}$$

$$i_L = (1/L) \, {}_{\alpha}\!\int^{\omega t} V(t)dt = (V/\omega L)(\sin \omega t - \sin \alpha) \tag{4.9}$$

Thyristor valve opens as the current reaches zero expression (4.9) and is applicable for duration α ≤ ωt ≤ π–α. For subsequent half cycle intervals the same expression remains justifiable but for negative half cycle intervals the sign of the terms in expression (1) becomes opposite. In above expression (1) term (V/ωL) sin α = 0 is basically α based which shifts down for positive and up for negative half cycles. Figure 4.1 shows that the valve automatically turns off at the moment of current zero crossing. This process usually controls the conduction interval of the thyristor valve. The delay angle α defines the prevailing conduction angle σ: (σ = π□□α). So when the delay angle α rises there is a decrease in the conduction angle α of the valve and the reduction of the reactor current .At the maximum of v/ωL, at which both the conduction angle and the reactor current becomes zero.

It is clear that the value of the current in the reactor can be changed continuously by this method of delay angle control from maximum (α=0) to (α=π/2) where reactor current, together with its fundamental component are shown in fig.4.5 at different delay angles.

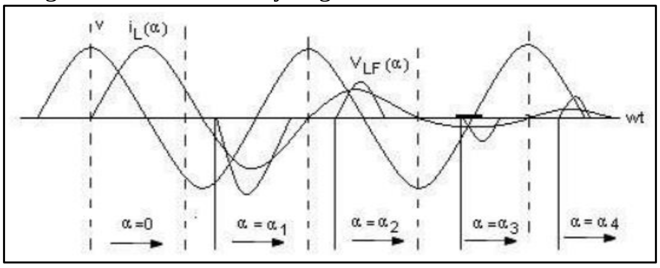


Fig. 4.5: Operating waveforms of TCR

Typical arrangement using a fixed capacitor along with Thyristor Controlled Reactor is shown in Figure.4.6. Controlled reactor may be considered necessarily to consist a variable reactor which is regulated by delay angle α and fixed capacitor.

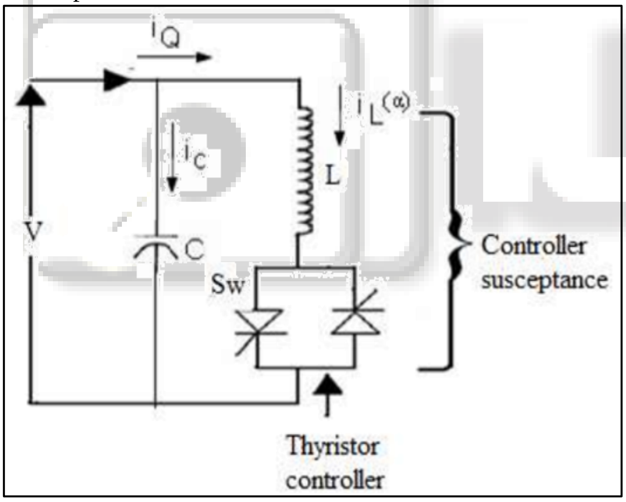


Fig. 4.6: Typical diagram of FC-TCR

Fig.4.7 shows the plot between VAR demand and VAR output In the fixed capacitive VAR generator (Qc) of fixed is opposed by the variable VAR absorption (Qc) of TCR, to yield the total VAR output Q is needed. At maximum capacitive VAR output thyristor controlled reactor is switched off (α=90). To reduce the capacitive output, the current in the reactor is improved by decreasing delay angle α. At zero VAR output, the inductive and capacitive currents become equal and thus inductive and capacitive VARs cancel out with further decreases of angle α, the inductive current becomes greater than the capacitive current. At zero delay angle the TCR conducts current over the full 180o duration, resulting in maximum inductive VAR output which is equal to the difference between the VARs generated by the capacitor and those absorbed by the reactor which is fully conducting in nature.

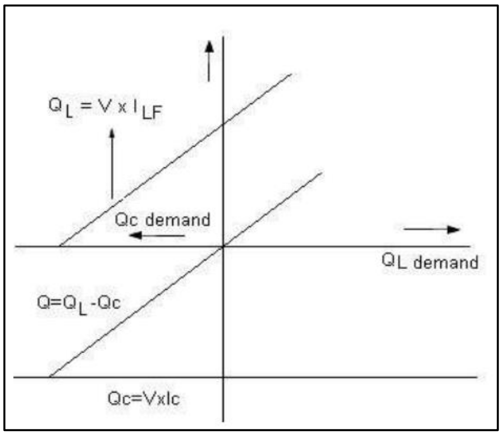


Fig. 4.7: Plot between VAR demand and VAR output

In Fig.4.8 voltage defines the V-I operating area of the FC-TCR VAR generator and is defined by the maximum sustainable capacitive and inductive admittance and by the voltage and current ratings of the major power element (capacitor, reactor and thyristor valve) as illustrated in Fig.4.8 the ratings of the power element are derived from application requirements.

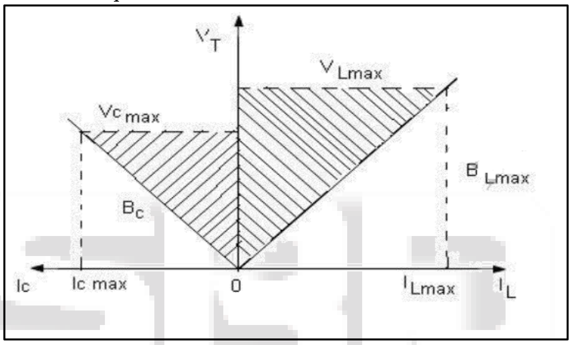


Fig. 4.8: V-I characteristics of the FC-TCR

VII. PROPOSED FUZZY LOGIC CONTROLLER

Fig.4.10 shows the basic structure of the fuzzy logic inference system in MATLAB Fuzzy logic toolbox. For a closed loop, control input m a y be elected as voltage current or resistance, according to type of control. To obtain the linear triangular membership the function is taken with fifty percent overlapping. The output of fuzzy system is taken as pulse generator that generates and provides synchronous triggering pulses to SCRs as shown in fig.4.10. The Fuzzy Logic controller is a rule based controller, here a set of rules represents a control decision mechanism to correct the effect of certain causes coming from power system . In fuzzy logic controller, seven linguistic variables exhibited by fuzzy sets described on their appropriate universes of discourse. The rule of this table can be chosen by the experienced engineers and simulation results observed from the performance of the system about its stable equilibrium points .

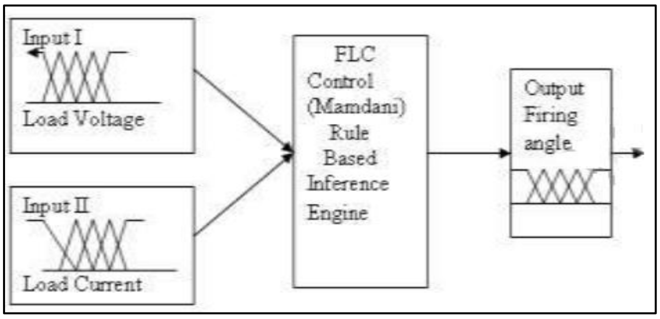


Fig. 5.1: Fuzzy Logic controller

VIII. COMPARATIVE PERFORMANCES

Fast response and good dynamic performance are important prerequisites for choice of controller for SAPF action. Table 1 shows the comparative performance on the basis of complexity between MRGN, RGN and SRFT. It is obvious from Table 1 that the RGN algorithm cannot be used for PQ improvement because of high complexity and large execution time. MRGN is a simplified form of Gauss–Newton method and can be executed in 45 μs when compared with SRFT, which requires 55 μs to run. MRGN method is an effective technique requiring few mathematical operations for fast estimation of supply fundamental current. The algorithm is accurate and gives very good performance under variety of connected load.

Shunt Active Filter	Fuzzy Logic
Harmonics reduced to 3.4%	Harmonics reduced to 5.6%
Shunt active filters are not able to compensate the current in an effective manner	By using Fuzzy controller we can compensate the current in an effective manner.
Shunt active filter alone cannot be used to determine power angle.	A lookup table to obtain the power factor and the respective power angle in order to compensate the current taken by the load
Performance is low when compared to fuzzy logic	It is found that the SHPF-TCR compensator offers a good level of performance.

IX. RESULT & DISCUSSION

In order to validate the performance of the grid system, Shunt active filter is designed with the source modelling in MATLAB /Simulink and the experimental waveforms are obtained. The performance of the converter is studied under steady state condition. The performances of the converter under the shunt active filter schemes are validated with the models to their efficiency conditions.

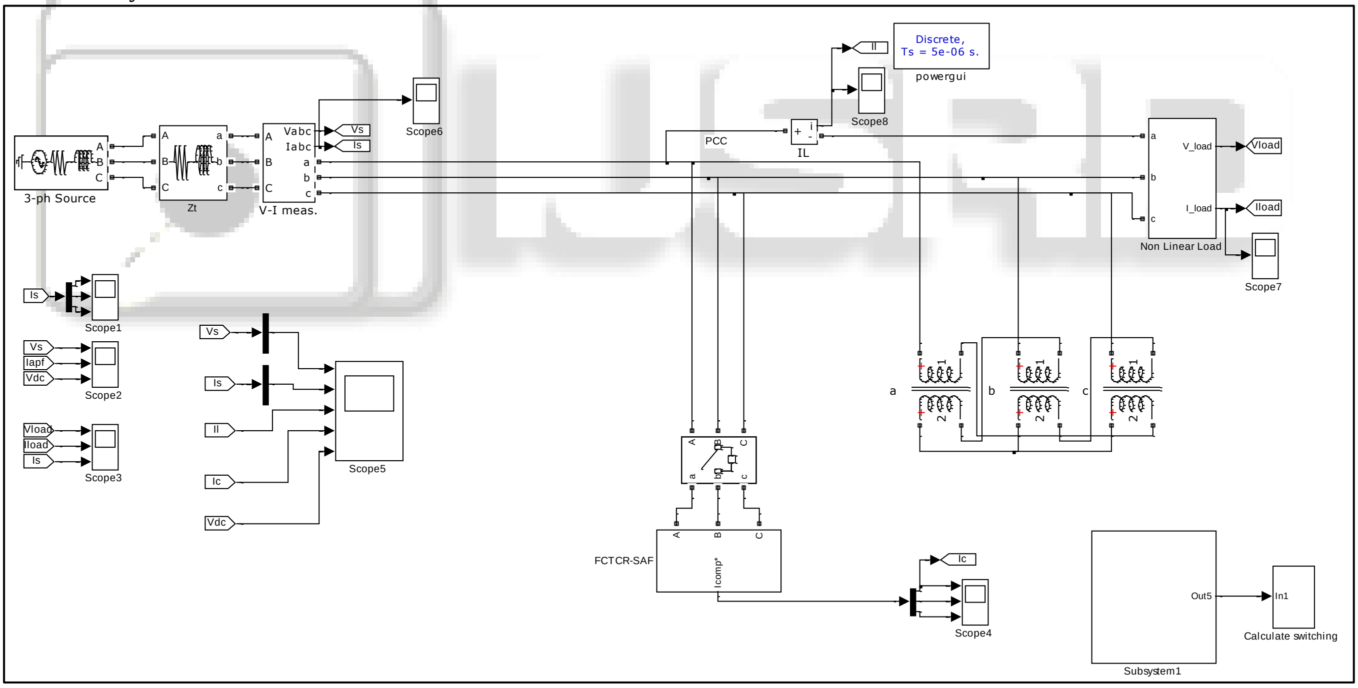


Fig. 7.1: shows the simulation diagram of the existing system.

A voltage source converter with capacitor on its DC side is used as an SAPF and connected at the point of common coupling (PCC). Interfacing inductors are designed and connected in between PCC and SAPF. It represents a three-phase, four-wire system incorporating zigzag transformer for neutral current compensation.

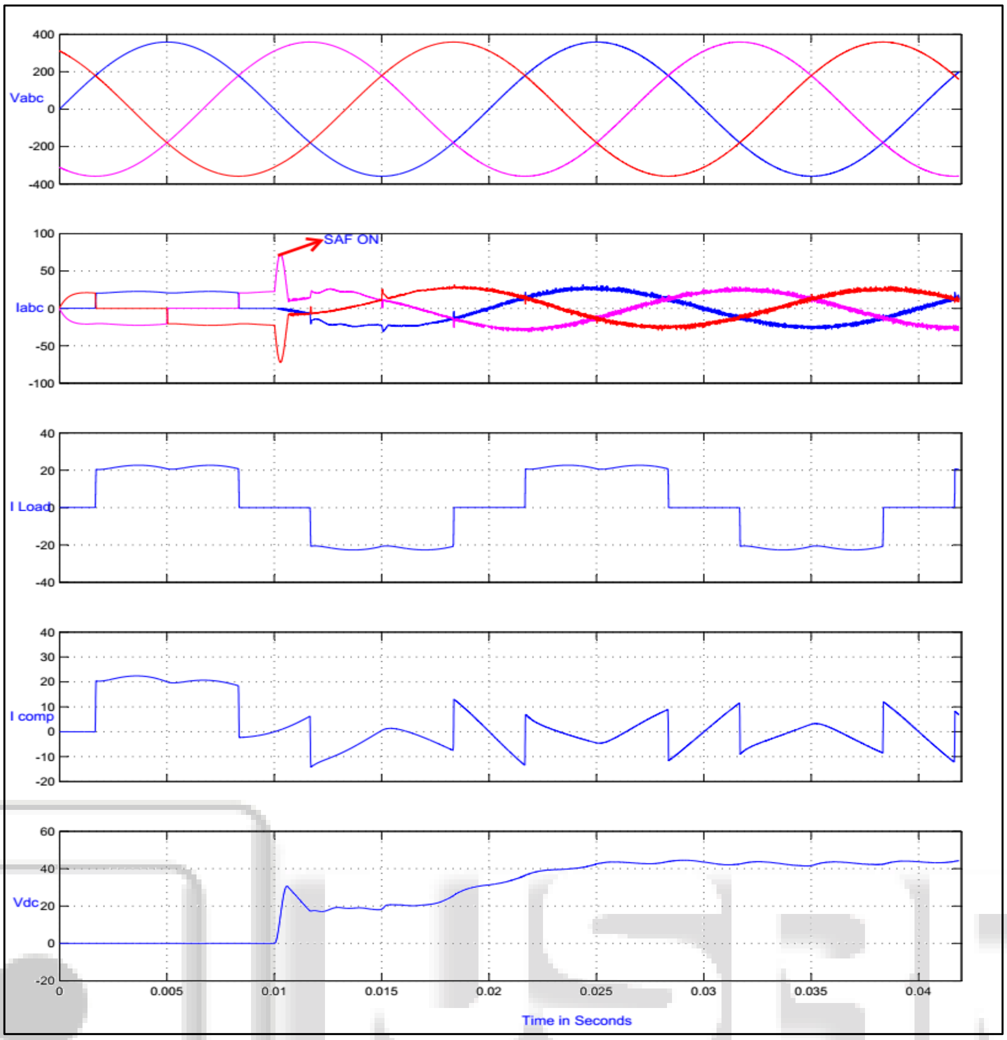
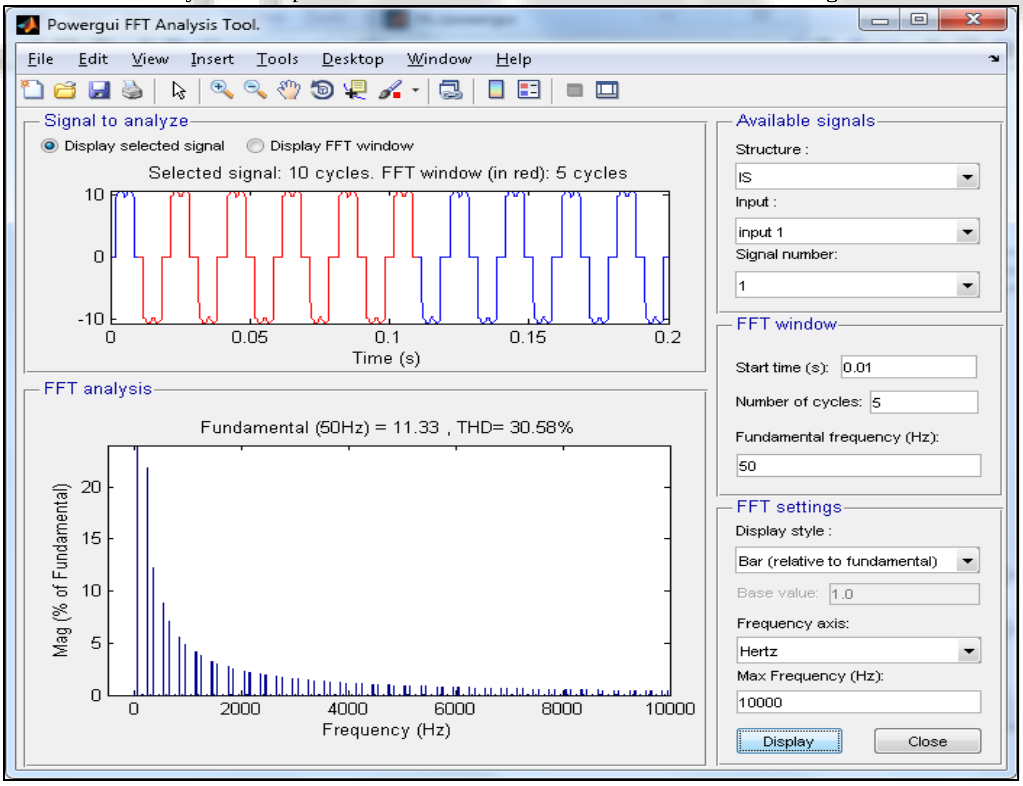
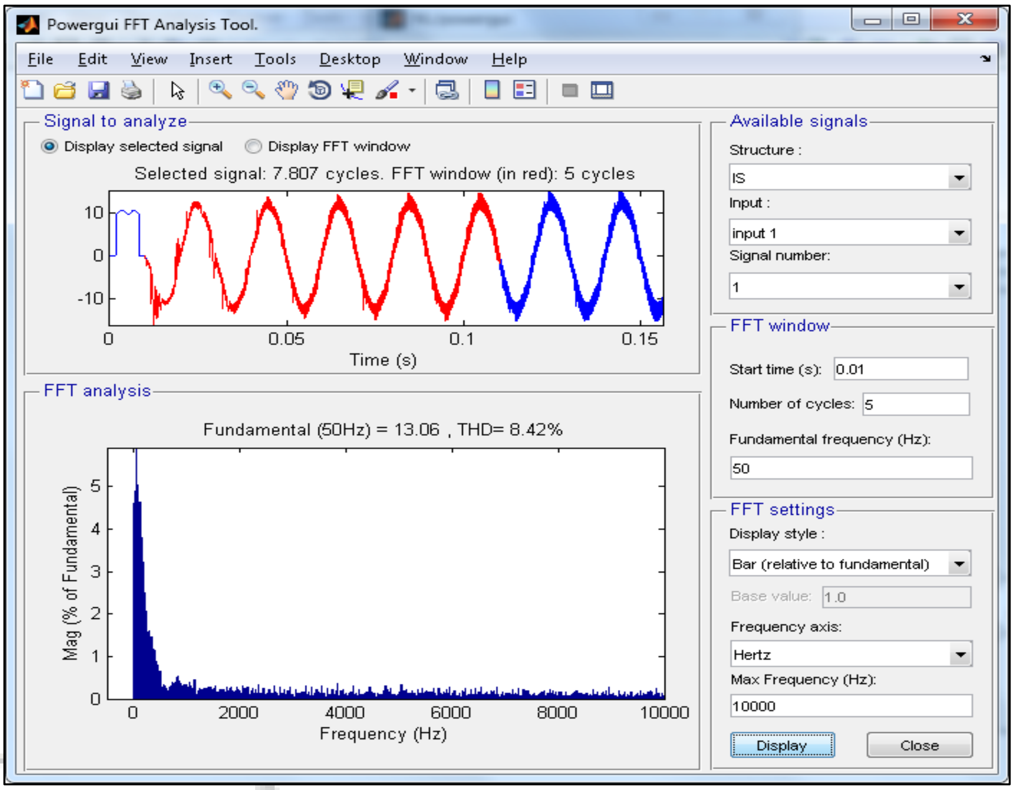


Fig. 7.2: shows the Steady state response of the Shunt active filter under a Harmonic generation load condition.



A. Before compensation



After compensation (using Shunt Active filter)
Fig. 7.3: shows the harmonic spectrum of source current phase A,

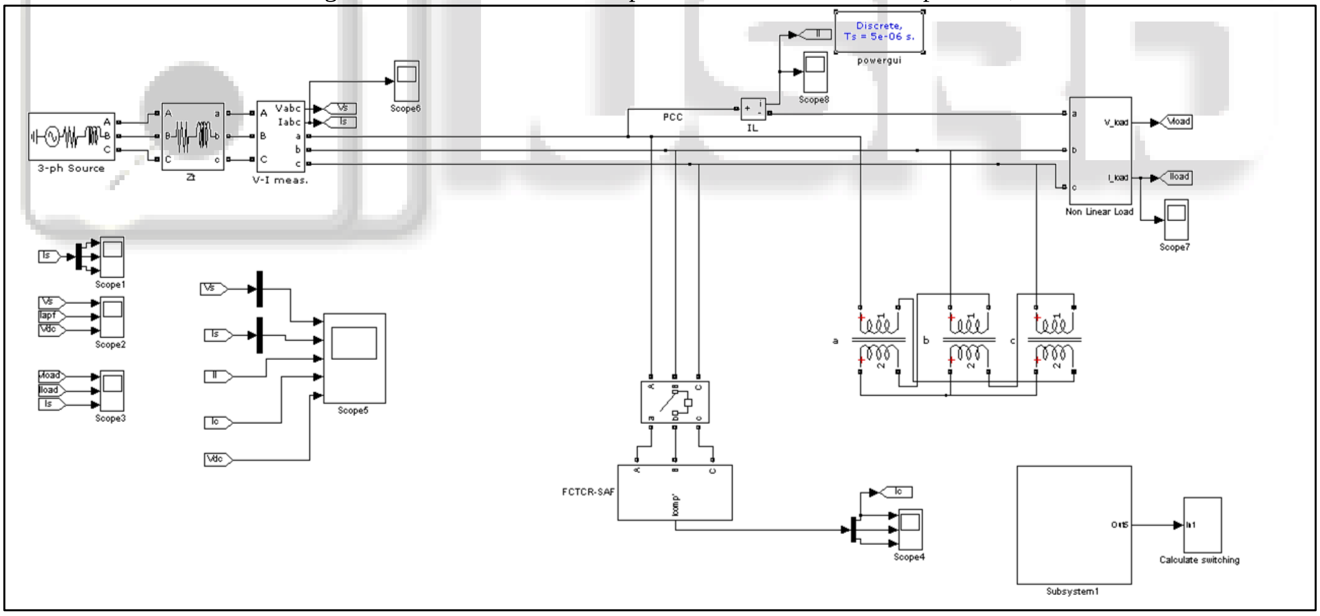


Fig. 7.4: shows the simulation diagram of the proposed system.

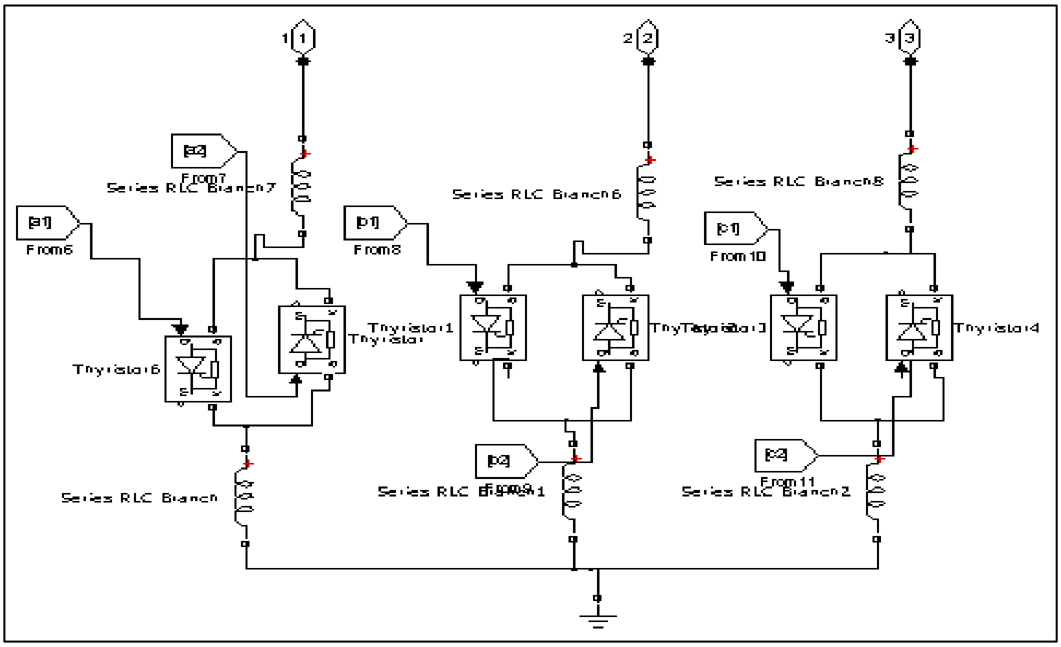


Fig. 7.5: shows the TCR configuration

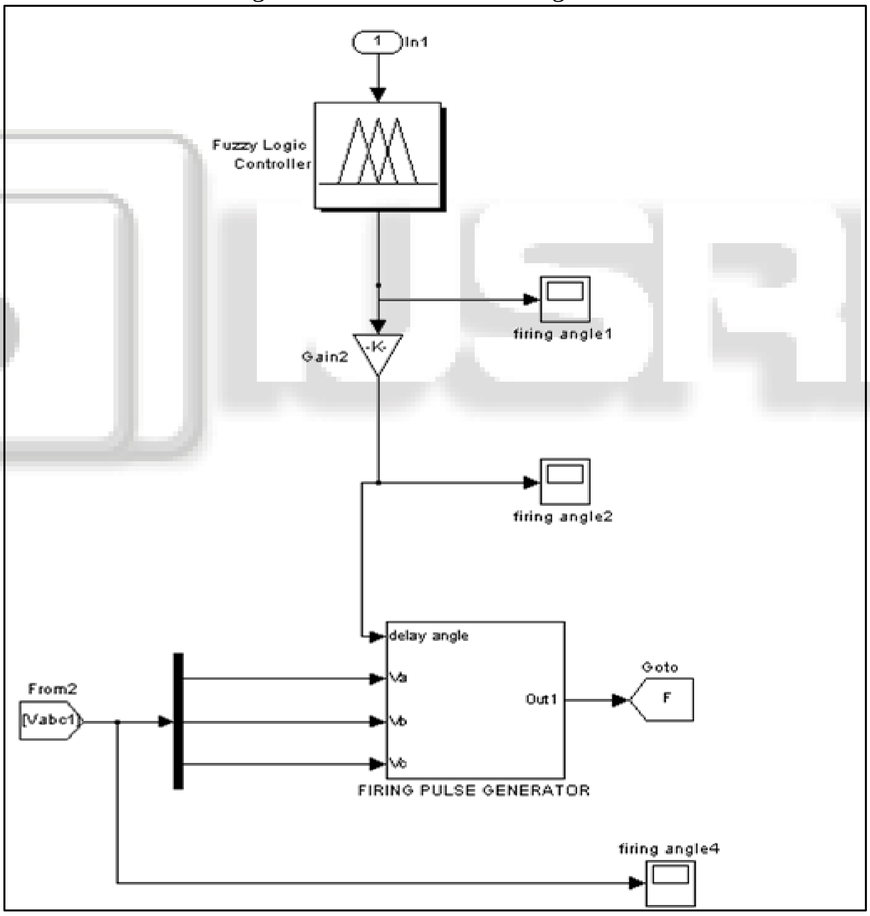


Fig. 7.6: shows the fuzzy controller

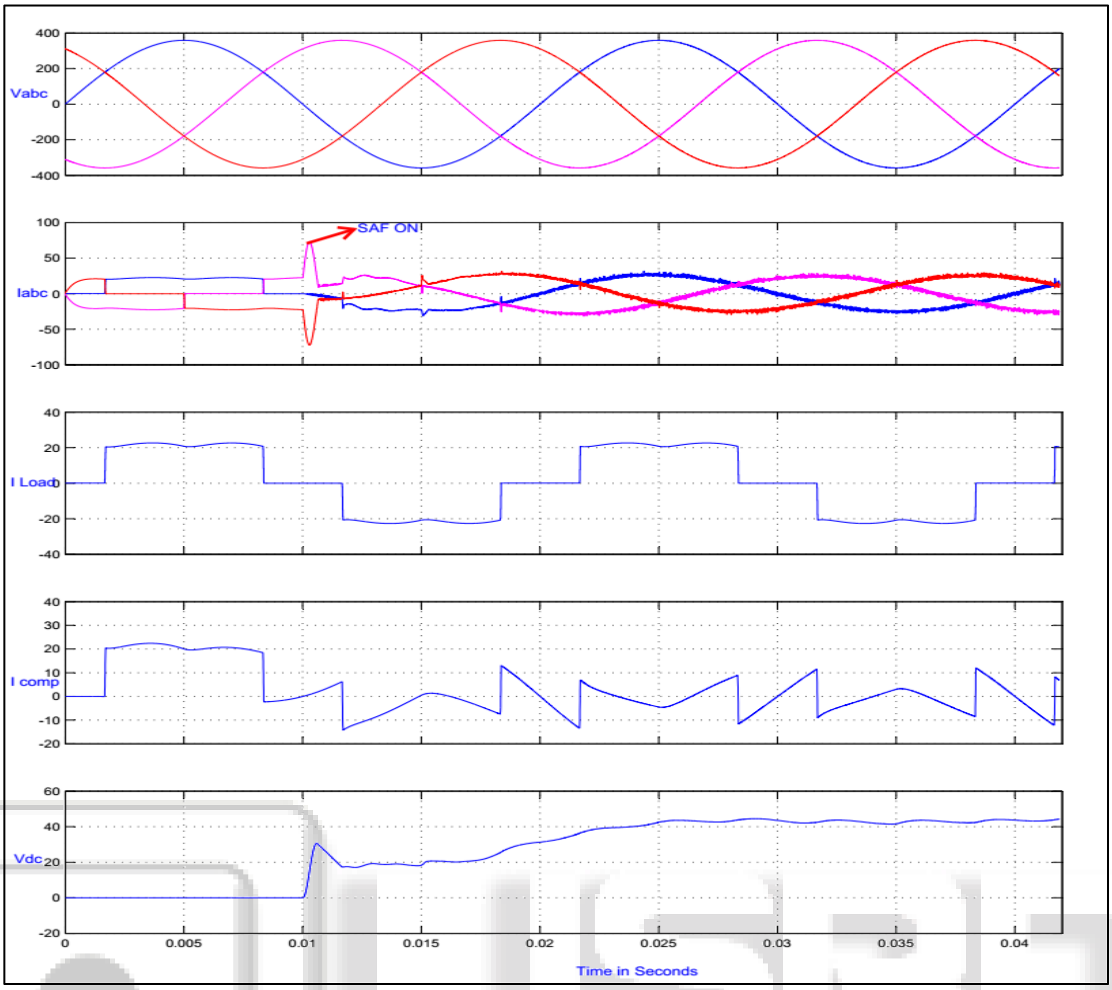


Fig. 7.7: shows the Steady state response of the Fuzzy logic controller

The supply voltage, the supply current, the load current, the SHPF-TCR current in phase 1, and the dc bus voltage (*V*DC) are depicted in this figure.

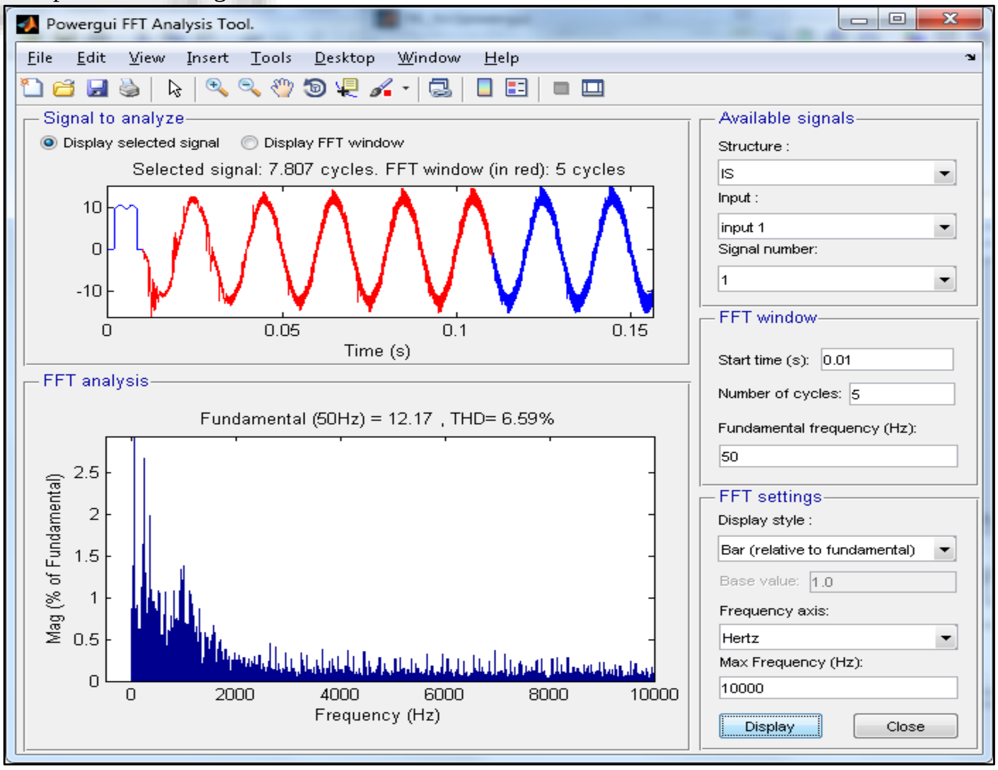


Fig. 7.8: shows the harmonic spectrum of source current phase A

Fig. Shows the harmonic spectrum of the supply current after compensation. The THD of the supply current is brought down. It is found that the SHPF-TCR compensator offers a good level of performance.

X. CONCLUSION

Due to the characteristics of the passive filters, the conventional hybrid filters are not able to compensate the current in an effective manner. Hence, in this work, a hybrid filter is proposed to use with the TCR. The combination of hybrid system with TCR has a fuzzy controller and a lookup table to obtain the power factor and the respective power angle in order to compensate the current taken by the load. In this proposed work, a source instantaneous power based control method of a shunt active power filter has been proposed. Calculation of source instantaneous power is needed to determine instantaneous power component that may not be created by the source. This calculation only needs source currents and phase information so the amount of sensors can be minimized. This control method can reduce the number of current sensors and is capable to operate under non-ideal main voltages with keeping force the source phase currents be sinusoidal. This method can be implemented in three-wire and four wire system. The neutral current at the source side can be significantly reduced in four-wire system. Simulation results show the effectiveness of the proposed control method.

XI. FUTURE SCOPE

In this project only the Simulation work has been carried out for the shunt active filter based on the fuzzy control method for a 3 phase balanced load. Experimental work can be carried out for the same and a model based on the given prototype based on three leg VSC and ANFIS controller can be developed to verify the simulation results. Similarly the work can be extended to determine the superior nature of the fuzzy control method for 3phase unbalanced condition.

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