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Fuzzy Controlled Shunt Hybrid Power Filter and Thyristor-Controlled Reactor for Power Quality

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ABSTRACT: This paper deals with the implementation of fuzzy logic based Shunt Hybrid Active Filter (SHAF) with nonlinear load to minimize the source current harmonics and provide reactive power compensation. Comparison with Proportional Integral (PI) based SHAF is also analyzed. Shunt Hybrid Active Filter is constituted by Active Filter connected in shunt and shunt connected three phase single tuned LC filter for 5th harmonic frequency with rectifier load. The proposed work study the compensation principle and different control strategies used here are based on PI/FUZZY controller of the shunt and TCR active filter in detail. The control strategies are modeled using MATLAB/SIMULINK. The performance is also observed under influence of utility side disturbances such as harmonics, flicker and spikes with Non-Linear and Reactive Loads. The simulation results are listed in comparison of different control strategies and for the verification of results.

KEYWORDS: Harmonic Suppression, Hybrid Power filter, Modelling, Hybrid Power filter And Thyristor-Controller Dreactor (SHPF-TCR Compensator), Fuzzy Logic Controller

I. INTRODUCTION

Power quality is becoming important due to proliferation of nonlinear loads, such as rectifier equipment, adjustable speed drives, domestic appliances and arc furnaces. These nonlinear loads draw non-sinusoidal currents from ac mains and cause a type of current and voltage distortion called as „harmonics‟. These harmonics causes various problems in power systems and in consumer products such as equipment overheating, capacitor blowing, motor vibration, transformer over heating excessive neutral currents and low power factor. Power quality problems are common in most of commercial, industrial and utility networks. Natural phenomena, such as lightning are the most frequent cause of power quality problems. Switching phenomena resulting in oscillatory transients in the electrical supply.Shunt active power filters (SAPF) represent a feasible solution to the problems caused by the non- linear loads. These loads draw non-sinusoidal currents from the 3-phase sinusoidal, balanced voltages which are classified as identified and unidentified loads. The SAPF can compensate for the harmonics, correct the power factor and work as a reactive power compensator, thus providing enhancement of power quality in the system [1, 2]. The control scheme of a SAPF must calculate the current reference waveform for each phase of the inverter, maintain the dc voltage constant, and generate inverter gating signals.

II. SYSTEM CONFIGURATION OF SHPF-TCR COMPENSATOR

Fig. 1 shows the topology of the proposed combined SHPF and TCR. The SHPF consists of a small-rating APF connected in series with a fifth-tuned LC passive filter. The APF consists of a three-phase full-bridge voltage-source pulse width modulation (PWM) inverter with an input boost inductor (Lpf, Rpf) and a dc bus capacitor (Cdc). The APF sustains very low fundamental voltages and currents of the power grid, and thus, its rated capacity is greatly reduced. Because of these merits, the presented combined topology is very appropriate in compensating reactive power and eliminating harmonic currents in power system. The tuned passive filter in parallel with TCR forms a shunt passive filter (SPF). This latter is mainly for fifth harmonic compensation and PF correction. The small-rating APF is used to filter harmonics generated by the load and the TCR by enhancing the compensation characteristics of the SPF aside from

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eliminating the risk of resonance between the grid and the SPF. The TCR goal is to obtain a regulation of reactive power. The set of the load is a combination of a three phase diode rectifier and a three-phase star-connected resistive inductive linear load.

III. MODELING AND CONTROL STRATEGY

A. Modeling of SHPF

The system equations are first elaborated in 123 reference frame. Using Kirchhoff's voltage law, one can write

$$\begin{aligned}
v_{s1} &= L_{\mathrm{PF}}\frac{di_{c1}}{dt} + R_{\mathrm{PF}}i_{c1} + v_{\mathrm{CPF1}} + v_{1M} + v_{\mathrm{MN}}\\
v_{s2} &= L_{\mathrm{PF}}\frac{di_{c2}}{dt} + R_{\mathrm{PF}}i_{c2} + v_{\mathrm{CPF2}} + v_{2M} + v_{\mathrm{MN}}\\
v_{s3} &= L_{\mathrm{PF}}\frac{di_{c3}}{dt} + R_{\mathrm{PF}}i_{c3} + v_{\mathrm{CPF3}} + v_{3M} + v_{\mathrm{MN}}\\
v_{\mathrm{CPF1}} &= L_T\frac{di_{c1}}{dt} - C_{\mathrm{PF}}L_T\frac{d^2v_{\mathrm{CPF1}}}{dt^2}\\
v_{\mathrm{CPF2}} &= L_T\frac{di_{c2}}{dt} - C_{\mathrm{PF}}L_T\frac{d^2v_{\mathrm{CPF2}}}{dt^2}\\
v_{\mathrm{CPF3}} &= L_T\frac{di_{c3}}{dt} - C_{\mathrm{PF}}L_T\frac{d^2v_{\mathrm{CPF3}}}{dt^2}\\
\frac{dv_{\mathrm{dc}}}{dt} &= \frac{1}{C_{\mathrm{dc}}}i_{\mathrm{dc}}.
\end{aligned} \tag{1}$$

The switching function *ck* of the *k*th leg of the converter (for *k* = 1, 2, 3) is defined as

$$c_k = \begin{cases} 1, & \text{if } S_k \text{ is On and } S'_k \text{ is Off} \\ 0, & \text{if } S_k \text{ is Off and } S'_k \text{ is On.} \end{cases} \tag{2}$$

A switching state function *d*nk is defined as

$$d_{\mathrm{nk}} = \left(c_k - \frac{1}{3}\sum_{m=1}^{3} c_m\right)_n \tag{3}$$

Moreover, the absence of the zero sequence in the ac currents and voltages and in the [*d*nk] functions leads to the following transformed model in the three-phase coordinates [15]:

$$\begin{aligned}
L_{\mathrm{PF}}\frac{di_{c1}}{dt} &= -R_{\mathrm{PF}}i_{c1} - d_{n1}v_{\mathrm{dc}} - v_{\mathrm{CPF1}} + v_{s1}\\
L_{\mathrm{PF}}\frac{di_{c2}}{dt} &= -R_{\mathrm{PF}}i_{c2} - d_{n2}v_{\mathrm{dc}} - v_{\mathrm{CPF2}} + v_{s2}
\end{aligned}$$

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$$L_{\mathrm{PF}}\frac{di_{c3}}{dt} = -R_{\mathrm{PF}}i_{c3} - d_{n3}v_{\mathrm{dc}} - v_{\mathrm{CPF3}} + v_{s3}$$

$$C_{\mathrm{dc}}\frac{dv_{\mathrm{dc}}}{dt} + \frac{v_{\mathrm{dc}}}{R_{\mathrm{dc}}} = d_{n1}i_{c1} + d_{n2}i_{c2} + d_{n3}i_{c3}. \quad (4)$$

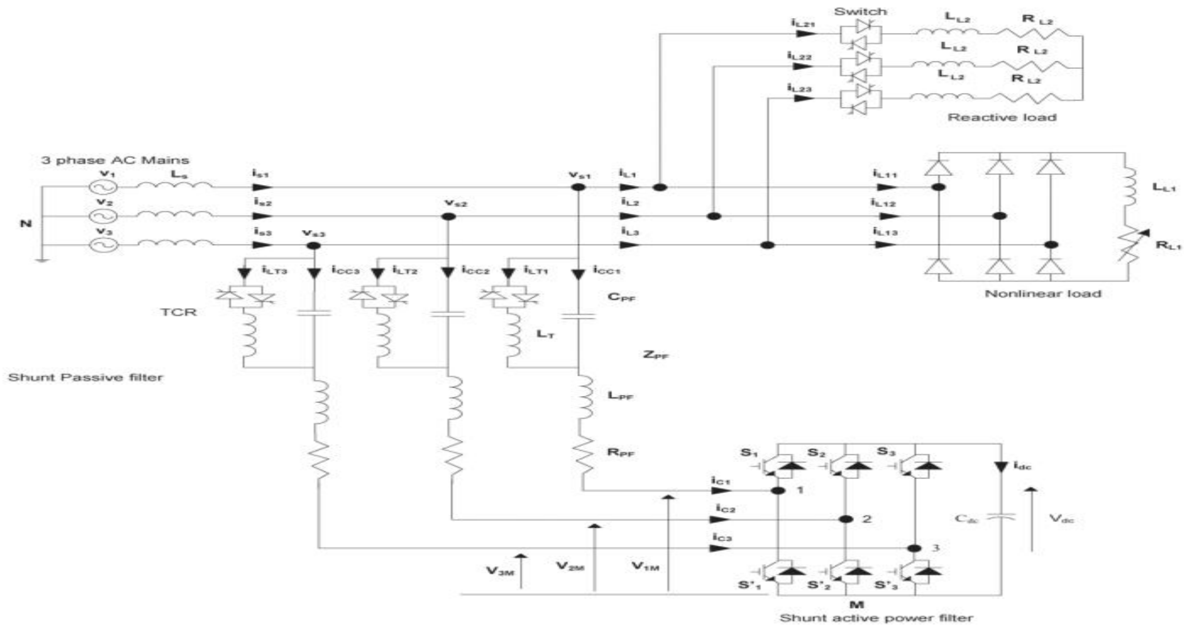

Fig.1. Basic circuit of the proposed SHPF-TCR compensator.

The system of (4) is transformed into the synchronous orthogonal frame using the following general transformation matrix:

$$C_{dq}^{123} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta - 4\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta - 4\pi/3) \end{bmatrix} \quad (5)$$

where $\theta = \omega t$ and the following equalities hold:

$$C_{123}^{dq} = (C_{dq}^{123})^{-1} = (C_{dq}^{123})^{T}$$

Then, by applying *dq* transformation, the state space model of the system in the synchronous reference frame.This model is nonlinear because of the existence of multiplication terms between the state variables *{id, iq, V*dc*}* and the switching state function *{d*nd, *d*nq*}*. However, the model is time invariant during a given switching state.
Furthermore, the principle of operation of the SHPF requires that the three state variables have to be controlled independently. The interaction between the inner current loop and the outer dc bus voltage loop can be avoided by adequately separating their respective dynamics.

B. Harmonic Current Control

A fast inner current loop, and a slow outer dc voltage loop, is adopted. The first two equations in the model can be written as shown in the Appendix by (27). Note that the first and the second time derivative TCR capacitor voltages

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have no significant negative impact on the performance of the proposed control technique because their coefficients are too low. Consequently, they can practically be ignored. Define the equivalent inputs by (28) as given in the Appendix.

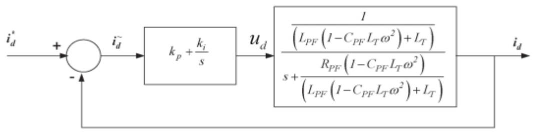

Fig.2.Inner control loop of the current i_d.

Thus, with this transformation, the decoupled dynamics of the current tracking is obtained. The currents *id* and *iq* can be controlled independently. Furthermore, by using proportional integral compensation, a fast dynamic response and zero steady-state errors can be achieved.

C. DC Bus Voltage Regulation

In order to maintain the dc bus voltage level at a desired value, acting on *iq* can compensate the losses through the hybrid power filter components. The output of the controller is added to the *q*-component current reference *iq* as shown in Fig. 4.

The dc component will force the SHPF-TCR compensator to generate or to draw a current at the fundamental frequency.

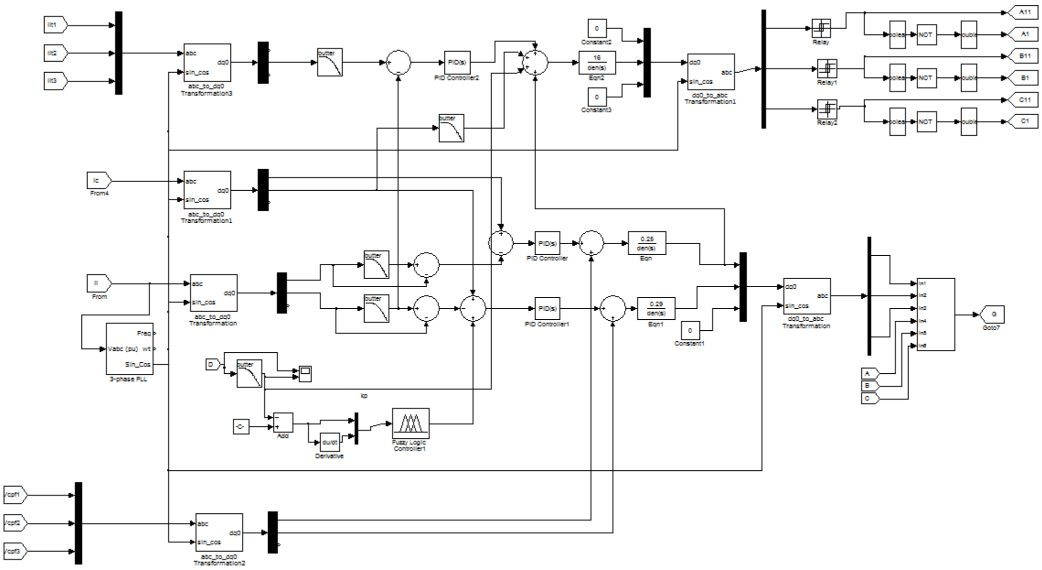

Fig.3.Control scheme of the proposed SHPF-TCR compensator.

The response of the dc bus voltage loop is a second-order transfer function and has the following form:

$$\frac{V_{\mathrm{dc}}(s)}{V_{\mathrm{dc}}^{*}(s)} = 2\zeta\omega_{\mathrm{nv}} \frac{s + \frac{\omega_{\mathrm{nv}}}{2\zeta}}{s^2 + 2\zeta\omega_{\mathrm{nv}}s + \omega_{\mathrm{nv}}^2}$$

The closed-loop transfer function of dc bus voltage regulation is given as follows:

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$$\frac{V_{\mathrm{dc}}(s)}{V_{\mathrm{dc}}^{*}(s)} = \frac{\frac{\sqrt{3}Z_{\mathrm{PF1}}k_p I_c}{\overline{V}_{\mathrm{dc}}C_{\mathrm{dc}}}s + \frac{\sqrt{3}Z_{\mathrm{PF1}}k_i I_c}{\overline{V}_{\mathrm{dc}}C_{\mathrm{dc}}}}{s^2 + \frac{\sqrt{3}Z_{\mathrm{PF1}}k_p I_c}{\overline{V}_{\mathrm{dc}}C_{\mathrm{dc}}}s + \frac{\sqrt{3}Z_{\mathrm{PF1}}k_i I_c}{\overline{V}_{\mathrm{dc}}C_{\mathrm{dc}}}}$$

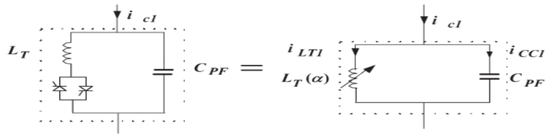

Fig.4 .TCR equivalent circuit.

V. INTRODUCTION TO FUZZY LOGIC CONTROLLER

A new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to dc-to-dc converter system. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of dc-to-dc converter and performance of proposed controllers. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of dc-to-dc converters. The basic scheme of a fuzzy logic controller is shown in Fig 5 and consists of four principal components such as: a fuzzy fication interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

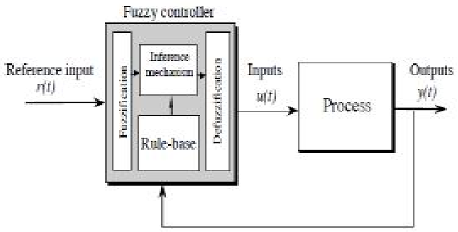

Fig.5. General Structure of the fuzzy logic controller on closed-loop system

The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical model [10]. Simulation is performed in buck converter to verify the proposed fuzzy logic controllers.

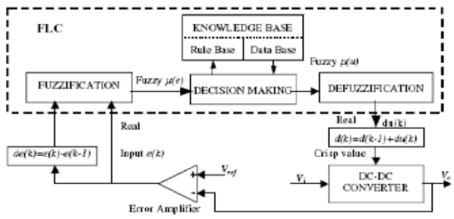

Fig.6. Block diagram of the Fuzzy Logic Controller (FLC) for dc-dc converters

Fuzzy Logic Membership Functions:

The dc-dc converter is a nonlinear function of the duty cycle because of the small signal model and its control method was applied to the control of boost converters. Fuzzy controllers do not require an exact mathematical model. Instead, they are designed based on general knowledge of the plant. Fuzzy controllers are designed to adapt to varying

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operating points. Fuzzy Logic Controller is designed to control the output of boost dc-dc converter using Mamdani style fuzzy inference system. Two input variables, error (e) and change of error (de) are used in this fuzzy logic system. The single output variable (u) is duty cycle of PWM output.

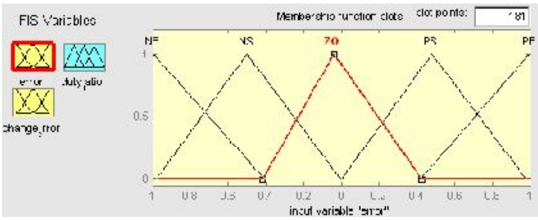

Fig. 7.The Membership Function plots of error

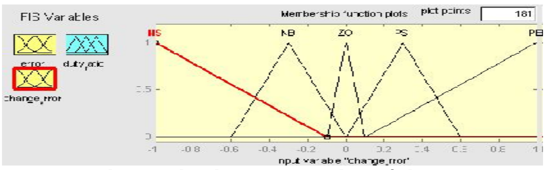

Fig.8. The Membership Function plots of change error

Fuzzy Logic Rules:

The objective of this dissertation is to control the output voltage of the boost converter. The error and change of error of the output voltage will be the inputs of fuzzy logic controller. These 2 inputs are divided into five groups; NB: Negative Big, NS: Negative Small, ZO: Zero Area, PS: Positive small and PB: Positive Big and its parameter [10]. These fuzzy control rules for error and change of error can be referred in the table that is shown in Table II as per below:

Table II
Table rules for error and change of error

(de) \ (e)	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

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VI.MATLAB/SIMULINK RESULTS

Case 1: Performance of SHPF-TCR for harmonic generated load with fuzzy

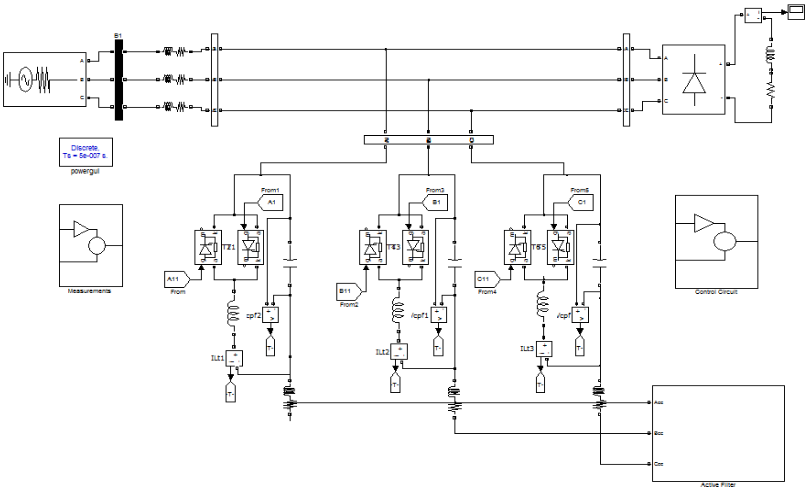

Fig.10.Simulink circuit for SHPF-TCR under harmonic generated load with fuzzy

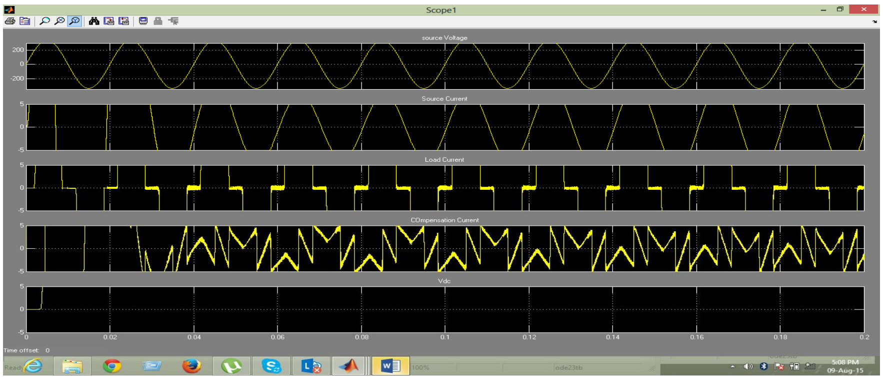

Fig.11.Simulation results for source voltage, source current, load current, compensation currents and dc link voltage

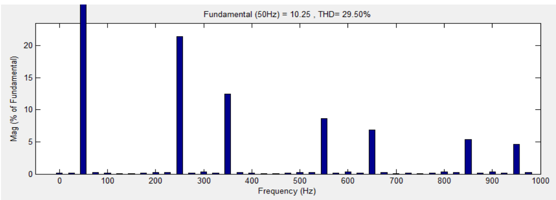

Fig.12.harmonic spectrum for source current without compensation

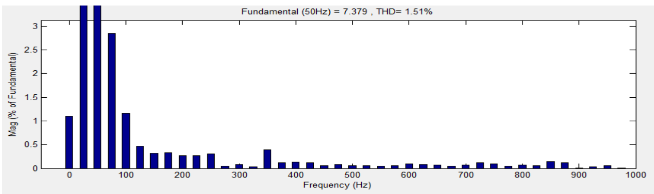

Fig.13.harmonic spectrum for source current with compensation

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Case 2: Performance of SHPF-TCR for harmonic and reactive type load

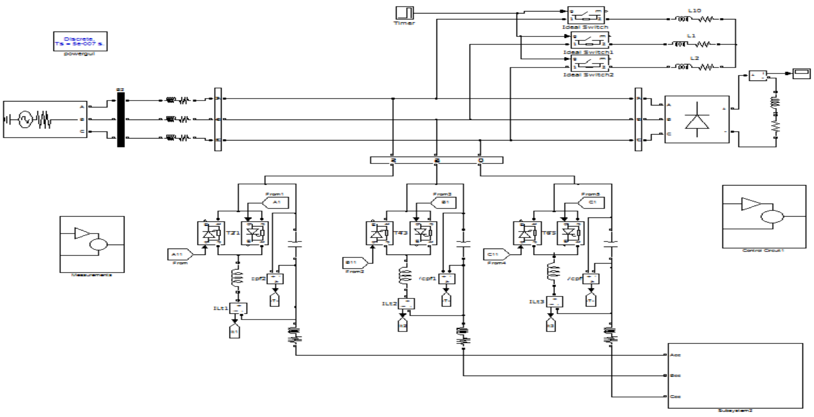

Fig.16.Simulink circuit for SHAF-TCR for harmonic and reactive type load

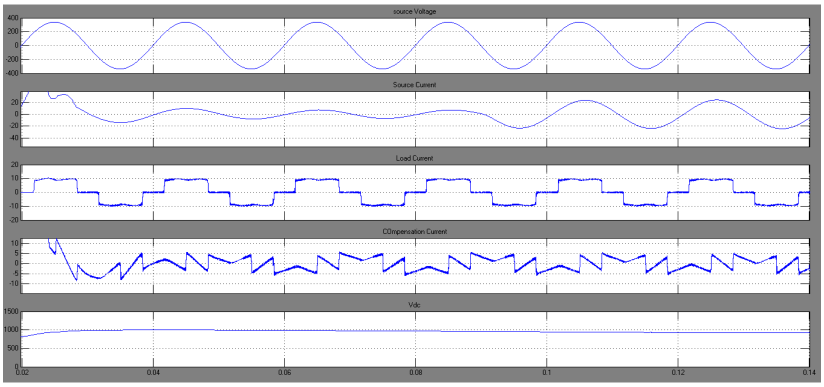

Fig.17.Simulation results for source voltage, source current, load current, compensation currents and dc link voltage

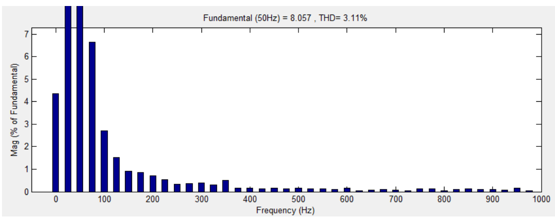

Fig.18.harmonic spectrum for source current with compensation

Case 4: Performance of SHPF-TCR for harmonic generated load with fuzzy controller

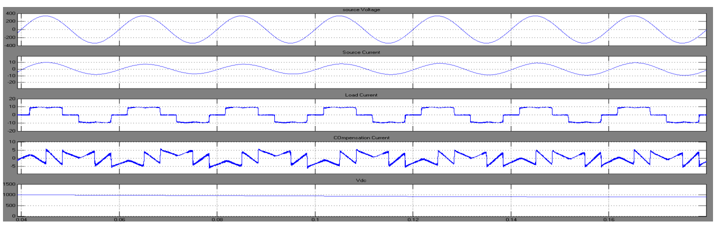

Fig.19.Simulation results for source voltage, source current, load current, compensation currents and dc link voltage

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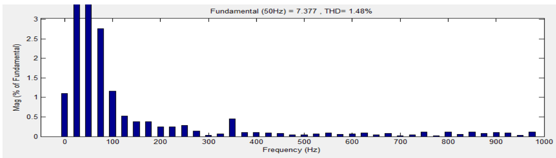

Fig.20.harmonic spectrum for source current with compensation

VII. CONCLUSION

In this paper, a SHPF-TCR compensator of a TCR and a SHPF has been proposed to achieve harmonic elimination and reactive power compensation. A proposed nonlinear control scheme of a SHPF-TCR compensator has been established, simulated, and implemented by using the DS1104 digital real time controller board of d SPACE. The shunt active filter and SPF have a complementary function to improve the performance of filtering and to reduce the power rating requirements of an active filter. The scheme has the advantage of simplicity and is able to provide self-supported dc bus of the active filter through power transfer from ac line at fundamental frequency. The performance of conventional PI controller and fuzzy controller has been studied and compared. Overall, the fuzzy controller gives the best SAPF performance in comparison with the PI controller in regards voltage regulation, 1.56% THD, settling time, current overshoot etc.

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