# Power Quality Improvement using Shunt Hybrid Power Filter (SHPF) and Thyristor Controlled Reactor (TCR)

S. Asha[1], B.Viswanath[2]

PG Scholar, Dept. of EEE, Vignan's Institute of Information Technology, Visakhapatnam, India[1]

Associate Professor, Dept. of EEE, Vignan's Institute of Information Technology, Visakhapatnam, India[2]

**ABSTRACT:**To improve the Power Quality of power supply system, this paper presents a study on       Shunt Hybrid Power Filter (SHPF) and Thyristor Controlled Reactor (TCR) compensator to reduce harmonics generated by different types of non-linear loads and provide reactive power compensation. The small rated Active Power Filter (APF) is used to improve filtering characteristics of the passive filter and isolate the line inductance from passive filter to avoid the possibility of resonance. The TCR is controlled using a PI controller and a look up table to extract the required firing angle which is used to compensate the reactive power consumed by the load.A decoupled control strategy is used to control APF for current tracking and voltage regulation. The control system may be divided into an inner fast current loop and outer slow voltage loop. Integral compensators are added in both current and voltage loops in order to eliminate the steady state errors.  The simulation study on SHPF-TCR compensator has been implemented using MATLAB/SIMULINK software and the simulation results are found to be quite satisfactory to suppress harmonic distortions and provide effective reactive power compensation.

**KEYWORDS:-**Hybrid power filter, modeling, reactive power compensation, nonlinear control, shunt hybrid power filter and thyristor controlled reactor (SHPF-TCR).

## I.INTRODUCTION

Nonlinear loads results in poor Power Quality, as they result in current distortion with poor input power factor (PF), voltage distortion, reactive power etc. which create serious problems at the power supply system. Earlier, passive filters were been used to eliminate current harmonics in the system. Due to the resonance problem that may occur between line inductance and passive filter, active filters are developed. These active filters though provide power quality improvement effectively, are not preferred due to high rating and high cost as they need to handle all the harmonic components. To overcome these drawbacks of both passive filter and active filter, hybrid filters are developed.

There are many configurations possible with hybrid filters. The most suitable configuration is selected based on the power quality problems and the non-linear loads. A nonlinear control technique for a three-phase Shunt Hybrid Power Filter (SHPF) to enhance its dynamic response when it is used to compensate for harmonic currents and reactive power. The "dq" frame model is divided into two separate loops, namely, the two current dynamic inner loops and the dc-voltage dynamic outer loop.PI controllers are utilized to control the SHPF input currents and dc-bus voltage. [2]The series and parallel resonance may occur between passive and line impedance. Active filters were developed to mitigate problems of passive filters [3]. To eliminatethe problem of passive and active filters, Hybrid filters provide economic harmonic compensation, especially for high-power nonlinear loads [4]–[5]. In this configuration, the Neutral Point Clamped (NPC) inverter is used to supply the total active power while the H-bridges operate as series active filters for the harmonic compensation of the NPC output voltage. In [6], a combination of a resonant impedance-type hybrid APF and athyristor controlled reactor (TCR) for harmonic mitigation, load balancing and reactive power compensation is presented. The controltechnique is based on the voltage vector transformation for compensating the negative-sequencecurrent due to the unbalance load without using Phase Locked Loop. A predictive current controller based on theSmith predictor isproposed to compensate the generalized current delay. A combined system of a Static VarCompensator (SVC) and a small-rated APF for harmonic suppression and reactive power compensation has been

reported in [7]. A combination of a three-phase three-level Neutral Point Clamped (NPC) inverter connected in series with a three-level H-bridge inverter with a novel control scheme to control the floating voltage source of the H-bridge stage has been presented in [8].

The control technique of TCR consists of a PI controller and a lookup table for the firing angle extraction to provide the reactive power compensation. A decoupled control of SHPF is implemented for current tracking and voltage regulation purposes. It considers that the controlled system can 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 50V. The proposed   control scheme has been simulated 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 voltage and the source current. The proposed technique is tested for a wide range of loads as discussed further. Simulation results show that the proposed configuration is suitable for effective harmonic mitigation and reactive compensation.

### II.SYSTEM CONFIGURTION OF SHPF-TCR COMPENSATOR

The configuration of the proposed SHPF-TCR compensator is depicted in Fig. 1. The SHPF is a fifth tuned passive filter connected in series with small rating APF. The APF has a three-phase full bridge pulse width modulated voltage source inverter with an input boost inductor ($L_{pf}$, $R_{pf}$) and a dc bus capacitor ($C_{dc}$). The combination of the passive filter connected in parallel with TCR forms a shunt passive filter. The objective of tuned passive filter is for harmonic compensation and power factor correction and the objective of the active filter is isolate the system impedance from the filter impedance to avoid resonance. The active filter is also participates in suppressing harmonics due to the load and TCR by enhancing the compensation characteristics of shunt passive filter. Though     SHPF suppresses the harmonics effectively, reactive power cannot be compensated due to the passive filter. Hence to inorder to regulate reactive power TCR is preferred. The non-liner loads considered are three-phase diode rectifier with RL load, three phase diode rectifier with RC load, three phase voltage controller.

### III.MODELING AND CONTROL STRATEGY

*A.Modeling of SHPF*

The system equations are first written in 123 reference frame. Using Kirchhoff's voltage law,

$$V_{s1} = L_{PF} \frac{di_{c1}}{dt} + R_{PF} i_{c1} + v_{CPF1} + v_{1M} + v_{MN} \quad (1)$$

$$V_{s2} = L_{PF} \frac{di_{c2}}{d\,t} + R_{PF} i_{c2} + v_{CPF2} + v_{2M} + v_{MN} \quad (2)$$

$$V_{s3} = L_{PF} \frac{di_{c3}}{dt} + R_{PF} i_{c3} + v_{CPF3} + v_{3M} + v_{MN} \quad (3)$$

$$v_{CPF1} = L_T \frac{di_{c1}}{dt} - C_{PF} L_T \frac{d^2 v_{CPF1}}{dt^2} \quad (4)$$

$$v_{CPF2} = L_T \frac{di_{c2}}{dt} - C_{PF} L_T \frac{d^2 v_{CPF2}}{dt^2} \quad (5)$$

$$v_{CPF3} = L_T \frac{di_{c3}}{dt} - C_{PF} L_T \frac{d^2 v_{CPF3}}{dt^2} \quad (6)$$

$$\frac{dv_{dc}}{dt} = \frac{1}{C_{dc}} i_{dc} \quad (7)$$

The switching function$C_k$ of the $k_{th}$ leg of the converter (for k=1, 2 ,3) is defined as

$$C_k = \begin{cases} 1, & if\ S_k\ is\ on\ and\ S_k'\ is\ off \\ 0, & if\ S_k\ is\ off\ and\ S_k'\ is\ on. \end{cases} \quad (8)$$

A switching state function $d_{nk}$ is defined as

$$d_{nk} = (C_k - \tfrac{1}{3}\textstyle\sum_{m=1}^{3} C_m)_n \quad (9)$$

Taking an assumption that the system is a balanced 3ph 3-wire system. From the assumption, one can deduce
(i) Zero sequence currents are absent.
(ii) Sum of 3-ph voltages at PCC point and 3-ph compensating currents are equal to zero i.e.

$$V_{s1} + V_{s2} + V_{s3} = 0 \text{ and}$$
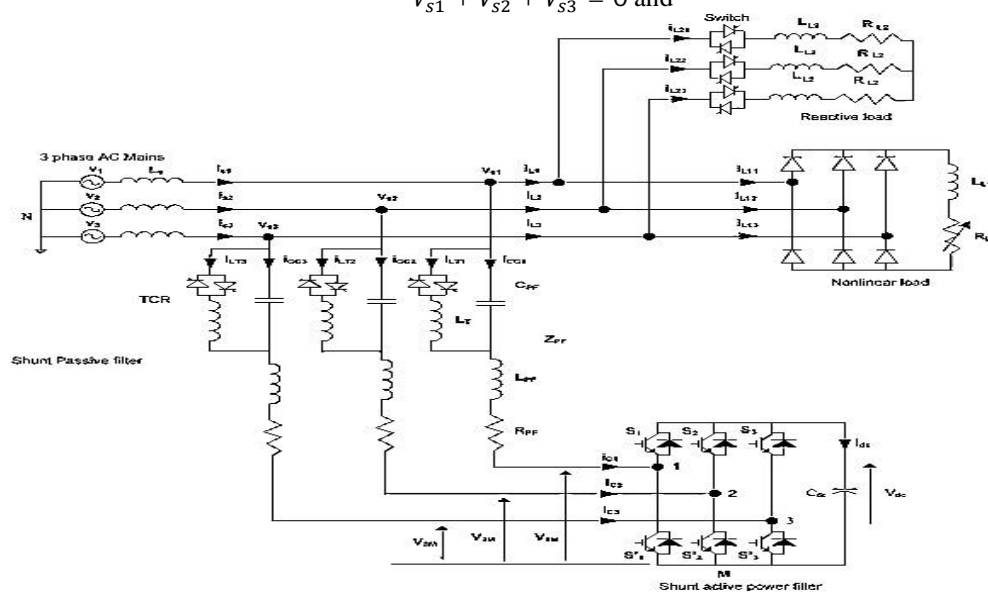


Fig.1. Basic Circuit of Proposed SHPF-TCR Compensator

Applying the assumptions, the modeling equations of SHPF are obtained as given below:

$$L_{PF}\frac{d}{dt}[i_{c123}] = -R_{PF}[i_{c123}] - [d_{n123}]v_{dc} - [v_{CPF123}] + [V_{s123}] \quad (11)$$

$$\frac{d}{dt}[i_{dq}] = \frac{-R_{PF}}{L_{PF} + L_T}[i_{dq}] - \frac{1}{L_{PF} + L_T}[d_{ndq}]v_{dc} - \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}[i_{dq}] + \frac{C_{PF}L_T}{L_{PF} + L_T}\frac{d^2}{dt^2}[v_{CPFdq}]$$

$$+ \frac{C_{PF}L_T}{L_{PF}+L_T}\begin{bmatrix} -\omega^2 & 0 \\ 0 & -\omega^2 \end{bmatrix}[v_{CPFdq}] + \frac{2c_{PF}L_T}{L_{PF}+L_T}\begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\frac{d}{dt}[v_{CPFdq}] + \frac{1}{L_{PF}+L_T}[V_{dq}] \quad (12)$$

This model is nonlinear as there are multiplication terms between the state variables $\{i_d, i_q, V_{dc}\}$ and the switching state function $\{d_{nd}, d_{nq}\}$.

*B.Harmonic Current Control*

The control of SHPF is implemented using a decoupled control strategy for current tracking and voltage regulation. The decoupled control strategy considers thecontrolled system divided into an inner fast loop and an outer slow dc voltage loop. By using the Park's transformation, the decoupled dynamics of the current tracking is obtained. Thus, the control of currents idand iqcan be done independently. Then by using proportional integral compensation, zero steady error and fast dynamic response is obtained. The equations of the tracking controllers are obtained as follows:

$$u_d = (L_{PF}(1 - C_{PF}L_T\omega^2) + L_T)\frac{di_d}{dt} + R_{PF}(1 - C_{PF}L_T\omega^2)i_d = k_p\tilde{\imath}_d + k_i\int \tilde{\imath}_d dt \quad (13)$$

$$u_q = (L_{PF}(1 - C_{PF}L_T\omega^2) + L_T)\frac{di_{dq}}{dt} + R_{PF}(1 - C_{PF}L_T\omega^2)i_q = k_p\widetilde{i_q} + k_i\int \widetilde{i_q}dt \qquad (14)$$

The switching state function for the SHPF is obtained as follows.

$$d_{nd} = \frac{1}{(1 - C_{PF}L_T\omega^2)v_{dc}}\left[\omega(L_{PF}(1 - C_{PF}L_T\omega^2) + L_T)i_q - (L_{PF}(1 - C_{PF}L_T\omega^2) + L_T)u_d + (1 - C_{PF}L_T\omega^2)v_d\right](15)$$

$$d_{nq} = \frac{1}{(1 - C_{PF}L_T\omega^2)v_{dc}}\left[\omega(L_{PF}(1 - C_{PF}L_T\omega^2) + L_T)i_d - (L_{PF}(1 - C_{PF}L_T\omega^2) + L_T)u_q + (1 - C_{PF}L_T\omega^2)v_q\right] \qquad (16)$$

Where$\widetilde{i_d} = i_d^* - i_d$and $\widetilde{i_q} = i_q^* - i_q$are current errors and$i_d^*$and $i_q^*$ denote reference signals of  $i_d$ and $i_q$ respectively.The transfer function of the PI controllers is given as

$$G_{i1}(s) = \frac{u_d(s)}{\tilde{i}_d(s)} = k_{p1} + \frac{k_{i1}}{s} \qquad\qquad G_{i2}(s) = \frac{u_q(s)}{\tilde{i}_q(s)} = k_{p2} + \frac{k_{i2}}{s} \qquad (17)$$
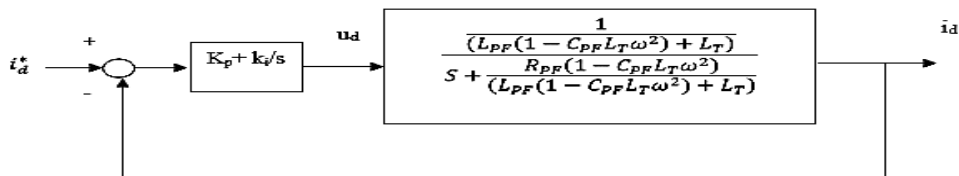


Fig.2.   Inner control loop of the current i$_d$.

The inner control loop of current i$_d$ is shown in Fig. 2. The closed loop transfer function of the current loops are

$$\frac{I_d(s)}{I_d^*(s)} = \frac{k_{p1}}{A}\frac{(s + \frac{k_{i1}}{k_{p1}})}{s^2 + \left(\frac{B + k_{p1}}{A}\right)s + k_{i1}} \quad (18)$$

$$\frac{I_q(s)}{I_q^*(s)} = \frac{k_{p2}}{A}\frac{(s + \frac{k_{i2}}{k_{p2}})}{s^2 + \left(\frac{B + k_{p2}}{A}\right)s + k_{i2}} \quad (19)$$

Where$A = L_{PF}(1 - C_{PF}L_T\omega^2) + L_T$ and$B = R_{PF}(1 - C_{PF}L_T\omega^2)$  ,
Comparing the above equations with general closed loop transfer function, the design relations can be derived as follows:
$$k_{p1} = k_{p2} = 2\varepsilon\omega_{ni}(L_{PF}(1 - C_{PF}L_T\omega^2) + L_T) - R_{PF}(1 - C_{PF}L_T\omega^2) \quad (20)$$
$$k_{i1} = k_{i2} = (L_{PF}(1 - C_{PF}L_T\omega^2) + L_T)\omega_{ni}^2$$
Where $\omega_{ni}$ is the outer loop natural frequency

*C.DC Bus Voltage Regulation*

The active filter produces a fundamental voltage which is in-phase with fundamental leading current of the passive filter. A small amount of active power is formed due to the leading current and fundamental voltage of the passive filter and it delivers to the dc capacitor. Therefore, the electrical quantity adjusted by the dc-voltage controller is consequently i$_q$. To maintain V$_{dc}$ equal to its reference value, the losses through the active filter's resistive-inductive branches will be compensated by acting on the supply current.

The third model equation is rewritten as

$$C_{dc}\frac{dv_{dc}}{dt} + \frac{v_{dc}}{R_{dc}} = d_{nq}i_q \quad (21)$$

The fundamental filter rms current I$_{C\text{ is}}$

$$I_C = \frac{i_q}{\sqrt{3}}. \quad (22)$$

The q-axis active filter voltage $v_{Mq}$ is expressed

$$v_{Mq} = q_{nq}v_{dc} = -Z_{PF1}i_{q1}^* \quad (23)$$

Where $Z_{PF1}$ is the impedance of the passive filter at 60 Hz and $i_{q1}^*$ is a dc component. An equivalent input $u_{dc}$ is defined as

$$u_{dc} = d_{nq}i_q. \quad (24)$$

The control effort of the dc voltage loop is deduced as

$$i_{q1}^* = \frac{v_{dc}}{-Z_{PF1}i_q}u_{dc} \quad (25)$$

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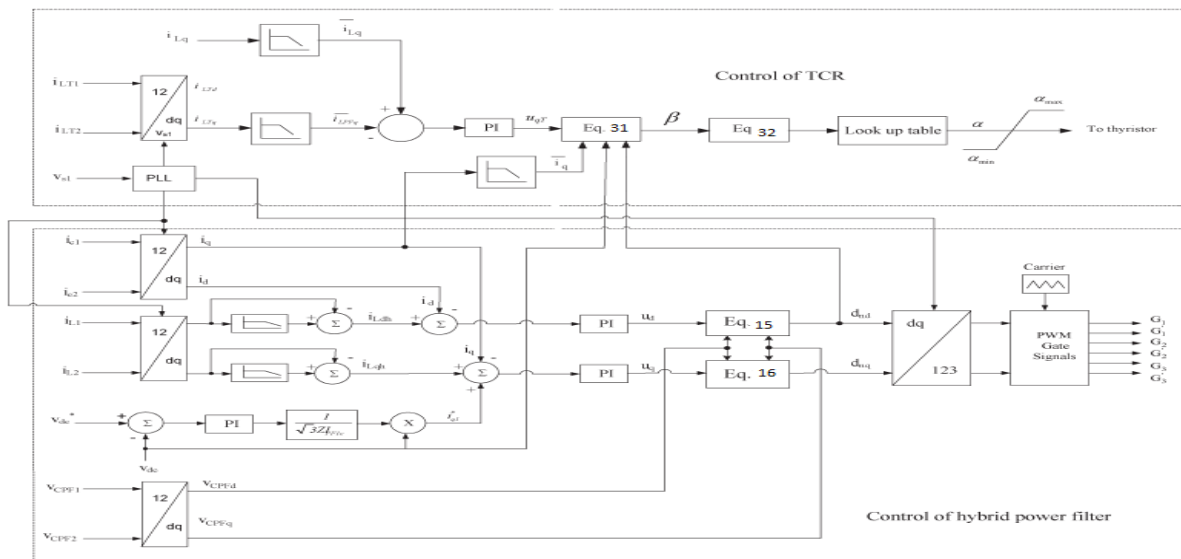


Fig.3. Control Scheme of SHPF-TCR Compensator.

To control the dc voltage $V_{dc}$, the error obtained when comparing the reference value with the actual value of $V_{dc}$ voltage is passed through a PI- type controller. Fig. 4 depicts the outer control loop of the dc bus voltage.
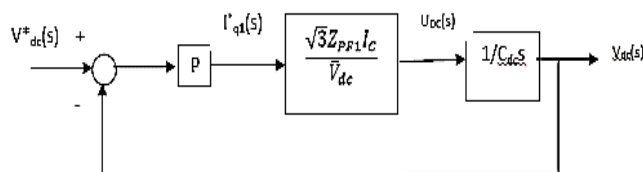


Fig.4. Outer Control Loop of DC Bus Voltage.

By designing the dc bus voltage loop slower than the inner current loop, there would be not be any interaction between the two loops. The non-linear controller of the SHPF-TCR compensator is shown in Fig. 3.

## IV.MODELING OF TCR

The equivalent circuit of TCR is shown in Fig. 5.
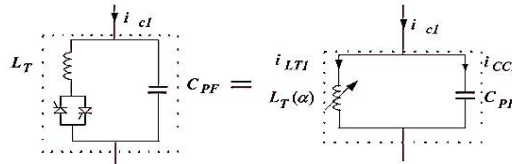


Fig.5.   Equivalent Circuit of TCR.

Using Kirchhoff' voltage law , the modeling equations of TCR are obtained as follows:

$$V_{S1} = L_T \frac{di_{LT1}}{dt} + L_{PF} \frac{di_{c1}}{dt} + R_{PF}i_{c1} + d_{n1}v_{dc}$$

$$V_{S2} = L_T \frac{di_{LT2}}{dt} + L_{PF} \frac{di_{c2}}{dt} + R_{PF}i_{c2} + d_{n2}v_{dc}$$

$V_{S3} = L_T \frac{di_{LT3}}{dt} + L_{PF} \frac{di_{c3}}{dt} + R_{PF}i_{c3} + d_{n3}v_{dc}$ (26)

On applying Park's transformation, the modeling equations of TCR are obtained as

$$L_T \frac{d}{dt}\left[C_{12}^{dq} i_{LTdq}\right] = -L_{PF} \frac{d}{dt}\left[C_{12}^{dq} i_{dq}\right] - R_{PF}\left[C_{12}^{dq} i_{dq}\right] - \left[C_{12}^{dq}\right]\left[d_{ndq}\right]v_{dc} + \left[C_{12}^{dq}\right]\left[V_{dq}\right] \text{ (27)}$$

$$L_T \frac{d}{dt} i_{LTq} = -L_T \omega i_{LTd} - L_{PF} \omega i_d - L_{PF} \frac{d}{dt} i_q - R_{PF} i_q - d_{nq}V_{dc} + V_q \quad (28)$$

Only the reactive part is chosen to control the reactive current so that $V_q=0$ and $L_f(\alpha)\omega i_{LTd}=0$.

$\frac{d}{dt} i_{LTq} = B(\alpha)\omega \left[-L_{PF}\omega i_d - L_{PF}\frac{d}{dt}i_q - R_{PF}i_q - \ d_{nq}V_{dc}\right]$(29)

Where $B(\alpha)=1/L_F(\alpha)\omega$ is the susceptance.An equivalent input $U_{qT}$ is defined as

$$U_{qT} = \frac{di_{LTq}}{dt} \qquad\qquad (30)$$

According to this expression, one deduces

$B(\alpha) = U_{qT}/\omega \left[-L_{PF}\omega i_d - L_{PF}\frac{d}{dt}i_q - R_{PF}i_q - \ d_{nq}V_{dc}\right]$  (31)

On the other hand, the equivalent inductance is given by

$L_{PF}(\alpha) = L_{PF} \frac{\pi}{2\pi - 2\alpha + \sin 2\alpha}$  (32)

The susceptance is given by

$B(\alpha) = B \frac{2\pi - 2\alpha + \sin 2\alpha}{\pi}$ (33)

where $B=1/L_{PF}\omega_0$.

For the control of TCR, the reactive component of load current ($i_{Lq}$)is measured and is passed through a LPF and then it is compared with $i_{LTq}$. The error so obtained is fed to a PI controller which forces the reactive current of the SHPF-TCR compensator to follow exactly the reactive current consumed by the load.

## V.SIMULATION RESULTS

The system specification parameters are given in Table I. Simulations of the proposed system were performed numerically using the "Power System Block-set" simulator operating under Matlab/Simulink environment. The system has been evaluated by performing a number of tests for each non-linear load: 1) without any filter 2) with SHPF-TCR compensator.

TABLE I
SYSTEM SPECIFICATION PARAMETERS

| | |
|---|---|
| L-L source voltage, and frequency | $V_{S-L-L}$=440V, $f_s$=60Hz |
| Line impedance | $L_S$=0.5mH,$R_S$=0.1Ω |
| Diode Rectifier with RL load | $L_{L1}$=10mH ,$R_{L1}$=40Ω |
| Diode Rectifier with RC load | $R_{L2}$=26Ω,$C_{L2}$=µF |
| Voltage controller | $L_{L1}$=20mH ,$R_{L1}$=27Ω |
| Passive filter parameters | $L_{PF}$=2.2mH,$C_{PF}$=120µF,$R_{PF}$=0.55 |
| Active filter parameters | $C_{dc}$=3000µF,$R_{dc}$=1000Ω |
| DC bus voltage of APF of SHPF | $V_{dc}$=50V |
| Switching frequency | 1920 Hz |
| Inner controller parameters | $K_{P1}$=43.38,$K_{P2}$=43.38 ;$K_{i1}$=374,$K_{i2}$=374 |
| Outer controller parameters | $K_1$=0.26,$K_2$=42 |
| Cut off frequency of the low pass filters | $F_C$=Hz |
| TCR inductance | $L_T$=25mH |
| TCR controller parameters | $K_P$=0.98,$K_I$=15 |

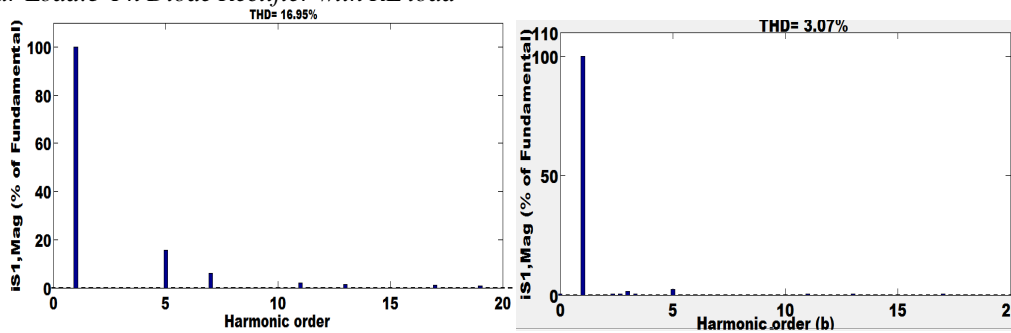*A. Non-linear Load:3-Ph Diode Rectifier with RL load*



Fig.6(a).Harmonic Spectrum of Source Current in phase 1 (a) before compensation. (b) after compensation
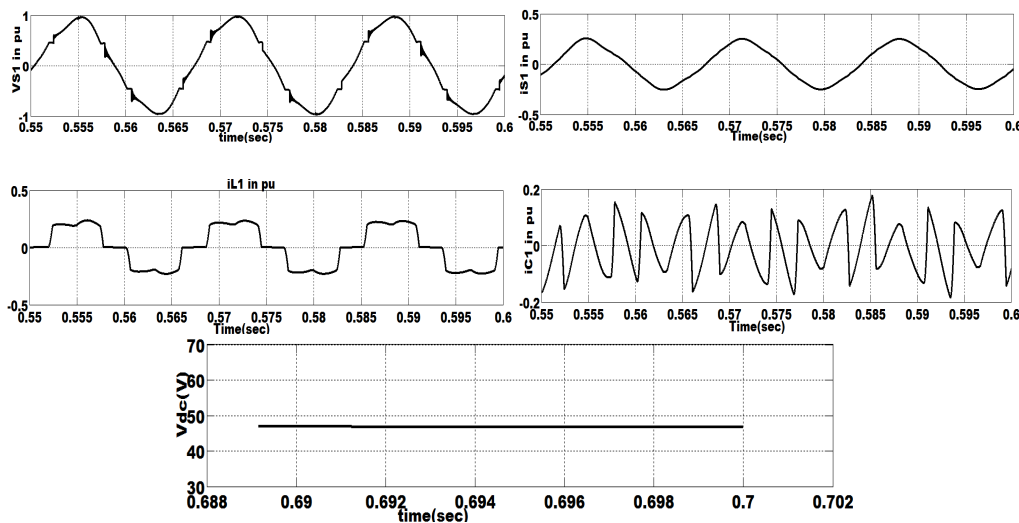


Fig. 6(b).Steady State Response of the SHPF-TCR Compensator with 3-Ph Diode Rectifier with RL

Fig. 6(a) shows the harmonic spectrum of source current in phase 1 with Diode Rectifier with RL load before nd after compensation. Fig.6(b) shows the response of the system with SHPF-TCR compensator with non-linear load(Diode Rectifier with RL load).The supply voltage($V_{S1}$), supply current($i_{s1}$),load current($i_{L1}$),filter current($i_{C1}$), dc bus voltage ($V_{dc}$ ) are depictedin this figure. The THD of the supply current is brought down from 16.95%to3.07%.
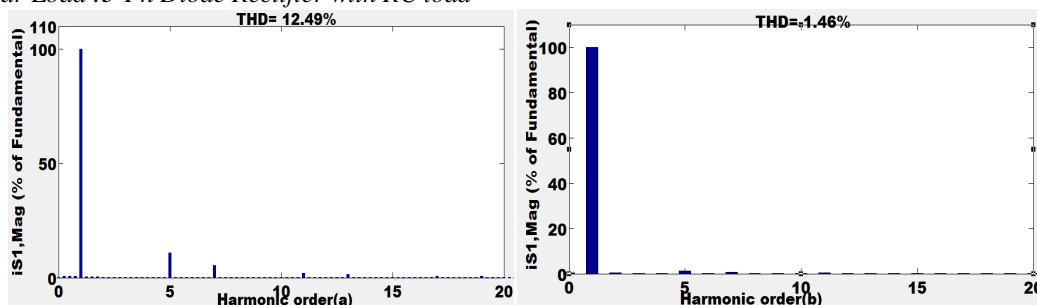
*B.Non-linear Load :3-Ph Diode Rectifier with RC load*



Fig. 7(a).Harmonic Spectrum of Source Current in Phase 1 (A) Before Compensation.   (B) After Compensation
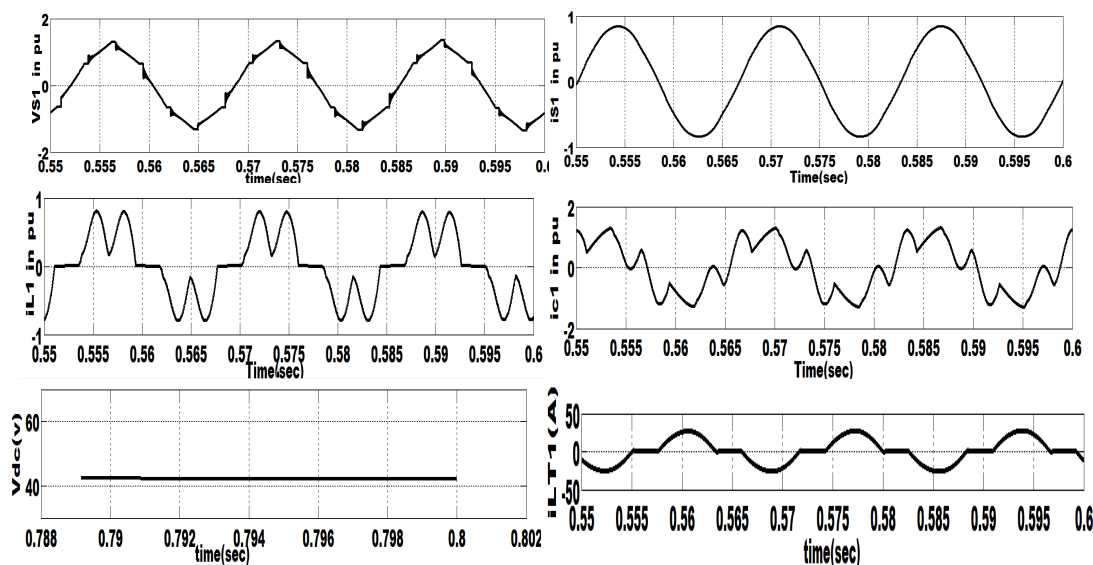


Fi    Fig. 7(b).Steady State Response of SHPF-TCR Compensator with 3-Ph Diode Rectifier with RC Load    and after compensation. Fig.7(b) shows the response of the system with SHPF-TCR compensator with non-linear load (Diode Rectifier with RC load) .The supply voltage($V_{S1}$), supply current($i_{s1}$),load current($i_{L1}$),filter current($i_{C1}$), $V_{DC}$, TCR current($i_{T1}$) are depicted in this figure. The THD of the supply current is brought down from 12.49% to 1.46%.
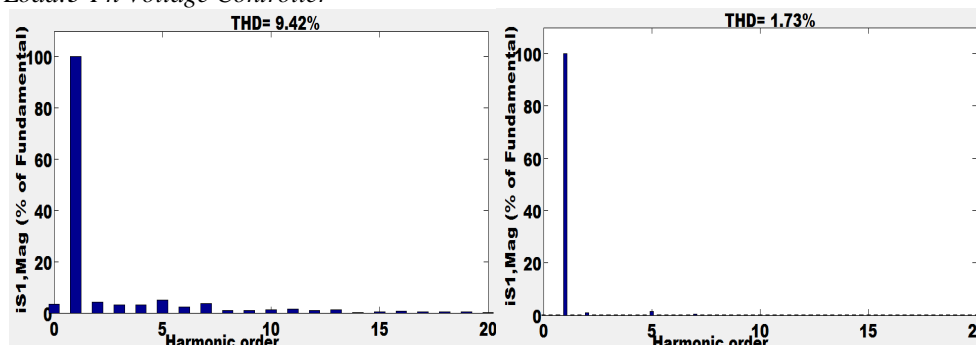
*C.Non-linear Load:3-Ph Voltage Controller*



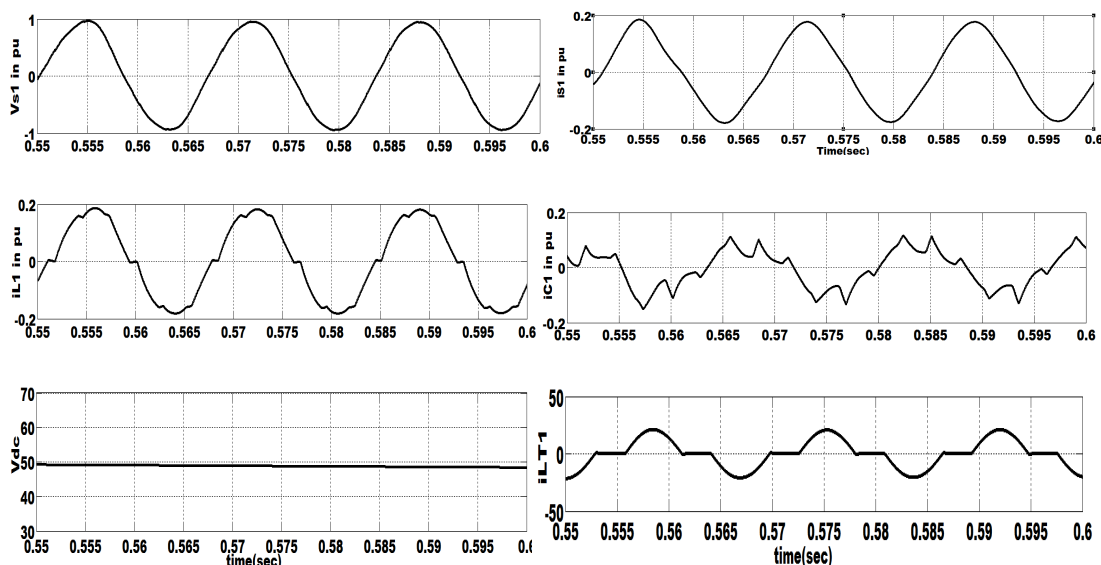Fig. 8(a). Harmonic Spectrum of Source Current in Phase 1 (a) before compensation. (b) After compensation

Fig. 8(b).Steady State Response of SHPF-TCR Compensator with 3-Ph Voltage Controller with RL Load.

Fig. 8(a) shows the harmonic spectrum of source current in phase 1 with 3-ph Voltage Controller with RL load. Fig. 8(b) shows the response of the system with SHPF-TCR compensator with non-linear load(3-ph Voltage Controller with RL load) .The supply voltage($V_{S1}$), supply current($i_{s1}$),load current($i_{L1}$),filter current($i_{C1}$), dc bus voltage ($V_{dc}$ ), TCR current($i_{LT1}$)are depicted in this figure. The THD of the supply current is brought down from 9.42% to 1.73%.

## VI.CONCLUSION

In this paper, a SHPF-TCR compensator is presented to achieve harmonic elimination andreactive power compensation. A nonlinear controlscheme of a SHPF-TCR compensator has been simulated. The shunt active filter andSPF have a complementary function to improve the performanceof filtering and to reduce the power rating requirementsof an active filter. It has been found that the SHPF-TCR compensatorcan effectively eliminate current harmonic and reactive power compensation for a variety of loads and is able to reducethe THD of supply currents well below the limit of 5% of theIEEE-519 standard.Here three types of non-linear load i.e. Diode Rectifier with RL load and Diode Rectifier with RCload and 3-ph Voltage Controller are implemented. The harmonic current control and DCcapacitorvoltage can be regulated under these three non-linear loads.

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