Simulation and Performance Evaluation of Shunt Hybrid Power Compensator Using a Control Method Based on Lyapunov Function for Power Quality Improvement

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Abstract: This paper deals with design and simulation of a three phase shunt hybrid power compensator consisting of a pair of 5^{th} and 7^{th} selective harmonic elimination passive power filters connected in series with a conventional active power filter with reduced kVA rating. The objective is to enhance the power quality in a distribution network feeding variety of nonlinear, time varying and unbalanced loads. In this work, a control scheme based an energy function using Lyapunov method has been formulated for a shunt hybrid power filter. The developed control law is based on synchronous rotating reference frame theory, which generates a state variable model of the nonlinear system which is linked to development of a switching function based scheme for controlling the active component of the hybrid filter. The stability of the state model following disturbances at the operating point is examined by introducing an energy function for applying Lyapunov's direct method. Here the derivative of the Lyapunov energy function is made to be negative definite by suitable choice of parameters for ensuring stability and quick response. The performance of the shunt hybrid compensation topology along with the proposed control strategy for balanced, unbalanced and various other loading conditions have been evaluated by simulation of the entire system in Matlab/Simulink platform. It is found that the designed hybrid compensator results in enhanced power quality in the distribution system, satisfying IEEE 519-1992 standards.

Keywords: Harmonics; Total Harmonic Distortion; Hybrid filter; direct method of Lyapunov, Power quality.

1. INTRODUCTION

A 3-phase power distribution system has to cater to various types of balanced and unbalanced linear and nonlinear loads. Since linear loads draw only sinusoidal currents, they do not contribute to power quality problems. On the other hand, nonlinear loads draw non sinusoidal currents resulting in introduction of harmonic frequency components in line currents and consequently the load side voltages which deteriorate quality of power delivered (Dugan et al., 2003). Based on their applications, the nonlinear loads can be further classified as voltage-fed or current-fed cases. Majority of the industrial utilities are three phase nonlinear loads, which demand special attention owing to their widespread use. These applications range from low end utilities such as battery chargers and low power dc supplies to high end uses such as adjustable speed drives, UPS etc (Tosak and Somchai, 2009). The harmonic levels, so generated, are highly detrimental to the efficiency of various appliances like transformers, motors etc due to excess heating, vibration and noise. This paper pertains to the power quality improvement of nonlinear voltage fed and current fed loads as shown in Fig.1.

Extensive research works has been carried out for the reduction of such harmonics and improve the reliability of the distribution system (Das, 2004; Singh et al., 2005; Na et al., 2009; Darwin et al., 2003). According to IEEE 519-1992 standard pertaining to low/medium voltage distribution system, the level of harmonic distortion as indicated by the total harmonic distortion (*THD*) has to be kept within 5%. It is a well known fact that the THD due to a nonlinear load can be minimized to a large extent by employing active and passive power filtering (PPF) techniques. The existing passive filtering techniques, even though being economical, are characterized by large size of their reactive elements, resonance with system impedance and related power losses. A solution to this problem is through the introduction of active power filters (APF). Active filtering, which is a power electronic converters based technique, is characterized by higher complexity, cost and switching noises (Salem et al., 2006; Haddad et al., 2016). Based on the connection with nonlinear load, these filters are categorized into two different types namely shunt and series active filter (El-Habrouk et al., 2000). Shunt active filters are not suitable for high peak harmonic current loads and it is best suited for nonlinear loads of current source type and not for the nonlinear loads of voltage source type (Salem R et al., 2006). Series active filters are connected in series with harmonic producing loads causes interfacing transformer current rating is high and equal to the load current. Hence, the Size of the filter is large due to its current rating and losses are more (Peng FZ, 1998; Nastran et al., 1994; Campos et al., 1994).

The problems associated with the above techniques can be mitigated by choosing hybrid active power filter (HAPF), which leads to performance improvement in passive filtering with cost effective solution. In general, the role of the passive filter in a hybrid topology is to mitigate the lower order dominant harmonics, whereas the active filter takes care of the function of eliminating higher order harmonics (Khanna et al., 2011; Fujita et al., 2000). As a result the major burden on the harmonic reduction is taken care by passive filter components, thereby reducing the rating and size of the APF. (Singh et al., 2005) have suggested a lot of HAPF topologies to mitigate the power quality issues in a power distribution system. Peng et al. have proposed series active filter and shunt connected passive filter topology on 1990 in 3-phase 3-wire system and the same topology for 3-phase 4-wire system has been proposed by Salmeron and Litran on 2010 respectively. Khositkame and Sangwongwanich have proposed shunt active filter and shunt connected passive filter topology with coupling transformer in 1997 and Corasaniti et al. also proposed the same in 2009. An APF connected in series with PPF topology is free from resonance problem also yields good performance (Ostroznik et al., 2010; Luo et al., 2009; Chandan and Mahesh, 2014; Jou et al., 2008; Subhashish et al., 1997). Even though the HPF topology has been properly chosen for harmonics reduction and compensation reactive power, the control strategy plays an important role in deciding its effective and efficient operation. A number of control techniques such as linear, nonlinear and adaptive controllers have been implemented in the literature to improve the hybrid power filter operation (Salem et al., 2013; Salem et al., 2014; Salem et al., 2009; Salem et al., 2012; Salmeron et al., 2010; An et al., 2010; Komurcugil and Kukrer, 2006; Hua et al., 2008; Albert Alexander and Thathan, 2014). Generally, time domain methods provide fast response, compared with frequency domain methods. Accordingly, many authors have proposed control methods such as instantaneous real and reactive power theory, synchronous rotating reference frame theory (SRF), sliding mode controller, neural network method and feed forward control to enhance the compensation performance of APFs and HPFs. One relevant idea that has not been gained much attraction is related to the introduction of Lyapunov function based controller in the hybrid compensation scheme for handling the inherently present nonlinear control problems.

The present paper portrays a control scheme based on Lyapunov function for 3-phase hybrid active power filtering technique to achieve global stability, while reducing the harmonic level in the distribution system to less than 5% as specified by IEEE 519 standard. This method of control with negligible time delay in extracting the reference current for compensation does not depend on the load and filter circuit parameters.

2. SYSTEM CONFIGURATION OF 3-PHASE SHUNT HYBRID COMPENSATOR

Fig.1 depicts the three phase distribution circuit feeding different types balanced and unbalanced nonlinear loads along with the proposed hybrid filter. The hybrid filter consists of a fixed selective harmonic elimination shunt passive filter for eliminating the 5th and 7th harmonic currents drawn by the load and a IGBT's 6 pulse based voltage source inverter terminated on a dc bus capacitor. The controller implements a nonlinear reference current generation which is instrumental in Pulse Width Modulation (PWM) generation at the gates of IGBT's.

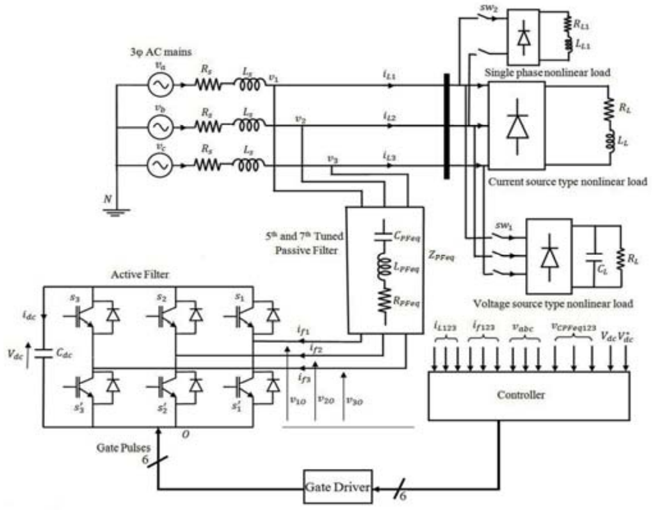


Fig. 1. Configuration of the shunt HAPF.

3. SHUNT HYBRID COMPENSATOR MODELING

By applying Kirchhoff's voltage and current laws for the hybrid scheme shown in Fig.1 the following equations in differential form in *abc* coordinates are obtained (Luo et al., 2009). Here L_{PFeq}, R_{PFeq} and C_{PFeq} are the equivalent parameter values of the 5th and 7th selective harmonic passive filters.

$$v_1 = L_{PFeq}\frac{di_{f1}}{dt} + R_{PFeq}\ i_{f1} + v_{CPFeq1} + V_{1O} + V_{ON} \tag{1}$$

$$v_2 = L_{PFeq}\frac{di_{f2}}{dt} + R_{PFeq} i_{f2} + v_{CPFeq2} + V_{2O} + V_{ON} \tag{2}$$

$$v_3 = L_{PFeq}\frac{di_{f3}}{dt} + R_{PFeq} i_{f3} + v_{CPFeq3} + V_{3O} + V_{ON} \tag{3}$$

$$i_{f1} = C_{PFeq}\frac{dv_{CPFeq\ 1}}{dt} \tag{4}$$

$$i_{f2} = C_{PFeq}\frac{dv_{CPFeq\ 2}}{dt} \tag{5}$$

$$i_{f3} = C_{PFeq}\frac{dv_{CPFeq\ 3}}{dt} \tag{6}$$

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} i_{dc} \tag{7}$$

For a balanced supply system the sum of instantaneous phase voltages and passive filter capacitor voltages are zero. Further voltage v_{ON} is expressed in terms of v_{1O}, v_{2O}, v_{3O} as follows.

$$v_{ON} = -\frac{1}{3}\sum_{j=1}^{3} v_{jO} \tag{8}$$

The three output voltages v_{kO} of active filter can be expressed using the switching function q_k (Salem et al., 2014) which indicates the leg-wise logic level.

Thus, $v_{kO} = q_k V_{dc}$ where, k=1, 2, 3.

Equations (1) - (3) can be combined and written in the following form.

$$\frac{di_{fk}}{dt} = \frac{-R_{PFeq}}{L_{PFeq}} i_{fk} - \frac{v_{CPFeqk}}{L_{PFeq}} - \frac{1}{L_{PFeq}} \left[q_k - \frac{1}{3} \sum_{j=1}^{3} q_j \right] V_{dc} + \frac{v_k}{L_{PFeq}} \tag{9}$$

The switching state function d_{nk} is defined as,

$$d_{nk} = \left[q_k - \frac{1}{3} \sum_{j=1}^{3} q_j \right]_n$$

Transformation of the $[q_k]$ variables into $[d_{nk}]$ takes the following form.

$$\begin{bmatrix} d_{n1} \\ d_{n2} \\ d_{n3} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} \tag{10}$$

Analyzing the dc components of voltages and currents in the active filter leads to the following equation (Salem et al., 2009).

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} i_{dc} = \frac{1}{C_{dc}} \sum_{j=1}^{3} q_j i_{fj} = \frac{1}{C_{dc}} \sum_{j=1}^{3} d_{nj} i_{fj} \, . \tag{11}$$

By considering the nonexistence of zero sequence currents in the distribution system the equation (11) can be expressed as,

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} \left(2d_{n1} + d_{n2}\right) i_{f1} + \frac{1}{C_{dc}} \left(d_{n1} + 2d_{n2}\right) i_{f2} \tag{12}$$

The entire model of the HAPF system in 3-phase coordinates is given by,

$$\frac{d}{dt} \begin{bmatrix} i_{f1} \\ i_{f2} \\ i_{f2} \end{bmatrix} = \begin{bmatrix} -\frac{R_{PFeq}}{L_{PFeq}} & 0 & -\frac{d_{n1}}{L_{PFeq}} \\ 0 & -\frac{R_{PFeq}}{L_{PFeq}} & -\frac{d_{n2}}{L_{PFeq}} \\ \frac{2d_{n1}+d_{n2}}{C_{dc}} & \frac{d_{n1}+2d_{n2}}{C_{dc}} & 0 \end{bmatrix} \begin{bmatrix} i_{f1} \\ i_{f2} \\ V_{dc} \end{bmatrix} - \frac{1}{L_{PFeq}} \begin{bmatrix} v_{CPFeq1} \\ v_{CPFeq2} \\ 0 \end{bmatrix} + \frac{1}{L_{PFeq}} \begin{bmatrix} v_1 \\ v_2 \\ 0 \end{bmatrix} \tag{13}$$

Transformation of the above model into synchronous orthogonal rotating reference frame by using Park's transformation, equation (13) takes the form as given below.

$$\frac{di_d}{dt} = -\frac{R_{PFeq}}{L_{PFeq}} i_d + \omega i_q - \frac{1}{L_{PFeq}} v_{CPFeqd} - \frac{d_{nd}}{L_{PFeq}} V_{dc} + \frac{1}{L_{PFeq}} v_d \tag{14}$$

$$\frac{di_q}{dt} = -\frac{R_{PFeq}}{L_{PFeq}} i_q - \omega i_d - \frac{1}{L_{PFeq}} v_{CPFeqq} - \frac{d_{nq}}{L_{PFeq}} V_{dc} + \frac{1}{L_{PFeq}} v_q \tag{15}$$

$$\frac{dv_{CPFeqd}}{dt} = \frac{1}{C_{PFeq}} i_d + \omega v_{CPFeqq} \tag{16}$$

$$\frac{dv_{CPFeqq}}{dt} = \frac{1}{C_{PFeq}} i_q - \omega v_{CPFeqd} \tag{17}$$

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} d_{nd} i_d + \frac{1}{C_{dc}} d_{nq} i_q \tag{18}$$

where, d_{nd} and d_{nq} are the switching functions in global.

The following state variables have been chosen $x_1 = i_d - i_d^*$, $x_2 = i_q - i_q^*$, $x_3 = v_{CPFeqd} - v_{CPFeqd}^*$, $x_4 = v_{CPFeqq} - v_{CPFeqq}^*$ and $x_5 = V_{dc} - V_{dc}^*$. i_d^* and i_q^* are the required current reference deduced from load currents, v_{CPFeqd}^* and v_{CPFeqq}^* are the required voltage reference obtained from shunt PPF capacitor (Salem et al., 2012; Hua et al., 2008).

The steady state switching functions are obtained from equations (14) and (15) as follows.

$$D_{nd} = \frac{L_{PFeq}}{V_{dc}^*} \left[-\frac{di_d^*}{dt} - \frac{R_{PFeq}}{L_{PFeq}} i_d^* + \omega i_q^* - \frac{v_{CPFeqd}^*}{L_{PFeq}} + \frac{1}{L_{PFeq}} v_d \right] \tag{19}$$

$$D_{nq} = \frac{L_{PFeq}}{V_{dc}^*} \left[-\frac{di_q^*}{dt} - \frac{R_{PFeq}}{L_{PFeq}} i_q^* - \omega i_d^* - \frac{v_{CPFeqq}^*}{L_{PFeq}} + \frac{1}{L_{PFeq}} v_q \right] \tag{20}$$

By considering only perturbation quantities which are state variables, the following equations are obtained from the reference and actual currents by using equations (14) to (18).

$$\frac{dx_1}{dt} = -\frac{R_{PFeq}}{L_{PFeq}} x_1 + \omega x_2 - \frac{x_3}{L_{PFeq}} - \frac{d_{nd}}{L_{PFeq}} \left(x_5 + V_{dc}^*\right) - \frac{D_{nd}}{L_{PFeq}} V_{dc}^* \tag{21}$$

$$\frac{dx_2}{dt} = -\frac{R_{PFeq}}{L_{PFeq}} x_2 - \omega \; x_1 - \frac{x_4}{L_{PFeq}} - \frac{d_{nq}}{L_{PFeq}} \left(x_5 + V_{dc}^*\right) - \frac{D_{nq}}{L_{PFeq}} V_{dc}^* \tag{22}$$

Equations (16) and (17) in steady state yields the following equations,

$$-C_{PFeq}\frac{dv^*_{CPFeqd}}{dt}+i^*_d+C_{PFeq}\omega v^*_{CPFeqq}=0$$

$$-C_{PFeq}\frac{dv^*_{CPFeqq}}{dt}+i^*_q-C_{PFeq}\omega v^*_{CPFeqd}=0$$

$$\frac{dx_3}{dt}=\frac{1}{C_{PFeq}}x_1+\omega\ x_4 \tag{23}$$

$$\frac{dx_4}{dt}=\frac{1}{C_{PFeq}}x_2-\omega\ x_3 \tag{24}$$

From equation (18) the following state equation is deduced.

$$\frac{dx_5}{dt}=\frac{1}{C_{dc}}\left[d_{nd}\left(x_1+i^*_d\right)+d_{nq}\left(x_2+i^*_q\right)+D_{nd}i^*_d+D_{nq}i^*_q\right] \tag{25}$$

Equations (21) to (25) describe the complete state space model of the filter with switching functions.

4. LYAPUNOV FUNCTION BASED CONTROL STRATEGY

Lyapunov's direct method based control strategy formulated in this work is related to examining the total energy of the hybrid filter which can be used for checking the stability due to perturbation of the system (Salem et al., 2012; Komurcugil and Kukrer, 2006). Accordingly the following conditions based on the energy function *W(x)* and its derivatives $\dot{W}(x)$ have to be satisfied.

$$W(x)=0$$

$$W(x)>0,\quad for\ all\ \ x\neq 0$$

$$\dot{W}(x)<0,\quad for\ all\ \ x\neq 0$$

$$W(x)\to\infty,\quad as\ \ \|x\|\to\infty.$$

Here *W(x)* is chosen based on the energy stored in the shunt hybrid filter in terms of the state variables $x_1 - x_5$, and given as follows.

$$W(x)=\frac{3}{2}L_{PFeq}x_1^2+\frac{3}{2}L_{PFeq}x_2^2+\frac{3}{2}C_{PFeq}x_3^2+\frac{3}{2}C_{PFeq}x_4^2+\frac{1}{2}C_{dc}x_5^2 \tag{26}$$

The derivative $\frac{dW}{dt}$ of the energy function is obtained as,

$$\frac{dW}{dt}=3L_{PFeq}x_1\dot{x}_1+3L_{PFeq}x_2\dot{x}_2+3C_{PFeq}x_3\dot{x}_3+3C_{PFeq}x_4\dot{x}_4+C_{dc}x_5\dot{x}_5 \tag{27}$$

Substituting equations (21) to (25) in (27), we get

$$\frac{dW}{dt}=-3R_{PFeq}x_1^2-3R_{PFeq}x_2^2+d_{nd}\left[x_5i^*_d-3x_1(V^*_{dc}+\frac{2}{3}x_5)\right]+d_{nq}\left[x_5i^*_q-3x_2(V^*_{dc}+\frac{2}{3}x_5)\right]+D_{nd}\left[x_5i^*_d-3x_1V^*_{dc}\right]+D_{nq}\left[x_5i^*_q-3x_2V^*_{dc}\right] \tag{28}$$

Since the ripple voltage x_5 across the capacitor in the dc link is quite small compared with the dc link voltage reference V^*_{dc}, the following approximation is obtained.

$$V^*_{dc}+\frac{2}{3}x_5\cong V^*_{dc}.$$

Accordingly equation (28) is reduced as follows.

$$\frac{dW}{dt}=-3R_{PFeq}x_1^2-3R_{PFeq}x_2^2+\left(d_{nd}+D_{nd}\right)\left(x_5i^*_d-3x_1V^*_{dc}\right)+\left(d_{nq}+D_{nq}\right)\left(x_5i^*_q-3x_2V^*_{dc}\right) \tag{29}$$

In the above equation the first two terms in the right hand side are negative. Further, by judicious choice of the switching functions as given in (30) and (31) below $\dot{W}$ is made negative definite.

$$d_{nd}=\alpha\left(x_5i^*_d-3x_1V^*_{dc}\right)-D_{nd} \tag{30}$$

$$d_{nq}=\alpha\left(x_5i^*_q-3x_2V^*_{dc}\right)-D_{nq}\ \text{with}\ \alpha<0 \tag{31}$$

where, α is controller gain

Since it is desirable that the response time of the controller following a disturbance should be minimum, a reasonable choice of the gain $|\alpha|$ from practical considerations is required. Accordingly the gain α is set at -5 in this work.

5. DC BUS VOLTAGE CONTROL

The power loss in the active filter of hybrid compensation technique is to be properly controlled by keeping the dc link capacitor voltage as constant value. DC link voltage regulation is also essential to enhance the filtering performance as well as reactive power compensation of the proposed filter. The losses due to the switching of power semiconductor switches present in the APF must be made identical to the active power flow into the hybrid power filter for maintaining the capacitor voltage of the dc-link as constant (Luo et al., 2009). A PI controller has been proposed and its parameter values are chosen properly in order to keep the link voltage across the dc bus capacitor equal to V_{dc}^* under various operating conditions.

Focusing on the reactive component i_q for charging the link capacitor voltage, the governing equation is given below

$$C_{dc}\frac{dV_{dc}}{dt}=q_{nq}i_q \tag{32}$$

Defining the input equivalent voltage as $u_{dc}=q_{nq}i_q$, the active filter reactive current is given by

$$i_q = \frac{u_{dc}}{q_{nq}} = \frac{u_{dc}V_{dc}}{q_{nq}V_{dc}} \tag{33}$$

Under normal operating conditions of active filter $q_{nq}V_{dc} \cong V_{Oq}$ which is called voltage of q axes of the active filter and is expressed as

$$V_{Oq} = -Z_{PFeq1}i_{q1}^{*} \tag{34}$$

where, Z_{PFeq1} represents the equivalent impedance of the selective harmonic elimination passive filter at 50 Hz and i_{q1}^{*} is the dc component of the reactive current perturbation.

Now the dc loop control law is deduced as,

$$i_{q1}^{*} = \frac{V_{dc}}{-Z_{PFeq1}i_q}u_{dc} \tag{35}$$

The filter current in three phases can be given as

$$\begin{bmatrix} i_{f1} \\ i_{f2} \\ i_{f3} \end{bmatrix} = \sqrt{\frac{2}{3}}i_q \begin{bmatrix} -\sin\theta \\ -\sin\left(\theta - 2\pi/3\right) \\ -\sin\left(\theta - 2\pi/3\right) \end{bmatrix} \tag{36}$$

The rms value of the fundamental component of the filter current i_f is given by,

$$i_f = \frac{i_q}{\sqrt{3}} \tag{37}$$

Substitution of equation (37) in (35) and taking Laplace transform of the control law we get,

$$I_{q1}^{*}(s) = \frac{V_{dc}}{\sqrt{3}Z_{PFeq1}I_f}U_{dc}(s) \tag{38}$$

In order to keep the dc link voltage close to the reference value, a PI controller for processing the corresponding error signals is introduced. Expressions for design of parameters of the PI controller are obtained through modeling of the closed loop system, where the second order transfer function corresponding to the outer loop is derived as follows.

$$\frac{V_{dc}(s)}{V_{dc}^{*}(s)} = \frac{\frac{\left(\sqrt{3}Z_{PFeq1}I_f\right)k_P}{C_{dc}V_{dc}}s + \frac{\left(\sqrt{3}Z_{PFeq1}I_f\right)k_I}{C_{dc}V_{dc}}}{s^2 + \frac{\left(\sqrt{3}Z_{PFeq1}I_f\right)k_P}{C_{dc}V_{dc}}s + \frac{\left(\sqrt{3}Z_{PFeq1}I_f\right)k_I}{C_{dc}V_{dc}}} \tag{39}$$

The general structure of a second order transfer function is of the form

$$\frac{V_{dc}(s)}{V_{dc}^{*}(s)} = 2\varsigma\omega_{nv}\frac{s + \frac{\omega_{nv}}{2\varsigma}}{s^2 + 2\varsigma\omega_{nv}s + \omega_{nv}^2} \tag{40}$$

By comparing equations (37) and (38) k_P and k_I are determined as

$$k_P = 2\varsigma\omega_{nv}\left(\frac{C_{dc}V_{dc}}{\sqrt{3}Z_{PFeq1}I_f}\right) \text{ and } k_I = \omega_{nv}^2\left(\frac{C_{dc}V_{dc}}{\sqrt{3}Z_{PFeq1}I_f}\right)$$

where, ω_{nv} is natural frequency of oscillation of outer loop, ζ is damping ratio and V_{dc} is average voltage value of the dc link which is set at 25V.

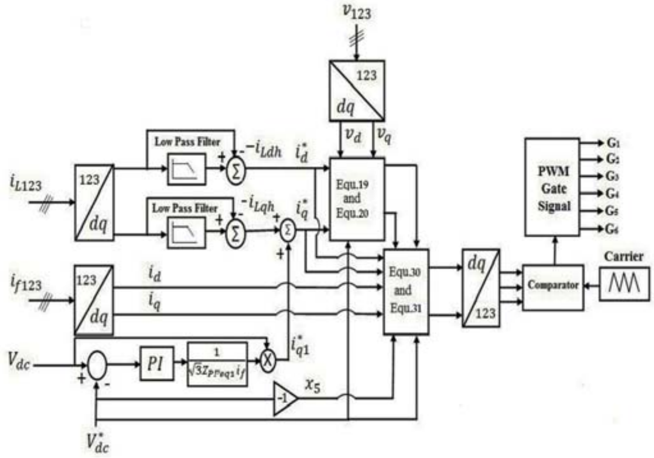


Fig. 2. Lyapunov direct method based control circuit.

The overall block diagram consisting of Lyapunov direct method based control algorithm, global switching function and outer loop PI controller along with axes transformation functional blocks is shown in Fig.2. The switching functions D_{nd} and D_{nq} are generated first based on dq parameters obtained from load currents. Finally the global switching functions are obtained from steady state switching functions and the dq parameters of the filter current. This forces the active power filter to mitigate harmonics and maintain the dc link voltage as constant.

6. MATLAB-SIMULINK MODEL OF SHUNT HAPF

Fig. 3. depicts the Simulink schematic of the distribution system along with the proposed shunt HAPF. The nonlinear load is modeled using a 3-phase full bridge diode rectifier feeding RL load and RC load separately as subsystems and connected to the three phase mains. At the source side resistor- inductor combination is used to represent the line impedance before PCC. The unbalance case in the nonlinear load is created by connecting a diode bridge rectifier of single phase type feeding RL load between phase1 and ground. The hybrid filter consists of a parallel connection of selective 5th and 7th harmonics elimination passive filters as shown in Fig.1 along with APF. The APF comprises 3-phase voltage source inverter using IGBTs switches and terminated with dc link capacitor at dc side. The nonlinear control subsystem contains *abc* to *dq* transformation blocks for filter currents, load currents and supply voltages respectively. The synchronization of subsystem with main supply frequency is accomplished by using three phase discrete PLL block. Load current in *dq* coordinate is processed using a pair of fourth order Butterworth low pass filters with cut off frequency set at 50Hz in order to extract the harmonic current references alone. A PI controller is used to extract power loss component from dc link capacitor and added with q axes current obtained from the load current. Finally *dq* reference

current and *dq* transformed supply voltages along with passive filter parameters form the input data to the subsystem for generating the control signals D_{nd} and D_{nq}.

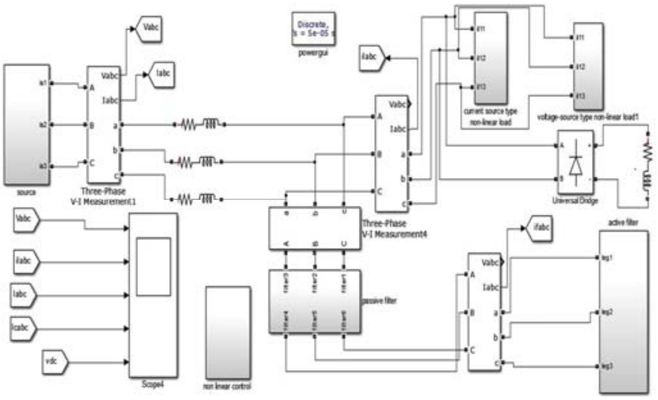


Fig. 3. Simulink model of the shunt hybrid compensator system.

The dq transformed actual current of the designed filter with the obtained control signals D_{nd} and D_{nq} are used to obtain the final global switching state d_{nd} and d_{nq} of the active power filter. The control signals obtained are finally converted to gate trigger signals for the 6 IGBT power switches of the active filter. The entire system simulation is carried out in a discrete mode, variable step size with ode45 (Dormand-Prince) solver. In this work the control signals are obtained based on the modeling of the entire system depicted in the earlier section. Those equations are realized as control block by Matlab functions using Matlab coding as well as in built Simulink blocks. In order to verify the steady state response of the proposed compensator under varying load conditions load variation in simulink can be achieved by connecting parallel resistance across load by programmed switches.

7. SIMULATION RESULTS

The Lyapunov based control strategy proposed in this work is simulated using Matlab/Simulink software. To examine the hybrid filter performance, the simulation of the whole system has been carried out. The operations of the filter under the following cases are analyzed using simulation results.

(i) Compensation of harmonics produced by rectifier fed RC load

(ii) Performance of the hybrid filter following fluctuation in rectifier fed RC load

(iii) Performance of the designed filter for rectifier fed RL load

(iv) Response of the hybrid filter for variation in rectifier fed RL load

(v) Performance of the designed filter under unbalanced loading conditions

(vi) Performance of the hybrid filter under variation of passive filter parameters

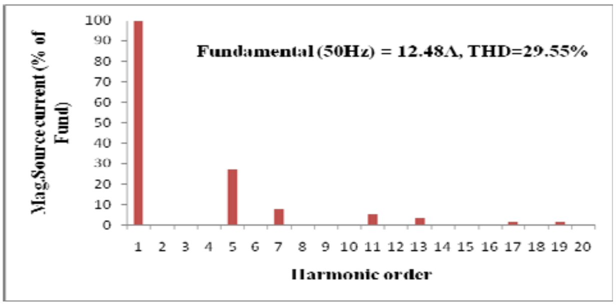
Table 1 defines the nominal values of operational values and designed system parameters

Table 1. Parameters of the designed system.

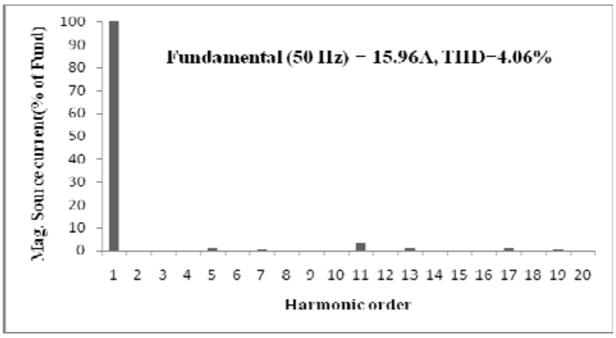
Phase voltage and Frequency	V_{srms} = 230 V and f_s = 50 Hz
Impedance of the Line	R_s =0.1 Ω, L_s = 4mH
3-phase rectifier fed RL load	L_L = 10mH, R_L = 50Ω
3-phase rectifier fed RC load	C_L = 1000μF, R_L = 36Ω
DC-link voltage of compensator and Capacitance value.	V_{dc} =25V, C_{dc} = 6600μF
PI controller parameter values	K_P =0.6 and K_I = 6.2

Case (i): Rectifier fed RC load

The harmonic currents generated by the rectifier fed RC loads are compensated by the proposed hybrid topology. This nonlinear load chosen replicates the characteristics of an adjustable speed drives load used in industries. Figs. 5(a)-(e) depict the waveform of supply voltage (V_{s1}), current of the load (I_{L1}), current of the source (I_{s1}), filter current (I_{f1}) and dc link voltage respectively. The source current waveforms after filtering, approach nearly sinusoidal as shown in the figure. The Fourier analysis of source current without and with compensator has been depicted in Figs. 4(a) and (b). *THD* of the supply current which is 29.55% before compensation is reduced to 4.06% after compensation which is less than the standard specified by IEEE 519-1992.



(a) Without compensator



(b) With compensator

Fig. 4. FFT analysis of supply current for rectifier fed RC load.

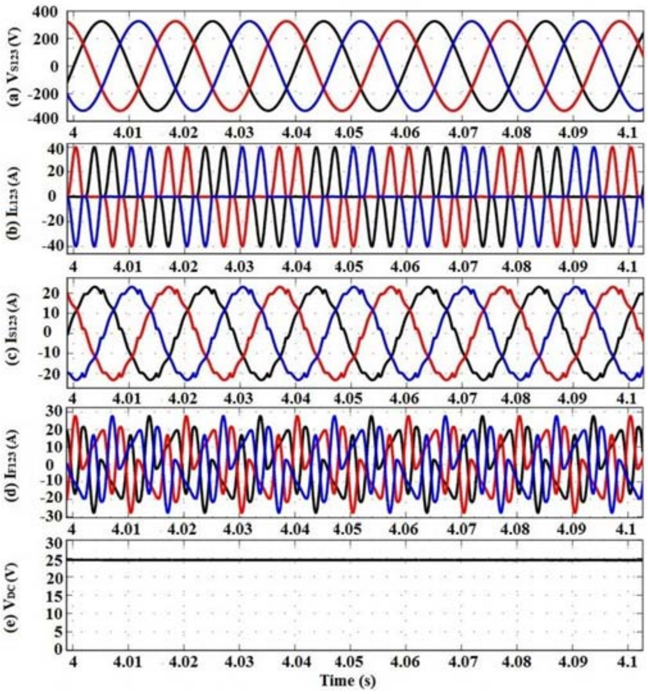


Fig. 5. Performance of the filter for RC load.

Case (ii) Response for fluctuation in rectifier fed RC load

The performance of the proposed filter under varying load condition is analyzed by introducing a 100% step increase and decrease in current of the load successively. Fig.6 depicts the performance of the hybrid filter designed by Lyapunov direct method based control. In the load current a step change is initiated at t = 4s and t =4.1s respectively in order to examine the subsequent operation of the proposed filter. The obtained results indicate that the desirable features in the performance of the hybrid filter are maintained even after the step changes in the load within a very short time.

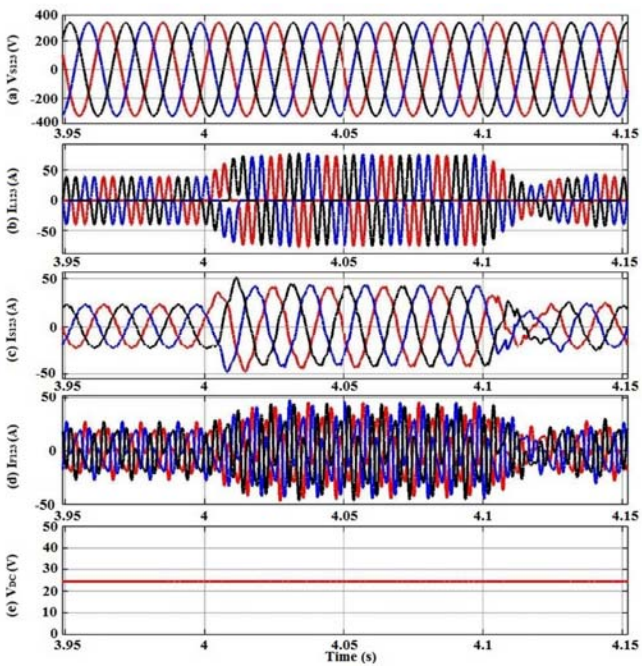


Fig. 6. Filter response to variation in RC load.

Case (iii) Rectifier fed RL load

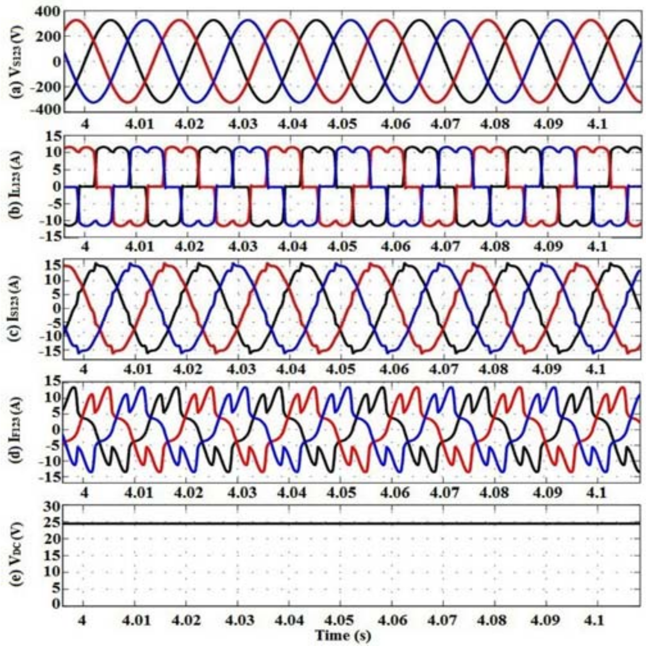


Fig. 7. Response of the filter to RL Load.

Fig.7 depicts the simulation results at steady state of the controller adopted in this work for the reduction of harmonics by shunt hybrid filter with rectifier fed RL load. The performance improvement of the filter is assessed based on the waveforms of load current, supply voltage, filter current, supply current and dc link voltage presented in the Figs. 7(a)-(e). The FFT spectrum of the source current before filtering and after filtering is depicted in Figs.8 (a) and (b) respectively. It has been observed from the FFT analysis that the THD of the source current is reduced from 25.74% to 3.16% after filtering, which shows the efficacy of the suggested control strategy deduced using Lyapunov-function.

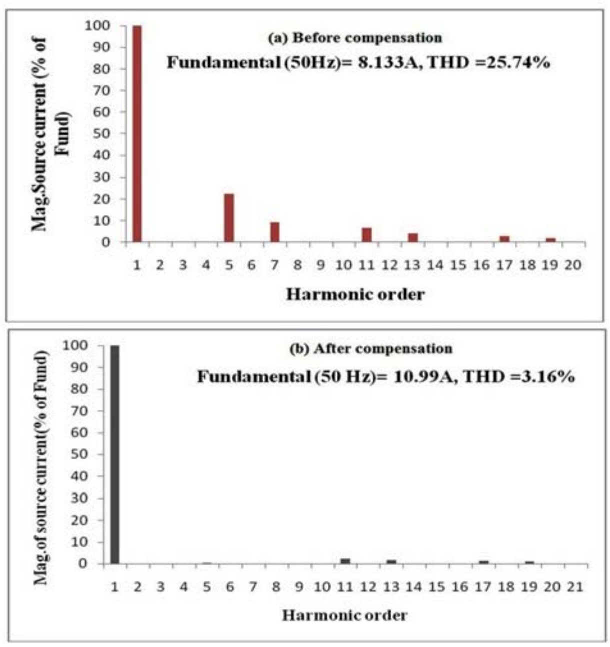


Fig. 8. FFT analysis of the supply current.

Case (iv) Response for fluctuation in rectifier fed RL load

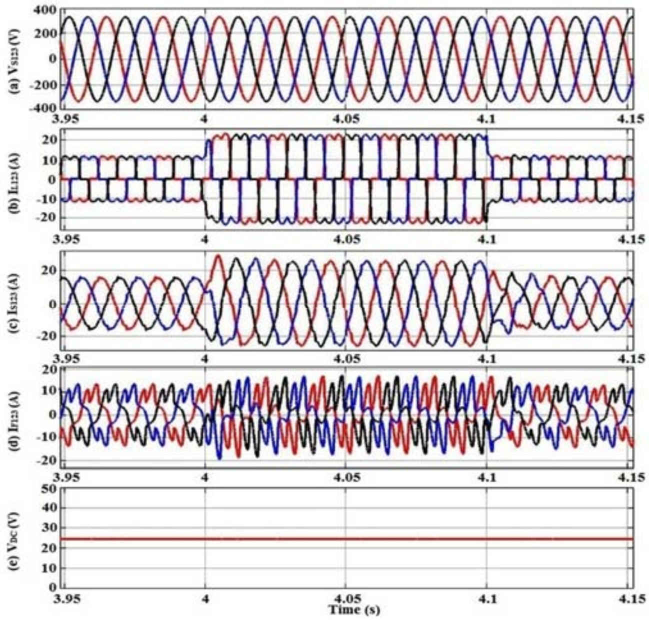


Fig. 9. Response of the filter to RL load variation.

The response of the designed filter for varying load condition with the proposed control method has been examined by incorporating a 100% sudden variation in the load current. The simulation results of supply current, filter current, supply voltage, load current and dc link voltage are depicted in Fig.9. It has been verified from the waveforms that the designed filter has fast transient response of harmonic compensation while the distribution system is subjected to successive step changes in load current equal to ± 100% at t= 4s and 4.25s respectively.

Case (v) Performance of the HAPF under unbalanced loading conditions

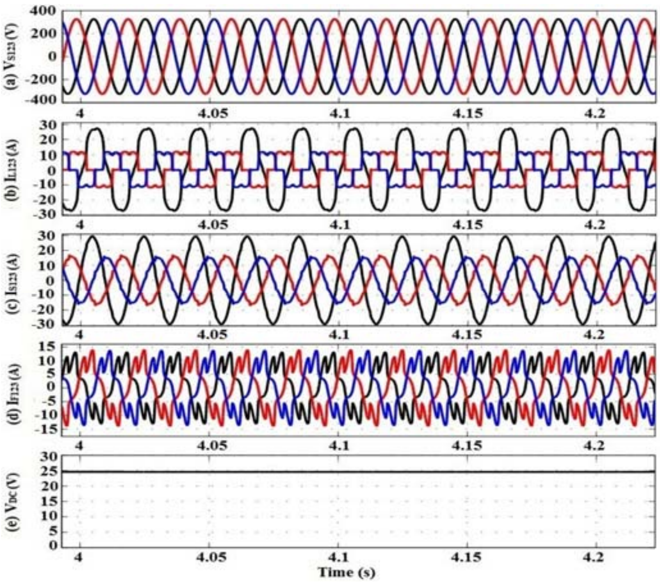


Fig. 10. Filter response to unbalanced load.

In order to study the response of shunt HAPF employing Lyapunov function based control method, an unbalance in load is created by connecting a single phase rectifier across first two phases of the supply. The compensation performance at steady state of the designed filter is shown in Fig.10. The supply and filter currents, load current, supply voltage and dc link voltage waveforms are depicted in the Fig.10. The *THD* of supply phase-1 current has been reduced from 9.28% to 1.96% after mitigation. At the same time the supply current *THD's* of remaining two phases are reduced from 25.38% to 3.57% after filtering. Obtained results clearly show the effectiveness of the proposed filter in terms of reducing harmonics from the supply current.

Case (vi) Performance of the hybrid filter under variation of passive filter parameters

In practical systems aging and temperature effects cause changes in the reactance and capacitance of the passive filter which leads to detuning the filter. Under this circumstance in the designed shunt hybrid filter system a 5% change in passive filter reactance alone is introduced to verify the effectiveness of the proposed method. The simulation results clearly confirm that the *THD* of the source current is obtained as 3.47%. Similarly a change of 5% is made on the capacitance of the filter and the simulation results show that *THD* of the source current is observed to be 3.65%. Finally as a worst case both the filter parameters are varied by 5% but the response of the shunt HAPF shows *THD* of the supply current is 4.85%. From the above worst case results it has been confirmed that the performance of the HAPF with proposed control scheme satisfy the harmonics standard described by IEEE 519-1992. The detuning problem of passive filter parameters in hybrid scheme is effectively addressed by the proposed topology and control scheme.

Table 2. Comparison of Lyapunov based control with other control techniques proposed in the literature.

Control Methods	Lyapunov Based Control	Fuzzy Based Control (Balasubramanian et al., 2017)	SRF Theory Based Control (Day P and Mekhilef S, 2014	Parallel Connected SHAPF(Bhattacharya et al., 2012)
THD % RL load	3.16	3.43	-	4.7
THD % RC load	4.06	4.08	-	-
Unbalanced load % THD	1.96 to 3.57	2 to 4	1.18 to 2	4.5 to 4.7

Table. 2 shows the performance comparison of Lyapunov function based control with other control techniques proposed in the literature. The results depict that Lyapunov based control technique with adopted hybrid power filter topology gives better compensation for all types of nonlinear loads compared with other methods.

8. CONCLUSION

In this work a Lyapunov function based on the direct method has been introduced in the control scheme for a shunt hybrid compensator in order to mitigate the harmonics in the distribution system due to the nonlinear loads of different types. The hybrid topology composed of parallel connected 5^{th} and 7^{th} selective harmonic elimination PPFs in series with APF. In this topology the passive filters eliminate the lower order harmonic currents, thereby reducing the burden on the active filter, leading to lower rating of the active filter. The compensation scheme makes use of energy based nonlinear control theory in conjunction with SRF theory based reference current generation and DC link voltage regulation. The supporting mathematical derivations and control algorithm are presented. The overall system is simulated using Power system block set of MATLAB SIMULINK software for different type of nonlinear loads. The simulation results confirm that the proposed compensator with control method performs well for both voltage source type as well as current source type nonlinear loads. The Fourier analysis indicates that the THD has been reduced to 3.16% for current source type nonlinear load. The phase voltage and current waveform depicts that the power factor is maintained around 0.9. Similar results have been obtained when the supply system feeds RC type nonlinear loads. Further, the obtained results indicate that the filter response for sudden variation in both the type of loads is found to be very fast and simultaneously the harmonics are reduced within the IEEE 519-1992 standard. Furthermore the simulation results show that the proposed compensation scheme is insensitive to variations in the parameters of the PPF components, due to aging and consequent detuning. The simulation results with load disturbances, system unbalance and parameter variations show that the hybrid filter is capable of maintaining the power quality of the distribution system by elimination of harmonics along with improved power factor. Further, it is observed that in all the above mentioned load conditions the source currents are maintained nearly sinusoidal and also in-phase with the respective system voltages. Thus, the introduction of Lyapunov function based controller is capable of suppressing the harmonics present in the supply currents and improves the source side power factor.

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