

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: In this work, a control scheme based on an energy function using Lyapunov method has been formulated for a shunt hybrid power filter so as to reduce current harmonics in a power distribution system. The hybrid scheme contains a parallel connected selective harmonic elimination passive filter tuned at 5th and 7th harmonic frequencies in series with a low power active 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 have 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).

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. Singh et al. (2005) have suggested a lot of HAPF topologies to mitigate the power quality issues in a power distribution system. An APF connected in series with PPF topology is free from resonance problem also yields good performance (Ostrozniak et al., 2010; Luo et al., 2009; Chandan and Mahesh, 2014; Jou et al., 2008; Subhashish et al., 1997). 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).

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 PWM generation at the gates of IGBT's.

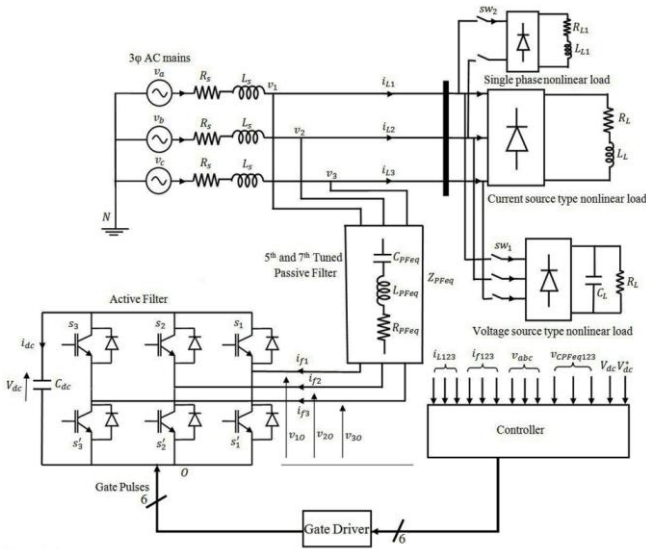


Fig.1. Configuration of the shunt HAPF

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.

$$v_1 = L_{pFeq} \frac{di_{f1}}{dt} + R_{pFeq} i_{f1} + v_{CPFeq1} + V_{10} + V_{ON} \quad (1)$$

$$v_2 = L_{pFeq} \frac{di_{f2}}{dt} + R_{pFeq} i_{f2} + v_{CPFeq2} + V_{20} + V_{ON} \quad (2)$$

$$v_3 = L_{pFeq} \frac{di_{f3}}{dt} + R_{pFeq} i_{f3} + v_{CPFeq3} + V_{30} + V_{ON} \quad (3)$$

$$i_{f1} = C_{pFeq} \frac{dv_{CPFeq1}}{dt} \quad (4)$$

$$i_{f2} = C_{pFeq} \frac{dv_{CPFeq2}}{dt} \quad (5)$$

$$i_{f3} = C_{pFeq} \frac{dv_{CPFeq3}}{dt} \quad (6)$$

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

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_{10} , V_{20} , V_{30} as follows.

$$V_{ON} = -\frac{1}{3} \sum_{j=1}^3 v_{j0} \quad (8)$$

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.

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

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.

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

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

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} i_{dc} = \frac{1}{C_{dc}} \sum_{j=1}^3 q_j i_{fj} = \frac{1}{C_{dc}} \sum_{j=1}^3 d_{nj} i_{fj} \quad (11)$$

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

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

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

$$\frac{d}{dt} \begin{bmatrix} i_{f1} \\ i_{f2} \\ i_{f3} \end{bmatrix} = \begin{bmatrix} \frac{R_{pFeq}}{L_{pFeq}} & 0 & -\frac{d_{n1}}{L_{pFeq}} \\ 0 & -\frac{R_{pFeq}}{L_{pFeq}} & -\frac{d_{n2}}{L_{pFeq}} \\ \frac{2d_{n1} + d_{n2}}{C_{dc}} & \frac{d_{n1} + 2d_{n2}}{C_{dc}} & 0 \end{bmatrix} \begin{bmatrix} i_{f1} \\ i_{f2} \\ V_{dc} \end{bmatrix} - \frac{1}{L_{pFeq}} \begin{bmatrix} v_{CPFeq1} \\ v_{CPFeq2} \\ 0 \end{bmatrix} + \frac{1}{L_{pFeq}} \begin{bmatrix} v_1 \\ v_2 \\ 0 \end{bmatrix} \quad (13)$$

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

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

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

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

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

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

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.

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

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

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).

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

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

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

$$-C_{PFeq} \frac{dv_{CPFeqd}^*}{dt} + i_d^* + C_{PFeq} \omega v_{CPFeqq}^* = 0$$

$$-C_{PFeq} \frac{dv_{CPFeqq}^*}{dt} + i_q^* - C_{PFeq} \omega v_{CPFeqd}^* = 0$$

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

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

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

$$\frac{dx_5}{dt} = \frac{1}{C_{dc}} \left[d_{nd}(x_1 + i_d^*) + d_{nq}(x_2 + i_q^*) + D_{nd}i_d^* + D_{nq}i_q^* \right] \quad (25)$$

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.

$$W(x) = 0$$

$$W(x) > 0, \text{ for all } x \neq 0$$

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

$$W(x) \rightarrow \infty, \text{ as } \|x\| \rightarrow \infty.$$

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.

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

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

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

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

$$\begin{aligned} \frac{dW}{dt} = & -3R_{PFeq}x_1^2 - 3R_{PFeq}x_2^2 + d_{nd} \left[x_5i_d^* - 3x_1(V_{dc}^* + \frac{2}{3}x_5) \right] + \\ & d_{nq} \left[x_5i_q^* - 3x_2(V_{dc}^* + \frac{2}{3}x_5) \right] + D_{nd} \left[x_5i_d^* - 3x_1V_{dc}^* \right] \\ & + D_{nq} \left[x_5i_q^* - 3x_2V_{dc}^* \right] \end{aligned} \quad (28)$$

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.

$$\begin{aligned} \frac{dW}{dt} = & -3R_{PFeq}x_1^2 - 3R_{PFeq}x_2^2 + (d_{nd} + D_{nd})(x_5^*i_d^* - 3x_1V_{dc}^*) \\ & + (d_{nq} + D_{nq})(x_5^*i_q^* - 3x_2V_{dc}^*) \end{aligned} \quad (29)$$

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.

$$d_{nd} = \alpha(x_5 i_d^* - 3x_1 V_{dc}^*) - D_{nd} \quad (30)$$

$$d_{nq} = \alpha(x_{5i_q}^* - 3x_2V_{dc}^*) - D_{nq} \text{ with } \alpha < 0 \quad (31)$$

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

$$C_{dc} \frac{dV_{dc}}{dt} = q_{nq} i_q \quad (32)$$

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

$$i_q = \frac{u_{dc}}{q_{nq}} = \frac{u_{dc} V_{dc}}{q_{nq} V_{dc}} \quad (33)$$

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

$$V_{Oq} = -Z_{PFeql} i_{q1}^* \quad (34)$$

where, Z_{PFeq} 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,

$$i_{q1}^* = \frac{V_{dc}}{-Z_{PEM} i_a} u_{dc} \quad (35)$$

The filter current in three phases can be given as

$$\begin{bmatrix} i_{f1} \\ i_{f2} \\ i_{f3} \end{bmatrix} = \sqrt{\frac{2}{3}} i_q \begin{bmatrix} -\sin\theta \\ -\sin\left(\theta - \frac{2\pi}{3}\right) \\ -\sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \quad (36)$$

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

$$i_f = \frac{i_q}{\sqrt{3}} \quad (37)$$

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

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

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.

$$\frac{V_{dc}(s)}{V_{dc}^*(s)} = \frac{\frac{(\sqrt{3}Z_{PFeql}I_f)k_P}{C_{dc}V_{dc}}s + \frac{(\sqrt{3}Z_{PFeql}I_f)k_I}{C_{dc}V_{dc}}}{s^2 + \frac{(\sqrt{3}Z_{PFeql}I_f)k_P}{C_{dc}V_{dc}}s + \frac{(\sqrt{3}Z_{PFeql}I_f)k_I}{C_{dc}V_{dc}}} \quad (39)$$

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

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

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

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

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.

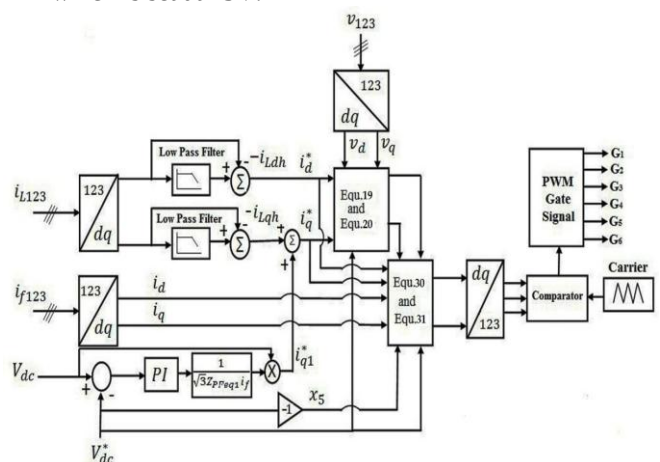
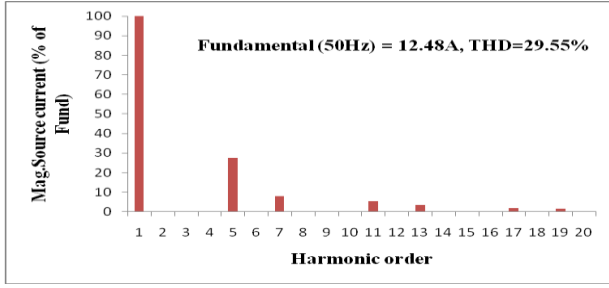


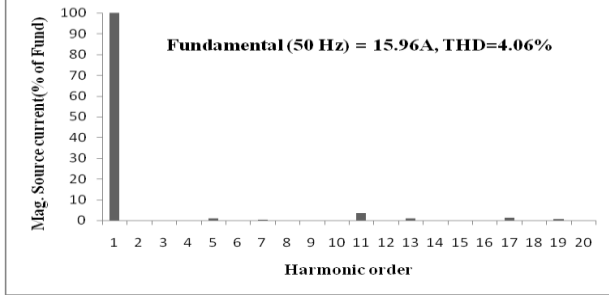
Fig. 2. Lyapunov direct method based control circuit

The overall block diagram consisting of Lyapunov direct method based control algorithm, global switching

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_{sl}), current of the load (I_{Ll}), current of the source (I_{sl}), filter current (I_{fl}) 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

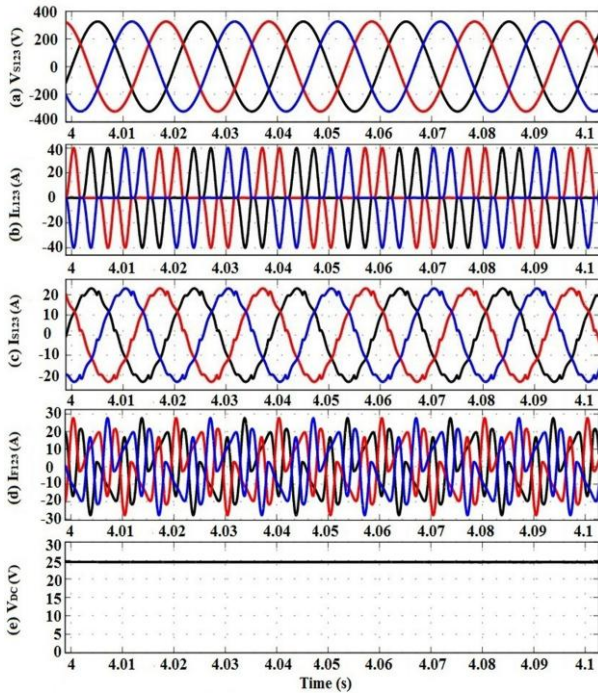


Fig. 5. Performance of the filter for RC load

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 $t = 4.25s$ 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.

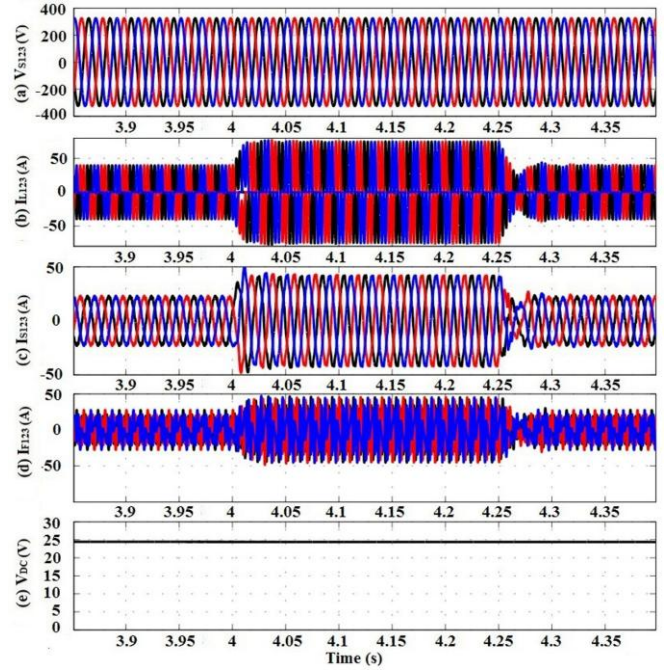


Fig. 6. Filter response to variation in RC load

Case (iii) Rectifier fed RL load

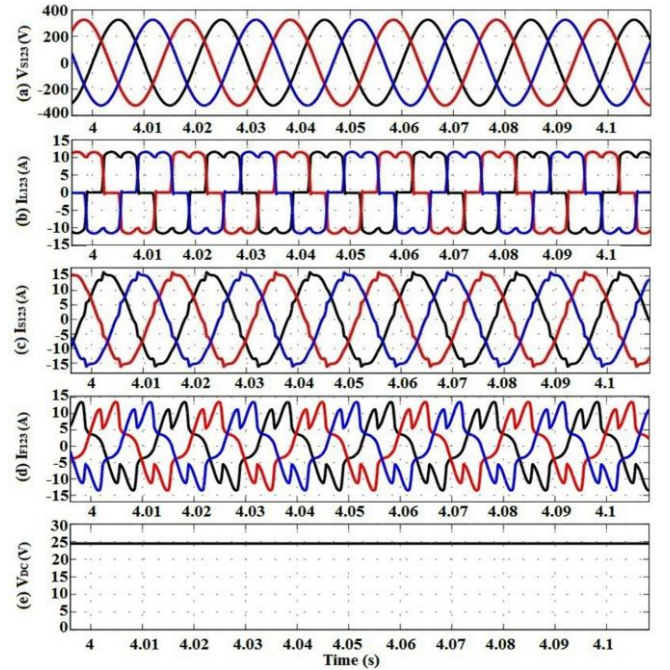


Fig.7. Response of the filter to RL Load

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.

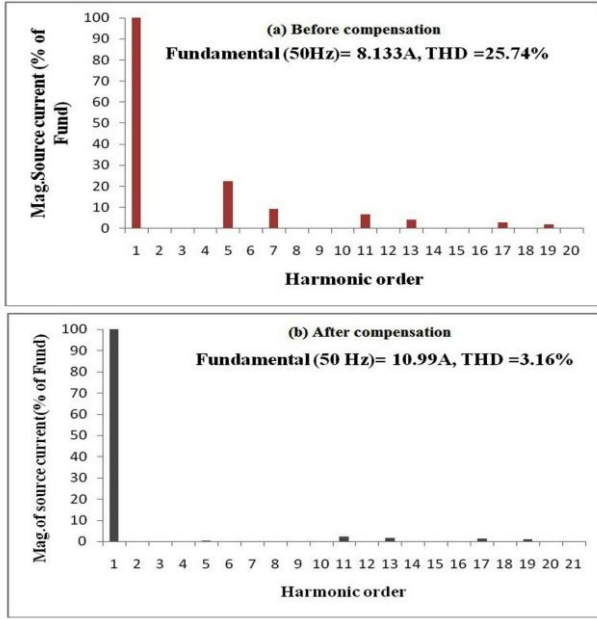


Fig. 8. FFT analysis of the supply current

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

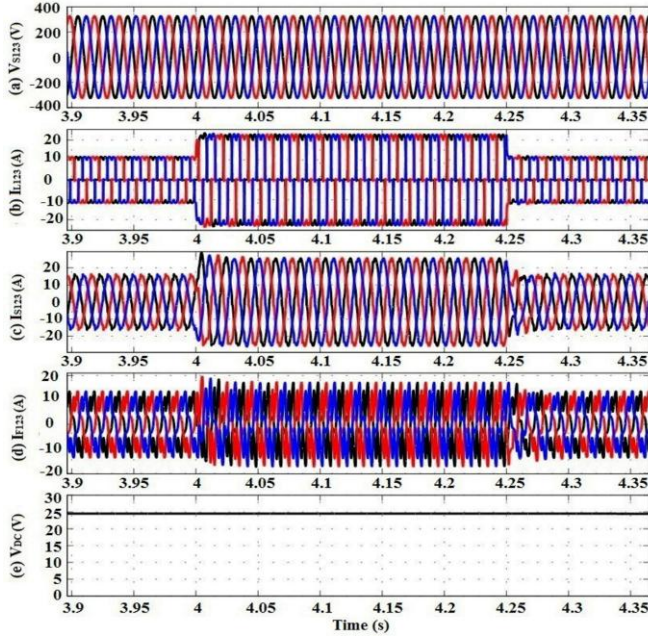


Fig. 9. Response of the filter to RL load variation

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 $\pm 100\%$ at $t=4s$ and $4.25s$ respectively.

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

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.

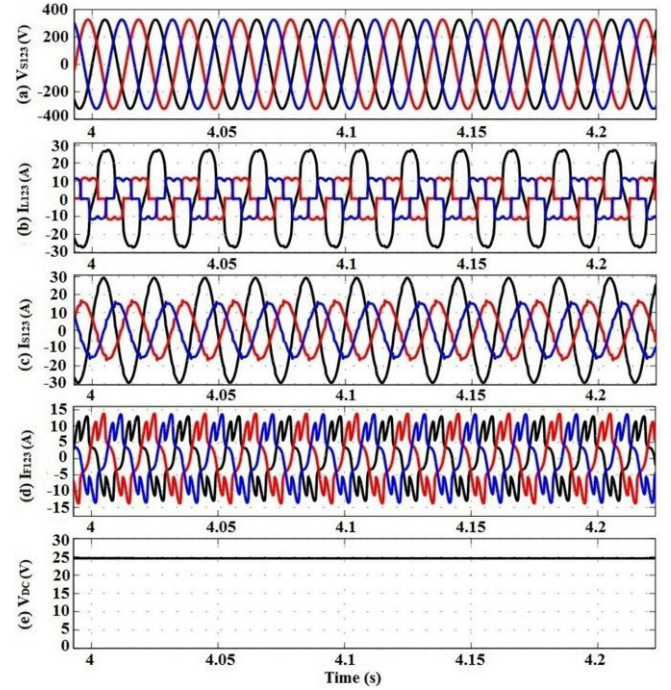


Fig. 10. Filter response to unbalanced load

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.

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 5th and 7th 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 complete system is simulated using SIMULINK software for obtaining minimum THD and improved power factor. 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. 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.

REFERENCES

- Roger CD, Mark FM, Surya S and Wayne B (2003) Electrical Power Systems Quality, 2nd edition. New York: McGraw Hill.
- Tosak T and Somchai C (2009) Planning Study of Harmonic Filter for ASDs in Industrial Facilities. *IEEE Transactions on industry applications* 45(1): 295-302.
- Das JC (2004) Passive Filters—Potentialities and Limitations. *IEEE Transactions on Industry Applications* 40(1): 232-241.
- Singh B, Verma V, Chandra A and Al-Haddad K (2005) Hybrid Filters for Power Quality Improvement. *IEE Proceedings - Generation, Transmission and Distribution* 152 (3): 365-378.
- Na H, Dianguo X and Lina H (2009) The Application of Particle Swarm Optimization to Passive and Hybrid Active Power Filter Design. *IEEE Transactions on Industrial Electronics* 56 (8): 2841-2851.
- Darwin R, Luis M, Juan WD and Jose RE (2003) Improving Passive Filter Compensation Performance with Active Techniques. *IEEE Transactions on Industrial Electronics* 50 (1): 161-170.
- Salem R, Kamal AH and Hadi YK (2006) A Comparative Study of Shunt Hybrid and Shunt Active Power Filters for Single Phase Applications: Simulation and Experimental Validation. *Mathematics and Computers in Simulation* 71(4-6): 345-359.
- Haddad M, Ktata S, Rahmani S and Al-Haddad K (2016) Real Time Simulation and Experimental Validation of Active Power Filter Operation and Control. *Mathematics and Computers in Simulation* 130: 212-222.
- Ostrozniak S, Bajec P and Zajec P (2010) A Study of a Hybrid Filter. *IEEE Transactions on Industrial Electronics* 57(3): 935-942.
- Luo A, Zhikang S, Wenji Z and John SZ (2009) Combined System for Harmonic Suppression and Reactive Power Compensation. *IEEE Transactions on Industrial Electronics* 56 (2): 418-428.
- Chandan K and Mahesh KM (2014) An Improved Hybrid DSTATCOM Topology to Compensate Reactive and Nonlinear Loads. *IEEE Transactions on Industrial Electronics* 61 (12): 6517-6527.
- Jou HL, Wu KD, Wu JC, Li CH and Huang MS (2008) Novel Power Converter Topology for Three Phase Four-Wire Hybrid Power Filter. *IET Power Electronics* 1: 164-173.
- Subhashish B, Po TC and Deepak MD (1997) Hybrid Solutions for Improving Passive Filter Performance in High Power Applications. *IEEE Transactions on Industry Applications* 33: 732-747.
- Salem R, Abdelhamid H, Kamal AH and Alolah AI (2013) A DSP based Implementation of an Instantaneous Current Control for a Three Phase Shunt Hybrid Compensator. *Mathematics and Computers in Simulation* 91:229-248.
- Salem R, Abdelhamid H, Kamal AH and Louis AD (2014) A Combination of Shunt Hybrid Power Filter and Thyristor-Controlled Reactor for Power Quality. *IEEE Transactions on Industrial Electronics* 61(5): 2152-2164.
- Salem R, Abdelhamid H, Nassar M and Louis AD (2009) A New Control Technique for Three-Phase Shunt Hybrid Power Filter. *IEEE Transactions on Industrial Electronics* 56 (8): 2904-2915.
- Salem R, Abdelhamid H, Kamal AH (2012) A Lyapunov-Function-Based Control for a Three-Phase Shunt Hybrid Active Filter. *IEEE Transactions on Industrial Electronics* 59(3): 1418-1429.
- Salmeron P and Litran SP (2010) A Control Strategy for Hybrid Power Filter to Compensate Four-Wires Three-Phase Systems. *IEEE Transactions on Power Electronics* 25 (7): 1923-1931.
- An L, Xianyong X, Lu F, Houhui F, Jingbing W and Chuanping W (2010) Feedback-Feed forward PI-Type Iterative Learning Control Strategy for Hybrid Active Power Filter with Injection Circuit. *IEEE Transactions on Industrial Electronics* 57 (11): 3767-3779.
- Komurcugil H and Kukrer O (2006) A New Control Strategy for Single Phase Shunt Active Power Filters Using a Lyapunov Function. *IEEE Transactions on Industrial Electronics* 53(1): 305-312.
- Albert Alexander S and Thathan M (2014) Design and Development of Digital Control Strategy for Solar Photovoltaic Inverter to Improve Power Quality. *CEAI* 16(4): 20-29.
- Hua CC, Li CH and Lee CS (2008) Control Analysis of an Active Power Filter Using Lyapunov Candidate. *IET Power Electronics* 2(4): 325-334.
- Luo A, Shuai Z, Shen ZJ, Zhu W and Xu X (2009) Design Considerations for Maintaining DC-Side Voltage of Hybrid Active Power Filter with Injection Circuit. *IEEE Transactions on Power Electronics* 24(1): 75-84.