



Analysis of Unit vector and Proportional-Resonant Current Controller for Harmonic Compensation in a Hybrid Active Power Filter

Ratnam Kamala Sarojini

M-tech Student Scholar Department of Electrical & Electronics Engineering, St. Mary's Engineering College, Chebrolu; Guntur(Dt); A.P, India.

G. Sunil kumar

Assistant Professor Department of Electrical & Electronics Engineering, St. Mary's Engineering College, Chebrolu; Guntur (Dt); A.P, India.

Abstract—

Active filtering of electric power has now become a mature technology for harmonic and reactive power compensation in ac networks. This paper proposes a combination of low- and high frequency hybrid active power filter (APF) to operate in parallel for better performance. The individual hybrid Active Power Filter is a series combination of passive filter with the corresponding voltage source inverter. The dc links of both inverters are connected in parallel, and the voltage of this dc link is maintained by the low-frequency inverter (LFI). The low-and high-frequency inverters eliminate lower and higher order harmonics respectively. In addition, it is possible to design the LFI such that it can also compensate the reactive power of the load. The individual passive filter of the hybrid topology is designed to take care of specific order of harmonics that are predominant in the load. In order to make the supply currents sinusoidal, an effective harmonic compensation method is developed with the aid of a conventional proportional-integral (PI) and vector PI controllers. The absence of the harmonic detector not only simplifies the control scheme but also significantly improves the accuracy of the APF, since the control performance is no longer affected by the performance of the harmonic tracking process. Furthermore, the total cost to implement the proposed APF becomes lower, owing to the minimized current sensors and the use of a four-switch three-phase inverter. Despite the simplified hardware, the performance of the APF is improved significantly compared to the traditional control scheme.

Index Terms-- active power filter (APF); PI controllers AND Shunt Active Power filter

I.INTRODUCTION

The controller design is equally important for an improved performance of an APF. A comparative assessment for different type of controllers including multiple rotating integrators, stationary frame generalized integrators, proportional-sinusoidal integrators, and vector proportional-integral controllers are reported. An outvoltage loop and an inner current loop are necessary for implementation of such linear current control scheme. A nonlinear control technique utilizing two inner current loops and an outer dc bus voltage loop is also proposed. The inner and outer loops are decoupled, and the system took about 1.5 cycles for the outer loop to converge. Passive filters have the advantages of low cost and losses; however, they have the problems of harmonic resonance with the source and/or the load. Moreover, they need to be tuned properly to take care of a wider frequency range. Active filter may completely replace the passive counterpart. This requires higher voltage/current switches for medium/high power applications. Use of hybrid filter, where a lower rating active filter is added in series with the passive filter, has the merit of operating the active filter at a convenient voltage and current.

Later researchers developed a dual hybrid configuration where the series filters are tuned to eliminate fifth and seventh current harmonics. Reduced switch topologies have the advantages of more reliability and less cost and complexity. Reduced switch APF with one cycle control is also proposed. The third leg of the inverter is eliminated, and the third phase is connected to the midpoint (derived by voltage splitting capacitors) of the dc bus.

This topology has the problem of voltagebalancing across the dc link capacitors. This is laterimproved by connecting the where third phase to thenegative pole of the dc link.

Hybrid APF with series resonant networks tuned atdifferent harmonic frequencies are reported and extendedthe application of an APF to PV cells. A different type ofhybrid filter is proposed that uses a series passive filterand a thyristor controlled reactor-based variableimpedance shunt passive filter to compensate for theharmonics and reactive power. Such systems haverelatively poor dynamic performance and are less suitablefor highly dynamic types of load.

In addition, different hybrid active power filter (HAPF) topologies composed of active and passive components inseries and/or parallel have been proposed, aiming to improve the compensation characteristics of PPFs and reducethe voltage and/or current ratings (costs) of the APFs, thus leading to improvements in cost and performance[2]. The HAPF topologies in consist of many passive components, such as transformers, capacitors,reactors, and resistors, thus increasing the size and cost of the whole system.A transformer less shunt hybrid active power filter(SHAPF) has been recently proposed and applied for currentquality compensation and damping of harmonic propagation in distribution power systems [12], in which ithas only a few passive components.

II. SYSTEM CONFIGURATION

Fig.1. shows the proposed circuit configuration. In this system, a nonlinear load is supplied by a balanced voltage source and compensated by the proposed HAPF. A ripple filter is used to reduce the high-frequency harmonic currents injected into the network.

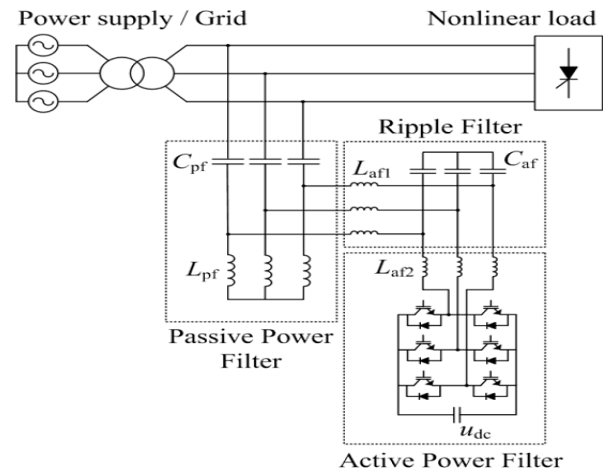


Fig.1. Scheme of The Proposed Shunt-Connected HAPF.

In Fig.2, a simplified, equivalent circuit of the proposed topological structure is shown. The symbols used are as follows: v_s supply voltage R_s and L_s are the supply-system resistance and inductance (short-circuit impedance and transformer impedance connected in series), R_l and L_l are the load resistance and inductance, is the passive filter capacitance C_{pf} , and are the passive filter resistance and inductance, and L_{af1} , L_{af2} and C_{af} are the ripple filter inductances and capacitance. The active part of the HAPF is presented with an ideal voltage source, while the nonlinear load is considered to be a current source i_{th} .

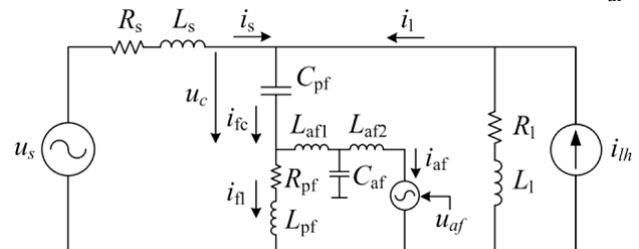


Fig.2.Simplified equivalent circuit of the HAPF.

A. Rating Analysis

The active filter has to provide a small component of fundamental voltage at the PCC in order to divert the fundamental reactive current to flow in the inductor. This voltage is equal to the voltage drop on the inductor for a pure passive filter and it depends on the tuned frequency of the passive part. It can be expressed as

$$u_{af,1} = u_{s,1} \frac{1}{1 - \left(\frac{f_t}{f_1}\right)^2} \quad (1)$$

Here, is the fundamental frequency (i.e., 50 Hz) and is the tuned frequency of the passive filter.

The harmonic voltage across the active part of the hybrid filter consists of two components: the component due to the distorted supply voltage (u_{sh}) and the component due to the harmonic load current (i_{lh}) flowing in the passive impedance. This voltage is given by

$$u_{afh} = u_{sh} + j \cdot i_{lh} \cdot X_{Ch}. \quad (2)$$

To obtain the worst case, no load impedance was considered when deriving (2), and the coupling impedance of the active

Table IV: Example Case Parameters

Parameter	Amplitude	Angle
Supply voltage		
$U_{s,1}$	1	0
$U_{s,h}$	0	0
Load current		
$I_{l,1}$	1	$\pi/4$
$I_{l,5}$	0.2	$5 \cdot \pi/4$
$I_{l,7}$	0.14	$7 \cdot \pi/4$
Filter		
f_i	240 Hz	

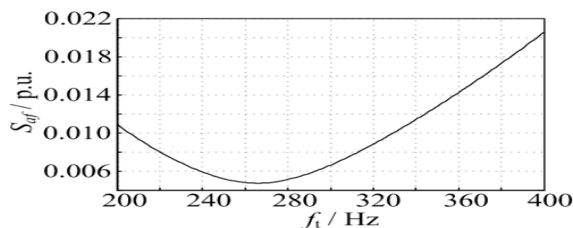


Fig.3. Active filter rated power versus tuned frequency of the passive part

Filter was neglected and the harmonic current flowing in the system was considered to be zero (ideal filtering). The current flowing in the active part also consists of two parts: the harmonic component due to the distorted supply voltage and the distorted load current. It is given by

$$i_{afh} = u_{sh} \frac{j \cdot f_t^2}{f_h f_1 X_{C1}} + i_{lh} \left(1 - \frac{f_t^2}{f_h^2}\right) \quad (3)$$

The power-rating requirement of the active part is finally given by

$$S_{af} = U_{af} \cdot I_{af}. \quad (4)$$

To better illustrate the power-rating requirements of the investigated HAPF's topological structure, let us consider the (hypothetical) example case in Table I.

For this case, the requiredPower of the active part is given by

$$S_{AF} = U_{AF,rms} \cdot I_{AF,rms} \quad (5)$$

As is clear from Fig.3, the power rating strongly depends on the tuned frequency of the passive filter. The hybrid active filter of the proposed topology is thus the most suitable for tuned filter branches, where the tuned frequency is as close as possible to the filtered harmonic. For the same load conditions, the rating of the active part for the series HAPF is equal to 0.0251 p.u., while the required rating of the pure active filter for this case is 0.2 p.u. (which does not include the reactive power compensation). An extensive overview of the power-rating requirements for most common current-sink HAPF topologies can be found.

III. CONTROL SYSTEM DESIGN

Proportional-resonant (PR) controllers are equivalent to conventional PI controllers implemented in the - reference frame, separately for the positive and negative sequences. Therefore, the PR controller is capable of simultaneously tracking the reference for the positive and negative sequence with zero steady state error. For example, a sixth harmonic PR compensator is effective for the fifth and seventh harmonics of both sequences; hence, four harmonics are filtered with one PR filter implemented in the SRF.

A. PR Controller Transfer Function

The relationship between the -components and the components is given by an anticlockwise rotating Park's Vector

$$i_d = i_\alpha \cdot \cos(\omega_0 t) + j \cdot i_\alpha \cdot \sin(\omega_0 t) = i_\alpha \cdot e^{j\omega_1 t}, \quad (6)$$

$$i_q = i_\beta \cdot \cos(\omega_0 t) - j \cdot i_\beta \cdot \sin(\omega_0 t) = i_\beta \cdot e^{-j\omega_1 t}. \quad (7)$$

Thus, the influence of the Park transformation can be expressed as the frequency shift of all the frequencies in the frequency domain. The equivalent transfer function of the PR controller is

in the SRF. $H_{PR}(S)$ can be derived from a PI controller implemented in positive- and negative-sequence HRFs, taking into account (6) and (7).

$$H_{PR}(s) = H_{PI}^+ + H_{PI}^- \quad (8)$$

$$\begin{aligned} H_{PR}(s) &= k_P + k_I \frac{s}{s + j\omega_1} + k_P + k_I \frac{s}{s - j\omega_1} = \\ &= 2k_P + 2k_I \frac{s}{s^2 + \omega_1^2} = K_P + \frac{K_I \cdot s}{s^2 + \omega_1^2}. \end{aligned} \quad (9)$$

For the non ideal integrators of $H_I = K_I / (1 + (s/\omega_C))$, the PR controller transfer function takes the form

$$H_{PR}(s) = K_P + K_I \frac{\omega_{PR} \cdot s}{s^2 + 2\omega_{PR} \cdot s + \omega_1^2} \quad (10)$$

Where ω_{PR} is the cutoff frequency, representing the limits of the integrator. In this paper, several HPR controllers are added in a cascade to control several harmonics simultaneously. The current controller takes its final form

$$H_{PR}(s) = K_P + \sum_{h=5,7,\dots} K_{Ih} \frac{\omega_{PR} \cdot s}{s^2 + 2\omega_{PR} \cdot s + (h \cdot \omega_1)^2} \quad (11)$$

Equation (9) describes an ideal PR controller with infinite gain at the tuned frequency and no phase shift and gain at the other frequencies. The disadvantage of such a controller in practical applications is the possible stability problem associated with infinite gain, which can be avoided by using non ideal integrators: (10). Another feature is the very narrow bandwidth of the ideal PR controllers, which makes them highly sensitive toward slight frequency variation in a typical power system.

B. Control Algorithm

Fig.4 shows the proposed control scheme, which includes harmonic detection (Fig. 4.5), the PR-current regulation dc

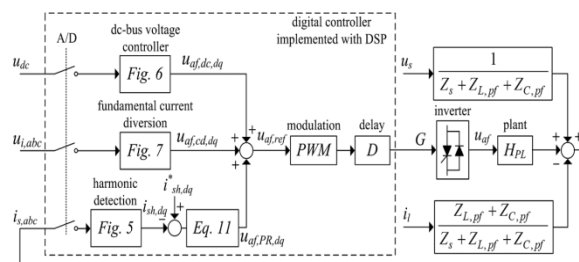


Fig.4. Control block diagram of the HAPF.

Suppression of Fundamental Negative Sequence Current Suppression of Fundamental Positive Sequence Current

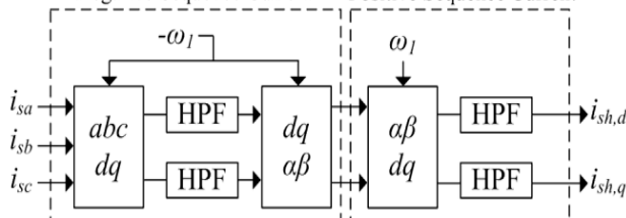


Fig.5. Block diagram of the harmonic current detection.

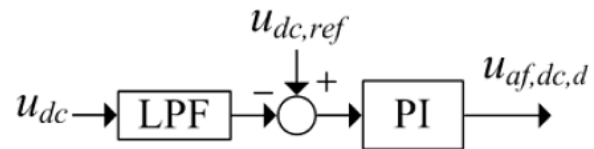


Fig.6. DC bus voltage control.

Voltage control (Fig.6), and the fundamental current diversion controller (Fig.7). The PR controller is closed with the measured and filtered values from the actual system. Since the objective is to eliminate the harmonics from the supply current, this current represents the PR controller input. At first, the fundamental-frequency component has to be extracted from the measured current. This is done by using first-order, high-pass filters in the fundamental frequency and synchronous reference frame with a cutoff frequency of 20 Hz. Fundamental angular frequency is obtained using a conventional q PLL system. Due to the fact that the supply current may also contain, in the case of unsymmetrical line conditions, some fundamental negative-sequence component, this component is suppressed by the second part of the harmonic detection unit, where Park's transformation is performed with a clockwise synchronous rotation. As a result, the output of the harmonic detection unit is the supply-current harmonics which, in the next step, are compared to the reference values. The difference is then applied to a PR controller tuned on the resonance frequencies of 6, 12, 1 and 18. The output of the controller is the variable $u_{af,PR,\alpha\beta}$, which is added to the voltage reference $u_{af,ref}$.

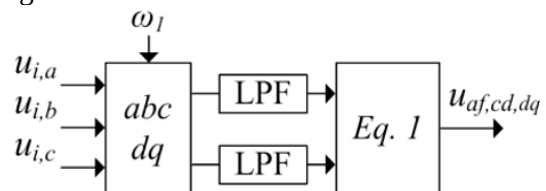


Fig.7. Feed forward control for the fundamental current diversion.

C. DC Bus Voltage Control

Proper control of the dc bus voltage is essential for the operation of this HAPF. The principle of controlling the dc bus voltage is based on active power control, that is, charging the dc capacitor with active power will increase the voltage while releasing a certain amount of active power, will decrease it. According to -theory, a dc component in the -coordinates corresponds to the active power and,

thus, dc bus voltage control is implemented in the SRF.

As can be seen from Fig.6, the difference between the reference value and the measured and filtered actual value is applied to a PI controller, which adjusts the direct axis current (the quadrature axis is set to zero). A low-pass filter (LPF) with a cutoff frequency of 15 Hz eliminates the harmonics from the measured dc bus voltage. The resulting control signal is added to the voltage reference.

D. Fundamental Current Diversion

In order to achieve the minimum current rating of the active part, the fundamental-frequency filter current needs to be diverted into a parallel inductance. This is done with a simple feedforward controller, represented in Fig.7. It calculates the voltage appearing across the passive filter inductor, which would occur in the absence of the active filter, using (1). As a result, only a small fundamental frequency current is flowing through the active elements, which is required for charging the dc capacitor.

4.3.5 Current Control Transfer Function

Fig.8. shows the main current control block diagram of the filter. The harmonic content of the system current is filtered from the measured system current.

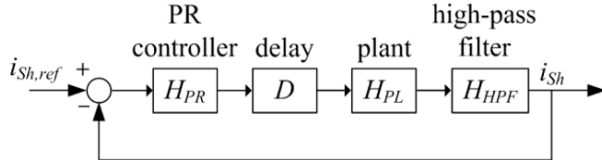


Fig.8. Main current-control block diagram.

The transfer function for the harmonic-detecting circuit can be expressed as

$$H_{HPF} = \frac{i_{s,h}}{i_s} = \frac{s - j\omega_1}{s - j\omega_1 + \omega_C} \quad (12)$$

Where ω_C is the cutoff angular frequency of the HPFs that extract the dc component in the coordinates, and ω_1 is the fundamental angular frequency. The detected harmonic current $i_{s,h}$ is compared with the current

reference $i_{sh,ref}$, and the difference e_h represents the input to the PR controller. This results in the production of the reference voltage $u_{af,ref}$ to be generated by the inverter. In the real control circuit [implemented on a digital signal processor (DSP)], the output signal is inherently delayed with respect to the input signal. The time delay is represented as

$$D = e^{-sT_s} \quad (13)$$

Where $100 \mu s$ is the sampling period. The plant transfer function is defined as (see Fig. 2)

$$H_{PL} = \frac{u_{af}}{i_s} = \frac{1}{Z_{af}} \cdot \frac{Z_{L,pf}}{Z_s + Z_{L,pf} + Z_{C,pf}} \quad (14)$$

Finally, the open-loop transfer function of the hybrid filter controller is given by

$$H(s) = H_{PR} \cdot H_{HPF} \cdot D \cdot H_{PL} \quad (15)$$

E. Filtering Characteristic

The filtering characteristic of the HAPF depends primarily on the control algorithm; however, all of the algorithms have something in common. It is well known that power-electronic converters in harmonic filtering applications may be controlled to behave in a similar fashion to a passive element. As will be shown, the PR-controlled HAPF proposed herein mimics several parallel resonant circuits added in parallel and tuned to the characteristic harmonic frequencies.

The filtering characteristic can be obtained by calculating the equivalent model of the network (Fig.2). Applying Kirchhoff's circuit laws yields

$$i_s = \frac{u_s - i_l \cdot (Z_{L,pf} + Z_{C,pf}) + Z_{L,pf} \cdot i_{af}}{Z_s + Z_{L,pf} + Z_{C,pf}} \quad (16)$$

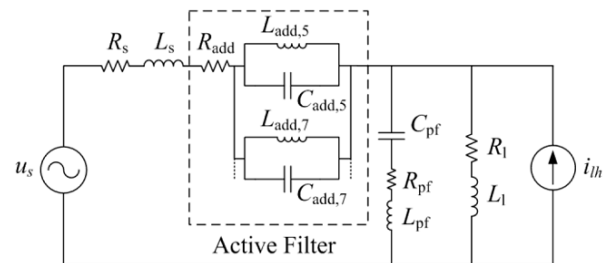


Fig.9. Equivalent circuit for the filtering characteristic analysis.

Taking into account (3.11) and (3.14) and neglecting the resistance of the passive filter inductor, we obtain

$$i_s = \frac{u_s - i_l \cdot (Z_{L,pf} + Z_{C,pf})}{Z_s + Z_{L,pf} + Z_{C,pf} + \frac{L_{L,pf}}{L_{af}} H_{PR}(s)} \quad (17)$$

Letting:

$$\begin{aligned} R_{add} &= K_P \frac{L_{L,pf}}{L_{af}}, \\ L_{add} &= K_I \frac{L_{L,pf}}{L_{af}(h \cdot \omega_1)^2}, \\ C_{add} &= \frac{1}{L_{add}(h \cdot \omega_1)^2} \end{aligned} \quad (18)$$

We obtain

$$i_s = \frac{u_s - i_l \cdot (Z_{L,pf} + Z_{C,pf})}{(Z_s + R_{add} + \sum_{h=5,7,\dots} \frac{j\omega L_{add,h} j\omega C_{add,h}}{j\omega L_{add,h} + j\omega C_{add,h}}) + Z_{L,pf} + Z_{C,pf}} \quad (19)$$

Equation (19) defines the filtering characteristic of the HAPF, which depends on the passive filter inductor and capacitor equivalent impedances

$Z_{L,pf}$ and $Z_{C,pf}$, the system impedance Z_s , and the active power filter transfer function given by (11). As can be seen from Fig. 9, representing a single-phase equivalent circuit of the system with a connected HAPF, the active filter behaves as a pure resistor $R_{add} (\Omega)$, with several parallel $L_{add,h} C_{add,h}$ circuits added in series.

IV. UNIT VECTOR CONTROLLER

Basically a three phase voltage source inverter (VSI) connected in parallel with a nonlinear load at the point of common coupling through an inductor L_F . The energy storage of the APF is a large capacitor located at the dc-link side of the inverter. The nonlinear load can be presented as a RL or RLC load connected to the power supply through a three-phase diode rectifier. As stated earlier, the APF must generate the harmonic currents to compensate harmonics produced by the nonlinear load and to make the supply currents sinusoidal. To fulfill these demands, the traditional control scheme requires a harmonic detector and current controller where both loops must be designed properly to achieve good control performance. However, it may cause excessive complexity in the design process.

In order to simplify the control scheme and to enhance the accuracy of the APF, an advanced control strategy is proposed, the proposed control scheme is implemented by using only the supply current (i_{sa} and i_{sb}) without detecting the load current ($i_{L,abc}$) and filter current ($i_{F,abc}$). Thereby, the load current sensors and filter current sensors in the typical hybrid APF can be eliminated. And also, the harmonic current detection is omitted. Due to the absence of harmonic detection, the proposed control scheme can be implemented with only two loops: the outer voltage control and the inner current control.

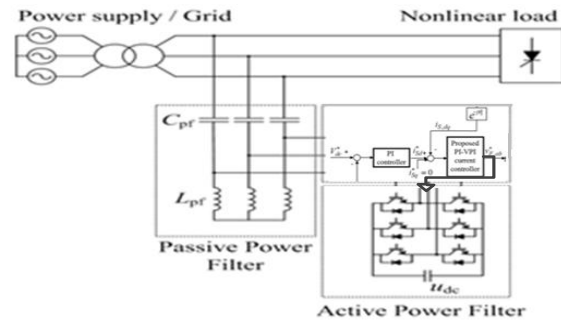


Fig10 Structure of the proposed control scheme for three-phase hybrid APF

The outer loop aims to keep dc-link voltage of the APF constant through a PI controller, which helps the APF deal with load variations. The output of this control loop is the reference active current in the fundamental reference frame (i_{sd}^*). Meanwhile, the reference reactive current (i_{sq}^*) is simply set to be zero, which ensures the reactive power provided by the power supply to be zero, and the reactive power caused by loads is supplied by the hybrid APF. The inner loop is then used to regulate the supply current in the fundamental reference frame ($i_{s,dq}$) by using the proposed PI-VPI current controller. The output of this loop becomes the control signal ($v_{F,ab}^*$) applied to the four-switch APF which is implemented by the FSTPI. Since the current control is executed without the harmonic detector, the control performance of the APF only relies on the current controller. In the next section, the analysis and design of the proposed current controller will be presented.

V. SIMULATION RESULTS

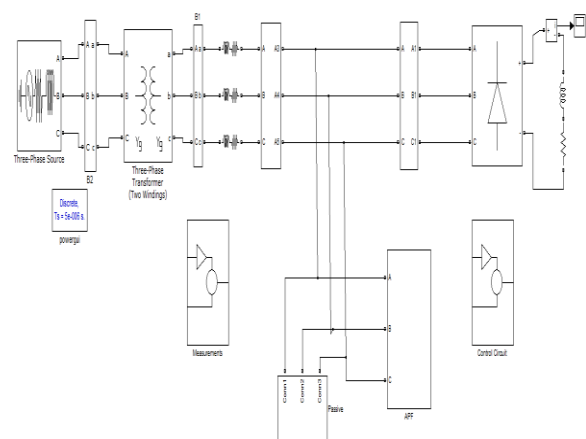


Figure.11. Matlab/Simulink Model Circuit of System with constant Load.

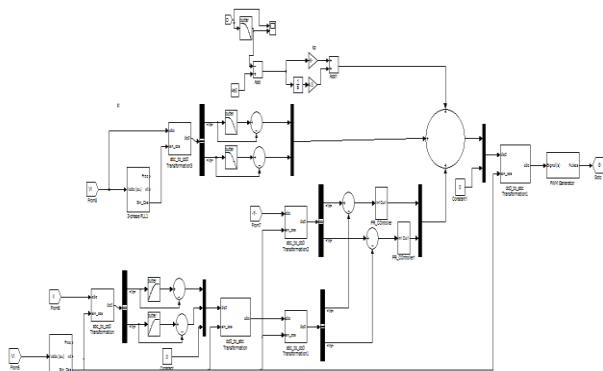


Figure.12.Control Circuit of System with Constant Load.

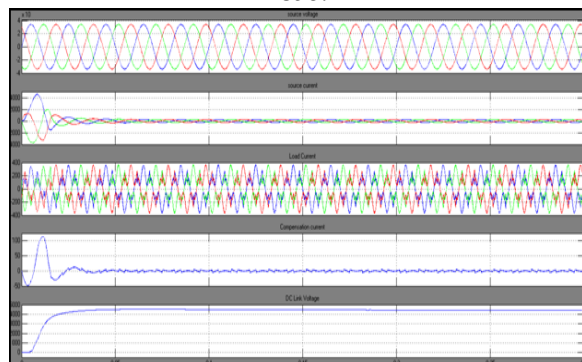


Figure.13.Simulated Waveforms In The Transient State –Hapf Start Up at for 3-Phase a).source voltage. b).source current c).load current d).compensation current e).DC link voltage

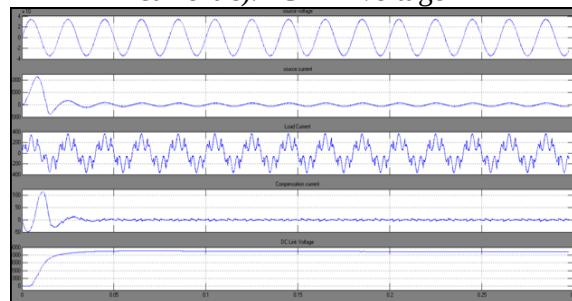


Figure.14.Simulated Waveforms In The Transient State –Hapf Start Up At Scope 1 for 1-Phase a).source voltage b).source current c).load current d).compensation current e).DC link voltage.

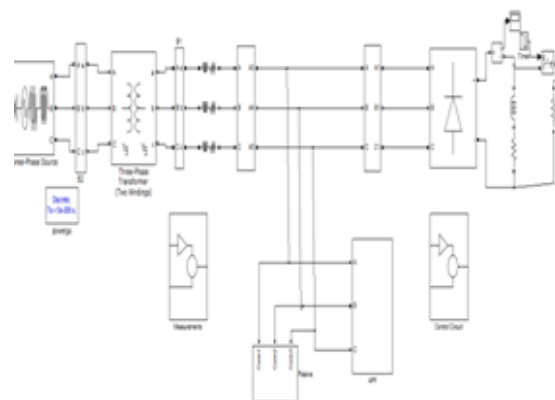


Figure.15.Matlab/Simulink Model Circuit of System With 50% Step Load Decrease/ Increase.

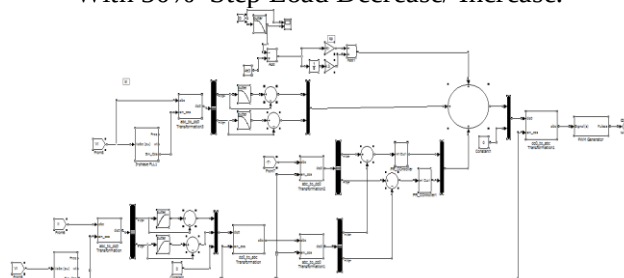


Figure.16.Control Circuit of System With 50% Step Load Decrease/ Increase.

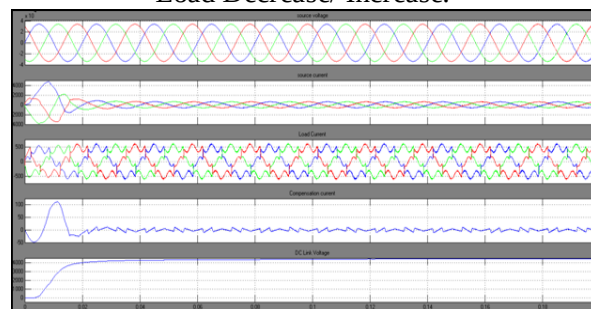


Figure.17 .Simulated Waveforms In The Transient State -50%Load Step Decrease / Increase For 3-PhaseAt a).source voltage b).source current c).load current d).compensation current e).DC link voltage

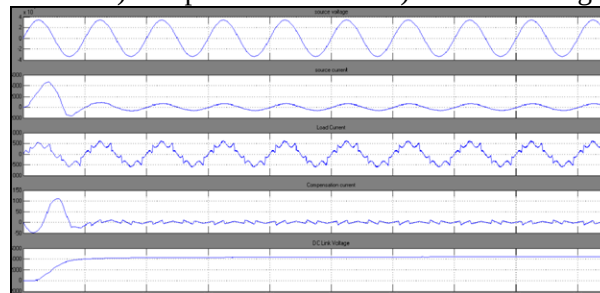


Figure.18. Simulated Waveforms in the TransientState -50% Load Step Decrease / Increase For 3-Phase a).source voltage b).source current c).load current d).compensation current e).DC link voltage

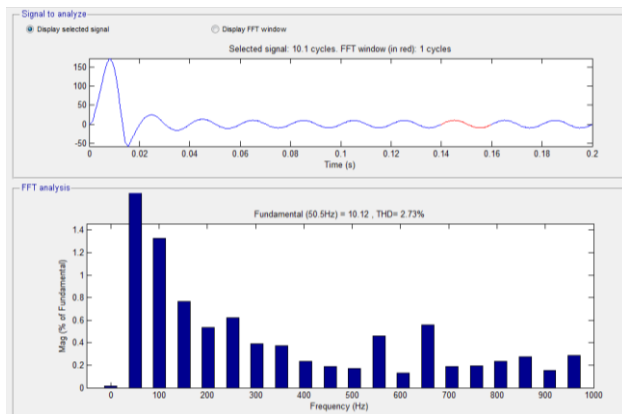


Fig.19. FFT Analysis of Source Current with Resonant Current Controller
THD value is 2.73%.

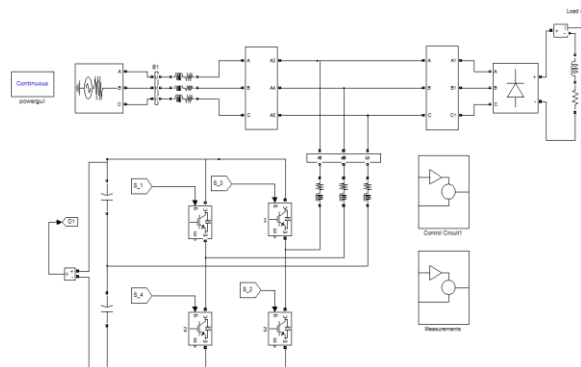


Fig.20. Matlab/Simulink Model of Proposed Sour Switch APF Operated under Several Control Strategies to Enhance PQ Features

Fig.20. shows the Matlab/Simulink Model of Proposed Sour Switch APF Operated under Several Control Strategies to Enhance PQ Features using Matlab/Simulink Environment.

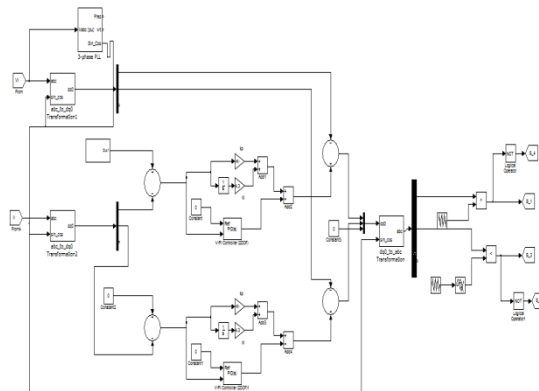


Fig.21. Matlab/Simulink Model of control circuit of proposed onverter.

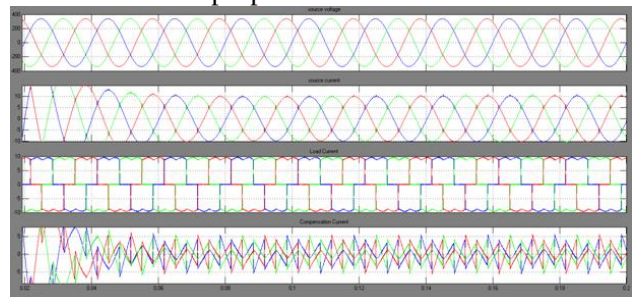


Fig.22. Simulated waveforms of Three phase source voltage, source current, load current and compensation current

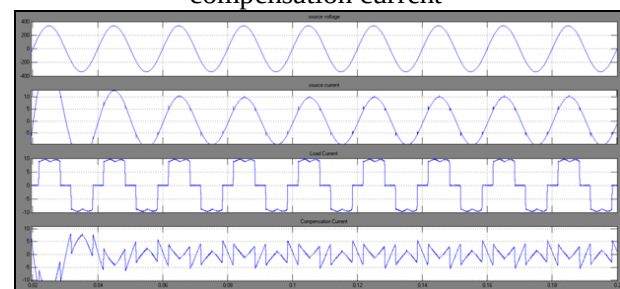


Fig.23. Source Voltage, Source Current, Load Current, Compensation Current

Fig.23.shows the Source Voltage, Source Current, Load Current,and Compensation Current of proposed Four Switch APF operating under PI-VPI Controller.

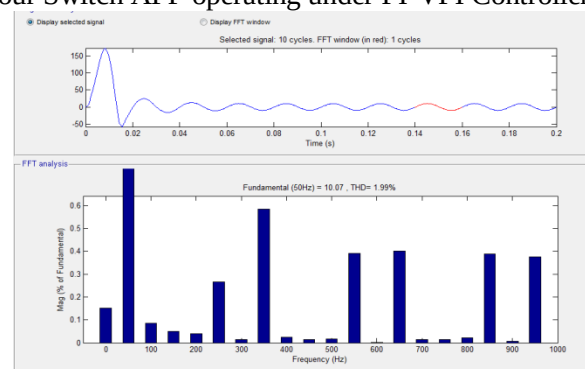


Fig.24. FFT Analysis of Source Current with Proposed Compensator

Fig.24. shows the FFT Analysis of Source Current with Proposed Four Switch APF with PI-VPI control strategy get THD value is 1.99%.

Table I
Comparison in THD Analysis

	Resonant Current Controller	Unit vector controller
T H D	2 . 7 3 %	1 . 9 9 %



V. CONCLUSION

In this paper, a hybrid active power filter for reactive power compensation and harmonics filtering has been presented. It is composed of a small-rating VSC connected in parallel with the inductor of a shunt single-tuned passive filter. Since the rated power of the active filter is relatively low, the HAPF represents a viable solution for reactive power compensation and harmonic filtering. A PR current control scheme for selective harmonics compensation with the HAPF has been proposed. As shown, each controller acts as a resonant filter tuned to a certain harmonic frequency. The proper selection of the parameters ensures high selectivity and improves the transient performance of the HAPF. Another key feature is that each pair of harmonics, is filtered by one controller and, thus, important savings in terms of computational burden are achieved. Theoretical analysis, along with the simulation results, obtained from a real industrial network model, verifies the effectiveness of the proposed hybrid filter, which represents an excellent solution for reactive power compensation and harmonic filtering.

REFERENCES

- [1] H. Akagi, "New trends in active filters for power conditioning," *IEEE Trans. Ind. Appl.*, vol. 32, no. 2, pp. 1312–1332, Nov./Dec. 1996.
- [2] F. Z. Peng, "Application issues of active power filters," *IEEE Ind. Appl. Mag.*, vol. 4, no. 5, pp. 21–30, Sep./Oct. 1998.
- [3] H. Akagi, E. H. Watanabe, and M. Aredes, *Instantaneous Power Theory and Applications to Power Conditioning*, M. E. El-Hawari, Ed. New York: Wiley, 2007.
- [4] R. I. Bojoi, G. Griva, V. Bostan, M. Guerriero, F. Farina, and F. Profumo, "Current control strategy for power conditioners using sinusoidal signal integrators in synchronous reference frame," *IEEE Trans. Power Electron.*, vol. 20, no. 6, pp. 1402–1412, Nov. 2005.
- [5] C. Lascu, L. Asiminoaei, I. Boldea, and F. Blaabjerg, "Frequency response analysis of current controllers for selective harmonic compensation in active power filters," *IEEE Trans. Ind. Electron.*, vol. 56, no. 2, pp. 337–347, Feb. 2009.
- [6] S. Buso, L. Malesani, and P. Mattavelli, "Comparison of current control techniques for active filters applications," *IEEE Trans. Ind. Electron.*, vol. 45, no. 5, pp. 722–729, Oct. 1998.
- [7] L. Malesani, P. Mattavelli, and S. Buso, "Robust dead-beat current control for PWM rectifiers and active filters," *IEEE Trans. Ind. Appl.*, vol. 35, no. 3, pp. 613–620, May/Jun. 1999.
- [8] S. Rahmani, N. Mendalek, and K. Al-Haddad, "Experimental design of a nonlinear control technique for three-phase shunt active power filter," *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3364–3375, Oct. 2010.
- [9] H. Hu, W. Shi, Y. Lu, and Y. Xing, "Design considerations for DSP controlled 400 Hz shunt active power filter in an aircraft power system," *IEEE Trans. Ind. Electron.*, vol. 59, no. 9, pp. 3624–3634, Sep. 2012.
- [10] Z. Chen, Y. Luo, and M. Chen, "Control and performance of a cascaded shunt active power filter for aircraft electric power system," *IEEE Trans. Ind. Electron.*, vol. 59, no. 9, pp. 3614–3623, Sep. 2012.
- [11] R. I. Bojoi, G. Griva, V. Bostan, M. Guerriero, F. Farina, and F. Profumo, "Current control strategy for power conditioners using sinusoidal signal integrators in synchronous reference frame," *IEEE Trans. Power Electron.*, vol. 20, no. 6, pp. 1402–1412, Nov. 2005.
- [12] C. Lascu, L. Asiminoaei, I. Boldea, and F. Blaabjerg, "Frequency response analysis of current controllers for selective harmonic compensation in active power filters," *IEEE Trans. Ind. Electron.*, vol. 56, no. 2, pp. 337–347, Feb. 2009.