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Harmonic Reduction by Using Shunt Hybrid Power Filter

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ABSTRACT:

This project report presents design, simulation and development of passive shunt filter and shunt hybrid power filter (SHPF) for mitigation of the power quality problem at ac mains in ac-dc power supply feeding to a nonlinear load. The power filter is consisting of a shunt passive filter connected in series with an active power filter. At first passive filter has been designed to compensate harmonics. The drawback associated with the passive filter like fixed compensation characteristics and resonance problem is tried to solve by SHPF. Simulations for a typical distribution system with a shunt hybrid power filter have been carried out to validate the presented analysis. Harmonic contents of the source current has been calculated and compared for the different cases to demonstrate the influence of harmonic extraction circuit on the harmonic compensation characteristic of the shunt hybrid power filter.

Keywords: *active power filter, alternating current, direct curren, harmonic compensation, modeling, Shunt passive filter, shunt hybrid power filter,*

I. INTRODUCTION

Now a day's power electronic based equipment are used in industrial and domestic purpose. These equipments have significant impacts on the quality of supplied voltage and have increased the harmonic current pollution of distribution systems. They have many negative effects on power system equipment and customer, such as additional losses in overhead and underground cables, transformers and rotating electric machines, problem in the operation of the protection systems, over voltage and shunt capacitor, error of measuring instruments, and malfunction of low efficiency of customer sensitive loads. Passive filter have been used traditionally for mitigating the distortion due to harmonic current in industrial power systems. But they have many drawbacks such as resonance problem, dependency of their performance on the system impedance, absorption of harmonic current of nonlinear load, which could lead to further harmonic propagation through the power system.

To overcome of such problem active power filters is introduced. It has no such drawbacks like passive filter. They inject harmonic voltage or current with appropriate magnitudes and phase angle into the system and cancel harmonics of nonlinear loads. But it has also some drawbacks like high initial cost and high power losses due to which it limits there wide application, especially with high power rating system.

To minimize these limitations, hybrid power filter have been introduced and implemented in practical system applications. Shunt hybrid filter is consists of an active filter which is connected in series with the passive filter and with a three phase PWM inverter. This filter effectively mitigates the problem of a passive and active filter. It provides cost effective harmonic compensation, particularly for high power nonlinear load.

II. SHUNT HYBRID POWER FILTER

2.1 Introduction

Hybrid filters provide cost-effective harmonic compensation particularly for high-power nonlinear load. A parallel hybrid power filter system consists of a small rating active filter in series with a passive filter. The active filter is controlled to act as a harmonic compensator for the load by confining all the harmonic currents into the passive filter. This eliminates the possibility of series and parallel resonance.

The schematic diagram of the shunt hybrid power filter (SHPF) is presented in Fig.1. The scheme contains the three phase supply voltage, three phase diode rectifier and the filtering system consists of a small-rating active power filter connected in series with the LC passive filter. This configuration of hybrid filter ensures the compensation of the source current harmonics by enhancing the compensation characteristics of the passive filter besides eliminating the risk of resonance. It provides effective compensation of current harmonics and limited supply voltage distortion. The hybrid filter is controlled such that the harmonic currents of the nonlinear loads flow through the passive filter and that only the fundamental frequency component of the load current is to be supplied by the ac mains.

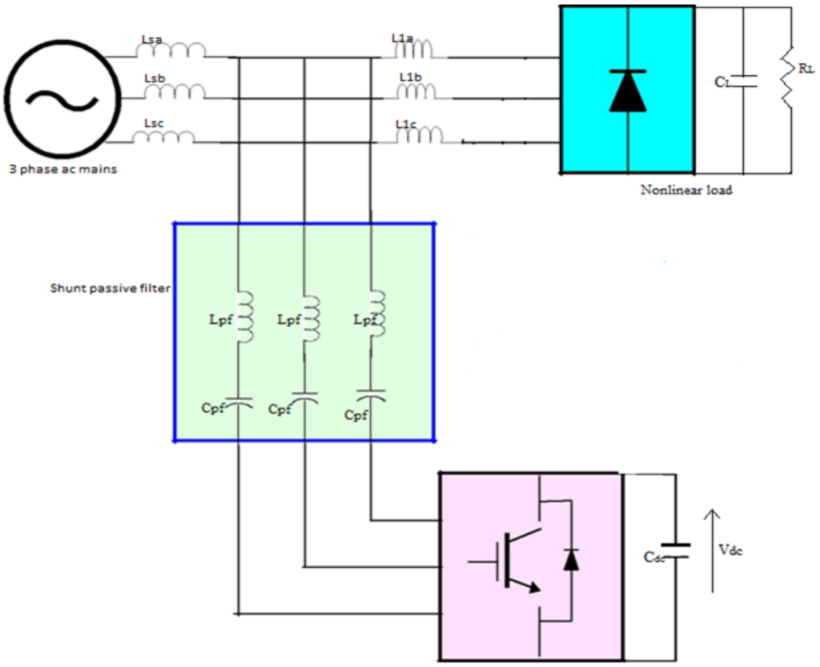

Fig.1Schematic diagram of 3-phase SHPF Supplying power to Nonlinear Load

2.2 Modeling of the SHPF

2.2.1 Model in a-b-c reference frame:

Kirchhoff's law of voltage and currents applied to this system provide three differential equations in the stationary "a-b-c" frame (for k = 1, 2, 3)

$$V_{sk} = L_{PF}\frac{di_{ck}}{dt} + R_{PF}i_{ck} + \frac{1}{C_{PF}}\int i_{ck}\,dt + V_{KM} + V_{MN} \qquad (1)$$

Differentiating (1) we get

$$\frac{dV_{sK}}{dt} = L_{PF}\frac{d^2 i_{CK}}{dt^2} + R_{PF}\frac{di_{cK}}{dt} + \frac{1}{C_{PF}}i_{CK} + \frac{dV_{KM}}{dt} + \frac{dV_{MN}}{dt} \qquad (2)$$

Assume that the zero sequence current is absent in a three phase system and the source voltages are balanced, so we obtain:

$$V_{MN} = -\frac{1}{3}\sum_{k=1}^{3} V_{kM} \qquad (3)$$

We can define the switching function C_k of the converter k^{th} leg as being the binary state of the two switches S_k and S'_k. Hence, the switching C_k (for k = 1, 2, 3) is defined as

$C_k = 1$, if S_k is On and S'_k is Off ,

$C_k = 0$, if S_k is Off and S'_k is On. (4)

Thus, with $V_{kM} = C_k V_{dc}$, and from (4), the following relation is obtained:

$$\frac{d^2 i_{cK}}{dt^2} = -\frac{R_{PF}}{L_{PF}}\frac{di_{cK}}{dt} - \frac{1}{C_{PF}L_{PF}}i_{CK} - \frac{1}{L_{PF}}\left(C_K - \frac{1}{3}\sum_{m=1}^{3} C_m\right)\frac{dV_{dc}}{dt} + \frac{1}{L_{PF}}\frac{dV_{SK}}{dt} \qquad (5)$$

Let the Switching state function be defined as

$$q_{nk} = \left(C_K - \frac{1}{3}\sum_{m=1}^{3} C_m\right)_n \qquad (6)$$

The value of q_{nk} depends on the switching state n and on the phase k. This shows the interaction between the three phases. Conversion from $[C_k]$ to $[q_{nk}]$ is as follows

$$q_{n1} = \frac{2}{3}C_1 - \frac{1}{3}C_2 - \frac{1}{3}C_3 \qquad (7)$$

$$q_{n2} = -\frac{1}{3}C_1 + \frac{2}{3}C_2 - \frac{1}{3}C_3 \tag{8}$$

$$q_{n3} = -\frac{1}{3}C_1 - \frac{1}{3}C_2 + \frac{2}{3}C_3 \tag{9}$$

Hence we got the relation as

$$\begin{bmatrix} q_{n1} \\ q_{n2} \\ q_{n3} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} \tag{10}$$

The matrix in (10) is of rank 2 q_{nk} has no zero sequence components. By the analysis of the dc component of the system it gives

$$dV_{dc} = \frac{1}{C_{dc}} i_{dc} = \frac{1}{C_{dc}} \sum_{k=1}^{3} q_{nk} i_{ck} \tag{11}$$

With the absence of zero sequence components in i_k and q_{nk} one can gets

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}}(2q_{n1} + q_{n2})i_{c1} + \frac{1}{C_{dc}}(q_{n1} + q_{n2})i_{c2} \tag{12}$$

Hence the complete model of the active filter in “a-b-c” reference frame is obtained as follows

The application of (5) for phase 1 and 2 with (13)

$$L_{PF}\frac{d^2 i_{c1}}{dt^2} = -R_{PF}\frac{di_{c1}}{dt} - \frac{1}{C_{CF}} i_{c1} - q_{n1}\frac{dV_{dc}}{dt} + \frac{dV_{s1}}{dt}$$

$$L_{PF}\frac{d^2 i_{c2}}{dt^2} = -R_{PF}\frac{di_{c2}}{dt} - \frac{1}{C_{CF}} i_{c2} - q_{n2}\frac{dV_{dc}}{dt} + \frac{dV_{s2}}{dt}$$

$$C_{dc}\frac{dV_{dc}}{dt} = (2q_{n1} + q_{n2})i_{c1} + (q_{n1} + q_{n2})i_{c2} \tag{13}$$

The above model is time varying and nonlinear in nature.

2.2.2 Model Transformation in to “d-q” reference frame:

Since the steady state fundamental components are sinusoidal, the system is transformed into the synchronous orthogonal frame rotating at constant supply frequency. The conversion matrix is

$$C_{dq}^{123} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\theta & \cos\left(\left(\theta - {}^{2\pi}/_{3}\right)\right) & \cos\left(\left(\theta - {}^{4\pi}/_{3}\right)\right) \\ -\sin\theta & -\sin\left(\left(\theta - {}^{2\pi}/_{3}\right)\right) & -\sin\left(\left(\theta - {}^{4\pi}/_{3}\right)\right) \end{bmatrix} \tag{14}$$

where θ = ωt, and the following equalities hold:

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

Now (13) is

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}}(q_{n1})^{T}(i_{c123}) \tag{15}$$

Applying coordination transformation

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}}\left[C_{123}^{dq}\left(q_{ndq}\right)^{T}\right]\left[C_{123}^{dq}\left(i_{dq}\right)\right] = \frac{1}{C_{dc}}\left[\left(q_{ndq}\right)^{T}\right]\left[\left(i_{dq}\right)\right] \tag{16}$$

On the other hand, the two first equations in (13) are written as

$$\frac{d^2[i_{c12}]}{dt^2} = -\frac{R_{PF}}{L_{PF}}\frac{d}{dt}[i_{c12}] - \frac{1}{C_{PF}L_{PF}}[i_{c12}] - \frac{1}{L_{PF}}[q_{n12}]\frac{dV_{dc}}{dt} + \frac{1}{L_{PF}}\frac{d}{dt}[V_{c12}] \tag{17}$$

The reduced matrix can be used

$$C_{dq}^{12} = \sqrt{2}\begin{bmatrix} \cos\left(\theta - \frac{\pi}{6}\right) & \sin\theta \\ -\sin\left(\theta - \frac{\pi}{6}\right) & \cos\theta \end{bmatrix} \tag{18}$$

It has the following inverse

$$C_{12}^{dq} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\left(\theta - \frac{\pi}{6}\right) & \cos\left(\theta - \frac{\pi}{6}\right) \end{bmatrix} \tag{19}$$

Apply this transformation into (17)

$$\frac{d^2\left[C_{12}^{dq}[i_{dq}]\right]}{dt^2} = -\frac{R_{PF}}{L_{PF}}\frac{d}{dt}\left[C_{12}^{dq}[i_{dq}]\right] - \frac{1}{C_{PF}L_{PF}}[i_{dq}] - \frac{1}{L_{PF}}\left[C_{12}^{dq}[q_{ndq}]\right]\frac{dV_{dc}}{dt} + \frac{1}{L_{PF}}\frac{d}{dt}\left[C_{12}^{dq}[V_{dq}]\right] \qquad (20)$$

With the following matrix differential property

$$\frac{d\left[C_{12}^{dq}[i_{dq}]\right]}{dt} = C_{12}^{dq}\frac{d}{dt}[i_{dq}] + \left(\frac{d}{dt}C_{12}^{dq}\right)[i_{dq}] \qquad (21)$$

$$\frac{d^2\left[C_{12}^{dq}[i_{dq}]\right]}{dt^2} = C_{12}^{dq}\frac{d^2}{dt^2}\left[[i_{dq}]\right] + \left(\frac{d}{dt}C_{12}^{dq}\right)\left[[i_{dq}]\right] + \left(\frac{d}{dt}C_{12}^{dq}\right)\frac{d}{dt} + \left(\frac{d^2}{dt^2}C_{12}^{dq}\right)\left[[i_{dq}]\right] \qquad (22)$$

Now the following relation is derived:

$$\frac{d^2[i_{dq}]}{dt^2} = -\begin{bmatrix} \frac{R_{PF}}{L_{PF}} & -2\omega \\ 2\omega & \frac{R_{PF}}{L_{PF}} \end{bmatrix} d[i_{dq}] \begin{bmatrix} -\omega^2 + \frac{1}{L_{PF}C_{PF}} & -\omega\frac{R_{PF}}{L_{PF}} \\ \omega\frac{R_{PF}}{L_{PF}} & -\omega^2 + \frac{1}{L_{PF}C_{PF}} \end{bmatrix}[i_{dq}] - \frac{1}{L_{PF}}[q_{ndq}]\frac{d}{dt}[V_{dc}] + \frac{1}{L_{PF}}\frac{d}{dt}[V_{dc}] + \frac{1}{L_{PF}}\begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}[V_{dq}] \qquad (23)$$

Now the complete model in the d-q frame is obtained from (16) and (23)

$$L_{PF}\frac{d^2 i_d}{dt^2} = -R_{PF}\frac{di_d}{dt} + 2\omega L_{PF}\frac{di_d}{dt} - \left(-\omega^2 L_{PF} + \frac{1}{C_{PF}}\right)i_d + \omega R_{PF}i_q - q_{nd}\frac{dV_{dc}}{dt} + \frac{dV_d}{dt} - \omega V_q$$

$$L_{PF}\frac{d^2 i_q}{dt^2} = -R_{PF}\frac{di_q}{dt} - 2\omega L_{PF}\frac{di_d}{dt} - \left(-\omega^2 L_{PF} + \frac{1}{C_{PF}}\right)i_q - \omega R_{PF}i_d - q_{nq}\frac{dV_{dc}}{dt} + \frac{dV_q}{dt} + \omega V_d$$

$$\mathrm{C_{dc}}\frac{\mathrm{dV_{dc}}}{\mathrm{dt}} = \mathrm{q_{nd}id + q_{nq}i_q} \qquad (24)$$

The model is time invarient during a given switching state.

2.3 Harmonic current control

$$L_{PF}\frac{d^2 i_d}{dt^2} + R_{PF}\frac{di_d}{dt} + \left(-\omega^2 L_{PF} + \frac{1}{C_{PF}}\right)i_d = 2\omega L_{PF}\frac{di_q}{dt} + \omega R_{PF}i_q - q_{nd}\frac{dV_{dc}}{dt} + \frac{dV_d}{dt} - \omega V_q$$

$$L_{PF}\frac{d^2 i_q}{dt^2} - R_{PF}\frac{di_q}{dt} + \left(-\omega^2 L_{PF} + \frac{1}{C_{PF}}\right)i_q = -2\omega L_{PF}\frac{di_d}{dt} - \omega R_{PF}i_d - q_{nq}\frac{dV_{dc}}{dt} + \frac{dV_q}{dt} + \omega V_d$$

(25)

$$V_d = 2\omega L_{PF}\frac{di_q}{dt} + \omega R_{PF}i_q - q_{nd}\frac{dV_{dc}}{dt} + \frac{dV_d}{dt} - \omega V_q$$

$$V_q = 2\omega L_{PF}\frac{di_d}{dt} - \omega R_{PF}i_d - q_{nq}\frac{dV_{dc}}{dt} + \frac{dV_q}{dt} + \omega V_d \qquad (26)$$

Now the transfer function of the model is:

$$\frac{I_d(S)}{V_d(S)} = \frac{1}{L_{PF}S^2 + R_{PF}(S) + {}^{1}\!/_{C_{PF}} - L_{PF}\omega^2} \qquad (27)$$

Transfer function of the P-I controller is given as

$$G_i(S) = \frac{U_d(S)}{I_d(S)} = \frac{U_q(S)}{I_q(S)} = K_p + \frac{K_i}{S} \qquad (28)$$

The closed loop transfer function of the current loop is

$$\frac{I_q(S)}{I'_q(S)} = \frac{I_d(S)}{I'_d(S)} = \frac{K_p}{L_{PF}}\frac{S + \frac{K_i}{K_p}}{S + \frac{R_{PF}}{L_{PF}}S^2 + \left(\frac{1}{C_{PF}L_{PF}} - \omega^2 + \frac{K_p}{L_{PF}}\right)S + \frac{K_i}{L_{PF}}} \qquad (29)$$

The control loop of the current i_q is shown in the fig.2 below and the control law is

$$q_{nd} = \frac{2\omega L_{PF}\frac{di_q}{dt} + \omega R_{PF}i_q + \frac{dV_d}{dt} - \omega V_{q-}u_d}{\frac{dV_{dc}}{dt}}$$

$$q_{nq} = \frac{2\omega L_{PF}\frac{di_d}{dt} + \omega R_{PF} i_d + \frac{dV_q}{dt} - \omega V_{d\,-} u_q}{\frac{dV_{dc}}{dt}} \qquad (30)$$

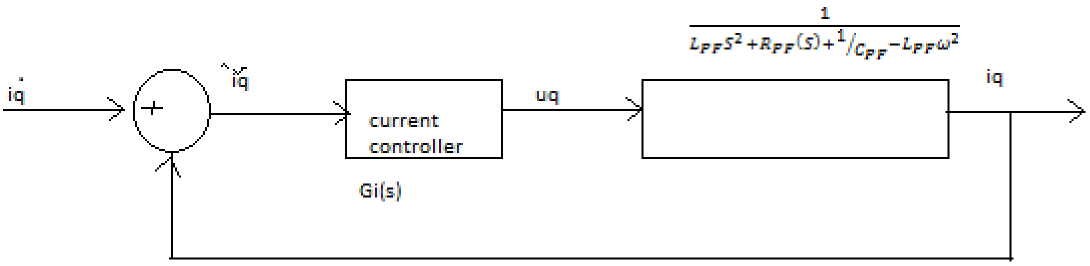

Fig.2 Control loop of the current.

Note that the inputs q_{nd} and q_{nq} consist of a nonlinearity cancellation part and a linear decoupling compensation part.

2.4 Regulation of DC voltage

The active filter produces a fundamental voltage which is in-phase with fundamental leading current of the passive filter. A small amount of active power is formed due to the leading current and fundamental voltage of the passive filter and it delivers to the dc capacitor. Therefore, the electrical quantity adjusted by the dc-voltage controller is consequently $i_q{}^{*}{}_{1}$. To maintain V_{dc} equal to its reference value, the losses through the active filter's resistive-inductive branches will be compensated by acting on the supply current.

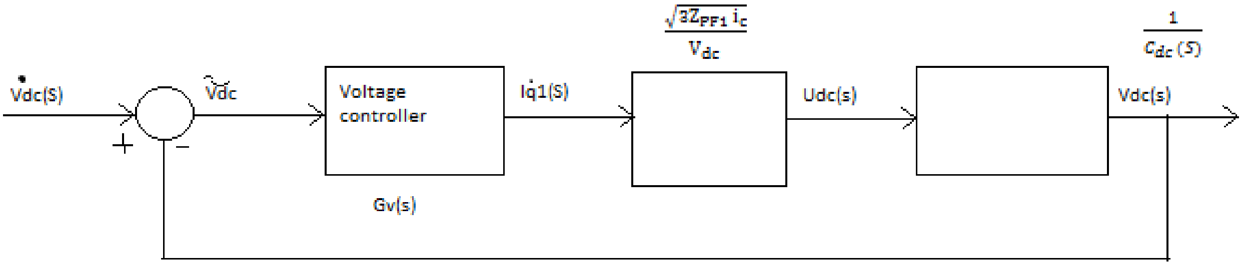

Fig.3 Control loop of the voltage

From (24) we can deduced to

$$C_{dc}\frac{dV_{dc}}{dt} = q_{nq}\,i_q \qquad (31)$$

An equivalent u_{dc} is defined as

$u_{dc} = q_{nq}i_q$ ----------------------(32)

Hence the reactive current of the active filter is

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

Now assume ${}^{q}{}_{nq}{}^{v}{}_{dc} \approx {}^{v}{}_{Mq}$ and q_{nd} $V_{dc} \approx V_{Md}$

hence

$$i_q = \frac{u_{dc}V_{dc}}{V_{mq}} \qquad (34)$$

the q axes active filter voltage V_{Mq} is given by

$V_{Mq} = -Z_{PF1}i_q{}^{*}{}_{1}$

Where Z_{PF1} is the impedance of the passive filter at 50 Hz and $i_q{}^{*}{}_{1}$ is a dc component.

The control effort of the dc-voltage loop is

$$i_{q_1}^{*} = \frac{u_{dc}V_{dc}}{-Z_{PF1}i_q} \qquad (35)$$

The three phase filter current are expressed as

$$\begin{bmatrix} i_{C1} \\ i_{C2} \\ i_{C3} \end{bmatrix} = \sqrt{\frac{2}{3}}\, i_q \begin{bmatrix} -\sin\theta \\ -\sin\left(\theta - {}^{2\pi}/_{3}\right) \\ -\sin\left(\theta - {}^{2\pi}/_{3}\right) \end{bmatrix} \qquad (36)$$

The fundamental filter rms current I_c is given by

$$I_C = \frac{i_q}{\sqrt{3}} \qquad (37)$$

The laplace form of the control effort can be derived as follows:

$$i_{q_1}^{*} = \frac{V_{dc}}{\sqrt{3Z_{PF1}\, i_c}}\, u_{dc}(S) \qquad (38)$$

The outer control loop of the dc voltage is shown in Fig. To regulate dc voltage $V_{dc,}$ the error $V_{dc}^{\sim} = V_{dc}^{*} - V_{dc}$ is passing through a P-I type controller given by

$$u_{dc} = K_1 V_{dc}^{\sim} + K_2 \int V_{dc}^{\sim}\, dt \qquad (39)$$

hence the closed loop transfer function is

$$\frac{V_{dc}(S)}{V_{dc}^{*}(S)} = 2\varepsilon\omega_{nv} \frac{S + \frac{\omega_{nv}}{2\varepsilon}}{S^2 + 2\varepsilon\omega_{nv} + \omega^2} \qquad (40)$$

Where ω_{nv} is the outer loop natural angular frequency and ζ is the damping factor.
The transfer functions of Fig. is

$$\frac{V_{dc}(S)}{V_{dc}^{*}(S)} = \frac{\frac{\sqrt{3}\, Z_{PF1} K_1 I_c}{V_{dc} C_{dc}}(S) + \frac{\sqrt{3}\, Z_{PF1} K_2 I_c}{V_{dc} C_{dc}}}{S^2 + \frac{\sqrt{3}\, Z_{PF1} K_1 I_c}{V_{dc} C_{dc}}(S) + \frac{\sqrt{3}\, Z_{PF1} K_2 I_c}{V_{dc} C_{dc}}} \qquad (41)$$

The proportional k_1 and integral k_2 gains are then obtained as:

$$K_1 = 2\varepsilon\omega_{nv} \frac{V_{dc} C_{dc}}{\sqrt{3}\, Z_{PF1} I_c}$$

$$K_2 = \omega_{nv}{}^{2} \frac{V_{dc} C_{dc}}{\sqrt{3}\, Z_{PF1} I_c} \qquad (42)$$

III. SIMULATION RESULT

The shunt hybrid power filter which is connected to a non-linear load is simulated by using MATLAB/SIMULINK environment. The scheme is first simulated without any filter to find out the THD of the supply current. Then it is simulated with the hybrid filter to observe the difference in THD of supply current.

3.1 Simulation response without filter

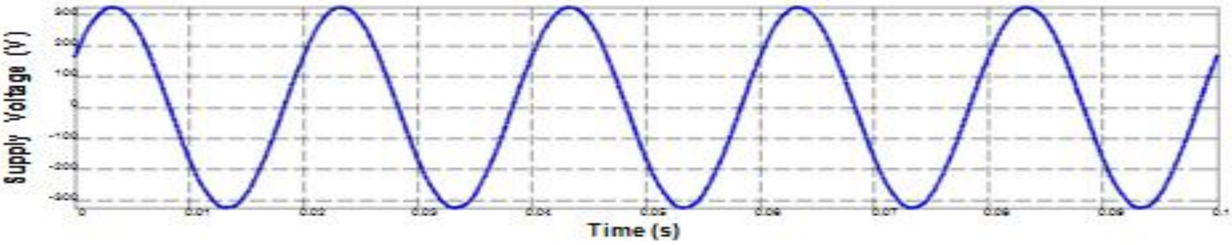

Fig.4 Wave forms of Supply Voltage (V) without filter.

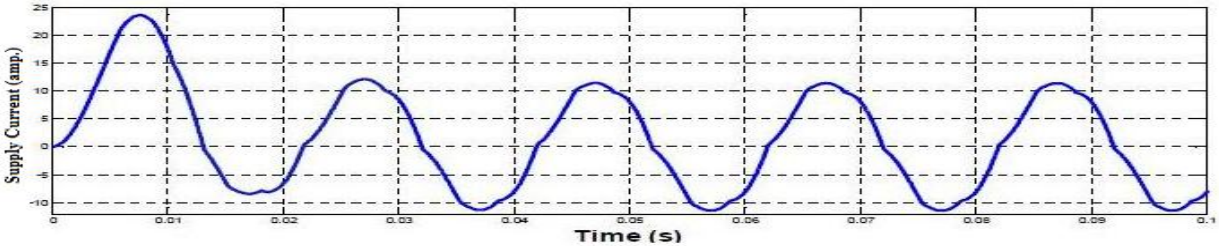

Fig.5 Wave forms of Supply Current (A) without filter

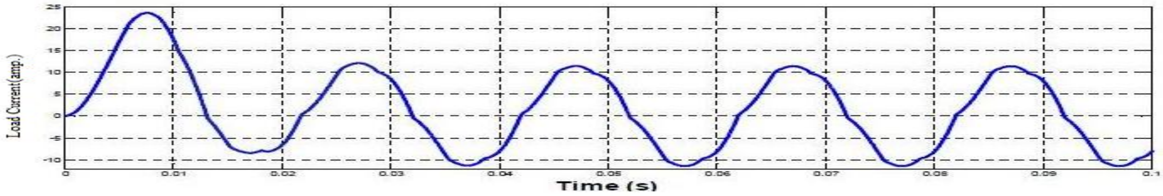

Fig.6 Wave forms of Load current (A) without filter.

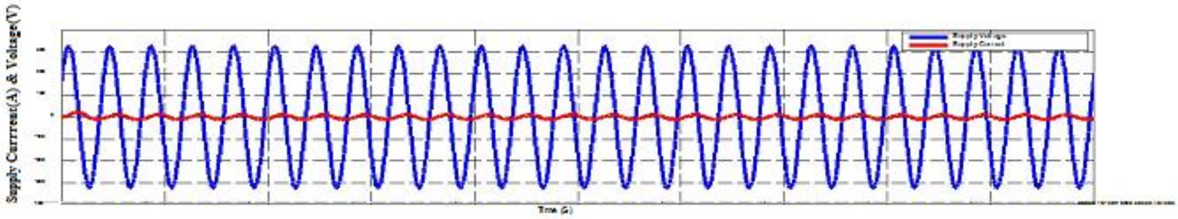

Fig.7 Wave forms of Supply Voltage (V) and Current (A) without filter.

Fig.7 shows the supply voltage and current without filter, we can see that the current is not in phase with the voltage.

3.2 Simulation response with shunt hybrid power filter

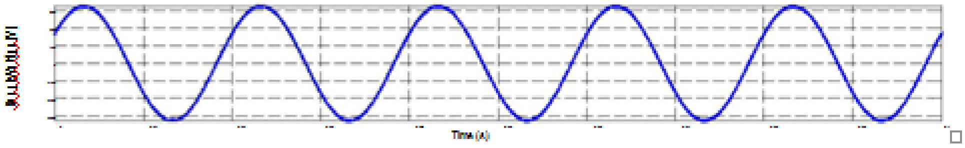

Fig.8 Wave forms of Supply Voltage (V) with hybrid filter.

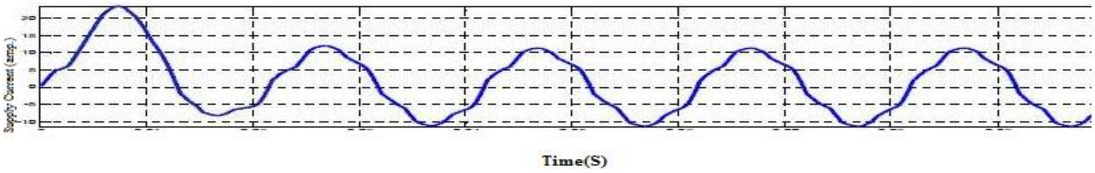

Fig.9 Wave forms of Supply Current (A) with hybrid filter.

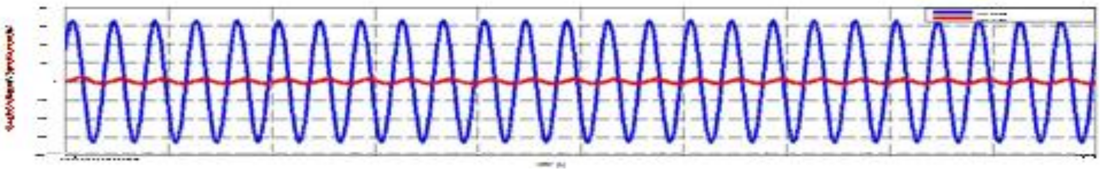

Fig.10 Wave forms of Supply Voltage and Current with hybrid filter.

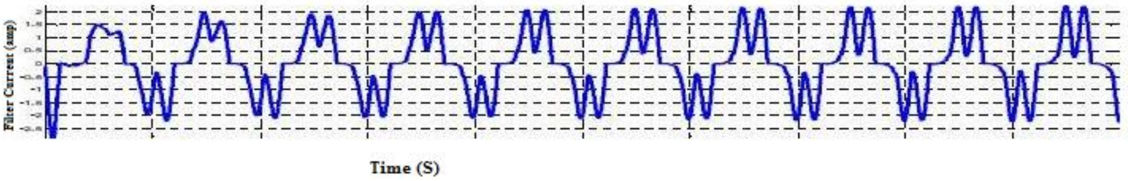

Fig.11 Wave forms of filter Current (A) With hybrid Filter

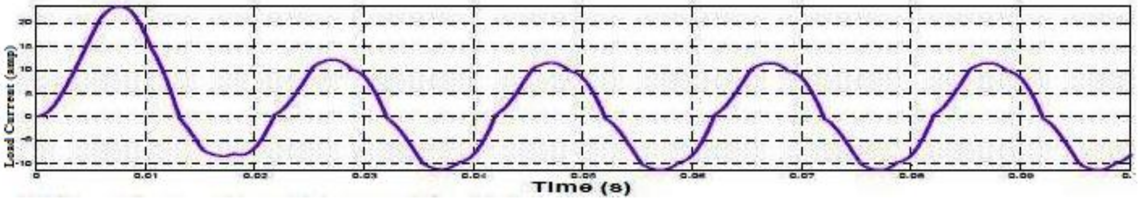

Fig.12 Wave forms of Load Current (A) with hybrid filter.

Fig.8-Fig.12 represents the simulation responses by using hybrid filter. Here we can see that in Fig.9 the supply current harmonic is quite reduced, but in the current is in phase with the voltage.

IV. CONCLUSION

This project work presents design of shunt hybrid power filter for a distribution system. The hybrid filter reduces the harmonics as compare to open loop response. This hybrid filter is tested and verified using MATLAB program. The implemented for three phase shunt hybrid power filter. Here non-linear load implemented. The harmonic current control and DC-capacitor voltage can be regulated under-linear loads. We obtained it from the simulation responses. The shunt hybrid power filter is verified with the simulation results. Hence we obtained comparative results by using these SHPF and without filter. The comparative simulation result presented in the table-1 and simulation parameter represented in table-2

Table-1

Nonlinear Load

Currents	THD(%) before compensation	THD(%) before compensation
	Without filter	With hybrid filter
Supply Current	23.24	8.51
Load Current	23.24	11.11
Filter Current	NIL	43.14

Hence we got the simulation responses for nonlinear load. In nonlinear load the THD is compensated from 23.24% to 8.51SHPF which is represented in Table 1.

Table-2

Specification Parameters

Phase voltage and frequency	V_s=230v(rms), f_s=50Hz
Supply /line inductance	$L_{sa}=L_{sb}=L_{sc}$=4 mH
Rectifier front-end inductance	$L_{la}=L_{lb}=L_{lc}$=30 mH
For V-S Type Load resistance, load capacitance	R_L=20 Ω , C_L=500 μF
Passive filter parameters	L_{pf}=14 mH, C_{pf}= 24 μF
Inverter dc- bus voltage and capacitance	V_{dc}=50v, C_{dc}=3000 μF
Controller Parameter	K_p=300, K_i=0.007

V. 5 SCOPE OF FUTURE WORK

- Experimental investigations can be done on shunt hybrid power filter by developing a prototype model in the laboratory to verify the simulation results for P-I Controller.
- Experimental investigations can be done on shunt hybrid power filter by developing a prototype model in the laboratory to verify the simulation results for hysteresis controllers.
- For the further experiment a smith controller used for the best result.
- Again For the further experiment a PID Controller used for the best result.
- In this thesis not consideration of the signal time delay, now Further investigation of the consideration of the signal time delay.
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