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Research Article

Harmonics and Reactive Power Compensation Using Shunt Hybrid Filter

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Abstract: The supply current is distorted by the nonlinear load such UPS, DC drives, AC drives and arc furnace. This current harmonics derates the electrical equipments. Thus the current harmonics are reduced from the supply line using Shunt Hybrid filter. The Hysteresis controller controls the active filter thus the supply current tracks the reference fundamental current extracted by the synchronous reference frame unit. So supply current is free from harmonics and also it provides harmonic compensation. The passive filter is tuned for the dominant harmonic frequency so it reduces the rating of the active filter. The total harmonic distortion and power factor of the supply current of three phase controlled rectifier load with filter and without filter is analyzed using MATLAB simulink and the results are presented.

Keywords: Active filter, harmonics, hybrid filter, MATLAB simulink, passive filter

INTRODUCTION

More usage of power converters pollutes the supply current. This supply current harmonics causes voltage distortion, derating the electrical equipment and mal function of the protective devices (Akagi, 1996; Singh and Verma, 2006), so the supply current harmonics should be minimized from the supply line. Also the non linear load consumes reactive power from the supply line. The bank of capacitors is added to reduce the reactive power from the supply line. But there is a resonance effect between the line impedance and the capacitor bank due the harmonic content supply current. The passive filters are used to reduce the supply current harmonics and provide reactive power compensation. The cost of the passive filter is cheap and simple design. But the filtering characteristics depend upon the line impedance and it is not suitable for variable load (Chandra *et al*., 2000; Mattavelli, 2001).

The shunt active filter was used to reduce the current harmonics from the supply system and also injects the reactive power (Gharedaghi *et al*., 2012). The voltage source inverter/ current source inverter are used as an Active filter. The current source inverter needs super conducting material for lossless dc reactor. The cost of the active filter is high because it carriers the harmonic current and the fundamental reactive current. It is difficult to construct the filter with quick current response (Hayashi *et al*., 1991). Various hybrid filter topology was investigated in recent years. The parallel hybrid filter with the transformer connection leads to high insulation voltage (Fujita and Akagi, 1991). In this study, the Shunt hybrid filter without transformer was used to reduce the current harmonics which is shown in Fig. 1. This filter uses only one dominant harmonic passive filter (resonant filter) and shunt active filter. There is no intermediate transformer between the supply line and the active filter. This reduces the cost of the filter design (Salem *et al*., 2012).

For reactive power compensation for variable nonlinear load TSC-TCR are used in Power system (VijayaKumar *et al*., 2010). This filter provides reactive power compensation so TSC is not required. The Synchronous Reference Frame (SRF) theory is used to generate the fundamental component(reference) of the supply current at the frequency of 50 Hz and the hysteresis controller controls the active filter according to the reference current generated by the SRF unit (Sriranjani and Jayalalitha, 2011). The cost of the active filter is reduced because the active filter carries only the fundamental reactive current and the harmonic current other than the dominant harmonic current. The dominant harmonic current (higher amplitude harmonic current) is injected by the resonant filter which is simple to design and low cost device.

MATHEMATICAL MODELING

Non linear load: The three phase diode rectifier with parallel RC load is used as a nonlinear load which distorts the supply current and generates harmonics. The supply current contains fundamental component and harmonic component. It also consumes reactive power from the supply line.

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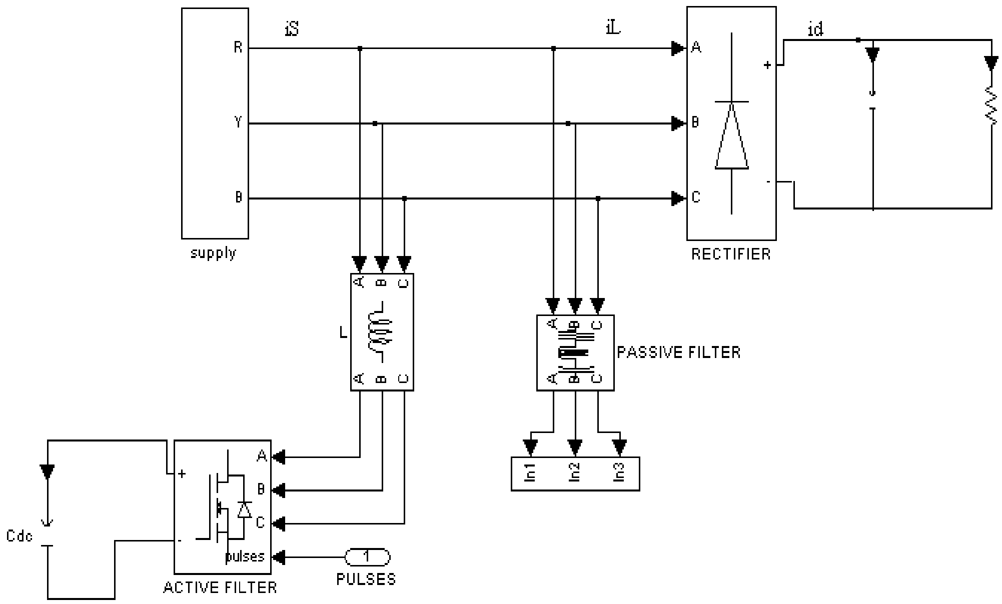

Fig. 1: Shunt hybrid filter configuration

In this study, the Hybrid filter is used for compensating the reactive power and reducing the current harmonics of the supply line. The supply voltage is a sinusoidal signal where the supply current is non sinusoidal due to the non linear load connected to the supply line.
The source voltage is given by:

$$Vs = V_m \sin(\omega_1 t)\, s \tag{1}$$

Due to the nonlinear load, the load current contains fundamental component and harmonics component:

$$i_L(t) = \sum_{k=1}^{\infty} I_k \sin(k\omega_1 t + \Phi_k) \tag{2}$$

$$i_L(t) = I_1 \sin(\omega_1 t + \phi_1) + \sum_{k=2}^{\infty} I_k \sin(k\omega_1 t + \Phi_k) \tag{3}$$

I_1 : Fundamental current
I_k : k^{th} harmonic current
V_m : Maximum supply voltage
φ_k : Phase angle between the supply voltage and current of the k^{th} harmonic component

Shunt active filter and passive filter: The Active filter and resonant filter are connected in parallel with the supply mains and the resonant filter is tuned for the dominant harmonic frequency of the load current. The active filter provides the reactive power compensation

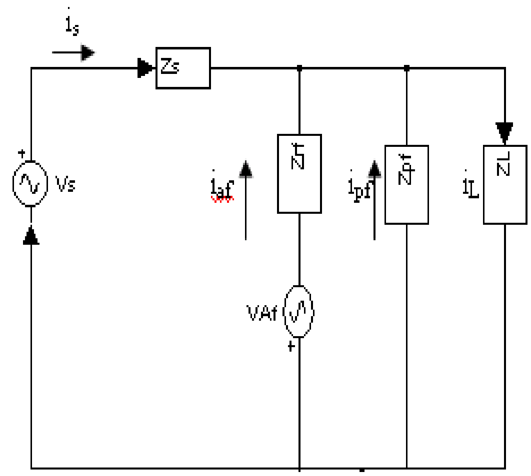

Fig. 2: Equivalent circuit of the system

and harmonic compensation. Figure 2 shows the equivalent circuit of the system. The active filter is inductively coupled with the source.

The load current contains the fundamental component and the harmonic component:

$$i_L(t) = i_f(t) + i_h(t) \tag{4}$$

For harmonic compensation and reactive power compensation, the supply current should have the fundamental component and it should be in phase with the supply voltage.
Thus the supply current is given by:

$$i_s(t) = I_1 \sin(\omega_1 t) = i_f(t) \quad (5)$$

where, I_1 is the amplitude of the fundamental component of the load current and ω_1 is the supply frequency (50 Hz).

From the equivalent circuit, the load current is given by:

$$i_L = i_s + i_{af} + i_{pf} \quad (6)$$

I_{af} is the current injected by the active filter and i_{pf} is the resonant filter current. Comparing the Eq. (4) and (6), the harmonic current is given by:

$$i_h(t) = i_{af}(t) + i_{pf}(t) \quad (7)$$

In this study the resonant filter is tuned for the dominant harmonic frequency:

$$f_r = \frac{1}{2\Pi\sqrt{L_p C_p}} \quad (8)$$

where, L_p and C_p are the inductor and capacitor of the resonant filter.
The Eq. (3) is expressed as:

$$i_L(t) = I_1 \sin(\omega t) * \cos \varphi_1 + I_{r1} + I_d + I_{hr} \quad (9)$$

where,

$$I_{r1} = I_1 \cos(\omega_1 t) * \sin \phi_1 \quad (10)$$

$$i_{pf} = I_d = I_{dm} \sin(d\omega_1 t + \phi_d) \quad (11)$$

$$I_{hr} = \sum_{k=2}^{\infty} I_k \sin(k\omega_1 t + \phi_k) \text{ for } k \neq d \quad (12)$$

The filter current is given by:

$$i_{af} = I_{r1} + I_{hr} \quad (13)$$

where, I_{r1} is the fundamental reactive current component, I_d is the dominant harmonic current, d is the dominant harmonic order and I_{hr} is the remaining harmonic component of the supply current. φ denotes the phase angle between the corresponding current and supply voltage.

The Z_{pf} is the resonant filter tuned for the dominant frequency so that it will inject the i_{pf} to the supply mains. The shunt active filter will inject the I_{hr} and I_{r1} current so that the supply is free from harmonics and power factor is near to unity.

Reference current extraction: In this study, the fundamental component of the supply current is compared with the actual supply current so that the active filter will inject the reactive current and the harmonic current other than the dominant harmonic current. So the reference source current at the fundamental frequency is extracted using dq transformation. The supply voltage is sinusoidal signal where the supply current is non sinusoidal due to the non linear load connected to the supply line.

Figure 3 Shows the extraction of reference current at the fundamental frequency from the supply current. The synchronous reference frame is used to extract the fundamental component of the supply current.

The fundamental component is extracted by dq transformation (Singh and Verma, 2006). The fundamental component is transformed to dc quantities and all the harmonic components are shifted to ω_1 (at 50 Hz). The transformations equations are:

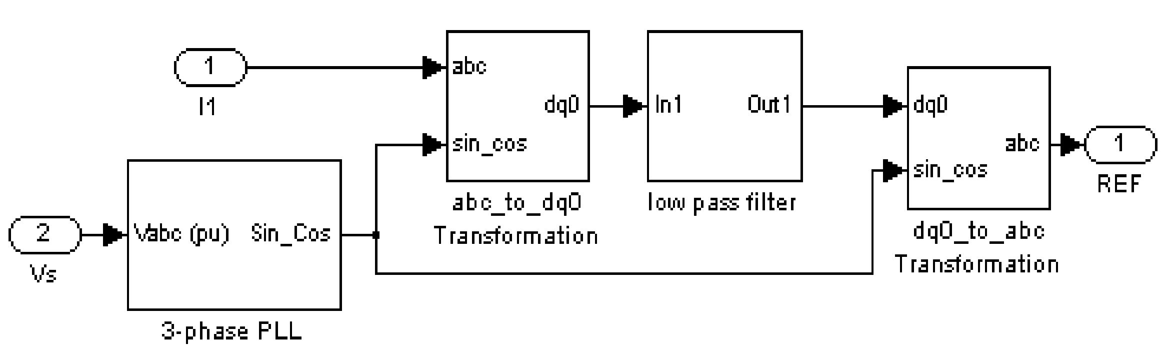

Fig. 3: Reference current extraction

$$i_{std} = 0.67(i_{sta}\sin(\omega_1 t) - i_{stb}\sin(\omega_1 t - \frac{2\pi}{3}) + i_{stc}\sin(\omega_1 t + \frac{2\pi}{3}) \quad (14)$$

$$i_{stq} = 0.67(i_{sta}\cos(a) + i_{stb}\cos(b) + i_{stc}\cos(c) \quad (15)$$

where, $a = \omega_1 t, b = \omega_1 t - \frac{2\pi}{3}$ and $c = \omega_1 t + \frac{2\pi}{3}$

The dq components i_{std}, i_{stq} are filtered by the Bessel filter. This filters filtering the ripple content of the dq component and it is transformed to a-b-c coordinates to obtain the fundamental components of source currents as given by:

$$i_{ra} = i_d \sin(\omega_1 t) + i_q \cos(\omega_1 t) \quad (16)$$

$$i_{rb} = i_d \sin(\omega_1 t - \frac{2\pi}{3}) + i_q \cos(\omega_1 t - \frac{2\pi}{3}) \quad (17)$$

$$i_{rc} = i_d \sin(\omega_1 t + \frac{2\pi}{3}) + i_q \cos(\omega_1 t + \frac{2\pi}{3}) \quad (18)$$

i_{ra}, i_{rb} and i_{rc} are reference current and i_{sta}, i_{stb} and i_{stc} are the three phase supply current. In order to reduce the inverter losses, the dc bus voltage is regulated by the PI controller (k). The actual dc bus voltage is compared with the reference voltage of 300 V and it is regulated to a desired level (An *et al.*, 2009). The reference current is determined by:

$$i^*_{ra} = K(i_{ra}) + i_{ra} \quad (19)$$

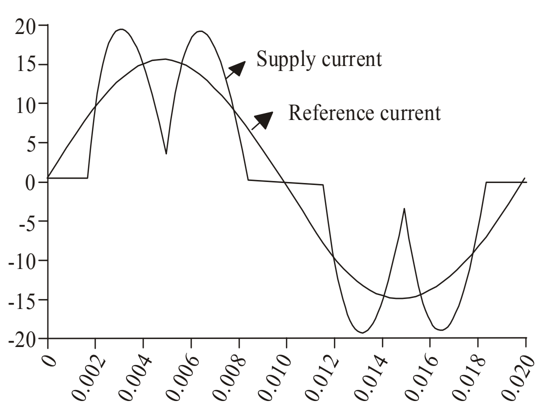

Fig. 4: Comparison of supply current and reference current

Hysteresis controller: The hysteresis controller is used to generate pulses for the Shunt active filter, which extracts the harmonic component of same magnitude and opposite in phase with the load current. The three phase voltage source inverter is used as an active filter. Mosfet is the device used in inverter which can be easily turned on and turned off.

The switching patterns for the each leg is obtained by comparing the instantaneous value of the supply current and the reference current which is shown in Fig. 4. The switching pattern for leg-1 is:

$i_{sta} \le i_{ra} + h_b$, upper switch is ON
$i_{sta} \ge i_{ra} - h_b$, lower switch is ON

The switching pattern for other legs has the similar pattern.

Design of active filter and passive filter: The switching ripples due the active filter is filtered by the inductor which is designed by:

$$L = \frac{|V_s| - |V_{dc}|}{\frac{di_L}{dt} / \min} \quad (20)$$

And the capacitor is given by:

$$C_{dc} = \frac{Vs_{max}\Delta I_L T}{Vc^2_{ref} - Vc_{min}} \quad (21)$$

Table 1: Specification shunt hybrid filter

Parameters	Value
Maximum supply voltage	150 V
Load resistor, capacitor	17 Ω, 1 mF
Inverter capacitor	1 mF
Inverter inductor	3 mH
Passive filter	4.05 μH,10 Mf
Active filter	1.3 kVA

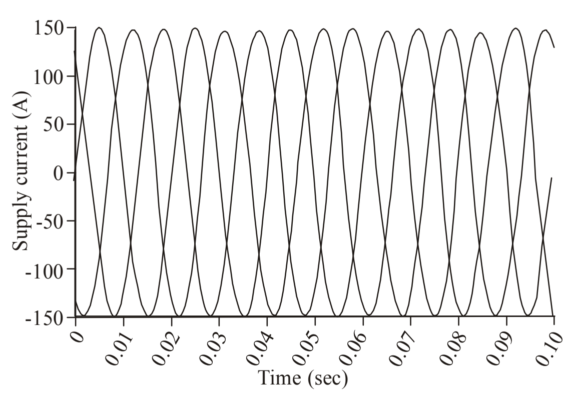

Fig. 5: Supply voltage waveform

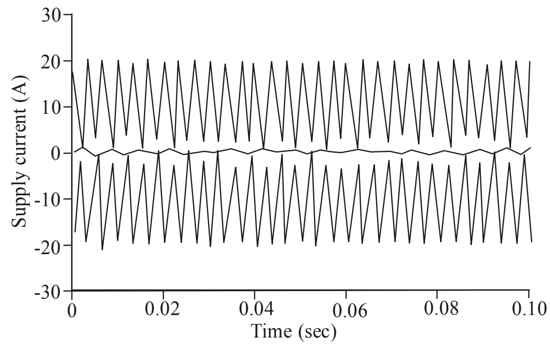

Fig. 6: Supply current waveform without filter

where,

I_L : Load current
T : The switching period
V_{cref} : The reference dc bus voltage
V_{dc} : The dc bus voltage (Bouchikha and Ghers, 2008)

The passive filter is tuned for the fifth harmonics and it is given by:

$$f_r = \frac{1}{2\Pi\sqrt{L_p C_p}} \tag{22}$$

where, f_r is the dominant frequency, L_p and C_p are the inductor and capacitor of the passive filter.

Rating of the hybrid filter: When the passive filter is tuned for the dominant harmonic frequency, the active filter will inject the remaining harmonic component of the supply current to the load. This will reduce the rating of the active filter:

$$\text{KVA rating} = 3V_s\,(I_1 + \sum_{k=7}^{\infty} I_k) \tag{23}$$

The passive filter is tuned for the fifth order harmonics and the remaining harmonics are flowing in the active filter.

MATLAB SIMULATION RESULTS

The shunt active filter is simulated using MATLAB Simulink. Power system Blockset is used to design the Shunt Active Filter.

Here the diode rectifier is simulated and the supply harmonics and power factor are measured. The passive filter is designed in such way that it will reduce the dominant harmonics. Finally the shunt Hybrid filter is connected and the harmonics and power factor are measured. Selection of parameters is given in Table 1. Figure 5 shows the supply voltage waveform and Fig. 6 shows the supply current waveform before compensation. After inserting the Hybrid filter the response of the proposed system is shown in Fig. 7. The HSAF gives near to unity power factor and reduces the current harmonics. The dc bus voltage is maintained at 300 V. When the Hysteresis controlled shunt active filter is connected, the supply is free from harmonics. Figure 8 and 9 shows the frequency spectrum of supply current before and after compensation. The THD of the

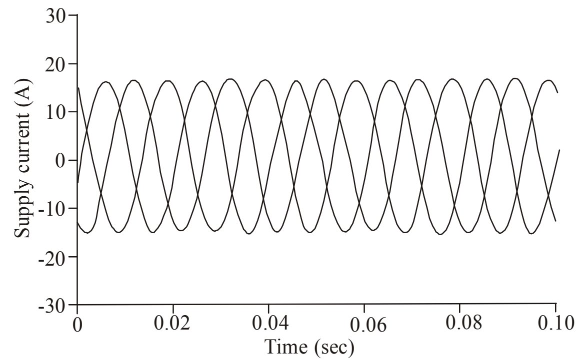

Fig. 7: Supply current waveform with filter

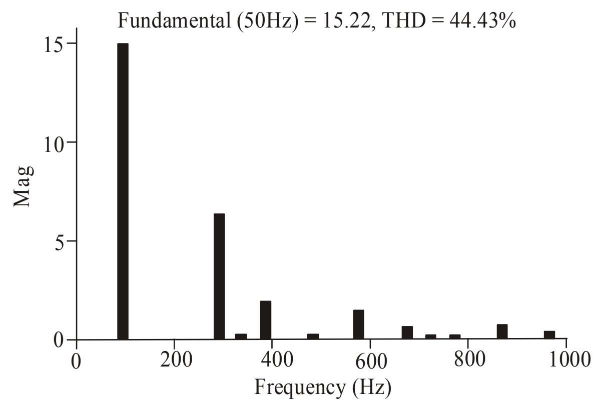

Fig. 8: Frequency spectrum of the supply current before compensation

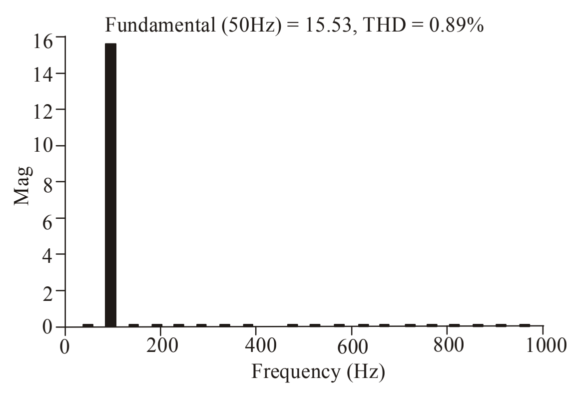

Fig. 9: Frequency spectrum of the supply current after compensation

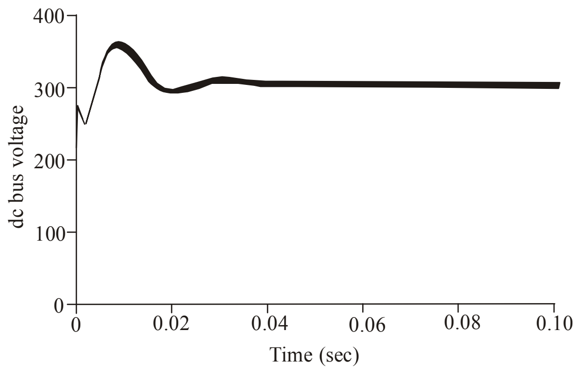

Fig. 10: DC bus voltage waveform of the active filter

Table 2: Harmonics and power factor of the supply current

Is	5^{th} %	7^{th} %	11^{th} %	THD %	Pf
Is1	32.99	3.85	8.0	44.40	0.94
Is2	0.35	0.32	0.1	0.89	0.99

I_{s1}: Supply current without filter; I_{s2}: Supply current with filter; Pf: Power factor

supply current is reduced from 44 to 0.77% and also the power factor reaches near to unity. Thus the shunt Hybrid filter overcomes the drawbacks of the passive filter and active filter. Figure 10 shows the dc bus voltage of the Shunt active filter. The PI controller limits the dc bus voltage to 300 V. Table 2 shows the MATLAB simulation results of the Individual Percentage harmonics, Total harmonic distortion and Power factor of the supply current with filter and without filter. This results show that the Hybrid filter reduces the supply current harmonics from 44.4 to 0.89% and Power factor reaches 0.99.

CONCLUSION

The resonant filter injects fifth order harmonic current to the load and Active filter injects the fundamental reactive current and harmonic current other than fifth order harmonic current using Synchronous reference framed hysteresis controller. The waveform and frequency spectrum of the supply current analysis in MATLAB simulink shows the reduction of supply current harmonics and improvement in the power factor. Thus the Hysteresis controlled Shunt hybrid filter has improved performance in harmonic compensation and reactive power compensation.

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