DESIGN and IMPLEMENTATION of a SHUNT ACTIVE POWER FILTER with REDUCED DC LINK VOLTAGE

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ABSTRACT

This paper presents a shunt hybrid active power filter application mainly for current harmonic elimination and fixed reactive power compensation. The proposed system consists of a small rated voltage source active power filter and a series of LC passive filter connected to each phase. Besides, no additional switching filter is required for the current ripples. Effectiveness of the system is confirmed by the experimental results obtained from a laboratory prototype.

I. INTRODUCTION

Voltage and current harmonics has become a serious problem in transmission and distribution systems in recent years. To solve the current harmonic related problems, passive filters connected in several circuit configurations present a low cost solution. However, passive filter implementations to filter out the current harmonics have the following disadvantages:

- Possibility of resonances with the source impedance
- Supply impedance dependent system performance
- Fixed compensation

In order to diminish the preceding disadvantages of the passive filters, active power filters (APF) have been worked on and developed in recent years. Elimination of the current harmonics, reactive power compensation and voltage regulation are the main functions of active filters for the improvement of power quality. There exist several active power filter topologies in the literature in accordance with their circuit configurations and connection types [1]. Among these configurations, conventional parallel voltage source active power filter, shown in Fig-1.a, is widely used. The DC link capacitor voltage is required to be higher than the peak value of the utility voltage; otherwise, the generated compensation currents can not be injected to the mains [2]. So, for high power applications, the required high DC link voltage restricts the active power filter implementations due to the increase in the losses, rating and the total cost of the APF. As a result, various hybrid filter topologies have been developed which combine the advantages of both the passive and the active filters [3]. Within these topologies, shunt hybrid filters formed with the use of a three phase voltage source PWM inverter and a series connected LC passive filter are superior to the conventional shunt APFs due to the reduced DC link voltage and the converter rating. The series connected LC filter absorbs the current harmonics arising from the non-linear load; however, the filtering characteristic of just the passive filter itself is not satisfactory. Hence, active filter is used to improve the filtering performance of the overall system. In this paper, a hybrid filter (Fig-1.b) formed by a low-rated APF and a LC passive filter tuned to 350 Hz is presented. The proposed filter ensures a low DC link voltage and a superior filtering performance by the applied feedback and feedforward control methods. In addition, no switching ripple filter is used since the LC filter also operates as a switching ripple filter at high frequencies. The start up procedure used in the laboratory and the experimental results obtained from a 300V laboratory prototype are also presented to show the effectiveness of the overall system.

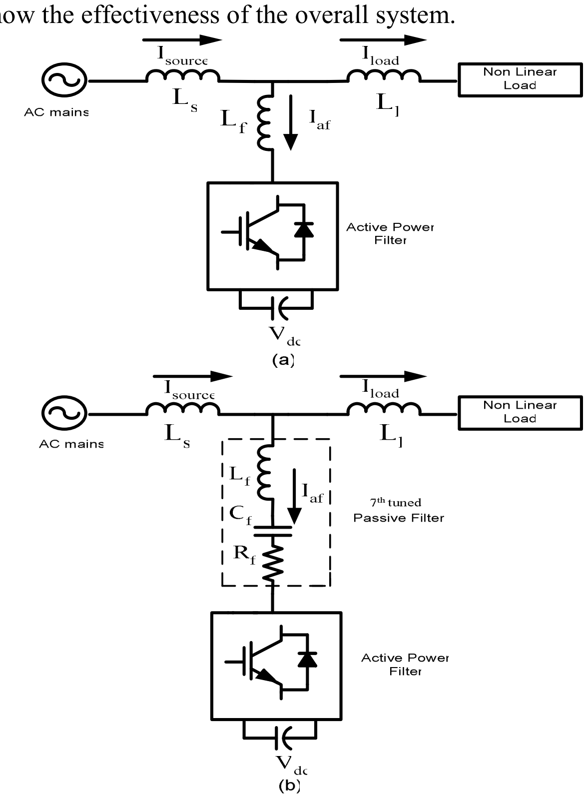


Fig-1 (a) Voltage Source APF (b) Hybrid Power Filter

II. SYSTEM DESIGN

i) Voltage Reference Generation

Synchronous reference frame method is used to calculate the harmonic components of the mains current [4, 5]. Three phase supply voltage and current vectors are transformed into d (direct) and q (quadrature) frames rotating at the fundamental frequency w1 by applying Clarke & Park transformations. For this reason the fundamental component of the mains current turns out to be a DC signal and the harmonic components which are still AC signals are rotating with respect to the reference frame. Harmonic current components are extracted by a second order high pass filter with 20 Hz cut off frequency. Applying inverse Clarke & Park transformations reproduces the supply harmonic current components in abc frames. Each harmonic component is amplified by a gain of K to obtain a voltage reference for each phase.

DC voltage control is maintained by a PI regulator and the current reference (Δid1) obtained in the proposed control method is added to the reactive current component I_d (Fig-2).

Moreover, since the feedback gain K is limited to the certain values due to the stability problems of the system, additional feedforward control loop (Fig-2) is presented [6, 7] for the elimination of 5^{th} harmonic current component. The reference voltages in the proposed feedforward control are generated by using 250 Hz components of the load currents as indicated in eqn-1.

$$Vd_5^* = Rf * ild_5 + (-w_5*Lf + 1/(w_5*Cf)) * ilq_5$$

$$Vq_5^* = (w_5*Lf - 1/(w_5*Cf)) * ild_5 + Rf * ilq_5$$

$$w_5 = -5w_1 \qquad \text{(Eqn-1)}$$

ii) Modulation Method

Sinusoidal Pulse Width Modulation (SPWM) is used as the modulation method. The voltage references (V_a^*, V_b^*, V_c^*) formed by the feedback, feedforward and the DC link voltage control are compared with a 12.5 kHz carrier wave to obtain the gate signals of the semiconductors.

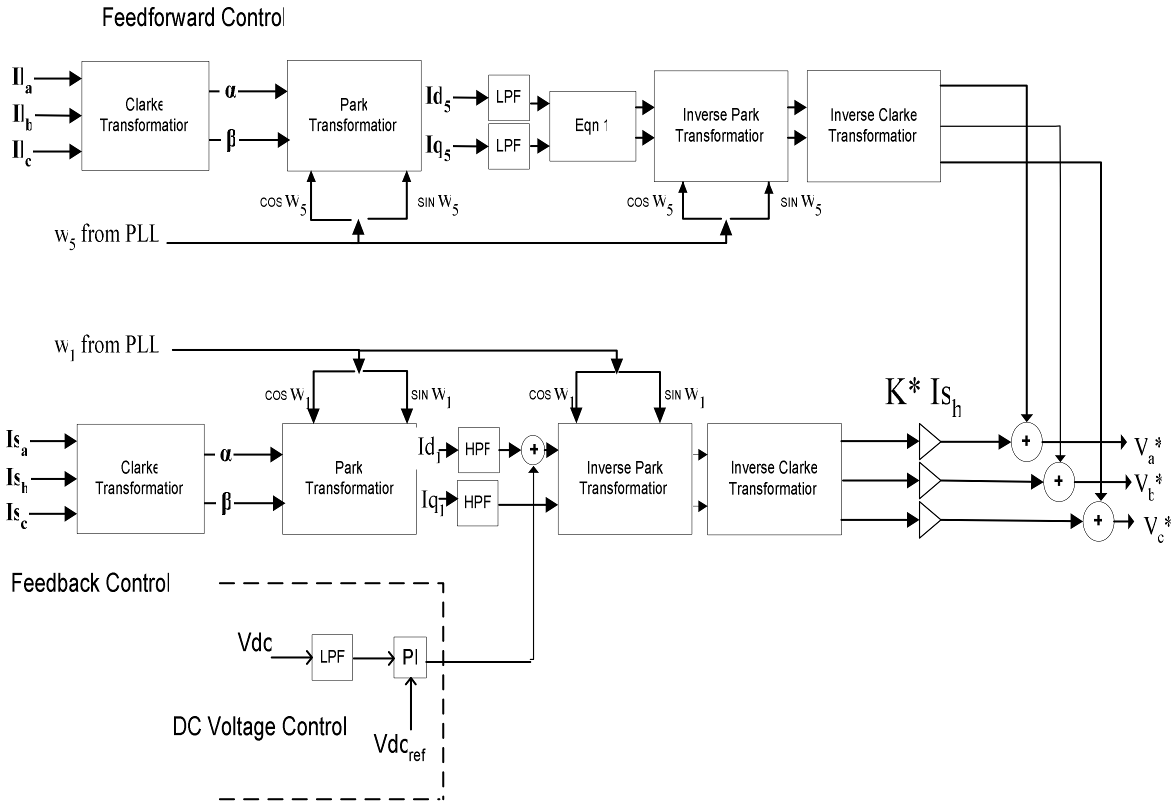


Fig-2 Voltage Reference Generation in Synchronous Reference Frame

iii) Passive filter configuration and filtering characteristics

In the proposed system, conventional APF is connected in series with a passive LC filter. LC passive filter is tuned to a dominant harmonic component [8] and the active filter acts as a damping resistor which also improves the filtering characteristics of the overall system. Since the passive filter tuned at 350 Hz shows lower impedance at 550Hz and 650 Hz than a passive filter tuned at 250 Hz, it has better filtering characteristics when 11th and 13th harmonics are taken into account. LC passive filter tuned at 350 Hz amplifies the 5th harmonic current components at the mains side; however, it is suppressed by the active power filter with the applied feedback and feedforward control explained above. Fig-3 illustrates the single phase equivalent circuit of the system and the harmonic equivalent circuit of the system when the feedback control loop is applied. The load is shown as an ideal current source and the APF is considered as a voltage source. When active filter is not connected (K=0) the following relation takes place between the supply and the load harmonic currents.

$$I_{sh} = \frac{Z_{fh}}{Z_{fh} + Z_{sh}} I_{lh}$$

(Eqn-2)

As the APF is connected to the system with the proposed feedback control, the feedback gain K acts as a damping resistor which suppress the resonance between the supply and the passive filter. The mains harmonic current is now as indicated in Eqn-3:

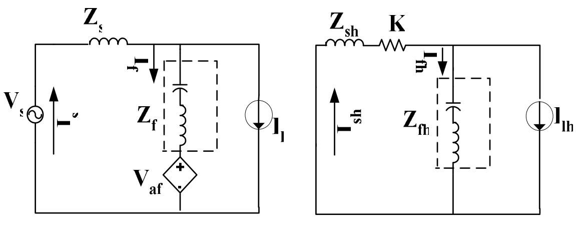
$$I_{sh} = \frac{Z_{fh}}{Z_{fh} + Z_{sh} + K} I_{lh}$$

(Eqn-3)

iv) Experimental System

A 300 V laboratory prototype has been implemented with the specified system parameters in Table-I. The proposed control algorithm is implemented on a Digital Signal Processor (DSP) of Texas Instruments which is ezDSP28F12. In the experimental set up, additional series resistors (R) and contactors (S1, S2) are used for the start up procedure of the proposed system. The experimental circuit configuration is shown in Fig-4 and a view from the laboratory prototype is given in Fig-5. The start up procedure [7] is as follows:

- Initially, three upper IGBTs are turned ON and three lower IGBTs are turned OFF. During this time interval, active filter is not operating, and DC side of the active filter is seen as a short circuit by the mains side.
- When S1 is turned on, the system operates only as a passive LC filter, and to avoid any inrush current, S2 is remained OFF so that hybrid filter is connected to the supply through the resistors R for a predefined time duration t.
- After 5 cycles have passed, S2 is turned ON and the hybrid filter is directly connected to the mains.



(a) (b)

Fig-3 (a) Single phase equivalent circuit (b) Harmonic equivalent circuit

Table-I Experimental System Parameters

Line voltage	300 V-rms
Line frequency	50 Hz
Supply inductance	343 uH
Rectifier inductance	1.5 mH
Filter Capacitor	120 uF
Filter Inductor	1.8 mH
Tuned freq. of series filter	342 Hz
APF rating	1.47 kVA
DC link capacitor	1.3 mF

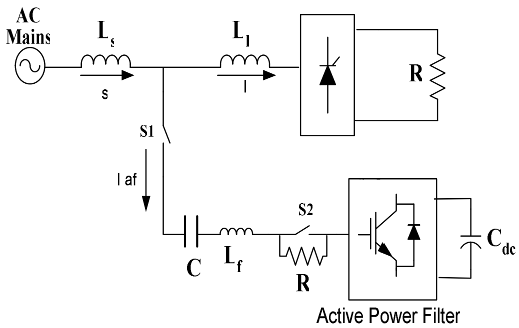


Fig-4 Experimental System

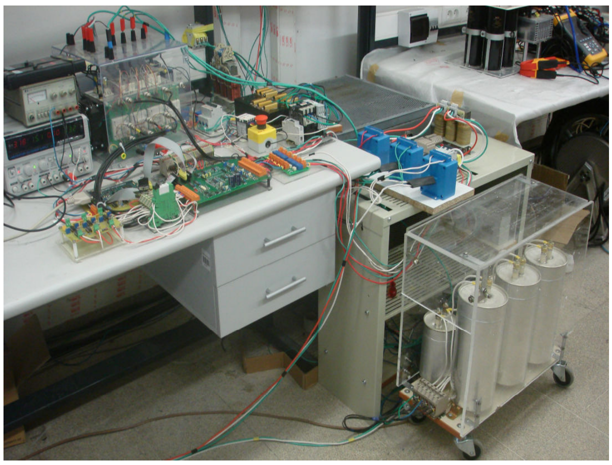


Fig-5 Hybrid Power Filter Prototype

In Fig-6 experimental waveforms obtained during the start up procedure are shown. It is inferred that only passive filter is operating and possible inrush current is minimized. When DC link capacitor voltage reference is set to 60V and APF starts to operate with the feedback control, the waveforms shown in Fig-7 & Fig-8 are obtained. The mains current becomes nearly a pure sinusoidal, DC link voltage is kept stable at 60V and filter current is ripple free. When feedforward control is included in the system, the waveforms shown in Fig-9 & Fig-10 are obtained. Addition of feedforward control results in 0.9 A reduction on the 5^{th} harmonic current component and nearly 1.0% reduction on THD (Table-II). The non-linear thyristor rectifier load used in the experimental set up introduces considerable amount of higher order harmonics (Fig-11, Fig-12), so unavoidable notches appear on the mains current in both of the applied control methods.

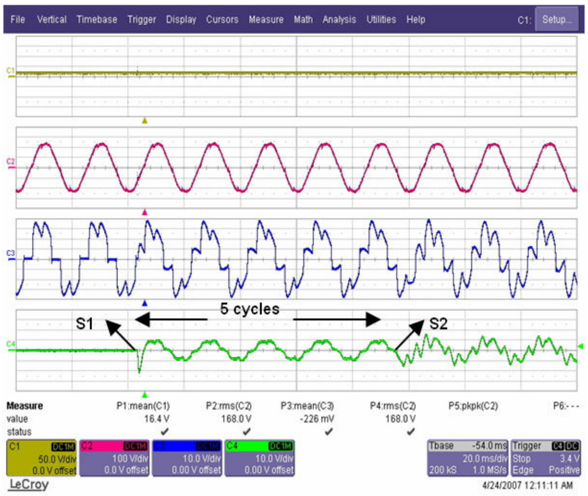


Fig-6 During Start Up, C1 DC link voltage (50V/div), C2 Mains voltage (100V/div), C3 Mains current (10A/div), C4 Filter current (10A/div)

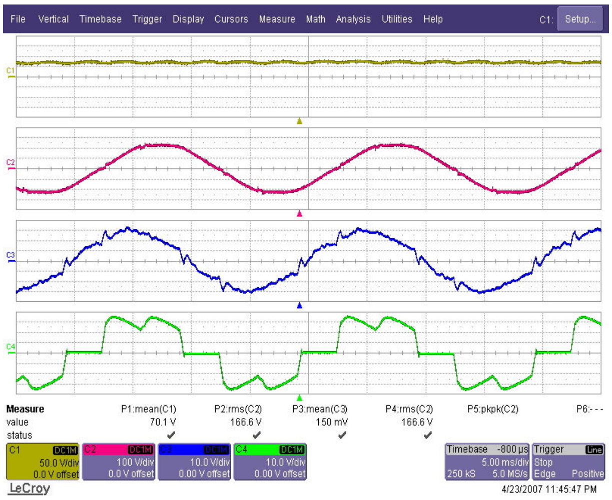


Fig-7 Only Feedback Control, C1 DC link voltage (50V/div), C2 Mains voltage (100V/div), C3 Mains current (10A/div), C4 Load current (10A/div)

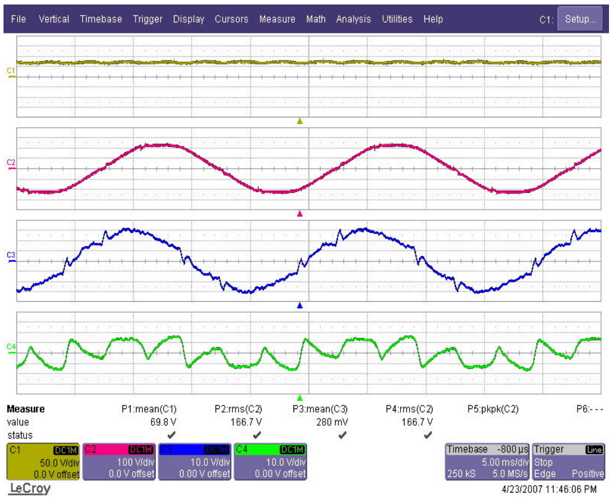


Fig-8 Only Feedback Control, C1 DC link voltage (50V/div), C2 Mains voltage (100V/div), C3 Mains current (10A/div), C4 Filter current (10A/div)

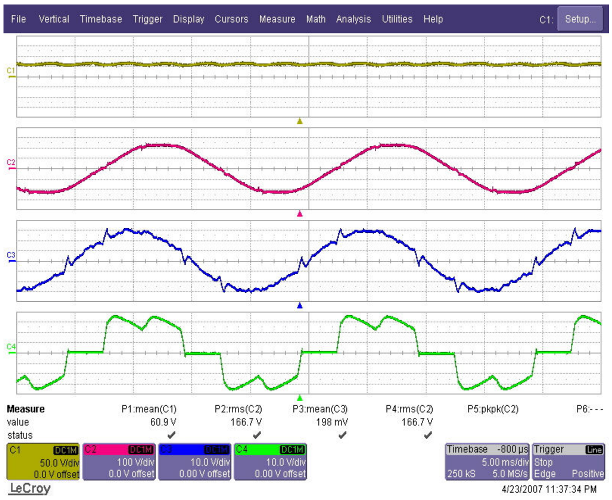


Fig-9 Feedback & Feed forward Control, C1 DC link voltage (50V/div), C2 Mains voltage (100V/div), C3 Mains current (10A/div), C4 Load current (10A/div)

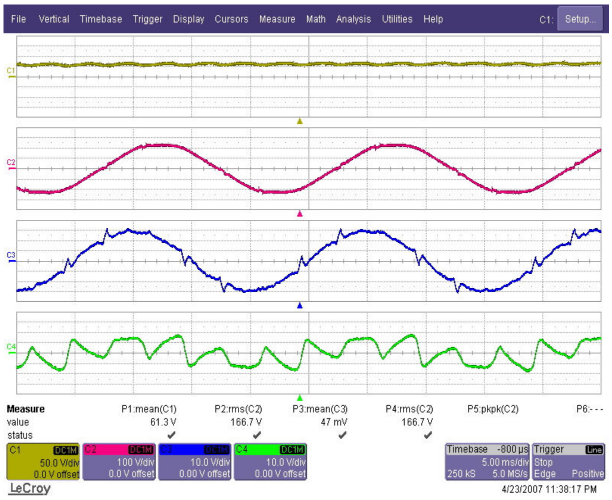


Fig-10 Feedback & Feed forward Control, C1 DC link voltage (50V/div), C2 Mains voltage (100V/div), C3 Mains current (10A/div), C4 Filter current (10A/div)

Table-II Mains Current Under Different Conditions

Cases	THD%	Mains Current (A_{RMS})				
		I_1	I_5	I_7	I_{11}	I_{13}
Load	**30.6**	21.3	6	1.8	2.1	0.7
PF	**42**	20.5	7.8	1.0	1.6	0.6
FB	**9.5**	20.5	1.0	0.1	0.6	0.6
FF	**8.6**	20.7	0.1	0.1	0.6	0.6

(PF: passive filter, FB: active filter with feedback control, FF: active filter with feedforward control)

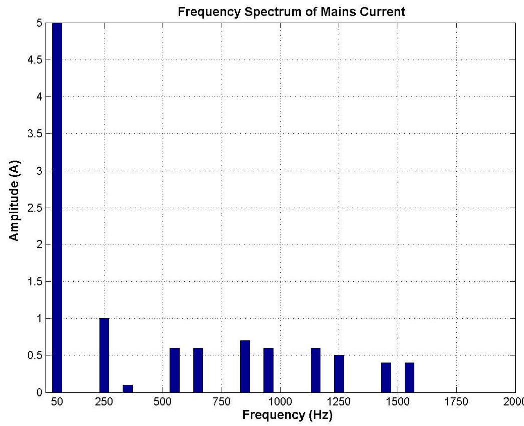


Fig-11 Mains Current Frequency Spectrum (only Feedback Control, $I_{fund} = 20A_{RMS}$)

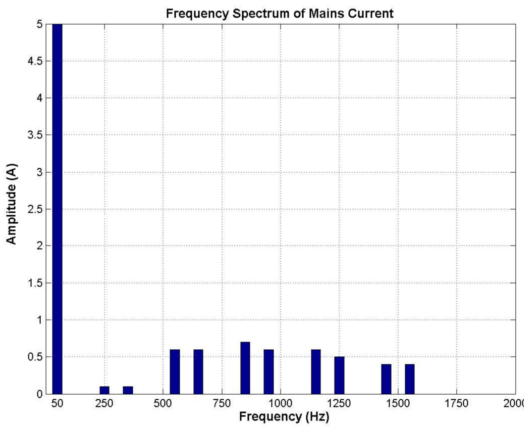


Fig-12 Mains Current Frequency Spectrum (Feedback & Feedforward, $I_{fund} = 20A_{RMS}$)

III. CONCLUSION

This paper has analyzed a shunt hybrid active power filter consisting of a small rated voltage source active power filter and a series 7^{th} tuned LC passive filter. The series LC filter used in the proposed system results in an increase on the current flowing through the active power filter. However, the required DC link voltage is much less when compared with a standard voltage source type active power filter. As a result, rating of the active filter is greatly reduced with the proposed system. If the harmonics of the load indicated in Table-II is to be filtered by a conventional voltage source type active power filter, the rating of the APF is nearly 9 kVA. However, in the proposed system it is reduced to 1.47 kVA. Although no additional switching filter is used, high frequency current ripples are also minimized with the applied system. Moreover, experimental results have shown the effectiveness of the feedback and feedforward control methods which are also easy to implement. As a result, the advantages listed above shows that especially for large power applications, hybrid power filters are seem to be an appropriate solution.

IV. ACKNOWLEDGEMENT

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