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Three-Phase Hybrid Shunt Filters for Power Quality Improvement

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ABSTRACT

Active power filters can be cost-effective for use in practical systems with the insertion of a few passive elements in shunt or series configuration. The resulting hybrid filters can be designed to provide dominant lower order harmonic elimination and reactive power support by the passive elements so that the burden on the active filter counterpart is reduced. In this paper, the rate reduction in the shunt active filter is estimated when it is connected in parallel with suitable passive tuned harmonic filters. The active filtering system is based on an appropriate control scheme. The simulation and the experimental results of the shunt active filter, along with the estimated value of reduction in rating, show that the hybrid shunt filtering system is quite effective in compensating for the harmonics and reactive power, in addition to being cost-effective.

Keywords: Hybrid filter, Power quality, Active power filter, passive filter

1. Introduction

Ever since power semiconductor devices and switched converters have come into existence, there has been faster and more efficient control. However, the quality of power has been deteriorating with the presence of various current and voltage harmonics, low power factor, voltage sags and swells, flicker and many other disturbances. For a long time, power quality improvement has been a challenge for researchers. Passive tuned filters, active power filters and their hybrid combinations have emerged as the means of power quality improvement in retro-fit systems [1,2]. The power electronic converters themselves can be modified and redesigned in new installations to offer better power quality. These are known as Improved Power Quality Converters (IPQCs). There have been several techniques and algorithms suggested by various researchers for achieving effective shunt active filtering [3,4]. In this context, the authors had proposed [5] a new control algorithm for shunt active power filtering, whose simplicity in circuit configuration and functioning makes it a better option compared to various commonly used control algorithms. Despite various advantages of an active power filter, the complexity and cost have always been drawbacks. Combining passive elements with the active power filter results in a hybrid configuration that brings down the cost of the active filter drastically [6,7]. In this paper, an attempt is made to estimate the cost effectiveness of a shunt active filter when suitable passive elements are used in conjunction with the active filter. The reduction in the rating of the active power filter while adding passive filters with different VAR ratings, is

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estimated. Thus, this paper proposes a combination of active and passive filters as an effective means of power quality improvement.

2. Shunt Active Filtering Algorithms

The control algorithm used to generate the reference compensation signals for the active power filter determines its effectiveness. The control scheme derives the compensation signals using voltage and/or current signals sensed from the system. The control algorithm may be based on frequency domain techniques or time domain techniques. In frequency domain, the compensation signals are computed using Fourier analysis of the input voltage/current signals. In time domain, the instantaneous values of the compensation voltages/currents are derived from the sensed values of input signals. There are a large number of control algorithms in time domain such as the instantaneous PQ algorithm, synchronous detection algorithm, synchronous reference frame algorithm and DC bus voltage algorithm.

The instantaneous PQ algorithm by Akagi [8] is based on Park's transformation of input voltage and current signals from which instantaneous active and reactive powers are calculated to arrive at the compensation signals. This scheme is most widely used because of its fast dynamic response but gives inaccurate results under distorted and asymmetrical source conditions.

In the synchronous detection algorithm [9], the average real power consumed by the load with respect to the three phases is computed. From these, the desired mains currents are derived, assuming they are balanced and in-phase with the supply voltages after compensation. The reference compensation signals are then derived as the difference between the load currents and the desired mains currents. Here, the computation steps and the hardware involved are less complicated when compared to the instantaneous reactive power theory.

In the synchronous reference frame (SRF) theory proposed by Divan [10], the compensation signals are calculated based on a synchronously rotating reference frame. The SRF method becomes quite complicated under asymmetrical source and load conditions.

The DC bus voltage algorithm by Jou [11] is based on the fact that any power unbalance affects the average voltage of the DC capacitor of the inverter. The voltage fluctuation is monitored and used to vary the mains currents suitably. The computations and circuit design are still simpler than the conventional algorithms.

3. Shunt Active Power Filter Based on I.CosΦ Control Algorithm

The shunt active power filter is controlled to provide compensation for the harmonic and reactive portion of the three-phase load current, apart from any imbalance, to ensure that balanced, sinusoidal, unity power factor (UPF) currents are drawn from the mains. Thus, the mains are required to supply only the active portion of the load current.

In the I.cosϕ algorithm, the desired mains current is hence assumed to be the product of the magnitude I.cosϕ (i.e, the fundamental active component of load current) and a unit amplitude sinusoidal wave in phase with the mains. The magnitude I.cosϕ is deduced as the magnitude of the fundamental component of the active part of the load current where 'I' is the amplitude of the fundamental component of load current and 'cosϕ' is the displacement power factor of the load. The three-phase mains voltages are used as templates to generate unit amplitude sine waves in phase with mains voltages. The desired mains current is derived as the product of the magnitude I.cosϕ and the unit amplitude sinusoidal wave in phase with the mains voltage.

The reference compensation currents for the shunt active filter are thereafter computed as the difference between the actual load currents and the desired mains currents for the three phases. In case the mains voltages are distorted, the fundamental components of the mains voltages are extracted using second order low pass filters tuned to the fundamental frequency and used as the templates. The voltage fluctuations at the DC bus capacitor of the active power filter are used to calculate the extra power loss in the inverter and the interface transformer thereby ensuring a self-supporting DC bus. The reference compensation currents for the shunt active filter are thereafter computed as the difference between the actual load currents and the desired mains currents for the three phases.

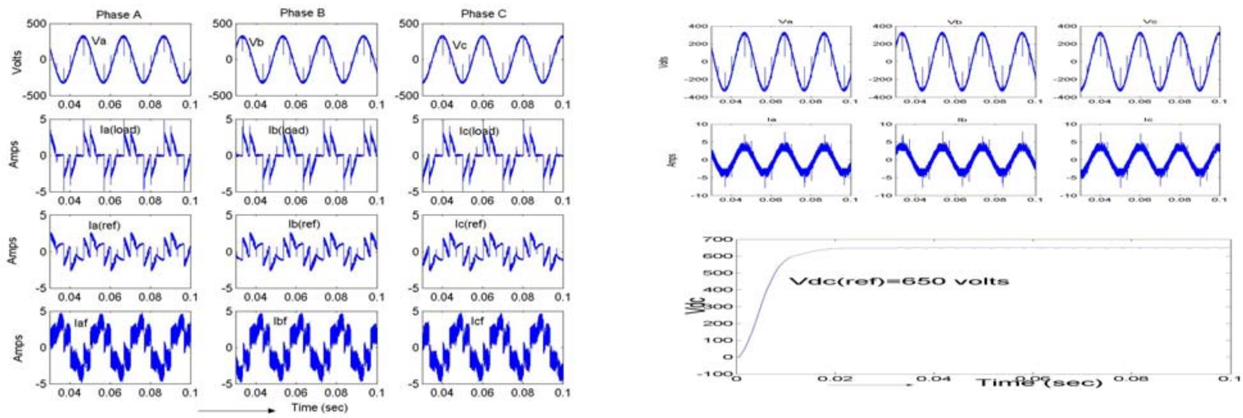

Fig. 1 Simulation results under balanced conditions: (a) Phase voltage, load current, reference compensation current & Actual filter current, (b) Phase voltage & Source current after compensation (c) DC Link capacitor voltage, V_{dc}

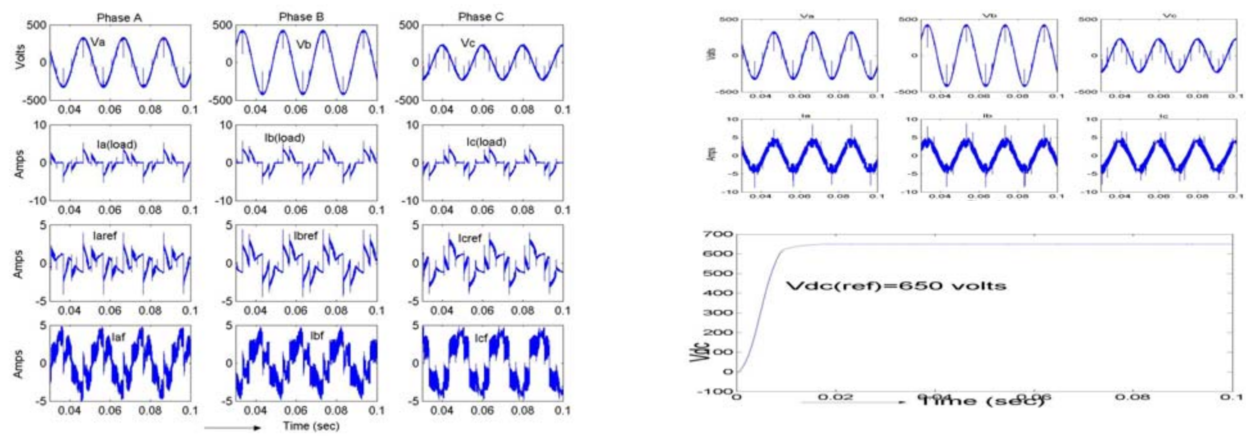

Fig. 2 Simulation results for unbalanced source voltages: (a) Phase voltage , load current, ref. compensation current & actual filter output current (b)Phase voltage & source current after compensation (c) DC link capacitor voltage, Vdc

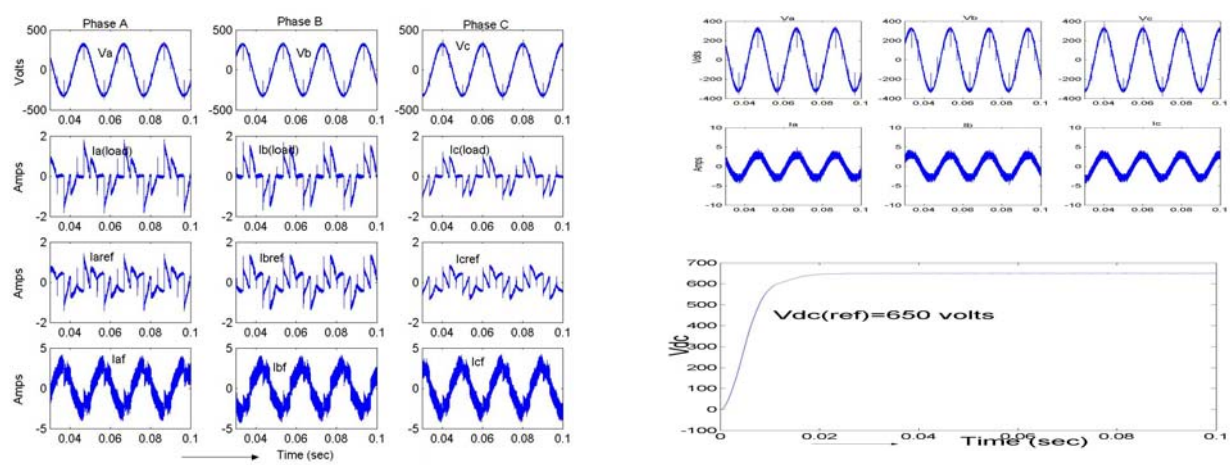

Fig. 3 Simulation results for load unbalance: (a) Phase voltage , load current, reference compensation current & actual filter output current (b) Phase voltage & source current after compensation (c) DC Link capacitor voltage, Vdc

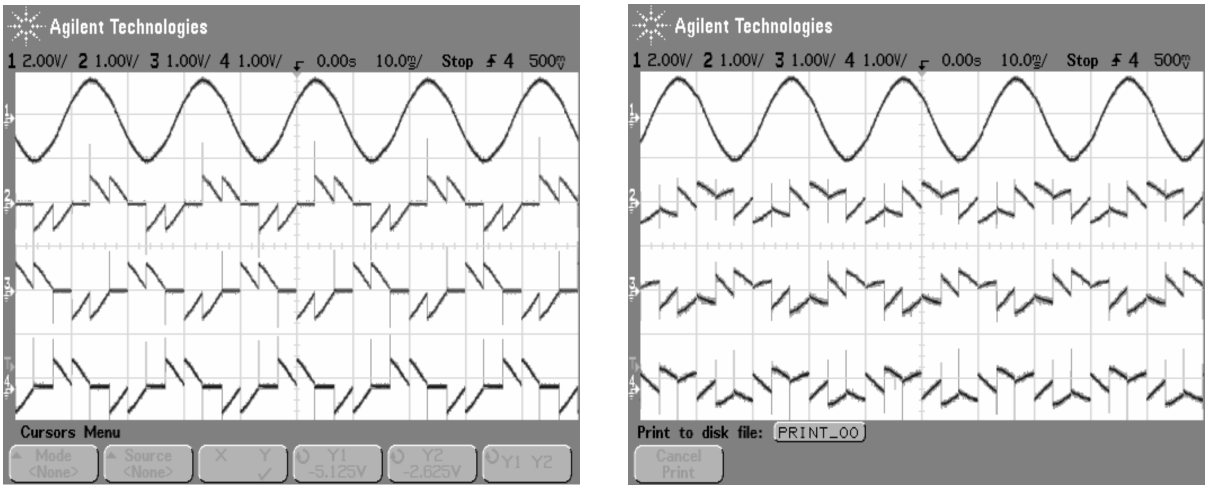

Fig. 4 Three-phase currents for a thyristor converter at α=60°: (a) Source voltage in a-phase, load currents in three phases (b)compensation currents in three phases

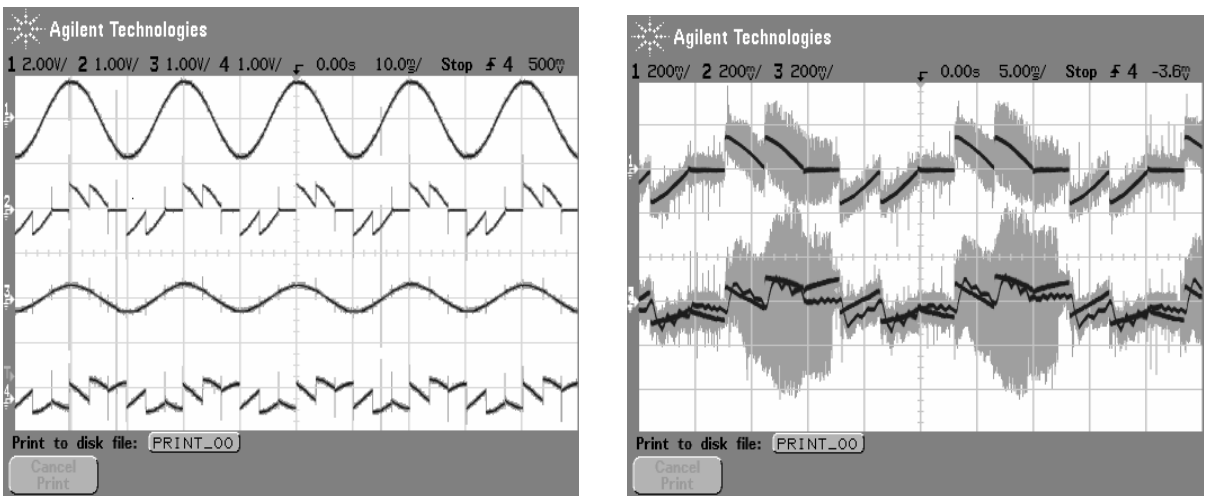

Fig. 5 Waveforms for the active filter in a-phase: (a) Source voltage, load current, desired source current & reference compensation current (b) Load current, reference & actual compensation currents (superimposed) Amps

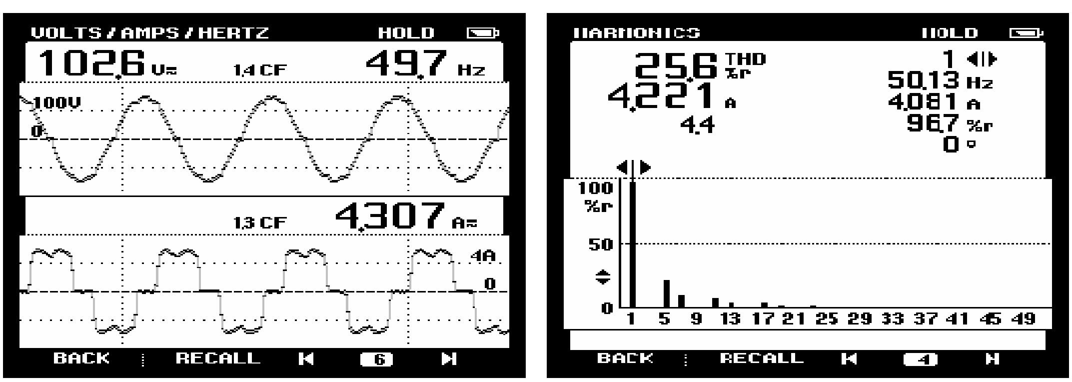

Fig. 6 (a) Source current and its THD before compensation

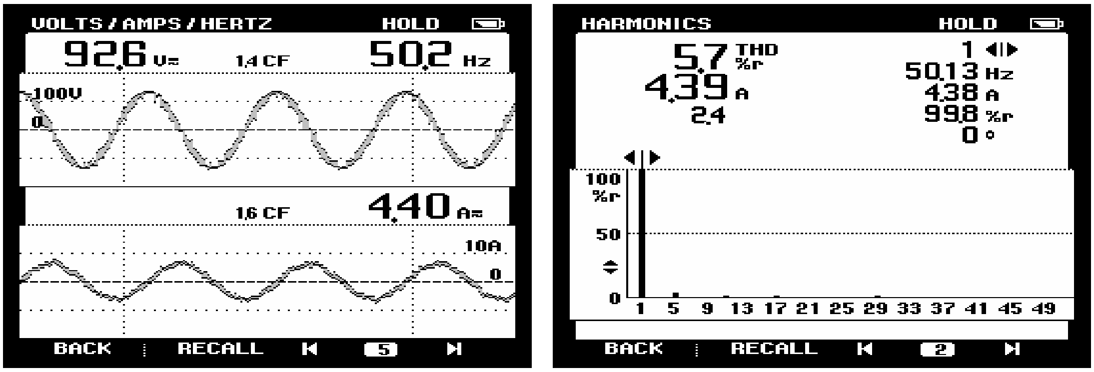

Fig. 6 (b) Source current and its THD after compensation

The system considered for simulation, is a three-phase balanced source supplying a thyristorized bridge rectifier feeding a resistive load, operating at a firing angle of 60º. This load draws a highly non-linear current rich in harmonics with a substantial reactive power requirement. A three-phase, VSI based shunt active power filter is connected to the system for reactive power compensation and harmonics elimination. The simulation is done in the SIMULINK/MATLAB environment with the system parameters being phase voltage of 230 V and load resistance on the DC side of 150 Ω value. Fig.1 shows the simulation results under ideal conditions of balanced source and balanced load. Fig.2 shows the simulation results under the unbalanced source-balanced load condition. Fig.3 shows the simulation results under the balanced source-unbalanced load condition. Testing of the three-phase shunt active filtering system is done experimentally on a 2 kW laboratory model where a balanced, sinusoidal 3-phase voltage supply of 440V, 50 Hz is applied to a thyristor converter feeding a resistive load of 20Ω, with the thyristors fired at $\alpha = 60°$. Fig.4 and 5 show the experimental results under the ideal condition of balanced source and balanced load. Fig.6 shows the source current THD spectrum before and after compensation.

The I.cosϕ controller, as proved by the simulation and experimental results from Figs.1-6, is quite effective in controlling the shunt active filtering system and providing accurate compensation as required.

4. Necessity of Hybrid Filter and its Design

Active power filters are capable of successfully eliminating all the disadvantages of the conventional passive filters such as fixed compensation, problems due to resonance, huge size etc. However, the major disadvantage of an active filter is its prohibitively high cost. Hybrid filters which are different combinations of active and passive filters could be a solution to this problem. The shunt active filter used here is guarding the three-phase system against pollution by providing the entire harmonic and the reactive power requirements of the load. The passive filter, when connected in shunt with the mains and the active filter, is capable of reducing the burden on the active filter by supplying some portion of the reactive power and also by eliminating certain harmonic currents, thereby reducing its rating and cost. In this work, an estimation of rate and cost reduction of active power filter with the insertion of tuned passive filters is done, in simulation.

The passive filter design is done as follows: The reactive power requirement of the load is calculated under the worst possible condition. The 5^{th} and the 7^{th} order harmonic shunt filters are designed to sink-in the respective harmonic currents. The capacitors for the passive filters are designed to supply a specified percentage of the total reactive power requirement of the load. The reactive power to be supplied by each of the tuned harmonic filters is decided by the corresponding harmonic component's weighted presence in the unfiltered source current [12]. For example, for the diode rectifier load, the 5^{th} order harmonic present in the source current before filtering is around 23% and the 7^{th} order harmonic is about 11%. The division of reactive power supply is also done in the same ratio of 23:11. The proposed control scheme, thereby, generates the reference compensation currents for the active power filter with the lower order harmonics and VAR being taken care of by the passive tuned filters. The design equations for the passive filter are given below.

Let (VAR_L) be the total three-phase VAR requirement of the load. Let ($x_p.VAR_L$) be the fraction of the VAR supplied by the three-phase passive filters where x_p may be varied between 50% to 100%. The passive filter element values (R, L and C) per phase are calculated as follows.

VAR supplied by passive filters per phase, $VAR_{p\,(ph)} = (x_p.VAR_L)/3$.

This can be equated to V^2/X_C where V is the per phase (rated) voltage across the passive filter and X_C =capacitive reactance per phase at fundamental frequency.

$VAR_{p\,(ph)} = V^2/X_C = V^2.\omega.C$ which gives,

$$C = VAR_{p\,(ph)} / V^2.\omega. \tag{1}$$

Only the 5^{th} and the 7^{th} order harmonic passive filters have been inserted along with their active counterpart. These filters sink in the 5^{th} and 7^{th} order harmonic currents from the three-phase system in addition to supplying the %VAR as specified. $VAR_{p\,(ph)}$ is shared between one 5^{th} order and one 7^{th} order passive filter in each phase according to the ratio of these harmonics' presence in the source current. The inductances (L_h) of these filters are calculated as follows.

$$\frac{1}{\sqrt{L_h C}} = \omega_h \quad \text{gives,}$$

$$L_h = \frac{1}{\omega_h^2.C} \tag{2}$$

where ω_h is the specific harmonic frequency to be absorbed by the filter.(ω_5 for 5^{th} and ω_7 for 7^{th}.)

For a given quality factor Q of the inductance, where $Q = \dfrac{X_{L_h}}{R_h}$, the corresponding resistance R_h of the passive filter is calculated.

$$R_h = \frac{X_{L_h}}{Q} = \frac{\omega.L_h}{Q} \tag{3}$$

In this estimation study, the VAR supplied by the passive filters is varied from 50% to 100% (50%, 60%, 75% and 100%) for (a) equal division of VAR between 5^{th} and 7^{th} and (b) division of VAR in accordance with the weighted presence of 5^{th} and 7^{th} harmonic currents in the unfiltered source current. For different magnitudes of VAR chosen, the value of C varies and the corresponding value of L_h will change too. Thus, the C, L_h and R_h design values of each harmonic order passive filter, are mutually dependent on each other and also on the chosen values of the parameters such as VAR and Q factor.

The estimation is repeated for two different firing angles of the thyristor converter load to determine the best choice of passive filter design in each case.

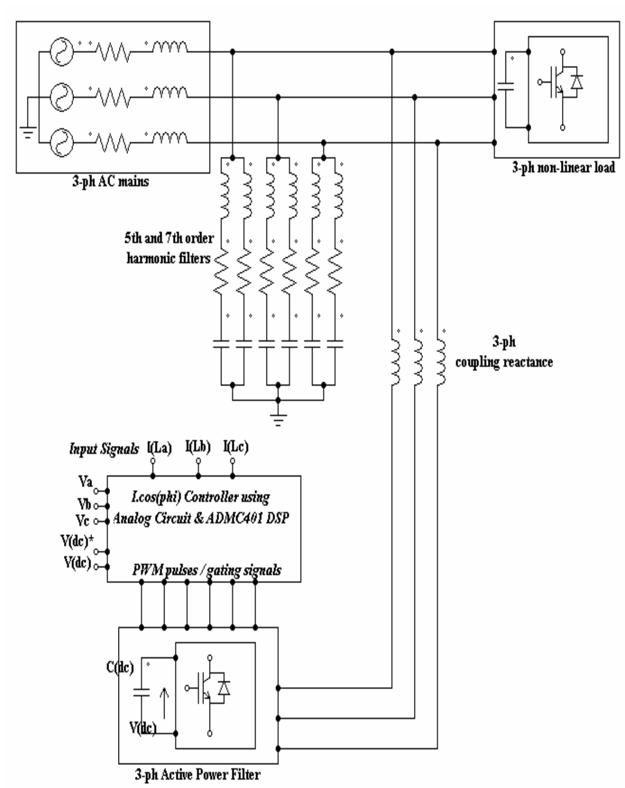

Fig. 7 Block Diagram of the three-phase system with hybrid filter

Table 1 Estimation of reduction in rating of APF with α =0° (Diode rectifier)

Passive filter VAR rating (3phase) →	90 VAR (50% of load VAR) (equal division- 5^{th} & 7th)		108 VAR (60% of load VAR) (equal division- 5^{th} & 7th)		135 VAR (75% of load VAR) (equal division- 5^{th} & 7th)		180 VAR (100% of load VAR) (5^{th} & 7^{th}- equal division & based on harmonics)	
Active filter rate reduction →	3 Phase VA rate reduction	% rate reduction	3 Phase VA rate reduction	% rate reduction	3 Phase VA rate reduction	% rate reduction	3 Phase VA rate reduction	% rate reduction
Q = 100	195.27	68.2%	222.66	77.75%	258.75	90.3%	260.8	91.08%

Table 2 Estimation of reduction in rating of APF with α =60°(Thyristor Converter)

Passive filter VAR rating (3phase) →	300 VAR (50% of load VAR) (equal division- 5^{th} & 7th)		360 VAR (60% of load VAR) (equal division- 5^{th} & 7th)		450 VAR (75% of load VAR) (equal division- 5^{th} & 7th)		600 VAR (100% of load VAR) (5^{th} & 7^{th}- equal division & based on harmonics)	
Active filter rate reduction →	3 Phase VA rate reduction	% rate reduction	3 Phase VA rate reduction	% rate reduction	3 Phase VA rate reduction	% rate reduction	3 Phase VA rate reduction	% rate reduction
Q = 100	358.8	51%	400.2	56.86%	490	69.6%	634.8	90.2%

7. Conclusions

In this paper, an analysis has been carried out for the estimation of the reduction in size and cost of the active filtering unit with the passive tuned filters inserted for partial compensation. The shunt active filter system based on the I.cosϕ control scheme compensates for the harmonics and reactive power burden on the mains currents making them pure sinusoids at unity power factor. The estimation has been done for varying VAR compensation of the passive filters. The percentage reduction in rating of the active power filter increases steadily with the increase in reactive power compensated by the passive filters reaching a maximum at 100% compensation, as expected. The estimation further strengthens the fact that the shunt active filtering system based on the I.cosϕ control scheme can be made quite cost-effective with the addition of a passive counterpart, as required in practical applications, for power quality improvement in retrofit systems.

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