

# Power Quality Enhancement in Variable Frequency Drive using Hybrid Filters- An Shunt Passive and Series Active Combination

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**Abstract**— This paper presents a new Hybrid Filter for compensating voltage/current harmonic in Variable Frequency Drives (VFD). It is a combined system of Shunt Passive Filter (SPF) and a Series Active Filter (SAF) is a cost-effective and practical way of mitigating both current and voltage harmonics generated in a power system due to the presence of non-linear loads. In this paper a practical VFD system installed for the ID fan in SAIL has been chosen as the non-linear load for which a hybrid filter comprising of a shunt passive and series active filter is employed for improving the power quality at the source end. The design of passive and series active filters have been done from scratch; their modeling has been taken up in MATLAB / Simulink environment and the simulation has been carried out under varying load conditions.

**Index Terms**— Hybrid Active Filter, power quality, Voltage and Current Harmonics, Power Factor Correction, Series Active Filters.

## I. INTRODUCTION

Solid-state conversion of AC power using diodes and thyristors is widely adopted to control a number of processes such as adjustable speed drives (ASD), furnaces, chemical processes such as electroplating etc., Voltage harmonic distortion, created mainly by non-linear loads, cause serious problem to power system's installation and control equipment. The reactive power and the harmonics lead to poor power factor, low efficiency and harmful disturbance to neighbouring appliances. In addition to these, they, also create the problems of poor utilisation of distribution system, RFI and EMI noise, interference to communication systems, voltage distortion, disturbance to neighbouring consumers, poor power quality at AC source such as notch, sag, swell, noise, spikes, surge, flicker, unbalance, low-frequency oscillations and malfunction of protection systems. In early days, lossless passive filters (LC) have been used to reduce harmonics, and capacitors have been chosen for power-factor correction of these nonlinear loads. In order to help mitigating the problems of harmonic pollution, many international standards, such as IEEE519-1992, have been established. Passive filters alone have been used to

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eliminate the harmonics in utilities due to their low cost and high efficiency. But passive filters have the demerits of fixed compensation; large size and resonance with the supply system.

Active filters (AFs) [1, 2, 3, and 4] have been explored in shunt and series configurations to compensate for different types of nonlinear loads. However, they have the drawback the rating is sometimes very close to load in some typical applications and thus it becomes a costly operation of power quality improvement in a number of situations. In response to these factors, a series of hybrid filters has been involved and extensively used in practice as a cost-effective solution for the compensation of nonlinear loads. Moreover, these hybrid filters are found to be more effective in providing complete compensation of various types of nonlinear loads. Therefore, it is considered timely to present a broad perspective on hybrid filter technology for the power community dealing with power quality issues [5, 6].

This paper presents a topological structure for a hybrid series active filter which reduces power ratings of the active filter. It consists of a series active power filter and shunt passive filter [7]. The series active power filter provides high impedance for current harmonics so that all the current harmonics flow into the passive filter. Moreover series active filter cancels the reactive power and the voltage harmonics. Furthermore, it provides a high impedance at the fundamental frequency and a very low-impedance shunt branch to the load's current harmonics, thus compensating effectively all current harmonics flowing into the source. The advantages of this configuration are small rating and low cost. Furthermore, the series APF can also attenuate the resonance between shunt passive filter and source impedances. Generally, the rating of APF is 30% of the load rating when only used for compensating harmonics and will be much higher when used to compensate reactive power simultaneously. In this paper VFD system models developed in Matlab/Simulink environment were simulated and the source side current waveforms were analyzed. The firing angle of the converter has been kept at 30 degree. The Series Active Filter is implemented by a 6-pulse 3-phase IGBT VSI coupled with a DC side battery system. The

bridge firing is done by a PWM pulse generator, the reference signal or the modulating signal of which is obtained by subtracting a pure sinusoidal voltage of rated magnitude from the load terminal voltage for each phase. The systems performance is evaluated in terms of source current Total Harmonic Distortion (THD), input power factor, DC voltage regulation and robustness toward any type of load under distorted source conditions.

II. SYSTEM CONFIGURATION

A diode rectifier with smoothing dc capacitor creates considerable current and voltage distortion. The current harmonic amplitude is greatly affected due to ac side or source impedance, however, the input rectifier voltage distortion is caused by the energy storing capacitor in the dc side. Passive Filters have been used in power system to mitigate these harmonic distortions primarily due to their low cost. A Parallel Passive Filter provides low impedance to harmonic currents drawn by the load, thus reducing harmonic currents flowing into the source.

In the present work a typical non-linear load comprising an R-L load supplied by a 6-pulse Thyristor Bridge with a variable firing angle control has been taken for analysis as a test system. Series active and shunt passive filters have been used to eliminate the current and voltage harmonics generated due to the non-linear load. This system configuration is shown in Fig 1. It has a line side converter fed by a 50 Hz three phase supply feeding the motor side converter which converts its input DC to variable frequency AC supply.

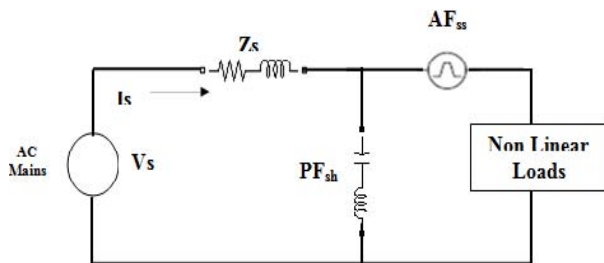


Fig 1. Configuration of Series Active & Shunt Passive Filter with Nonlinear Load

Operation and maintenance manuals, drawings and other reference material of General Electric LCI drives [11] had been studied. The Load Commutated Inverter (LCI) is a static, adjustable frequency drive system which controls a synchronous motor from near zero to rated speed. The basic system consists of a line commutated, phase controlled thyristor converter which feeds a load commutated thyristor converter through a dc link reactor.

Twelve-pulse operation is like two identical, separate, six-pulse drives operating from a common source at the same current and firing angle, with the firing reference angles shifted by 30° using the isolating transformers. The two motors are combined into one frame. This reduces the motor cost, including installation, and reduces the torque pulsation amplitude while raising the torque pulsation frequency. This is achieved by separating the

stator winding into two identical windings, but isolated and phase-shifted by 30°. Typical connections of twelve pulse LCI drive is shown in Figure 2.

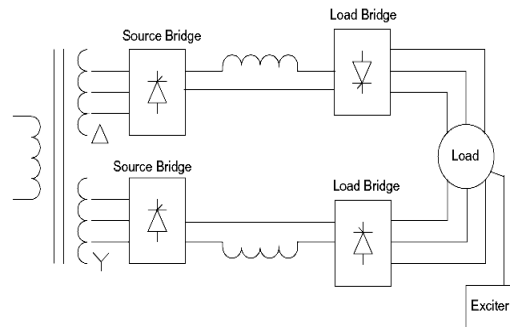


Fig.2 - Twelve pulse LCI drive schematic diagram

Inter-channel communication allows one channel to be the master and the other the slave, which takes its torque reference from the master. This communication allows the two motor winding currents to be balanced. Thus the channels deliver equal power, take equal current, and fire at the same relative firing angle. This utilizes the motor and drives' capabilities to the best extent and also minimizes the harmonic distortion on the power systems, as the first two harmonics present in each six-pulse channel cancel (5th and 7th harmonics). Other higher-order harmonics will be present, but their amplitudes are much smaller. The specifications of the LCI drive system to be listed in Table I.

TABLE I  
SPECIFICATIONS OF THE LCI DRIVE

Motor data	
6 pulse operation	607 kw, 1x1170 v, 1x3 phase, 1x352 a, 550 rpm, 0.9pf, 36.7 Hz
12 pulse operation	1325 kw, 2x1200 v, 2x3 phase, 2x369 a, 704 rpm, 0.9pf, 46.9 Hz
Dc link inductor data	
L1, r1	10 mH, 28.5 mΩ
L2, r2	10 mh, 28.5 mΩ
Snubber data	
R, c	40ω, 0.1 μf
Transformer data	
Rating	900 kva
Hv winding	6600 v
Lv winding	1250 v

The data will be utilized for preparing the simulation models for six and twelve pulse operation of VFD.

III FILTER DESIGN

a. Shunt passive filter

The shunt passive filter is a 2nd order damped filter, which consists of a parallel combination of L-C

components. The filter's impedance is inductive for lower frequencies (below the fundamental frequency) and capacitive for all higher harmonics [8]. The source inductance has much influence on the behaviour of the shunt passive filter when used alone. It moves the cut-off frequency of the latter toward lower ones. The parallel passive filters are shown in Figure 3. The passive filter impedance can be found as:

In a series R-L-C circuit impedance is given by  $Z = R + j(\omega L - \frac{1}{\omega C})$  and at resonance frequency

( $f_n$ ) the value of Z reduces to R. Two basic design parameters are considered prior to selection of R, L and C.

Quality Factor: 
$$Q = \frac{X_0}{R} \quad (1)$$

$X_0$  = Inductor impedance at resonance frequency.

Relative frequency deviation:

$$\delta = \left( \frac{\omega - \omega_n}{\omega_n} \right) \quad (2)$$

Or, 
$$\omega = \omega_n (1 + \delta) \quad (3)$$

Where,  $\omega_n = \frac{1}{\sqrt{LC}}$  in the above expression  $\omega$  and

$\omega_n$  are dependant on system frequency, variation of L, C around ambient temperature, manufacturing tolerances and ageing. Typically the value of  $\delta$  lies between 0.01 to 0.02.

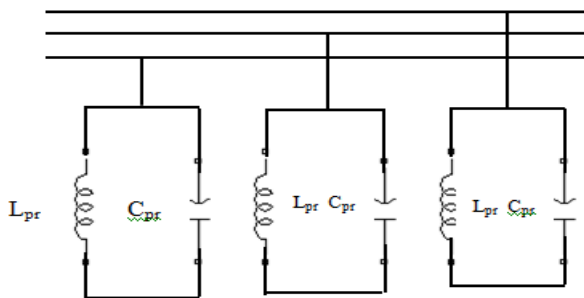


Fig 3 Shunt Passive Filter System

Designing a damped or band pass filter is based upon two parameters; Cut in frequency the Value of m typically lies

$$f_0 = \frac{1}{2\pi RC} \quad \text{and} \quad m = \frac{L}{R^2 C} \quad (4)$$

between 0.5 and 2.0.  $f_0$  being the cut in frequency of the higher order band pass filter meaning the band pass filter shall pass through the harmonic currents of order  $f_0$  and above.

*b. Series Active Filter*

The Series Active Filter is implemented by a 6-pulse 3-phase IGBT VSI coupled with a DC side battery system. The inverter switching frequency selected is 5000 Hz. The bridge firing is done by a PWM pulse generator, the reference signal or the modulating signal of which is obtained by subtracting a pure sinusoidal voltage

of rated magnitude from the load terminal voltage for each phase. 5000 Hz triangular wave generator acts as the carrier signal and a switched representation of the error voltage or the harmonic voltage is obtained across the inverter output terminals. The inverter output voltage is then added to the load terminal voltage in phase opposition through a 1:1 ratio Coupling Transformer (CT) in order to get the required harmonic isolation to the source. A passive ripple filter eliminates high frequency switching harmonics generated in the inverter and the filter out put voltage is supplied to the CT primary.

The leakage inductance of the series CT is the critical design parameter. It has to be very low since a higher leakage inductance shall contribute to higher fundamental voltage drop and hence higher fundamental VA which is to be supported by the series active filter inverter, thus increasing its VA rating.

If we consider  $X_m, R_m \ll Z_{Lh}, Z_{SAF}, Z_L$ , we can write

$$\frac{V_{Lh}}{Z_{Lh} + Z_{shPF}} Z_{shPF} = \frac{V_{SAF}}{(Z_{SAF} + Z_L) + Z_{shPF}} Z_{shPF} \quad (5)$$

Again, for  $V_{Lh} = V_{SAF}$ , it may be simplified as  $Z_{Lh} = Z_{SAF} + Z_L$ . As we understand the value of  $Z_L$  must be very small, so quantitatively  $Z_L \ll Z_{SAF}, Z_{Lh}$  [9], [10], [11] explains the design criterion of input inductor  $L_f$  for shunt active filter.

Where,  $V_{Lh}$  - Equivalent harmonic voltage due to non-linear load,  $Z_{Lh}$  - Series impedance of load,  $Z_{shPF}$  - Impedance of shunt passive filter,  $X_m$  - Magnetizing reactance of coupling transformer,  $R_m$  - Loss resistance of coupling transformer,  $V_{SAF}$  - Compensating voltage from series active filter,  $Z_{SAF}$  - Equivalent impedance of series active filter inverter and DC source.

$$L_f = \frac{U_s}{2\sqrt{6} f_{sw} \hat{i}_{ripple}} \quad (6)$$

Where,  $f_{sw}$  = switching frequency and  $\hat{i}_{ripple}$  = peak ripple current to be compensated and  $U_s$  = per phase system voltage.

IV. MODELING AND SIMULATION OF THE SYSTEM

The model has been simulated in MATLAB / SIMULINK for the three load conditions. The source current and voltage harmonics are analyzed. The break up of different harmonic contents in the source current has been assessed and accordingly a modified filter design has been carried out. The source side current and voltage harmonics are again assessed. The VFD system models also simulated and the source side current waveforms

were analyzed. The firing angle of the converter has been kept at 30 degree. We observe that as the reactive power rating of the shunt passive filter increases, source current

harmonic content (or % THD) decreases and consequently the source voltage harmonic content (or % THD) decreases as a secondary effect.

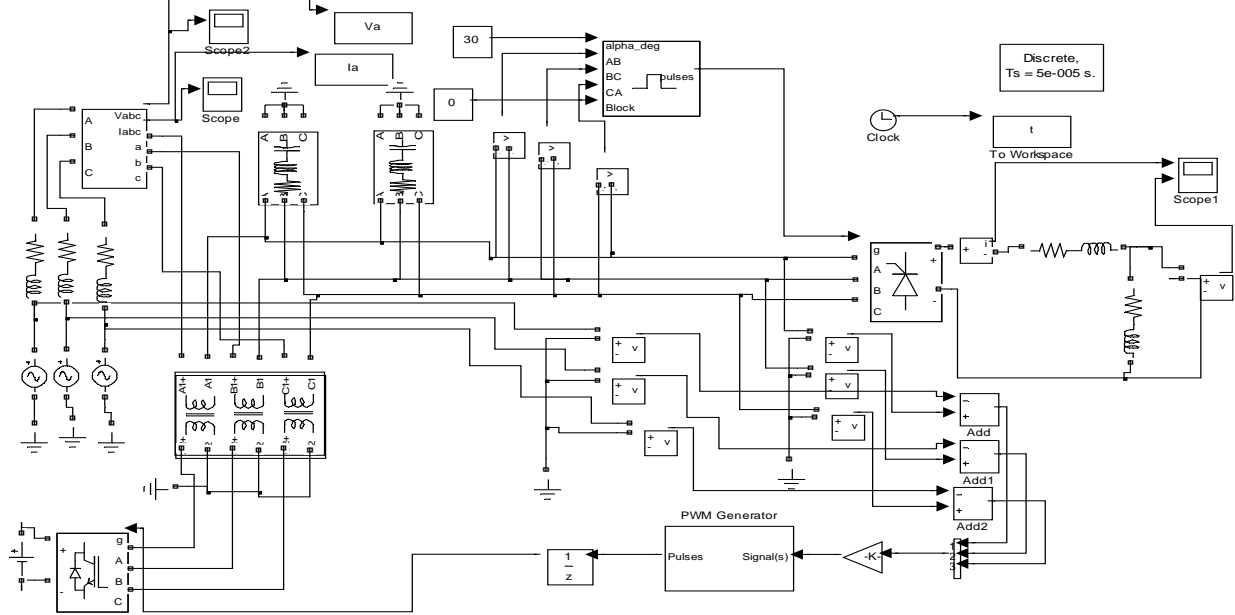


Fig 4- 6 Pulse Operation with Shunt passive and series active filter)

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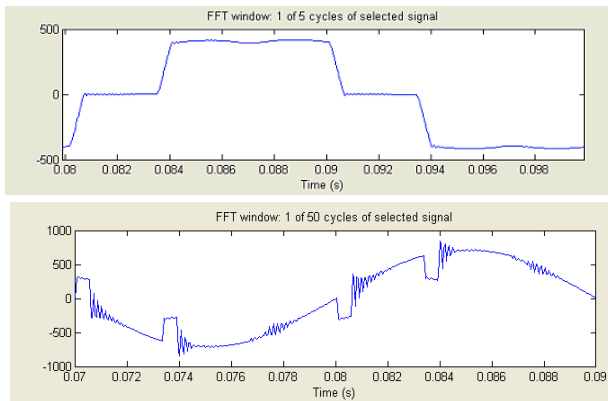


Fig 5. 6 pulse source side current and voltage

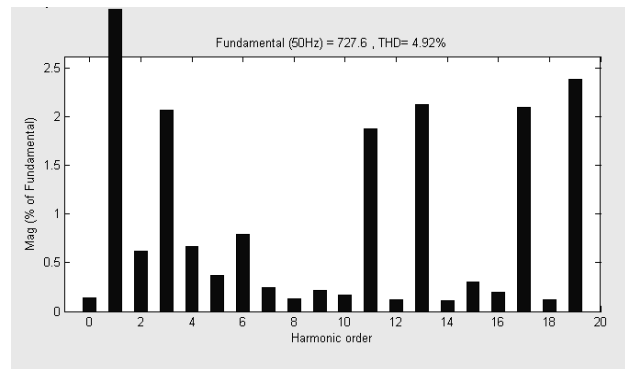


Fig 7 - 6 pulse Source Current Harmonic with Filter

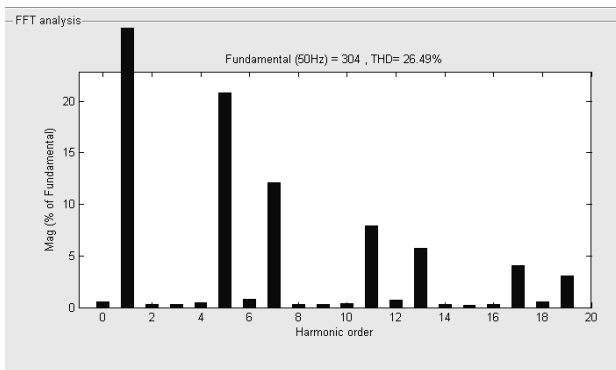
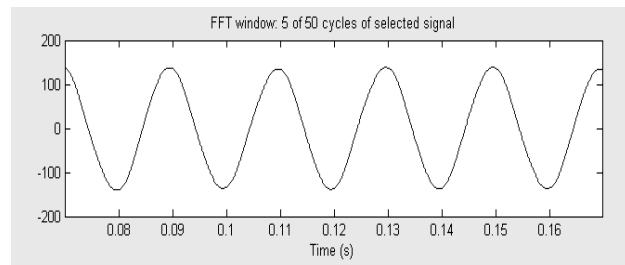


Fig 6- 6 pulse Source Current Harmonic Spectrum without filters



The Six pulse source side current and THD before compensation is obtained from the simulations and shown in Figs. 5 and 6 respectively. Fig 4 shows the simulation model of the six pulse operation with Hybrid

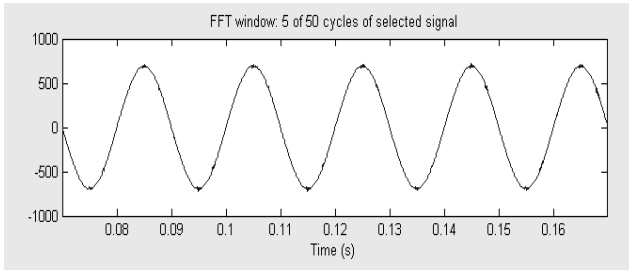


Fig.8 - 6 Pulse Source Current and Voltage Waveform with shunt Passive, series active and ripple filters

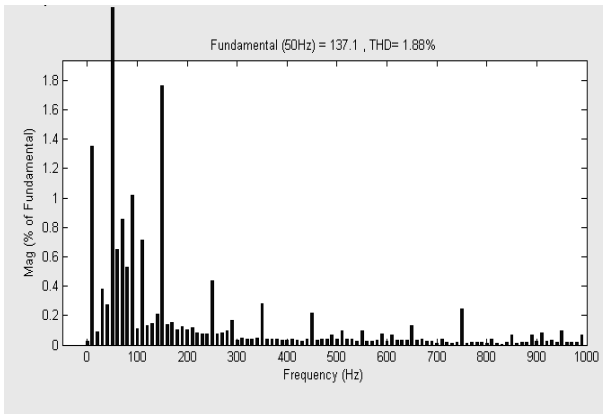


Fig.9 - 6 Pulse Source Current Harmonic with shunt passive, series active and ripple filters

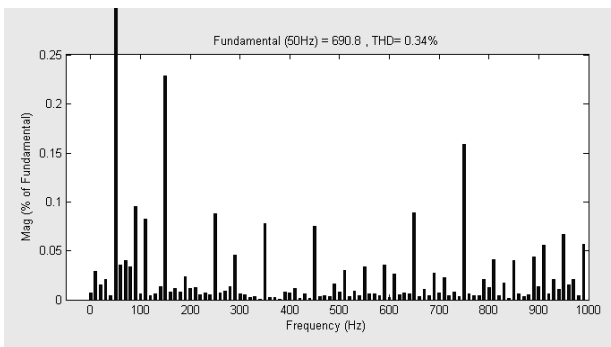


Fig.10 - 6 Pulse Source Voltage Harmonic with shunt passive, series active and ripple filters

Fig. 8 clearly shows that the source voltages and the corresponding source currents are in-phase with each other after the Hybrid active filter starts functioning. Fig 9 and 10 shows the Total Harmonic Distortion (THD) in the source current and source voltage after compensation with shunt passive, series active and ripple filters. This shows that shunt passive filters are sufficient for mitigation of harmonics for 12 pulse operation and Series active filter is required only for 6 pulse operation. After incorporating series active filter along with shunt passive filters for 6 pulse operations the source current THD came down to 1.88% and voltage THD came down to 0.34%.

V. CONCLUSION

This paper has presented a comprehensive solution to the Power Quality Problems in Variable Frequency

Drives using Hybrid Filters. Appropriate filters are designed in accordance with design procedure. The results obtained with shunt passive filters alone for 12 pulse operation and shunt passive & series active filter combination for 6 pulse operation are found satisfactory. The THD contents in source current and source voltage are 1.88% and 0.03 to 0.34% respectively which are within IEEE 519 standard limit for all load conditions. In all, an effective solution for the power quality problem is suggested here in the form of implementation of a hybrid filter consisting of shunt passive filters and series active filter. The work may be treated as a useful tool in mitigating power system harmonics in adjustable speed drives. The series active filter assists the passive filter if this last compensates harmonics and reactive power. The hybrid series active filter is effective and economic for solving harmonics problem in large capacity nonlinear load.

VI. REFERENCES

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VII. BIOGRAPHIE



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