Power Quality Improvement in Industries Using Hybrid Active Filter

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Abstract- *This paper presents the Hybrid Active Power Filter (HAPF) for harmonic mitigation and power factor improvement in a non-linear rectifier system. HAPF, which is composed of passive filter and an active filter in series connection, operates as variable harmonic conductance with dynamically tuning characteristic according to the voltage total harmonic distortion, so the damping performance of the active filter can be adjusted in response to load change and power system variation. Simulations for the proposed system with HAPF have been carried out in MATLAB/ Simulink. 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 hybrid power filter.*

Keywords- Hybrid active power filter, Active power filter, Passive power filter, Harmonic resonance, Total harmonic distortion.

I. INTRODUCTION

The use of non-linear loads such as diode bridge rectifiers, adjustable speed-drives and cyclo-converters have been increased nowadays such that the generation of harmonic currents has steadily increased and has heightened the interests in power quality [1].Majority of the consumer devices end in both industrial and domestic region are non-linear in nature. The power system results in injection of harmonics due to non-linear load and these draw reactive component of current. If these non-linarites are not controlled it will affect the whole power system and the system performance [2-4].Active power filters (APF) and the shunt connection has been the most studied topology, where the APF is connected in parallel with the load and have shown to be an effective technology to eliminate harmonics and to compensate nonlinear loads [5-7]. One of its traditional uses is the elimination of current harmonics produced by loads which generates such disturbances, this is HCS loads (Harmonic Current Source) [8,9]. However, the parallel APF is not suitable in situations where the load generates voltage harmonics, HVS loads (Harmonic Voltage Source). In this case, series connection APF configuration has been proposed and different control strategies have been tried out [10].Compensation systems composed only APF and passive filter connected in series or shunt connection which solve the problem of the harmonic elimination for any type of load [5]. This combines active and passive filters either series or parallel topologies. This paper proposes a hybrid active filter to reduce the harmonic resonance in the power system as well as mitigate the harmonic current. A capacitor is connected in series with the HAPF for power factor correction. The harmonic conductance is determined according to the voltage total harmonic distortion (THD) at the installation location of the hybrid active filter. Based on this control, the damping performance of the active filter can be dynamically adjusted to maintain harmonic voltage distortion at an allowable level in response to load change and power system variation, where the allowable voltage THD can be regulated according to the harmonic voltage limit in IEEE std. 519-1992 [11]. The capacitor which is connected in series with the system is responsible for sustaining the fundamental component of grid voltage, the active filter can be operated with low voltage compared with shunt active filter [12]. This method is a great advantage, in terms of both the rated kVA capacity and the switching ripples of the active filter.

II. IMPROVEMENT OF POWER QUALITY USING HAPF

The schematic diagram of the hybrid active power filter (HAPF) is presented in Fig. 1. This circuit contains the three phase supply voltage, the three phase diode rectifier and the filtering system consists of a small-rating active power filter connected in series with the LC passive filter. Through this configuration of hybrid filter connected to the power supply enhances the compensation current and reduces the harmonic resonance by eliminating the risk of resonance. The hybrid active filters limited supply voltage distortion. The hybrid filter is used to control 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.

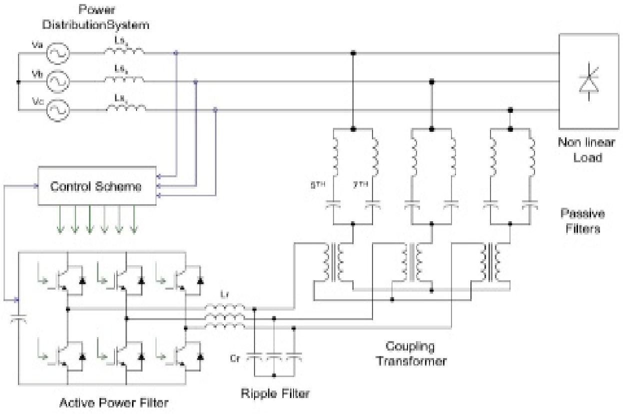

Figure 1. Schematic of the HAPF

In this paper, we further present designing consideration of the hybrid filter. For the designing of this system an active and passive filters are connected in series. A prototype circuit of hybrid active filter with supply range of 220-V/10-KVA and the steady state behaviour, stability analysis and theoretical analysis is discussed. In this project we also focus on the filtering deterioration due to capacitive filters, line impedance, line resistance, system unbalance in the power system. In this paper the HAPF is designed to eliminate the harmonic resonance and the harmonic distortion in the grid due to the approach of non-linear loads.

III. SELECTION OF COMPONENTS

The criteria used for the design of major components present in the shunt HAPF are described below [13-16].

(a) Selection of resonant frequency (f_r) of the LC filter

The resonant frequency of passive LC filter present in the shunt HAPF is given by,

$$f_r = \frac{1}{2\pi\sqrt{L_f C_f}} \qquad (1)$$

Sensibly the resonant frequency should be selected close to the predominant load current harmonic frequency which needs to be compensated. Since the passive filter selected is a single tuned filter, while selecting the resonant frequency, the focus should be to minimize the impedance offered to the load current harmonics that are being compensated. In this work the load harmonics considered for compensation are 5th, 7th, 11th and 13th order. Hence the resonant frequency is chosen as 7th harmonic order, since it offers less impedance to the 11th and 13th harmonic components, compared to that tuned for 5th harmonic frequency. Hence, if f is nominal grid frequency,

$$\frac{f_r}{f} = 7 \qquad (2)$$

(b) Design of filter inductor, L_f and filter capacitor, C_f

The selection of inductance, L_f, and capacitance, C_f, has many criteria that should be considered simultaneously. The PPF should have minimum impedance at the frequencies of harmonic that are being compensated, such as 5th, 7th, 11th and 13th, which can be achieved by increasing bandwidth by reducing the characteristic impedance given by,

$$Z = \frac{L_f}{C_f} \qquad (3)$$

Characteristic impedance, from (3), can be reduced by increasing C_f and reducing L_f .But large value of C_f will introduce a large capacitive reactive current to flow through the shunt HAPF, which will have more impact on source pf. and increase the current rating. On the other hand, reducing the value of L_f increases the switching ripple in the shunt HAPF current. Hence, selection of L_f and C_f is a trade-off between various conditions, which is represented in inequalities detailed below:

(i) The upper limit of the filter capacitor value is fixed such that capacitive reactive current drawn by it is only 10% of the rated load current. In such condition, even if the load feeder pf. is unity the grid is degraded only by 0.5%, whereas for lagging load pf. it will improve the situation. If the resistance of passive filter and the relatively small fundamental pole voltage of converter are neglected, this capacitive reactive current is given by

$$I_{conv(fund)} = \frac{V_{grid}}{2\pi f L_f - \frac{1}{2\pi f C}} \leq 0.1 I_{L_f} \qquad (4)$$

where, V_{grid} is the rated phase to neutral grid voltage, f is the nominal grid frequency and I_L is the rated load current.

Rewriting (4) by applying (1) and (2),

$$L_f \geq \frac{V_{grid}}{9.6\pi f\, I_L} \qquad (5)$$

(ii) Choosing a smaller value of L_f increases the switching voltage ripple at Point of Common Coupling (PCC). By considering high frequency equivalent circuit of figure 1, the source inductance L_s and passive filter inductance L_f will form a voltage divider circuit at the switching frequency. Hence, the ratio of switching ripple voltage at PCC to the active power filter terminal is given by,

$$\frac{V_{sw\,(PCC)}}{V_{sw\,(APF)}} \approx \frac{L_S}{L_S + L_f} \qquad (6)$$

where, L_s is the source inductance, which is equal to the leakage inductance of transformer T_1 shown in figure 1. Limiting the maximum switching ripple appearing at PCC voltage due to APF voltage to 10%, (6) can be rewritten as,

$$L_f \geq 9L_s \qquad (7)$$

Consider a half switching cycle. It can be shown from the Space vector PWM generation technique, that when the magnitude of B-phase modulating signal is highest among the three phases and that of Y-phase is lowest, R-phase terminal switches between 0 and ± $V_{dc}/3$, with respect to the fictitious neutral point. Since, maximum peak to peak ripple in the active filter current occurs when switches are in the active vector stage and duty ratio is 50%,

$$\Delta i_{pk-pk} = \frac{V_{dc}}{3}\frac{T_{on}}{L_f} = \frac{V_{dc}}{3}\frac{T_s/2}{L_f} = \frac{V_{dc}}{6L_f f_s} \qquad (8)$$

where V_{dc} is the dc voltage, T_{on} is ON time of the switch, T_s is the switching period and f_s is the switching frequency of active power filter.

Limiting the maximum peak to peak ripple to 15% of the rated active filter current, (8) can be rewritten as

$$L_f \geq \frac{V_{dc}}{0.9 f_s I_{conv}} \qquad (9)$$

where, I_{conv} is the peak value of rated shunt HAPF current.

As discussed earlier, for better bandwidth of passive filter, L_f should be minimized. The minimum value of L_f is given by the minimum of (5), (7) and (9) which also give the upper limit of C_f. Once L_f is fixed, C_f can be calculated from (1).

(c) DC voltage of HAPF

Since the fundamental frequency grid voltage is dropped across C_f, the dc. voltage is required only to inject the harmonic current required by the load, by the help of the converter. The harmonic voltage appearing across the passive filter when active power filter inject this current is given by,

$$v_{filter} = R_f i_{conv} + L_f \frac{di_{conv}}{dt} + \frac{1}{C_f}\int i_{conv} dt \qquad (10)$$

where R_f is the equivalent resistance of the passive filter. Here the dc bus voltage is fixed as 300V which is sufficient to generate harmonic voltage v_{filter}.

(d) DC bus capacitance (C_{dc}) and its ripple current

If the internal losses in the shunt HAPF is neglected the power balance equation between dc and ac variable is given by,

$$VdcIdc = VRgridIRconv + VYgridIYconv + VBgridIBconv$$

(11)

where, V_{Rgrid}, V_{Ygrid} and V_{Bgrid} are the R-phase, Y-phase and B-phase grid voltages respectively, I_{Rconv}, I_{Yconv} and I_{Bconv} are the R-phase, Y-phase and B-phase shunt HAPF current respectively and $I_{dc}$is the averaged dc current of shunt HAPF.

For a balanced system the average value of the dc current will result into zero. But due to switching action the instantaneous current through the capacitor is not zero and exact analytical method to derive dc current is complex in nature. An empirical formula derived for the r.m.s. value of ripple current in the dc capacitor, C_{dc}, shown in equation 1, using simulation by taking various conditions is given by,

$$I_{c(rms)} = \frac{I_{conv}}{2} \qquad (12)$$

For the worst case design, considering the frequency of ripple current as 6th harmonic, capacitance of the dc bus capacitor, C_{dc}, is given by,

$$C_{dc} = \frac{I_{c(rms)}}{3\sqrt{2\pi} f \Delta V_{dc(pk-pk)}} \qquad (13)$$

where, $\Delta V_{dc(pk-pk)}$ is the peak to peak ripple in the d.c. voltage.

Table 1. System Parameters.

Parameters	**Values**
V_i (3 phase)	415 V
L_s	0.01 mH
f	50 Hz
C_{dc}	3000 mH
V_{dc}	325 V
L_f	5 mH
Transformer Ratio	1:1 N_P/N_S= 230V/230V, 50Hz
Nonlinear Load	R=20mho, L=25µh

IV. SIMULATION RESPONSE

The proposed HAPF is modelled using MATLAB Simulink and the results have been plotted. Initially the HAPF is disconnected from the rest of the system and the performance is analysed. The simulated waveforms shows that due to the absence of HAPF the load current is nonlinear in nature with THD of 19.02%.The waveforms of the system in the absence of HAPF is shown in the Fig(2).

The HAPF is then connected to the system and the waveforms pertaining to this case is shown in Fig(3).From the waveforms it is observed that ,system connecting HAPF, the source current THD is brought down to a lower value and the expected IEE 519 standard

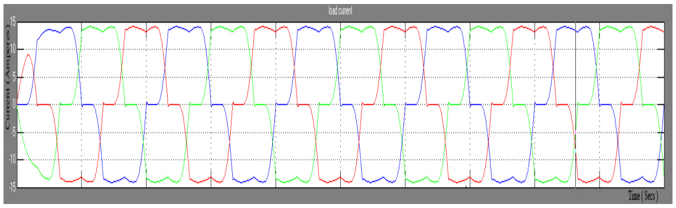

Figure 2. Simulation waveforms before compensation
(a)Source voltage

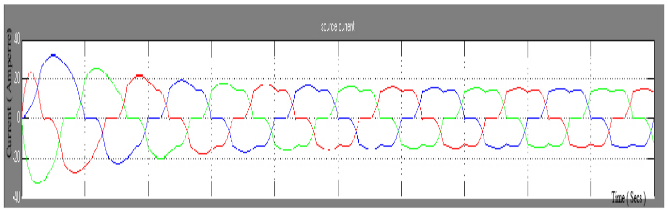

Figure 2. Simulation waveforms before compensation
(b) Load current

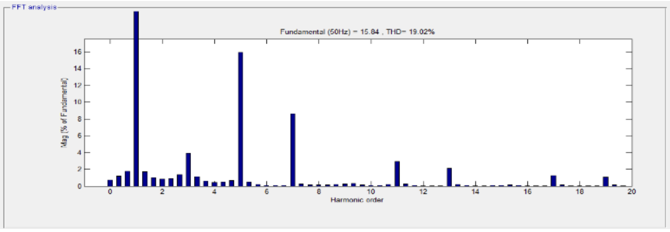

Figure 2. Simulation waveforms before compensation
(c) Harmonic spectra of load current

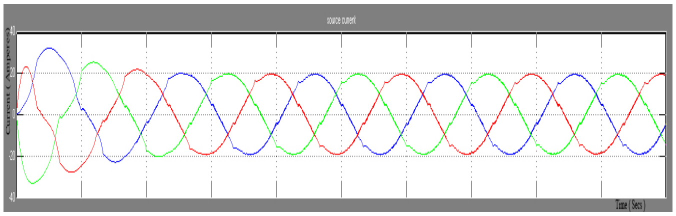

Figure 3. Simulation waveforms after compensation
(a)Source voltage

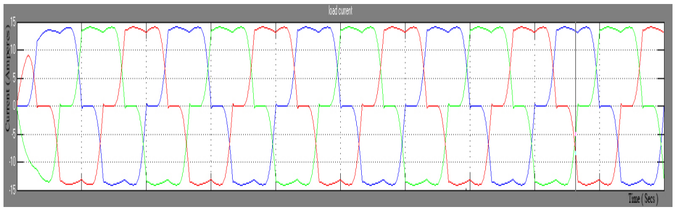

Figure 3. Simulation waveforms after compensation
(b) Load current

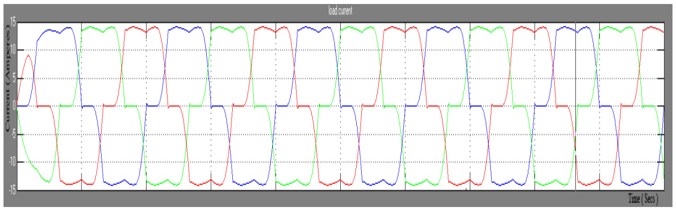

Figure 3. Simulation waveforms after compensation
(c) Filter current

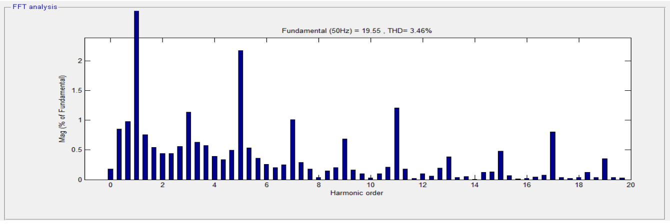

Figure 3 Simulation waveforms after compensation
(a)Harmonic spectra of load current

V. EXPERIMENTAL SETUP

A 220 V laboratory prototype has been implemented with the specified system parameters in Table-II. The Proposed control algorithm is implemented on a dsPIC30F4011 controller. In the experimental set up, an additional series resistors (R) and contactors (S1, S2, S3, and S4) are used for the start-up procedure of the proposed system.

- Initially, two upper IGBTs are turned ON and two 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.

The hardware rating and its experimental setup of the proposed system is shown in Table – 2 and Fig.(4) respectively.

Table 1. Rating of the proposed system

Parameters	**Values**
Line voltage	220V,AC
Line frequency	50 Hz
Supply inductance	0.01mH
Filter Capacitor	0.1µF
Filter Inductor	5mH
HAPF rating	55V,49A
DC link capacitor	1000 µf

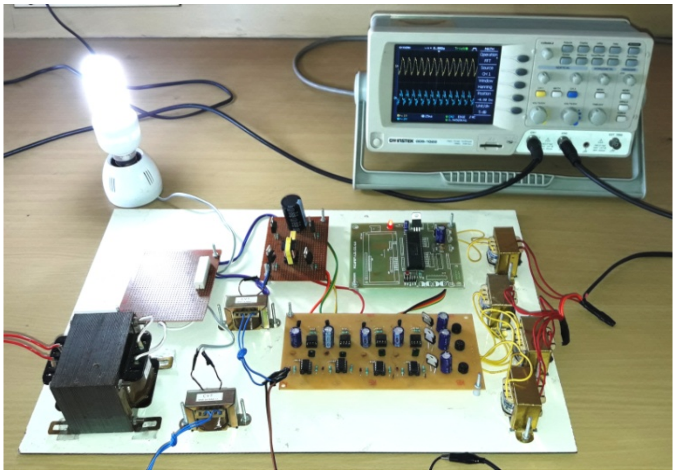

Figure 4. Experimental setup of proposed system

VI. EXPERIMENTAL RESULTS

The Fig (5) shows the experimental waveform obtained when connected with digital storage oscilloscope. The waveforms of source current, load current and source current with HAPF are obtained. The non-linear load with harmonics is shown in the output waveform Fig (b).This harmonics will injected into the source wave such that power drawn from the supply will be more than that of the rated source voltage .Hence hybrid active power filter is introduced in the system and the harmonic wave distortion in the supply is reduced and it is shown in the wave form Fig (c).

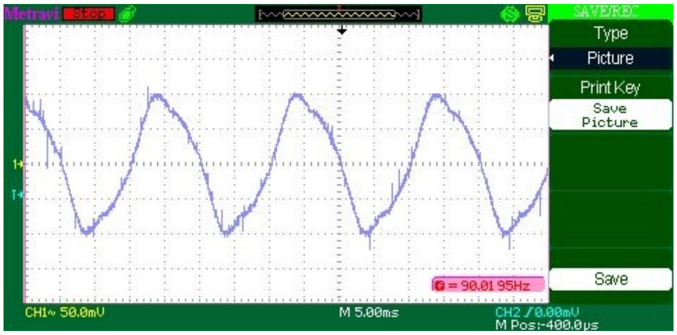

Figure 5. Experimental waveforms
(a) Source current

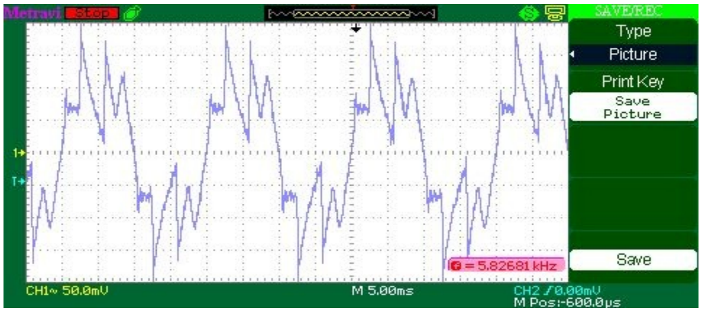

Figure 5. Experimental waveforms
(b) Load current

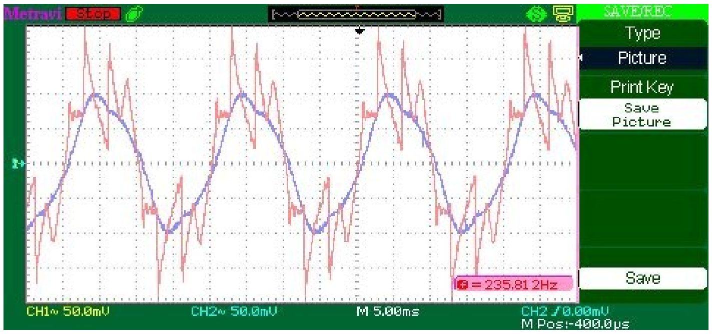

Figure 5. Experimental waveforms
(c) combined Waveform

VII. CONCLUSION

In this paper the performance of HAPF in improving the power quality of the grid power supply is analysed. The HAPF is modelled using MATLAB/Simulink and the simulation results are verified with the hardware prototype. The control unit consists of dsPIC30F4011 microcontroller. It has been shown that the use of HAPF helps in reducing the harmonics produced in the system due to nonlinear loads. The performance of the proposed system has been verified with simulation results and found to be satisfactory. The proposed system improves the THD of grid current from 19.02% to 3.36%.

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