Digital Simulation of a Hybrid Active Filter - An Active Filter in Series with a Shunt Passive Filter

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Abstract – **Active filters have been in use for filtering load harmonics. In this paper, the digital simulation results of a hybrid active filter system for a rectifier load are presented. The active filter is used for filtering higher order harmonics as the dominant harmonics get filtered by the passive filter. This reduces the rating of the active filter significantly. The DC capacitor voltage of the active filter is controlled using a PI controller.**

INTRODUCTION

The need for efficient use of electrical power has increased the areas of application of power electronics. Many such power electronic converters draw non-sinusoidal current and inject harmonics into the power distribution system. These harmonics lead to higher losses in the system. Some of the harmonic producing loads are rectifiers, arc-furnaces, cycloconverters and adjustable speed drives. IEEE 519 Harmonic Standards specify the voltage harmonic limits at the point of common coupling (PCC) and the current harmonic limits at the PCC between the customer and the utility. The utility is responsible for the voltage distortion and the individual customer for the current distortion.

Passive filters had been used initially to compensate for the current harmonics injected by large industrial non-linear loads. This was due to their low cost, simplicity and higher efficiency. But they are susceptible to series and parallel resonances with the supply and the load, and their filtering characteristics are influenced by the supply impedance. Tuned passive filters are also susceptible to load and line switching transients, and they are always off-tuned. Hence active filtering became necessary.

Active filters can be used for compensating harmonics as well as damping resonance in a power distribution system [1-2]. The functions of the active filter can be extended to meet reactive power compensation, flicker compensation, voltage regulation against sags and swells, etc. to improve the power quality in a distribution system [3].

Active filters can be of various types - shunt, series, hybrid active filters and unified power quality conditioner. Each in turn can be of a voltage source inverter (VSI) type or a current source inverter (CSI) type. An active filter consisting of a VSI with a capacitor on the DC side is preferred over that of a CSI with an inductor on the DC side, due to its lower initial costs and higher efficiency. This paper deals with a hybrid active filter which is a combination of an active filter in series with a shunt passive filter. The load considered for compensation is a rectifier load. This configuration (Fig.1) is preferred due to improvement in both the source current and the voltage at the PCC for the load considered. Also the protection necessary here is simple compared to other configurations [4-5].

The hybrid active filter configuration proposed by Fujita *et al* [5] has been chosen for the study. The control scheme for this was based on the Instantaneous Reactive Power (IRP) theory [6]. Recent work using this configuration for active filtering and voltage regulation, based on the IRP theory, was by van Zyl *et al* [3]. Several papers have been reported on other configurations, *viz.*, the shunt active filter and the hybrid series active filter. The control scheme adopted in this paper is based on the Synchronous Reference Frame (SRF) theory proposed by Bhattacharya *et al* [7]. The details of these are presented later in this paper.

PRINCIPLE OF OPERATION

An active filter requires sensing of a suitable signal for evaluating its reference. The signals that can be sensed for a hybrid active filter are

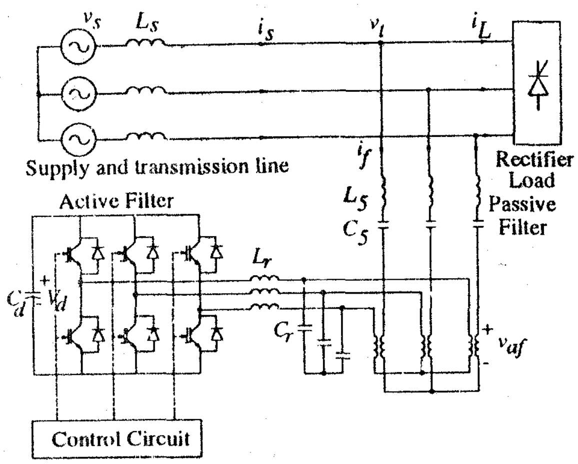


Fig. 1. Circuit configuration of the hybrid active filter system.

the source current ($\bar{I}_s$) and the voltage ($\bar{V}_t$) at the PCC, the most suitable signal being $\bar{I}_s$ [1]. Therefore, the active filter is controlled as a voltage source

$$\bar{V}_{af} = K\,\bar{I}_{sh} \tag{1}$$

where $\bar{I}_{sh}$ is the harmonic component of the source current and K is a constant that can have a complex value.

Consider a non-linear load which is connected to the PCC. This load can be modelled as a current source $\bar{I}_L$. A passive filter of impedance Z_f is connected to compensate for the harmonics in $\bar{I}_L$. For harmonic analysis, a simplified model of the distribution system is considered [5]. Here the source voltage ($\bar{V}_s$) and the source impedance (Z_s) are approximated as the Thevenin equivalents as seen from the PCC. The equivalent circuit for the hybrid active filter system is shown in Fig.2(a). The harmonic contents in $\bar{V}_t$ and $\bar{I}_s$ are regulated according to IEEE 519 standards.

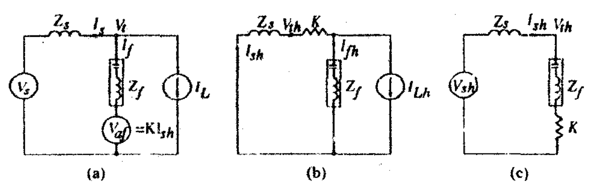


Fig. 2. Equivalent circuit for the hybrid active filter system, (a)Single-phase equivalent circuit, (b)Harmonic equivalent circuit for the load current, (c)Harmonic equivalent circuit for the source voltage.

The harmonic analysis of the circuit in Fig.2(a) is carried out using the superposition principle. First consider the load alone to inject harmonics ($\bar{I}_{Lh}$) into the system. The source current harmonic component ($\bar{I}_{sh}$) and the harmonic component of the voltage ($\bar{V}_{th}$) at the PCC are given by

$$\bar{I}_{sh} = \frac{Z_f}{K + Z_s + Z_f}\,\bar{I}_{Lh} \tag{2}$$

$$\bar{V}_{th} = \frac{-Z_s\,Z_f}{K + Z_s + Z_f}\,\bar{I}_{Lh} \tag{3}$$

From eqns.(2) and (3), it is seen that there is an improvement in the filtering characteristics for the load current harmonics for a large value of K. For a low harmonic content in source current, the condition $|K| >> max(|Z_s|, |Z_f|)$ is to be satisfied. A purely imaginary value for K might result in resonance in the system, and hence the very objective of using an active filter is lost; whereas a purely real value for K will make the active filter act as a resistance at harmonic frequencies and helps in damping resonance in the system. Hence K is selected to be real. The equivalent circuit for the load current harmonics is realized from eqn.(2) and as shown in Fig.2(b).

Considering next, the source alone to inject harmonics ($\bar{V}_{sh}$) into the system; $\bar{V}_{sh}$, $\bar{I}_{sh}$ and $\bar{V}_{th}$ are related by

$$\bar{I}_{sh} = \frac{1}{K + Z_s + Z_f}\,\bar{V}_{sh} \tag{4}$$

$$\bar{V}_{th} = \frac{K + Z_f}{K + Z_s + Z_f}\,\bar{V}_{sh} \tag{5}$$

From eqns.(4) and (5) it is seen that eventhough $\bar{I}_{sh}$ is reduced significantly, $\bar{V}_{th}$ worsens if K is selected such that $K >> |Z_s + Z_f|$. Hence this configuration of a hybrid active filter is not suitable if the source voltage harmonics are to be filtered. Realization of eqns.(4) and (5) results in the equivalent circuit for the source voltage harmonics, shown in Fig.2(c).

A disadvantage of selecting K to be real is that the active filter draws real harmonic power from the system. This will lead to variation in its DC capacitor voltage (V_d) [5]. As the regulation of V_d is necessary for the successful operation of the active filter, a PI controller is used here. The block diagram for the DC capacitor voltage control is shown in Fig.3. The use of the PI controller increases the system *type* by one. Therefore, the steady state error of the system for a step input in its reference (V_{d_ref}), is reduced to zero. Here

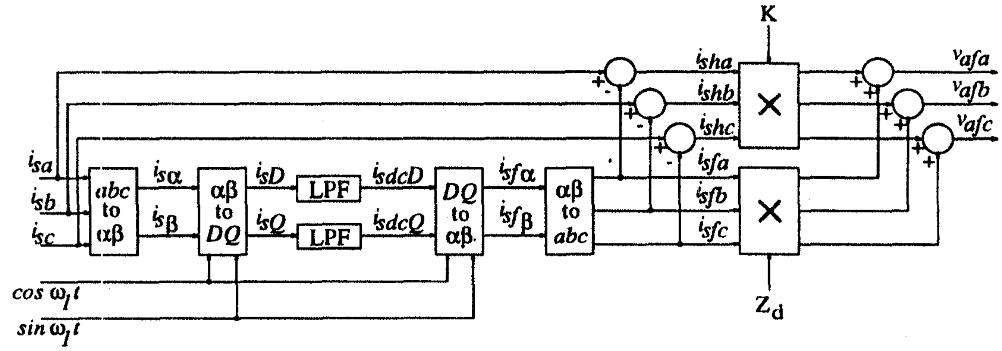


Fig. 4. Control scheme for the SRF based compensator.

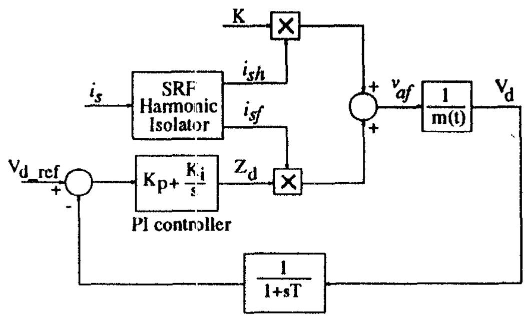


Fig. 3. Block diagram for the DC capacitor voltage control.

$m(t)$ is a function of the modulation index of the PWM inverter used as the active filter. If Z_d is the output of the PI controller, the reference to the active filter is given by

$$v_{af} = K\, i_{sh} + Z_d\, i_{sf} = m(t)\, V_d \tag{6}$$

where i_{sf} and i_{sh} are the fundamental and the harmonic components of the source current respectively. Here i_{sf} and i_{sh} are extracted using the SRF harmonic isolator. Thus, the real harmonic power drawn by the active filter is injected back into the system at fundamental frequency.

CONTROL SCHEME

The performance of the active filter is greatly influenced by the filtering algorithm employed for the extraction of the fundamental and harmonic components of the source current. This extraction can be done using time-domain or frequency-domain techniques. The time-domain techniques are preferred due to their easy implementation, fast response and little computational burden. Among the time-domain techniques, the IRP approach [6] and the SRF approach [7] are presently the most popular ones. SRF approach is used here.

Fig.4 shows the control scheme for the proposed SRF based compensator. The three-phase source currents i_{sa}, i_{sb} and i_{sc} are transformed from their $a-b-c$ coordinates into two-phase Kron's $D-Q$ coordinates using eqns.(7) and (8).

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} i_{sD} \\ i_{sQ} \end{bmatrix} = \begin{bmatrix} cos(\omega_1 t) & -sin(\omega_1 t) \\ sin(\omega_1 t) & cos(\omega_1 t) \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \tag{8}$$

In the synchronously rotating $D-Q$ reference frame, the components at the fundamental frequency ω_1 are transformed into DC quantities and those at the harmonic frequencies into non-DC quantities. They undergo a frequency shift in the spectrum. The DC components in $D-Q$ reference frame are extracted according to

$$\begin{bmatrix} i_{sdcD} \\ i_{sdcQ} \end{bmatrix} = G(s) \begin{bmatrix} i_{sD} \\ i_{sQ} \end{bmatrix} \tag{9}$$

where $G(s)$ is the transfer function of the first order LPF. The DC components are transformed back into three-phase $a-b-c$ coordinates to obtain the fundamental and the harmonic components as shown below:

$$\begin{bmatrix} i_{sf\alpha} \\ i_{sf\beta} \end{bmatrix} = \begin{bmatrix} cos(\omega_1 t) & sin(\omega_1 t) \\ -sin(\omega_1 t) & cos(\omega_1 t) \end{bmatrix} \begin{bmatrix} i_{sdcD} \\ i_{sdcQ} \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} i_{sfa} \\ i_{sfb} \\ i_{sfc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sf\alpha} \\ i_{sf\beta} \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} i_{sha} \\ i_{shb} \\ i_{shc} \end{bmatrix} = \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} - \begin{bmatrix} i_{sfa} \\ i_{sfb} \\ i_{sfc} \end{bmatrix} \tag{12}$$

TABLE I

CIRCUIT PARAMETERS FOR DIGITAL SIMULATION

Supply phase voltage	V_s	50.81kV
Rectifier commutation inductance	L_{com}	129.6mH
Rectifier DC reactor	L_{dc}	1H
Line inductance	L_s	14.6mH
Line resistance	R_s	0.4587Ω
5th harmonic tuned filter inductor	L_5	60mH
5th harmonic tuned filter capacitor	C_5	6.7547μF
5th harmonic tuned filter quality factor	Q_5	20
Active filter DC capacitor	C_d	5mF
Active filter DC voltage reference	V_{d_ref}	50kV

From eqns.(11) and (12), the reference to the active filter (ref. eqn.(6)), can be computed as

$$\begin{bmatrix} v_{afa} \\ v_{afb} \\ v_{afc} \end{bmatrix} = K \begin{bmatrix} i_{sha} \\ i_{shb} \\ i_{shc} \end{bmatrix} + Z_d \begin{bmatrix} i_{sfa} \\ i_{sfb} \\ i_{sfc} \end{bmatrix} \quad (13)$$

SIMULATION RESULTS

Digital simulation using MATLAB SIMULINK, has been carried out on the use of a hybrid active filter shown in Fig.1 for a 3-phase, 50Hz, 88kV distribution system [3]. The non-linear load considered for compensation is a 20MVA, 6-pulse thyristor rectifier. The supply voltage is assumed to be sinusoidal. The short circuit ratio (SCR) of the system at the PCC is 84. The source impedance has an X_s/R_s ratio of 10. The passive filter consists of only a 5th harmonic tuned filter. Table I shows the circuit parameter values used in the simulation. A commutation inductance (L_{com}) is designed to have a voltage drop of 5%, as this will result in smaller notches in the voltage at the PCC. The switching frequency of the active filter is 15kHz. K is chosen to be a real quantity of magnitude 5 *p.u.* Therefore, the active filter inserts a resistance of 5 *p.u.* at harmonic frequencies.

Fig.5 shows the simulation waveforms before and after the active filter is switched on. The active filter is started at t=0.12 sec. The cut-off frequency for the LPF used in the SRF based harmonic isolator is 30 Hz. There is a significant improvement in the waveshape of i_s after starting the active filter.

Fig.6 shows the FFT of i_s before the active filter is started. The IEEE 519 harmonic standards limit the current distortion (for a 88 kV distribution system of SCR=84) to 5.0% for $h < 11$,

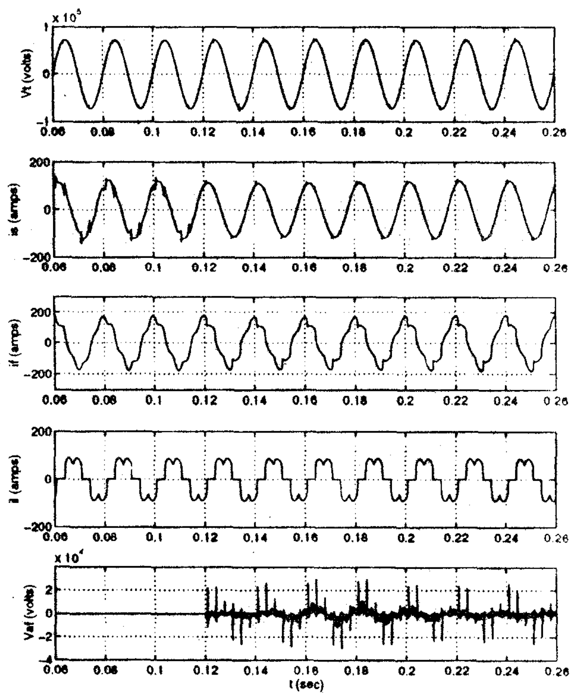
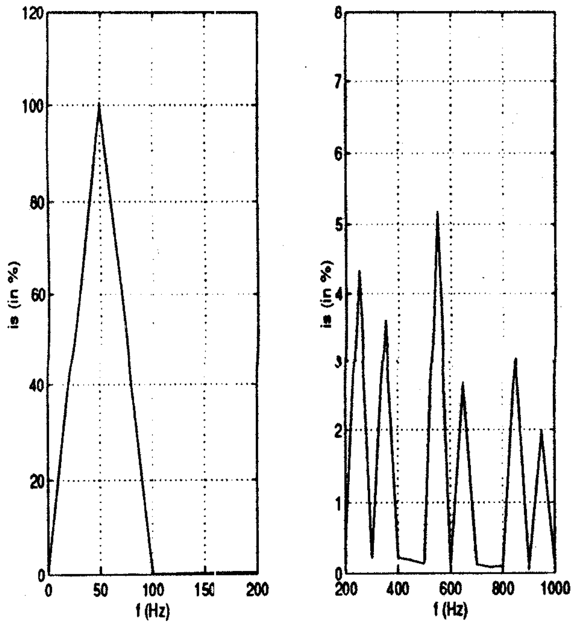


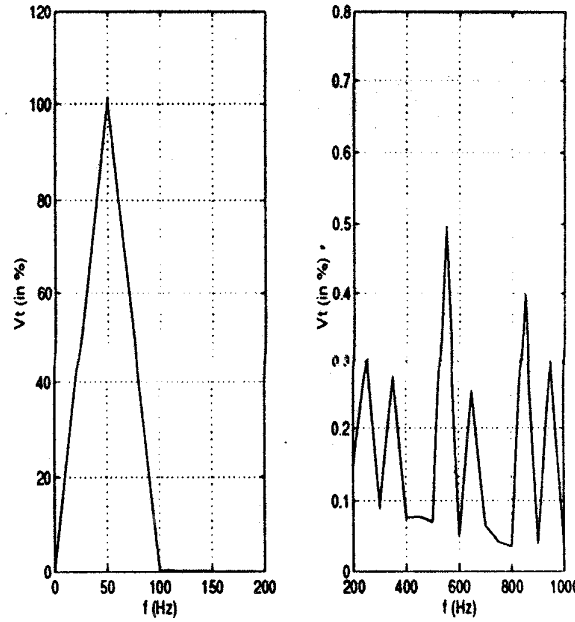
Fig. 5. Simulation waveforms for phase 'a'; the active filter is started at 0.12 sec.

2.25% for $11 \leq h < 17$, 2.0% for $17 \leq h < 23$, 1.25% for $23 \leq h < 35$, 0.35% for $35 \leq h$, and a total demand distortion (TDD) to 6%, where h is the harmonic no. It is seen that the current distortion limits are exceeded in the source current for harmonics of order 11 and above. Fig.7 shows the FFT of i_s after starting the active filter. The harmonic content in i_s is confined to within the limits stated above. Figs.8 and 9 show the FFTs of v_t before and after the active filter is started respectively. The IEEE 519 harmonic standards limit the voltage distortion for this system to 1.5% for individual harmonics and a total harmonic distor-



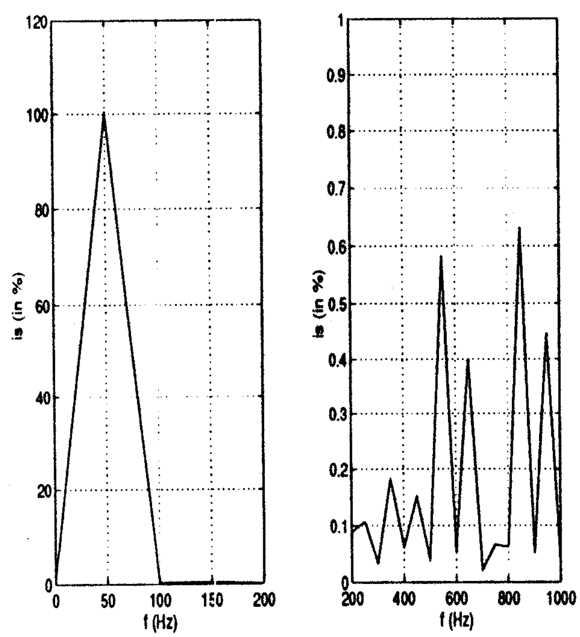
(a) (b)

Fig. 6. FFT of i_s before the active filter is started for (a) the fundamental frequency, (b) the harmonic frequencies.



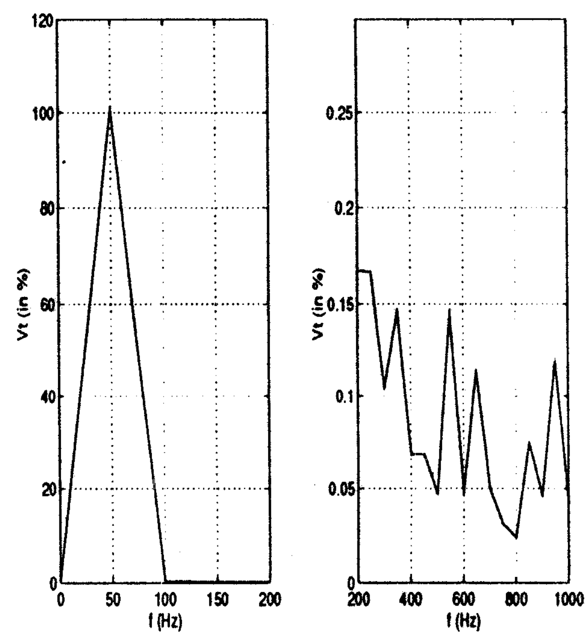
(a) (b)

Fig. 8. FFT of v_t before the active filter is started for (a) the fundamental frequency, (b) the harmonic frequencies.



(a) (b)

Fig. 7. FFT of i_s after the active filter is started for (a) the fundamental frequency, (b) the harmonic frequencies.



(a) (b)

Fig. 9. FFT of v_t after the active filter is started for (a) the fundamental frequency, (b) the harmonic frequencies.

tion (THD) to 2.5%. It is observed that the harmonic content in v_t is well within the limits before the active filter is started and reduces further after starting it.

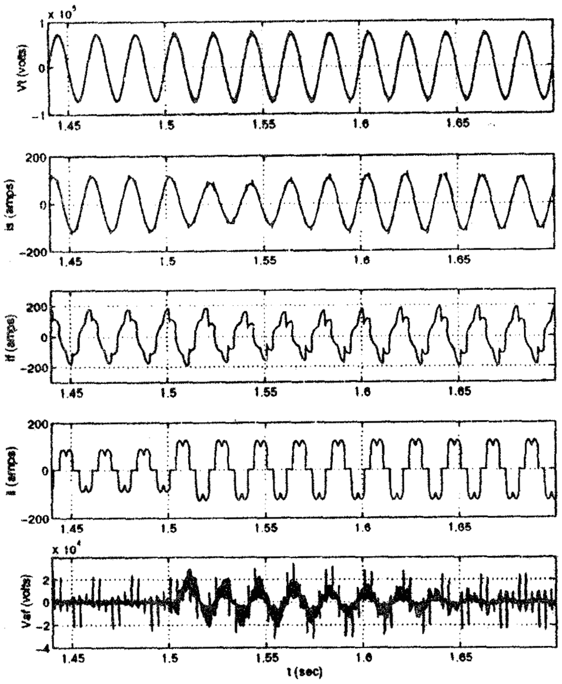


Fig. 10. Simulation results for phase 'a'; the load is varied at 1.5 sec.

Fig.10 shows the simulation waveforms for a 50% step increase in the load at t=1.5 sec. There is a drop in the amplitude of the source current when the load is increased, which gets restored after 0.05 sec. During this period, the output voltage of the active filter (v_{af}) consists of a fundamental component of notable magnitude. This is due to the action of the PI controller for the control of V_d.

The active filter has been implemented using the space-vector PWM technique. Fig.11 shows the trajectory of the voltage reference to the active filter as a space vector. The output voltage of the active filter (v_{af}) closely follows this reference.

Fig.12 shows the DC capacitor voltage V_d waveform of the active filter. This voltage is controlled using a PI controller of Kp=0.05 and Ki=0.1. A first order low-pass filter of cut-off frequency of 30 Hz is used in the feedback path of the V_d control system. This is to filter the high frequency voltage ripple in V_d. It is seen that V_d initially increases after the active filter is started at t=0.12 sec. This is due to the real power flow from the distribution system into the active filter. The use of the PI

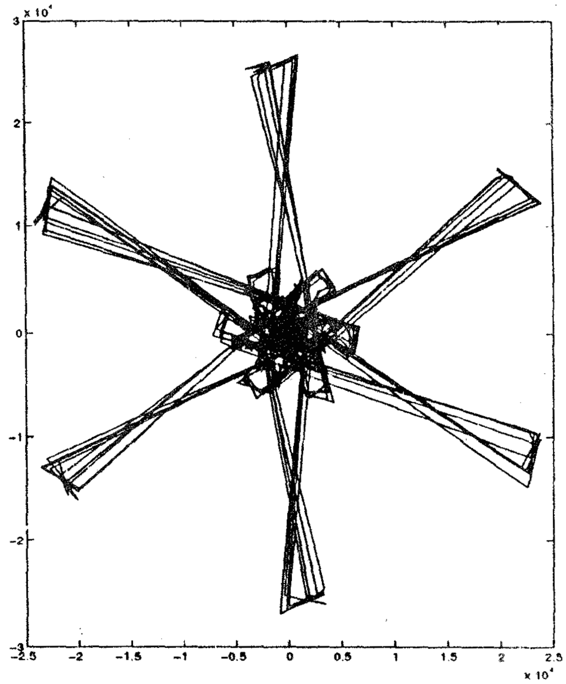


Fig. 11. Voltage reference to the active filter as a space vector.

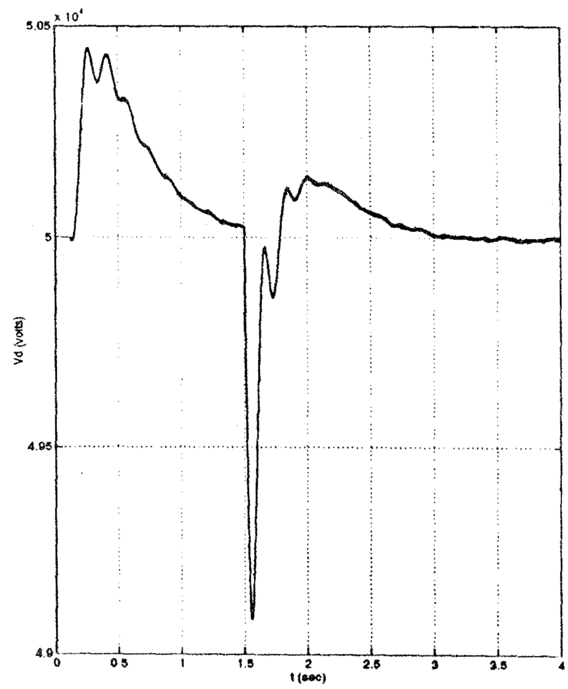


Fig. 12. DC capacitor voltage control of the active filter.

controller injects the real power back into the distribution system. There is a variation in V_d due to load disturbances also. It decreases temporarily for a step increase in the load at t=1.5 sec. The PI controller helps in maintaining a constant V_d with a zero steady-state error.

The apparent power rating of the active filter is given as $3^*V_{af}{}^*I_f = 1.4096$ MVA, where V_{af} and I_f are the RMS values of the active filter output voltage (v_{af}) and the filter current (i_f) respectively. This is 7.05% of the apparent power rating of the load, *i.e.*, 20 MVA. But as the active filter has to output a voltage whose peak value is very large compared to its RMS value, a true representation of the rating is given by its peak value. The devices used in the active filter also need to withstand these peak values. In accordance to the above argument, the peak power rating of the active filter is 9.6758 MVA, which is 24.19% of the peak power rating of the load, *i.e.*, 40 MVA. The active filter rating can be reduced by using more than one tuned passive filter and a high-pass filter. Another factor that effects the active filter rating is the value of K selected. A higher value of K would require a higher rated active filter and vice versa. The value of K has to be optimized to get satisfactory harmonic filtering with an acceptable rating [3].

CONCLUSIONS

In this paper results of the digital simulation of a hybrid active filter system are presented. A fifth harmonic tuned passive filter is used to compensate for the dominant harmonic injected by a 6-pulse rectifier load. The harmonic filtering required a low rated active filter. The rating can be further reduced by adding another tuned filter for the 7th harmonic frequency and a high-pass filter and optimizing the value of K to meet the IEEE 519 harmonic limits. The DC capacitor voltage control of the active filter is done using a PI controller which ensures a zero steady state error. Future work will be conducted to experimentally verify the results on a 3kVA laboratory scaled-down model.

References

[1] H.Akagi, "New trends in active filters for power conditioning," IEEE Trans. on Industry Applications, 1996, Vol.32, No.6, pp. 1312 - 1320.

[2] H.Akagi, "Control strategy and site selection of a shunt active filter for damping of harmonic propagation in power distribution systems," IEEE Trans. on Power Delivery, 1997, Vol.12, No.1, pp. 354 - 363.

[3] A.van Zyl, J.H.R.Enslin, R.Spee, "A new unified approach to power quality management," IEEE Trans. on Power Electronics, 1996, Vol.11, No.5, pp. 691 - 697.

[4] F.Z.Peng, H.Akagi, A.Nabae, "A new approach to harmonic compensation in power systems - A combined system of shunt passive and series active filters," IEEE Trans. on Industry Applications, 1990, Vol.26, pp. 983 - 990.

[5] H.Fujita, H.Akagi, "A practical approach to harmonic compensation in power systems - Series connection of passive and active filters," IEEE Trans. on Industry Applications, 1991, Vol.27, pp. 1020 - 1025.

[6] H.Akagi, Y.Kanazawa, A.Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage devices," IEEE Trans. on Industry Applications, 1984, Vol. IA-20, pp. 625 - 630.

[7] S.Bhattacharya, D.M.Divan, B.Banerjee, "Synchronous frame harmonic isolator using active series filter," Proc. 4th Euro. Conf. on Power Electronics and Appln., Florence, Italy, 1991, Vol.3, pp. 030 - 035.