Performance Analysis of Shunt Active Power Filter for Various Reference Current Generation Techniques

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Abstract

A number of reference current generation have been developed for analysis of shunt active power filter to mitigate the load compensation. Depending upon the type of load the technique have to be chosen. In this paper, six reference current generation techniques viz. instantaneous reactive power theory(IRP), Synchronous reference frame theory(SRF), Perfect harmonic cancellation(PHC), Unity power factor method(UPF), Self tuning filter method(STF), Predictive filtering method(PFM) are compared for different operating conditions. The harmonic are introduced because of non-linear loads in system. These harmonics are eliminated using above techniques. The results and performance of system simulated on MATLAB/Simulink platform. The system is experimentally implemented using DS1104 card of dSPACE system.
Keywords: SAPF, Power Quality, THD, IRP, SRF, dSPACE module DS1104

I. NOMENCLATURE

I total rms current
I_1 fundamental rms current
I_{sk} instantaneous source current for phase k= a, b, c.
I_{lk} instantaneous load current for phase k=a,b,c.
I_{ck} instantaneous compensator current for phase k=a,b,c
I_k instantaneous load current for co-ordinates k=0,α,β or for k=p,q,r
v_k instantaneous voltage for co-ordinates k= 0,α,β or for k=p,q,r
I_k^* reference current for phase k=a,b,c
ω Synchronous speed rad/sec
p_0 instantaneous 0-coordinate load power

II. INTRODUCTION

The increasing number of non-linear reactive loads such as fans, pumps, variable speed drives, rectifiers and more power electronic based loads creates a hunting impact on power supply. These non-linear loads cause a harmonic generation and lagging reactive power in system. Hence there is voltage and consequently current distortion results in poor power quality. The disturbance in the power quality affects the performance of the various equipment’s. The most of the equipment’s in system are more sensitive to the power quality and hence there is possibility of mal-operation of the equipment. Harmonics increases losses hence heat increase, harmonics cause interference with communication line, sometimes failure of transformer occurs, capacitor bank failure occurs. Due to this, elimination of harmonics is important power quality issue. To compensate the harmonics due to nonlinear and unbalanced loads, shunt active power filter (SAPF) is used. The performance of SAPF depends upon control algorithm used for generation of reference current components.

On the basis of power theories, a number of control algorithms were developed. In this paper, performance analysis of six control algorithm for SAPF viz. instantaneous p-q theory, synchronous reference frame method, perfect harmonic cancellation, unity power factor method, self-tuning filter method, predictive filter method has been done. The measure of performance of algorithms are source current total harmonic distortion (THD), total distortion content (TDC), magnitude of neutral current. The results obtained shows that under normal operating condition all algorithms are suitable for compensation.

Rest of the paper is organized as follows: In section III, brief discussion on different control algorithms compared is presented. In section IV, simulation results are described. Finally, in section V, conclusions are drawn.

III. CONTROL ALGORITHMS

A. Instantaneous p-q Theory

The voltages and currents from a-b-c frame are transformed into 0-α-β frame by using Clark's transformation as

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} * \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} * \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

Instantaneous three phase real and imaginary power respectively are given by

$$p = (v_0 * i_0) + (v_\alpha * i_\alpha) + (v_\beta * i_\beta) \quad (3)$$

$$q = (v_\alpha * i_\beta) - (v_\beta * i_\alpha) \quad (4)$$

From (1), (2) and (3)

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} * \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (5)$$

From this real and reactive power, the reference current for 0-α-β frame is given as

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{v_\alpha}{{v_\alpha}^2 + {v_\beta}^2} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} * \begin{bmatrix} p \\ q \end{bmatrix} \quad (6)$$

Thus the compensator current can derived as

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix} * \begin{bmatrix} i_0^* \\ i_\alpha^* \\ i_\beta^* \end{bmatrix} \quad (7)$$

B. Synchronous Reference Frame Theory

This method is also known as *d-q* or Id–Iq method. It is based on Reference Frame transformation i.e. the transformation of coordinates from a three-phase *a-b-c* stationery co-ordinate system to the 0-*d*- *q* rotating coordinate system. It is done using following equations

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

The output of this equation contains AC component or oscillating value as well as DC component or average value. To eliminate the AC component which contain harmonic component, low pass filter is used. So that DC component which is output of above equation is harmonic free.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i_d} + \tilde{i_d} \\ \bar{i_q} + \tilde{i_q} \end{bmatrix} \quad (3)$$

Now this harmonic free signal in 0-*d*-*q* rotating frame is converted back into *a -b-c* stationery frame as shown below.

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix}^{-1} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (4)$$

And

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \quad (5)$$

These reference currents are used for the generation of the PWM pulses by using the HCC i.e. hysteresis current controller .

C. Perfect Harmonic cancellation

The objective of PHC is to compensate all the harmonic currents and the fundamental reactive power demanded by the load in addition to eliminating the imbalance. Assume the voltages at the point of common coupling PCC are V_a, V_b, V_c, and loading currents are I_{La}, I_{Lb}, I_{Lc},

The instantaneous power of the load is given by,

$$P_L = V_a I_{La} + V_b I_{Lb} + V_c I_{Lc} \quad (1)$$

It contains mean and oscillating values

$$p_L = \tilde{P}_L + \bar{P}_L \quad (2)$$

The reference source current is given by:

$$i_{sref} = K v_+{}^1 \quad (3)$$

Where v+1 is the PCC voltage space vector with a single fundamental positive sequence component obtained from the phase-locked loop (PLL) circuit.

The power delivered by the source will be:

$$p_s = v i_{sref} = v K v_+{}^1 = K(v_\alpha v_{\alpha+}{}^1 + v_\beta v_{\beta+}{}^1) \quad (4)$$

The average (mean) power is calculated by using low pass filter (LPF).

The value of K parameter in the above equation is calculated by taking division of average load power and summation of the squared of the positive sequence component of the PCC voltages.

$$K = \frac{\bar{p}_L}{v_{\alpha1}^{+2} + v_{\beta1}^{+2}} \quad (5)$$

Once the parameter K is obtained, the source reference currents are calculated by multiplying it by the positive sequence component of the voltage

$$\begin{bmatrix} i_{s0}^* \\ i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} = K \begin{bmatrix} 0 \\ v_{\alpha1}^+ \\ v_{\beta1}^+ \end{bmatrix} = \frac{\bar{p}_L}{v_{\alpha1}^{+2} + v_{\beta1}^{+2}} \begin{bmatrix} 0 \\ v_{\alpha1}^+ \\ v_{\beta1}^+ \end{bmatrix} \quad (6)$$

The actual reference currents are calculated by taking inverse transformation of the above equation.

D. Unity Power Factor Method

This method is also known as voltage synchronization method. Because the current source waveform is in phase with voltage source waveform at the PCC will have identical wave shape with different amplitudes.

The reference source current is calculated from following equation

$$i_{sref} = K \cdot V \quad (1)$$

Where K is constant which value depends upon the source voltage and load current.

The power delivered by source

$$P_s = V i_s = V \cdot K \cdot V = K(V_0^2 + V_\alpha^2 + V_\beta^2) \quad (2)$$

Then the compensator current

$$i_c = i_L - i_{sref} \quad (3)$$
$$= i_L - K \cdot V \quad (4)$$

The conductance K can be finding by considering that the power delivered by the source equals the dc component of the instantaneous active power of the load

$$K = \frac{\bar{P}_{Le} + \bar{P}_{Lo}}{(V_0^2 + V_\alpha^2 + V_\beta^2)_{dc}} \quad (5)$$

Finally the reference source current are calculated as

$$\begin{bmatrix} i_{s0}^* \\ i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} = K \begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \frac{\bar{P}_{Le} + \bar{P}_{Lo}}{(V_0^2 + V_\alpha^2 + V_\beta^2)_{dc}} \cdot \begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} \quad (6)$$

These currents are in the form of 0-α-β, to get actual reference currents it is necessary to take inverse transformation of above equation.

E. Self Tuning Filter

It is a modified version of classical p-q theory. Basically this theory is useful for distorted supply voltage. The STF is used to extract the fundamental component directly from electrical signals. The load current are transformed into 0-α-β frame as

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} * \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (1)$$

Similarly the real and reactive power are calculated as

$$p = (v_0 * i_0) + (v_\alpha * i_\alpha) + (v_\beta * i_\beta) \qquad (2)$$

$$q = (v_\alpha * i_\beta) - (v_\beta * i_\alpha) \qquad (3)$$

This equation can be written as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} * \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (4)$$

The reference current is calculated as

$$i_\alpha^* = \widetilde{i_\alpha} + \frac{\overline{v_\alpha}}{\bar{v}_\alpha^2 + \bar{v}_\beta^2} \qquad (5)$$

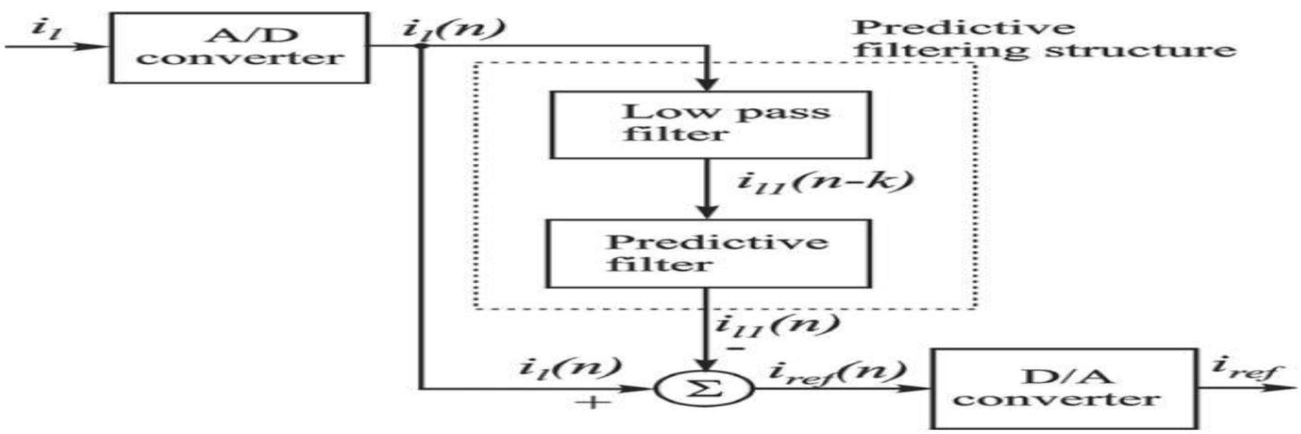
$$i_\beta^* = \widetilde{i_\beta} + \frac{\overline{v_\beta}}{\bar{v}_\alpha^2 + \bar{v}_\beta^2} \qquad (6)$$

By using these equations the compensation current is calculated as

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix} * \begin{bmatrix} i_0^* \\ i_\alpha^* \\ i_\beta^* \end{bmatrix} \qquad (7)$$

F. Predective Filtering Method

As like above techniques the predictive filtering method is also used for the reference current generation and harmonic compensation. The load current is converted to digital signal and filtered with low pass filter. At the output of low pass filter, the fundamental harmonic component is obtained. Hence the reference current is obtained by subtracting the fundamental harmonic component from the load current. As the reference current generated is digital hence it is converted to analog signal.



IV. SIMULATION RESULTS AND ANALYSIS

To assess the performance of different control algorithm, simulations are designed and implemented in MATLAB. In MATLAB simulation phase to phase source voltage is 400 volts, frequency 50Hz along with along with control techniques, non-linear load and gate pulse generation. Various waveforms for different algorithms are shown below.

First fig. shows the source current waveform when SAPF is not connected and second fig. shows source current waveform when SAPF is connected.

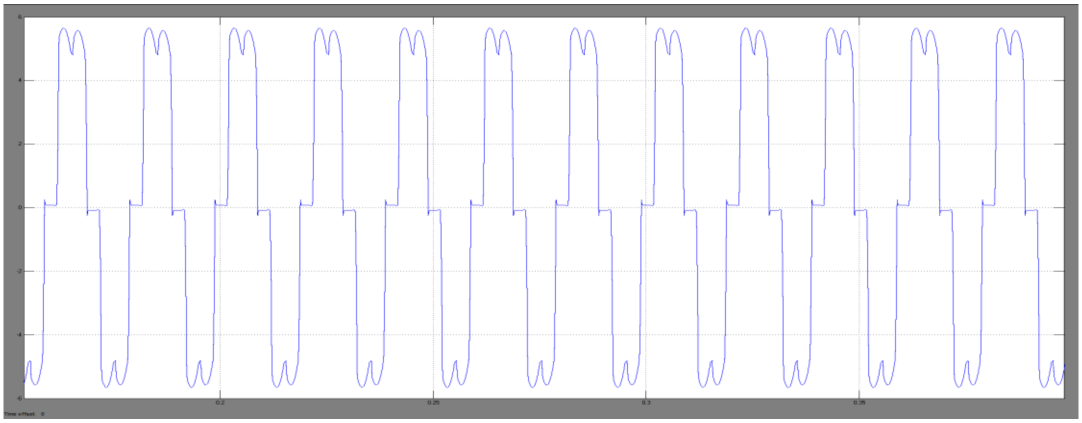


Fig. 1: Source Current without SAPF

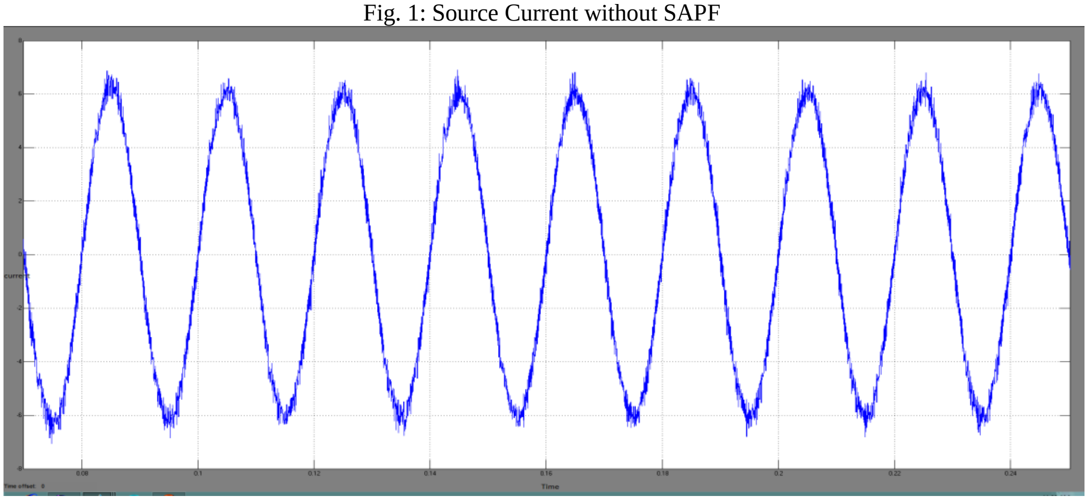


Fig. 2: Source Current When SAPF Is Connected

Following table shows the THD before compensation and after compensation

Sr. no.	*Theory*	*Before compensation In %*	*After compensation In %*
1	*IRP*	*25.01*	*4.41*
2	*SRF*	*25.01*	*4.83*
3	*PHC*	*25.01*	*2.39*
4	*UPF*	*25.01*	*5.92*
5	*STF*	*25.01*	*4.65*
6	*PFM*	*25.01*	*5.56*

V. CONCLUSION

To overcome the problem of harmonics, comparative analysis of six control algorithms of shunt active power filter is done in this paper. The harmonics generated in the system gets compensated by using these compensation techniques. The results shows that, from all the six algorithms the perfect harmonic compensation method is most efficient in comparison with all.

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