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Synchronous Reference Frame Fundamental Method in Shunt Active Power Filter for Mitigation of Current Harmonics

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ABSTRACT

This research presents compensation of current harmonic disturbance in power system network using shunt active power filter. In this paper, harmonic extraction using Synchronous Reference Frame Fundamental technique (SRFF) was investigated for three phase 3-wire system. It proposes a method based on direct current measurement of load currents using a band pass filter at low cut off frequencies to improve the filtering ability in highly contaminated loads. The proposed filter consists of second order low pass and high pass filters cascaded together at suitable frequencies, estimated based on the output of these units to mitigate the current harmonics. The performance of the system was simulated in Matlab Platform and evaluated considering total harmonic distortion of the source current in a three-phase balanced network. The simulation results show the ability of the proposed tracking scheme to accurately estimate harmonics.

Keywords: Shunt active power filter (SAPF), power quality, harmonics, synchronous reference frame (SRF), Low pass filter, high pass filter, band pass filter

INTRODUCTION

Non-linear loads, such as power electronic converters, generate harmonic current and voltage into power system network leading. to low power quality. This poor power quality may trigger improper function of devices arising from balanced or unbalanced non-sinusoidal currents. The harmonic spectrum of some common nonlinear loads like uninterrupted power supply, switching mode power supplies and fluorescent lamps consists of odd order harmonics, dominated by 3rd, 5th and 7th harmonic components and compensating them would go a long way eliminating large bulk of harmonic currents (Gautam, Yunqing, Kafle, Kashif, & Hasan, 2014). Various harmonic mitigating devices

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have been developed to adequately compensate not just harmonic current but also compensate reactive power, as well as unbalanced nonlinear and fluctuating loads. Thus, sinusoidal voltage and current with unity power factor will be supplied to the load. Shunt active power filter has been proven to be effective in compensating harmonic current and reactive power (Salam, Cheng, & Jusoh, 2006)(Jacob, Abraham, Prakash, & Philip, 2014)(Bojoi et al., 2005). It is designed to draw compensation current or voltage, from the utility, so that it cancels out the harmonic components on the ac side by injecting an equal but-opposite voltage or current distortion into the network.

The SAPF is connected in parallel to the load at PCC as shown in Figure 1. In a design of shunt active power filter, the controller is divided into : detection, dc bus control and current control (Newman, Zmood, & Holmes, 2002). The selection of methods to be adopted is a compromise between accuracy and computational intensity that influences real time application. Estimation of reference signal is initiated through detection of essential voltage/current signals to generate accurate system variables (information).The derivation of compensation signal from the disrupted wave that consists of both fundamental and harmonic contents, can be done by two different methods, either frequency domain or time domain approaches. In frequency domain, control strategy to extract compensating commands is based on Fourier analysis of the distorted voltage or current signals. Among its drawbacks, this technique involves a lot of mathematical computation which requires time to be executed. Also for efficient performance, a good and fast processor must be considered. Control strategy in time domain does not require much calculation, and are easy to be implemented (Singh, Al-haddad, & Chandra, 1999). It is based on instantaneous derivation of compensation commands in the form of either voltage or current signals of distorted signals (voltage or current).

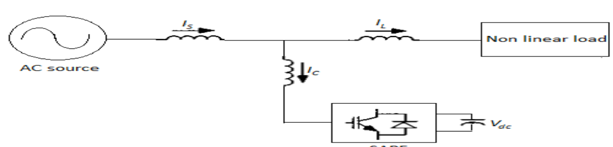


Figure 1. Shunt active power filter

Conventional current detection methods are usually based on harmonic detection of load currents using well-known control strategies in time domain, namely, instantaneous power theory (p-q theory) (Kale & Ozdemir, 2005), synchronous reference frame (SRF) (d-q theory) (Sundaram & Venugopal, 2016; Salim, Benchoula, & Goléa, 2011; Firouzjah, Sheikholeslami, Karami-Mollaei, & Heydari, 2009), synchronous detection method (George & Basu, 2008) etc. The control strategy based on synchronous reference frame (d-q theory) is the most widely popular because of its good performance in abnormal conditions and easy implementation (Giri Prasad, Dheeraj, & Naveen Kumar, 2012). Figure 2 shows block diagram of the harmonic current detection of this scheme. One way to improve accuracy and dynamics is the SRF technique which has faster response and small overshoot. In order to address problems HPF and low pass filter (LPF) were combined to develop a band pass filter (BPF). In LPF, its dc signal output has no phase shift and hence no delay. This design should improve the performance of the SRF technique in mitigating current harmonics. Second order LPF and HPF were used to produce a fourth order BPF due to the fact that higher order filters will provide better performance in term of accuracy, which improves filtering process in compensating low order harmonics, which are not completely eliminated by other control strategies This design is simple and easy to be implemented. The BPF is tuned in terms of bandwidth, attenuation and centre frequency to obtain the desired total harmonic distortion (THD). In Section 2, the proposed control strategy of the harmonic detection technique is explained. In Section 3, details of harmonic extraction with BPF, and in Section 4, simulation results are presented and discussed. Finally, section 5 presents the summary of the study.

HARMONIC CURRENT DETECTION TECHNIQUE.

The detection method used is the SRF technique, where the load current is transformed to rotating reference frame dq with θ being the transformation angle. In this method, θ as time varying angle represents the angular position of reference frame which is rotating at constant speed in synchronizing with the fundamental frequency of the AC system.

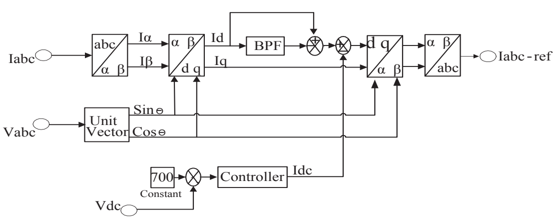


Figure 2. Block diagram of SRF method

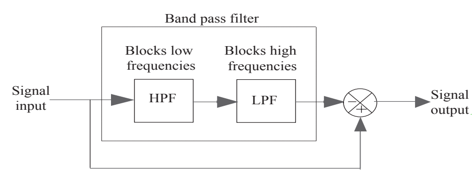


Figure 3. Cascaded HPF and LPF to band pass filter

Presented in Figure 2, is a block diagram of harmonic current detection technique as described in the following steps. In calculating the reference current for shunt active power filter using the SRF method, five steps are involved.

Step one starts with the three-phase supply current i_a, i_b and i_c are transformed to 2-ϕ (α−β) current in stationary reference frame i_α and i_β as shown below.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

Step two involves changing from the α − β plane to current reference in d-q frame, using a unit vector for generation of sine and cosine signals required for synchronization with the various phase to neutral voltages. The d-q currents obtained consist of AC and DC parts. The fundamental component of current becomes fixed DC part and the AC part represents the harmonic components. These harmonic components can easily be extracted using the BPF, as cascaded second order LPF and HPF, as shown in Figure 3.

Current expression in d-q reference frame, is given in equation 2

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

where θ represent, the phase angle of voltage.

In step three, the detection of harmonics becomes a matter of removing the AC signal with the BPF.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d & i_d \\ \bar{i}_q & i_q \end{bmatrix} \quad (3)$$

Thus, i_α and i_β are obtained as given below in step four:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \sin(\theta) & -cos(\theta) \\ cos(\theta) & sin(\theta) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (4)$$

The reference current $i_{\alpha\text{-ref}}$ and $i_{\beta\text{-ref}}$ is given by

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta) & -cos(\theta) \\ cos(\theta) & sin(\theta) \end{bmatrix} \begin{bmatrix} \tilde{i_d} + i_{dc} \\ \tilde{i_q} \end{bmatrix} \quad (5)$$

Finally, in step five, the abc reference frame is obtained using inverse transformation so that, current is as given below:

$$\begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} \quad (6)$$

The extracted harmonic current reference is compared with output current from inverter or filter current, thus, generating the required switching pulses for the inverter.

DESIGN OF BAND-PASS FILTER

In order to mitigate low order harmonics and reactive power with BPF, two second-order LPF and HPF were designed and cascaded. In the fundamental dq-frame, overall harmonic compensation is achieved due to the fact that fundamental frequency is transposed to dc-signal. Its together with all harmonics using both LPF and HPF from the load current, gives a band of selected harmonic current spectrum. The literature suggests that fundamental d-q-frame does not allow specific selective harmonic current compensation; however, it has an interesting property in having characteristic of harmonic orders, in each is designed for one pair i.e. $k= 6n \pm 1$ of positive and negative sequence harmonics (Gautam et al., 2014; Lascu, Asiminoaei, Boldea, & Blaabjerg, 2007). There is therefore an advantage to compensate two harmonic orders at once. In (Lascu et al., 2007)specific loads, such as diode or thyristor rectifiers for example, the 5th harmonic consists of only negative-sequence component and that of 7th harmonic has only positive component. Both harmonics are derived from the sixth harmonic in fundamental reference frame, so that only a single regulator in the fundamental positive-sequence reference frame could be used for both harmonics. At lower cut-off frequencies with pass band to be set at 10 Hz, the BPF is tuned in terms of bandwidth, attenuation and centre frequency at the

desired harmonic frequency. With appropriate cut-off frequencies of BPF (as determined by equations 9 and 10), separation of fundamental and harmonic currents from measured system load current was achieved. This approach, effectively mitigates almost completely the more harmful harmonics from the load current, which are not sufficiently attenuated with other control schemes. Numerical filtering is a key issue in determining accuracy and dynamics of the harmonic detection mechanism. In selecting the characteristics of filter, a compromise between these two has to be made. These are determined by the cut-off frequency and order of the filter; filters with higher order and lower cut-off frequency improve attenuation of harmonics but, at a cost of slowed down response in event of load variation. Therefore, the trade-off is between accuracy and speed (response time) should be discovered.
Equations 7-10 are given below, used for determining filter parameters:

Bandwidth $BW = f_2 - f_1$. (7)

Quality factor $Q = \frac{f_0}{BW}$ (8)

High pass filter cut-off frequency $f_1 = \sqrt{\left(\frac{BW}{2}\right)^2 + f_0^2} - \frac{BW}{2}$ (9)

Low pass filter cut-off frequency $f_2 = \sqrt{\left(\frac{BW}{2}\right)^2 + f_0^2} + \frac{BW}{2}$ (10)

Where BW = Bandwidth, Q = Quality factor, f_1 = low cut-off frequency, f_2 = high cut-off frequency, f_0 = centre frequency.

RESULTS AND ANALYSIS

The shunt APF performance was investigated using Matlab/Simulink software in the simulation study. A 3-ϕ voltage supply with uncontrolled rectifier with resistor-inductor (RL) load (non-linear load) is used as the test system. To mitigate harmonics, shunt APF is connected with the test system via filter inductor L. Figures 4 to 6 below displayed the related results from the simulation work. The THD due to non-linear load of distorted line current is 25.60% as depicted in Figure 4 from fast Fourier transform (FFT) analysis of load current before compensation. This result, clearly shows that, supply current is distorted due to presence of non-linear load. The harmonic spectrum of the distorted waveform is displayed in Figure 4a. In order to eliminate the current harmonics, the shunt active power filter successfully reduced THD of source current to 1.16% (as obtained from FFT analysis shown in Figure 4b). Figure 5a shows waveform of load current before compensation, while Figure 5b displays the source current after compensation, Figure 6a displays the compensation current, and Figure 6b displays DC bus capacitor voltage. The analyses were carried out for the proposed BPF, and with LPF too, for comparison.

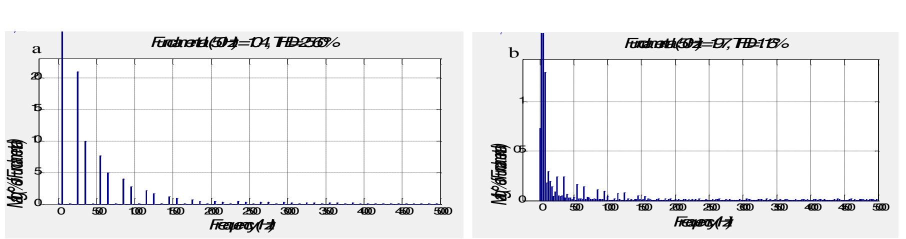
Table 1 shows findings obtained from the analyses. The BPF shows a better performance in terms of THD. The smaller bandwidth results in better finding. At lower cut-off frequency with pass band of 10 Hz, the BPF produces good performance. With appropriate cut-off frequencies of BPF, separation of fundamental and harmonic currents from the measured load current was achieved, and this shows effectiveness of the configuration in mitigating low order harmonics. Different loads were test to verify the performance of the SAPF with both LPF and BPF. The result is presented in Table 2. Again, the BPF has displayed better performance in mitigating current harmonics.

Table 1
THD with and without shunt active power filter

Harmonic order	THD %		
	Without SAPF	With SAPF LPF tr = 0.159	With SAPF BPF tr = 0.17
1st	100.00	100.00	100.00
3rd	0.00	1.23	0.20
5th	20.96	0.58	0.24
7th	9.92	0.33	0.24
9th	0.00	0.15	0.03
11th	7.63	0.18	0.17
13th	4.94	0.14	0.14
THD%	25.60	3.00	1.16

Table 2
THD with and without shunt active power filter

THD %		
Loads	LPF	BPF: (LPF & HPF)
50Ω 100mH	3.64	1.11
20Ω 20mH	3.32	1.49
40Ω 100mH	2.90	1.18
30Ω 10mH	2.90	1.25
30Ω 5mH	2.90	1.25
40Ω 10mH	2.98	1.16
40Ω 90mH	2.91	1.16
30Ω 50mH	3.00	1.25



(a) (b)

Figure 4. FFT analysis of source current (a) before and (b) after compensation

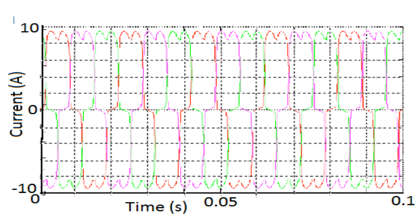


Figure 5. (a) Source current before compensation

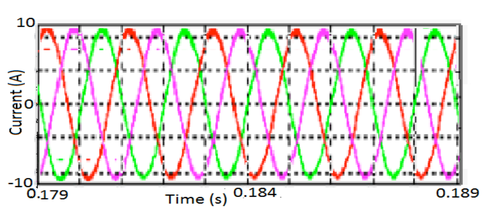


Figure 5. (b) Source current after compensation

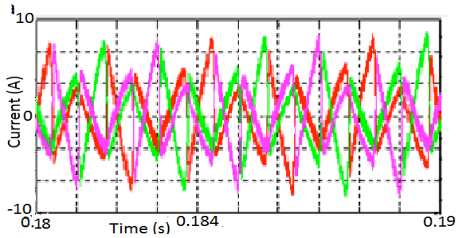


Figure 6. (a) Compensation current

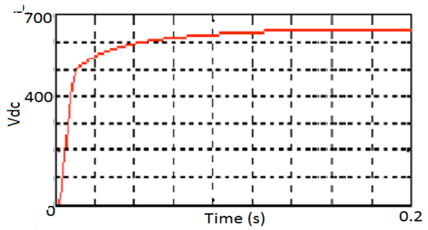


Figure 6. (b) DC bus capacitor voltage

CONCLUSION

In this work, an improvement in filtering performance of the dq reference frame technique was presented. This was achieved by combining the properties of HPF and LPF in developing BPF. Interestingly, the dc output signal of LPF has zero phase shift; therefore, it has no delay. Second order LPF and HPF were used to produce fourth order BPF, as higher order filters provide better performance, being more accurate thus improving the filtering process. in compensating low order harmonics, which are not completely eliminated by other control strategies. The design is simple and easy to be implemented. The simulation results show effectiveness of this method in mitigating low order harmonics in the system with THD reducing from 25.60% to 1.16%.

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