International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 5, Number 1 (2012), pp. 37-47

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Simulation of Shunt Active Power Filter using Hysteresis Current Control Technique

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Abstract

This paper presents a comprehensive design and simulation of three-phase shunt active power filter to compensate the harmonics of nonlinear loads. The paper describes the complete design aspects of power circuit elements and control circuit parameters. The process is based on sensing line currents, line voltages and DC side capacitor voltage to compensate the harmonics in the nonlinear load. In this paper, hysteresis current control band is used in order to obtain switching signals to compensate the harmonics. The graphical outcomes show that the active filter brings the THD of the system well below 15%, while it shows 30% THD without filter.

Keywords: active power filter, harmonics, hysteresis current band

Introduction

In recent years, many power electronic converters utilizing switching devices have been widely used in industrial as well as domestic applications. These power converters offer nonlinear characteristics. Some of the small power domestic electrical appliances, like TV sets, computers, microwave oven set, also draw much distorted currents. These nonlinear loads lead to generation of current/voltage harmonics; draw reactive power and cause problems in ac power lines. The increase in such nonlinearity causes different undesirable features, like low system efficiency and poor power factor. The effect of this nonlinearity could become sizeable over the next few years. Hence, it is very important to overcome these undesirable features. The active power filter is now seen as a viable alternative over the classical passive filters to compensate for harmonics and reactive power requirements of the nonlinear load. The objective of the active filtering is to solve these problems by combining the advantages of regulated systems with a reduced rating of the necessary passive components.

This paper presents a comprehensive design and simulation of a shunt active power filter to compensate for harmonics of nonlinear load. The three-phase currents/ voltages are detected using only two current/ voltage sensors, as compared to three sensors used in [1]. DC capacitor voltage is regulated to estimate the reference current.

Principle

Principle of Shunt Active Power Filter

Fig. 1 shows the basic compensation principle of the shunt active power filter. It is controlled to draw or supply a compensating current. This compensating current injected by the active filter makes the supply current sinusoidal. In this manner, a shunt active filter can be used to eliminate the current harmonics in the system.

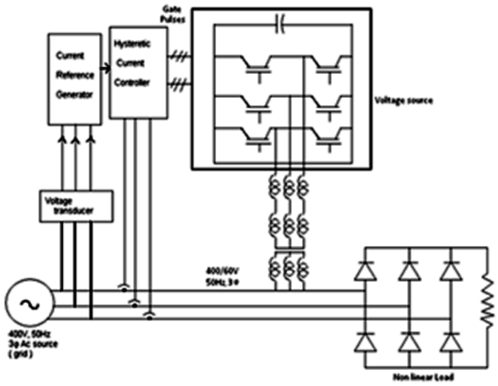

Figure 1: Schematic diagram of Active Filter connecting with Non Linear Load

Current Supplied by Source

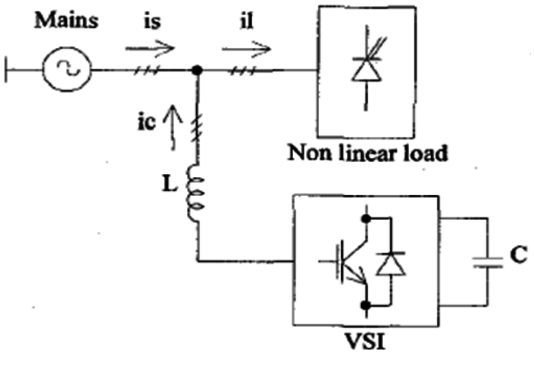

Figure 2: Basic compensation principle

From Fig.2, the instantaneous currents can be written as

$$i_s(t) = i_L(t) - i_c(t) \tag{1}$$

The source voltage is given by

$$v_s(t) = V_m \sin\omega t \tag{2}$$

If a nonlinear load is applied, then the load current will have a fundamental component, and the harmonic components can be represented as

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \varphi n) = I_1 \sin(\omega t+\varphi_1) + \sum_{n=2} I_n \sin(n\omega t+\varphi_n) \tag{3}$$

Instantaneous load power can be given as

$$P_L(t) = v_s(t) * i_L(t) = V_m I_1 \sin^2\omega t * \cos\varphi_1$$
$$+ V_m I_1 \sin\omega t * \cos\omega t * \sin\varphi_1 + V_m \sin\omega t$$
$$* \sum_{n=2} I_n \sin(n\omega t+\varphi_n) \tag{4}$$
$$= p_{f(t)} + p_r(t) + p_h(t) \tag{5}$$

from Equation (4), real (fundamental) power drawn by the load is given by

$$p_f(t) = V_m I_1 \sin^2\omega t * \cos\varphi_1 = v_s(t) * i_s(t) \tag{6}$$

from equation(6), the source current supplied by the source, after compensation

$$i_s(t) = \frac{p_f(t)}{v_s(t)} = I_1 \cos\varphi_1 \sin\omega t = I_{sm} \sin\omega t$$

where

$$I_{sm} = I_1 \cos\varphi_1.$$

Also, there are some switching losses in the PWM converter. Hence, the utility must supply a small overhead for the capacitor leaking and converter switching losses in addition to the real power of the load.

Hence, total peak current supplied by the source

$$I_{sp} = I_{sm} + I_{sL} \tag{7}$$

If the active filter provides the compensation current, then $i_s(t)$ will be in phase with the utility voltage and pure sinusoidal. At this time, the active filter must provide

$$i_c(t) = i_L(t) - i_s(t)$$

Hence, for the accurate and instantaneous compensation of reactive and harmonic power, it is necessary to calculate $i_s(t)$, the fundamental component of load current, as the reference current.

Estimation of Reference Source Current

The peak value of the reference current I_{sp}can be estimated by controlling the dc side capacitor voltage. The ideal compensation requires the main current to be sinusoidal and in phase with the source voltage irrespective of the nature of load current. The desired source currents after compensation can be given as

$$i^*_{sa}=I_{sp}\sin\omega t$$

$$i^*_{sb}=I_{sp}\sin(\omega t-120^\circ)$$

$$i^*_{sc}=I_{sp}\sin(\omega t+120^\circ)$$

where $I_{sp}=(I_1\cos\varphi_1 + I_{sL})$ is the amplitude of the desired source current, while the phase angles can be obtained from the sourcevoltages.

Hence, the waveform and phases of the source currents are known; only the magnitudes of the source currents need to be determined. This peak value of the reference current has been estimated by regulating the dc side capacitor voltage of the PWM converter. This capacitor voltage is compared with a reference value, and the error is processed in a PI controller.

The output of the PI controller has been considered as the amplitude of the desired source current, and the reference currents are estimated by multiplying this peak value with the unit sine vectors in phase with the source voltages.

DC Capacitor

The dc side capacitor serves two main purposes: (1) it maintains a dc voltage with a small ripple in steady state, and (2) it serves as an energy storage element to supply the real power difference between load and source during the transient period. In the steady-state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate for the losses in the active filter. Thus, dc capacitor voltage can be maintained at a reference value.

However during the change in load conditions the real power balance between the source and the load will be disturbed. This real power difference is to be compensated by the dc capacitor. This changes the dc capacitor voltage away from the reference voltage. In order to keep the satisfactory operation of the active filter, the peak value of the reference current must be adjusted to change proportionally the real power drawn from the source. This real power charged or discharged by the capacitor compensates for the real power consumed by the load. If the dc capacitor voltage is recovered and attains the reference voltage, the real power supplied by the source is supposed to equal that consumed by the load again.

Design Considerations

Design of Shunt Active Power Filter

Design of a power circuit includes three main parameters:

1. Selection of inductor, L_c
2. Selection of dc side capacitor, C_{dc}, and
3. Selection of reference value of dc side capacitor voltage, V_{dc}.

Selection of L_c and $V_{dc,ref}$

The design of these components is based on the following assumptions:

1. The ac source voltage is sinusoidal
2. To design the L_c, the ac side line current distortion is assumed to be 5%
3. There is fixed capability of reactive power compensation of the active filter
4. The PWM converter is assumed to operate in the linear modulation mode ($0 \leq m_a \leq 1$)

Thus, the amplitude modulation factor m_a is expressed as

$m_a = \frac{V_m}{V_{dc/2}}$, where $v_m = \sqrt{2V_{c1}}$.

hence, $V_{dc} = 2\sqrt{2V_{c1}}$ for $m_a = 1$.

The filter inductor L_c is also used to filter the ripples of the converter current. Hence, the design of L_c is based on the principle of harmonic current reduction. The ripple current of the PWM converter can be given in terms of maximum harmonic voltage that occurs at the frequency $m_{f\omega}$:

$$I_{ch}(m_{f\omega}) = \frac{V_{ch}(m_f\omega)}{m_f \omega L_c} \tag{8}$$

where m_f is the frequency modulation ratio of the PWM converter.

As the switching frequency is not fixed with the hysteresis controller, a practically feasible value of 10kHz has been assumed. From the values obtained from Tables 1 and 2, the values of L_c and $V_{dc,ref}$ are finalized

Table 1: Variation of % THD with inductor

L_c(mH)	%THD (of the 10th cycle)
3.35	1.75%
4.0	1.82%
4.4	2.45%

Table 2: System performance with variation in reference capacitor voltage

$V_{dc,ref}$ (volts)	V_{dc} rise/dip (% of $V_{dc,ref}$)	Settling time	%THD
600	3	0.25	2.43
680	2.5	0.15	1.75
1000	2	0.2	1.79

Design of DC side Capacitor (C_{dc})

The selection of C_{dc} can be governed by reducing the voltage ripple. As per the specification of peak-to-peak voltage ripple($V_{dc,p-p(max)}$) and rated filter current ($I_{c1,rated}$), the dc side capacitor C_{dc} can be found from

$$C_{dc} = \frac{\pi * I_{c1,rated}}{\sqrt{3}\omega V_{dr,p-p(max)}} \tag{9}$$

From the above test results, the values of the following parameters are finalized $V_{dc,ref}$= 680V, L_c=3.35mH, C_{dc} = 2000μF

Proposed Control Scheme

The complete schematic diagram of the shunt active filters developed is shown in Fig.3. The actual capacitor voltage is compared with a set reference value. The error signal is then fed to a PI regulator. The output of the PI regulator is considered as the peak value of the supply current.This peak value of the current is multiplied by the unit sine vectors (u_{sa} and u_{sc}) in phase with source voltages to obtain the reference currents (i^*_{sa} and i^*_{sc}). The third reference current i^*_{sb} has been obtained by a negative adding circuit. These reference currents and actual currents are given to a hysteresis based PWM controller to generate the switching signals.

The difference of the reference currents and actual currents decides the operation of the switches. To increase the current of a particular phase, the lower switch of that particular phase is switched on; while to decrease the current, the upper switch of the respective phase is switched on. These switching signals after proper isolation and amplification are given to the switching devices. Because of these switching actions, current flows through the filter inductor L_c, to compensate the harmonic current.

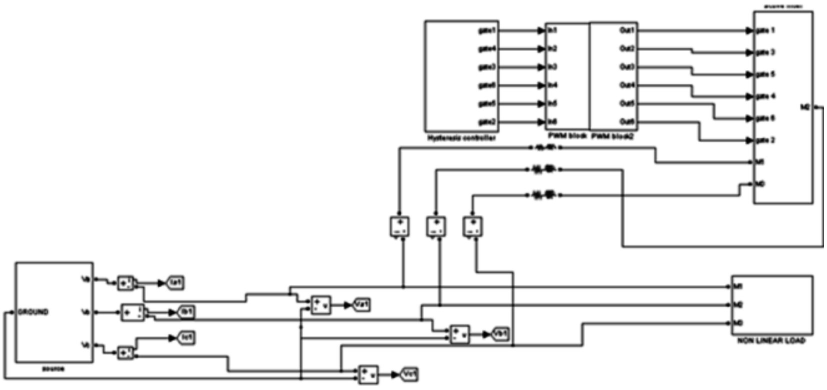

Figure 3: Schematic diagram of Shunt Active Filter

Transfer Function of PWM Converter(K_c)

The transfer function of the PWM converter is obtained by the following expression:

$$K_c = \frac{V_{dc}}{I_c} = \frac{3[Vs - LcIccos - 2Ic\omega Rc]}{CdcVdcos} \tag{10}$$

Design of PI Controller Parameters

The characteristic equation of the voltage control loop is used to obtain the constants of the PI regulator:

$$1+\left(K_p+\frac{K_i}{s}\right)\frac{3[Vs-LcIcos-2IcoRc]}{CdcVdcos}=0 \qquad (11)$$

The parameters of PI regulators are obtained as $K_p = 0.2$ and $K_i = 10.4$ for the selected system.

Hysteresis Current Controller

This scheme involves selection of two levels of current; one slightly above the reference current and other slightly below the reference current. The scheme is explained diagrammatically in Fig. 4

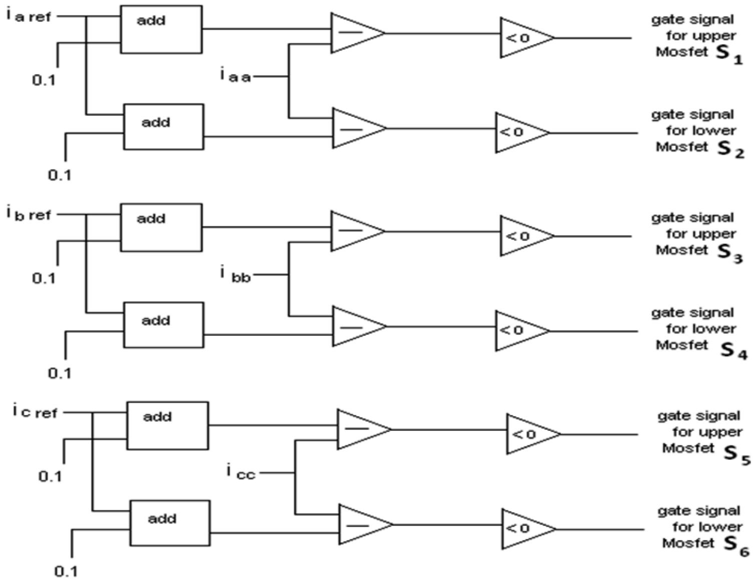

Figure 4: Hysteretic current control.

Feedback signal from the actual current is taken. When the actual current is below the lower value, the MOSFETs are switched on; and when the current crosses the upper value, the MOSFETs are switched off. As a result, the actual current remains within the upper and lower bands of the current reference.

Simulation Results

Fig. 5 shows the source current of the system without compensation with a THD of 27.02%.

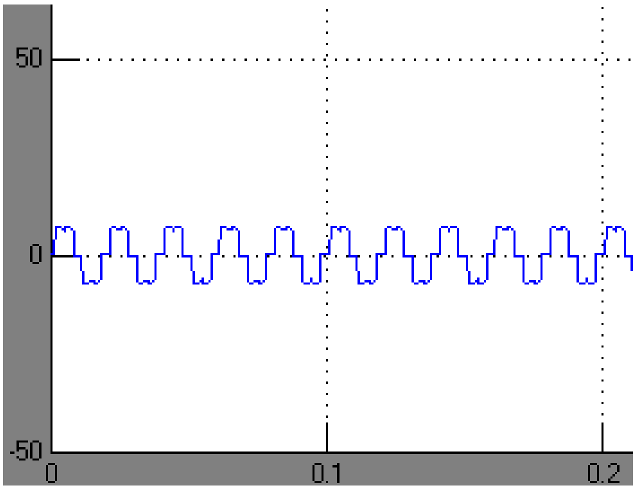

Figure 5: Source Currents before compensation

Fig. 6 shows the source current of the system with compensation with a THD of 14.78%

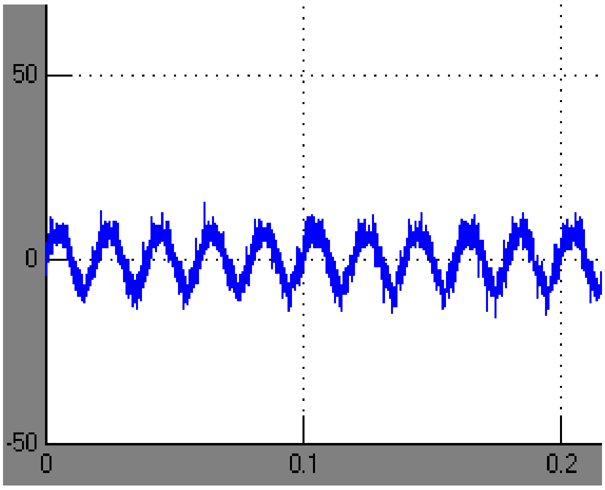

Figure 6: Source Currents after compensation

Fig. 7 shows the generation of reference currents according to the above said control scheme

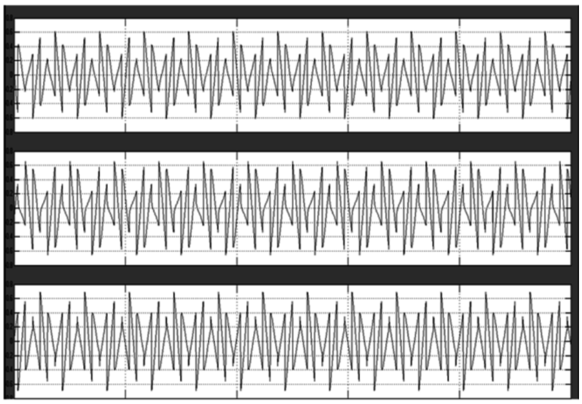

Figure 7: Reference currents generated by active filter controller.

Fig. 8 shows the Hysteresis band for the obtained reference signals

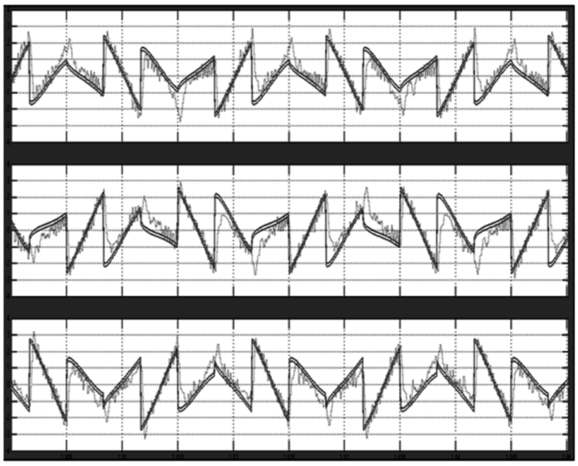

Figure 8: Hysterisis band of the reference currents

Fig.9 shows the DC side capacitor voltage.

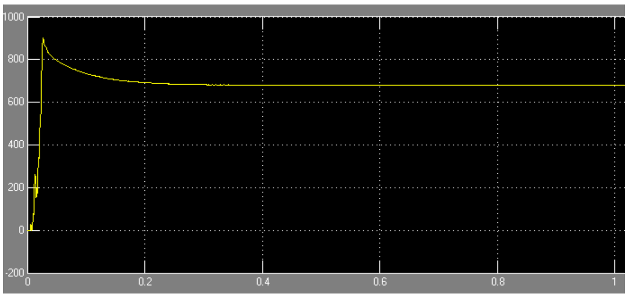

Figure 9: DC side capacitor voltage

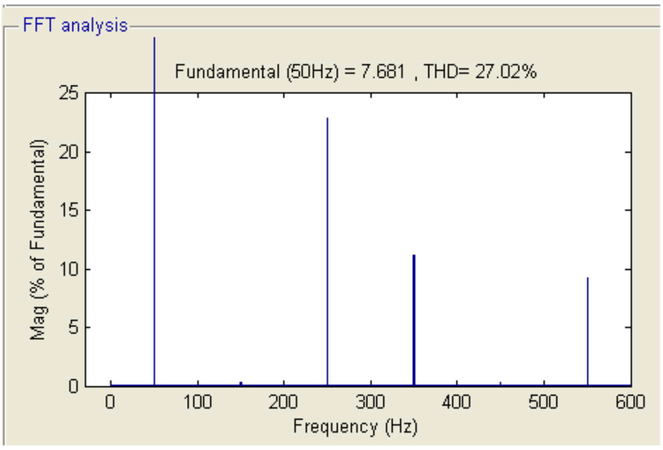

Fig.10 THD of source currents before Compensation

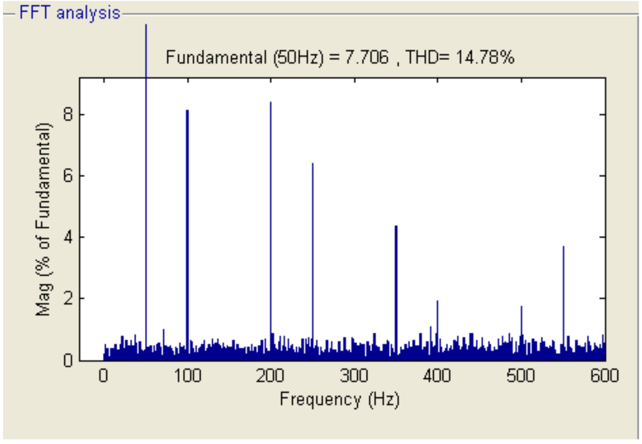

Fig.11 THD of source currents after compensation

Conclusions

It is found that the shunt active filter produces better results with hysteretic control scheme. Using shunt active filter, there is a reduction in Total Harmonic Distortion from 27.02% to 14.78%. Various parameters affecting the performance of the controller were investigated and the results were presented.

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