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Power Factor Improvement Using a Three Phase Shunt Active Power Filter

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Abstract

The increasing growth in the use of electronic equipment in recent years has resulted in a greater need to ensure that the line current harmonic content of any equipment connected to the ac mains is limited to meet regulatory standards. Shunt Active Power Filters (SAPF) are used to compensate both harmonic and reactive current component for the power supplies. It also improves the power quality and power factor on power utility. In this paper, Application of Direct Testing and Calculating Method (DTCM) in Shunt Active filters is proposed to estimate reference current signal, and apply hysteresis control to generate gate pulses. The results of simulation study of control scheme presented in this paper is found quite satisfactory for eliminate harmonics and reactive power components from utility, successful in meeting the IEEE 519 recommended harmonic standard limits.

Keywords: Shunt Active Power Filters, Harmonic currents, reference Current signal, hysteresis control.

Nomenclature

K_{φ} displacement factor
K_d distortion factor
i_p active current component
i_q reactive current component
i_h harmonic load current
I_F reference current signal
I_s^* the estimated current
I_L load current signal
α phase shift angle
H a signal deviation
I_f^* Reference Current signal

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1. Introduction

Modern electrical systems cause an increasing harmonic disturbance in the ac main currents, due to wide spread of power conversion units and power electronics equipments. These harmonic currents cause adverse effects in power systems such as overheating, perturbation of sensitive control and communication equipment, capacitor blowing, motor vibration, excessive neutral currents, resonances with the grid and low power factor [1].
The power factor values measures how much the mains efficiency is affected by both phase lag φ and harmonic content of the input current. Its value lies in the range between 0 and 1 and it is computed as the ratio of the real power to the apparent power. Power Factor can be calculated as:

$$PF = \frac{P}{S} = \frac{V_{rms} \times I_{1rms} \times \cos\varphi_1}{V_{rms} \times I_{rms}} = \frac{I_{1rms}}{I_{rms}} \times \cos\varphi_1 = K_d \times K_\varphi \qquad (1)$$

Where,

K_φ is the displacement factor $= \cos\varphi_1$ (2)

, K_d the distorition factor $= \frac{I_{1rms}}{I_{rms}}$ (3)

Another important parameter that measure the percentage of distortion is known as the Current Total Harmonic Distortion (THD) which is defined as follows:

$$THD = \frac{\sqrt{I_{2rms}^2 + I_{3rms}^2 + \cdots + I_{nrms}^2}}{I_{1rms}} \qquad (4)$$

From equations (2), (4) we get the relationship between the THD and the K_d:

$$K_d = \frac{1}{\sqrt{1+THD^2}} \qquad (5)$$

Where: $I_{rms} = \sqrt{I_{1rms}^2 + I_{2rms}^2 + I_{3rms}^2 + \cdots + I_{nrms}^2}$ (6)

Harmonic distortion in power distribution systems can be suppressed using two approaches namely, passive and active powering. The passive filtering is the simplest conventional solution to mitigate the harmonic distortion [2,3]. Although simple, passive filters have many disadvantages, such as large size, resonance, and fixed compensation characteristics. Therefore, it does not provide a complete solution [4]. In order to solve these problems, the concept of APF was presented. Active power filters, which compensate harmonic and reactive current component for the power supplies, can improve the power qualities and improve the power factor on power utility. In recent 40 years from APF presented, the continual innovation of control strategies mainly impels the APF techniques to be developed rapidly.
In the active filter a controller determines the harmonics that are to be eliminated and generates appropriate gating signals for the inverter. Many harmonic detection techniques for active power filters have been studied. In frequency domain, Discrete Fourier Transform (DFT) and Fast Fourier Transform (FFT) have been widely used [5,6]. The main disadvantage of these techniques is the time delay associated with sampling and computation of Fourier coefficients, which makes them difficult for real-time application on dynamically varying load [7]. On the other hand, the time domain methods require less calculations and are widely

followed for computing the reference current. The time-domain methods include, instantaneous reactive power theory p-q method [1 and 7-11], Synchronous Reference Frame (SRF) [12, 13], Direct Testing and Calculating Method (DTCM) and Notch Filtering. This paper presents modeling and simulation of a direct testing and calculating control algorithm of active power filter using MATLAB Simulink. Direct testing and calculating control algorithm offers an advantage to compensate the harmonics generated through the load application [14]. The proposed scheme provides an additional feature over compensating harmonics only by compensating both harmonics and reactive power simultaneously.

2. SAPF Operating Principles

Many researches have been carried out to find the best performed control strategy for the shunt APF. However, before developing the controller, the basic concept of active filter control used in the design has to be defined. Operating principle of shunt APF depends on providing reactive power and harmonic components of load current. By this way, filter and load together behaves like a resistive load and only fundamental component of load current in phase with voltage is drawn from ac mains [15]. If the load current (I_L) is $i_p + i_q + i_h$ where i_p is the fundamental active component, i_q is the reactive component and i_h is the harmonic load current, then the SAPF should inject a negative current of amplitude ($i_q + i_h$) to obtain the active component i_p only, which is sinusoidal and in phase with the mains voltage. A description of the SAPF components as shown in Fig.1 is the voltage source inverter (VSI), the control unit, the modulation unit, the DC link is a capacitor (C) as storage energy, and the inductors (L_f). The control unit generates the reference currents of the shunt APF. The reference current signal (I_F) and the estimated current (I_s^*) are the inputs to the modulation unit to generate the gating signals for the VSI [16].

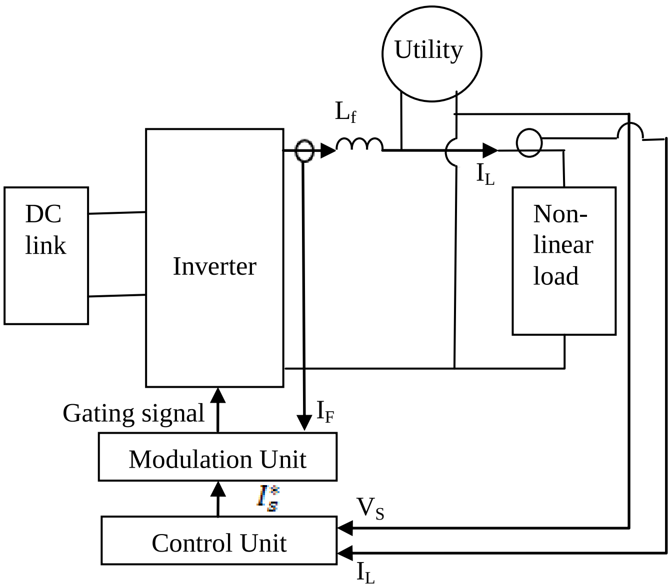

Fig. 1 Three-phase shunt APF

3. Proposed Method

The control strategies of the active filters are implemented mainly in three steps: Signal measuring, generating the reference signal and generation of gating signals for switching devices. The proposed method for generating the reference current signal is Direct Testing and Calculating Method (DTCM). Which is used widely in the signal processing in recent years. This reference current signal is fed to the hysteresis current control to have the PWM pulses. Fig. 2 Shows block diagram of the proposed system.

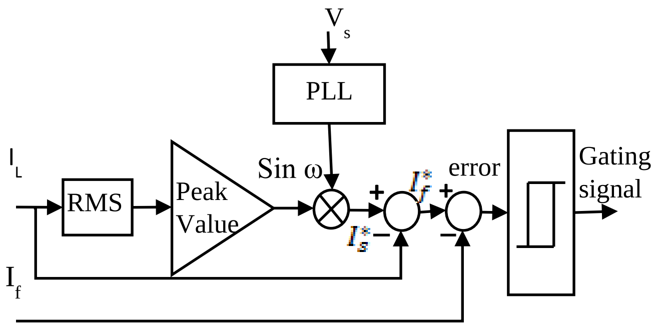

Fig. 2 Block diagram of the proposed system

The proposed scheme provides an additional feature over compensating harmonics only [14] by compensating both harmonics and reactive power simultaneously. The PLL generates a signal (ω) synchronized with the fundamental component of load current (I_{1rms}) [14]. The power factor (P.F) in this case is less than unity as explained in the following equations.

$$P.F = \frac{I_{1rms}}{I_{srms}} * \cos\alpha \tag{7}$$

Where $I_s^* = I_{1rms}$ $\quad , \alpha = \varphi$

$$P.F = \cos\varphi \tag{8}$$

Where α is phase shift angle of required source current (I_s^*) and in phase with load current. While in our case the power factor is equal to unity.

Where $I_s^* = I_{1rms}$ $\quad , \alpha = 0$

$$P.F = 1 \tag{9}$$

Where α is phase shift angle of required source current (I_s^*) and in phase with source voltage.

3.1 . Direct Testing and Calculating Method (DTCM)

The aim of reference current signal generator is to separate the harmonic and reactive components from the load current. The main characteristic of this method is the direct derivation of the compensating component from the load current, without the use of any reference frame transformation [17].

The block diagram of the direct testing and calculating method is shown in Fig. 3. In the circuit, the distorted load current (I_L) is filtered to extract the fundamental component by low pass filter (LPF) then multiplies by peak value to produce (I_M). PLL generates a signal (ω) synchronized with the source voltage (V_S). The calculated current signal (I_M) is synchronized with the respective source voltage (V_S) through the application of PLL. The output signal from PLL (ω) is then multiplied by the amplitude of the fundamental component to obtain the required source current (I_s^*). The calculated current (I_s^*) is subtracted from the load current (I_L) to have the required filter current I_f^* (Reference Current signal).

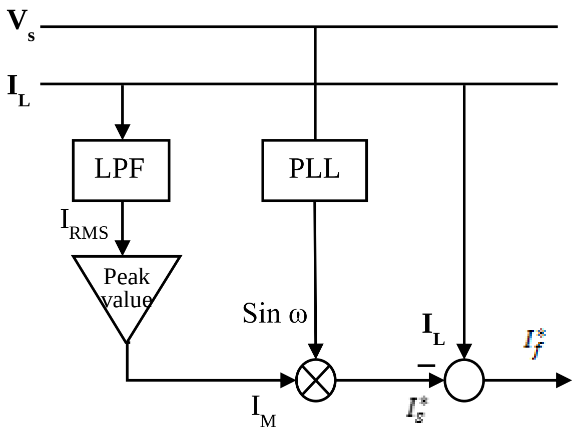

Fig. 3 Block diagram of the direct testing and calculating method

3.2. Hysteresis current control conclusion

The third stage of the shunt APF control circuit is generating appropriate gating signals for the power switches that forces the filter current (I_f) signal to follow its estimated reference current signal (I_f^*) within a certain tolerance band to reduce the current error. This control scheme is shown in Fig. 4. In this control scheme, a signal deviation (*H*) is designed and imposed on I_f^* to form the upper and lower limits of a hysteresis band. Hysteresis current controller with a fixed *H*. To obtain a compensation current (I_f) with switching ripples as small as possible, the value of *H* can be reduced. However, doing so results in higher switching frequency. Thus, increases losses on the switching transistors. The advantages of using the Current hysteresis control are its excellent dynamic performance and controllability of the peak-to-peak current ripple within a specified hysteresis [18].

Fig. 5 Shows the Gating signal generation by hysteresis current control technique. An error signal (e) is used to control the switches in an inverter. This error is the difference between the desired filter current (I_f) and its estimated reference current signal (I_f^*) as (e=ΔI= I_f - I_f^*). When the error reaches an upper limit as ΔI ≥ H/2, the transistors are switched to force the current down. When the error reaches a lower limit as ΔI ≤ -H/2, the current is forced to increase.

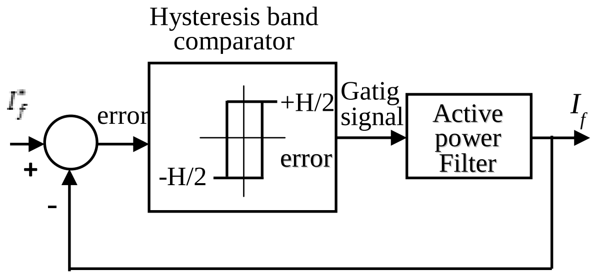

Fig. 4 Block diagram of current hysteresis control technique

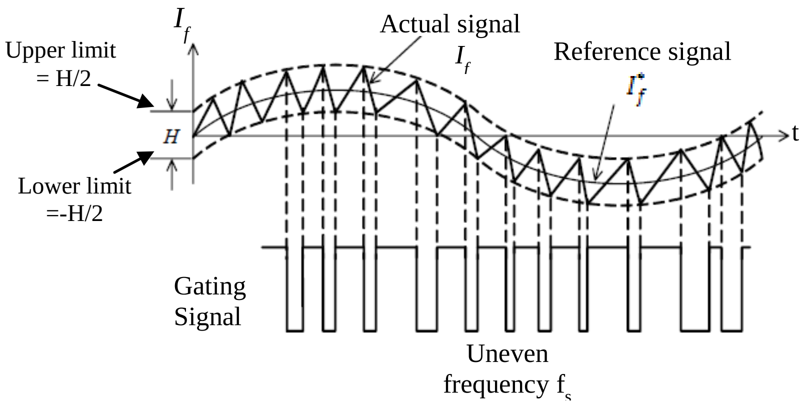

Fig. 5 Gating signal generation by hysteresis current control technique

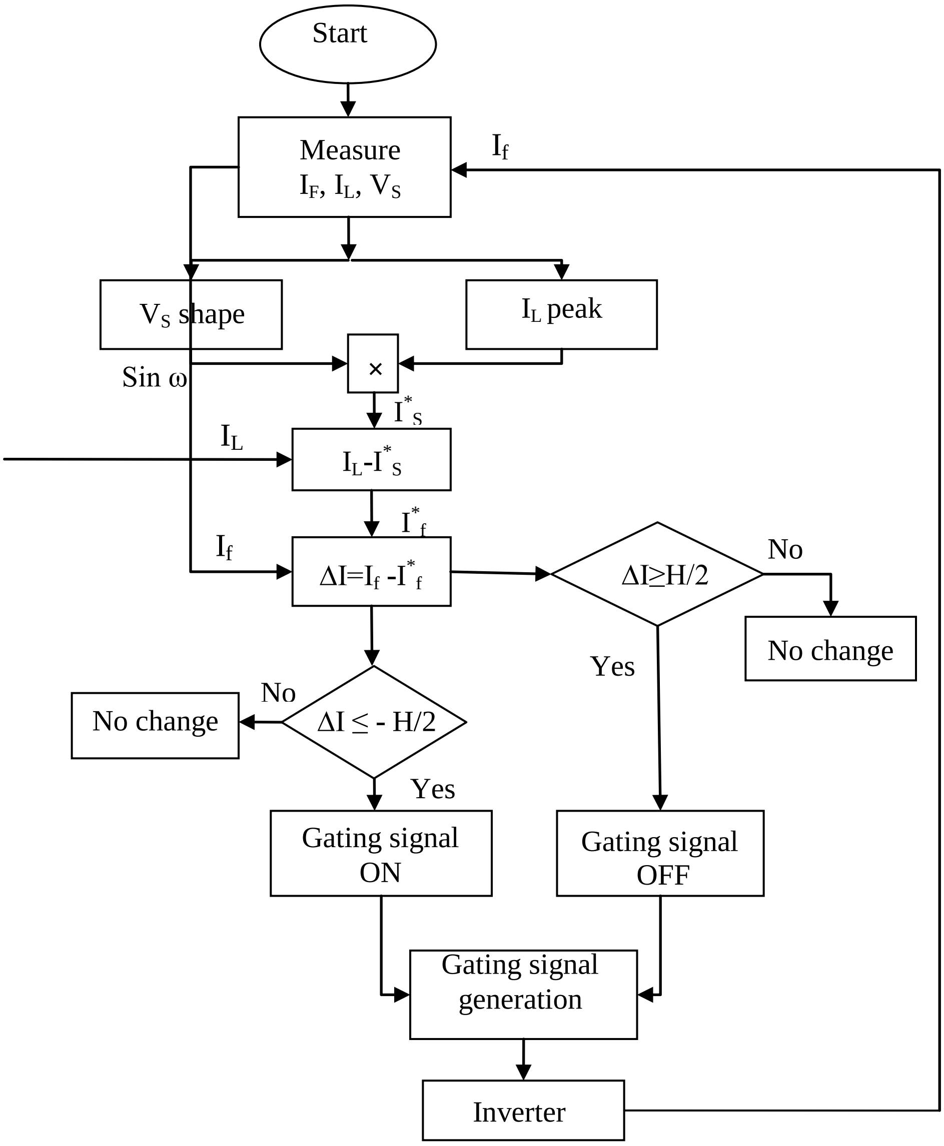

Fig. 6 Flow chart for the proposed control process

4. Simulation Results

The Matlab/Simulink simulation tool [19] used to develop a model that allow the simulation and testing of the DTC theory calculations Fig. 6 Shows Flow chart for the controller of the shunt active power filter. The flow chart procedures are described in steps:

a) Measured the variable parameters (I_F, I_L,V_S).

b) Extract the fundamental component of load current peak value (I_L peak) from the measured I_L.

c) Extract the shape of source voltage (V_S shape) from the measured V_S.

d) Generate the reference source current signal (I_s^*) by multiply the second and third steps.

e) Generate the reference filter current signal (I_f^*) by subtract the reference source current signal (I_s^*) from the load current signal (I_L).

f) Subtract the reference filter current signal (I_f^*) from the filter current signal (I_F) to obtain error signal (ΔI).

g) If the error signal (Δ) equal or greater than the half value of signal deviation (*H)* then the gating signal off will be obtained.

h) If the error signal (ΔI) don't equal or greater than the half value of signal deviation (*H*) then no change.

i) If the error signal (ΔI) equal or smaller than the negative half value of signal deviation (*H*) then the gating signal on will be obtained.

j) If the error signal (ΔI) don't equal or smaller than the negative half value of signal deviation (*H*) then no change.

k) The pulses generated through steps 7 and 9 will be obtained to delivered to the inverter switches and the steps will be repeated as well as the system under operation.

Shunt Active Filtering (SAF) operation has been simulated using the MATLAB/SIMULINK. The system parameters considered for the study of APF for DTCM controller with hysteresis current controller are given in Table 1

Table 1 APF System Parameters

System Parameters	Value
Line Voltage	380 V
Supply Frequency	50 HZ
Source Impedance:(Resistance Rs, Inductance Ls)	(1 Ω, 1mH)
Diode rectifier load resistance (R1, R2)	30 Ω, 15 Ω
Filter Impedance:(Resistance R_f, inductance L_f)	(1 Ω, 1mH)
Dc side capacitance	$250\mu F$

Fig. 7 shows the simulation results V_s, I_s and I_L of the system before compensation. Fig. 8 presents the simulation results after compensation. As seen I_s is sinusoidal and in phase with V_s. Fig. 9 shows simulation results for I_s harmonic spectrum before and after compensation. Before harmonic compensation the THD of the supply current was 15.71% and after the harmonic compensation, it was reduced to 3.37% which complies with the IEEE 519 harmonic standards [20]. The power factor is increase from 0.51 before compensation to 0.989 after compensation.

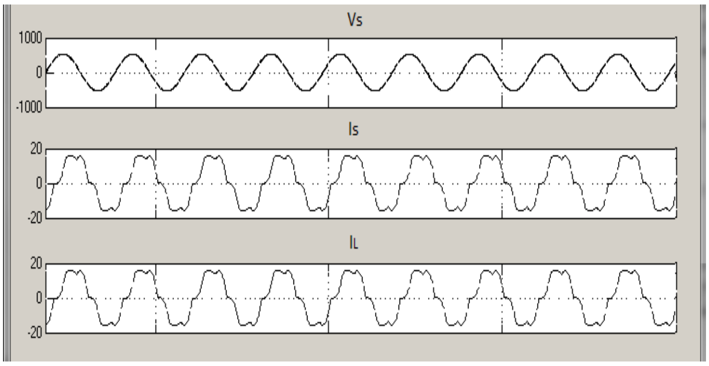

Fig. 7 simulation results for source voltage (V_s) , source current (I_s) and load current (I_L) before compensatin

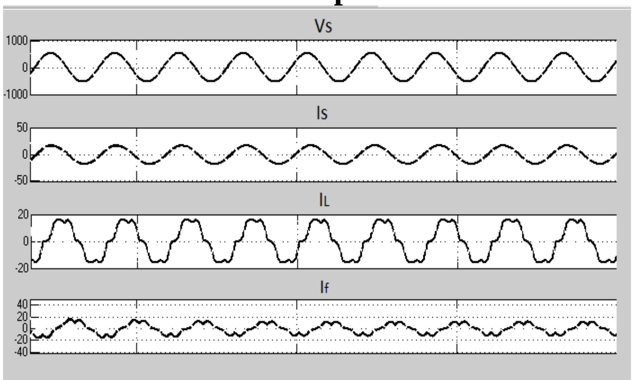

Fig. 8 waveforms of source voltage, source current, load current and filter current after compensating

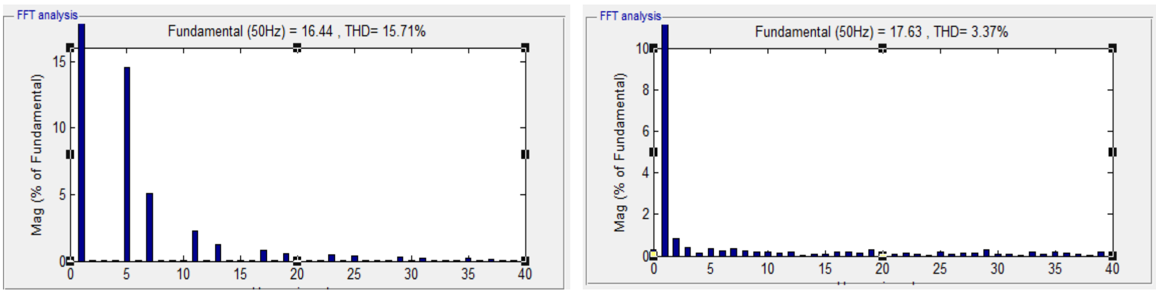

Fig. 9 (a) Input current harmonic spectrum before compensating (b) Input current harmonic spectrum after compensating

5. Conclusion

In this paper a direct testing and calculating (DTC) approach theory based three-phase shunt active power filter has been proposed. The simulating results demonstrate the validity of the proposed SAPF for compensating reactive power and current harmonic components to improve the power factor. The THD of the source current is reduced below the 5% limit imposed by IEEE STD. 519-1992 standard and the power factor close to unity for nonlinear load using the SAPF.

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