ISSN: 2582-8118 ***Volume 1, Issue 3; May 2021***

INTERNATIONAL JOURNAL OF RESEARCH AND ANALYSIS IN SCIENCE AND ENGINEERING

Web: https://www.iarj.in/index.php/ijrase/index

2. Power Quality Improvement Using Active Power Filter

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ABSTRACT

The active power filter produces equal but opposite harmonic currents to the point of connection with the nonlinear load. This results in a reduction of the original distortion and correction of the power factor. A three-phase insulated gate bipolar transistor based current controlled voltage source inverter with a dc bus capacitor is used as an active filter. The firing pulses to the shunt active filter will be generated by using sine PWM method. The models for three-phase active power filter controller for balanced and unbalanced non-linear load is made and is simulated using Matlab/Simulink software.

KEYWORDS

Active power filter, Harmonics, PWM

Introduction

Power electronic equipment usually introduces current harmonics. These current harmonics result in problems such as a low power factor, low efficiency, and power system voltage fluctuations and communications interference. Traditional solutions for these problems are based on passive filters due to their easy design, simple structure, low cost and high efficiency. These usually consist of a bank of tuned LC filters to suppress current harmonics generated by nonlinear loads. Passive filters have many disadvantages, such as resonance, large size, fixed compensation character and possible overload. To overcome these disadvantages, active power filters have been presented as a current-harmonic compensator for reducing the total harmonic distortion of the current and correcting the power factor of the input source .Fig. 3.1 shows the configuration of a three-phase active power filter. A personal computer (PC) based digital control is used to implement the control scheme.

The active power filter is connected in parallel with a nonlinear load. Its main power circuit is composed of a pulse-width- modulation (PWM) converter. The inductor L2 is used to perform the voltage boost operation in combination with the DC-link capacitor C2 and functions as a low pass filter for the line current of an active power filter.

The principle of operation of an active power filter is to generate compensating currents into the power system for canceling the current harmonics contained in the nonlinear load current. This will thus result in sinusoidal line currents and unity power factor in the input power system. At present, calculation of the magnitude of the compensating currents of an active power filter is based either on the instantaneous real and reactive powers of nonlinear loads or the integrative methods of Fourier analysis

Both these approaches neglect the delay time caused by low pass high pass filters when compensating current calculations. The method considered the instantaneous power delay caused by the current regulators and DC-link voltage feedback circuit and presented a load power estimation method to improve the dynamic response of input power regulations. In this paper, besides considering the current regulator delay and the DC-link voltage feedback delay, the low pass filter delay is also discussed. In addition, the design of the cutoff frequency for the low pass filter, current regulators and DC-link voltage regulator are also given. The control strategies of the active power filter focus on the controller design for both the line current regulators of the active power filter and the DC-link voltage regulator.

A simplified analytical model of the active power filter system is proposed. Using the derived analytical model, analyses of DC-link voltage response and current tracking capability for the active power filter will be easier. Applying the proposed control strategy, the current harmonics of a nonlinear load can be compensated quickly and the fluctuations of DC-link voltage during transient and steady states are effectively suppressed. The exclusive features of this paper are summarized as follows:

Active Power Filter Control

Introduction

The active power filter was a recently developed piece of equipment for simultaneously suppressing the current harmonics and compensating the reactive power. Fig 1 shows the configuration of a three-phase active power filter. A personal computer (PC) based digital control is used to implement the control scheme. The active power filter is connected in parallel with a nonlinear load. Its main power circuit is composed of a pulse-width modulation (PWM) converter.

The inductor is used to perform the voltage boost operation in combination with the DC-link capacitor and functions as a low pass filter for the line current of an active power filter. The principle of operation of an active power filter is to generate compensating currents into the power system for canceling the current harmonics contained in the nonlinear load current. This will thus result in sinusoidal line currents and unity power factor in the input power system.

Principle of Operation

The proposed three-phase active power filter consists of a power converter, a DC-link capacitor and a filter inductor. To eliminate current harmonic Components generated by nonlinear loads, the active power filter produces equal but opposite harmonic currents to the point of connection with the nonlinear load. This results in a reduction of the original distortion and correction of the power factor. For the sake of simplicity, in the calculation of reference currents and description of the control scheme, the reference frame transformation method will be used.

Compensating Current Calaulations

Consider Fig 1 where e_a, e_b, e_c and v_{af} , v_{bf}, v_{cf} represent the phase voltages of a power system and the input voltages of a power converter, i_{af} , i_{bf}, i_{cf} and v_{dc2} denote the input currents of the active power filter and the DC-link voltage, respectively.

Neglecting the reactors L_s of the input power system, the differential equations of the three-phase active Power filter in Fig.1 can be described as follows.

$$L_2 \frac{d}{dt} i_{af} = e_a - R_2 i_{af} - v_{af} \quad \text{....................} \quad (1)$$

$$L_2 \frac{d}{dt} i_{bf} = e_b - R_2 i_{bf} - v_{bf} \quad \text{....................} \quad (2)$$

$$L_2 \frac{d}{dt} i_{cf} = e_c - R_2 i_{cf} - v_{cf} \quad \text{...................} \quad (3)$$

$$C_2 \frac{d}{dt} v_{dc2} = f_a i_{af} + f_b i_{bf} + f_c i_{cf} \quad \text{.............} \quad (4)$$

Where C_2 is the capacitance of the DC-link capacitor, R_2 and L_2 are the resistance and inductance of the active power filter line reactors, respectively, f_a, f_b, f_c are Switching functions, and the possible values are $0, \pm\frac{1}{3}\, and \pm\frac{2}{3}$.

For model analysis and controller design, the three-phase voltages, currents and switching functions can be transformed to a *d*-*q*-*o* rotating frame. This yields,

$$\begin{bmatrix} x_d \\ x_q \\ x_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin\,\theta_e & \sin\left(\theta_e - \frac{2\pi}{3}\right) & \sin\left(\theta_e + \frac{2\pi}{3}\right) \\ \cos\,\theta_e & \cos\left(\theta_e - \frac{2\pi}{3}\right) & \cos\left(\theta_e + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad \text{.......(5)}$$

Where θ_e is the transformation angle of the rotating frame and x denotes currents, voltages or switching functions. From equations (3.1)-(3.5), the state model in the rotating frame can be written as.

$$L_2 \frac{d}{dt} i_{df} = e_d - R_2 i_{df} + \omega_e L_2 i_{qf} - v_{df} \quad .... \quad (6)$$

$$L_2 \frac{d}{dt} i_{qf} = e_q - R_2 i_{qf} - \omega_e L_2 i_{df} - v_{qf} \quad .... \quad (7)$$

$$C_2 \frac{d}{dt} v_{dc2} = \frac{3}{2} (f_d i_{df} + f_q i_{qf}) \quad .... \quad (8)$$

where

$$v_{df} = f_d v_{dc2} \quad .... \quad (9)$$

$$v_{qf} = f_q v_{dc2} \quad .... \quad (10)$$

ω_e Is the frequency of the power system and the subscripts 'd' and *'q'* are used to denote the components of the *d*- and *q*-axis in the rotating frame, respectively.

Equations will be used to derive the block diagram of the active power fitter and calculate the input voltage commands of power converter.

Let transformation angle θ_e be equal to the angle of phase voltage. Assume that the three-phase voltages are balanced. This yields the voltage components:

$e_d = V_m$ .... (11) $e_q = 0$ .... (12) Where V_m is the peak value of the phase voltage of the input power system? Under the above balanced three-phase voltage condition, the instantaneous real power p_L and reactive power q_L on the load side can be expressed as:

$$P_L = \frac{3}{2} V_m i_{dL} \text{.......... (13)} \quad q_L = 0 \text{......... (14)}$$

Equations. (13) And (14) are suitable for both balanced and unbalanced loads. When the phase voltages of power system are balanced, p_L and q_L depend only on i_{dL} and i_{qL}, respectively. For a fully harmonic-current compensated active power filter system, the instantaneous real power p_s and reactive power q_s from the power system can be expressed as:

$$Ps = \frac{3}{2} V_m i_1 \quad .... \quad (15) \qquad q_s = 0 \quad .... \quad (16)$$

Where the fundamental component of the load current i_1 can be obtained from the *d*-axis current i_{dL} by means of a low pass filter.

The corresponding reference currents, i_{df}^* and i_{qf}^* of the active power filter in the rotating filter are.

$i^*_{df} = i_1 - i_{dl}$ .... (17) $i^*_{qf} = -i_{ql}$ .... (18)

Equations (17) and (18) are obtained from the proposed novel calculation method for reference currents of the active power filter by using the load current feedback, reference frame transformation and a digital low pass filter. It is noted that the reference currents can be obtained simply by subtracting the fundamental component from the measured load currents regardless of whether the load is balanced or not.

Power Converter Control

To reduce the DC-link capacitor fluctuation voltages and compensate the system loss, a proportional-integral controller $G_{DC}(S)$ is used in the DC-link voltage control loop. As a result, the d-axis reference current of the active power filter has to be modified to:

$$I^*_{df} = I_1 - I_{dl} + I_{dc} \quad .... \quad (19)$$

$$I_{dc} = G_{dc}(s)\left(V^*_{dc2} - V^{'}_{dc2}\right) \quad .... \quad (20)$$

Where I_{dc} is the current command of the DC-link voltage regulator, V^*_{dc2} and $V^{'}_{dc2}$ are the command and feedback of the DC-link voltage, respectively. The variables in capitals represent the Laplace transforms of the corresponding variables in the time domain. The block diagram of *d*-and *q*-axis reference currents of an active power filter are shown in Fig. 3.2, where the voltage detection represents the Dclink voltage detecting circuits.

The input voltage commands, V^*_{df} and V^*_{qf} of the power converter can be obtained by using equations. This yields:

$$V^*_{df} = V_m - R_2 I_{df} + \omega_e L_2 I_{qf} - U_{df} \,..........(21)$$

$$V^*_{qf} = -R_2 I_{qf} - \omega_e L_2 I_{df} - U_{qf} \,...............(22)$$

Where U_{df} and U_{qf} are the voltage commands of current regulators of an active power filter.

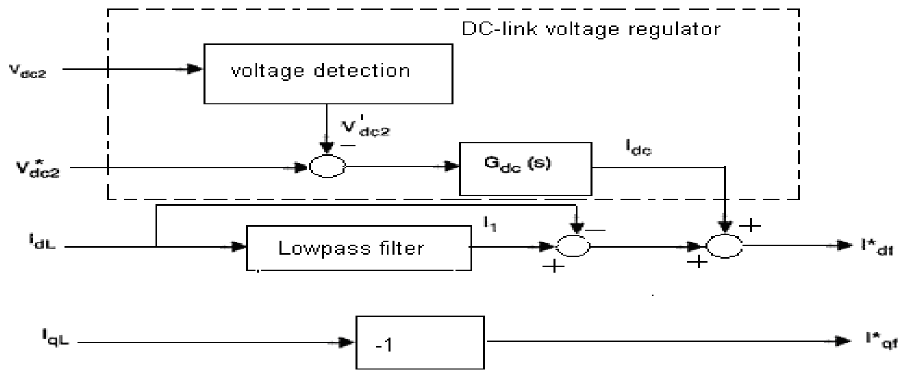


Fig. 2 Block diagram of d- and q-axis reference current of active power filter.

It is seen from equations. (21) And (22) that the cross coupling terms $\omega_e L_2 I_{df}$, and $\omega_e L_2 I_{qf}$ exist in the *d-q* current control loops. To decouple the *d-q* current loops and simplify the control scheme, the voltage de couplers can be designed as follows:

$$U_{df} = G_{df}(s)(I^*_{df} - I_{df}) \ldots\ldots\ldots\ldots\ldots \quad (23)$$
$$U_{qf} = G_{qf}(s)(I^*_{qf} - I_{qf}) \ldots\ldots\ldots\ldots\ldots\ldots \quad (24)$$

Where G_{df} and G_{qf} are the proportional-integral controllers' gain of *d-* and *q*-axis current control loops of the active power filter, respectively.

The block diagram of the *d-q* current control loops can be derived from equations. As shown in Fig.3 Applying the inverse transformation of the rotating frame, the three-phase input voltage commands and of the power converter can be obtained as

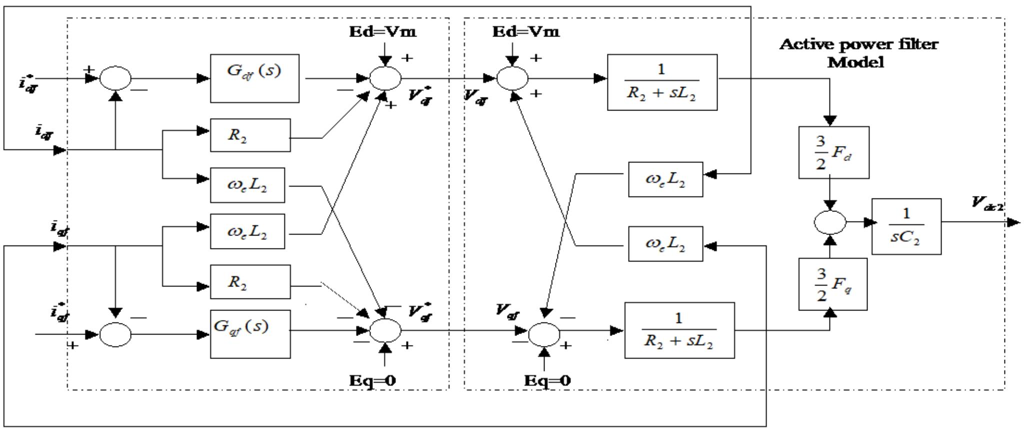


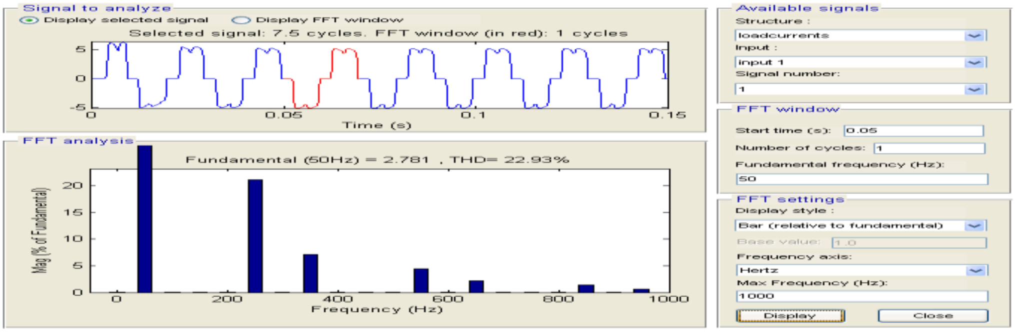
Fig.3 Control block diagram of d- and q- axis current controllers of active Power filter.

$$\begin{bmatrix} v^*_{af} \\ v^*_{bf} \\ v^*_{cf} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\ \theta_e & \cos\ \theta_e & 1 \\ \sin(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e - \frac{2\pi}{3}) & 1 \\ \sin(\theta_e + \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} v^*_{df} \\ v^*_{qf} \\ 0 \end{bmatrix} \ldots.(25)$$

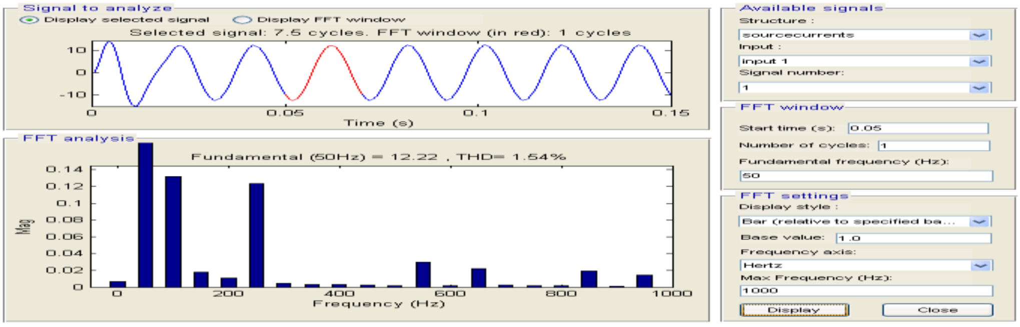
The output for three-phase input voltage commands V^*_{af}, V^*_{bf} and V^*_{cf} can be_obtained through the input/output (*o/p*) interfaces of a personal computer.

These commands are then compared with a 10 kHz triangular-wave carrier to produce the switching pattern for the IGBT devices.

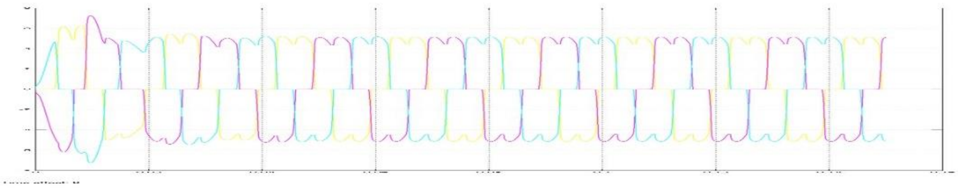
Simulation Results



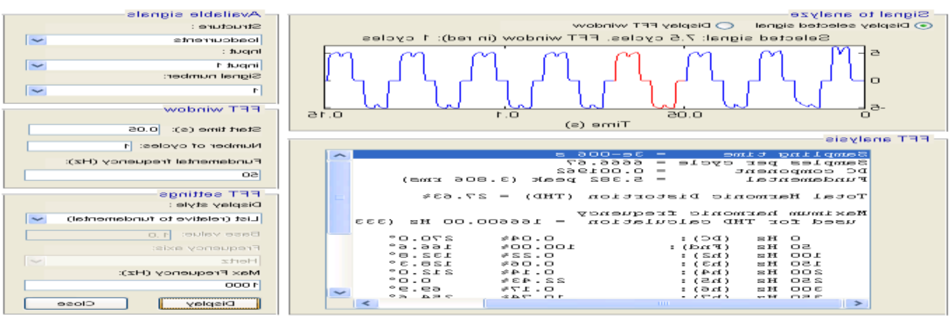
fet analysis for load currents without apfc:



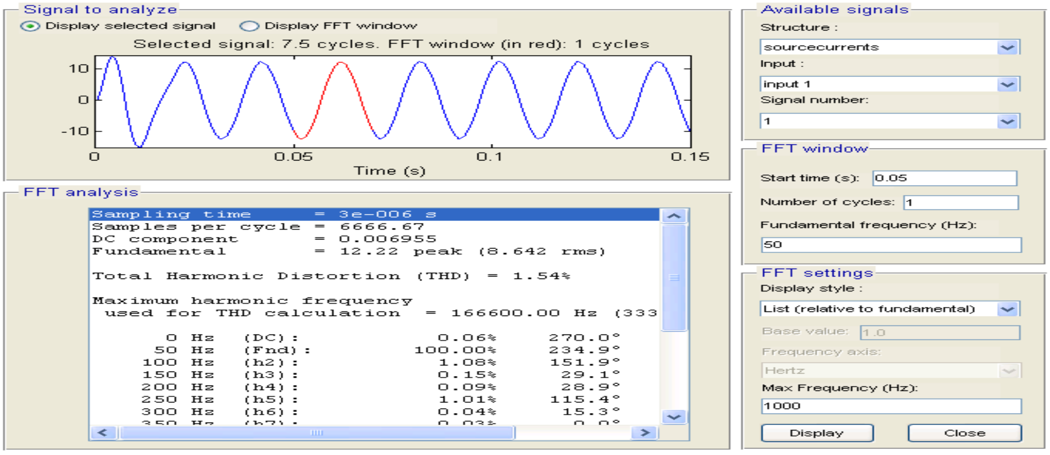
thd calculation for source current



Waveform for source current with apfc



thd calculation for load current



thd calculation for source current

Total Harmonic Distortion (thd)

The Total Harmonic Distortion (THD) in the source current of the proposed three phase system of nonlinear balanced and unbalanced load with and without active power filter controller.

Similarly, from section 5.1 the Harmonic order and Total Harmonic Distortion (THD) in the source current of three phase system connected to unbalanced nonlinear load (Diode bridge rectifier) with ActivePower Filter Controller. Then the corresponding Harmonic order as follows

thd	without apfc	with apfc
initial	22.93	22.93
final	22.93	1.54

Results

Results for following four cases of three-phase power system connected to non-linear load. For the design of active power filter controller, the proposed tree phase system parameter uses as follows.

Peak value of the phase voltage (V_m) = 98 V., Frequency of the power system (ω_e) = 377 rad/sec., DC-link voltage (V_{dc2}) = 240 V., Resistance and inductance of the line (R_1, L_1) =3.1 mH, 0.03 Ω

Resistance and capacitor of the nonlinear load (R_0, C_0) =8.67Ω, 3300μF DC-link capacitor (C_2) = 4700 μF

Resistance and inductance of the active power filter (R_2, L_2) =0.03 Ω, 5 m., DC-link voltage (v_{dc2}) = 240

Conclusion

The active power filter controller has become the most important technique for reduction of current harmonics in electric power distribution system.

In this project a model for three-phase active power filter for balanced non-linear load is made and simulated using Matlab/Simulink software for the reduction harmonics in source current.

The simulation result indicates that the total harmonic distortion (THD) of the current reduced from 0.1725 without active power filter to 0.0726 with active power filter for balanced nonlinear load and 0.3577 without active power filter to 0.1912 with active power filter for unbalanced nonlinear load and the power factor improved .

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