Three-phase Active Power Filter with Integrator-Proportional control

Mustapha Sarra, Kamal Djazia, Abdelmadjid Chaoui and Fateh Krim

Abstract- This paper presents the simulation study of novel IP (Integrator Proportional) controlled DC bus voltage of three phase shunt active power filter (APF), to improve power quality by compensating harmonics and reactive power required by nonlinear load. The compensation process is based on sensing mains currents only, an approach different from conventional methods, which require harmonics or reactive volt-ampere values of the load. PWM signal generation is based on hysteresis control comparators to obtain the switching signals. The control system of APF is implemented using a dSPACE system. Various simulation and experimental results are presented under steady state and transient conditions.

Index Terms- Harmonics, Three phase APF, IP controller, hysteresis control.

I. INTRODUCTION

In recent years, the widespread applications of nonlinear loads the harmonic-related problems in utility and industrial power systems. The compensation for harmonic and reactive increased currents becomes increasingly important owing to the wide use of power electronic equipment. Traditionally passive LC filters have been used to eliminate line current harmonics and to improve the load power factor. However, in practical applications these passive second order filters present many disadvantages such as aging and tuning problems, series and parallel resonance, and the requirement to implement one filter per frequency harmonics that needs to be eliminated. In order to overcome these problems, different kinds of active power filters, based on force-commutated devices, have been researched and developed [1] [2]. In recent years, shunt active power filters based on current controlled PWM converters have been widely investigated and organized as viable solutions. However, most of them are based on sensing harmonics [3] and reactive volt-ampere requirements of non linear load [4] [6], and require complex control. Duke and Round [7] have proposed a scheme, in which the required compensating current is determined using a simple synthetic sinusoid generation technique by sensing the load current.

This scheme is further modified by sensing line current only [8], which is simple and easy to implement.

In this paper, the control scheme is based on sensing line currents only, an approach different from conventional ones, which are based on sensing harmonics and reactive volt-amperes requirements of the nonlinear load. The three phase current/voltages are detected using only two current/voltages sensors. The IP controller is used for the generation of a reference current template. The IP controller is studied in order to give better performances in time response and system stability, compared to PI one. The DC capacitor voltage is regulated to estimate the reference current template. The hysteresis for mains current to generate PWM signals is due to its simplicity and its intrinsic speed. In simulation mode, the sinusoidal shape of mains voltage does not affect the results and the THD. Detailed simulation and experimental results on the developed APF systems are given and discussed, to demonstrate their ability for harmonic elimination and reactive power compensation.

II. SYSTEM CONFIGURATION AND BASIC COMPENSATION PRINCIPLE

The basic compensation principle of a shunt active power filter is shown in Fig.1. It is controlled to draw/supply a compensating current \( i_c \) from/to the utility, so that it cancels current harmonics on AC side, and makes the source current in phase with the different waveforms. The current drawn from the power system at the coupling point of the shunt APF will result sinusoidal as shown in Fig.2.

A.

Fig.1. Basic compensation principle of the shunt APF.

Fig.2. Non-linear load, compensation and source current waveforms
A. Current Supplied By the Active Filter

The source voltage is given by

\[ v_s(t) = V_m \sin(\omega t) \]  

Source current can be written as

\[ i_s(t) = i_L(t) - i_c(t) \]  

Where \( i_L(t) \) and \( i_c(t) \) are the load and filter current respectively.

The load current will have a fundamental and harmonics components which can be written as

\[ i_L(t) = \sum_{n=1}^{\infty} \sin(n\omega t + \phi_n) \]

\[ i_c(t) = I_L \cos(\phi_c) + I_L \sin(\phi_c) \]

Where \( I_L \)-cos\( (\phi_c) \) and \( I_L \)-sin\( (\phi_c) \)

The instantaneous load power can be given as

\[ P_L(t) = v_s(t) \times i_L(t) \]

\[ + V_m \sin(\omega t) \sum_{n=2}^{\infty} \sin(n\omega t + \phi_n) \]

\[ = P_f(t) + P_r(t) + P_h(t) \]

From (5), the real (fundamental) power drawn by the load is:

\[ P_f(t) = V_m I_L \sin^2(\omega t) = v_s(t) \times i_L(t) \]

From (7), the source current supplied by the source after compensation, is:

\[ i_s(t) = P_f(t)/v_s(t) = I_L \sin(\omega t) = I_m \sin(\omega t) \]

Where \( I_m = I_L \cos(\phi_c) \)

B. Role of DC side capacitor

The DC side capacitor serves two main purposes: it maintains a DC voltage with small ripple in steady state, and it serves as an energy storage element to supply a 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 demands of the load plus a small power to compensate the losses in the active filter. Thus, the DC capacitor voltage can be maintained at a reference value.

However, when the load condition changes the real power balance between the mains 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 satisfactory operation of the active filter, the peak value of the reference current must be adjusted to proportionally change the real power drawn from the source. This real power charged/discharged by the capacitor compensates 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 be equal to that consumed by the load again.

Thus, in this fashion the peak value of the reference source current can be obtained by regulating the average voltage of the DC capacitor. A smaller DC capacitor voltage than the reference voltage means that the real power supplied by the source is not enough to supply the load demand. Therefore, the source current needs to be increased, while a larger DC capacitor voltage than the reference voltage tries to decrease the reference source current. This change in capacitor voltage has been verified from the simulation results.[9]

C. Basic relation between DC bus capacitor voltage \((V_d)\) and mains current \((I_s)\)

The compensation current \(i_c(t)\) is provided by the bilateral converter. The DC source comes from the energy-storage capacitor, as it provides only the reactive power to the load. However, owing to the switching loss of the converter, the utility must supply a small overhead for the capacitor leakage and converter switching losses in addition to the real power of the load. The total peak current supplied by the source is therefore:

\[ I_{SP} = I_m + I_L \]

If the active filter provides the total reactive and harmonic power, \(i_c(t)\) will be in phase with utility voltage and purely sinusoidal. At this time, the active filter must provide the following compensation current:

\[ i_c(t) = I_c(t) + i_c(t) \]

Hence, for accurate and instantaneous compensation reactive and harmonic power it is necessary to estimate the fundamental component of the load current as reference current.

\[ E_{cr} = \frac{1}{2} C V_d^2 \]

While the instantaneous energy in the capacitor is:

\[ E_C(t) = \frac{1}{2} C V_d^2 \]

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Therefore, the energy loss of the capacitor in one period will be:

\[ \Delta E_c(t) = E_{cr} - E_c(t) = \frac{C}{2} \left( V_{dr}^2 - V_d^2(t) \right) \]

Assuming that \[ V_{dr} + V_d(t) = 2V_{dr} \]

\[ \Delta E_c(t) = CV_d\{V_{dr} - V_d(t)\} = KI\{V_{dr} - V_d(t)\} \]  

Since this energy loss must be supplied by the utility voltage source, the peak value of the charging current \( I_{sc} \) can be estimated as follows:

\[ I_{sc} = - \frac{2}{TV_{sm}} \Delta E_c = K2 \Delta E_c \]  

Where \( K2 = 2 / TV_{sm} \)

The peak value of the charging current \( I_{sc} \) can be obtained as in the following:

\[ I_{sc} = K2 \Delta E_c = K2K1 \{V_{dr} - V_d(t)\} \]  

Hence,

\[ I_{sc} = K2 \Delta E_c = \frac{2CV_d}{TV_{sm}} \{V_{dr} - V_d(t)\} \]  

Equation (16) reveals that the average voltage of the DC capacitor can be controlled by adjusting the amplitude of the supply current.

As a result, the total peak current provided by the voltage source is:

\[ I_{sm} = I_s + I_{sc} \]

By multiplying \( I_{sm} \) with \( \sin (\omega t) \), it is possible to obtain the reference source current:

\[ I_{s*}(t) = I_{sm} \sin \omega t \]  

The above theory is exploited in this work in order to control the amplitude of the reference sinusoidal supply current on-line every voltage cycle, which in turn controls the DC voltage.

III. PROPOSED CONTROL SCHEME

Fig.3 shows the block diagram of the proposed control scheme of a shunt active power filter. In order to implement the control algorithm in closed loop, the DC side capacitor voltage is sensed and then compared with a reference value. The obtained error \( \varepsilon = V_{dr} - V_d \) at the \( n \)th sampling instant is used as input for IP controller.

After a limiter block, the output is considered as the amplitude of the reference current \( I_{max} \). This current \( I_{max} \) takes care of the active power demand of the load and the losses in the system. The switching signals for the PWM converter are obtained by comparing the actual source current (\( i_{sa}, i_{sb} \) and \( i_{sc} \)) with the reference current templates (\( i_{s*sa}, i_{s*sb} \) and \( i_{s*sc} \)) in the hysteresis current controller.

A. DC Voltage IP controller

To reduce the DC-link capacitor fluctuation voltages and compensate the system loss, an integral-proportional controller \( G_{IP}(s) \) is used in the DC-link voltage control loop. \( G_{vsi} \) is the PWM voltage source inverter (VSI) transfer function.

At high operating switching frequency, the inner current control must be much faster, which means that the current \( I_s \) follows \( I_{s*} \). Hence, we can assume that a closed loop current controller transfer function will be equal to unity.

\[ G_{i}(s) = \frac{I_{s*}}{I_s} = 1 \]

Therefore, the choice of IP parameters \( (K_i, K_p) \) is based on step response of the closed loop shown in Fig.4.

\[ \frac{V_d}{V_0} = \frac{K_p}{C \cdot \sigma + K_p} \]  

Then,

\[ \frac{V_d}{V_{dr}} = \frac{K_pK_i / C}{C \cdot \sigma + K_pK_i / C} \]  

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From (19) the relation between $V_d$ and $V_{dr}$ has a form of a second order transfer function:

$$\frac{V_d}{V_{dr}} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$  \hspace{1cm} (20)

Where $\omega_n$ is natural frequency and $\xi$ is damping coefficient. The TF contain two poles and does not possess a zero, this proves that the IP controller insures a fast response and good stability for transient states comparing to the PI one.

By equaling (19) and (20):

$$\frac{k_k}{c} = \omega_n^2 \quad \text{and} \quad \frac{k_i}{c} = 2\xi\omega_n$$

Hence,

$$k_k = 2\xi\omega_n c \quad \text{and} \quad k_i = \omega_n / 2\xi$$

IV. MODELLING AND SIMULATION OF THE SYSTEM

To simulate the IP controlled shunt active power filter, a model in Matlab/Simulink™ and SimPowerSystems Blockset is developed. Fig.9 shows the simulation block diagram. The complete active filter system is composed mainly of a three-phase source, a nonlinear load, a PWM voltage source inverter, and an IP controller.

The parameters used for simulation are: $V_S = 100$ V (rms), $R_S = 0.1 \ \Omega$, $L_S = 0.15 \ \text{mH}$, $R_C = 0.01 \ \Omega$, $L_C = 0.66 \ \text{mH}$, $R_{L1} = 6.7 \ \Omega$ and $L_{L2} = 13.4 \ \Omega$, $L_{L1} = 20 \ \text{mH}$, $V_{dc} = 220$ V, $C = 2000 \ \mu F$, $K_i = 0.27$ and $K_p = 9.32$.

To study the performance of the APF, first simulation is done on fixed load ($R_{L1}$ & $L_{L1}$) and the filter is switched on at 0.05s. Simulation results are presented in Fig.6.

We see that before the connection of the APF, the capacitor was been charged initially at 120V and the mains current has a same waveform of the load current. At 0.15s, the APF is connected. So, the $V_d$ voltage stepped to reach the $V_{dr}$ with $\xi = 0.707$ imposed previously to estimate IP parameters, mains current will be sinusoidal and exactly in phase with source voltage.

Still in Fig.7 a-b; a spectrum analysis shows that IS current which contained harmonics and a THDi = 27.26%, will have one specter at fundamental frequency, all harmonics disappear and the THDi = 0.34%.

To prove the dynamical response of the controller at a transient condition, the DC side resistance is changed from $R_{L1}$ to $R_{L2}$ at 0.17s and then from $R_{L2}$ to $R_{L1}$ at 0.33s. It is clear from simulation results in Fig.10 that we obtain good transient performance of the source current, DC side capacitor voltage for the IP controller and the mains current maintains its sinusoidal waveform.
V. EXPERIMENTAL RESULTS

The IP controlled shunt active power filter Simulink model is implemented using a dSPACE system [12]-[20] that allows to implement a real-time controller directly in Matlab/Simulink™ environment [21]. The Simulink file is automatically converted in a C-code file by the Real Time Workshop (RTW) of dSPACE system. The C-code file becomes source for the Real-Time Interface (RTI) of dSPACE system, which, with the help of a C compiler/Linker, produces and downloads the machine code in the controller board (DS 1104 R&D).

When the application is running on the real-time hardware, the control over each individual variable (K_p, K_i, L_c, R_L, L_L...) is possible using the experiment software :controldesk shown in Fig.10.

Fig.11 shows the experiment results. The mains current has a sinusoidal waveform and is in phase with the source voltage, hence, both harmonics and reactive power are compensated simultaneously.

Fig.8 Load perturbation response of IP controlled shunt APF

Fig.9 General view of experimentation.

Fig.10 Controldesk.

(a)

(b)

(c)

(d)

Fig.11 Experiment shunt APF results : (a) mains current, (b) non-linear current, (c) compensation current, (d) DC side capacitor voltage.
VI. CONCLUSION

This paper proposes a new IP controlled shunt APF with only source current measurement. The proposed technique has been studied to improve the power quality by compensating both harmonics and reactive power requirement of the nonlinear load. The performance of the IP controller has been studied in simulation and has been developed in real time process with dSPACE system and successfully tested in the laboratory to verify the simulation results. It is clear from simulation and experimental results that the compensation process is simple. The strategy control gave a very high factor power and small ripple in current line supply.

VII. REFERENCES

[12] dSPACE Release New features and migration
[18] DS1104 R&D Controller Board Hardware Installation and Configuration