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A Novel Three-Phase Active Power Filter

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Abstract – *The performance and dynamic characteristics of a three-phase three-wired active power filter is proposed and analysed. In this paper both sliding mode (SLMC) and proportional-integral (PI) control algorithms are used. The SLMC controller regulates the external DC voltage control-loop that keeps the voltage across the DC capacitor constant, while the PI controller deals with the internal current control-loop for harmonic current suppression. The reactive power compensation is achieved without sensing or computing the reactive current of the load. Current harmonic compensation is implemented in the time domain allowing a fast time response. This proposed scheme employed the shunt APF topology together with the three-phase PWM voltage-source inverter. The principles of operation of the proposed three-phase active power filter along with the control circuit components are discussed in detail. The performance of this system has been assessed, using pspice simulator and the encouraging results are given in the full paper.*

Résumé – *L'étude des performances et des caractéristiques dynamiques d'un filtre de puissance actif a trois phases et trois câbles sont proposées. Deux algorithmes de contrôle sont utilises, sliding mode (SLMC) et proportionnel intégral (PI). En effet, les deux algorithmes de contrôle sont complémentaires ainsi ils sont utilises pour l'asservissement de la boucle de contrôle. Alors, pour la régulation de la tension DC externe sliding mode contrôleur (SLMC) est utilise, la technique permet de maintenir une tension constante au borne du condensateur ; tendis que le contrôleur PI agit sur le courant interne, la méthode permet de filtrer les harmoniques du courent. La compensation de la puissance réactive est assurer sans mesure ou calcule du courant réactif de la charge. La compensation des harmoniques du courant est implémentée comme une fonction du temps pour assurer un temps de réponse rapide. Dans le modèle propose la topologie shunt APF et l'inverseur tension source PWM a trois phases sont uligineuses. Le principe de fonctionnement du filtre de puissance actif a trois phases en combinaison avec le circuit de contrôle sont pressentes en détails. La performance de ce système a été évaluée, on employant l'émulateur Pspice, des résultats encourageant on été obtenus et pressentes ci-dessous.*

Keywords: Three phase – Power filter – Sliding mode controller – PI controller – PWM.

1. INTRODUCTION

Over the recent years, power quality has been given attention due to the intensively use of power electronic controlled applications in all branches of industry, such as controlling or converting AC power to feed electrical loads. As a result, harmonics were generated from the power converters or non-linear loads that caused the power system operate with low power factor, low efficiency, voltage and current distortions, and increased losses in transmission and distribution lines. Conventionally, passive LC filters have been employed to eliminate line-current harmonics and to improve the power factor. However, the harmonic problem still persists because of its inability to compensate random frequency variations in currents, tuning problems and parallel resonance. Therefore, the alternative method is by active power filters (APFs). The research and development of various APF configurations with their respective control strategies have been proposed, and have been gradually recognised as a viable solution to the problems created by high-power non-linear loads [1-4]. Active filters have been divided into AC and DC filters, DC filters compensate for voltage and current harmonics on the DC side of the converters for HVDC systems and on the DC link of a PWM inverter for traction systems [1]. However, this paper emphasises on active AC filters because most active filters are often referred to as active AC filters and it's based on shunt APF with VSI-PWM configuration. The reactive power compensation presented in this proposed APF system is achieved without the need of sensing the reactive current component of the load and the current compensation is done in the time domain allowing fast time response. Further more, the current control is achieved with constant switching frequency, producing a better switching pattern than the hysteresis current control [5-6]. This reduces the high-frequency current harmonics of the DC capacitor voltage.

The aforementioned non-linear loads have led to the concerns over the allowable amounts of harmonic distortion injected into the supply system. Standards such as IEEE-519 have emerged to set and impose limits and recommended practices so that the harmonic distortion levels are kept in check, thereby promoting better practices in the design and operation of power system and electric equipment [7]. Based on observations from various references, a practical limit of less than 5% of the total harmonic distortion (THD) must be employed by any system designers and/or end-users to ensure compliance with the established standards [1,7].

2. DESCRIPTION OF PROPOSED APF

The basic principle of a shunt active power filter is shown in Figure 1 as

$$I_C = I_S - I_L \tag{1}$$

where I_C is the compensation input current, I_S is the source current and I_L is the load current, respectively. The main feature of the active power filter is that the supply current is forced to be sinusoidal and in phase with the supply voltage regardless of the characteristics of the load. Therefore, the shunt APF is harmonics cancellation and reactive power compensation by injecting equal but opposite harmonic and reactive currents into the supply line by means of solid-state amplifier circuits.

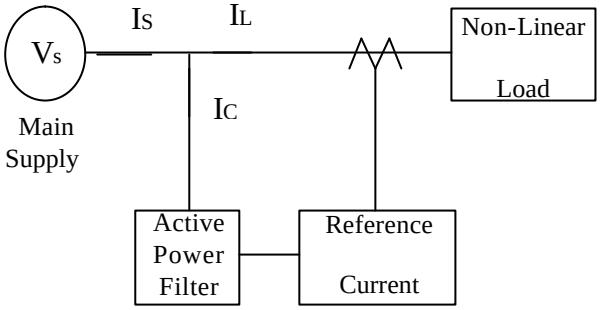

Fig. 1: Basic shunt active power filter block diagram.

The three-phase active power filter shown in Figure 2 may be described as a PWM synchronous rectifier that is connected to a DC busbar. It consists of six power switches in a single three-phase full-bridge configuration, with anti-parallel diodes connected to each switch to provide a mechanism for bi-directional flow of compensation current to be either absorbed from or injected into the supply system. The purpose of the filter inductor, L is to regulate the maximum allowable magnitude ripple current flow into the APF, by means of closed-loop control. A proper design of the controller has to be established in order to actively shape the supply current to a sinusoid wave-shape.

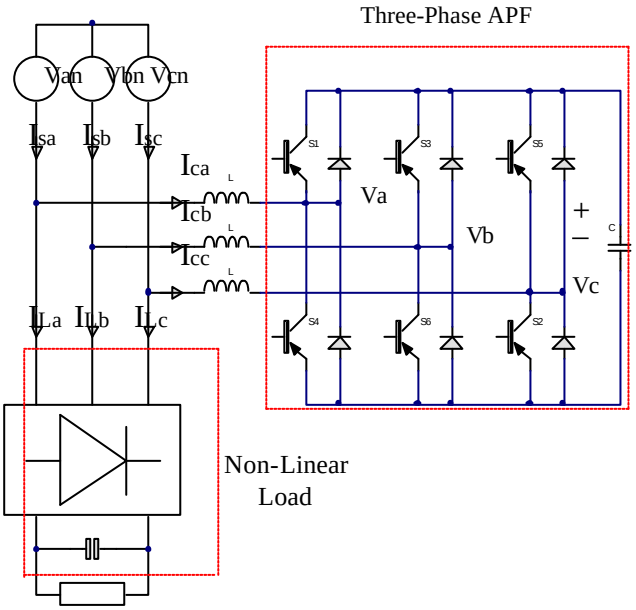

Fig. 2: Proposed three-phase APF configuration.

3. THREE-PHASE APF SYSTEM ANALYSIS

To simplify the system analysis, the power switches are assumed to be ideal. For a balance three-phase system without a neutral line, the sum of the instantaneous three-phase voltages and currents is zero:

$$I_{sa} + I_{sb} + I_{sc} = 0 \tag{2}$$

$$V_{an} + V_{bn} + V_{cn} = 0 \tag{3}$$

where,

$$V_{an} = V_m \sin(w_s t) \tag{4}$$

$$V_{bn} = V_m \sin(w_s t - 2p/3) \tag{5}$$

$$V_{cn} = V_m \sin(w_s t + 2p/3) \tag{6}$$

V_m and w_s are the maximum phase voltage and angular frequency of the power source, respectively. The circuit equations on the AC side are expressed as:

$$V_{an} = L\frac{dI_{ca}}{dt} + V_a \tag{7}$$

$$V_{bn} = L\frac{dI_{cb}}{dt} + V_b \tag{8}$$

$$V_{cn} = L\frac{dI_{cc}}{dt} + V_c \tag{9}$$

where I_{ca}, I_{cb} and I_{cc} are the compensated input currents and V_a, V_b and V_c are the voltages generated from the PWM rectifier bridge. From equation 1, the supply currents I_{sa}, I_{sb} and I_{sc} are the summations of the load currents and the compensated currents of each phase as below:

$$I_{sa} = I_{ca} + I_{La} \tag{10}$$

$$I_{sb} = I_{cb} + I_{Lb} \tag{11}$$

$$I_{sc} = I_{cc} + I_{Lc} \tag{12}$$

where I_{La}, I_{Lb} and I_{Lc} are the load currents of each phase.

4. CONTROL STRATEGY OF THE PROPOSED APF SYSTEM

The Time Domain Harmonic Detection Strategy of the supply current is utilised in this proposed three-phase APF system. Generally, there are two control loops, voltage control loop (VCL) and current control loop (CCL).

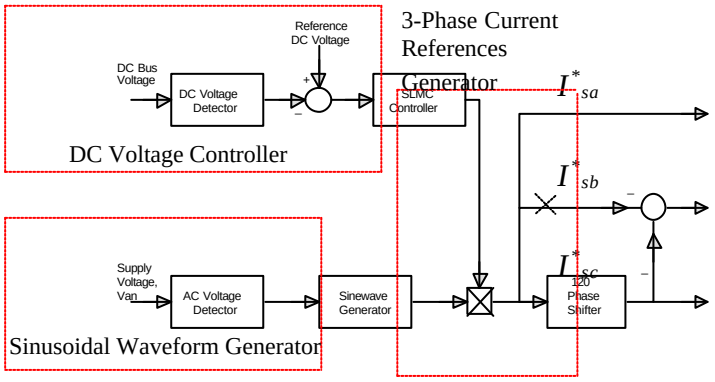

Fig. 3: Block diagram of voltage control loop.

In this work, the sliding-mode controller (SLMC) is employed to tune-up the VCL and the proportional-integral (PI) controller is used to regulate the CCL. The control block diagrams of the time domain harmonic injection system are shown in Figure 3 and 4.

The proposed scheme is mainly composed of a DC-voltage controller and a three-phase sinusoidal wave- form generator, as shown on Figure 3. In this circuit, the detected DC-capacitor voltage is subtracted from the reference DC voltage and its error is fed into the sliding mode controller (SLMC). The detail description of SLMC theory has been given in [8]. The generated output signal of the SLMC controller is the desired amplitude of the supplies current. By multiplying the DC signal with the sinusoidal waveform produced from the sinusoidal waveform generator, the reference current signal is obtained. The amplitude of this reference current is equal to the amplitude of the fundamental component of the load current plus or minus the error signal obtained from the VCL. If the detected amplitude of the DC capacitor is less than the reference DC voltage, this implies that the supplied real power from the mains has to be increased in order to compensate the demand from the load, and vice versa.

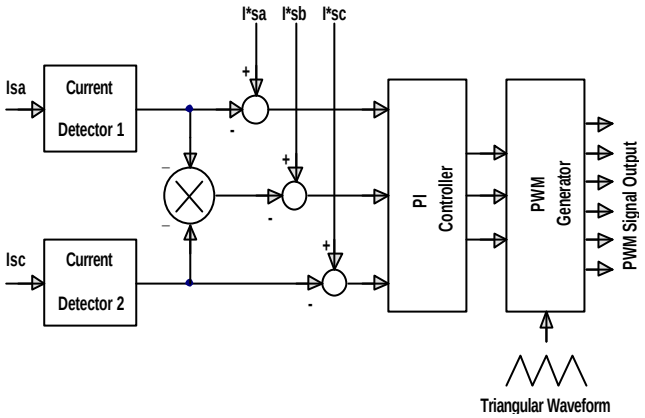

Fig. 4: Block diagram of current control loop.

Figure 4 shows the block diagram of CCL. In this circuit, the supply currents are first detected through the current detectors. From equation 2,

$$I_{sb} = -(I_{sa} + I_{sc}) \tag{13}$$

Using a negative adding circuit, I_{sb} can be obtained.

These currents (actual) are then compared with the generated three-phase reference currents obtained from the VCL. The difference (error) is then sent to the PI-controller. A constant switching frequency is achieved by comparing the PI-controller's output signal with the reference triangular waveform. This method can be explained by considering the bang-bang hysteresis technique plus the addition of a fixed frequency triangular waveform inside the imaginary hysteresis window [9]. The purpose of using the triangular waveform is to stabilise the converter switching frequency by forcing it to be constant and equal to the triangular waveform frequency. If the variation of the generated current error from the PI-controller is larger than the peak of the reference triangular waveform, there will not be an intersection between the current error and the triangular waveform. The switching pattern will remain unchanged until the current error signal is decreased and a new intersection occurs. It is important to note that the stability of the APF is reflected by its ability to keep the capacitor voltage as close as possible to the DC reference value. However, the DC capacitor voltage variation cannot be prevented due to the real power and reactive power injections and/or absorptions. The reactive power injections result in the ripple of the DC capacitor voltage and the active power absorptions from the mains also change the averaged DC capacitor voltage. This DC capacitor has two main purposes, act as an energy storage element and to maintain the DC voltage as constant as possible in the steady state.

5. SIMULATION RESULTS

Simulations test is performed to confirm the validity of the proposed scheme. The simulated results were obtained by using microsim pspice simulator software. The non-linear load is a three-phase full-bridge diode rectifier with RC component on it. The SLMC controller is used to determine the three phases reference currents and the PI-controller is used to regulate the current error. The complete system configuration is shown in Figure 5.

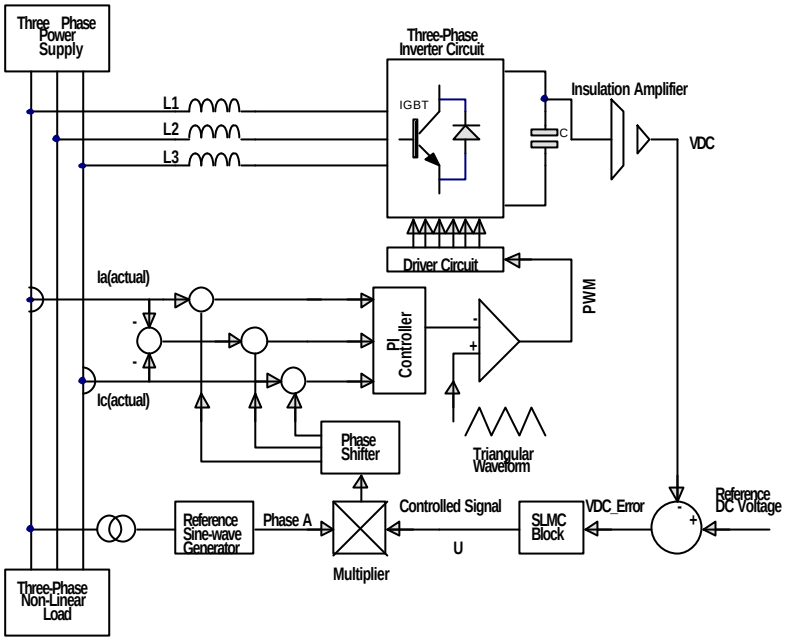

Fig. 5: Complete three-phase APF system configuration.

The circuit components of the adopted converter are L=5.5mH and C=1500uF. The phase voltage is 240V and the fundamental frequency is 50Hz. The frequency of the reference triangular waveform is 10kHz. The maximum value of the load current is 5A. The simulation results are shown in following figures.

Figure 6 shows the DC capacitor for the three-phase APF system. The maximum voltage ripple is less than 1.5% of its rated value and the sudden change of the load current occurred at time 65ms, the maximum of the DC capacitor voltage drop during this event is about 8.1%.

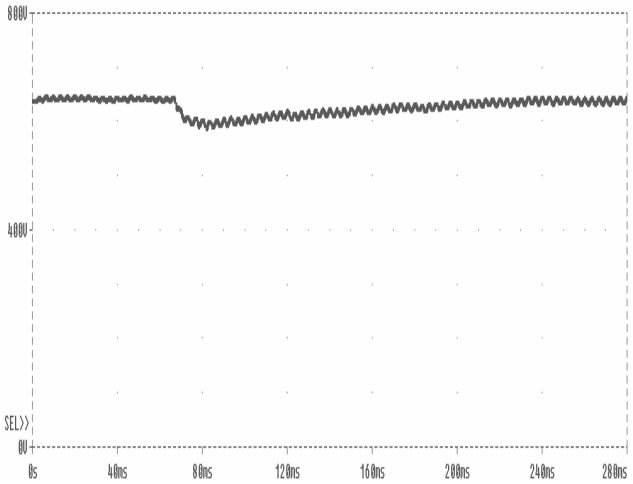

Fig. 6: DC capacitor voltage.

The phase A of supply current, load current and compensation current are shown in Figure 7, 8 and 9. The supply current shown in Figure 7 proved that the proposed controller is capable to respond very fast to regulate the sudden increase of the load current at time 65ms in less than a cycle of the fundamental frequency.

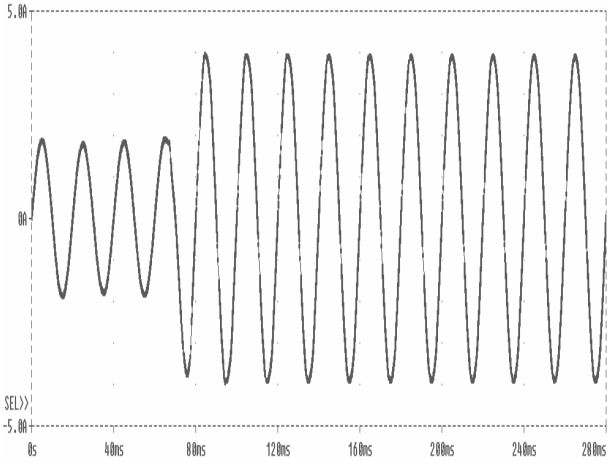

Fig. 7: Phase A supply current waveform.

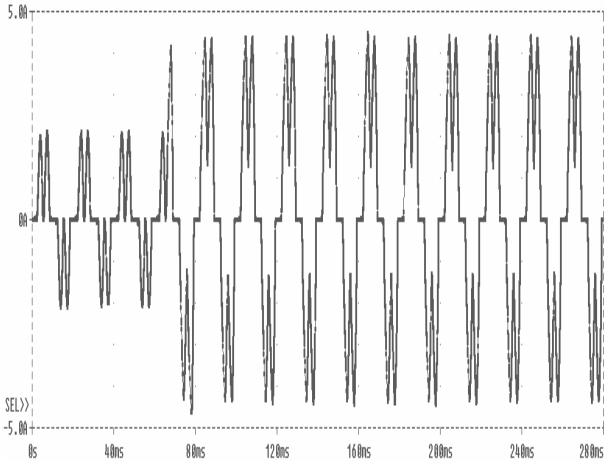

Fig. 8: Phase A load current waveform.

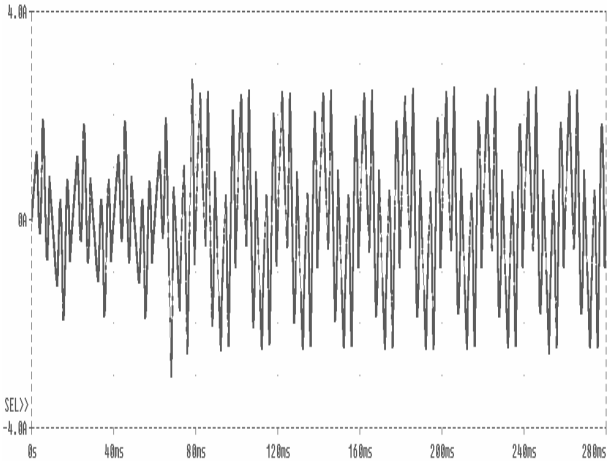

Fig. 9: Phase A compensation current waveform.

Figure 10 shows the three-phase supply current waveforms , to verify that they are balanced. The current and voltage waveforms of phase A are shown in Figure 11 to verify that they are in phase.

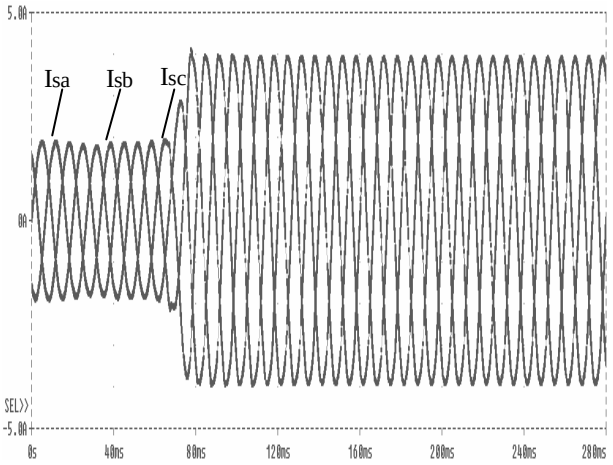

Fig. 10: Three-phase supply current waveforms.

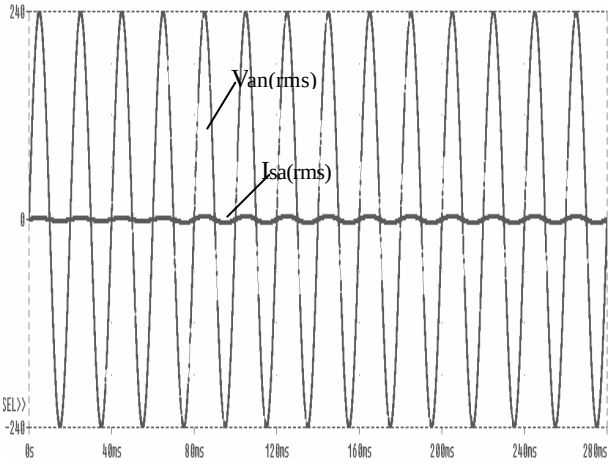

Fig. 11: Phase A supply voltage and supply current waveforms.

Figure 12 and 13 show the harmonic spectra of phase A supply current and load current respectively. There clearly show that the APF has actively filtered the unwanted harmonics in the supply current.

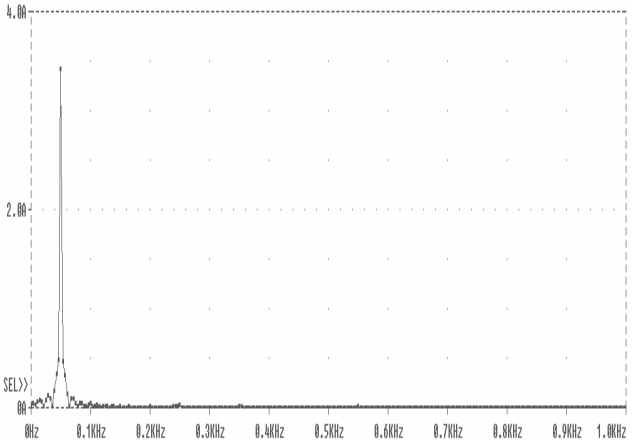

Fig. 12: Harmonic spectrum of phase A supply current.

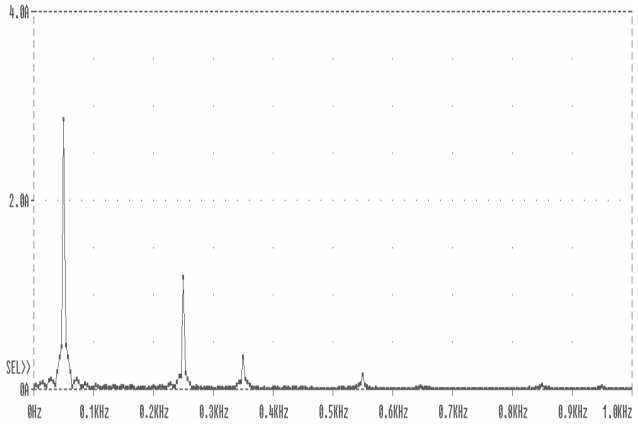

Fig. 13: Harmonic spectrum of phase A load current.

6. CONCLUSION

In this paper, a three-phase APF employing a SLMC controller for VCL together with the PI-controller for the CCL have been presented. Simulation tests have clearly shown attractive results for the three-phase currents and the effectiveness of the proposed scheme.

With this scheme, care must be taken for the design of the controllers. For the VCL, the output signal of the SLMC has to be limited in order to achieve maximum stability in steady state. This can be achieved by adding an anti-wound up integration circuit for the SLMC's integrator. For the CCL, the PI-controller has to be tuned properly so that the three-phase currents are balanced. If the PI-controller is not adjusted in such the way, unbalance three-phase currents will occur even though the system is in balanced condition.

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