The Efficiency of Current Prediction Controlled Shunt Active Power Filter Based on Three Level Inverter in Balanced and Unbalanced Network Cases

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Abstract: This paper presents a comparison study between two control methods associated with a shunt active power filter based on three-level type cascaded inverter. The first method is based on the conventional PI regulator and the second is based on the predictive current controller. The three-level type cascade inverter has more advantages relatively to the two-level inverter; among them: better total harmonic distortion, reduced semiconductor switches ratings and reduced switching losses. The capacitor voltage control technique is used for harmonic extraction algorithm. The latest is advantageous compared with many harmonic current extraction techniques. To improve the performance of the active filter a predictive current controller based on the supply current is applied. Simulation results demonstrate that the shunt active filter associated with a predictive current controller leads to an excellent performance compared to the PI controller.

Keywords: Shunt active filter, Three-level inverter, PI controller, Predictive controller, Harmonic extraction algorithm.

1. Introduction

Harmonics is one of the power quality issues that influence to a great extent transformer overheating, rotary machine vibration, voltage quality degradation, destruction of electric power components and malfunctioning of medical facilities [1], [2], [3]. In normal conditions, generated and distributed electric energy must be sinusoidal with predetermined frequency and magnitudes [4], [5]. Since the beginning of the power systems, there has been harmonic distortions due to nonlinear equipment's such as generators, transformers, motors, etc. furthermore, harmonic pollution in power systems has significantly increased owing to large proliferation of power electronic devices. Consequently, the reactive power compensation in non-sinusoidal conditions became one of the most important problems in power systems [6], [7]. Among the disadvantages also of harmonics on electric systems: communication interference; losses as heating; solid-state device mal function.

These harmonic problems have been dealt initially with using passive filters consisting of capacitors, inductors and damping resistors [8]. They provide simple solutions but have large size and weight; they cannot provide flexible compensation and may cause resonance problems. Nowadays, with the development of power electronics and microelectronics it is possible to consider active power filters, which can provide flexible current harmonic compensation and contribute to reactive power control and load balancing. Active Power Filters (APF), are widely used in the case of system to compensate, current harmonics, reactive power, load current unbalance [9].

APF are relatively new types of devices for eliminating harmonics [10], [11]. This kind of filter is based on power electronic devices and is much more expensive than passive filters. They have the distinct advantage that they do not resonate with the power system and they work independently with respect to the system impedance characteristics [12], [13]. They are used in difficult circumstances where passive filters don't operate successfully because of resonance problems and they don't have any interference with other elements installed anywhere in the power system. They can also address more than one harmonic at the same time and solve other power quality problems like flicker.

During the last decades, the presence of multi-level inverters has been steadily increasing in a variety of applications in the manufacturing, transport, energy, mining and other industries [14]. A multi-level inverter has four main advantages [15],[16], [17]. First, the voltage stress on each switch is decreased due to series connection of the switches. Therefore, the rated voltage and consequently the total power of the inverter could be safely increased. Second, the rate of change of voltage dv/dt is decreased due to the lower voltage swing of each switching cycle. Third, harmonic distortion is reduced due to more output levels. Fourth, lower acoustic noise and Electro-Magnetic Interference (EMI) is obtained [18].

There are three well established topologies of multi-level inverters (table 1): Neutral Point Clamped (NPC) [1], flying capacitor [4] and Cascaded H-Bridge (CHB) [6].

Table 1 : comparison of multi-level inverter topologies

Converter type	Switches or freewheeling diodes	Clamping diodes	Flying capacitors	Level capacitors	Isolate Dc supplies
cascaded H-bridge	6(m-1)	0	0	3(m-1)/2	3(m-1)/2
Clamping diodes	6(m-1)	3(m-1)*(m-2)	0	(m-1)	0
Flying capacitor	6(m-1)	0	3(m-1)(m-2)/2	(m-1)	0

With m: number of levels of the inverter

In this paper, the MATLAB- Simulink model is used to show the performance of the three - level CHB inverter with the predictive current control technique.

The three-level inverters can provide an efficient alternative to high power applications, providing a high quality output voltage; there are main advantages of the cascade H-bridge three-level inverter [11], [19].

- Requires a low number of components per level.
- Possibility to implement soft-switching.
- Uncomplicated voltage balancing modulation.
- Modularized structure without clamping component. Increasing the efficiency, robustness and reduce voltage stress on switches as lower voltage will be imposed by the DC side capacitor voltage.

A cascaded H-bridge converter with equal dc voltage has been widely used for active filter application because of natural modular and high-quality output spectrum, compared with other types of converters [15],[16].

Considering the advantages of the circuit and the simplicity, cascaded H-bridge three levels, is chosen for the presented work (figure. 1).

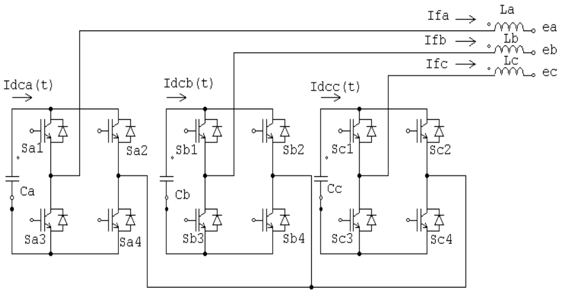


Fig.1. Three level Cascade H-Bridge inverter

The process industry is characterized by ever tighter product quality specifications, increasing productivity demands, new environmental regulations and fast changes in the economical market. Over the last two decades, predictive control has proven to be a very successful controller design strategy, both in theory and practice. The main reason for this acceptance is that it provides high performance controllers that can easily be applied to difficult high-order and multivariable processes.

Predictive control techniques have been receiving increasing attention for about ten years. They have been applied with great success to a large number of complex industrial control processes [2],[20]. In recent years predictive control algorithms have been used more and more even for fast mechanical systems.

Many predictive control algorithms are known in the literature: MAC (Model Algorithmic Control) introduced by Richalet, also studied by Rouhani & Mehra and in a modified version by Bruijn & Verbruggen; DMC (Dynamic Matrix Control) by Cutler & Ramaker; EHAC (Extended Horizon Adaptive Control) by Ydstie and finally EPSAC (Extended Prediction Self-Adaptive Control) by De Keyser & Van Cauwenberghe. This stragy has been used in current control for inverter, as well as for rectifiers and active power filters. One of advantage of predictive current control is the possibility to include nonlinearities of the system in the predictive model, and hence calculate the behavior of the variables for different conduction states [21].

The common theme of these strategies was the idea of using a dynamic model of the process to predict the effect of the future control actions [22].

Predictive current control [1], [7] is a linear control technique suitable for APF applications offering the advantage of precise current tracking over a wide frequency range. A predictive current controller is model based controller; therefore knowledge of system parameters is essential for satisfactory performance. In particular, stability problems occur in ac drive applications [8], when fcem needs to be estimated. This drawback doesn't apply for active power filtering systems because line voltage is available and can be measured.

2. Basic Configuration of the Active Power Filter

Shunt active filter acts as a current source injecting equal but opposite harmonic and quadrature components of load current at the point of common coupling (figure 2). In effect, the system views the nonlinear load together with the active filter as an ideal resistor.

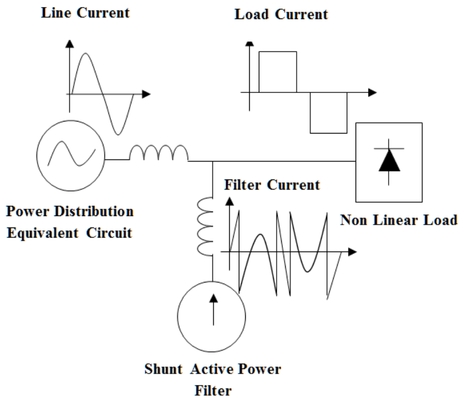


Fig.2. Shunt active filter operating principle

In this paper, we present a comparison study between two control methods, associated with a shunt APF based on three-level inverter. The first method is based on the conventional regulator PI and the second method is based on predictive current control. Therefore, the APF must compensate current harmonics and the reactive power in balanced and unbalanced network cases. For that it is necessary to see the evaluation of the apparent power of the shunt APF necessary for compensation of perturbations that will allow us to judge the filter of view point energetic and technique [23].

2.1 Compensation of harmonic currents

The active power P_{ch}, the reactive power Q_{ch} and the power deforming D_{ch} composed the apparent power of a non-linear load (S_{ch}), which is indicated by the following equation:

$$S_{ch}=\sqrt{P_{ch}^2+Q_{ch}^2+D_{ch}^2}=3.V_s I_{n-ch} \qquad (1)$$

With:
V_s : The mains voltage connecting point
I_{n-ch} : The current of the nonlinear load

The apparent power of the active filter (S_f) compensating the harmonic current I_h, is given by the following equation:

$$S_f=\sqrt{D_{ch}^2}=3.V_sI_h \qquad (2)$$

This harmonic current I_h is to be created by the active filter, it can be written as follows:

$$I_h=\sqrt{I_{n-ch}^2-I_{fon}^2} \qquad (3)$$

With I_{fon} is the fundamental current consumed by the nonlinear load.

The fundamental current and the load current according to the forward current of the non-linear load Id can be written as follows:

$$I_{n-ch}=\frac{\sqrt{2}}{3}I_{d-\alpha}\ ,I_{fon}=\frac{\sqrt{6}}{\pi}I_{d-\alpha} \qquad (4)$$

By deferring relations (3) and (4) in those of (1) and (2), the power ratio (τ_h) is given by:

Note $I_{d-\alpha}=I_d*\cos\alpha$

$$\tau_h=\frac{S_f}{S_{ch}}=\frac{3*V_s.*\sqrt{I_{n-ch}^2-I_{fon}^2}}{3*V_s*\sqrt{\frac{2}{3}}I_{d-\alpha}} \qquad (5)$$

An ignition angle α = 0 ($I_{d-\alpha}=I_d$) , the thyristor Graetz bridge, we can establish the following relationship:

$$S_{ch}=3*V_s*\sqrt{\frac{2}{3}I_{d-\alpha}}=3*V_s*\sqrt{\frac{2}{3}I_d} \qquad (6)$$

$$\tau_h=\left(\frac{\sqrt{3}}{2}*\frac{\sqrt{2\pi^2-18}}{3\pi^2}\right).\cos\boxed{f()}\alpha=\left(\frac{\sqrt{\pi^2-9}}{\pi}\right).\cos\boxed{f()}\alpha\approx0.3\cos\boxed{f()}\alpha$$

The following figure shows the variation of the power ratio (τ_h) of the shunt APF with respect to that of the non-linear load, depending on the ignition angle of the thyristors (α).

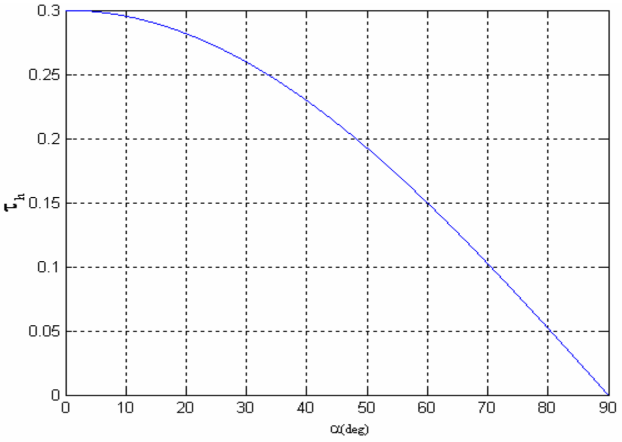


Fig 3. variation of the power ratio τ_h depending on the ignition angle (α)

2.2 Compensation of Harmonic Currents and Reactive Power

In this second study, we are interested to the calculation of the ratio of the apparent powers when the harmonic currents and the reactive power consumed by the non-linear load are compensated. In this case, the ratio of the apparent powers τ_{hr} is given by the following relationship:

$$\tau_{hr}=\frac{S_f}{S_{ch}}=\frac{\sqrt{Q_{ch}^2+D_{ch}^2}}{3.V_s.I_{n-ch}} \qquad (8)$$

This last relation can also be rewritten as follows:

$$\tau_{hr}=\frac{\sqrt{(3.V_s.I_h)^2++(3.V_s.I_{fon}.\sin\boxed{f()}\alpha)^2}}{3.V_s.I_{n-ch}} \qquad (9)$$

By deferring the relationships (3) and (4) these in (6) and (9), the expression of the power ratio (τ_{hr}) is given as follows:

$$\tau_{hr} = \frac{\sqrt{\left(3*V_s*\frac{2\pi^2-18}{3\pi^2}I_{d-\alpha}\right)^2+\left(3*V_s\frac{\sqrt{6}}{\pi}I_{d-\alpha}*sin\alpha\right)^2}}{3*V_s*I_d} = \cos\boxed{f()}\alpha\sqrt{1-\frac{9}{\pi^2}\cos\boxed{f()}\alpha^2}$$

Figure 4 gives the graphical representation of the power ratio (τ_{hr}) based on the ignition angle.

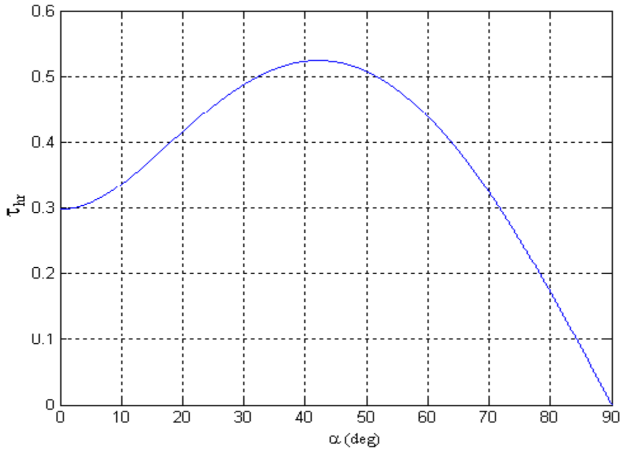


Fig 4. Power ratio for compensating harmonic currents and reactive power

The active power filter gives the maximum of the power $S_f \approx 52 \quad S_{ch}$ for an angle $\alpha = 42°$. For an angle α = 0, one finds the same power ratio as that obtained in the previous compensation case $S_f \approx 30 \quad S_{ch}$.

2.3 Compensation of Harmonic Currents and Reactive Power in the Unbalanced Network Case

The compensation of harmonic currents and reactive power is realized for an unbalanced network. The current imbalance is represented only by the inverse sequence current I_i of the non-linear load. The new power ratio (τ_{hri}) is given as:

$$\tau_{hri} = \frac{S_f}{S_{ch}} = \frac{\sqrt{\left(3.V_s.I_h\right)^2+\left(3.V_s.I_{fon}.\sin\boxed{f()}\alpha\right)^2+\left(3.V_s.I_i\right)^2}}{3.V_s.I_{n-ch}}$$

I_i : Inverse sequence current

By deferring the relationships (3) and (4) in equation (11), the expression of the power ratio is obtained as follows:

$$\tau_{hri} = \sqrt{\cos\boxed{f()}\alpha^2.\left(1-\frac{9}{\pi^2}\left(1-\sin\boxed{f()}\alpha^2\right)\right)+\frac{9}{\pi^2}\left(\frac{I_i}{I_{fon}}\right)^2} \qquad (12)$$

Posing: $x = \frac{I_i}{I_{fon}}$

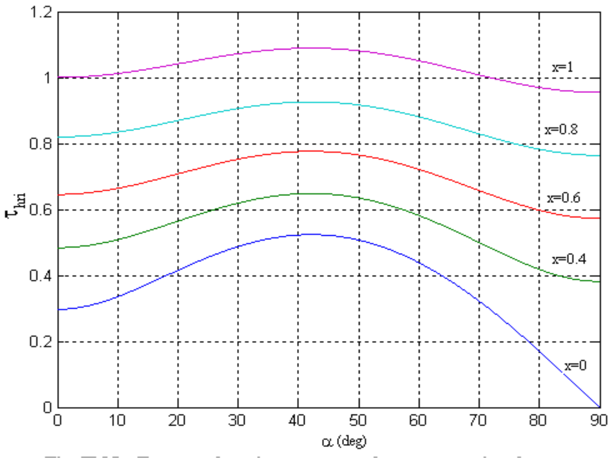


Fig5. Variation of the power ratio τ_{hri} in the case compensating harmonic currents and reactive power with an unbalanced network

Figure 5 represents the variation of the power ratio (τ_{hri}) depending on the ignition angle (α). The power ratio is given for various values of the reverse current rate ($x = \frac{I_i}{I_{fon}}$). It is noted firstly that the power ratio increases nearly linearly with the increased rate of the reverse current. For $x=0$, the same curve as in the case of balanced system is obtained. In the rest of the article, the considered nonlinear load is a diode rectifier with R-L load.

3. Tree Level Cascade Inverter Based Active Power Filter

3.1 Importance of Cascade Three Level Inverter

A typical three phase shunt APF connected in parallel between the nonlinear load and the input supply voltage is shown in Figure 6 , is used for getting high power quality and sinusoidal waveforms currents.

The three-level cascade inverter can be synthesized by a series of single phase full bridge inverter, assuming that the DC voltage of each full bridge cell is the same and equal to V_{dc}. Each full bridge inverter can switch between

$-V_{dc}$, 0 and V_{dc}. Therefore, a higher level can easily be implemented by adding classical H bridge cells in this configuration.

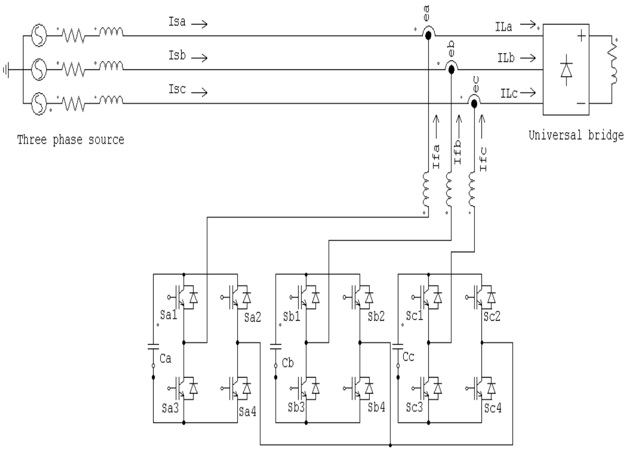


Fig 6. Three-level cascade inverter based a shunt active power filter

3.2 Three-level Inverter Control Strategies

The Pulse Width Modulation (PWM) techniques for CHB inverter are characterized by the following advantages [17],[18]: the output voltage control is easier with PWM than other schemes and can be achieved without any additional components; the lower order harmonics are either minimized or eliminated altogether; the filtering requirements are minimized as lower order harmonics are eliminated and higher order harmonics are filtered easily. It has very low power consumption. The entire control circuit can be digitized which reduces the susceptibility of the circuit to interference.

The most popular PWM techniques for CHB inverter are: Phase Shifted PWM; Alternative Phase Opposition; Phase Disposition PWM; Unipolar Multi-carrier PWM schemes and Phase Opposition Disposition PWM.

In this article, the considered technique is the Phase Disposition PWM. Because this technique is also well applicable to cascade inverters, its gives rise to the lowest harmonic distortion.

To control the three-level inverter, two unipolar carriers are generated. By the comparison of the carriers with the reference signal, the pulses are produced (figure 7).

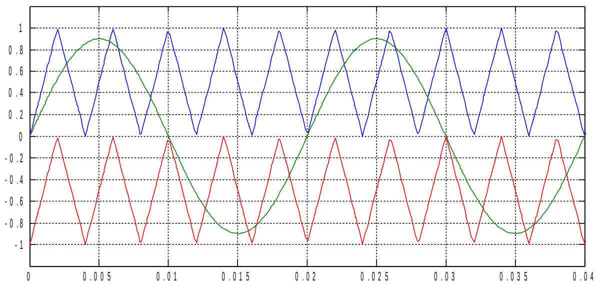


Fig7. PDPWM technique for cascade three-level inverter

4. Principe of the Control Methods

There are two important controlling parts of the shunt APF design. The first is the harmonic extraction technique based on the conventional regulator PI and the second is the predictive current control.

4.1 Harmonic Extraction Technique Based on the PI Controller

Among the presented methods for identifying harmonic component of the load current, a simplified and applicable method with high performance is presented [18], [23],[24], [25]. The important question of the APF is how to calculate the appropriate compensation current, which will be detailed in the next section.

The block diagram of the proposed harmonic extraction method is performed using the capacitor voltage control shown in Figure 8. It consists of two parts; one is the reference current generator and another is the switching patterns generator, so controlling the capacitor voltage using a PI controller, results in an output which is proportional to the instantaneous changes in power balance.

Multiplying this output by the per unit voltages of the common coupling point, results in the corresponding reference supply currents. Figure 8 shows the proposed block diagram.

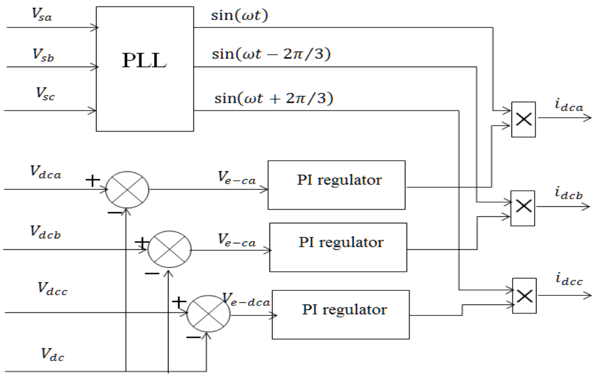


Fig 8. capacitor voltage control

4.2 Predictive Current Controller

With its performance and ease of implementation, the predictive control, has a big success in industry [20], [22], [23].[24]

As in [20],[24] [25], measured supply currents and voltages of the CCP, are used to predict the reference output voltage of the inverter, required to make the measured current reach its reference at the next sampling instant [20]. The predicted inverter output voltages are used to obtain the switching decision of the inverter switches. In Figure.9, the equation relating the shunt APF current, the inverter output voltage and the CCP voltage is given as:

$$v_x = L_x \frac{d i_{fx}}{dt} + e_x \qquad (13)$$

Where x represents the phases a, b or c, Lx is the interfacing inductance, v_x is the APF output voltage for the x phase, e_x is the phase voltage of the CCP and i_{fx} is the phase APF current. The inductor resistance is neglected. Equation (13) can be represented in the discrete form as follows:

$$v_x^*(n+1) = L\left(\frac{i_{fx}^*(n+1) - i_{fx}(n)}{T_s}\right) + e_x \qquad (14)$$

Where $i_{fx}^*(n+1)$ and $v_x^*(n+1)$ are the phase APF current and the predicted output voltage references respectively, at the sampling instant (n+1) and T_s is the sampling time. Using Kirchhoff's current law at the CCP:

$$i_{fx}(n) = i_{Lx}(n) - i_{sx}(n) \qquad (15)$$

Where $i_{Lx}(n)$ and $i_{sx}(n)$ are the phase load and supply currents respectively at the sampling instant (n). Since the sampling instant (n+1) is not available, $i_{fx}^*(n+1)$ is replaced by $i_{fx}^*(n)$. This introduces one sampling time delay which becomes less significant as the sampling frequency increases. The reference current of the shunt APF can be expressed as:

$$i_{fx}^*(n) = i_{Lx}(n) - i_{sx}^*(n) \qquad (16)$$

Substituting (15) and (16) into (14) gives:

$$v_x^*(n+1) = L_x\left(\frac{i_{sx}(n) - i_{sx}^*(n)}{T_s}\right) + e_x(n) \qquad (17)$$

Equation (17) represents the predicted inverter output voltage expressed in terms of the reference and the actual supply currents.

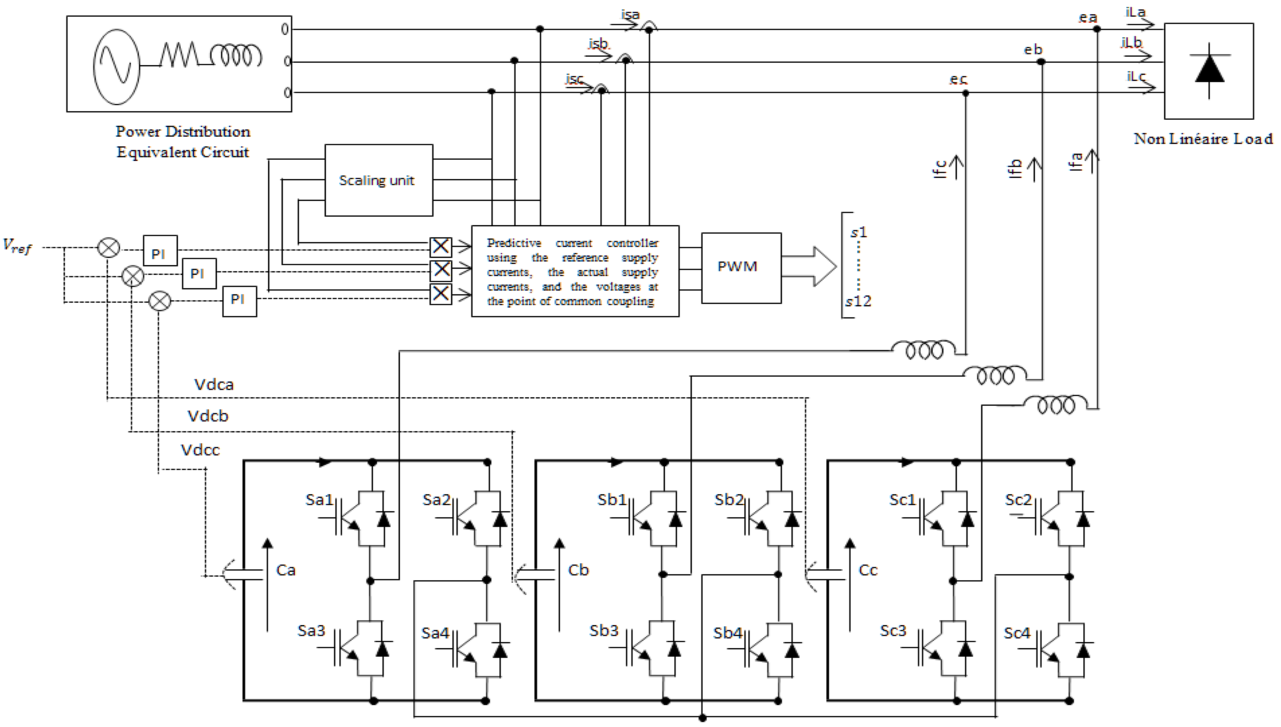


Fig 9. Predictive current control of the APF

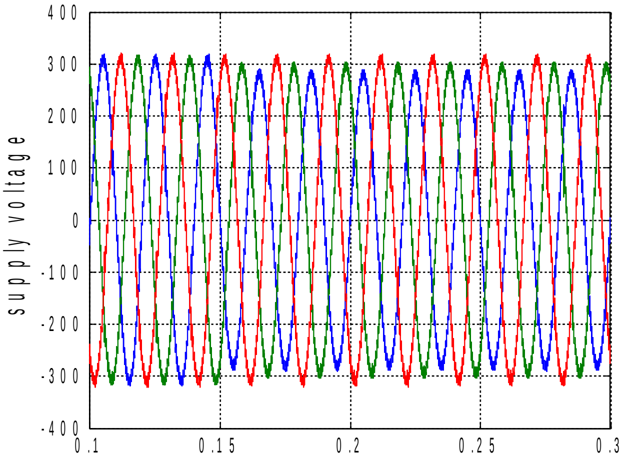
Table 2 : The system parameters

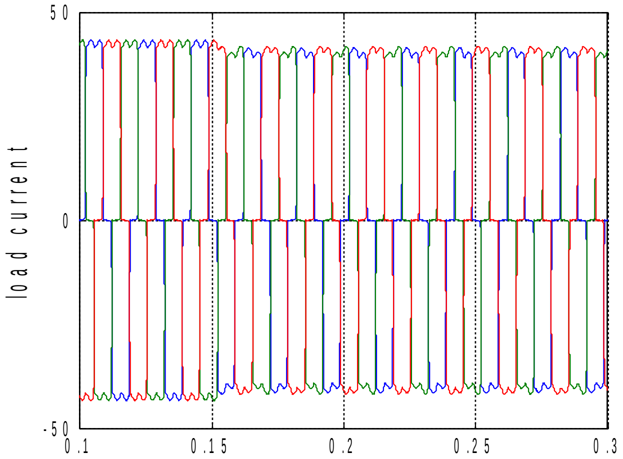
Parameter	Value
Supply voltage	220 V
Supply resistance; supply inductance	1.4e-3Ω;44.9e-6mH
diode rectifier with R-L load	R=12 Ω,L=20mH
vdc	700 V
Cdc	4.4mH
Switching frequency f	9000Hz
Sample time T_s	2e-6 s

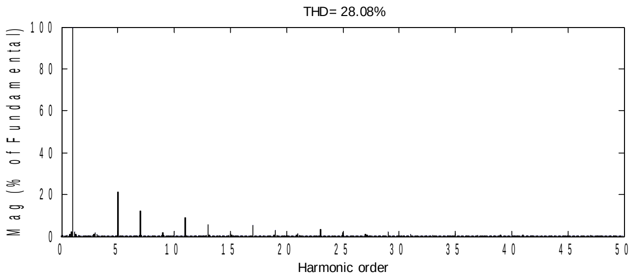
The block diagram for controlling the shunt APF using predictive control, based on three-level inverter is simulated using MATLAB/Simulink.

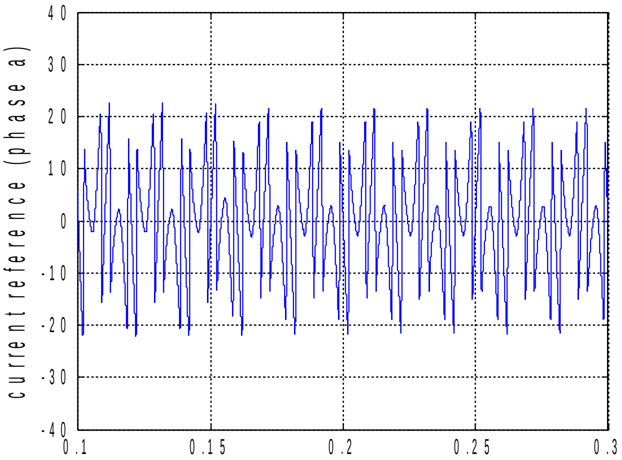
5. Simulation Results of the APF Based on the PI Controller

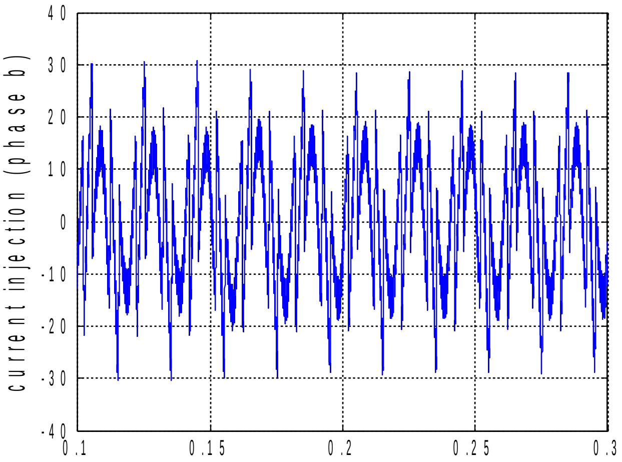
The generate reference source current signals is shown in section 4.1. In order to quantify the contribution of the proposed control strategy, at the t= 0.15s a scenario that involves an imbalance of voltage source has been simulated. The values of phase voltages a, b and c, are 300 V,292 V and 305 V, respectively.

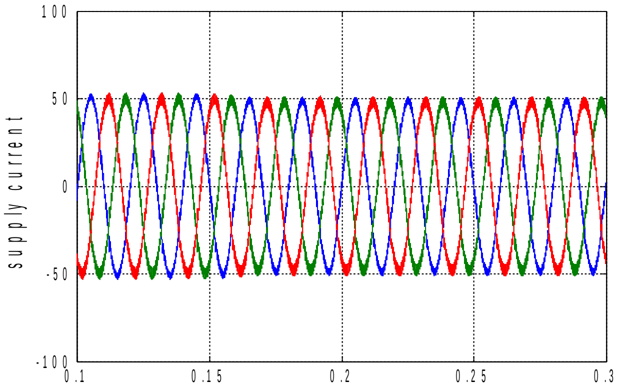












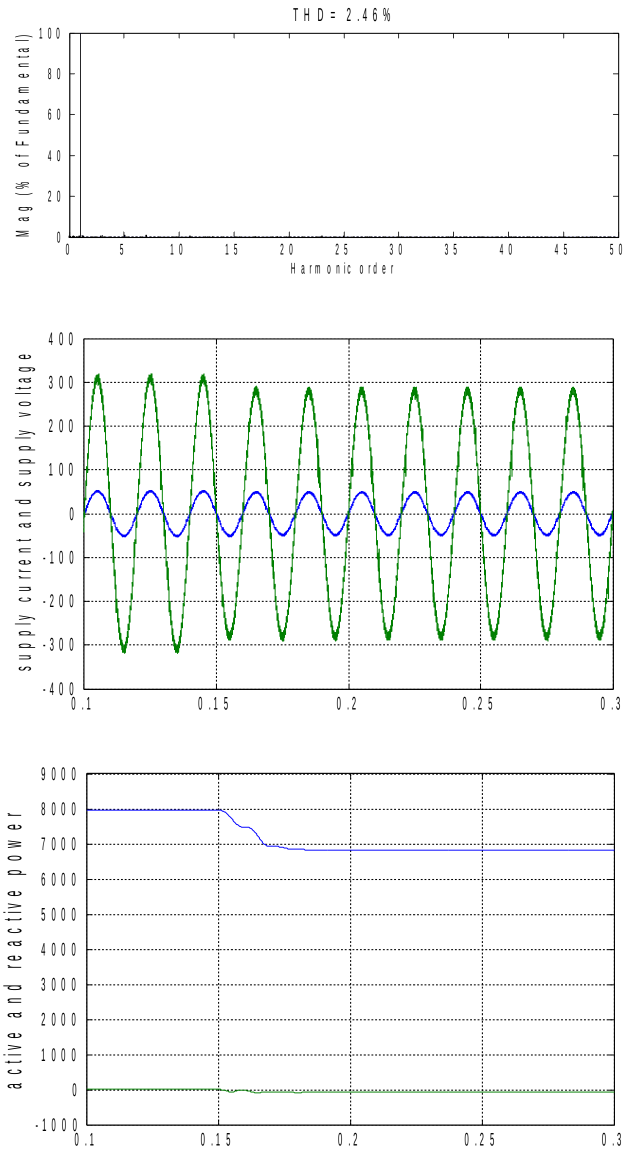


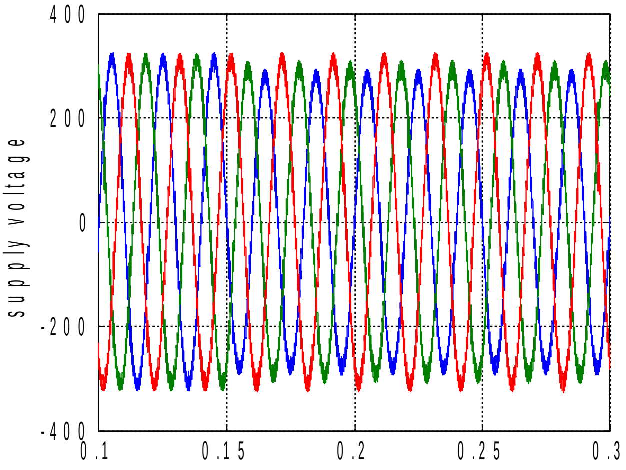
Fig. 10. Load phase current; Frequency spectrum of the load phase current; Injected current; Reference current; Source current; Frequency spectrum of the source phase current, Source voltages

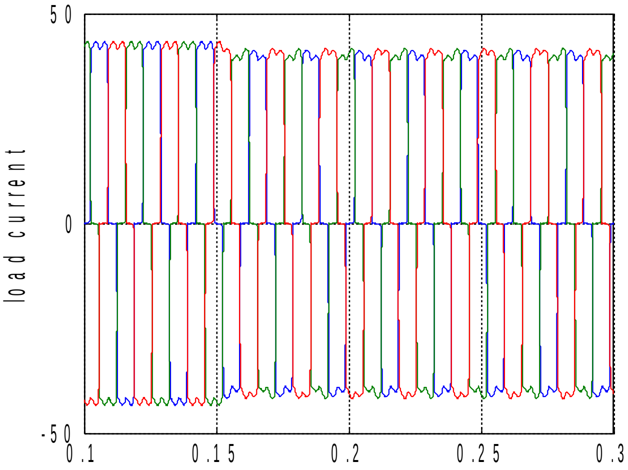
The performance of the shunt APF associated with the PI controller, based on three-level inverter is illustrated through the previous results. The Total Harmonic Distortion (THD) of the source current is reduced to 2.46%. Hence, the source current is close to the sinusoidal form. Firstly, the APF is tested with a balanced network; so that each phase will consume the same effective current. Secondly, the APF is tested with an unbalanced network (from t=0.15 s).

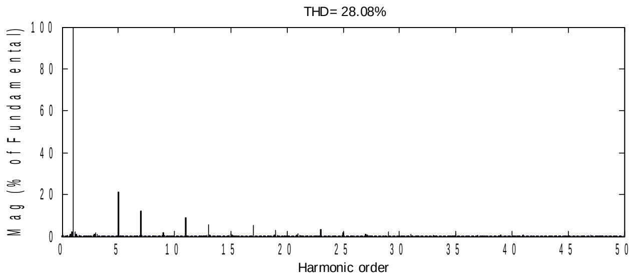
It is also important to remark that the instantaneous active power at the source side depends on the value of the source voltage and the imaginary power is forced to zero. This means that the reactive power is successfully compensated. Although the reactive power doesn't contribute to the transfer of active power, it can increase the phase current. By forcing the reactive power to zero, it is possible to minimize the current flowing at the source side and the power factor is a unity.

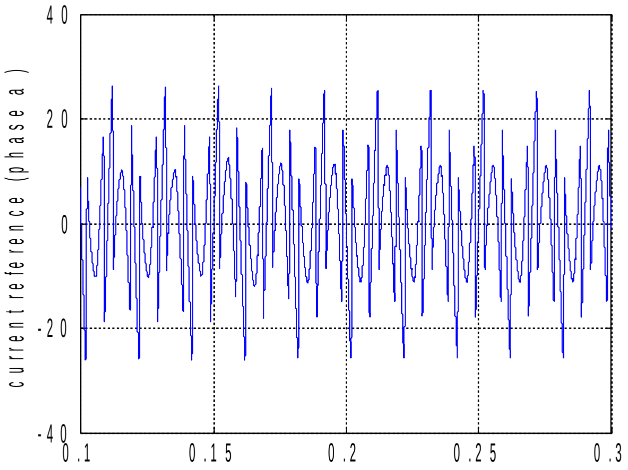
6. Results and Discussion of the APF Based on the Predictive Controller

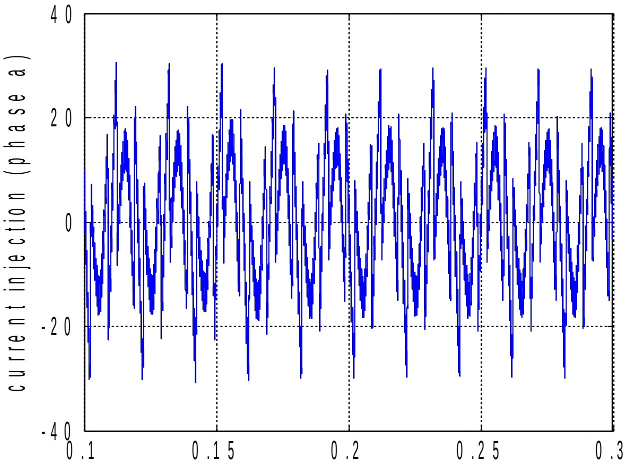
Figure 11 shows the injected current and its reference; the source current and its frequency spectrum and finally the active and the reactive power.

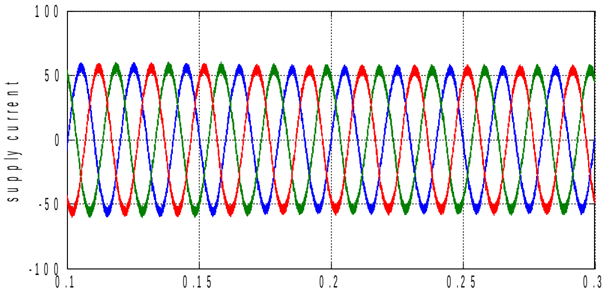


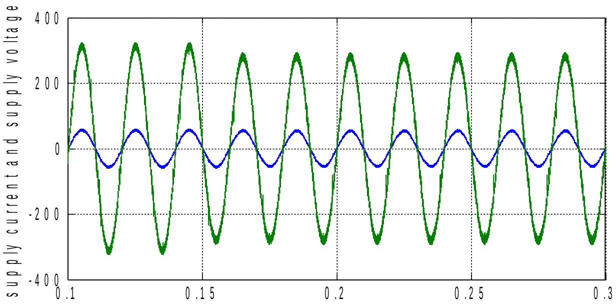


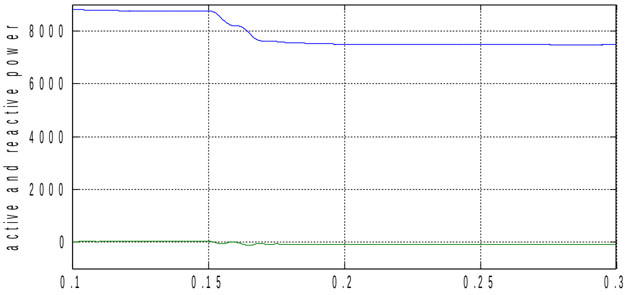












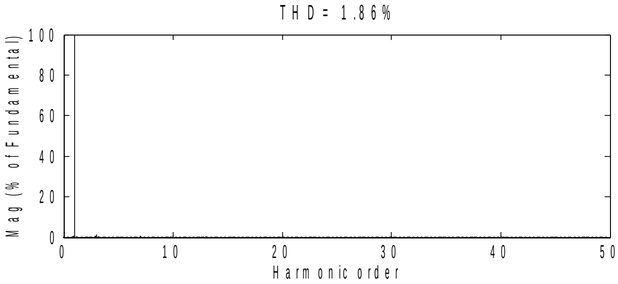


Fig.11. Injected current; Reference current; Source current; Frequency spectrum of the source phase current; active and reactive power

Predictive control is a very wide class of controllers that have found rather recent application in power converters.

The performance of the shunt APF associated with the predictive controller, based on three-level inverter is illustrated through the previous results (Fig.11). To observe further the performance of this filter, it is necessary to carry out the simulation under unbalanced network condition. The THD of the source current is reduced to 1.86%, compared with the conventional PI controller (2.46%). The instantaneous active power at the source side depends on the value of the source voltage and the imaginary power is forced to zero (0 VAR) with a unity power factor (cos phi =1). Simulation results demonstrate that the shunt APF associated with the predictive current controller leads to a superior performance compared to the PI controller.

The results obtained by predictive control current have confirmed its good performances; (the influence of such voltage unbalance is negligible, the THD of the resulting current is eligible)

7. Conclusion

In this paper a comparison study between two control methods associated with a shunt APF, based on three-level type cascaded inverter. The first method based on the conventional PI controller and the second based on the predictive current controller. Simulation results demonstrate that the shunt APF associated with a predictive current controller leads to an excellent performance compared to the PI controller in various operating conditions (balanced and unbalanced network). This method has several advantages compared with conventional controller; it provides simple control algorithm with less computational burden minimizes the number of sensors and reduces both of the system's size and cost.

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