Flatness-Based-Control of Three-phase shunt active power filters based on five-level NPC inverter

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Abstract— **The problem of controlling three-phase shunt active power filter (SAPF) is addressed in presence of nonlinear loads. In this paper, a flatness control of three-phase shunt active power filter based on five-level neutral-point-clamped (NPC) inverter is proposed. The control objectives are twofold, the first one consists on compensating the current harmonics and the reactive power absorbed by the nonlinear loads, and the second one concerns the regulation of the inverter DC capacitor voltage. To achieve these objectives, two cascaded loops are designed, an outer loop for the DC voltage regulation, where the inner loop is dedicated for harmonic current compensation. The simulation results are developed under Matlab/Simulink environment to prove the performances of the proposed controller.**

Keywords— SAPF, multilevel inverter, NPC, flatness control

I. INTRODUCTION

In recent days, power quality in electrical energy systems has become a major challenge for engineers to maintain the sinusoidal waveform in the electrical system. Harmonics are a problem arises due to the increasing use of Non-linear loads, such as power converters motor drives and other power electronics products.The current harmonics result in several harmful effects e.g.: overheating of transformers and distribution lines, they can also cause the distortion of the voltage and worsen power factor correction(PFC).

Shunt Active Power Filters (SAPF) are the most popular solution used to eliminate the undesired current components by injection of compensation currents in opposition to them. The most power converter used in SAPF is the two-level voltage source inverter, due to its power handling capabilities of power semiconductors, these inverters are limited to low power applications. Multilevel inverters have been successfully employed to serve the mentioned objectives. The advantages of the multilevel voltage source inverter have been applied typically in medium and high-power applications. The NPC inverter is particularly suitable in high-voltage applications since it guarantees equal voltage sharing of series-connected power devices in each phase.

The controller is the main part of the shunt active power filter operation and has been a subject of many researches in recent years. Various current control techniques have been reported in the literature in ordre to improve the power quality of the electrical systems. Among these techniques, the hysteresis current control is considered as the most extensively used technique due to its ease of implementation, which offers a high accuracy and a fast response performance. In the hysteresis control technique, the error function is centered in a preset hysteresis band. When the error exceeds the upper or lower hysteresis limit, the hysteretic controller makes an appropriate switching decision to control the error within the preset band. However, variable switching frequency and high ripple content are the main disadvantages of hysteresis current control. To improve the SAPF operation performances, there are many techniques for controlling a three-phase SAPF including nonlinear control while in most available papiers the most existing controllers are designed under the averaged nonlinear model.In[1]a Lyapunov technique is designed to control the power factor and current harmonic compensation of SAPF.A nonlinear control using sliding mode technique is addressed to ensure compensation of harmonic and reactive currents in[6].However to offers an excellent performance of the controller design a new method for SAPF was presented in [7] In order to control multicellular SAPF based on flatness controller.

In this work, we are considering the problem of controlling a three-phase SAPF based on five-level NPC inverter the proposed topology has the advantage to achieve a very good performances of compensation of harmonic and reactive currents the controller structure is developed and based on two cascaded loops. An inner loop is designed using flatness approach by compensation the harmonic current and reactive power absorbed by the nonlinear load with an excellent steady state performance. In outer loop is developed with the same controller approach for the regulation of the output voltage to track a desired reference.

This paper is organized as follows: section II is devoted for system presentation and modeling, in the section III the controller design is presented, then the simulation results which prove the effectiveness of the proposed controller are given in section IV, at last a conclusion and a reference list is given.

II. SYSTEM PRESENTATION AND MODELING

The operation of SAPF is to produce reactive and harmonic current components in order to compensate undesirable current harmonics produced by the nonlinear load. The block diagram of the investigated three-phase three- wire SAPF system is shown in Fig.1. A diode rectifier, with RL load is used as a non-linear load.

The proposed three-phase shunt active power filter is shown in Fig.2, it consists of a five-level NPC inverter with a capacitive storage divider $C_{eq} = C/4$ placed at the DC side. From the AC side the APF is connected in parallel with nonlinear loads through a filtering inductor (L_f, r_f).

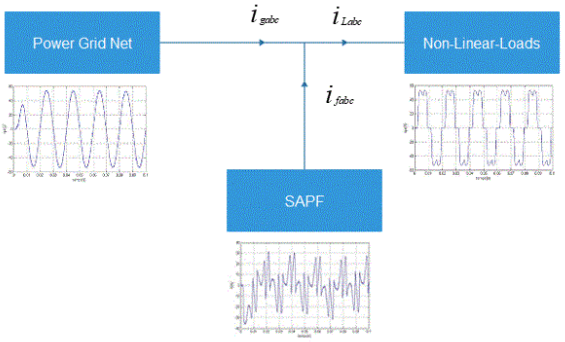

Fig. 1. Compensation principle of SAPF

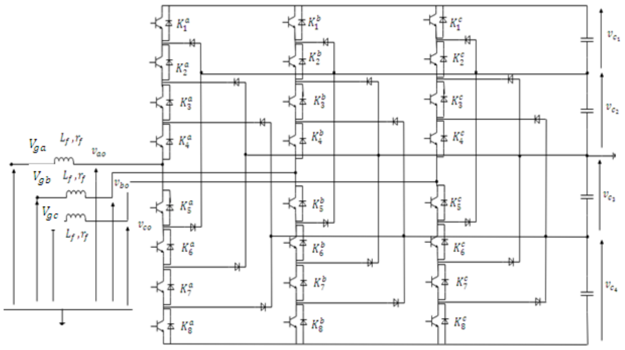

Fig. 2. Five-level NPC shunt active power filter

Applying Kirchhoff's laws to the above circuit, one gets:

$$L_f \frac{d}{dt} i_{fa} = V_{ao} - V_{ga} - r_f i_{fa} \tag{1a}$$

$$L_f \frac{d}{dt} i_{fb} = V_{bo} - V_{gb} - r_f i_{fb} \tag{1b}$$

$$L_f \frac{d}{dt} i_{fc} = V_{co} - V_{gc} - r_f i_{fc} \tag{1c}$$

Where:

$$V_{ao} = F_1^a V_{c1} + F_2^a V_{c2} - \overline{F_3^a} V_{c3} - \overline{F_4^a} V_{c4} \tag{2a}$$

$$V_{bo} = F_1^b V_{c1} + F_2^b V_{c2} - \overline{F_3^b} V_{c3} - \overline{F_4^b} V_{c4} \tag{2b}$$

$$V_{co} = F_1^c V_{c1} + F_2^c V_{c2} - \overline{F_3^c} V_{c3} - \overline{F_4^c} V_{c4} \tag{2c}$$

Where F_i^j represents the switching function , defined by

$F_i^j = 1$ when this switch is closed, $F_i^j = 0$ when it is open.

As well as $(j = a, b, c)$ and $(i = 1,2,3,4)$

In the case where the voltages at the terminal of the capacitors are equal :

$$V_{c1} = V_{c2} = V_{c3} = V_{c4} = V_c \tag{3}$$

The system (2a-c) is written:

$$V_{ao} = (F_1^a + F_2^a - \overline{F_3^a} - \overline{F_4^a}\ ) V_c \tag{4a}$$

$$V_{bo} = (F_1^b + F_2^b - \overline{F_3^b} - \overline{F_4^b}\ ) V_c \tag{4b}$$

$$V_{co} = (F_1^c + F_2^c - \overline{F_3^c} - \overline{F_4^c}\ ) V_c \tag{4c}$$

The equations(1a-c) represent the instantaneous model of the five-level NPC SAPF, nevertheless this model is not suitable for designing a continuous control due to the switched nature of the control inputs. To overcome this problem, the above five-level NPC SAPF will be presented with the following averge model:

$$L_f \frac{d}{dt} i_{fa} = \frac{V_c}{2} U_a - V_{ga} - r_f i_{fa} \tag{5a}$$

$$L_f \frac{d}{dt} i_{fb} = \frac{V_c}{2} U_b - V_{gb} - r_f i_{fb} \tag{5b}$$

$$L_f \frac{d}{dt} i_{fc} = \frac{V_c}{2} U_c - V_{gc} - r_f i_{fc} \tag{5c}$$

In the $(\alpha\!-\!\beta)$, reference frame, Eq. (5a-c) become:

$$L_f \frac{d}{dt} i_{f\alpha} = \frac{V_c}{2} U_\alpha - V_{g\alpha} - r_f i_{f\alpha} \tag{6a}$$

$$L_f \frac{d}{dt} i_{f\beta} = \frac{V_c}{2}\ U_\beta\ - V_{g\beta} - r_f i_{f\beta} \tag{6b}$$

III. DESIGN OF THE FLATNESS-BASED-CONTROLLER

In this section, the design of a non-linear controller based on differential flatness control is presented as shown in Fig.3. This controller will be developed using two loops, an inner loop (AC current control) which consists on injecting reactive and harmonic current components to compensate undesirable current harmonics produced by the nonlinear load, and an outer loop for the DC voltage regulation.

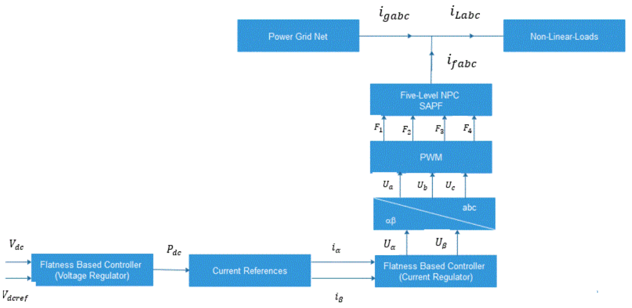

Fig. 3. The structure of the overall system.

The control strategies to generate compensation commands are based on frequency domain or time-domain correction techniques. In our proposed system, the $p-q$ theory is used for the generation of the current compensating command which is a time domain analysis method [5]. The $p-q$ theory, first transforms voltage and currents from the abc to $\alpha\beta$ coordinates, and then defines instantaneous power on these coordinates. The compensated imaginary parts of the power are denoted by p^* and q^* , whereas the real part of the power is P_{dc} and Q_{dc}, then we calculate the reference currents in $\alpha\beta$. Fig.4. shows the generation of compensation currents for shunt active filter using $p-q$ theory.

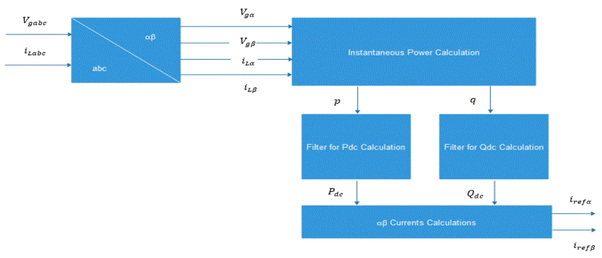

Fig. 4. Block diagram of reference current generator using $p-q$ theory.

A. *AC current regulator (inner loop design)*

- Flatness description

The concept of differential flat systems was introduced by Fliess and al. [2]. Differential flatness is a structural property of a class of nonlinear systems, for which, roughly speaking, all system variables can be written in terms of a set of specific variables (the so-called flat outputs) and their derivatives without any integration [3]. More precisely, if the system has a state vector $x \in R^n$, and an input vector $u \in R^m$, then the system is considered to be differentially flat if a flat output $y \in R^m$, the equations of x , y and u can be found as follows:

$$y = \emptyset(x, u, \dot{u}, \dots, u^{(s)}) \tag{7}$$

$$x = \varphi(y, \dot{y}, \dots, y^{(r)}) \tag{8}$$

$$u = \psi(y, \dot{y}, \dots, y^{(r+1)}) \tag{9}$$

- Flatness Differential of the system

According to the control objectives, we propose to define the candidate flat outputs vector as follow:

$$y = \begin{bmatrix} y_\alpha = i_{f\alpha} \\ y_\beta = i_{f\beta} \end{bmatrix} = \emptyset(x) \tag{10}$$

The state vector $(x = \left[i_{f\alpha}\ i_{f\beta}\right]^T)$ and the control vector $u = \left[U_\alpha\ U_\beta\right]^T$ are defined by:

$$x = \begin{bmatrix} i_{f\alpha} = y_\alpha \\ i_{f\beta} = y_\beta \end{bmatrix} = \varphi(y) \tag{11}$$

$$\begin{cases} \frac{V_c}{2} U_\alpha = L_f \frac{dy_\alpha}{dt} + r_f y_\alpha + V_{g\alpha} \\ \frac{V_c}{2} U_\beta = L_f \frac{dy_\beta}{dt} + r_f y_\beta + V_{g\beta} \end{cases} \tag{12}$$

As it can be seen, the components of the state variable vector (11) and the control variable vector (12) are expressed as a function of the output vector components and its derivatives. It proves that the system is flat. In the following, the reference trajectory generation will be explained.

- Trajectory planning

The trajectory planning is so important in a differential flatness-based control because it defines the evolution of all the state and control variables (equations (8)-(9)). It is therefore interesting to impose a known trajectory to predict analytically the evolution of variables[4].

To plan the desired trajectories on the output variable components, a second-order filter is applied to the reference values, $y_{ref} = \left[y_{ref\alpha}\ \ y_{ref\beta}\right]$, to protect the system against the rapid and instantaneous changes of the variables. Therefore, the reference trajectory can be written as:

$$y_{ref\alpha}{}^* = y_{ref\alpha}(1 - (1 + \omega_0 t)e^{-\omega_0 t}) \tag{13a}$$

$$y_{ref\beta}{}^* = y_{ref\beta}(1 - (1 + \omega_0 t)e^{-\omega_0 t}) \tag{13b}$$

Where ω_0 is the angular frequency of the second order system which is defined according to the desired rise time of the variables $y_{ref} = \left[y_{ref\alpha}\ \ y_{ref\beta}\right]$.

- Control Law

In order to control the output vector $y = \left[y_\alpha\ y_\beta\right]^T$ to track its reference trajectories $y_{ref} = \left[y_{ref\alpha}\ y_{ref\beta}\right]^T$, a state feedback controller is used :

$$(\dot{y}_{ref\alpha} - \dot{y}_\alpha) + k_1(y_{ref\alpha} - y_\alpha) + k_2 \int \left(y_{ref\alpha} - y_\alpha\right) d\tau = 0 \tag{14a}$$

$$(\dot{y}_{ref\beta} - \dot{y}_\beta) + k_1(y_{ref\beta} - y_\beta) + k_2 \int \left(y_{ref\beta} - y_\beta\right) d\tau = 0 \tag{14b}$$

Such that:

$$\begin{cases} \dot{y}_\alpha = \gamma_\alpha \\ \dot{y}_\beta = \gamma_\beta \end{cases} \tag{15}$$

The integral terms ensure a zero-static error in steady state and compensate the model errors. The coefficients of regulators are designed such that the operating points are stable.

Substituting the fictive variables γ_α and γ_β, obtained by the regulators in the equation (12), it leads to calculate the control vector components. These control variables are used to generate the command signals of the related converter.

Each of these equations is equivalent to a second-order equation of the following form:

$$P(s) = s^2 + 2m\omega_n s + \omega_n{}^2 \tag{16}$$

An optimal choice of the parameters k_1 and k_2 can be obtained by making an identification of the polynomial equation (14) to a characteristic polynomial equation $P(s)$ given by the equation (16), thus, one obtains by identification:

$$\begin{cases} k_1 = 2m\omega_n \\ k_2 = \omega_n{}^2 \end{cases} \tag{17}$$

Fig.5 shows the block diagram of the AC current control

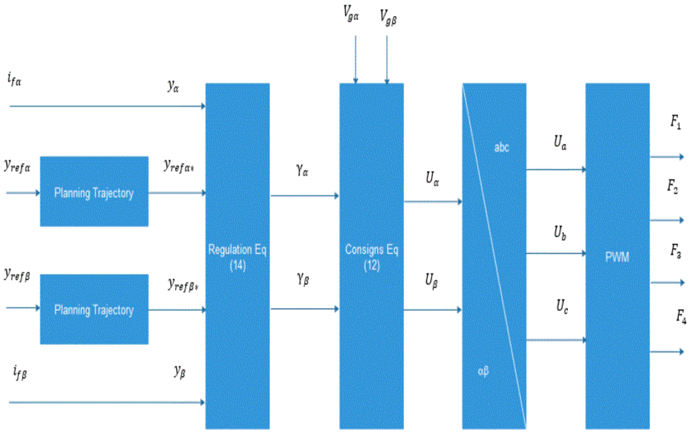

Fig. 5. Functional diagram of the proposed AC current control.

B. *DC bus voltage regulator (outer loop design)*

The continuous power of the system is given by the following equation:

$$P_{dc} = C_{eq} V_{dc} \frac{dV_{dc}}{dt} \tag{18}$$

The state vector is $U_1 = P_{dc}$ and we define the candidate flat outputs vector by $y_1 = V_{dc}$. Therefore, the flatness properties are verified.

$$P_{dc} = C_{eq}V_{dc}\ \gamma_1 = \psi(y_1, \dot{y}_1) \tag{19}$$

with: $$\gamma_1 = \frac{dV_{dc}}{dt} \tag{20}$$

where γ_1 corresponds to the first order drift term of the voltage V_{dc} which comes from an input/ output linearization given by:

$$\dot{y}_1 = (\dot{y}_{1ref} - \dot{y}_1) + k_1(y_{1ref} - y_1) + k_2 \int (y_{1ref} - y_1) d\tau \tag{21}$$

Therefore, the reference trajectory can be written as:

$$y_{1ref}{}^{*} = y_{1ref}(1 - (1 + \omega_0 t)e^{-\omega_0 t}) \tag{22}$$

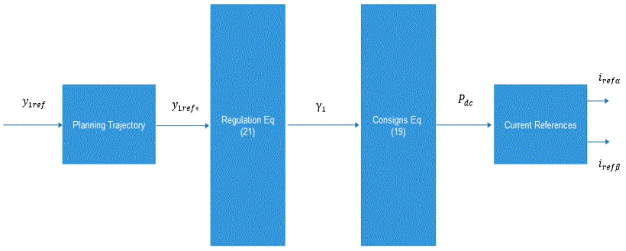

Fig. 6. shows the block diagram of the DC voltage control

IV. SIMULATION RESULTS

In this section, the controller that has been designed in the above section will be tested in the MATLAB SimPowerSystems environment using the characteristics presented in the next table.

TABLE I. SYSTEM PARAMETRES

RMS value of the network voltage E_{eff} and frequency	***220V,50Hz***
Reference DC voltage $V_{dc}{}^{*}$	***790V***
Impedance at the input of the polluting load L_c	***1mH***
Filter impedance L_f, r_f	***2mH, 8mΩ***
Diode bridge L, R	***20mH, 10Ω***
Capacitor C	***37mF***

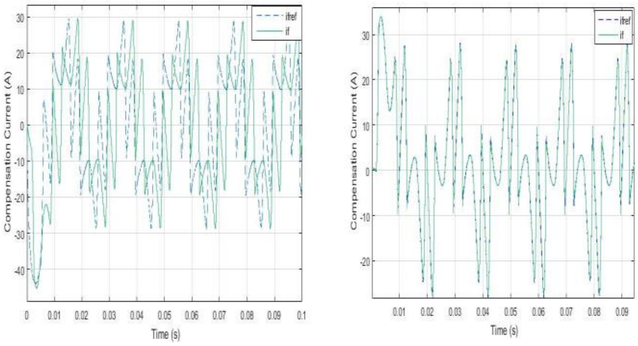

Fig. 7. The compensation current (i_{fa})

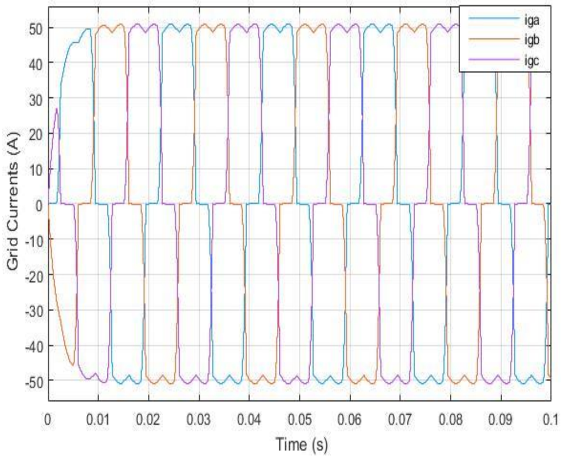

Fig. 8. The grid currents before filtering

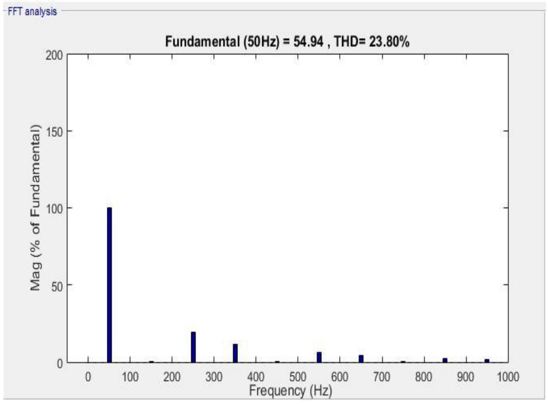

Fig. 9. THD before filtering

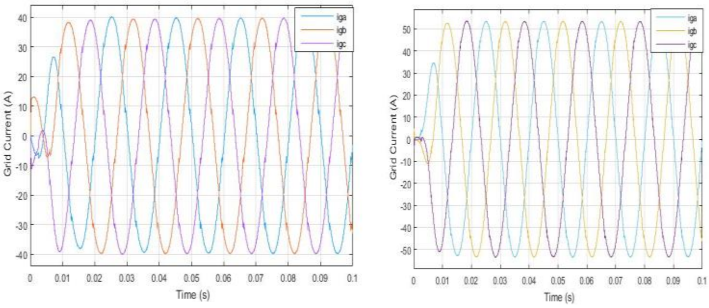

Fig. 10. The grid currents after filtering

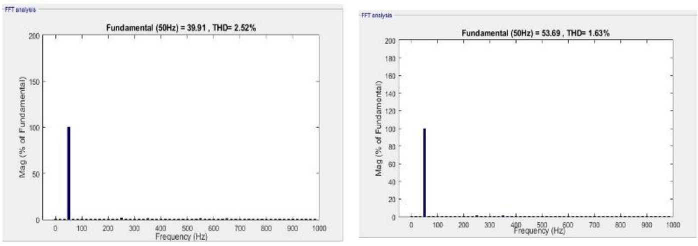

Fig. 11. THD after filtering

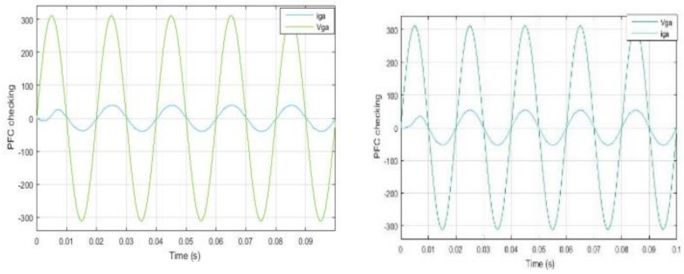

Fig. 12. PFC checking

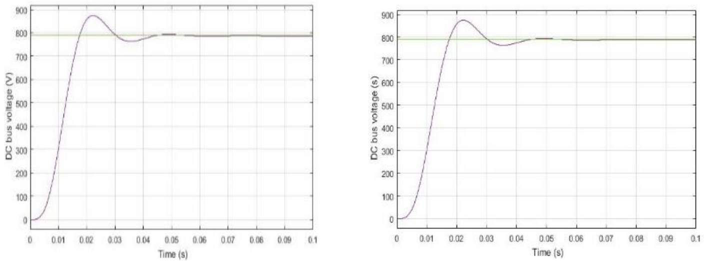

Fig. 13. DC bus voltage

The form in which the current generated by the active filter follows its reference has undergone too improvements as observed in Fig. 7. Flatness control has generated a current shown in Fig. 7 where we see perfectly pursue its reference against the order by PI controller.Fig.9 shows the spectral analysis of the three-phase currents before the filtering, which has a THD of the order of 23.80% ,we notice that the current of the source before the filtering is very rich in harmonic. With the application of the shunt active power filter controlled by two controllers PI and flatness. We obtained the source currents shown in Fig. 10. It is noted that the current source has improved and takes an almost sinusoidal. The harmonic spectrum of the current in Fig.11 shows a THD of 2.52% for the PI controller and 1.63% for the flatness controller. In the Fig. 12, we observe that the current i_{ga} and the source voltage vga are almost in phase, despite a little bit of shift generated by L_f. We can see in Fig.13 the DC bus voltage tracks its reference with a very small ripple.

V. CONCLUSION

We have considered the problem of controlling a three-phase SAPF based on five-level NPC inverter a nonlinear controller is designed using a differential flatness approach based on averaged nonlinear model. From simulation results, the proposed controller has successfully demonstrated better performance of compensation at the same time the harmonic and the reactive currents with a lower THD values which complies with the limit set by alternative standard and the regulation of the voltage with its designed reference finally, it is formally demonstrated that the control objective are actually achieved .

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