Finite Control Set - Model Predictive Control Applied in a Three-Level NPC Acting as Shunt Active Power Filter

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***Abstract*—Considering the widespread use of power electronics in electrical systems, this work uses a three-level Neutral Point Clamped (NPC) voltage source type converter as the base component of a parallel power filter to compensate for undesirable source current components, as well as to improve the power factor of the load. The method chosen to control the current value is called the Finite Control Set Predictive Control (FSC-MPC). By using this control method it is possible to correct the undesirable components of the source current caused by nonlinear loads connected to the grid. The converter switching sequences are defined by minimizing a cost function, which uses the converter output voltage values and system parameters to compute the current value closest to the reference. The algorithm used in this work adopts a prediction horizon of one sampling period.**

***Index Terms*—Active Power Filter, NPC, Finite Control Set Model Predictive**

I. INTRODUCTION

The Electric Power Quality (EPQ) control is an aspect of paramount importance in modern worldwide power scenario, be it in power generation, transmission or distribution [1]. Many factors can influence the EPQ assessment and among those that can intervene in a degrading way, it can be mentioned the introduction of loads that generate harmonics (equipment whose voltage / current relationship is non-linear) in the system [2]. The Active Power Filters (APF), in particular, act directly on this type of anomaly, eliminating undesirable voltage and/or current components from the network.

The Shunt Active Power Filter (SAPF) discussed in this work is the most common configuration among the other topologies [1], such as rectifier circuits embedded in low/medium power equipment and due to its widespread utilization have become a matter of concern. The SAPF is widely employed to eliminate the harmonic components of the load current, as well as to eliminate the circulation of reactive power through the load [3]. This equipment acts on the system establishing the source current as a sinusoidal waveform, containing only the fundamental component in phase with the voltage.

The filter implemented in this paper, depicted in Fig. 1, is formed by a three-phase NPC voltage source type converter [4] and with configuration according to Fig. 2, with inductive filter in its output as means of filtering its own harmonic components, caused by the commutation of the electronic switches. The performance of the equipment will basically depend on two variables, the first being a reference current and the second the control system implemented.

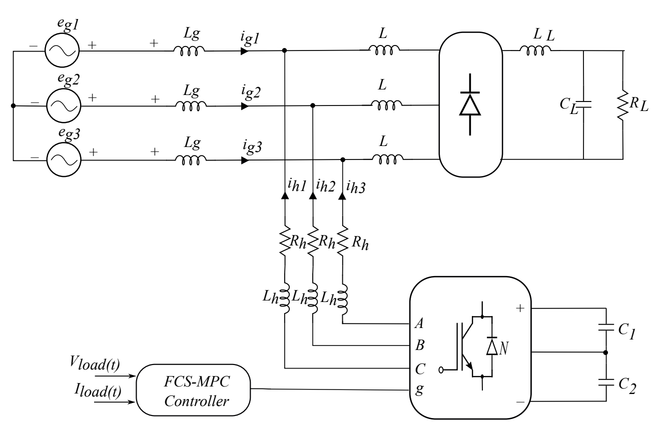

Fig. 1. Three Phase Parallel Active Filter.

In the literature there are many methods that can be used to compensate both current harmonics and power factor, based on time or frequency domain [5]. The technique used in this paper was proposed by Akagi et al. 1983, and it is called the Instantaneous Active and Reactive Power Theory.

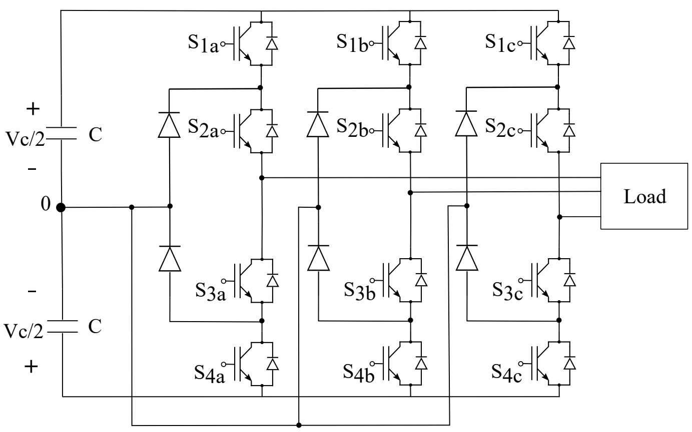

Fig. 2. Three-level Neutral-Point-clamped multilevel inverter.

The PQ Theory, as it is known, is based on the Clarke transform, in which it transforms three-phase voltages or currents into stationary coordinates, $\alpha\beta0$, where p represents the real power flux and q is the imaginary portion that represents the power that does not perform work [1].

Using this method, the power fractions that need to be corrected by the filter will be calculated and the currents that generate those power components will be obtained through the Clarke Inverse Transform [6]. Several control algorithms can be found for the type of filter under study. The control method used in this paper is a specific predictive control algorithm known as Model Predictive Control (FCS-MPC).

This technique is characterized by the use of a system model to predict future behavior of the controlled variable [7], [8]. The values found are used to attain the optimal performance state of the controller. A quadratic function called cost function represents quantitatively the system states and the minimization of this function will determine the next switching states of the filter's converter [9].

The three-phase converter of the filter under analysis has twenty-seven switching states and the Finite Control Set Model Predictive Control (FSC-MPC) algorithm evaluates the cost function for each of these states [10], being updated in every sampling period. This configuration of the MPC, in addition to minimizing the computational effort, has similar results of a continuous time MPC, being able to be implemented in problems that have restrictions and non-linearities.

In [10] the SAPF filter topology is applied to a system with nonlinear RL loads and presented good THD results from the source current. This work evaluates the performance of a Neutral Point Clamped (NPC) converter acting as an active parallel filter with an FSC-MPC type control, connected in an electrical system with non-linear loads.

In order to validate the control effectiveness, the magnitude of the odd harmonics of order 5th, 7th and 11th are compared to the parameters set by international organizations, namely the Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC).

The used reference standards were the IEEE 519 [11] and the IEC 61000 3-2 [12], additionally, the third-order harmonics and its multiples were not considered, because the system under analysis will be three wires and these harmonic components are null [6] and the effect of a harmonics component is inversely proportional to its order of magnitude, [1], for this reason, only those low-order harmonics were analyzed.

The next sections discuss the characteristics of the filter main components. The following section presents the filter topology. Afterwards, an analysis is performed to derive the equations used in the switching optimization control algorithm and the algorithm flowchart is presented. Finally, the article presents the results of the simulations performed in the MATLAB/SIMULINK textit software.

II. SHUNT ACTIVE POWER FILTER TOPOLOGY

In Fig. 1 it can be seen a power filter connected in parallel with a system composed by a three-phase source feeding a load of non-linear nature. The SAPF acts injecting enough current into the electrical system in order to improve the power factor of the load and eliminate the current harmonic components introduced by a nonlinear load. The load is composed of an inductive impedance on the ac side followed by a thyristor full-bridge rectifier connected to a series inductor and parallel resistor-capacitor association.

The filter acts by injecting current at the common coupling point in order to control the source current, making it sinusoidal and in phase with the source voltage. It consists of a three-level NPC, Fig. 2, converter that has two pairs of complementary switches in each phase, producing three voltage levels at its output. The switching states and voltage levels are shown in Table.I.

TABLE I
SWITCHING STATES FOR EACH PHASE OF THE INVERTER.

Voltage Level	Pair N.01		Pair N.02		Vout
	S1	S2	S3	S4	
1	1	0	1	0	VDC/2
2	0	1	1	0	0
3	0	1	0	1	-VDC/2

The filter will have on the ac side an inductive impedance to filter high frequencies and on the dc side will have two capacitors in series serving as dc voltage source and having its midpoint defined as neutral point.

The setup seen in Fig. 1 in the modeling. It is observed that in the filter structure the zero-sequence current has null value, considering components $\alpha\beta0$, [13], for being a three-wire system, [9], so a single-phase circuit can represent the system model as can be seen in Fig. 3. Applying Kirchhoff's Current Law at the common coupling point of the system, the relation is reached:

$$I_l = I_g + I_h \tag{1}$$

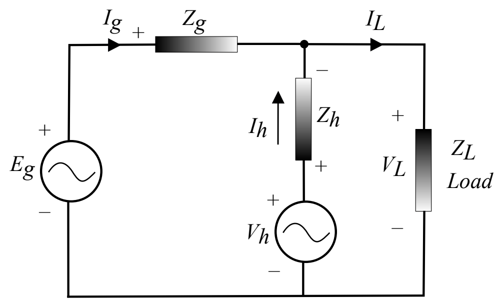

Fig. 3. Parallel Active Filter Mesh Model.

Being I_l the load current, I_g the source current and I_h representing the current flowing through the filter. From the manipulation of (1) and the use of Kirchhoff's Voltage Law, supply voltage can be derived in function of the voltages that are present in the system:

$$E_g = Z_g I_g + V_h - Z_h I_h \tag{2}$$

E_g is the source voltage, V_h is the output voltage of the filter and impedance Z_h is the equivalent filter impedance, $R_h + jwl_h$. Through (2) and assuming the source impedance tends to zero it is possible to obtain the differential equation of the system.

$$L_h \frac{dI_h}{dt} = V_h - R_h I_h - E_g \tag{3}$$

III. CONTROL CHARACTERISTICS

The control method used is a factor of great importance in the performance of filter, depending on the variables to be controlled. The control algorithm is based on three calculation fronts:

- Calculation of Predicted Currents.
- Calculation of Reference Currents.
- Minimization of the Cost Function.

A. Calculation of Predicted Currents

The FSC-MPC control uses an equivalent discrete model of the system. Using (3),and replacing the derivative of the filter current with an equivalent approximation of Euler [9]:

$$\frac{di_g}{dt} \approx \frac{i_g(t+1) - i_g(t)}{Ts} \tag{4}$$

where *t* represents the discrete time instant and *Ts* the sampling period of the controller. Thus, it can be found the discrete equivalent expression that allows the computation of the predicted output current of the filter at the instant *(t+1)*.

$$L_h\left(\frac{I_h(t+1) - I_h(t)}{Ts}\right) = V_h(t) - R_h I_h(t) - E_g(t) \tag{5}$$

so,

$$I_h(t+1) = \left(1 - \frac{R_h Ts}{L_h}\right) I_h(t) + \frac{Ts}{L_h}(V_h(t) - E_g(t)) \tag{6}$$

From (6) it is possible to determine the current to be compensated for each estimated value of $V(t)_h$, which represents the voltage vector for each switching state of the inverter, as observed in Table.I .

B. Reference Currents Calculation

The reference currents have the role of compensating for all the harmonic components that differ from the fundamental component. Such reference values are generated using the source voltage, filter current and dc bus voltage Fig. 4 shows the calculation block for the references. First of all, the voltages used for reference generation are applied to the positive sequence detector block, such as the Fig 4, where $a = e^{j2\pi/3}$.

In PQ Theory the powers are divided into mean powers $\overline{p}\ \overline{q}$ and oscillating powers $\tilde{p}\tilde{q}$. [1].The oscillating parts represent a flow of power between the three phases and do not represent power exchange between source and load. In this work the components $\tilde{p}\tilde{q}$ are responsible for the presence of harmonics in the load current and combined with $\overline{q}$ (average reactive power of the system) are components used to generate the reference. For the calculation of the oscillating part of p a low pass filter is used with cut off frequency equal to 60 Hz and unit damping factor, as can be seen in Fig. 4.

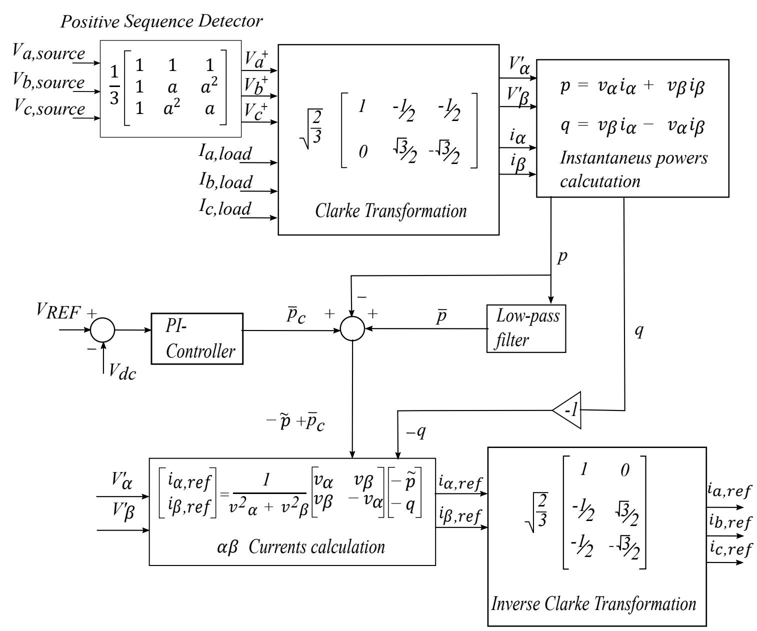

Fig. 4. Reference Generator Block.

The input component p_c is calculated by the difference between the present voltage value of the dc side and a constant voltage reference, applied to a PI controller, expressed as:

$$p_c = k_p(V_{REF} - V_{dc}) + k_i \int_{-\infty}^{t} (V_{REF} - V_{dc}) \tag{7}$$

with V_{dc} voltage present of the dc side, k_p and k_i the proportional and integral gains respectively. This power value refers to the power required to keep the dc side capacitor voltage constant. Thus, p_c will be added the oscillating part of the average power for the calculation of the references. Considering that the analyzed system is balanced, there will be no contribution from the zero sequence component, so it will be disregarded.

C. Cost Function Minimization

The cost function, evaluates the error between the predicted currents and the references [9] so that future source currents follow the desired reference. The converter used in this paper is three-phase three-level, presenting 27 switching states that apply 19 voltage vectors as seen in Fig. 5.

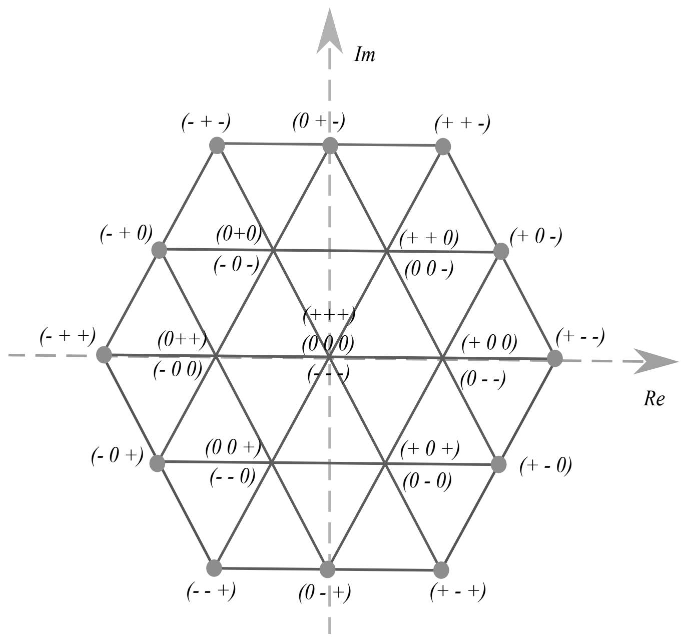

Fig. 5. Voltage vectors generated by NPC three-level converter.

Then the switching state that promotes the smaller prediction error is applied to the filter. In Fig. 6 all steps of the filter control algorithm are shown and the cost function shown will be as follows.

$$g = \mid I_{ref} - I_h(t+1) \mid_\alpha + \mid I_{ref} - I_h(t+1) \mid_\beta \quad (8)$$

with α and β representing the real and imaginary stationary variables, respectively.

Through the diagram it is possible to see that the cost function is evaluated in the 27 switching states of the converter. When the value that minimizes the cost function is found, the switching state is chosen and applied in the next sampling period, according to the voltage vectors of Table.I.

IV. RESULTS

In order to analyze the efficiency of the FSC-MPC control strategy applied to the SAPF in steady state, the chosen tool was the software MATLAB / Simulink. The values used in the simulation are in Table II.

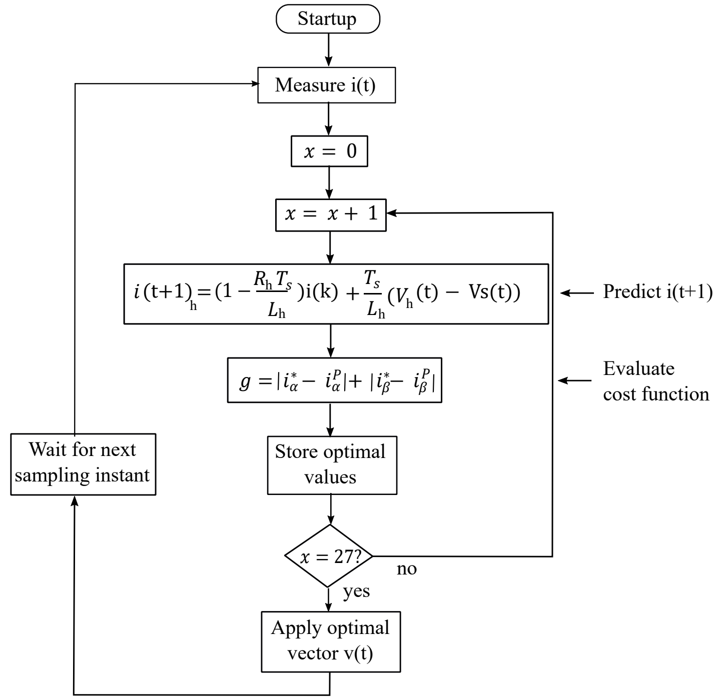

Fig. 6. Control Diagram.

TABLE II
SIMULATION PARAMETERS.

Parameter		***Value***
V_g	Source Voltage ph-ph	380 V
f_g	System Frequency	60 Hz
L_g	Line Indutance	76.61 μH
R_g	Line Resistance	28.88 mΩ
L_l	Load Indutance	2 mH
C_l	Load Capacitance	10 μC
R_l	Load Resistance	50 mΩ

The parameters were inserted in a model according to Fig. 1,The SAPF is composed of a three-phase converter whose dc side is connected to capacitor of $4400uF$ and the ac output is connected to the coupling point through a filter with inductive characteristics of $4.4mH$ and $10m\Omega$.

As a way of introducing a distorted current into the system, a non-linear load consisting of a three-phase thyristor rectifier bridge was used, feeding an RLC load, with characteristics according to Table II.The controller algorithm operates with a sampling period of $10us$.

With the system operating with full load and without the actuation of the SAPF, the distorted current of the source is seen in as in Fig. 7. After the action of the controller, the current of the source begins to have a sinusoidal waveform and is in phase with the voltage of the source, as can be seen in Fig. 8.

The power factor of the load becomes close to the unit, with a value o 0.97, Fig. 9 and the Total Harmonic Distortion (THD) of the source current has a reduction of 30.01% to only 2.41% and as seen in the Table III and Table IV. The individual values of the analyzed harmonics were within the levels claimed as acceptable by IEEE-519, but with respect to IEC 61000 3-2, the results exceeded the limit values for the 3rd and 7th harmonics.

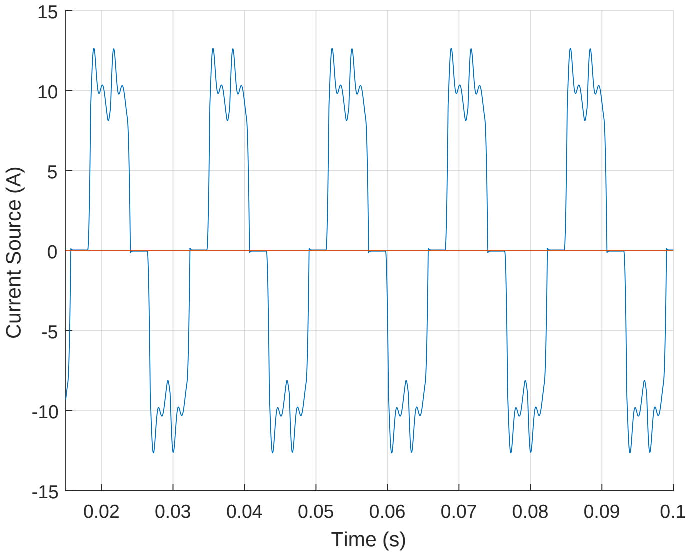

Fig. 7. Source Current Without Filter Action.

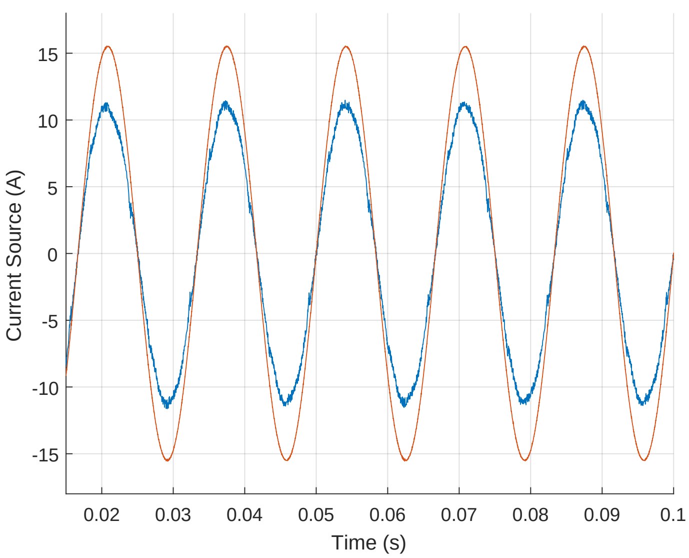

Fig. 8. Source Current After Filter Action.

TABLE III
COMPARISON BETWEEN THE IEEE-519-RECOMMENDED DISTORTION AND THE VALUE MEASURED WITH THE FILTER.

Distortion	**Order of Harmonics**				
	5°	7°	11°	13°	THD
Recommended	12	12	5.5	5.5	15
Measured	0.57	1.529	0.797	0.558	2.41

TABLE IV
COMPARISON BETWEEN THE IEC 61000 3-2-RECOMMENDED DISTORTION AND THE VALUE MEASURED WITH THE FILTER.

Distortion	**Order of Harmonics**			
	5°	7°	11°	13°
Recommended	1.14	0.77	0.33	0.21
Measured	0.57	1.529	0.797	0.558

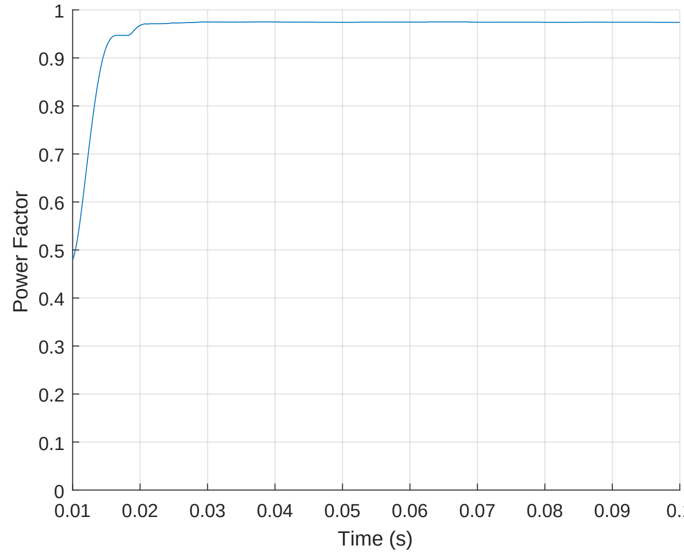

Fig. 9. Load Power Factor.

It can be noticed that the FCS-MPC control provides to the filter fast response dynamics, as it takes less than a period to compensate the transients, guaranteeing continuous compensation. An average switching frequency of $8kHz$ was achieved with the selected sampling period.

The Fig. 10 shows the capacitor voltage at the dc side of the filter with which it is possible to see a good load dynamics

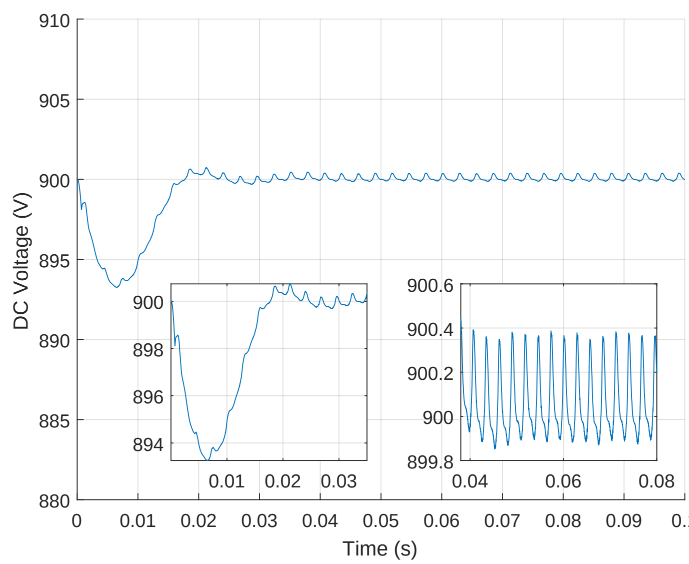

Fig. 10. dc Voltage.

The Fig. 11 shows the percentage of harmonics in relation to the fundamental frequency, as a way to further evidence the effectiveness of the topology used.

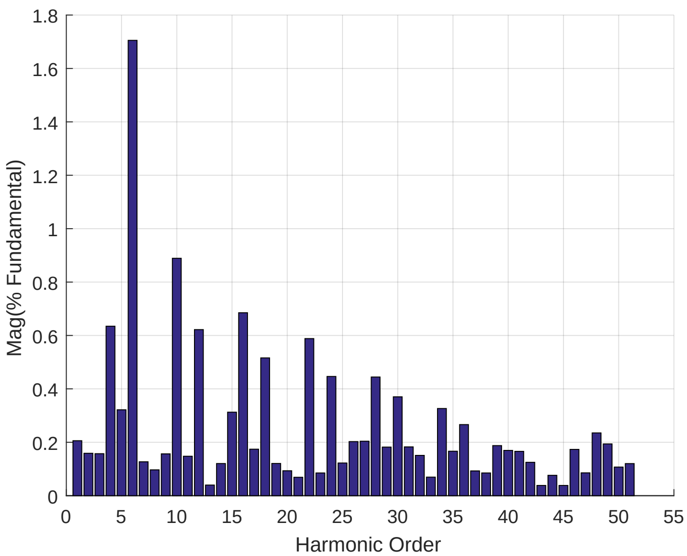

Fig. 11. Harmonic Distortion of I_g After Compensation.

V. CONCLUSION

In present day electrical systems the maintenance of the dynamism, quality and efficiency of power distribution are factors with rigorous standards. In this context, this paper presents a powerful tool to reduce the THD of a system with nonlinear loads. The FSC-MPC method is used as a way to control the switching of a three-level NPC converter, acting in the system as a Shunt Active Power Filter.

The control algorithm selects the optimal switching position from the 27 possible, and each switch position has a voltage level that is choosen by minimizing the cost function. The references are variable, dependent on system parameters and computed using the p-q Theory.

The control system was effective and was able to eliminate harmonic components from the source current as well as maintain the DC bus voltage. The THD of the source current had a considerable reduction, regarding the IEC and IEEE standards.

This proves the effectiveness of the control method in a SAPF, even under nonlinear conditions. As future work, it is suggested the application of the control technique to a Universal Power Filter (UPF). The UPF is composed by a Shunt Filter and a Series Filter sharing the DC bus [3] and its analysis are of great value to deepen the studies of the FSC-MPC method.

VI. ACKNOWLEDGMENTS

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