Active power filter with selective control for reducing harmonic in photovoltaic systems

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Abstract—**In order to to improve the power quality from energy generated by the photovoltaic systems connected to the network, this paper presents the results of two types of filters, first the active power filter with conventional control scheme and second, active power filter with a selective control scheme in order to reduce the harmonic content injected by the inverter in a photovoltaic system. The results are presented and compared by means of harmonic distortion (individual and THD). This is a novel proposal, since studies before to this, always have been interested in the compensation of harmonics arising from non-linear loads but rarely from a voltage source, as in this case.**

Index Terms— **Active power filters (APFs), power quality, harmonics current, photovoltaic inverter, selective control**

I. INTRODUCTION

Nowadays the use of generation of clean and renewable energy, as is the case of photovoltaic systems, has been gradually becoming a viable alternative within the diagrams of distributed generation. The use of these clean energies is becoming a common practice in the world, with an annual growth rate of 16%.

To convert solar radiation into electrical energy is necessary the use a system composed of photovoltaic components. For systems connected to the network, the components are: photovoltaic field, photovoltaic inverter, protection devices and the energy meter. The photovoltaic inverter generates and injects harmonic content to the network, due to its switching during the conversion process of direct current (DC) to alternating current (AC), being able to produce a negative impact on it, as well as in the final users. This performance is not presented in other types of generation systems because they do not inject harmonic content to the network during the generation process.

The motivation of this work is to improve the power quality from the photovoltaic systems connected to the network, compensating the harmonic content injected by the photovoltaic inverter using active power filters (APFs). Two types of filters are going to be considered, conventional control scheme and selective control scheme. That is an innovative aspect within the literature, since studies prior to this, always have been interested in the compensation of harmonics from non-linear loads but rarely from a voltage source.

The active filters are designed to take into account the operating characteristics and harmonic content of the photovoltaic inverter and, therefore, it adapts by itself to the dynamic operating conditions of the photovoltaic system (due to the stochastic nature of the solar radiation). When a conventional control is used, the filter controls the entire harmonics as a total, whereas the selective control eliminates the harmonics individually by means of selective regulators that treat every harmonic separately. The second one can control the harmonics more efficiently as is shown in this paper, due to the selective regulators improve the response of the filter because the filter is tuned to the specific frequencies (for example harmonics 3rd, 5th, 7th and 9th).

II. CURRENT HARMONICS GENERATED BY PHOTOVOLTAIC SYSTEMS

The photovoltaic systems connected to the network are able to generate currents harmonic during the conversion process from DC to AC. This conversion process happens across the inverters which are composed of power electronic devices that constitute a current source that inject harmonics to the network.

The current harmonic generated by the photovoltaic systems is related to the performance of the inverter under different load conditions. Consequently, the harmonic distortion generated by the photovoltaic systems depends strongly from the generated power, when this power is low, the harmonic distortion is high; on the other hand, the harmonic distortion is low. This behavior is appreciated clearly in Figure 1, which shows the change of the total harmonic distortion of current (THD_i) of a photovoltaic generator[1] in regard to the generation rate P_G/P_n, where P_G is the generated power by the photovoltaic system and P_n is the nominal power of the photovoltaic generator.

The analysis of the harmonic distortion caused by the photovoltaic system at the point of common coupling (PCC) is, at first, similar to the analysis that is realized to determine the harmonic content caused in an isolated system of interconnected inverters. Nevertheless, also takes into account some peculiarities as the influence of climate variables as: the temperature, solar radiation and shadow effect. These variables impact significantly on the current and voltage waveform and establish the operating conditions and generation.

[1] P_n=5 kW; frequency PWM 16 kHz; without transformer.

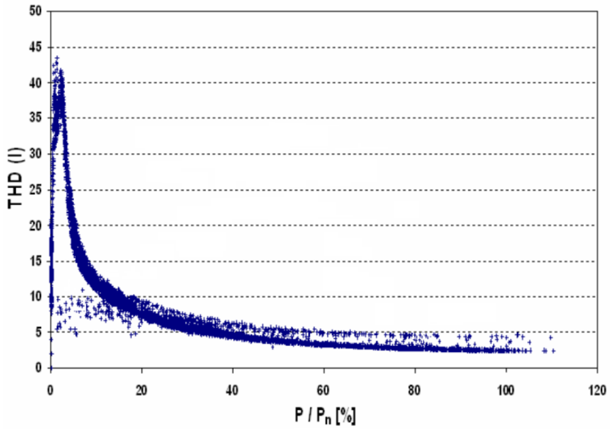

Fig. 1. Total harmonic distortion of a photovoltaic inverter ($P_{DC/AC}$=5 kW) for different loading conditions [11]

All types of photovoltaic inverter can be characterized by a similar dependency between the harmonic current injected to the network and the generated power. Figure 2 shows the THD_i and the generated power of an inverter of 5 kW throughout one summer day. During the ignition and shutdown of the generator, in the dawn and at nightfall respectively, the THD_i for about 5 hours is higher than during the rest of the day.

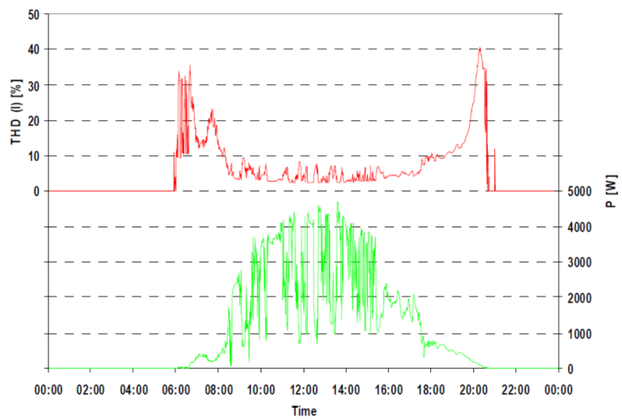

Fig. 2. THD_i (upper curve) and generated power (lower curve) of the photovoltaic inverter ($P_{DC/AC}$=5 kW) [11]

The individual current harmonics have a behavior similar to the THD_i, especially the harmonics of the lowest order. Figure 3 shows the relative values of the odd current harmonics for different load conditions in the inverter of 5 kW. The even harmonics are negligible and they will not be considered, because their magnitudes are very low. Whereas, the harmonics of order 3rd, 5th, 7th and 9th will be studied by special care, because they are the highest generated by the inverter.

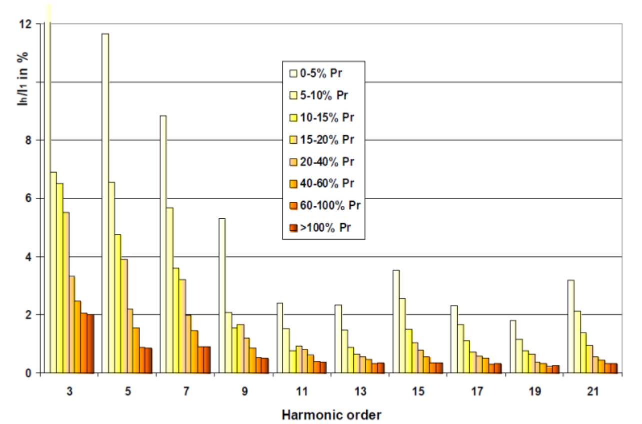

Fig. 3. Current harmonics of the photovoltaic inverter ($P_{DC/AC}$=5 kW) for different loading conditions [11]

III. Control of Shunt Active Power Filter

Figure 4 shows the scheme of a shunt APF connected to the network. In the same point, there are a linear load and the photovoltaic system, which makes circulate current harmonics to the main electrical supply. The main goal of the APF control is to compensate the current harmonics that the photovoltaic system injects to the network in order to avoid that these harmonics travel to the rest of the electrical system.

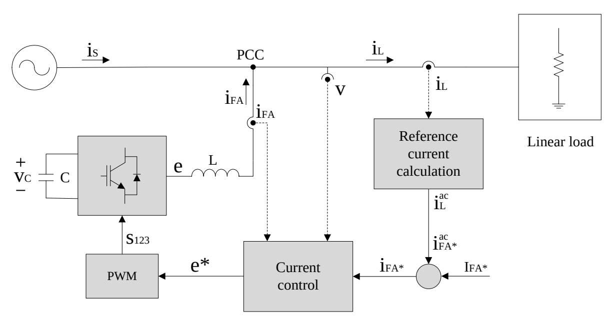

Fig. 4. Schematic diagram of the simulation with linear load

The control system of the shunt APF was divided in two parts: internal control and selective control. The internal control of the shunt active filter has the goal of control the output current and, simultaneously, the voltage of the capacitors of the DC stage . Whereas, selective control has the task of improving the response of the shunt active filter for specific harmonics [10].

A. *Internal control model of APF.*

The dynamic equations of the shunt APF is divided in two: the equations of network connection, the equations of power exchange and the equations of DC circuit. In order to make easier the control techniques, the Park's transformation is used to change the three-phase reference system (in axis *a*, *b* and *c*) of the shunt APF, to another orthogonal and equivalent reference system in axis 0, *d* and *q* [8].

Applying the transformation to the dynamic equations of the shunt APF, is obtained:

1) Equations of the network connection circuit [9]:

$$e_d - v_d = Ri_{FAd} - L\omega_1 i_q + L\frac{di_{FAd}}{dt} \quad (1)$$

$$e_q - v_q = Ri_{FAq} + L\omega_1 i_d + L\frac{di_{FAq}}{dt} \quad (2)$$

where R and L are the resistance and inductance of each coil connection to the network. The subscripts d and q indicate the component in axis d and q, respectively.

2) Equations of power exchange [9]:

$$p = v_d i_{FAd} + v_q i_{FAq} \quad (3)$$

$$q = v_d i_{FAq} + v_q i_{FAd} \quad (4)$$

where p and q are the instantaneous active and reactive power injected by the shunt APF to the system.

3) Equation of the DC circuit [9]:

$$\frac{1}{2}C\frac{dv_C^2}{dt} = -p \quad (5)$$

where C is the total capacitance and p is the power supplied by the capacitors. If v_C^2 is a state variable, the equation (5) is linear, in this case, the losses of the coils connection to the network are negligible, consequently, equation (3) is the same with p of the DC circuit.

Commonly, the control system of the shunt APF is implemented in a digital platform. Consequently, the equations of the network connection circuit, equations (1) and (2), have to be discretized with a transformation (for a retainer of order zero), as it was made in [4] and [6]. In state variables the connection system is represented by:

$$\begin{bmatrix} i_{FAd}(k+1) \\ i_{FAq}(k+1) \end{bmatrix} = \underbrace{\begin{bmatrix} \phi_1 & \phi_2 \\ -\phi_2 & \phi_1 \end{bmatrix}}_{\Phi} \underbrace{\begin{bmatrix} i_{FAd}(k) \\ i_{FAq}(k) \end{bmatrix}}_{i_{FAdq(k)}} + \underbrace{\begin{bmatrix} \gamma_1 & \gamma_2 \\ -\gamma_2 & \gamma_1 \end{bmatrix}}_{\Gamma} \underbrace{\begin{bmatrix} e_d(k) - v_d(k) \\ e_q(k) - v_q(k) \end{bmatrix}}_{\Delta e_{dq}(k)} \quad (6)$$

where $\mathbf{\Phi}$ and $\mathbf{\Gamma}$ are the state matrixes at discrete time.

B. Selective Control for APF

The selective control is a technique of linear control that is based on Internal Model Principle (IMP) [3]. This technique establishes that to follow a waveform without error is necessary to include its model in the regulator of the control system. Therefore, to follow a sinusoidal waveform without error is possible to include in the model this expression:

$$S_h(s) = K_h \frac{s}{s^2 + (2h\pi/T_p)^2} \quad (7)$$

where K_h is the gain of the transfer function, T_p is the period of the waveform and h is the harmonic component.

It is necessary to clarify that to eliminate several harmonic frequencies is necessary to include, inside the control loop, so many transfer functions (7) in series or in parallel as harmonic to be eliminated.

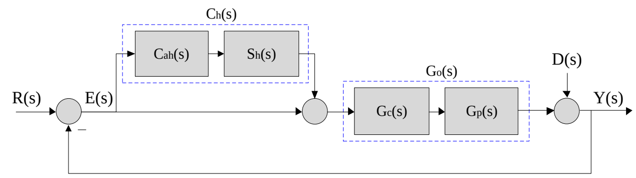

Fig. 5. Selective controller structure in continuous-time

Figure 5 shows the block diagram of a selective regulator in continuous time. In this case, the selective regulator is included, $G_p(s)$, it is controlled by a conventional regulator, $G_c(s)$. The selective regulator is represented by [5]:

$$C_h(s) = \underbrace{\frac{1+(\alpha_c/\omega_h)s}{1+f(\alpha_c/\omega_h)s}}_{C_{ah}(s)} \cdot \underbrace{\frac{K_h\omega_h s}{s^2+\omega_h^2}}_{S_h(s)} \quad (8)$$

where $S_h(s)$ is the model of the sinusoidal waveform and $C_{ah}(s)$ is a compensation network added to stabilize the system.

The control algorithms used in this work, for the implementation of the active filter with selective compensation, have been designed and proved for non-linear loads [10], however, they have been modified in order to represent the harmonic content presents in the photovoltaic systems, where the harmonics more representative are 3rd, 5th, 7th and 9th [11]. The main function of these control algorithms is to eliminate individual current harmonics by means of selective regulators, which is tuned at specific frequencies reducing the monitoring error in the control system.

There have been designed two selective regulators $C_4(s)$ and $C_8(s)$, for the harmonics 4th and 8th in *dq0* components, which are equivalent to the harmonic 3rd, 5th, 7th and 9th in the three-phase *abc* system.

IV. Results

The results of the APF prototype have been validated by means of simulation. Figure 4 represents the schematic diagram of the photovoltaic system with linear load and shunt APF. For this case, the only harmonic source in the system is represented by the photovoltaic inverter and, therefore, the APF will have to compensate selectively the harmonics injected from the photovoltaic system.

Given that the harmonic content depends and changes with the load conditions of the photovoltaic system, for that reason, more representative load conditions have been considered to evaluate the flexibility and performance of the APF proposed, taking into account dynamic changes in the electrical parameters of the system. The APF must fit continuously to all operational condition; these conditions are dynamics due to the changes in the weather variables that define the performance of the photovoltaic system. The load conditions used were:

- Very low load: between 5 % and 10 % of the nominal power of the photovoltaic inverter. This case represents the most adverse operation condition, because the harmonic content is the highest according to Fig. 2.
- Low load: between 10 % and 20 % of the nominal power of the photovoltaic inverter.
- Medium load: Between 40 % and 50 % of the nominal power of the photovoltaic inverter.

The case of high load has not been considered in this work because this load condition in the photovoltaic system has not a representative harmonic content, as it was shown in Figure 3.

TABLE 1. Cases considered during the simulation

Loading conditions of the photovoltaic inverter	Type of load	Simulation case
Very low load	Linear	Case I
Very low load with harmonics 3rd and 5th tripled	Linear	Case II
Low load	Linear	Case III
Medium load	Linear	Case IV

Table I summarizes the cases simulated with the APF proposed in this work. The main purpose of these simulations is to verify that the filter injects correctly the currents to compensate the harmonic current distortion generated by the photovoltaic inverter. In all cases, the simulations tried to guaranty, as close as possible, characteristic and conditions of a real installation.

As previously mentioned, in the photovoltaic system the inverter is the main responsible of the harmonic injection to the network, therefore to reproduce the harmonic content is enough to represent the inverter by means of the voltage source at fundamental frequency (60 Hz) and current sources at specific frequencies to simulate the harmonic content according to the cases described in Table 1 [11].

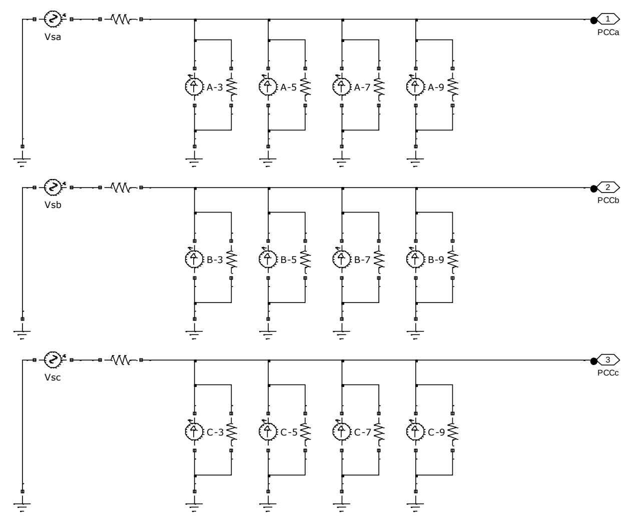

Fig. 6. Representation of the photovoltaic inverter

For the simulation was used a three-phase photovoltaic inverter of 500 kW; technical data was obtained from the Inverters Catalogue of Schneider Electric.

The photovoltaic inverter has been simulated as a voltage source in parallel with current sources, such as in Figure 6. The voltage source is responsible for supplying the fundamental current and fixing the voltage level of the system; whereas, the current sources are responsible for generating the harmonic currents that, as a whole, represent the harmonic content injected by the inverter.

A. Case I.

The results obtained with and without the use of the APF proposed are summarized.

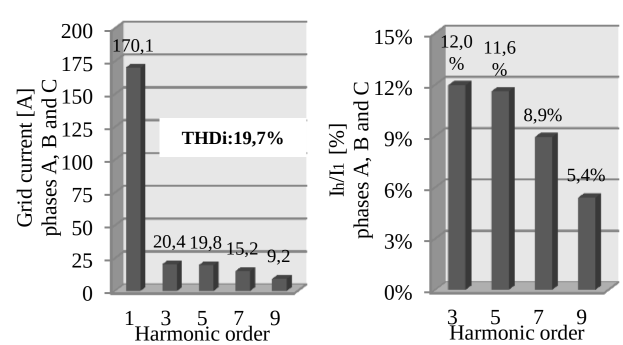

Fig. 7. Current harmonics in the network without APF with selective controller for Case I

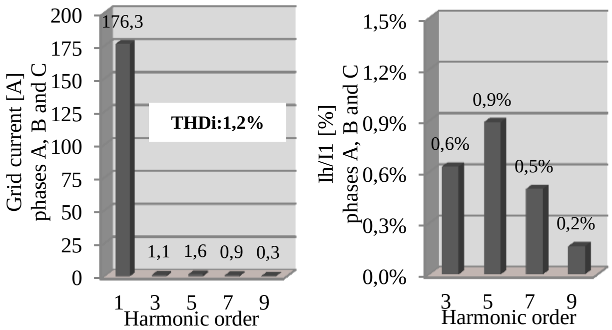

Fig. 8. Current harmonic in the network with APF with selective controller for Case I

The results show that the APF proposed compensates the current harmonics and, consequently, reduces the THD_i in the network (from 19,7 % to 1,2 %). This reduction is reached because the filter injects the current harmonics of equal magnitude but in negative phase to the harmonics injected by the photovoltaic inverter.

B. Case II.

The results show again that the APF proposed compensates the current harmonics, including those of high magnitude, as well, reduces the THD_i in the network (from 51,1 % to 1,3 %). These results indicate that the APF proposed is highly selective to identify and to compensate those individual harmonics of high magnitude, as it is shown in Figure 10 whit the harmonics 3rd and 5th, whose magnitudes were tripled; the filter reduced them near to 1%.

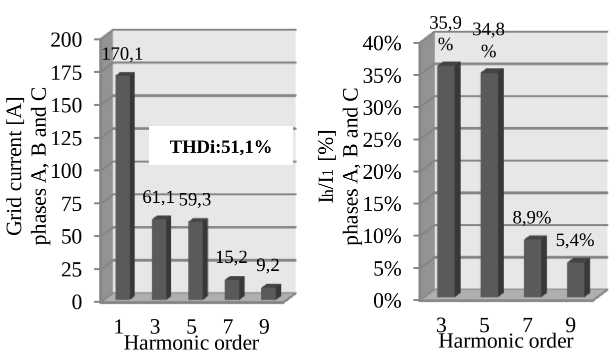

Fig. 9. Current harmonics in the network without APF with selective controller for Case II

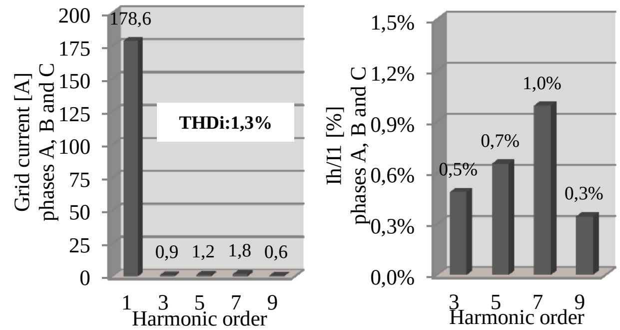

Fig. 10. Current harmonics in the network with APF with selective controller for Case II

C. Case III.

The results show that the APF proposed compensates individually the current harmonics and, consequently, reduces the THD_i in the network (from 9,9 % to 0,7 %).

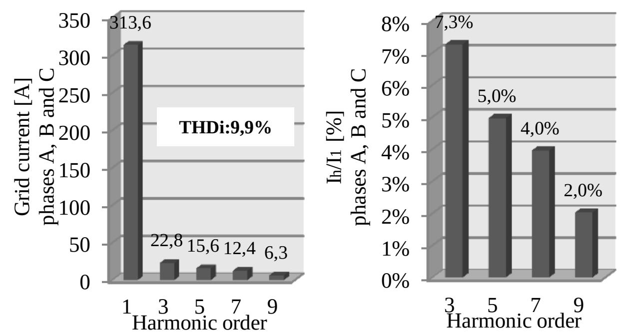

Fig. 11. Current harmonics in the network without APF with selective controller for Case III

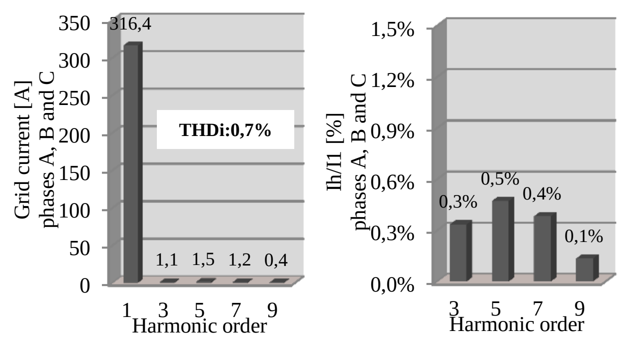

Fig. 12. Current harmonics in the network with APF with selective controller for Case III

D. *Case IV.*

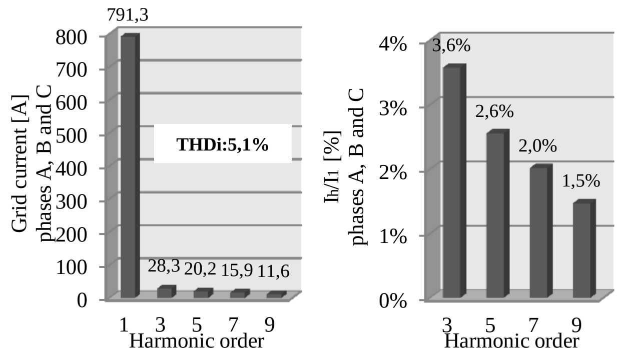

Fig. 13. Current harmonics in the network without APF with selective controller for Case IV

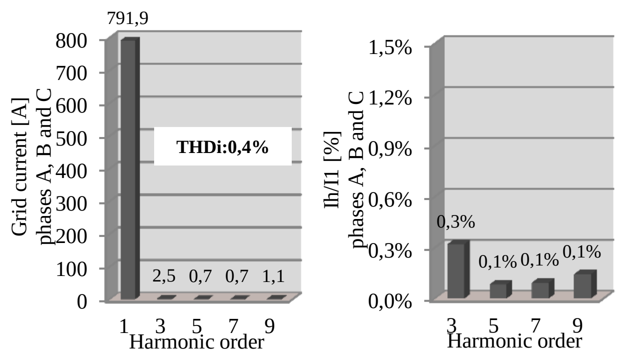

Fig. 14. Current harmonics in the network with APF with selective controller for Case IV

Once again, the results show that the APF proposed compensates current harmonic and, consequently, reduces the THD_i in the network (from 5,1 % to 0,4 %).

V. Conclusions

The harmonic current generated by the photovoltaic inverter depends strongly on the power generated by the photovoltaic system: when the generated power is low, the harmonic distortion is high; on the other hand, the harmonic distortion is low. They were modeled four loud cases and the results were presented.

The APF proposed was tuned at specific frequencies to inject current harmonics of equal magnitude but in negative phase to the harmonics injected by the photovoltaic inverter in order to reduce the individual harmonics and THDi. The results were satisfactory.

The APF proposed was highly selective to identify and to compensate those individual harmonics of high magnitude, for example, the harmonics 3rd and 5th were tripled from the original values presented in in Figure 3, and the APF reduced them to low values.

The APF proposed was able to reduce the harmonic content and THDi from photovoltaic systems to low levels for different load sceneries, according to international standard IEEE 519. The APF was compared with other conventional control loops (no selective control), and the APF shows the best results.

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