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Intelligent Solar Shunt Active Power Filter Based on Direct Power Control Strategy

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ABSTRACT

This paper deals with a double-stage grid-connected photovoltaic (PV) system, operating as a shunt active power filter in order to improve the power quality and to supply the extracted PV power to the utility, simultaneously. On the grid side, a direct power control (DPC) is developed to supply the harvested PV energy into the electrical network based on the provided reference, which is estimated for unwanted harmonics and reactive power eliminations. On the PV side, an intelligent method of tracking the maximum power point based on fuzzy logic has been adopted to eventually solve the problem of the rapidly changing weather conditions. The overall control scheme is examined by simulation using MATLAB/Simulink software. The obtained simulation results demonstrate the feasibility, performance, and robustness of these control strategies under different test conditions.

KEY WORDS

Direct power control; Parallel active power filter; IP controller; Solar photovoltaic System; Fuzzy logic MPPT controller

I. INTRODUCTION

So far, most of the world's energy is produced from fossil fuels (coal, oil, and gas). The consumption of these energy sources contributes to harmful gas emissions which are heavily involved in the global warming, as well as inducing pollution of the earth and organisms [1]. The excessive consumption of non-renewable natural resources systematically leads to the reduction of reserves of this kind of energy potential whose repercussions will be harmful to future generations. Moreover, energy production is still a challenge of great importance for the coming years since it is employed almost everywhere, i.e., in residential, commercial, and industrial areas. On the other hand, the regeneration of renewable energies such as hydroelectric, geothermal, biomass, wind, and PV operates without pollution effects on the atmosphere after using one of these energies [2]. The availability of solar energy as an environment-friendly, unlimited, and free energy on the entire globe surface [1] has prompted researchers to select it among other existing sources of renewable energy for study and investigation.

Meanwhile, the rapid growth of nonlinear loads integration causes serious problems in the electrical power systems, such as the harmonic currents and reactive power [3-6]. Active power filters (APF) are the most popular solution for mitigating these unwanted issues in the electrical grids [7]. Within the APF family, the shunt active power filter (SAPF), which is paralleled to the grid to inject a current that is opposing both the current harmonics and reactive power emitted by the load, is commonly employed. After the APF is integrated, it eventually makes the current supplied by the electrical power system sinusoidal and in phase with its voltage [8]. In the literature, many control strategies have been presented to control the APF. One among the popular ones is Direct Power Control (DPC), which is does not require current control loops or pulse-width-modulator (PWM) blocks. The switching table based on the correction of the reactive and active powers, as well as based on the sector indicating the angular position of the source voltage vector, is intended to select the switching states of the converter [7-9]. In most cases, the DPC is fed by a reference of zero reactive power and active one produced via the Integral-Proportional (IP) regulator of the converter dc-link voltage [7].

As the solar insolation varies, several algorithms of maximum power point tracking (MPPT) [1, 2], [10-12] such as perturb and observe (P&O), incremental conductance (IC) and hill climbing (HC) have been proposed [1, 2], [10]. Due to the deficiencies of the aforementioned algorithms especially during dynamically changing weather conditions, intelligent controllers like fuzzy logic has been used in tracking the maximum power point in PV systems [11, 12].

In this paper, a new control scheme composed of two layers, where the first layer consists of controlling the SAPF through DPC approach, while the second layer consists of tracking the MPP of the PV array using fuzzy logic, is proposed. The introduced modification offers greatly improved performance of the overall system as will be shown later. This paper includes the following sections: Description of the operating principle of the SAPF is presented in Section II; The principle of the DPC controller applied to the SAPF, integral-proportional to regulates the DC- link voltage, and fuzzy logic controller (FLC) for tracking the maximum power point, are presented in section III. Simulation results are given and discussed in section IV. Finally, the presented work is concluded in section V.

II. GENERAL DESCRIPTION OF THE SAPF

APFs are, in simple words, systems that are used to eliminate the harmonics pollution along the power line caused by the non linear loads, as well as the reactive power induced by the loads regardless of their nature [3]. The voltage source connected in parallel with the non-linear load, becomes almost sinusoidal since the SAPF injects harmonic currents with the same amplitude and opposite in phase with the load's one. Regarding the reactive power, it is compensated by injecting filtering current with a phase that is opposed to the line's one [4-8]. In this way, the source's current would have the following form [7-13]:

$$I_s = I_l + I_f \tag{1}$$

where I_s is the current of source; I_l is the current of the load; and I_f is the compensation current.

III. DESCRIPTION OF THE PROPOSED CONTROL SYSTEM

The basic principle of DPC was inspired from the direct torque control (DTC) of electrical machines [7, 9]. In the DPC approach, reactive and active powers imitate, respectively, the electromagnetic torque and the amplitude of the stator flux of the DTC. This non-linear method is known as a direct power control technique because it chooses the appropriate voltage vector without need for any modulation technique or coordinates transformation. The basic concept of the DPC is to select the appropriate switching state from the switching table based on localisation of the source voltage vector and errors [3]. These errors are limited by a hysteresis band corresponding to the reactive and active powers as depicted in Fig. 1. The instantaneous active and reactive powers are calculated starting from the following equations:

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

$$Q_s = \frac{1}{\sqrt{3}}\left[\left(V_{sb} - V_{sc}\right) I_{sa} + \left(V_{sc} - V_{sa}\right) I_{sb} + \left(V_{sa} - V_{sb}\right) I_{sc}\right] \tag{3}$$

$$S_s = P_s + jQ_s \tag{4}$$

The reference of the reactive power is maintained at zero to ensure a unity power factor, whereas the reference of the active power is developed by multiplying the peak value of the current source generated by the IP regulator and the optimal value of the PV generator voltage. This method is based on two hysteresis regulators using as input the error signal between the references values and the calculated reactive and active powers. Then, the powers are compared with their respective references and the obtained errors are applied to the hysteresis regulators [7, 8], [13].The used hysteresis regulators permit maintaining the errors of the instantaneous reactive and active powers in predefined bands. The output of the controller switches between 0 and 1. If the error is positive, the controller output is equal to 1, otherwise it is 0. The switching table has as inputs the signals from the two outputs of the hysteresis comparators and an information on the localization of the source voltage vector.

The angle between the α axis and the inverter output voltage reference is determined by an inverse trigonometric function based on the vector components of the voltage in the fixed reference frame (*α, β*) and the output one as follows:

$$\theta_p = \tan^{-1}\left(\frac{V_{s\beta}}{V_{sa}}\right). \text{ p=1, 2, ..., 12.} \tag{5}$$

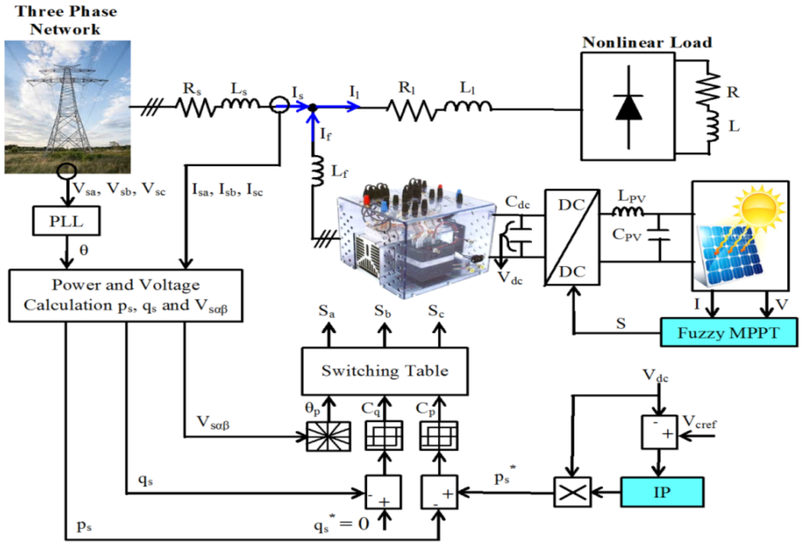

Fig. 1. General structure of the SAPF controlled by the proposed DPC approach, considering the inclusion of a PV system.

Table 1. Switching table for the DPC strategy.

C_p	C_q	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
1	1	v_6	v_7	v_1	v_0	v_2	v_7	v_3	v_0	v_4	v_7	v_5	v_0
1	0	v_7	v_7	v_0	v_0	v_7	v_7	v_0	v_0	v_7	v_7	v_0	v_0
0	1	v_6	v_1	v_1	v_2	v_2	v_3	v_3	v_4	v_4	v_5	v_5	v_6
0	0	v_1	v_2	v_2	v_3	v_3	v_4	v_4	v_5	v_5	v_6	v_6	v_1

The switching table indicated in Table 1is a paramount part in the direct power control [7-13]. It selects the appropriate voltage vector of the inverter in order to set the instantaneous reactive and active powers in their desired values.

A. IP CONTROLLER FOR THE DC BUS VOLTAGE REGULATION

In order to control the dc-link voltage to the desired reference, an integral-proportional (IP) controller is adopted, as shown in Fig. 2. It can be noted from the same figure that, the adopted IP control embraces anti-windup capability. The dc-bus voltage is sensed and then compared to its reference v_{dcref}. The resulted error of comparing From Fig. 2, the DC voltage closed loop transfer function can be expressed as follows:

$$G_{Vdc(ip)} = \frac{V_{dc}}{V_{dcref}} = \frac{k_p \cdot k_i / k}{s^2 + k_p / k \cdot s + k_p \cdot k_i / k} \tag{6}$$

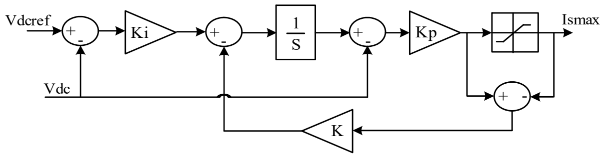

Fig.2. Anti-windup IP controller system.

where:

$$k = \frac{\sqrt{2} \cdot C_{dc} \cdot V_{dcref}}{3 \cdot V_s} \tag{7}$$

From (2) it can be seen that the relation between V_{dc} and V_{dcref} is a second order transfer function (TF) in the form of:

$$\frac{V_{dc}}{Vdcref} = \frac{k_p.k_i/k}{s^2 + k_p/k.s + k_p.k_i/k} = \frac{w_n^2}{s^2 + 2.\xi.w_n \; .s + w_n^2} \tag{8}$$

Where w_n is the natural frequency and ξ is a damping coefficient. The transfer function contains two poles and does not possess a zero. This proves that the IP controller ensures a fast response and good stability during transient states compared to the PI controller [7]. By comparing (6) to (8) considering equal poles, the IP parameters can be chosen as: $k_i = w_n/2\xi$ and $k_p = 2\xi k w_n$.

B. FUZZY LOGIC MPPT CONTROLLER

The fuzzy logic method is employed for tracking the MPP of the PV array in order to achieve good efficiency under any weather conditions. The fuzzy logic approach is very efficient for both linear and nonlinear systems and without the need of a mathematical model. The FLC has three functional blocks: fuzzification, rules inference, and defuzzification [11, 12, 14]. Fuzzification step is the process of changing the digital input variables into linguistic equivalent, which are achieved by using membership functions. Rules inference step determines the output of the fuzzy logic controller by Mamdani method with a max-min technique according to the set belonging to the rule base. Defuzzification step converts the linguistic variables into a crisp value which computes the incremental duty cycle.

The inputs of FLC-based MPPT are usually an error E and a change in that error ΔE:

$$E(K) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{9}$$

$$\Delta E = E(k) - E(k-1) \tag{10}$$

where p(k), p(k-1), v (k), and v (k-1) are respectively the PV power and voltage at the sampling times k and (k-1).

The proposed algorithm has two input variables, ΔP(k) and ΔV(k), while the output variable is the duty cycle ΔD(k). The input variables are assessed in the following way [14, 15]:

$$\Delta P = P(k) - P(k-1) \tag{11}$$

$$\Delta V = V(k) - V(k-1) \tag{12}$$

where at the MPP of the PV array, ΔP(k) / ΔV(k) is null.

The input variables ΔP(k) and ΔV(k) are divided into five fuzzy sets which are denoted as: Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB). The rule base connects the fuzzy inputs to the fuzzy output by the master rule of syntax: " *if* X *and* Y, *then* Z."[11], [15]. For example: *if*ΔP is PB *and*ΔV is NB *then*: ΔD is NS, as given in Table 2. For ease of calculation, equilateral triangle membership functions are chosen. The center of gravity method for defuzzification step is used to calculate the incremental duty cycle ΔD as:

$$\Delta D = \frac{\sum_{j=0}^{n} w_j \Delta D_j}{\sum_{j=0}^{n} w_j} \quad (13)$$

Finally, the duty cycle is achieved by adding this change to the previous value of the control duty cycle as:

$$D(K+1) = D(K) + \Delta D(K) \quad (14)$$

Table 2. Decision table

ΔP\ΔV	*NB*	*NS*	*Z*	*PS*	*PB*
NB	*PS*	*PB*	*PB*	*PB*	*NS*
NS	*Z*	*PS*	*PS*	*PS*	*Z*
Z	*Z*	*Z*	*Z*	*Z*	*Z*
PS	*Z*	*NS*	*NS*	*Z*	*Z*
PB	*NS*	*NB*	*NB*	*Z*	*PS*

IV. SIMULATION RESULT AND DISCUSSION

The whole system depicted in Fig.1 has been simulated using the MATLAB/Simulink software in order to test the proposed control techniques performance. The implementation parameters used for these tests are shown in Table 3.

Table 3.SIMULATION PARAMETERS

Parameters	V_s, F_s	L_s, R_s	L_l, R_l	L_f, R_f, C_{dc}	L, R	C_{pv}, L_{pv}	V_{dcref}	$F_{switching}$ (DC/DC converter)	$F_{switching}$ (DC/AC converter)
Values	70 V, 50 Hz	0.1 mH, 0.1 Ω	0.566 mH, 0.01 Ω	2.5 mH, 0.01Ω, 2200 µF	10 mH, 40 Ω	20 µF, 3 mH	226 V	5 kHz	20 kHz

Fig. 3 shows the PV array current and power under varying solar irradiation profile obtained by the proposed control system. Firstly, the system started with null solar irradiance until 0.4 s. Then, from 0.4 s to 2s they follow their trajectories imposed by the applied irradiation profile. Consequently, the irradiance increases from 0 to 600W/m^2 until 0.8s passes, providing 3kW with 25A by applying the FLC based MPPT algorithm. At 0.8 s, the solar irradiance decreases from 600 to 400W/m^2 tailed by a power decrease to 1.99kW with decreasing current to 15A. At 0.9s, the solar irradiance increases gradually until it reaches 1000W/m^2 at 1s, and continues at this level until the end of the profile by generating 5kW with 40A.

Fig. 4 shows the powers and DC bus voltage variations, obtained by the DPC equipped with IP regulator and fuzzy MPPT controller. When the irradiation (G) is null, the electrical network supplies all the power (Ps) to the load (Pl). After the PV array starts in the time interval [0.4, 2] s, it simultaneously supplies the demanded power (Pl) by the non-linear load and the rest of the energy is transferred to the network "Pl+Ps". During the time interval [0.1, 2] s, while the (SAPF) is inserted, the reactive power of the network (Qs) becomes null since the reactive power demanded by the load is ensured by the SAPF. While, before filtering it was the grid who provides the reactive power to the non-linear load.

On the other hand, the DC bus voltage stabilizes to its reference value (V_{dcref}) during the insertion of the SAPF, and it returns to V_{dcref} at each irradiation variation due to the change in exchange of power between the grid, the non-linear load, and the APF, as shown in Fig. 4.

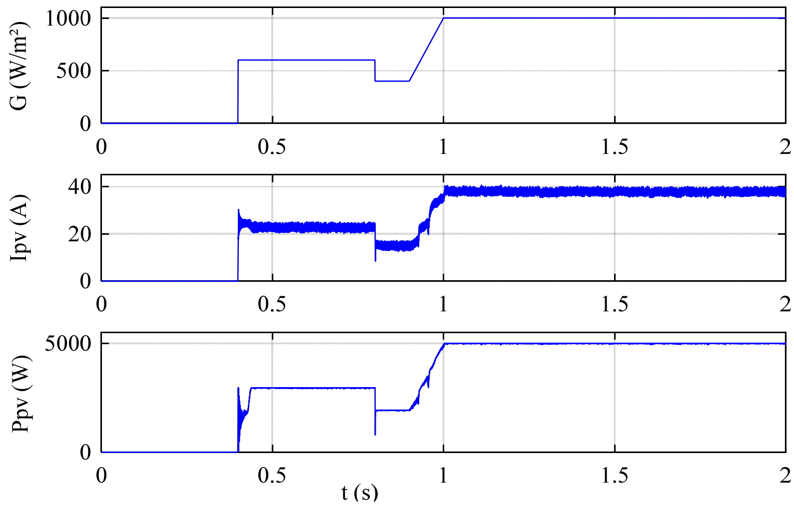

Fig.3. Irradiation profile, current, and power of the PV array.

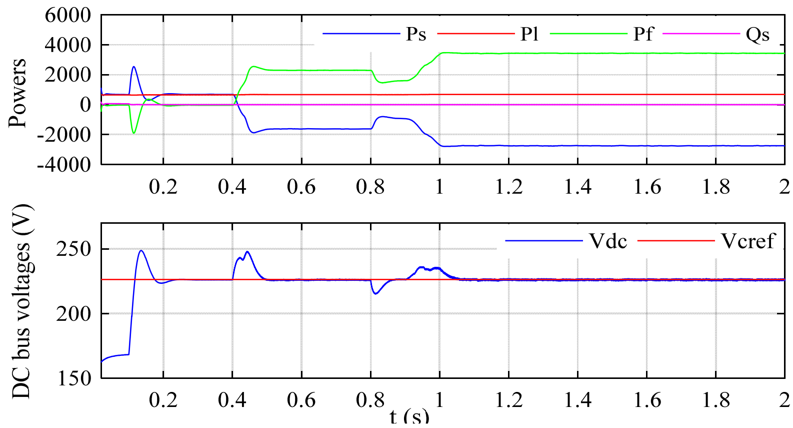

Fig. 4. Powers and DC bus voltage of the SAPF based on DPC strategy associated with fuzzy logic MPPT controller.

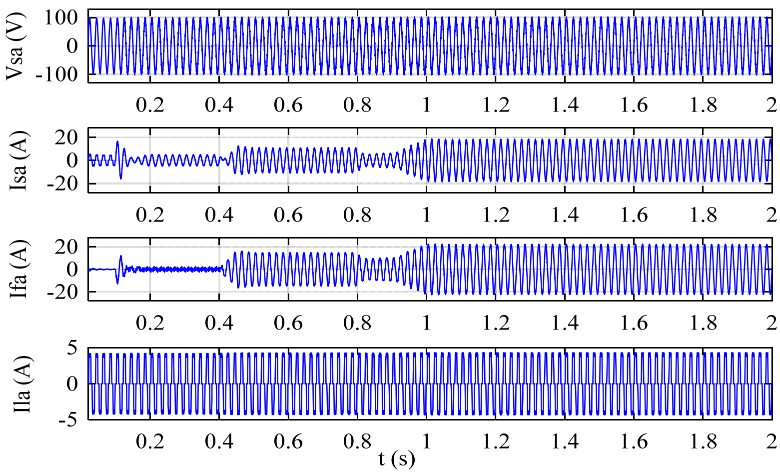

Fig. 5. Simulation results of the SAPF based on DPC strategy associated with fuzzy logic MPPT controller: source voltage and currents, filter and load currents.

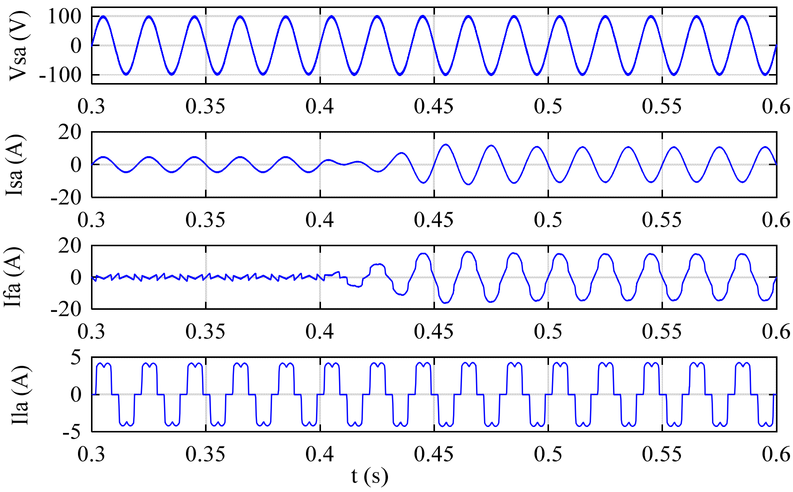

Fig. 6. Zoomed-in view on the simulation results of the SAPF based on DPC strategy associated with fuzzy logic MPPT controller: source voltages and currents, filter and load currents.

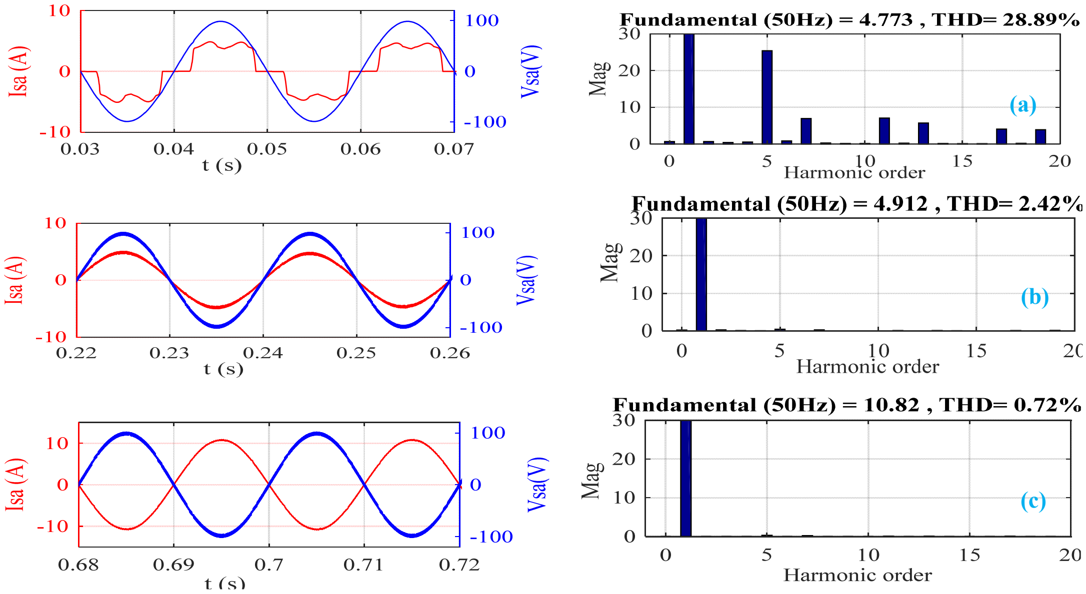

Fig. 7. Source voltage and current with FFT of the latter of the SAPF based on DPC strategy associated with fuzzy logic MPPT controller: (a) without SAPF, (b) with SAPF and (c) with solar SAPF.

Figs. 5, 6 and 7 show the waveforms of the voltage (Vs) and current of the source (Is) along with their FFT Analysis, the current of the filter (If), and the current of the load (Il), before and after filtering, and without and with PV array. Before filtering and when G = 0W/m^2 between 0 s and 0.1 s, the form of the source current is distorted and rich in harmonics, which are generated by the nonlinear load. The value of current harmonics distortion was measured as 28.89%. However, the source current becomes sinusoidal and in phase with the network voltage after the insertion of the SAPF at the instant 0.1 s, where the total harmonic distortion (THD) decreased to 2.42 %. Then from 0.4 to 2 s, the solar irradiance level increases, where the SPAF is supposed to injected power to the load and grid. The source current remains sinusoidal despite the change in the irradiation and in opposed phase with the corresponding voltages. Consequently, THD is 0.72%, meaning compliance with IEEE-519 standard [8].

V. CONCLUSION

This paper presented a multifunctional grid connected PV system, which includes a SAPF that is controlled by DPC for power quality improvement. On the grid side, a DPC strategy is applied to ensure both supplying a part of the load demand through the extracted PV power, and compensating both of the harmonics and reactive power caused by the nonlinear load on the grid current. Whereas on the PV side, an intelligent method of MPPT using FLC strategy has been presented to mitigate from the power loss during fast changing weather conditions. The results of simulation obtained by the MATLAB/Simulink software confirmed the performance of the proposed system: harmonic and reactive power compensation while feeding PVpower into the utility grid.

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