Abstract — Distributed solar photovoltaic (PV) generation is becoming more popular. Similarly, the number of electronic loads has increased along with the need to improve power quality. The PV-Shunt Active Filter (PV-SAF) is a system capable of injecting the PV power generated in the electrical grid and eliminating harmonics of current and reactive power of the local installation load. In the single-stage topology, the PV array is connected directly to the SAF DC bus, without the need for an intermediate DC-DC converter. In this paper, a three-phase single-stage PV-SAF system is evaluated in partial shading conditions. For this, a Global Maximum Power Point Tracking (GMPPT) technique capable of quickly tracking the point of maximum power even in the presence of several peaks in the power-voltage curve of the PV array is proposed. A night-time mode is implemented for the system operation when there is no PV generation. The instantaneous power theory and the adaptive hysteresis band current controller are used to control the SAF currents. The results obtained through an experimental prototype show that the PV-SAF system with the control strategies adopted is capable of simultaneously injecting into the grid the maximum power of the PV system and compensating harmonics and reactive power.

Keywords — DC-AC power converters, Distributed power generation, Maximum power point trackers, Photovoltaic systems, Power conditioning, Shunt active filter.

I. INTRODUCTION

The distributed generation of solar photovoltaic (PV) has several advantages, such as reducing the power grid demand, thus reducing conduction losses in the grid cables, and allowing consumers to participate in the energy market by selling the surplus generated or by means of energy compensation programs. In addition, the energy generated comes from a clean and sustainable source. With lower costs and increased financial incentives, global PV generation capacity has increased significantly. In 2017, there was a growth of one third, reaching 402 GW [1]. On the other hand, it is useful to measure and limit harmonics and reactive power produced by electronic loads, power supplies, motors, etc. The presence of harmonic currents in power systems or in electrical installations is a relevant problem because it can cause excessive heating in cables and equipment, vibrations and loss of torque in motors, stress and heating in capacitors, failure and reduced life of electronic devices and other sensitive loads. The presence of reactive power in the electric grid can cause conductor overloading, overheating and problems in the voltage level.

The PV generation is usually connected to the electric grid via a Voltage Source Converter (VSC). This structure can also be used simultaneously as a Static Synchronous Compensator (STATCOM) for reactive power support [2]. This system was first called PV-STATCOM by [3]. The first standards for small grid-tied PV systems, such as IEEE 1547:2003 [4] and EN 50160 [5], prevented that these systems from providing reactive support. However, the support of reactive power by PV systems is under discussion in several countries [6]. It is also possible to use the VSC structure of a PV system to act as a Shunt Active Filter (SAF), thus forming the so-called PV-SAF. This system, besides compensating for reactive power of the installation load, can also eliminate current harmonics. IEEE Std. 519:1992 sets limits for harmonic distortion in power systems [7].

The PV-SAF system mainly has two topologies, double-stage or single-stage. The first one has a DC-DC converter to perform the maximum power point tracking (MPPT) of the PV module array and a DC-AC converter to connect to the electric grid. In a single-stage topology, only a DC-AC converter is used to perform the MPPT of the PV array and to connect to the grid. Because this configuration involves fewer components, it has better efficiency than double-stage topology [8], [9]. In [10], a double-stage conversion single-phase PV-SAF system implementation is presented.

In order to extract the maximum power from the PV array, some MPPT techniques were proposed [11], [12]. However, when the PV array is under Partial Shading Condition (PSC), the MPPT can be trapped in some local maximum power peak (LMPP), decreasing system efficiency. Global maximum power point tracking (GMPPT) algorithms ensure that the system will operate on global maximum power peak (GMPP) [13]. The strategies already presented in the literature are diverse, varying in complexity, tracking speed, precision and type of application. These techniques can be classified into three categories: techniques based on conventional methods, techniques that use computational intelligence algorithms and techniques that combine conventional methods with computational intelligence algorithms.
Among the techniques based on conventional methods, [14] estimates the position of the local power peaks using the voltage measured in each one of the modules and use the algorithm Perturb & Observe (P&O) to fine-tune the result, the proposal is simple and fast but requires voltage sensors in each module, which increases the installation complexity and financial costs for implementation. In [15], a region between 50% and 90% of the open circuit voltage ($V_{oc}$) was defined, and this region is the one with the greatest probability of having GMPP tracked. This region is sliced into parts where P&O is applied. In [16] voltage ramps were used in the entire range from 0 to $V_{oc}$, instead of steps during GMPPT. This reduces voltage ripple and guarantees a faster sweep in the voltage range. The technique proposed by [17] tracks the global maximum continuously through variations applied to a PI power controller, however the tracking is relatively slow and can generate power losses because it is done continuously, not evaluating the real need to search for the entire curve. In [18], fractions of 0.8 $V_{oc}$ were used to estimate the location of possible power peak, as well as the Hill Climbing method to fine-tune the tracking.

In the category of techniques that use algorithms with computational intelligence, the Particle Swarm Optimization (PSO) algorithm does not depend on information from the PV module manufacturer datasheet or the PV array and requires low computational cost. However, it requires a large number of interactions and produces severe voltage fluctuations during tracking [19]. In [20], the Lagrangian Interpolation was used, by employing information from the PV module manufacturer datasheet, to estimate and direct the initial particles of the PSO technique to points close to possible local peaks (LI-PSO). The convergence time is reduced compared to the traditional PSO. In the Accelerated PSO (APSO) algorithm, proposed by [21], the initial particles are no longer generated randomly and are determined by points in the voltage range. The speed factor is also changed to accelerate convergence. Differential Evolutionary PSO (DEPSO) ensures faster convergence with low computational cost. However, it generates a lot of voltage fluctuation [22]. The Adaptive Velocity PSO (AVPSO) technique minimizes the chances of the particles getting trapped at a local peak, in addition to reducing the voltage fluctuations, as the particles have their positions classified at each iteration [23]. Other computational intelligence techniques were also used in GMPPT, such as the Weibull Pareto Sine-Cosine Optimization (WPSCO) technique used by [24], the Gray Wolf Optimization (GWO) used by [25], the Flower Pollination Algorithm (FPA) used by [26] and the Firefly Algorithm (FA) used by [27] and [28].

Some works have proposed hybrid techniques, which use a conventional method combined with a computational intelligence algorithm to accelerate the tracking convergence or use them in different shading conditions. Regardless of the category, the complexity of the GMPPT technique in PSC increases when compared to conventional techniques used in USC. In this sense, the literature has presented proposals for the detection of PSC and USC, so that the most complex part of the GMPPT is used only in the case of PSC. Thus, GMPPT tracking is guaranteed using the appropriate techniques for each type of shading condition. As a result, the tracking time is minimal and prevents loss of power [29], [30].

In PV-SAF systems with single-stage topology, only conventional MPPT techniques were employed, and they were only evaluated under Uniform Shading Condition (USC). Incremental Conduction (IC) algorithm was used in [31] and [32], while [33]–[38] used the P&O algorithm. In these works, the PV array was sized for its maximum power point voltage ($V_{mp}$) to match the DC bus voltage of the VSC ($V_{dc}$). Thus, there is no extensive $V_{dc}$ scan to perform the MPPT.

This work proposes a GMPPT technique for the PV-SAF with a single-stage topology that estimates the LMPP location and verifies which one produces more power. Then, a precise and continuous search with the P&O algorithm is performed while detecting changes in the irradiance conditions and has a night-time mode operation.

Several techniques to generate the reference currents of PV-SAF were used, such as the instantaneous power theory ($p-q$ Theory) in [38]–[41], the Synchronous Reference Frame Theory (SRF) in [37] and [33], the Lattice Wave Digital Filter (LWDF) in [42], adaptive controls schemes in [31], the Character of Triangle Function (CTF) in [34], the volterra filter-based control algorithm in [32], the modified Decorrelation Normalized Least Mean Square (DNLMS) in [36] and [35], Low-Pass Filters (LPFs) in [43], Robust Extended Complex Kalman Filter (RECKF) in [44] and the Leaky Least Logarithmic (LLL) in [45] and [46]. In the proposed PV-SAF, the $p-q$ Theory was used, which is well established and capable of generating reference currents for harmonic and reactive power compensation, in addition to injecting the generated PV power with low total harmonic distortion (THD).

To generate the switching commands in PV-SAF systems already proposed, the hysteresis current control technique was used, which, according to [47], has better performance when compared to Linear Control and Deadbeat Control. The proposed PV-SAF uses an adaptive hysteresis band current controller to generate the switching commands for the VSC. This technique reduces the variation of the switching frequency, the THD of the current and the interference between phases [48]–[50]. The main contributions of this work are:

1. For the first time, PV-SAF with single-stage topology is evaluated experimentally in partial shading condition (PSC);
2. Proposal of a GMPPT algorithm;
3. Sizing of the DC bus voltage range of the VSC;
4. Implementation of night-time mode in PV-SAF;
5. Implementation of adaptive hysteresis band current controller in PV-SAF to improve current control.

The proposed system is evaluated experimentally under different loads and shading conditions.

II. PV-SAF SYSTEM STRUCTURE AND CHARACTERISTICS

Figure 1 shows details of the grid-tied PV-SAF system with three-wire single-stage topology. The PV-SAF system structure consists of a PV module array and a VSC connected by a common capacitive DC bus. The VSC is connected to the
point of common coupling (PCC) by coupling inductors that limit the output current ripple. The electric grid and the load, which can be linear or non-linear, are also connected to the PCC. The load currents \( i_{Labc} \), the PV-SAFC currents \( i_{Fabc} \), the PCC voltages \( v_{Sabc} \), the DC bus voltage \( V_{DC} = V_{PV} \) and the PV array current \( I_{PV} \) are measured. The control systems operate to:

1) Perform the proposed GMPPT and control \( V_{DC} \);
2) Obtain the grid voltage positive-sequence component and calculate the reference currents for PV power injection and undesired load current component compensation using the \( p-q \) Theory;
3) Generate the switching signals using the adaptive hysteresis band current controller.

To propose a GMPPT algorithm, the following section presents the PV array behavior in PSC.

III. PV ARRAY CHARACTERISTICS UNDER PSC

To implement the GMPPT algorithm, it is important to understand how a PV array behaves under PSC. The PV array considered consists of a set of PV modules connected in series to reach the required voltage.

A PV module is composed of a series of PV cells that converts the energy of light directly into electricity by the photovoltaic effect. The PV cell's electric model contains a diode in parallel with a current source, a series resistor \( R_S \), and a shunt resistor \( R_{sh} \) [51]. The output current of the PV cell \( I_{cell} \) is given by

\[
I_{cell} = I_{ph} - I_0 (e^{\frac{q(V_{cell} + I_{cell} R_s)}{n k T}} - 1) - \frac{V_{cell} + I_{cell} R_s}{R_{sh}}
\]  

(1)

where \( k \) is the Boltzmann constant, \( q \) is the elementary charge, \( n \) is the diode ideality factor, \( T \) is the temperature in Kelvin, \( I_{ph} \) is the photocurrent, \( I_0 \) is the diode reverse saturation current and \( V_{cell} \) is the PV cell output voltage.

Figure 2 (a) shows how PV cells are placed in the KC65T module manufactured by Kyocera. This module has 36 cells and a bypass diode for each string of 18 cells. When a PV cell is shaded, the current of all other cells of the same string is affected. In order not to limit the entire array or module current...
by a less-illuminated cell, bypass diodes are used. This diode acts as an alternative path for the current and limits heat dissipation in the shaded cell [51].

Figure 2 (b) shows an array of 6 KC65T modules connected in series and subject to four different shading patterns (SP1, SP2, SP3 and SP4). The module temperature considered is T=50 °C and the irradiance is G=1000 W/m². The shaded modules are under a fraction of this irradiance, as shown in the figure. As shown in Figure 2 (c), the power-voltage (p-v) curve of the PV array for SP1, obtained through simulation in the PSIM 9.0 simulator, has only one power peak when all modules are subjected to the same irradiance (USC). However, each cell string with a bypass diode can produce a power peak on the p-v curve if it is subject to different irradiance from the other cell strings. Thus, in the case of the studied array, since there are 6 modules connected in series and each module has 2 cell strings with bypass diodes, it is possible to produce up to 12 (total bypass diodes) power peaks in the p-v curve of the PV array, if each of these cell strings is subject to a different irradiance [52].

IV. PV-SAF CONTROL STRATEGY

The proposed PV-SAF control strategy is divided into three main functions. The first one consists of the GMPPT algorithm for extracting the maximum power available in the PV array. The second is the p-q Theory used to generate the reference currents. And, finally, the third is the current control technique.

A. GMPPT Algorithm

The Fractional Open-Circuit Voltage technique has been employed to estimate the GMPP location using $V_{MP} = V_{OC,m} \cdot N \cdot k$, where $N$ is the number of modules connected in series, $V_{OC,m}$ is the module open circuit voltage and $k$ is a proportionality constant and has a value between 0.71 and 0.85 [11], [53]. This technique has an advantage of being easy to be implemented; however, when a PV array is in PSC or when $N$ is large, this relation presents an extremely high estimation error and becomes unusable. To improve this relation, [54] proposes a way to estimate the possible power peak location by (2).

$$V_{MP,j} = [\alpha \cdot (j - 1) + k] \cdot V_{OC,m}$$  \hspace{1cm} (2)

In (2), $\alpha$ and $k$ are constants that depend on the module physical characteristics and the operating conditions. $V_{MP,j}$ is the voltage relative to the $j$-th MPP, where $j$ is the number of the possible power peaks that vary from $N$ to 1. However, as seen in Figure 2, the number of possible power peaks is equal to the bypass diode number in the array and it is possible to occur PSC in one module. Therefore, considering $N_{bd}$ as the bypass diode number in each module, (2) can be rewritten as

$$V_{MP,j} = [\alpha \cdot (j - 1) + k] \cdot (V_{OC,m} \cdot N_{bd})$$  \hspace{1cm} (3)

where $j$ varies from $N_{bd} \cdot N$ to 1. Just like $k$, the value of $k$ can vary from 0.71 to 0.85. According to [54], constant $\alpha$ can take values between 0.8 and 0.97, and it was used as a function of the irradiance on the modules. However, it is difficult to obtain the value of the irradiance in practice. Even using pyranometers or PV reference cells for each module, it is possible that the measurement of these sensors does not reflect reality, since it is common to experience shading only in part of the module. Thus, this work proposes the use of a fixed value for $\alpha$, like what happens with the constant $k$. Thus, it is still possible to make a more accurate estimate compared to the Fractional Open-Circuit Voltage technique.

The parameters $\alpha$ and $k$ are obtained from the analysis of the p-v curves of the PV array under various shading conditions. The values are chosen to obtain the smallest estimation error in several shading patterns. For the case of a PV array formed by the series association of 6 modules Kyocera KC65T, the constants obtained are $\alpha=0.9$ and $k=0.6$. The average estimation error was reduced from 4.2 V to 1.3 V compared to the conventional Fractional Open-Circuit Voltage technique.

Figure 3 shows the workflow of the proposed GMPPT algorithm. Using (3), in addition to considering the possible occurrence of partial shading in a PV module, it is possible to find the GMPP more quickly by jumping directly between points where the LMPPs would appear and measure which of these peaks is the highest.

In the first step, the tracking starts at the rightmost LMPP on the p-v curve ($j=N_{bd} \cdot N$). The peak location ($V_{MP,j}$) is estimated by (3). The estimated voltage values are used as a reference for the voltage controller ($V_{DC}$). The PV power generated at each possible peak ($P_{PV,j}$) is measured. The variable $j$, which represents the current peak, is decremented until the estimated voltage is less than the minimum allowable voltage to the system ($V_{DCmin}$). To maintain acceptable controllability in the SAF current, $V_{DC}$ must be within a
permissible voltage range. According to [55], the minimum value for \(V_{DC} (V_{DCmin})\) as a function of the grid voltage \(V_s\) is:

\[
V_{DCmin} = 2\sqrt{2} \frac{V_s}{3}
\]

then, \(V_{MPP} \leq V_{DCmin}\) is the condition for stopping searching and returning to the peak that led to the highest power.

After that, in the second step, the algorithm executes the P&O function to fine-tune the GMPP. It was set to small voltage steps to avoid voltage ripple.

While performing the P&O function, the proposed GMPPT algorithm verifies if the generated power \((P_{PV})\) has changed more than 20%. If that is the case, then the GMPPT restarts. During this stage, it is also verified if \(P_{PV}\) is smaller than \(P_{crit}\) to enter in Night-Time Mode. In this mode, the generated power is negligible and the PV-SAIF operates with \(V_{PV}\) maintained at 100 V for better harmonics compensation. \(P_{crit}\) was set at 15 W and \(V_{DCup}\) equal to 19.7 V, relative to the temperature of 47 °C.

The proposed GMPPT algorithm generates the reference voltage for DC bus \((V_{DC})\). This reference is the input for the DC bus voltage scheme control, as shown in Figure 4. The proportional gain and the integrative time obtained for the PI (proportional-integral) voltage controller are 35.2 and 0.00286 s, respectively.

B. SAF Control

Figure 4 shows the PV-SAIF scheme control using the \(p-q\) Theory. To compensate for harmonic current components when the grid voltage is distorted, as can be observed in real environments, the Positive-Sequence Detector (PSD) is used to extract the fundamental positive sequence component of the grid voltage. The electric grid phase angle \((\theta_t)\) is obtained by a Quadrature Phase-Locked Loop (QPLL) [56]. The PSD is based on the \(p-q\) Theory, the auxiliary currents \((i_{1a}a\) and \(i_{1b}\)) are used to calculate the auxiliary real power \((p_1)\) by (5). The continuous component of \(p_1\) \(p_L\) is extracted by a Low-Pass Filter (LPF) and used to calculate the fundamental positive-sequence grid voltage in \(\alpha-\beta\) axis \((v_{\alpha\beta})\) by (6) [39].

\[
\begin{align*}
\alpha-axis: & \\
\beta-axis: &
\end{align*}
\]

The reference currents were generated using the \(p-q\) Theory. The load demands include real power \((p_L)\) and imaginary power \((q_L)\) and are calculated by (7). Generally, the real and imaginary powers have two components: an average one \(\bar{p}_L\) and \(\bar{q}_L\) and an oscillating one \(\tilde{p}_L\) and \(\tilde{q}_L\).

\[
\begin{align*}
p_L & = v_{S\alpha}i_{S\alpha} + v_{S\beta}i_{S\beta} \\
q_L & = v_{S\alpha}i_{S\alpha} - v_{S\beta}i_{S\beta}
\end{align*}
\]

The load power components chosen to be compensated are \(\bar{p}_L\) and \(\bar{q}_L\), referring to the harmonics and current phase displacement in relation to the PCC voltage, respectively.

Thus, the reference powers for the PV-SAIF \((p^*\) and \(q^*)\) are calculated in (8), where \(P_{LOSS}\) is the output of the DC bus voltage controller and equals the converter losses. In (8), the positive power components are drained, and the negative ones are injected by the PV-SAIF in PCC.

\[
\begin{align*}
p^* & = P_{LOSS} - \bar{p}_L - P_{PV} \\
q^* & = -\bar{q}_L
\end{align*}
\]

The reference currents \((i_{\alpha\beta})\) are then calculated by (9) and transformed from \(\alpha-\beta\) axis to \(abc\) axis \((i_{abc})\) to be used by the current controller.

\[
\begin{align*}
\begin{bmatrix} p^* \\ q^* \end{bmatrix} & = \begin{bmatrix} 1 \\ v_{S\alpha}^2 + v_{S\beta}^2 \end{bmatrix} \begin{bmatrix} v_{S\alpha} \\ v_{S\beta} \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} \\
\begin{bmatrix} i_{F\alpha}^* \\ i_{F\beta}^* \end{bmatrix} & = \begin{bmatrix} v_{S\alpha}^2 - v_{S\beta}^2 \\ v_{S\alpha}v_{S\beta} \end{bmatrix} \begin{bmatrix} p^* \\ q^* \end{bmatrix}
\end{align*}
\]

C. Current Control

To control the converter currents and generate the switching signals, the Hysteresis Current Controller (HCC) is the most used controller in the PV-SAIF systems [38, 44, 46]. According to [47], the hysteresis controller shows better performance in Active Filter applications. The main advantages of the HCC are simple implementation, robustness, excellent dynamic performance and independence of load parameters. In addition, this controller tracks the reference current without ripples or delays that may occur in other controllers, such as those that have integrators (PI, LQR and LQG controllers). The disadvantages of this controller are limitation by sampling frequency, switching frequency that is variable and dependent on the load time constant, which makes it difficult to design the coupling inductors.
In the proposed PV-SAF system, the Adaptive Hysteresis Band Current Controller (AHBCC) was used. This controller has a dynamic hysteresis band to reduce the switching frequency variation, in addition to minimizing the harmonic distortion rate and reducing interference from phase currents [48]–[50].

Unlike the conventional HCC, which uses the fixed hysteresis band, the AHBCC uses measurements of the DC bus voltage ($V_{DC}$), the grid voltage ($V_{abc}$) and the derivative of the instantaneous reference current for compensation ($di_{abc}/dt$) to calculate the hysteresis band and thus reduce the switching frequency variation.

The dynamic Hysteresis Band ($HB$) of each phase is calculated by (10), and the parameters used are shown in Table I.

$$HB_{abc} = \frac{V_{DC}}{8f_{S}L_{F}} \left[ 1 - \frac{4L_{F}}{V_{DC}^{2}} \left( \frac{V_{Subc}}{L_{F}} + \frac{di_{abc}}{dt} \right)^{2} \right]$$

The DC bus maximum voltage allowed ($V_{DCmax}$) is calculated to maintain the current ripple within the acceptable magnitude. In this work, it was calculated according to [57], and the value is shown in the Table I.

In a simulation of practical application at a voltage of 380 V, PV array of 30 modules and a 17 kVA converter, the allowable DC voltage would be in the range of 620 V to 840 V.

V. EXPERIMENTAL EVALUATION OF PV-SAF SYSTEM

To validate the proposed control system and strategies, a prototype of the PV-SAF system was implemented in the laboratory and subject to tests. Table I presents the electrical grid and SAF parameters used. A photograph of the system prototype developed in the laboratory is depicted in Figure 5. The converter stand used is equipped with a VSC, current and voltage sensors, coupling inductors, DC bus and with a DSP TMS320F28335 for digital processing of the control.

A series array of 6 PV modules KC65T from the manufacturer Kyocera was used. The electrical parameters of this module model are specified in Table II.

\begin{table}[h]
\centering
\caption{GRID AND SAF PARAMETERS}
\begin{tabular}{|c|c|c|}
\hline
Symbol & Parameter & Value \\
\hline
$V_{DC}$ & Electrical grid line voltage & 40 V \\
$f$ & Electrical grid fundamental frequency & 60 Hz \\
$R_{S}$ & Electrical grid series resistor & 0.5 Ω \\
$L_{S}$ & Electrical grid inductance & 0.6 mH \\
$R_{T}$ & Coupling resistance & 0.5 Ω \\
$L_{T}$ & Coupling inductance & 2 mH \\
$C_{DC}$ & DC bus capacitance & 1100 μF \\
$V_{DCmax}$ & DC bus minimum voltage & 65.3 V \\
$V_{DCmax}$ & DC bus maximum voltage & 236 V \\
$P_{in-SAF}$ & Converter Power & 2.08 kVA \\
$f_{S}$ & Sampling frequency & 48 kHz \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{PV PARAMETERS UNDER STANDARD TEST CONDITIONS (STC*)}
\begin{tabular}{|c|c|}
\hline
Parameter & Value \\
\hline
Cell number & 36 \\
Maximum Power & 65 W \\
Maximum Power Voltage & 17.4 V \\
Maximum Power Current & 3.75 A \\
Open Circuit Voltage & 21.7 V \\
Short Circuit Current & 3.99 A \\
\hline
\end{tabular}
\end{table}

*STC: Irradiance 1000 W/m², AM1.5 spectrum, module temperature 25 °C

In the following subsections several tests under different conditions of shading, irradiation and different types of loads are presented to prove the multifunctional characteristic of the proposed system, as well as the operation and the advantages of the control strategies adopted.

A. Injecting PV power into the grid under different shading conditions and non-linear load

The performance of the proposed GMPPT technique is analyzed under different shading conditions. Simultaneously, the SAF acts to compensate harmonics and reactive power of a non-linear load composed of a three-phase rectifier bridge with R-L load ($R=26$ Ω and $L=80$ mH). The active power of this load at the fundamental frequency is 113 W. Some materials were applied to cover a set of cells in the PV module to allow the incidence of irradiance ($G$) in three levels (0%, 66%, and 80%) to simulate a partial shading condition. The $p$-v curves in Figure 6, obtained experimentally for four shading conditions and non-linear load are presented to prove the multifunctional characteristic of the proposed system, as well as the operation and the advantages of the control strategies adopted.
The performance of the proposed GMPPT technique even in PSC. Small differences are noted due to irradiance and temperature variations during the tests. The time to reach the GMPP in these conditions averaged 45 ms. In all shading patterns, the PV array generates more power than the load demand. Consequently, the excess power is injected into the electric grid. It can also be observed that the open circuit voltage in the shading patterns SP3 and SP4 is reduced since the 6 completely shaded cells ($G=0$ W/m²) limit the generation of all 18 cells in series that are paralleled with a bypass diode. The generated power is higher under USC (SP1).

To obtain less distortion in the injected current, parameters on the GMPPT algorithm can be set to get a longer tracking time. In real systems in distribution voltage, the tracking time can be longer due to the bigger DC bus capacitance, bigger PV array and bigger DC voltage range allowed. Considering a system at a grid voltage of 380 V and a PV array of 30
Figure 10 shows the performance of the PV SAF with a non-linear load (422 W) and a non-linear load (370 W). The excess power generated is injected into the electric grid. As can be observed, there is a 60 Hz component in $i_{sa}$, and the grid current ($i_{sa}$) is in counter phase to the grid voltage ($v_{sa}$).

Figure 9 (a) shows the performance of the PV SAF when the non-linear load demand is greater than the generated power. In this case, the load demands 422 W, while the PV generated power is 330 W. The load demand overbalance is supplied by the electric grid. It can be observed that $i_{sa}$ is sinusoidal and in phase with $v_{sa}.$ The load and PV-SAF currents on $d-q$ axis are shown in Figure 9 (b) and (c). The average component of $i_{ld}$ (positive) is relative to the active power demand of the load and the average component of $i_{qd}$ (negative) is relative to the PV power generated and the losses in the converter. It can be seen that $i_{dq}$ compensates for $i_{ld}$ and the oscillating component of $i_{ld}$ is compensated for $i_{ld}.$

The proposed PV-SAF is demonstrated to act by improving the power quality through the harmonic and reactive compensation of the load. At the same time, it injects into the electric grid the maximum power provided by the PV array.

C. Performance of PV-SAF under non-linear load in Night-time Mode

In Night-time Mode, the PV array generated power is negligible; therefore, the PV-SAF acts only to compensate for harmonic and reactive components of the load, keeping $V_{DC}$ at a fixed value. Figure 10 shows the performance of the PV-SAF in Night-time Mode when the load is non-linear, composed of a three-phase rectifier bridge with load $R-L$ that demands 113 W, and the PV Array generates 370 W. The excess power generated is injected into the electric grid. As can be observed, there is a 60 Hz component in $i_{sa}$, and the grid current ($i_{sa}$) is in counter phase to the grid voltage ($v_{sa}$).

Figure 9 (a) shows the performance of the PV-SAF when the non-linear load demand is greater than the generated power. In this case, the load demands 422 W, while the PV generated power is 330 W. The load demand overbalance is supplied by the electric grid. It can be observed that $i_{sa}$ is sinusoidal and in phase with $v_{sa}.$ The load and PV-SAF currents on $d-q$ axis are shown in Figure 9 (b) and (c). The average component of $i_{ld}$ (positive) is relative to the active power demand of the load and the average component of $i_{qd}$ (negative) is relative to the PV power generated and the losses in the converter. It can be seen that $i_{dq}$ compensates for $i_{ld}$ and the oscillating component of $i_{ld}$ is compensated for $i_{ld}.$

The proposed PV-SAF is demonstrated to act by improving the power quality through the harmonic and reactive compensation of the load. At the same time, it injects into the electric grid the maximum power provided by the PV array.

B. Performance of PV-SAF under non-linear load during PV power generating

Now, the performance of PV-SAF under different loads is analyzed, keeping the PV generation at USC (SP1). Figure 8 shows the performance of PV-SAF under non-linear load with demand lower than the PV power generated. The load is a three-phase rectifier bridge with load $R-L$ ($R=26 \, \Omega$ and $L=80 \, mH$) that demands 113 W, and the PV Array generates 370 W. The excess power generated is injected into the electric grid. As can be observed, there is a 60 Hz component in $i_{sa}$, and the grid current ($i_{sa}$) is in counter phase to the grid voltage ($v_{sa}$).
In this paper, a control strategy for a single-stage PV-SAF system was proposed and validated experimentally by an experimental prototype. A GMPPT algorithm that estimates the possible location of power peaks was proposed and tested under several partial shading conditions, ensuring that the maximum power available from the PV array is extracted, unlike the conventional techniques used in previous proposals. The proposed GMPPT was performed at low tracking time and produced negligible voltage ripple. The experimental results showed that the GMPPT can be used in the PV-SAF system even with single-stage topology and in the occurrence of PSC. The elimination of current harmonics and reactive power was satisfactory, within the limits of IEEE Std. 519. PV-SAF has been demonstrated to be a modern and intelligent solution that integrates the distributed generation with improvement of the power quality.

VI. CONCLUSION

In this paper, a control strategy for a single-stage PV-SAF system was proposed and validated experimentally by an experimental prototype. A GMPPT algorithm that estimates the possible location of power peaks was proposed and tested under several partial shading conditions, ensuring that the maximum power available from the PV array is extracted, unlike the conventional techniques used in previous proposals. The proposed GMPPT was performed at low tracking time and produced negligible voltage ripple. The experimental results showed that the GMPPT can be used in the PV-SAF system even with single-stage topology and in the occurrence of PSC. The elimination of current harmonics and reactive power was satisfactory, within the limits of IEEE Std. 519. PV-SAF has been demonstrated to be a modern and intelligent solution that integrates the distributed generation with improvement of the power quality.

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