Comparative static and dynamic analysis of single- and double-stage multifunctional 3-phase grid-tied photovoltaic systems

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Abstract
This paper presents a comparison analysis involving four multifunctional grid-tied photovoltaic (MPV) systems, divided in single-stage and double-stage architectures. The functionalities can be pointed out as generation/injection of active energy into the utility grid, and active power conditioning including reactive power and load unbalance compensation, as well as load harmonic currents suppression. Thus, beyond the photovoltaic systems’ conventional functions, the MPV systems also contribute to improve power quality indicators. Single-phase full-bridge (1-FB) inverters are used to build two grid-tied inverter configurations. In the first, called as MPV-FB, three 1-FB inverters share the same DC-bus, while in the second, named as MPV-3FB, each of the three 1-FB inverters operates with an individual DC-bus. Each inverter configuration integrates the MPV system architectures with single-stage and double-stage, where in the single-stage configuration the photovoltaic array is directly connected to the inverter DC-bus, whereas in the DS one, a step-up DC–DC converter is inserted between the photovoltaic array and the inverter DC-bus. Under several scenarios of operation, the four MPV systems named as MPV-FB-SS, MPV-FB-DS, MPV-3FB-SS and MPV-3FB-DS, are experimentally tested to compare constructive aspects, evaluate static/dynamic performances and power quality issues, as well as capability to operate with photovoltaic array failure.

1 | INTRODUCTION

The growth in demand for electricity perceived in recent years has strongly been associated to the quality of life and social economic development indices. As recent projections point that world electrical energy consumption will grow further [1], the planning of the energy sectors, to meet the need to expand power generation, becomes increasingly mandatory.

On the other hand, the socioeconomic situation and the serious environmental impacts caused both by the construction of large capacity hydroelectric power plants and by the use of energy sources based on fossil fuels such as coal, natural gas and oil, have driven governments and researchers worldwide, to seek other solutions and strategies for serving growing energy demand. In this context, the generation of electric energy from alternative and renewable sources has been considered a sustainable option to increase the energy supply [2]. This model presents itself as a high disruptive potential in the energy landscape that can combine financial economics, modernization of the electrical power system (EPS), reduction of aggressions to the environment and promote the diversification of the global energy matrix.

The current and always promising trend for taking advantage of renewable energy sources is based on distributed generation (DG) systems, which usually employ photovoltaic (PV) systems, fuel cells, wind turbines, among others, connected to the EPS distribution network through installations located closer to consumers [3–4]. Given this scenario, the generation based on solar PV energy has achieved prominence and its use has grown significantly due to its inherent characteristics, mainly those related...
to the low environmental impact, ease and quick installations in residential, commercial and industrial plants [5–7].

The connection of PV systems to the electrical distribution network must meet safety requirements, as well as power quality (PQ) criteria, generally established by technical standards [8], so that the performance of the electrical system does not be impaired. Since the electrical energy generated from PV arrangements is in DC, it is necessary to convert this energy into AC so that it can be properly injected into the electrical grid through proper DC/AC converters (inverters). Usually, the energy conversion process can be carried out in two different ways, namely, double-stage (DS) or single-stage (SS). In the SS configuration [9, 10], the PV array is directly connected to the inverter DC-bus, whereas in the DS configuration [11–13], the PV array is indirectly connected to the inverter DC-bus by means of an interfacing DC–DC converter inserted between the PV array and the grid-tied inverter. In addition to the basic attribute related to the injection of active power into the network, many ancillary services or functionalities can be incorporated into the PV systems [14]. Additional multi-tasks are attributed to the called multifunctional PV (MPV) system, whose intention is to contribute for improving PQ indicators once, besides PV-based DG systems, local loads connected to EPS are also involved [14–19]. In other words, the task associated to active power-line conditioning, involving reactive power compensation, load unbalance compensation, suppression of load harmonic currents, and others, can also be considered.

In ref. [18], flexible power control strategy exploring integration issues was proposed adding functionalities to a single-phase PV system, such as reactive power compensation. Based on a multitask control strategy, the single-phase PV system presented in ref. [19] can act as shunt active power filter (S-APF) or as a voltage drop compensator for PQ improvement at the point of common coupling of the electrical system. Considering three-phase three wire (3P3W) systems, control algorithms and techniques have been proposed in refs. [20, 21] to improve PQ issues in electric distribution systems, acting on load unbalancing compensation, harmonic suppression, and power factor correction. The functionalities of a 3P4W single-stage PV system operating as S-APF [16], as well as integrated to a unified power quality conditioner [22], have been explored.

In this paper, four MPV systems connected to a 3P4W electrical system are compared to each other in terms of static and dynamic performances. In all MPV systems, single-phase fullbridge (1-FB) inverters are used to build the grid-tied inverter. The first, called as MPV-FB, is composed of three 1-FB inverters sharing the same DC-bus [23], as shown in Figure 1(a). In the second, named as MPV-3FB, the inverter configuration is composed of three 1-FB inverters operating with their own
DC-buses, as shown in Figure 1(b). Each inverter is connected to its respective PV arrangement adopting both the SS and DS configurations. Thus, in this paper, the PV systems that adopt the SS configuration are named as MPV-FB-SS and MPV-3FB-SS, while the last two systems that adopt the DS configuration are named as MPV-FB-DS and MPV-3FB-DS.

Operating with the conventional maximum power point tracking (MPPT) technique based on perturb and observe (P&O) algorithm [24], the static and dynamic performances of the four MPV systems are evaluated considering four different scenarios (SC) described as follows: (1) SC 1: only active energy is injected into the grid; (2) SC 2: only active energy is injected into the grid but now a failure in a PV array string is considered; (3) SC 3: the PV systems operate only with filtering task (S-APF); and (4) SC 4: the PV systems operate injecting energy into the grid and, simultaneously, perform active power-line conditioning.

Furthermore, the following aspects are considered in the comparative analysis, as follows: (1) constructive aspects involving the switching devices, filtering elements, number of voltage and current transducers, number of digital signal controllers (DSC), and others; (2) capability to drain from the grid sinusoidal and balanced currents; (3) capability to inject into the grid sinusoidal and balanced currents, considering the PV systems operating without failure, as well as with failure in a PV array string; and (4) minimum allowed inverter DC-bus voltage amplitude to guarantee normal operation of each PV system in study.

2 | DESCRIPTIONS OF THE MPV SYSTEMS

Figure 1 shows the power circuit schemes involving the four MPV systems implemented in this paper. The MPV-FB presented in Figure 1(a) is implemented by using three 1-FB inverters coupled in the same DC-bus \(V_{dc}\). In this topology, in addition to the use of the inductive filters \(L_{dc(a,b,c)}\), the use of three single-phase transformers is mandatory to ensure galvanic isolation.

As previously mentioned, in the MPV-FB implementations, both SS and DS configurations are adopted as shown in Figure 1(c). In the MPV-FB-SS, the PV array is composed of three parallel-connected strings, where each string contains eight series-connected PV modules, whereas in the MPV-FB-DS a DC–DC boost converter is employed and the PV array is composed of four parallel-connected strings, where each one of them has six series-connected PV modules.

The MPV-3FB schemes presented in Figure 1(b) employs three 1-FB inverters connected to their own DC-bus \(V_{dc(a,b,c)}\). Inductive filters \(L_{dc(a,b,c)}\) are required to couple the MPV system to the utility grid. It can be noted that the MPV-3FB systems use three independent PV arrays in both SS and DS configurations, as shown in Figure 1(d). In the MPV-3FB-SS, each PV array is comprised of eight series-connected PV modules directly connected to the inverter DC-bus. Meanwhile, in MPV-3FB-DS, the PV array is composed of two parallel-connected strings, where each one has four series-connected PV modules. Three DC–DC boost converters perform the interface between the PV arrays and the inverter DC-bus.

Since the number of PV panels is the same for all systems, it is realized that the photovoltaic energy generated will also be the same. Thus, the power generation of all MPV systems is around 5.884 kWp at standard test condition (STC). Moreover, the PV arrangements were determined considering operational and safety requirements, such as the minimum DC-bus voltage amplitude allowed to operate.

2.1 | Algorithm for generation of the 1-FB inverter current references

Figures 2 and 3 present the respective algorithms employed to generate the current references \(i^e_c, i^e_h, \) and \(i^e_c\) used in the control loops of the MPV-FB and MPV-3FB systems. It can be emphasized that since three 1-FB inverters are used in all systems, the per-phase independent current control is allowed. Thus, supposing that up to two 1-FB inverters are damaged, the PV system can still remain in operation.

Assuming that the active power-line conditioning functionality is integrated to the control, the referred current references will be composed of active components, that represent the energy produced by the PV arrays, as well as non-active components. It is worth mentioning that both the algorithms presented in Figures 2 and 3 perform suppression of the load harmonic currents and reactive power compensation. However, only the algorithm shown in Figure 2 allows load unbalance compensation.

2.1.1 | MPV-FB systems

As shown in Figure 2, the current references used in the 1-FB inverters control loops of the MPV-FB structure can be calculated by:

\[
i^e_{c(a,b,c)} = i^e_{dc(a,b,c)} + i^h_{c(a,b,c)}
\]

where \(i^e_{dc(a,b,c)}\) and \(i^h_{c(a,b,c)}\) represent the respective active and non-active current components.

The non-active current components \(i^h_{c(a,b,c)}\) are computed by using an algorithm based on the single-phase synchronous reference frame (SRF) [25]. Moreover, in the MPV-FB system, a load unbalance compensation algorithm is also implemented, as can be observed in Figure 2(a,b). Thus, for such purpose, the measured load currents \(i_{a(a,b,c)}\) can be represented into the fictitious two-phase stationary reference frame \(a\beta\), as follows:

\[
\begin{bmatrix}
i_{a(a,b,c)} \\
i_{b(a,b,c)}
\end{bmatrix} = \begin{bmatrix}
in_{a(a,b,c)}(\omega t) \\
in_{b(a,b,c)}(\omega t - \frac{\pi}{2})
\end{bmatrix}
\]
After that, the αβ-axes quantities \( i_{\alpha(a,b,c)} \) and \( i_{\beta(a,b,c)} \) are transformed into the SRF dq-axes, in which the \( d \) quantities are given by:

\[
id_d(a,b,c) = i_{\alpha(a,b,c)} \cos(\theta_{(a,b,c)}) + i_{\beta(a,b,c)} \sin(\theta_{(a,b,c)}) \tag{3}
\]

where \( \cos(\theta_{(a,b,c)}) \) and \( \sin(\theta_{(a,b,c)}) \) represent the coordinates of the synchronous unit vector calculated using the utility grid phase-angle \( \theta_{(a,b,c)} \), which are estimated by means of an PLL system. In this paper, three single-phase αβ-pPLL proposed in ref. [26] were employed for this purpose.

The resulting \( d \)-axis currents \( i_d(a,b,c) \) are composed of DC components, which represent the fundamental load currents, and AC components representing the load harmonic currents. Thereby, using low pass filters (LPF), the DC components \( i_{d_{dc}(a,b,c)} \) can be obtained.
Subsequently, by means of the load unbalance compensation algorithm presented in Figure 2(b), the fundamental current references $i^{*}_{s(a,b,c)}$ are generated as follows:

$$\begin{bmatrix}
i^{*}_{sa} \\
i^{*}_{sb} \\
i^{*}_{sc}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & 0 & -1/2 \\
-1/2 & \sqrt{3}/2 & 0 \\
-1/2 & -\sqrt{3}/2 & 0
\end{bmatrix} \begin{bmatrix} i_a \\
i_b \\
i_c
\end{bmatrix} \tag{4}$$

where

$$\begin{bmatrix} i_a \\
i_b \\
i_c
\end{bmatrix} = \frac{1}{id_{dc}} \begin{bmatrix} \cos(\theta_a) \\
\sin(\theta_a)
\end{bmatrix}, \tag{5}$$

and

$$id_{dc} = \sqrt{\frac{3}{2}} \left( \frac{id_{dca} + id_{dcb} + id_{dcc}}{3} \right). \tag{6}$$

Therefore, the non-active current components $(\dot{i}_{h(a,b,c)})$ can be properly found subtracting the fundamental current references $(i^{*}_{s(a,b,c)})$ from the respective measured load currents $(\dot{i}_{l(a,b,c)})$, as follows:

$$\dot{i}_{h(a,b,c)} = \dot{i}_{l(a,b,c)} - i^{*}_{s(a,b,c)}. \tag{7}$$

On the other hand, the active current components $i^{*}_{dc(a,b,c)}$ inserted in Equation (1) can be calculated by:

$$i^{*}_{dc(a,b,c)} = (i_{dc} + i_{ff}) \cos(\theta_{a,b,c}), \tag{8}$$

where $i_{dc}$ is obtained from the DC-bus voltage controller, while $i_{ff}$, whose calculation is explained in detail in Section 2.2, is the feed-forward current determined by a feed-forward-control loop (FFCL). The FFCL is employed to accelerate the computation of the inverter-current references, which represent the active-current components of the system, in order to reduce the DC-bus voltage oscillations in the presence of abrupt solar irradiation transients. Both controllers operate integrated with the 1-FB inverters current control loops (see Figure 2(c)).

Finally, the errors obtained from the comparison between the currents $i_{c(a,b,c)}$ and their respective current references $i^{*}_{c(a,b,c)}$ act as inputs to the PI current controllers, which provide the control signals to the pulse-width modulators (PWM), as shown in Figure 2(d).

### 2.2.1 MPV-3FB systems

Similarly, the current references used in the MPV-3FB current control loops are also determined from Equation (1) and are composed of active and non-active components. Nevertheless, it can be observed in Figure 3 that the load unbalance compensation algorithm is not considered. In this case, the single-phase SRF based algorithms are employed to obtain the non-active current components of the current references.

Accordingly, from Figure 3(a), the measured load currents $(\dot{i}_{l(a,b,c)})$ are transformed into the SRF $dq$-axes by applying Equations (2) and (3). Then, the fundamental current references $(i^{*}_{s(a,b,c)})$ can be generated as follows:

$$i^{*}_{s(a,b,c)} = id_{d(e(a,b,c))} \cos(\theta_{a,b,c}) \tag{9}$$

where $id_{d(e(a,b,c))}$ are obtained using LPFs.

Thus, the non-active current components $(\dot{i}_{h(a,b,c)})$ can be determined from Equation (7).

Besides that, for the MPV-3FB, the active current components $i^{*}_{dc(a,b,c)}$ expressed in Equation (1) are calculated as follows:

$$i^{*}_{dc(a,b,c)} = (i_{dc(a,b,c)} + i_{ff(a,b,c)}) \cos(\theta_{a,b,c}) \tag{10}$$

where $i_{dc(a,b,c)}$ are provided by the inverter DC-bus voltage control loops, while $i_{ff(a,b,c)}$ are determined by the FFCLs (see Figure 3(b)).

Likewise, for the MPV-FB systems, the currents $i_{c(a,b,c)}$ are compared with their respective current references $i^{*}_{c(a,b,c)}$, resulting the inputs to the PI current controllers, as can be observed in Figure 3(c).

### 2.2 Feed-forward control loops

In this paper, FFCLs are employed to accelerate the power balance between the PV array and the utility grid. Once the DC-bus voltage control presents slow dynamics, a proper FFCL helps to speed up the calculation of the active current components $i^{*}_{dc(a,b,c)}$ under occurrence of disturbances like abrupt transients of solar irradiation or temperature [27].

#### 2.2.1 FFCL in the SS configurations

Disregarding the power losses, the power balance into the PV systems occurs when the power from the PV array ($P_{pv}$) is equal to the power injected into the utility grid ($P_{s}$). Thus, for the respective MPV-FB-SS and MPV-3FB-SS systems, the power balance can be represented by:

$$P_{pv_{_FB}} = r_{pv} \hat{i}_{pv} = \frac{3V_{sp}I_{sp}}{2} = P_{s_{FB}} \tag{11}$$

$$P_{pv_{_3FB}} = r_{pv(a,b,c)}\hat{i}_{pv(a,b,c)} = \frac{V_{sp(a,b,c)}I_{sp(a,b,c)}}{2} = P_{s_{3FB}} \tag{12}$$

where $r_{pv}$ and $r_{pv(a,b,c)}$ are the PV arrays voltages; $\hat{i}_{pv}$ and $\hat{i}_{pv(a,b,c)}$ are the PV arrays currents; $V_{sp}$ and $V_{sp(a,b,c)}$ represent the peak amplitudes of the grid voltages that are estimated using the $\alpha$-$\beta$-pPLL [20]; $I_{sp}$ and $I_{sp(a,b,c)}$ represent the amplitudes of the grid injected currents.
From Equations (11) and (12), $I_p$ and $I_{p(a,b,c)}$ are calculated as:

$$I_p = \frac{2v_{pv}i_{pv}}{3v_{sp}} \quad (13)$$
$$I_{p(a,b,c)} = \frac{2v_{p(a,b,c)}i_{p(a,b,c)}}{V_{sp(a,b,c)}} \quad (14)$$

Thus, the feed-forward currents for the MPV-FB-SS and MPV-3FB-SS systems can be, respectively defined as $i_{ff} = I_p$ and $i_{ff(a,b,c)} = I_{p(a,b,c)}$. Both, represented into the SRF ($dq$-axes), are respectively given by:

$$i_{ff} = \sqrt{\frac{3}{2}} I_p = \sqrt{\frac{2}{3}} \frac{v_{pv}i_{pv}}{v_{sp}}$$

$$i_{ff(a,b,c)} = I_{p(a,b,c)} = \frac{2v_{p(a,b,c)}i_{p(a,b,c)}}{V_{sp(a,b,c)}} \quad (16)$$

### 2.2.2 FFCL in the DS configurations

Disregarding the losses, the power balance is achieved when $P_{pv}$ is equal to the output power of the DC–DC boost converter ($P_{dc}$) or ($P_{r}$). Hence, power balances for the MPV-FB-DS and the MPV-3FB-DS can be, respectively, represented by:

$$v_{pv}i_{pv} = v_{dc}i_{dc} = \frac{3v_{sp}I_p}{2}$$

$$v_{pv(a,b,c)}i_{pv(a,b,c)} = v_{dc(a,b,c)}i_{dc(a,b,c)} = \frac{v_{sp(a,b,c)}I_{p(a,b,c)}}{2} \quad (18)$$

where $v_{dc}$ and $v_{dc(a,b,c)}$ represent the DC-buses voltages; while $i_{dc}$ and $i_{dc(a,b,c)}$ are the DC-buses currents. Furthermore, the static-gain of the DC–DC boost converters implemented in this paper is given by:

$$G_b = \frac{i_{pv}}{i_{dc}} = \frac{1}{(1 - d)} = \frac{v_{dc}}{v_{pv}} \quad (19)$$

where $d$ represents the duty-cycle of the boost converter.

Thus, the feed-forward currents for the MPV-FB-DS and the MPV-3FB-DS systems are, respectively, obtained as:

$$i_{ff} = \sqrt{\frac{3}{2}} I_p = \sqrt{\frac{2}{3}} \frac{v_{dc}i_{pv}}{v_{sp}} (1 - d)$$

$$i_{ff(a,b,c)} = \frac{v_{dc(a,b,c)}i_{pv(a,b,c)}}{V_{sp(a,b,c)}} (1 - d)$$

### 2.3 Methodology for generation of the 1-FB inverter DC-bus voltage reference

#### 2.3.1 SS configurations

As can be seen from Figures 2(c) and 3(b), in the SS MPV systems the inverters DC-buses voltage references ($V_{dc}^*$ and $V_{dc(a,b,c)}^*$) are provided by the MPPT-P&O algorithm. Once the MPV-FB-SS utilizes only one DC-bus voltage control loop, only one MPPT algorithm is required. On the other hand, in the MPV-3FB-SS three MPPT algorithms must be implemented to generate the voltage references for each DC-bus voltage control loop.

Considering the systems operating under STC and at MPP, the DC-buses voltage amplitudes of the PV arrays will be around 246.4 V in both MPV-FB-SS and MPV-3FB-SS systems. Nonetheless, in some situations, the MPV systems can be subjected to unfavourable weather conditions, such as partial shading. In these cases, the voltage reference could not be enough to guarantee the proper and safe operation of the inverters. However, if the voltage references provided by the MPPT algorithms were less than 220 V, $V_{dc}^*$ and $V_{dc(a,b,c)}^*$ must be set to 220 V. In other words, the MPV systems remain operating with constant DC-bus voltage references.

This minimum value for both $V_{dc}^*$ and $V_{dc(a,b,c)}^*$ was chosen considering the nominal peak amplitude of grid voltages (180 V), as well as the losses related to both the switching devices and passive elements of the power circuits.

### 2.3.2 DS configurations

Once in the DS MPV systems the PV array voltage control is carried out by the DC–DC boost converter, the PV voltage references ($v_{pv}^*$ and $v_{pv(a,b,c)}^*$) are generated by the MPPT algorithms. The inverters DC-bus voltage references adopted to the DS MPV systems are set to $V_{dc}^* = V_{dc(a,b,c)}^* = 230$ V, as shown in Figures 2(c) and 3(b).

### 3 MPV SYSTEMS: MATHEMATICAL MODELS AND CONTROL SYSTEMS

This section presents the mathematical development of the power circuit models associated to the MPV systems. The model efficiently predicts obtaining the transfer functions (TF) required to design the control systems, which include the current control loops related to the currents injected into the utility grid by the 1-FB inverters, the inverter DC-bus voltage control loops, as well as the multi-loop control employed in the DC–DC boost converter.

#### 3.1 Mathematical model of the 1-FB inverters

The dynamic model of the 1-FB inverters is obtained from the single-phase equivalent circuit shown in Figure 4. The secondary transformer impedance is referred to the primary side, and the adopted transformer turn ratio is 1. In Figure 4, $L_s$ is the transformer leakage inductance, $L_f$ is the filter inductance and $R_s$ and $R_f$ are their respective internal resistances. The small-signal model of the 1-FB inverter is derived from the average model by perturbation and linearization. Hence, the per-phase
open loop TF of the 1-FB inverters is given by:

$$G_{iFB}(s) = \frac{\dot{\hat{i}}_{dc}(s)}{\dot{\hat{v}}_{dc}(s)} = \frac{V_{dc}}{L_{eq} + R_{eq}}$$ (22)

where $L_{eq} = L_s + L_\text{FB}$ is the equivalent inductance, $R_{eq} = R_s + R_\text{FB}$ is the equivalent resistance and $\dot{\hat{i}}_{FB}(s)$ represents the 1-FB duty cycle.

It can be noted that, for structures that do not require isolation transformers, $L_s$ and $R_s$ are equal to zero.

Figure 5 shows the block diagram of the current control loop implemented in each one of the three 1-FB inverters. The gains $K_p$ and $K_i$ are the respective proportional (P) and integral (I) gains of the PI current controller and $K_{PWM}$ represents the PWM static gain that is calculated from the peak value of the PWM triangular carrier.

### 3.2 Mathematical model of the inverter DC-Bus

Assuming a single-phase system and disregarding the power losses, the power absorbed or furnished by the inverter DC-bus ($P_{dc}$) can be expressed by:

$$P_{dc} = P_{pv} + P_\text{s}$$ (23)

Further, the $P_{dc}$ can also be calculated as follows:

$$P_{dc} = C_{dc} \left( \frac{dr_{dc}}{dt} \right) r_{dc}$$ (24)

where, $C_{dc}$ represents the DC-bus capacitance and $r_{dc}$ is the inverter DC-bus average voltage. Thus, from Equation (24) and, considering that $P_\text{s}$ represents the real average power into the DC-Bus

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$$G_{v1}\phi (s) = \frac{\dot{\hat{v}}_{dc}(s)}{\dot{\hat{i}}_{dc}(s)} = \frac{v_d^2}{sC_{dc}V_{dc}}$$ (27)

Accordingly, for the structures that employ three 1-FB inverters coupled in the same DC-bus, the TF is given by:

$$G_{v3}\phi (s) = \frac{\dot{\hat{v}}_{dc}(s)}{\dot{\hat{i}}_{dc}(s)} = \frac{3v_d^2}{sC_{dc}V_{dc}}$$ (28)

Figure 6 shows the block diagram that represents the DC-bus voltage control loop of the MPV systems. The gains $K_p$ and $K_i$ are the respective P and I gains of the PI DC-bus voltage controller and $G_v(s)$ can represent either the TF obtained in Equations (27) or (28), according to the MPV system configuration.

### 3.3 Mathematical model of the DC–DC boost converter

The dynamic properties of the boost converter can be modelled using the equivalent circuit illustrated in Figure 7. In the mathematical analysis, the PV array power can be modelled as a resistance $R_{PV}$ according to ref. [28]. On the other hand, since the DC-bus voltage is controlled by the inverters, the output voltage of the boost converter ($V_{dc}$) is assumed to be constant.

The boost converter is controlled by adopting a multi-loop control strategy based on two main loops. An outer loop is employed to control the input voltage [$v_{pv}(t)$] whose voltage

$$C_{dc} \left( \frac{dr_{dc}}{dt} \right) r_{dc} = P_{pv} + \frac{v_d r_{dc}}{2}$$ (25)

where $v_d$ is the utility grid voltage in $d$-axis and $i_{dc}$ represents the active current drained from the grid to maintain controlled the inverter DC-bus voltage.

Thus, after some mathematical manipulations in Equation (25), the inverter DC-bus voltage derivative is given by:

$$\frac{dr_{dc}}{dt} = \frac{v_d^2}{2C_{dc}V_{dc}} + \frac{1}{C_{dc}V_{dc}} P_{pv}$$ (26)

After small-signal analysis, the TF that represents the DC-bus voltage dynamics related to $i_{dc}$ can be found as:

$$G_{r1}\phi (s) = \frac{\dot{\hat{r}}_{dc}(s)}{\dot{\hat{i}}_{dc}(s)} = \frac{v_d}{2s C_{dc}V_{dc}}$$ (27)

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The boost converter is controlled by adopting a multi-loop control strategy based on two main loops. An outer loop is employed to control the input voltage [$v_{pv}(t)$] whose voltage
reference is determined by the MPPT algorithm. Meanwhile, an inner loop is used to control the boost inductor current \( i_b(t) \), whose reference is provided by the voltage outer loop.

Hence, from Figure 7 and after the small-signal analysis, the following equations are obtained:

\[
L_b \frac{d i_b(t)}{dt} = v_{pv}(t) - R_{lb} i_b(t) + d(t) V_{dc} \tag{29}
\]

\[
C_{pv} \frac{dv_{pv}(t)}{dt} = -v_{pv}(t) R_{pv} - i_b(t) \tag{30}
\]

where \( d(t) \) is the duty cycle of the boost converter; \( R_{pv} = v_{pv}/i_{pv} \) represents the PV array impedance at MPP; \( C_{pv} \) is the PV array output capacitance; \( L_b \) is the boost inductance and \( R_{lb} \) is its internal resistance.

Therefore, after some mathematical manipulations in Equations (29) and (30), the open loop TFs of the respective outer and inner control loops can be represented as follows:

\[
G_{vi}(s) = \frac{\hat{v}_{pv}(s)}{\hat{i}_b(s)} = -\frac{R_{pv}}{1 + s C_{pv} R_{pv}} \tag{31}
\]

\[
G_{id}(s) = \frac{\hat{i}_b(s)}{d(s)} = \frac{V_{dc} (1 + s C_{pv} R_{pv})}{s^2 (C_{pv} R_{pv} L_b) + s (L_b + C_{pv} R_{pv} R_{lb}) + (R_{pv} + R_{lb})} \tag{32}
\]

The block diagram of the multi-loop control system is presented in Figure 8, where \( K_{pv}^b \) and \( K_{pv}^c \) are the respective P and I gains of the PI voltage controller (outer loop), while \( K_{bi}^b \) and \( K_{bi}^c \) are the respective P and I gains of the PI current controller (inner loop). In addition, the TFs expressed by Equations (31) and (32) are also presented, as well as the PWM gain (\( K_{PWM}^b \)).

4 EXPERIMENTAL RESULTS

The prototype setup shown in Figure 9 was used in the experimental tests. It is composed of three 1-FB inverters and three DC–DC boost converters. The control systems and references generation algorithms were embedded in the TMS320F28335 DSC (Texas Instruments). All the electrical quantities, such as power, voltage and current were measured using the digital power meter WT3000 (Yokogawa).

Table 1 presents the electrical characteristics of the PV modules, while Table 2 summarizes the main parameters of the MPV systems. In Table 3 the unbalanced single-phase nonlinear loads are presented, whereas the controller design specifications and controllers’ gains are shown in Table 4.

The MPV systems were tested considering four different operational scenarios (SC) described in Section 1. In addition,


| TABLE 2 | Parameters of the MPV systems |
|------------------------|---------------------------------|
| Nominal utility grid voltage (rms) | \( V_{a,b,c} = 127 \text{ V} \) |
| Nominal utility grid frequency | \( f_e = 60 \text{ Hz} \) |
| Sampling frequency A/D converter | \( f_s/d = 40 \text{ kHz} \) |
| Switching frequencies of the PWM converters (1-FB inverter and DC–DC boost converter) | \( f_{sw} = 20 \text{ kHz} \) |
| Inductive filters resistance of the 1-FB inverter | \( L_{a,b,c} = 1.5 \text{ mH} \) |
| Transformer leakage inductance | \( R_{a,b,c} = 0.22 \text{ Ω} \) |
| Transformer leakage resistance | \( R_{a,b,c} = 0.08 \text{ Ω} \) |
| 1-FB DC-bus capacitance | \( C_{d,b} = 2115 \text{ F} \) |
| 3-FB DC-bus capacitance | \( C_{d,b} = 705 \text{ F} \) |
| PWM gain for the 1-FB inverters | \( K_{PWM} = 2.666 \times 10^{-4} \) |
| Capacitive filter of the PV array | \( L_{a,b,c} = 16 \text{ mH} \) |
| Boost filtering inductance | \( R_{a,b,c} = 1.5 \text{ mH} \) |
| Resistance of the boost inductor | \( R_{a,b,c} = 0.22 \text{ Ω} \) |
| PWM gain for the boost converter | \( K_{PWM} = 5.33 \times 10^{-4} \) |

| TABLE 3 | Load parameters |
|------------------------|---------------------------------|
| Load 1 | | |
| Phase | Non-linear load | Resistance \((R_{a,b,c})\) | Inductance \((L_{a,b,c})\) | THD [%] | |
| a | 1-FB rectifier | 10.1 Ω | 16 mH | 21.6 | |
| b | 1-FB rectifier | 9.5 Ω | 16 mH | 23.4 | |
| c | 1-FB rectifier | 13.2 Ω | 16 mH | 21.7 | |
| Load 2 | | | | | |
| Phase | Non-linear load | Resistance \((R_{a,b,c})\) | Inductance \((L_{a,b,c})\) | THD [%] | |
| a | 1-FB rectifier | 28.9 Ω | 16 mH | 26.3 | |
| b | 1-FB rectifier | 20.1 Ω | 16 mH | 24.4 | |
| c | 1-FB rectifier | 37.7 Ω | 16 mH | 28.2 | |

in order to evaluate the performance of the FFCL in SS and DS configurations, static and dynamic results are presented for both MPV-FB-SS and MPV-FB-DS systems.

### 4.1 Evaluation scenarios of the MPV systems

In both SC 1 and SC 2, all the MPV systems (MPV-FB-SS, MPV-FB-DS, MPV-3FB-SS and MPV-3FB-DS) were tested and evaluated from stationary results. On the other hand, although the four MPV systems can operate in SC 3 and SC 4, in such scenarios only the SS MPV structures were experimentally verified, since the performances of the DS MPV systems are very close to those achieved for the SS MPV configurations.

#### 4.1.1 Scenario 1

The four MPV systems were tested without loads. Thus, all the energy produced by the PV arrays is injected into the utility grid.

Figure 10 presents the power \((P_{pv})\), voltage \((v_{pv})\) and current \((i_{pv})\) of the PV arrays used in each MPV system. The results related to the energy injected into the grid as the grid voltage of phase ‘a’\((v_{sa})\), the 3-phase grid currents \((i_{sa}, i_{sb}, i_{sc})\), and the grid neutral current \((i_n)\) are shown in Figure 11.

From Figure 11(a,b), it can be noted that, for the MPV-FB structures (MPV-FB-SS and MPV-FB-DS), the grid currents are sinusoidal and balanced, while \(i_n\) is in opposite-phase with the respective grid voltage. The grid neutral current \(i_n\) is approximately equal to zero.

On the other hand, for the MPV-3FB systems (MPV-3FB-SS and MPV-3FB-DS), the grid currents are sinusoidal and \(i_n\) is in opposite-phase with the respective grid voltage \(v_{sa}\). Nevertheless, since the MPV-3FB systems employ three independent PV arrangements, the power produced by them can be different to each other, and, hence, the currents injected into the grid will be unbalanced. Therefore, a small portion of grid neutral current \(i_n\) flows through the neutral conductor, as can be noted in Figure 11(c,d).

#### 4.1.2 Scenario 2

In this scenario, the four MPV systems operate similarly to the SC 1. However, in this case, the PV arrangements are subjected to failure occurrence in a string, as illustrated in Figure 12.
As presented in Figure 13, despite the condition of failure, the MPV-FB-SS and MPV-FB-DS systems remain injecting sinusoidal and balanced currents into the utility grid. Moreover, the grid neutral current $i_{sn}$ is approximately equal to zero, as can be verified from Figure 13(a,b). Differently, the MPV-3FB-SS and MPV-3FB-DS inject energy into the grid only in the ‘b’ and ‘c’ phases. As a result, high level of current flows to the neutral wire, as can be noted in Figure 13(c,d).

### 4.1.3 Scenario 3

In SC 3, both MPV-FB-SS and MPV-3FB-SS structures operate only as S-APFs. In these tests, unbalanced single-phase non-linear loads (see load 1 in Table 3) are connected to the 3P4W electrical system.

Figure 14 presents the grid currents ($i_{sa}$, $i_{sb}$, $i_{sc}$, $i_{sn}$) and these same quantities in conjunction with the grid voltages ($v_{sa}$, $v_{sb}$, $v_{sc}$), load currents ($i_{La}$, $i_{Lb}$, $i_{Lc}$) and compensation currents ($i_{ca}$, $i_{cb}$, $i_{cc}$), separately per-phase. As can be seen, both MPV-FB-SS and MPV-3FB-SS structures are able to perform the power-line conditioning compensating for reactive power and suppressing load harmonic currents. However, only the MPV-FB system performs load unbalance compensation.

### 4.1.4 Scenario 4

Figure 15 presents results associated to the MPV-FB-SS and MPV-3FB-SS systems performing active energy injection into the utility grid and, simultaneously, power-line conditioning. In SC 4, unbalanced single-phase non-linear loads (see load 2 in Table 3) are connected to the 3P4W electrical system. It can be observed that, for both MPV-FB-SS and MPV-3FB-SS structures, the 3-phase grid currents ($i_{sa}$, $i_{sb}$, $i_{sc}$) are nearly sinusoidal and are in opposite-phase with their respective grid voltages,
meaning that part of the energy produced by the PV arrays is used to feed the loads and the remaining is injected into the grid.

It can also be verified that, by comparing the results presented in Figure 15(a) with those presented in Figure 15(b), in the MPV-FB structure the grid currents are balanced, while in the MPV-3FB they are unbalanced.

### 4.2 Dynamic analysis

In order to test the dynamic responses of the inverter DC-bus voltages and the currents injected into the grid, two MPV configurations (MPV-FB-SS and MPV-FB-DS) were chosen to be tested under abrupt solar irradiation (0%–100%) and load variations (0%–100%–0%). Thus, the dynamics of the mentioned systems were evaluated with and without the use of the FFCLs discussed in Section 2.2.

Figure 16 presents the DC-bus voltages \( V_{dc} \) and the grid currents \( i_{sa}, i_{sb}, i_{sc} \) in the presence of sudden solar irradiation change. As can be seen in Figure 16(b,d), the use of the FFCLs contributes to accelerate the DC-bus voltage dynamics avoiding the voltage oscillations observed in Figure 16(a,c). In addition, under abrupt solar irradiation change, the FFCLs also contribute to accelerate the dynamic of the grid currents. Moreover, it can be noted that the MPV-FB-SS system achieved better performance with the FFCL use when compared with the MPV-FB-DS system. As can be seen, the DC bus voltage overshoot does not appear in the SS system (see Figure 16(b)). On the other hand, for the MPV-FB-DS system with FFCL a small overshoot can still be seen in Figure 16(d) due to the dynamics of the DC–DC boost converter to reach the power balance.

Figure 17 presents the tests for abrupt load variations, where following quantities are shown: DC-bus voltages \( V_{dc} \), load currents \( i_{La}, i_{Lb}, i_{Lc} \) and grid currents \( i_{sa}, i_{sb}, i_{sc} \). As can be noted, the DC-bus voltage controller is able to maintain controlled inverter DC-bus voltage. In addition, it can be noted that FFCLs have little effect on improving the dynamics of systems under load transients.

### 4.3 Total harmonic distortion

Considering all the scenarios (SC 1–SC 4) Table 5 presents the THDs of the grid currents, which were measured using the power quality analyser Fluke 43B.

It can be noted that the MPV systems can inject active energy into the grid with low THD, while their performances as active power conditioners provide an effective harmonic rejection. In SC 1, 2 and 3, the THDs of the grid currents were less than 5% and meet the IEEE 1547 standard [8]. On the other hand, in SC 4, the THDs were superior to 5%. Since in SC 4 the MPV systems operate injecting energy into the grid and, simultaneously, perform the power-line conditioning task, it is expected higher THDs in the SC 4 when compared to the SCs 1–3. Moreover, it can be emphasized that the IEEE 1547 standard does not establish requirements for multifunctional PV systems.

### 4.4 Constructive aspects of the MPV systems

Table 6 summarizes the main constructive characteristics involved in the grid-tied MPV systems, in which the number of semiconductor devices and passive elements used in the MPV power circuits’ structures, number of DSCs and communication boards, as well as number of voltage and current transducers are considered.

Regarding to the physical structures, all the MPV systems employ three 1-FB inverters and three coupling inductors, while the MPV-FB structure only requires three isolation transformers that contribute to increase both weight and cost. Furthermore, the DS MPV systems are bulkier and heavier than the SS systems, due to the integration of the DC–DC boost converters.

With respect to the measurement components, the MPV-FB-SS and MPV-FB-DS systems need to use 11 and 12 transducers, respectively, whereas for the MPV-3FB-SS and MPV-3FB-DS systems the costs associated to these components increase, once they require to employ 15 and 18 transducers, respectively. In addition, only one DSC board was needed to operate the SS MPV structures, whereas to operate the DS MPV two DSC boards were necessary, one was used to control the 1-FB inverters and the other one to control the boost converters.

### 4.5 Efficiency

The efficiencies of the MPV systems were evaluated by means of simulations, considering different levels of solar irradiation (100, 250, 500, 750 and 1000 W/m²). For this purpose, the conduction and switching losses related to the semiconductors’ devices, as well as the ohmic losses of the inductive filters and transformers were considered. Figure 18 presents the efficiency curves over the range of solar irradiation obtained for all the MPV systems.

It can be noted that the efficiencies of the DS MPV configurations are lower than those achieved for the SS MPV ones, due
FIGURE 13  Static experimental results of the four MPV systems considering the scenario 2 (SC 2): grid voltage ($v_{sa}$), grid currents ($i_{sa}$, $i_{sb}$, $i_{sc}$), and grid neutral current ($i_{sn}$) (50 V/div; 10 A/div; 5 ms/div) (a) MPV-FB-SS, (b) MPV-FB-DS, (c) MPV-3FB-SS, (d) MPV-3FB-DS

FIGURE 14  Static experimental results of the two MPV systems considering the scenario 3 (SC 3): grid voltages ($v_{sa}$, $v_{sb}$, $v_{sc}$), grid currents ($i_{sa}$, $i_{sb}$, $i_{sc}$), load currents ($i_{La}$, $i_{Lb}$, $i_{Lc}$), compensation currents ($i_{ca}$, $i_{cb}$, $i_{cc}$), and grid neutral current ($i_{sn}$) (50 V/div; 10 A/div; 5 ms/div) (a) MPV-FB-SS, (b) MPV-3FB-SS

TABLE 5  Total harmonic distortion (THD %) of the grid currents

| THD | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|-----|------------|------------|------------|------------|
|     | $i_{sa}$ | $i_{sb}$ | $i_{sc}$ | $i_{sa}$ | $i_{sb}$ | $i_{sc}$ | $i_{sa}$ | $i_{sb}$ | $i_{sc}$ | $i_{sa}$ | $i_{sb}$ | $i_{sc}$ |
| MPV-FB-SS | 2.0 | 1.8 | 1.9 | 2.8 | 2.5 | 2.9 | 3.2 | 3.4 | 3.5 | 6.2 | 7.0 | 6.2 |
| MPV-FB-DS | 3.0 | 3.1 | 3.0 | 3.5 | 3.8 | 3.8 | – | – | – | – | – | – |
| MPV-3FB-SS | 3.6 | 3.7 | 3.3 | – | 3.9 | 3.9 | 3.6 | 3.4 | 3.5 | 6.0 | 8.1 | 7.6 |
| MPV-3FB-DS | 2.7 | 3.1 | 3.0 | – | 3.2 | 3.9 | – | – | – | – | – | – |
FIGURE 15  Static experimental results of the two MPV systems considering the scenario 4 (SC 4): grid voltages \(v_{sa}, v_{sb}, v_{sc}\), grid currents \(i_{sa}, i_{sb}, i_{sc}\), load currents \(i_{La}, i_{Lb}, i_{Lc}\), compensation currents \(i_{ca}, i_{cb}, i_{cc}\) and grid neutral current \(i_{sn}\) (50 V/div; 10 A/div; 5 ms/div) (a) MPV-FB-SS, (b) MPV-3FB-SS

FIGURE 16  Solar irradiation change dynamic tests: Inverter DC-bus voltage and grid currents (20 V/div; 20 A/div; 250 ms/div) (a) MPV-FB-SS without FFCL, (b) MPV-FB-SS with FFCL, (c) MPV-FB-DS without FFCL, (d) MPV-FB-DS with FFCL

FIGURE 17  Load variation dynamic tests: Inverter DC-bus voltage (50 V/div; 1 s/div), load currents \(i_{La}, i_{Lb}, i_{Lc}\) (10 A/div; 1 s/div), and grid currents \(i_{sa}, i_{sb}, i_{sc}\) (20 A/div; 1 s/div) (a) MPV-FB-SS without FFCL, (b) MPV-FB-SS with FFCL, (c) MPV-FB-DS without FFCL, (d) MPV-FB-DS with FFCL
TABLE 6  Constructive characteristics

|                         | MPV-FB-SS | MPV-FB-DS | MPV-3FB-SS | MPV-3FB-DS |
|-------------------------|-----------|-----------|------------|------------|
| Number of 1-FB inverters| 3         | 3         | 3          | 3          |
| Number of DC–DC boost converters | –         | 1         | –          | 3          |
| Total semiconductor devices | 12       | 13        | 12         | 15         |
| Number of inductive filters | 3         | 3         | 3          | 3          |
| Number of isolation transformers | 3         | 3         | –          | –          |
| Number of voltage and current transducers | 11       | 12        | 15         | 18         |
| Number of DSC communication boards | 2         | 3         | 2          | 3          |
| Number of TMS320F28335 DSC devices | 1         | 2         | 1          | 2          |

FIGURE 18  Efficiency curves of the four MPV systems

to the use of the additional power-converter stage composed of boost converters. Moreover, the worst efficiency can be observed for the MPV-3FB-DS configuration since the power losses increase due to the use of three step-up DC/DC converters.

On the other hand, considering the SS MPV configurations, the MPV-3FB-SS does not present ohmic losses associated with transformers, making its efficiency slightly higher than the MPV-FB-SS.

5  CONCLUSION

This paper presented a comparative analysis involving grid-tied MPV systems operating with SS and DS configurations. The static and dynamic performances of the MPV systems were experimentally evaluated considering several scenarios of operation.

It was verified that the MPV-FB structures (MPV-FB-SS and MPV-FB-DS) could inject sinusoidal and balanced currents into the grid even operating with failure in a string of the PV array. This was possible due to their abilities to operate by conditioning the power grid, including compensation for load imbalance. On the other hand, in all the evaluated scenarios, the MPV-3FB systems (MPV-3FB-SS and MPV-3FB-DS) were also able to inject sinusoidal currents into the grid, though they are unbalanced. Hence, depending on the unbalance level, high amplitude of current can flow through the neutral conductor.

It was also demonstrated that, in both MPV-FB-SS and MPV-FB-DS systems, in the presence of sudden solar irradiation, the dynamic responses of the DC-bus voltage were enhanced when the FFCLs were employed. As a result, large DC-bus voltage oscillations were avoided when the MPV systems were subjected to abrupt transients of solar irradiation. In this regard, the MPB-FB-SS system presented superior performance when compared with MPV-FB-DS, since the dynamics related to the boost converter interfere minimally in the power balance of the system. On the other hand, the FFCLs do not interfere in the dynamic of the systems when abrupt load variations occur.

Finally, with respect to constructive aspects, the MPV-FB-DS is the most expensive structure, mainly due to the need to use isolation transformers, though always balanced grid currents are obtained under any operation condition (SC1–4). On the other hand, considering cost-effectiveness issues and efficiency, the MPV-3FB-SS can be regarded as the most attractive structure, though balanced grid currents are not achieved.

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REFERENCES
1. International Energy Outlook 2019 with projections to 2050, pp. 1–169. U.S. Energy Information Administration and U.S. Department of Energy, Washington, DC 20585 (2019) https://www.eia.gov/ieo
2. Renewable Energy Policy Network for 21st Century (REN21). Renewable 2018 Global Status Report, (2018)
3. Jain, S., et al.: Distributed generation deployment: State-of-the-art of distribution system planning in sustainable era. Renewable Sustainable Energy Rev. 77, 363–385 (2018)
4. Viral, R., Khatod, D.K.: Optimal planning of distributed generation systems in distribution system: A review. Renewable Sustainable Energy Rev. 16(7), 5146–5165 (2012)
5. Velasco-Quesada, G., et al.: Electrical PV array reconfiguration strategy for energy extraction improvement in grid-connected PV systems. IEEE Trans. Indus. Electron. 56(11), 4319–4331 (2009)
6. Adefarati, T., Bansal, R.C.: Integration of renewable distributed generators into the distribution system: A review. IET Renew. Power Gener. 10(7), 873–884 (2016)
7. Obi, M., Bass, R.: Trends and challenges of grid-connected photovoltaic systems - A review. Renewable Sustainable Energy Rev. 58, 1082–1094 (2016)
8. IEEE Standards Association: IEEE 1547–2018, IEEE standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces sponsored by the IEEE standard for interconnection and interoperability of distributed energy resources with associate. (2018)
9. Jain, S., Agarwal, V.: A single-stage grid connected inverter topology for solar PV systems with maximum power point tracking. IEEE Trans. Power Electron. 22(5), 1928–1940 (2007)
10. Jain, C., Singh, B.: Single-phase single-stage multifunctional grid interfaced solar photo-voltaic system under abnormal grid conditions. IET Gener. Transm. Distrib. 9(10), 886–894 (2015)
11. Wu, T.F., et al.: Power loss comparison of single-and two-stage grid-connected photovoltaic systems. IEEE Trans. Energy Convers. 26(2), 707–715 (2011)
12. Sangwongwanich, A., et al.: A sensorless power reserve control strategy for two-stage grid-connected PV systems. IEEE Trans. Power Electron. 32(11), 8559–8569 (2017)
13. da Silva, S.A.O., et al.: Feed-forward DC-bus control loop applied to a single-phase grid-connected PV system operating with PSO-based MPPT technique and active power-line conditioning. IET Renew. Power Gener. 11(1), 183–193 (2016)
14. Zeng, Z., et al.: Multi-functional grid-connected inverter: Upgrading distributed generator with ancillary services. IET Renew. Power Gener. 12(7), 797–805 (2018)
15. Zeng, Z., et al.: Multi-objective control of multi-functional grid-connected inverter for renewable energy integration and power quality service. IET Power Electron. 9(4), 761–770 (2016)
16. Campanhol, L.B.G., et al.: Dynamic performance improvement of a grid-tied PV system using a feed-forward control loop acting on the NPC inverter currents. IEEE Trans. Indus. Electron. 64(5), 2092–2101 (2016)
17. Kumar, R., Bansal, H.O.: Shunt active power filter: Current status of control techniques and its integration to renewable energy sources. Sustainable Cities Soc. 42, 574–592 (2018)
18. Yang, Y., et al.: Power control flexibilities for grid-connected multi-functional photovoltaic inverters. IET Renew. Power Gener. 10(4), 504–513 (2016)
19. Brandão, D., et al.: Estratégia de controle multifuncional para sistemas fotovoltaicos de geração de energia elétrica. Brazilian J. Power Electron. 18(4), 1206–1214 (2013)
20. Shah, P., et al.: Multi-resonant FLL-based control algorithm for grid interfaced multi-functional solar energy conversion system. IET Sci., Meas. Technol. 12(1), 49–62 (2017)
21. Srinivas, V.L., et al.: A multifunctional GPV system using adaptive observer based harmonic cancellation technique. IEEE Trans. Indus. Electron. 65(2), 1347–1357 (2017)
22. Campanhol, L.B.G., et al.: Single-stage three-phase grid-tied PV system with universal filtering capability applied to DG systems and AC microgrids. IEEE Trans. Power Electron. 32(12), 9131–9142 (2017)
23. Campanhol, L.B.G., et al.: Application of shunt active power filter for harmonic reduction and reactive power compensation in three-phase four-wire systems. IET Power Electron. 7(11), 2825–2836 (2014)
24. Brito, M.A.G., et al.: Evaluation of the main MPPT techniques for photovoltaic applications. IEEE Trans. Ind. Electron. 60(3), 1156–1167 (2013)
25. da Silva, S.A.O., Modesto, R.A.: A comparative analysis of SRF-based controllers applied to active power line conditioners. In: 34th Annual Conference of IEEE Industrial Electronics Society (IECON), Orlando, FL, 405–410 (2008)
26. Bacon, V.D., et al.: Stability analysis and performance evaluation of a single-phase phase-locked loop algorithm using a non-autonomous adaptive filter. IET Power Electron. 7(8), 2081–2092 (2014)
27. Takami, M.H.F., et al.: Dynamic performance comparison involving grid-connected PV systems operating with active power-line conditioning and subjected to sudden solar irradiation changes. IET Renew. Power Gener. 13(4), 587–597 (2019)
28. Femia, N., et al.: A technique for improving P&O MPPT performances of double-stage grid-connected photovoltaic systems. IEEE Trans. Ind. Electron. 56(11), 4473–4482 (2009)