

A Grid-Connected Photovoltaic System with Integrated Energy Management and Power Quality Enhancement Functions Utilising a Split Source Inverter

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Abstract - This project proposes to use a split-source inverter (SSI) for MFGC applications due to its better boosting capability and less number of components. In contrast to topologies utilised in impedance source inverters (ZSIs), the SSI can also work as an active power filter (APF). In order to regulate the DC and AC components of the MFGC system-based SSI, this research presents a sliding mode control (SMC) technique. The MFGC system is meant to compensate the reactive power on the grid, match the power demand of non-linear loads with the PV power that has been removed, and then inject the rest of the PV power back into the grid. In order to manage the DC input current and calculate the duty cycle that supplies the boosting capacity, the SMC scheme is applied on the DC side. The AC side of the system is subsequently regulated by a decoupled SMC-based control approach, which also estimates the reference voltages fed into a modified space vector modulation (MSVM) stage. Using the MATLAB/Simulink platform for simulation and real-time hardware for experimental validation, the entire system is evaluated in a closed-loop mode. When it comes to managing power and improving power quality, the findings from simulation and HIL setup reveal that the suggested management technique is successful and resilient.

Key Words: Multi-functional grid-connected (MFGC), photovoltaic system (PVS), sliding mode control (SMC), split-source inverter (SSI), active power filter (APF).

1.INTRODUCTION

Increasingly, people are looking to renewable energy sources (RESs) to power their homes and companies. Most renewable energy sources (RES) are to be connected to the grid via power converters [1, 2]. Unfortunately, the poor power quality at the point of common connection (PCC) might be attributed to the harmonics generated by nonlinear load connected to the grid [3]. To tackle this problem, increasing number of people are using multi-functional grid-connected (MFGC) systems. These systems have various advantages such as injecting active power generated by RESs, improving power quality by balancing reactive

power and reducing grid current harmonics. These systems can operate in several modes, such as partial active power filtering (P-APF), real power injection (RPI) and full active power filtering (F-APF) [3, 4, 5, 6]. If you are seeking for MFGC systems suitable for grid-connected PV applications, they can be generally identified based on the presence of one or two conversion stages. A two-stage arrangement realises two conversion phases. An initial DC-DC converter is used for the determination of the maximum power output of the PV generator and for the increase of the DC voltage at the DC connection to the desired voltage. The second stage uses a DC-AC converter to provide the load or grid with alternating current (AC) [4, 7]. Anyway, the configuration provides more control flexibility due to the increased degrees of freedom in the two converters. The increased number of passive components and switching devices reduces the total system efficiency, which makes the cost higher [7]. In contrast, the single-stage design uses a single DC-AC converter, which saves cost, increases efficiency and minimises the number of active and passive components [7], [8], [9]. The main disadvantage of this system is the deficiency of features increasing the output PV voltage. Improved control of PV power and hot-spot mitigation caused by diverse PV panel failures, including partial shading of the PV arrays, are key issues for grid-tied PV systems [10], [11]. The control design is also somewhat difficult as the inverter control algorithm must include controlling the maximum power point tracking (MPPT) [8].

Table 1. Nomenclature List

RES	Renewable energy source	RMSV	Regulated modified space vector modulation
PCC	Point of common coupling	FCS-MPC	Fuzzy control set model predictive control
MFGC	Multi-functional grid-connected	SMC	Sliding mode control
P-APF	Partial active power filter	MSVM	modified space vector modulation
RPI	Real power injection	PI	Proportional-integral
F-APF	Full active power filter	HIL	Hardware in the loop
PV	Photovoltaic	VSI	Voltage source inverter
MPPT	Maximum power point tracking	IL	Kirchoff's law
ZSI	Z-source inverter	VLC-SSI	Voltage Lift Cell Split-Source Inverter
Q-ZSI	Quasi Z-source inverter	PLL	Phase locked loop
SL-Q-ZSI	Switched inductor Quasi Z-source Network	SVM	Space vector modulation
SL-ZSI	Switched inductor Z-source inverter	THD	Total harmonic distortion
SN-QZSI	Switched network quasi Z-source inverter	SBPWM	single boost pulse width modulation
SSI	Split Source Inverter	QZ-SSI	Quadratic-Boost Split Source Inverter

This problem has been solved in several studies that combine the output PV voltage boosting capability with passive elements in a single-stage structure [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23]. The most common single stage topologies discussed in the literature for impedance source inverters are Z-source inverters (ZSIs) [13], quasi Z-source inverters (Q-ZSIs) [14], Switched inductor Quasi Z-source Network (SL-Q-ZSIs) [16], switched coupled inductor quasi-Z-Source inverter (SI-Q-ZSI) [17], Switched inductor Z-source Network (SLZSIs) [18], and Switched Network Z-source (SN-ZSI) [19]. All these topologies use a shoot-through state for enabling the buck/boost conversion capability. However, ZSI, SL-ZSI and SN-ZSI topologies are characterised by multiple problems such as unidirectional power flow, large number of passive components, large inrush current at starting and non-continuous input current. Proposed improvements to Q-ZSI and SL-Q-ZSI are to eliminate the above described inrush and discontinuous current. However, the number of passive components and unidirectional power transfer in Q-ZSI and other ZSI topologies still remain hurdles [21], [22], [23].

The split-source inverter (SSI) has been recently offered as a solution to the issues faced by the impedance source designs, beyond its buck/boost conversion functionalities. SSI is better than ZSI and Q-ZSI [21] as the number of passive components reduces and efficiency increases. Other designs in the SSIs category are the Voltage-Lift Cell Split-Source Inverter (VLC-SSI) [23] and the Quadratic Boost Split-Source Inverter (Q-B-SSI) [22]. The more amplification advantage of Q-B-SSI and VLC-SSI than SSI is both. In contrast, they require a larger number of diodes and passive components.

The SSI series is especially suitable for MFGC applications as it is a complete APF system. Therefore, a detailed study was done on the inverters which are mostly based on three-phase impedance sources. The results of our analysis are summarised in Table 2.

In some cases, the AC and DC components of an SSI can be managed independently as in a ZSI or Q-ZSI system [21]. The SSI setup has been addressed by several control approaches in the literature [24], [25], [26], [27], [28], [29]. In [24] authors offer a decoupled control system in three-phase grid-tied solar application combined with regulated modified space vector (RMSV) modulation. In contrast, [25] presents a peak power controller that controls the voltage of the DC-link capacitor by monitoring the maximum power point tracking (MPPT) due to the variations of solar radiation. The PI controllers used for controlling the variables at the AC and DC side in [24] and [25] have some limitations in terms of their linear property. For grid-tied SSI control, the authors in [28] proposed the FCS-MPC framework that is widely used in power electronics applications because to its ability to control

multivariable systems. However, although FCS-MPC has significant performance, it suffers from problems like the varying switching frequency and the low robustness to the changes of system parameters. The sliding mode control (SMC) has attracted a lot of attention in the study of power electronic converters control due to its attractive properties such as easy implementation, good dynamic performance and strong robustness [30, [31], [32], [33], [34]. There have been a lot of research done on the regulation of power electronic converters. In contrast, the chattering problem is an unwanted effect of the use of the traditional switching function (signum function) and results in a high switching frequency. In addition, there seems to be a lack of study on the investigation of SMC under the SSI framework.

TABLE 2. Comparison of numerous three-phase impedance sources inverters.

	ZSI [13]	Q-ZSI [14]	SL-Q-ZSI [16]	SLZSI [18]	SN [19]
No. of switch	6	6	6	6	6
No. of diodes	1	1	4	7	3
No. of passive components	4	4	5	6	2
boost capability	YES	YES	YES	YES	YES
Extra function (PFI)	YES	YES	YES	YES	YES
Extra function (P-APF)	YES	YES	YES	YES	YES
Extra function (F-APF)	NO	NO	NO	NO	YES
Input current	discontinuous	continuous	continuous	discontinuous	continuous

The research provides a new control scheme for an MFGC system using SSI based on the SMC technique combined with the modified space vector modulation (MSVM). The proposed system aims to meet the requirements of nonlinear loads for active and reactive power, the distorted power, to feed the surplus PV active power to the grid and to keep the grid power quality at the level required by international standards. Also, the SSI capabilities allows for SSI operation inside F-APF unlike impedance source inverter arrangements. For the control of the AC and DC components of the system, a Sliding Mode Controller (SMC) with seamless continuous switching has been designed and the chattering phenomenon noticed earlier has been removed.

The original SMC controller is designed to control the DC input current and predict the duty-cycle that enables the boost feature. The modified space vector modulation (MSVM) phase will receive the reference voltage, duty cycle and modulation index from a decoupled sliding mode control (SMC) system. The effectiveness of the suggested control technique is demonstrated with MATLAB/Simulink setups in different operational modes. The simulation results are validated by experimental tests conducted on a real-time hardware-

in-the-loop platform. This ensures that the results are accurate. To summarise, this research contributes mostly to the following areas: Explore the SSI in MFGC framework using several operating modes such as P-APF, RPI, and F-APF. Based on the SMC theory, a better method for dc side regulation is provided. The proposed control system is analysed for stability and the stability region is defined using the Lyapunov theory.

4) Experimental validation and simulation studies using the HIL platform based on the OPAL-RT 5600 real-time simulator and dSPACE 1103 card for verification of the performance of the proposed system. The balance of this paper is organised as follows: Section II describes the design and modelling of the system. The proposed sliding mode control mechanism and the stability analysis are described in Section III. The simulation results of the proposed control technique are discussed and analysed in Part IV. The experimental setup and HIL results are discussed in section V. The final climax of the book is in Section VI.

More and more people around the world are turning to renewable energy sources (RESs) to power their homes and businesses. The integration of renewable energy sources into the grid is a major need for power converters [1], [2]. Harmonics generated by nonlinear loads connected to the grid at the point of common coupling (PCC) unfortunately result in poor power quality at the PCC [3]. The advantages of multi-functional grid-connected (MFGC) systems such as active power injection from renewable energy sources, power quality improvement by compensating reactive power and eliminating grid current harmonics have motivated their use as a solution to this problem.

These systems can operate in many modes such as partial active power filter (P-APF), real power injection (RPI) and full active power filter (F-APF) [3, 4, 5, 6]. MFGC systems in grid-connected photovoltaic (PV) applications are often classified as single conversion stage or two conversion stages. Dual stage configuration has two stages of conversion. In the first part, a DC-DC converter estimates the peak power generated by the solar generator and boosts the DC voltage at the DC interface to the necessary level.

In the next stage, a DC-AC converter is added [4, 7] to feed alternating current (AC) to the load/grid. But the arrangement provides higher control flexibility due to the higher degrees of freedom of the two converters. In contrast, the total system efficiency decreases with the number of passive components as seen in Table 1.

RES	Renewable energy source	RMSV	Regulated modified space vector modulation
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With increasing cost, the list of switching devices also rises [7]. In contrast, the single-stage architecture uses a single DC-AC converter, which reduces the number of active and passive components, improves the efficiency and reduces the costs. Unfortunately, this setup has no qualities to increase the PV output voltage. These properties are useful for grid-connected solar applications, since they allow better control of the photovoltaic output and avoid hot spots caused by different faults of the photovoltaic panels, such as partial shading of the photovoltaic arrays. Furthermore, the control design complexity is quite high due to the inverter control algorithm must manage the maximum power point tracking (MPPT) [8].

This problem has been widely solved by combining the output PV voltage enhancement capacity with the passive components into a single-stage arrangement [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23]. The most common single-stage topologies mentioned in the literature for impedance source inverters are Z-source inverters (ZSIs) [13], quasi Z-source inverters (Q-ZSIs) [14], Switched inductor Quasi Z-source Network (SL-Q-ZSIs) [16], switched coupled inductor quasi-Z-Source inverter (SI-Q-ZSI) [17], Switched inductor Z-source Network (SLZSIs) [18] and Switched Network Z-source (SN-ZSI) [19]. All these topologies use a shoot-through state for enabling the buck/boost conversion capability. However, ZSI, SL-ZSI and SN-ZSI topologies are characterised by multiple problems such as unidirectional power flow, large number of passive components, large inrush current at starting and non-continuous input current.

Proposed improvements to Q-ZSI and SL-Q-ZSI are to eliminate the above-described inrush and discontinuous current. However, the number of passive components and unidirectional power transfer in Q-ZSI and other ZSI topologies still remain hurdles [21], [22], [23]. The split-source inverter (SSI) has been recently offered as a solution to the issues faced by the impedance source designs, beyond its buck/boost conversion functionalities. SSI is better than ZSI and Q-ZSI [21] as the number of passive components reduces and

efficiency increases. Other designs in the SSIs category are the Voltage-Lift Cell Split-Source Inverter (VLC-SSI) [23] and the Quadratic Boost Split-Source Inverter (Q-B-SSI) [22]. The more amplification advantage of Q-B-SSI and VLC-SSI than SSI is both. In contrast, they require a larger number of diodes and passive components.

The SSI series is especially suitable for MFGC applications as it is a complete APF system. Therefore, a detailed study was done on the inverters which are mostly based on three-phase impedance sources. The results of our analysis are summarised in Table 2.

TABLE 2. Comparison of numerous three-phase impedance sources inverters.

	ZSI [1]	Q-ZSI [2]	SL-Q-ZSI [3]	SL-ZSI [4]	SSI [17]
No. of switch	6	6	6	6	6
No. of diodes	1	1	4	7	3
No. of passive components	4	4	5	6	2
boost capability	YES	YES	YES	YES	YES
Extra function (RPI)	YES	YES	YES	YES	YES
Extra function (P-APF)	YES	YES	YES	YES	YES
Extra function (F-APF)	NO	NO	NO	NO	YES
Input current	discontinuous	continuous	continuous	discontinuous	continuous

3.SIMULATION RESULTS

Numerical simulations of MFGC system using SSI have been performed through Matlab/Simulink TM environment to evaluate the performance of the proposed scheme under different operating modes. It should be noted that, the SSI is supplied by an ideal voltage source with a nominal voltage of 80V; this emulates a PV voltage at the MPP. Simulation parameters are listed in Table 3. The SSI is used to inject the active power produced by the PV system into the load/grid. The non-linear load is composed of diode bridge rectifier connected to a passive load rated at ($P_{load} = 1800W$, $Q_{load} = 250VAR$). In some cases, the AC and DC components of an SSI can be managed independently as in a ZSI or Q-ZSI system [21]. The SSI setup has been addressed by several control approaches in the literature [24], [25], [26], [27], [28], [29].

In [24] authors offer a decoupled control system in three-phase grid-tied solar application combined with regulated modified space vector (RMSV) modulation. In contrast, [25] presents a peak power controller that controls the voltage of the DC-link capacitor by monitoring the maximum power point tracking (MPPT) due to the variations of solar radiation. The PI controllers used for controlling the variables at the AC and DC side in [24] and [25] have some limitations in terms of their linear property. For grid-tied SSI control, the authors in [28] proposed the FCS-MPC framework that is widely used in power electronics applications

because to its ability to control multivariable systems. However, although FCS-MPC has significant performance, it suffers from problems like the varying switching frequency and the low robustness to the changes of system parameters. Sliding mode control (SMC) has been a hot topic in the area of power electronic converters regulation due to its attractive properties such as simple implementation, good dynamic performance and strong robustness [30, [31], [32], [33], [34]. However, the problem of chatter results in an increased switching frequency, which is an unwanted effect of using the traditional switching function (signum function). Also, there is very little in the literature on inspection of SMC within the context of SSI.

The research provides a new control scheme for an MFGC system using SSI based on the SMC technique combined with the modified space vector modulation (MSVM). The proposed system aims to meet the requirements of nonlinear loads for active and reactive power, the distorted power, to feed the surplus PV active power to the grid and to keep the grid power quality at the level required by international standards. Also, the SSI capabilities allows for SSI operation inside F-APF unlike impedance source inverter arrangements. For the control of the AC and DC components of the system, a Sliding Mode Controller (SMC) with seamless continuous switching has been designed and the chattering phenomenon noticed earlier has been removed.

The original SMC controller is designed to control the DC input current and predict the duty-cycle that enables the boost feature. The modified space vector modulation (MSVM) phase will receive the reference voltage, duty cycle and modulation index from a decoupled sliding mode control (SMC) system. The effectiveness of the suggested control technique is demonstrated with MATLAB/Simulink setups in different operational modes. The simulation results are validated by experimental tests conducted on a real-time hardware-in-the-loop platform. This ensures that the results are accurate. To summarise, this research contributes mostly to the following areas: Explore the SSI in MFGC framework using several operating modes such as P-APF, RPI, and F-APF. Based on the SMC theory, a better method for dc side regulation is provided.

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2. SYSTEM CONFIGURATION AND MODELING

Figure 1. Photovoltaic array connected to microgrid control system through a smart sensor interface. In the parallel configuration, a three phase AC source is connected to the grid at the power conversion center (PCC) through an inductive filter (L_f). In the series configuration, a three phase AC source is connected to a diode bridge rectifier working on a nonlinear load. Presently a DC voltage source can be used to simulate the operation of the PV array. The buck/boost functionality of the SSI makes it ideally suited for utilisation in photovoltaic systems. The proposed setup can work in three modes, i.e., complete APF, authentic power injection and partial APF. The best power quality in terms of total harmonic distortion (THD) of the grid currents and power factor is achieved by using the SSI as an active filter to inject the required distorted and reactive power to the nonlinear load rather than the grid. This allows the injection of power generated by the PV array into the grid at the same time.

A.MFG CSSI Simulator

Controller design is based on a set of equations defining all the components of the investigated system and is crucial for modelling stage. The SSI is achieved by integrating a voltage source inverter (VSI) with a boost converter as shown in Figure 1. The VSI phase legs are coupled to a DC power source via an input inductor and three diodes. As a consequence, both the AC and the DC components of the integrated SSI have to be taken into account in the modelling method.

The recently proposed SSI topology, similar to the standard two-level VSI, uses eight switching states on the AC side, six active and two zero states [20]. Figure 2 shows that the SSI normally functions in two modes. In the first mode, the input DC source energises the inductor L by turning on one of the lower switches (S^-_a , S^-_b , S^-_c) as shown in Figure 2(a). Based on the two modes stated above, the state-space equations of SSI can be expressed by splitting each switching period T_s into two basic intervals: tonne, which indicates the charging time of L , and toff, which indicates the discharging

period of L . The SSI behaviour in the two periods is obtained using Kirchhoff's law (KL).

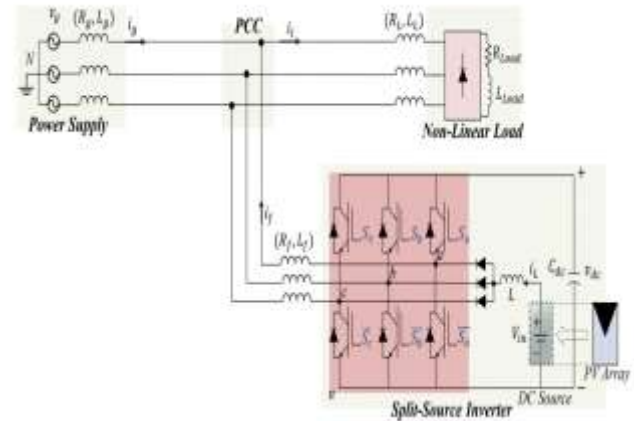


Fig. 1. Multifunctional grid-connected system based-split-source inverter.

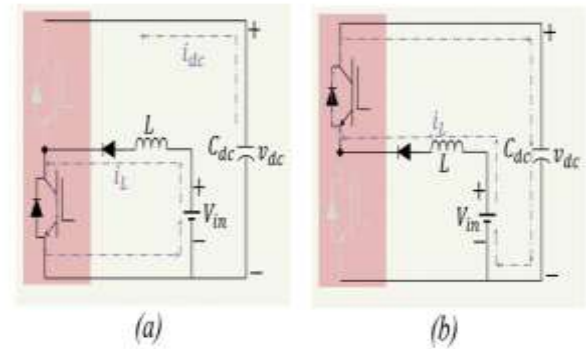


Fig. 2. The simplified equivalent circuit of the SSI topology during: (a) the charging mode of L ; (b) the discharging mode of L .

modes can be expressed as follows:

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L} V_{in} - \frac{(1-d)}{L} v_{dc} \\ \frac{dv_{dc}}{dt} = \frac{1}{C_{dc}} [i_L (1-d) - i_{dc} d] \end{cases} \quad (1)$$

where, d is equal to one during t_{ON} and equal to zero during t_{OFF} . On the grid side, the linear mathematical model for each phase of the MFGC system shown in Figure 1 can be described by applying Kirchhoff's Law (KL) as follows:

$$\begin{cases} v_{af} = R_f i_{af} + L_f \frac{di_{af}}{dt} + v_{ag} \\ v_{bf} = R_f i_{bf} + L_f \frac{di_{bf}}{dt} + v_{bg} \\ v_{cf} = R_f i_{cf} + L_f \frac{di_{cf}}{dt} + v_{cg} \end{cases} \quad (2)$$

where, v_{af} , v_{bf} and v_{cf} are the three phase output voltages generated by the SSI; v_{ag} , v_{bg} and v_{cg} are the three phase grid voltages; i_{af} , i_{bf} and i_{cf} are the three phase SSI output

currents. Thus, the dynamics of the output currents can be written as:

$$\frac{di_f}{dt} = \frac{1}{L_f} (v_{if} - R_f i_f - v_{ig}); i = (a, b, c) \quad (3)$$

Section III. The Control Theory of MFGC Sliding Regimes

In this part, the block diagram of the suggested control architecture for MFGC SSI management is shown. The variable in the synchronous reference (dq) frame is shown where the DC-side and AC-side are controlled individually and this fact is taken in to account during the creation of the control strategy. The regulation of the DC side is done by the duty cycle (d0) and the control of the AC side is done by the modulation index (M). The two control procedures were combined with the MSVM stage to produce the SSI gate signals.

As illustrated in Fig. 3, the control loop on the DC-side considers \$d_0\$ while maintaining the input current \$i_{L}\$ at the reference \$i_{L_ref}\$. In this study, the inverter can be supplied by a photovoltaic system or directly imposed, thus \$i_L\$ can be generated by the MPPT unit. An external loop is implemented for the regulation of the DC-Link voltage \$v_{dc}\$ to its reference value \$v_{dc_ref}\$ and for the computation of the \$i_{gd}\$ directly related to the harvested solar power.

To achieve unity power factor, \$i_{gd}\$ is set to zero. Thus, the three-phase grid voltages \$v_{g\{abc\}}\$, filter currents \$i_{f\{abc\}}\$ and load currents \$i_{L\{abc\}}\$ are translated to \$(dq)\$ coordinate system. The phase-locked loop (PLL) is used to implement the Park transformation and control the synchronisation of grid voltage and current. Hence, an internal current loop is employed to generate the reference voltages \$V_{df}\$ and \$V_{qf}\$ and to track the measured filter currents \$i_{df}\$ and \$i_{qf}\$ with their corresponding references \$i_{df}\$ and \$q_f\$. Then, the modulation index \$M\$ and the angle of the reference vectors \$\theta\$ are computed using \$V_{\alpha}\$, \$V_{\beta}\$ and the DC-link voltage \$v_{dc}\$.

Simulation results

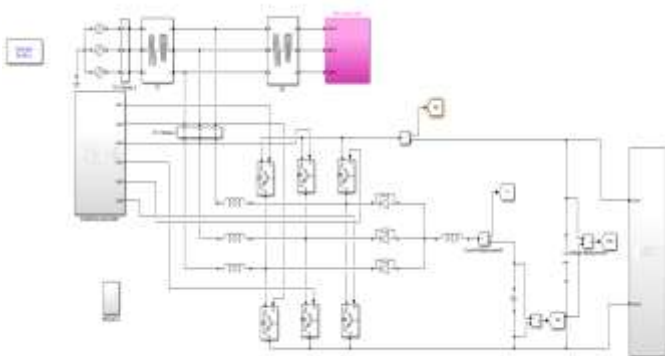


Fig.3.Simulation model

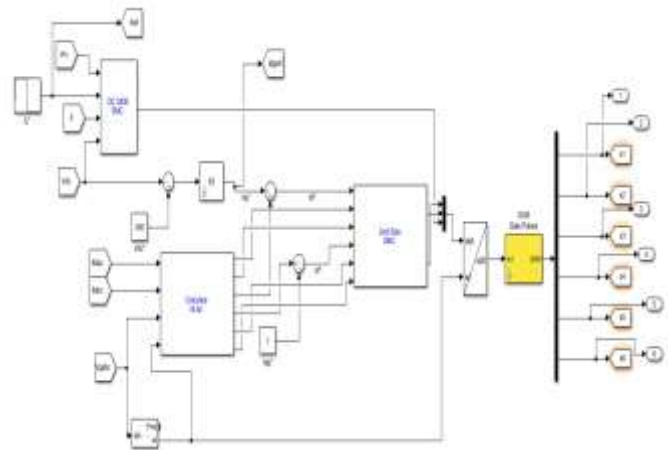


Fig. 4.Simulation diagram of control strategy

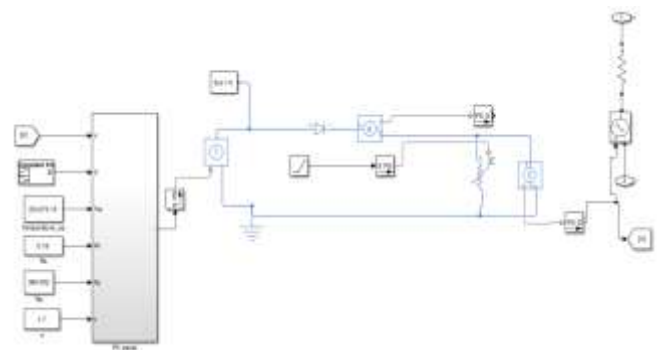


Fig. 5.simulation diagram photo voltaic model

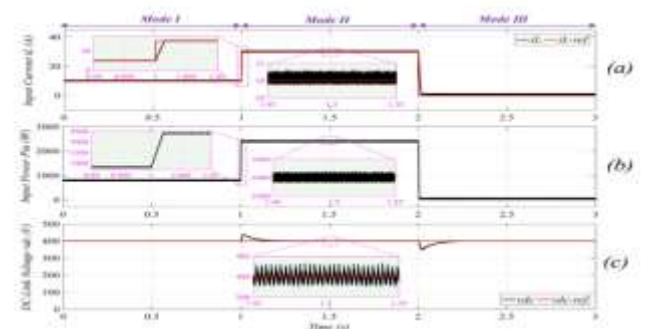


Fig.6. Simulation results of: (a) Input current (\$i_L\$), (b) Input power (\$P_{in}\$), (c) DC-Link voltage (\$v_{dc}\$); under variable input current reference

The proposed system is tested under three different operating modes. In Mode I, the input current reference (\$i_{L-ref}\$) is set at 10A in which the injected current from the filter is lower than the one requested by the non-linear load, consequently the system operates in a partial APF mode. In Mode II, \$i_{L-ref}\$ is set at 30A to satisfy the non-linear load demand and inject the surplus power into the grid and thus to operate in a real power injection mode. In Mode III, the current \$i_{L-ref}\$ is set at zero and makes the system operate in full APF when no active power being injected to the grid and only the distorted power requested by the non-linear load is generated by the inverter to clear the harmonics from the grid side.

Figure 6(a) shows the results when changing input current reference (i_L). Initially, Mode I is applied for a duration of 1 s. The input current (i_L) is well maintained at the desired value (10A) with minor fluctuation. The DC-Link voltage (v_{dc}) is also maintained at the provided reference (400V) with low voltage ripple ($< 5\%$) as shown in Figure 6(c). Figure 8 depicts the load currents (i_l), filter currents (i_f) and grid currents (i_g) respectively. As it can be noticed, the load currents have non-sinusoidal forms with a total harmonic distortion (THD) of around 26%. The filter generates the harmonic currents requested by the non-linear load, while the grid currents become sinusoidal with high quality (the THD is reduced to 1.45%) as shown in Figure 7(c).

Then, at 1 s, a step-up in the input current reference is conducted, this switch the system from Mode I to Mode II. The input current is well regulated at its desired references (30A) with fast dynamic response and minimum fluctuation. The presented results demonstrate the robustness and effectiveness of the proposed DC-side control scheme.

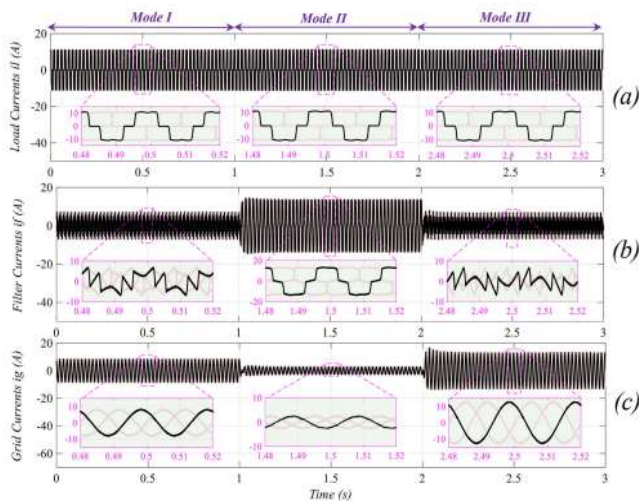


Fig. 7. Simulation results of MFGC: (a) Load currents (i_l), (b) Filter currents (i_f), (c) Grid currents (i_g); under variable input current reference.

Additionally, the DC-Link voltage is well regulated at the desired reference with a small overshoot ($< 20\%$) and a short settling time, as shown in Figure 7(c). Similarly, the dynamic response of the grid currents is very fast, and the grid currents become sinusoidal again after a change in their phases with a THD of 2.03%, because the filter in this mode satisfies the load demand and injects the excess power into the grid as shown in Figure 8(c) and Figure 7.

Finally, at instant 2s, a step-down in the input current reference from 30A to 0A is conducted. The system switched from Mode II to Mode III (RPI to F-APF), which demonstrate the capability of the proposed system in F-APF mode when no PV power being injected. Consequently, the input current rapidly falls to its

desired value (0A) as shown in Figure 7(a), while the DC-Link voltage is maintained at the desired value after a short transient with an undershoot of $< 20\%$ as shown in Figure 7(c). Furthermore, the grid current waveform remains sinusoidal and in phase with the grid voltage as shown in Figure 8(c) and Figure 8, because the grid is taking care of the load power demand, whereas the filter continues to provide only harmonic currents requested by the load. The latter proves the main advantage of the SSI topology with regard to other impedance source inverter topologies. Figure 9 illustrates how the effect of grid current reference (i_{dg-ref}) on the magnitude and phase of the grid currents

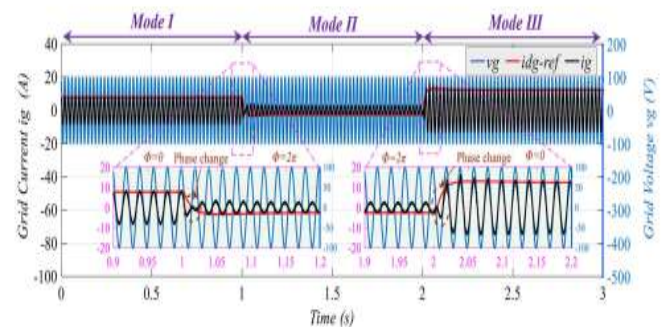


Fig. 8. Simulation results of: Grid current (i_{ga}), Grid peak current (i_{ag-ref}) and Grid voltage (v_{ga}); under variable input current reference

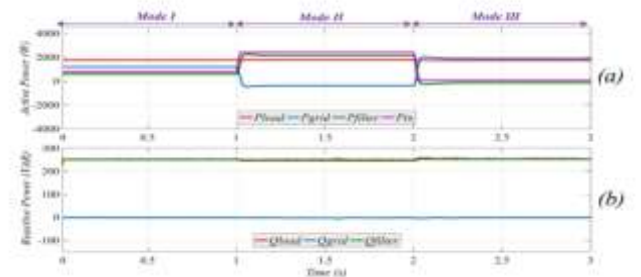


Fig.9. Simulation results of: (a) average active powers, (b) average reactive powers; under variable input current reference.

(i_{ga}). Figure 10(a) shows the average active powers of load (P_{load}), grid (P_{grid}), and filter (P_{filter}) under different operation modes. In Mode I, the generated PV power does not meet the load active power demand (1800W), the grid delivered the rest of the active power needed to satisfy the load. In Mode II, higher PV power being produced which satisfy the need of the load in terms of active power while the rest of the power is sent to the grid. In the last mode, the grid offers all the required load power as no PV power being produced to the absence of solar radiation. On the other hand, Figure 9(b) shows the averages reactive power of the entire system under different operation modes. As it can be seen, the requested reactive power by the load is always ensured by the filter, while the grid reactive power is maintained at zero to ensure unity power factor operation.

3. CONCLUSIONS

The proposed Multi-Functional Grid-Tied PV System using a Split Source Inverter offers an efficient and economical solution for modern renewable energy integration. By replacing the conventional two-stage converter with a single-stage SSI, the system achieves higher efficiency, reduced hardware complexity, and lower switching losses. In addition to maximum power extraction, it provides essential grid-support services such as reactive power compensation, harmonic mitigation, voltage regulation, and power factor correction. Simulation results confirm improved power quality, stable operation, and compliance with IEEE-519 standards, making the proposed system well suited for future smart grid and distributed energy applications.

split-source inverter (SSI) is proposed for single-stage multi-functional grid-connected (MFGC) systems due to its ability to work as a full active power filter (F-APF) in addition to its fewer number of components. Furthermore, a robust control scheme based on SMC theory is designed for the proposed system to achieve multiple functionalities including PV power generation, harmonic elimination and reactive power compensation at the grid side. Furthermore, the selections of the sliding surface and the stability analysis have been studied to confirm the proper functionality of the system and its high range of robustness.

The obtained simulation and experimental results confirm the effectiveness and reliability of the proposed control scheme in terms of regulation of DC input current, DClink voltage regulation, grid current quality enhancement, power management, transient and steady state performance. Moreover, the THD in both results across all operating modes remain within the IEEE standard limit of 5%. Furthermore, the SSI topology exhibits smooth transition between the various operating modes including partial APF, real power injection, and full APF which makes it an excellent fit for such applications.

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