Cost-Effective Grid-Tied PV System with Active Harmonic Compensation

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ABSTRACT: The split-source inverter (SSI), which provides superior boosting capability with fewer components, is suggested in this research for multi-functional grid-connected (MFGC) applications. Additionally, in contrast to the impedance source inverter (ZSI) topologies, the SSI may function as a full active power filter (APF). In order to control the DC and AC sides of the MFGC system-based SSI, this paper suggests a sliding mode control (SMC) scheme. The MFGC system seeks to compensate the reactive power at the grid side, use the extracted PV power to meet the non-linear load power demand, and inject the remaining PV power back into the grid. The SMC system is intended to regulate the DC input current on the DC side while calculating the duty cycle that guarantees the boosting capacity. The AC side of the system is then controlled using a decoupled control technique based on the SMC, which also estimates the reference voltages provided to a modified space vector modulation (MSVM) stage. The MATLAB/Simulink environment is used to model the complete system. The simulation results show that the suggested control strategy is robust and effective in managing power and improving power quality.

KEYWORDS: MVSM, HARMONICS, APF, ZSI, PV SYSTEM.

I.INTRODUCTION: As a possible manner to fulfill the growing power needs, the usage of renewable electricity resources (RESs) has attracted hobby on a international scale. The primary elements required to hyperlink the RESs to the grid are electricity converters [1], [2]. Poor electricity great at the point of not unusual coupling (PCC) can be because of harmonics produced by means of nonlinear masses linked to the grid [3]. Multi-functional grid-connected (MFGC) systems, which operate in more than one modes consisting of partial lively energy filter (P-APF), real energy injection (RPI), and full lively power clear out (F-APF), have these days attracted improved interest as a method to this trouble due to their advantages, which consist of injecting active energy extracted from RESs, improving the electricity best by compensating reactive strength, and doing away with grid current harmonics [3], [4], [5], [6]. In grid-tied photovoltaic (PV) gadget applications, the MFGC structures are broadly cut up into agencies, single and twin conversion degrees. In dual-level association, tow conversion ranges are deployed. The DC-DC converter inside the first level is used to song the PV generator's most electricity at the same time as raising the dc voltage at the dc-link to the required level. The DC-AC converter, that is interfaced with the load or grid to supply AC current, makes up the second one step [4], [7]. Despite this, this association provides greater manage flexibility because the 2 converters provide more degrees of freedom.

However, as the wide variety of switching devices and passive additives increases, the system's common performance decreases [7]. Conversely, the single-level architecture makes use of a single DC-AC converter, which reduces the variety of energetic and passive components, will increase efficiency, and lowers cost [7], [8], and [9]. Nevertheless, this configuration does not have a boosting function for the output PV voltage, that's essential for grid-tied PV applications to have a minimum range of PV panels linked in collection. It additionally aids in better control of PV electricity to prevent warm spots due to diverse PV panel faults, which includes partial shading of the PV arrays [10], [11]. Additionally, the inverter control set of rules needs to control the most energy factor tracking (MPPT), which offers sizeable manipulate layout troubles [8].

TABLE 1. Nomenclature list.

RES	Renewable energy source	RMSV	Regulated modified space vector modulation
PCC	Point of common coupling	FCS-MPC	Finite 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	KL	Kirchhoff's law
ZSI	Z-source inverters	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	simple boost pulse width modulation
SSI	Split Source Inverter	QB-SSI	Quadratic-Boost Split Source Inverter

This hassle has been addressed in some of research by way of changing the single-level setup to contain the passive output PV voltage boosting capability. The most often added single-stage topologies in the literature are impedance source inverters, such as Z-supply inverters (ZSIs) [13], quasi-Z-supply inverters (Q-ZSIs) switched inductor quasi-Z-source community (SL-Q-ZSIs) switched coupled inductor quasi-Z-supply inverter (SI-Q-ZSI) switched inductor Z-supply network (SLZSIs) and Switched Network Z-source (SN-ZSI). These topologies employ a shoot-thru country to provide buck/increase conversion capability. Nevertheless, there are sure risks to ZSI, SL-ZSI, and SN-ZSI topologies, together with discontinuous enter modern, high inrush current whilst starting, unidirectional energy go with the flow, and a big number of passive additives. Improvements were made to Q-ZSI and SL-Q-ZSI to clear up the aforementioned troubles, along with the elimination of the inrush and discontinuous current problems. Nevertheless, Q-ZSI and different ZSI topologies retain to have troubles with unidirectional power glide and a big range of passive components. In addition to its greenback/increase conversion potential, split-supply inverters (SSIs) have recently been evolved to address the shortcomings of impedance source topologies. SSI has fewer passive components and is more green than ZSI and Q-ZSI.

The Voltage-Lift Cell Split-Source Inverter (VLC-SSI) and the Quadratic Boost Split-Source Inverter (Q-B-SSI) [22] are two in addition topologies within the SSIs family. Both Q-B-SSI and VLC-SSI provide a higher boosting gain than SSI. But they also want more passive components and diodes. The SSIs circle of relatives is likewise appropriate for MFGC packages on account that it may function as a complete APF machine. As an end result, common 3-segment impedance supply inverters have been used in an intensive exam.

The AC and DC aspects of the SSI can be independently managed underneath specific conditions, much as ZSI and Q-ZSI topologies. The literature has provided a number of manipulate strategies for the SSI topology. While the authors advocate a peak strength controller to music the MPP beneath versions in solar radiation and convey a obligation cycle that guarantees the regulation of the DC-hyperlink capacitor voltage, the authors] advise a decoupled manage in conjunction with a regulated changed space vector (RMSV) modulation in a 3-section grid-linked PV utility. Proportional-crucial (PI) controllers, which have confined performance due to their linear nature, are used to manipulate the AC and DC side variables. Because it could take care of multivariable structures, finite control set model predictive manage (FCS-MPC) has been utilized extensively in power electronics-related packages. The authors of [28] introduced the FCS-MPC technique to adjust the grid-linked SSI. Even though FCS-MPC performs properly, it has low robustness in opposition to modifications in device parameters and suffers from fluctuating switching frequency.

Sliding mode manage (SMC) has been very well studied in the manipulate of power digital converters because of its potential advantages, which encompass high resilience, true dynamic overall performance, and ease of implementation. Nevertheless, it also encounters an unwanted issue called the chattering problem, which ends up in a excessive switching frequency and is inevitably produced by using the traditional switching characteristic (signum function). Additionally, as far as we're aware, the literature has now not but addressed the look at of SMC within the SSI structure.

II.PROPOSED SYSTEM: For an MFGC system using SSI, this research suggests new control architecture based on the SMC method in conjunction with modified space vector modulation (MSVM). The main goals of the proposed system are to inject excess PV active power into the grid, satisfy the nonlinear load demand in terms of active and reactive power in addition to the distorted power, and maintain the grid's power quality at the desired level set by international standards. Additionally, unlike the topologies of impedance source inverters, the special feature of SSI permits running the SSI in F-APF. The previously noted chattering phenomenon has been addressed by introducing SMC with smooth continuous switching to control the AC and DC side of the system. The purpose of the first SMC controller is to estimate the duty cycle that initiates the boost capability and regulate the DC input current. In the meantime, a decoupled control scheme based on SMC is created to estimate the reference voltage to be sent to the modified space vector modulation (MSVM) stage along with the duty cycle and the modulation index. To demonstrate the efficacy of the suggested control approach, the entire system is simulated using MATLAB/Simulink settings and tested under various operating modes. In summary, this paper's primary contributions are as follows:

1) SSI in the MFGC system in various operating modes, such as P-APF, RPI, and F-APF, is investigated.

2) A better DC side control strategy based on SMC theory is put forth.

3) Determining the stability region by analyzing the control scheme's stability using Lyapunov theory.

4) Examining the simulation performance of the suggested system.

4.1 Configuring and modeling the system

A PV array is interfaced with an MFGC with SSI in the system depicted in Figure 1. It consists of a three phase AC source coupled in series with a non-linear load based diode bridge rectifier, and the SSI is connected in parallel to the grid via an inductive filter (Lf) at the PCC. A DC voltage source can be used in the current arrangement to simulate the behavior of the PV array. Because of its buck/boost functionality, the SSI is a great choice for PV applications. Three modes of operation are available for the suggested configuration: complete APF, genuine power injection, and partial APF. By using the SSI as an active filter to feed the nonlinear load with the required distorted and reactive power rather than the grid, the primary goal is to inject the power produced by the PV array into the grid while maintaining good power quality of the grid in terms of total harmonic distortion (THD) of the grid currents and the power factor.

A. MODELLING OF THE MFGC SSI In order to develop a controller, the modeling phase is crucial and necessitates a set of equations that characterize every component of the system under study. As seen in Figure 1, the SSI combines a voltage source inverter (VSI) with a boost converter. Three diodes and an input inductor are used to link the VSI phase legs to the DC input source. As a result, both the DC and AC sides must be taken into account while modeling the introduced SSI. The eight switching states—six active states and two zero states—used by the traditional two-level VSI are also used by the newly developed SSI topology on the AC side [20]. As seen in Figure 2, the SSI typically functions in two modes. As illustrated in Figure 2(a), in the first mode, the inductor L is charged from the input DC source when one of the lower switches (S∗a, S“b, and S¢c) is ON. The inductor L is discharged in the alternative mode via the anti-Consequently, taking into account the two modes mentioned above, the state-space equations of SSI can be expressed by splitting each switching period Ts into two primary intervals: tON, which represents L's charge mode, and tOFF, which represents L's discharge mode. The equations that characterize the behavior of the SSI when the two parallel diodes to charge the capacitor Cdc when all the upper switches (Sa, Sb, and Sc) are simultaneously ON are derived using Kirchhoff's law (KL), as illustrated in Figure 2(b).

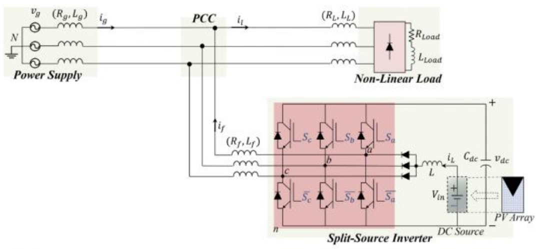


FIGURE 1. Multifunctional grid-connected system based-split-source inverter.

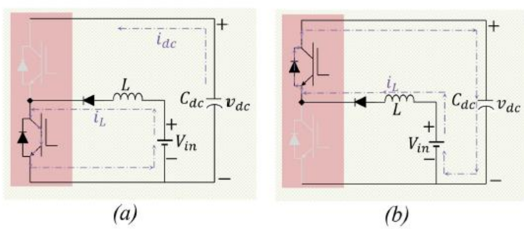


FIGURE 2. The simplified equivalent circuit of the SSI topology during: (a) the charging mode of L; (b) the discharging mode of L.

modes can be expressed as follc

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L} V_{in} - \\ \frac{dv_{dc}}{dt} = \frac{1}{C_{dc}} [i_L(\end{cases}$$

In this case, d equals zero during tOFF and one during tON. Kirchhoff's Law (KL) can be used to define the linear mathematical model for each phase of the MFGC system seen in Figure 1 on the grid side:

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

where iaf, ibf, and icf are the three-phase SSI output currents; vag, vbg, and vcg are the three-phase grid voltages; and vaf, vbf, and vcf are the three-phase output voltages produced by the SSI. As a result, the output current dynamics can be expressed as:

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

4.2 CONTROL OF MFGC SSI BASED SLIDING MODE THEORY The block diagram of the suggested control method used for MFGC SSI control is provided in this section. The design of the control system takes into account the variable's representation in a synchronous reference (dq) frame, where the DC-side and AC-side are managed independently. The modulation index (M) controls the AC side, and the duty cycle (d0) controls the DC side. The modified space vector modulation (MSVM) stage uses these two control actions to produce the SSI's gate signals. The DC-side control loop estimates d0 while controlling the input current iL at its reference i∗ L, as shown in Figure 3. In this situation, i∗ L can be produced by the MPPT unit if the inverter is directly imposed, as in this work, or provided by a PV system. On the AC side, an outer loop control estimates the i∗ gd, which is proportional to the extracted PV power, and controls the DC-Link voltage vdc over the required value v∗ dc. The i∗ gd is set to zero to guarantee unity power factor. As a result, the (dq) coordinate frame is created from the measured three-phase grid voltages v(abc)g, filter currents i(abc)f, and load currents i(abc)L. Therefore, the Park's transformation and the regulation of grid voltage and current synchronization depend on the phase-locked loop (PLL).

As a result, when producing the reference voltages V∗ df, V∗ qf, an inner current loop is utilized to enforce the observed filter currents idf, iqf to monitor their references i∗ df, i∗ qf. Next, using V∗ α, V∗ β, and DC-link voltage vdc, the modulation index M and the angle of reference vectors θ are computed. A. DC-SIDE CONTROLLER DESIGN USING SMC THEORY SMC's resilience to changes in system parameters, uncertainty, and outside disruptions is widely acknowledged. SMC is designed in two stages. The first step is to select an appropriate sliding surface that allows the system to provide the desired behavior. The creation of a control law that forces the system trajectory onto and then maintains it on the sliding surface is the second phase. Additionally, while the system is on the sliding surface, the stability requirement must be met [34]. As shown in Figure 4, SMC is intended to control the DC input current iL while estimating d0 in this portion. Consequently, the definition of the sliding surface manifold is:

$$s_L = i_L^* - i_L \tag{4}$$

:

$$\dot{s}_L = -\frac{di_L}{dt} = 0 \tag{5}$$

By using Eq. (1), Eq. (5) can be rewritten as:

$$-\frac{1}{L}V_{in} + \frac{(1-d)}{L}v_{dc} = 0 \tag{6}$$

where

$$V_{in} = (1-d)v_{dc} \tag{7}$$

Assume that $d_0 = (1-d)$, the nonlinear control law can be expressed as:

$$d_0 = \frac{V_{in}}{v_{dc}} - k\left(\frac{s_L}{||s_L|| + \epsilon}\right) \tag{8}$$

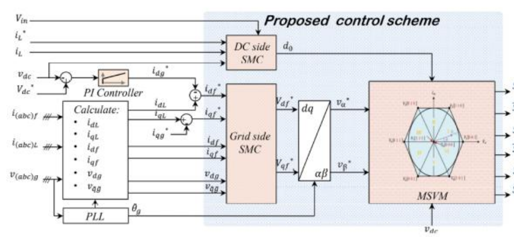
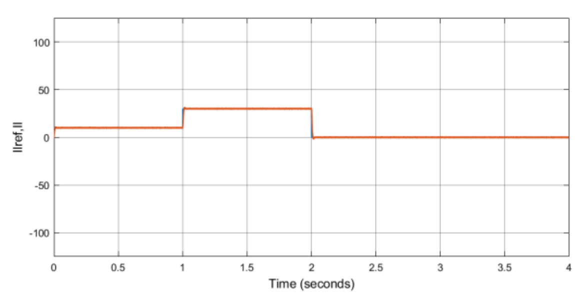
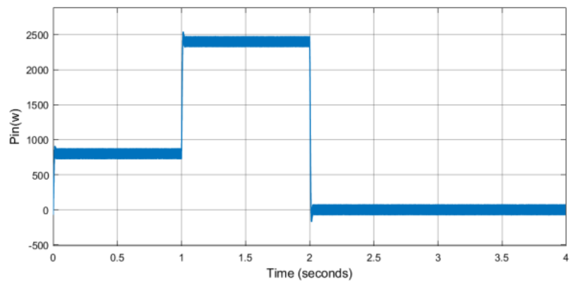


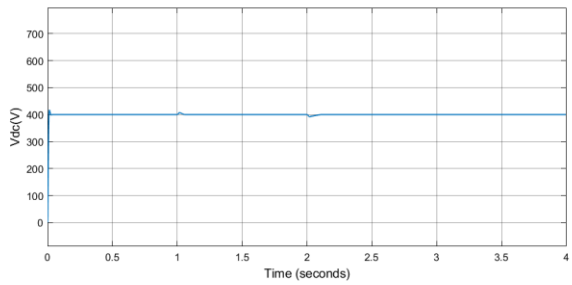
FIGURE 3. Block diagram of the proposed control scheme.

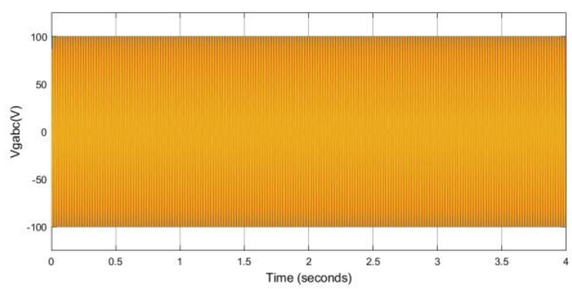
Where ϵ is the border width of a chosen small positive number and k is the proportional gain of discontinuous control portions. The Lyapunov function, which is used to assess control stability and is defined as follows, must be satisfied by the controller specified by Eq. (8):

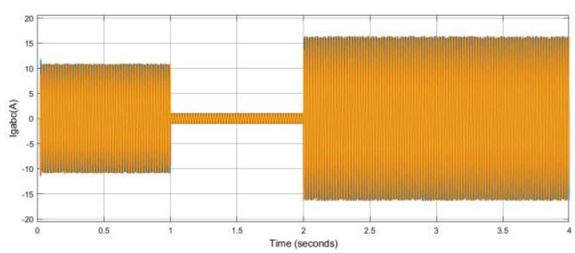
III.SIMULATION RESULTS:

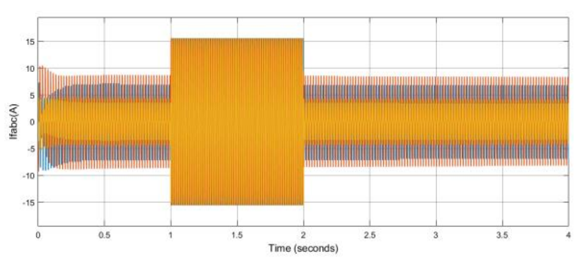


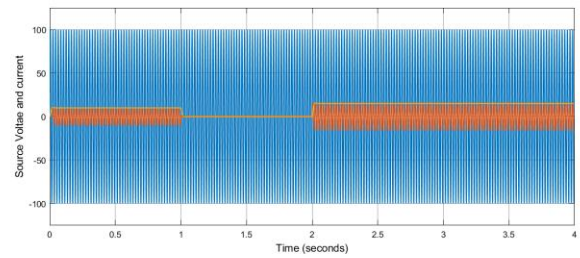


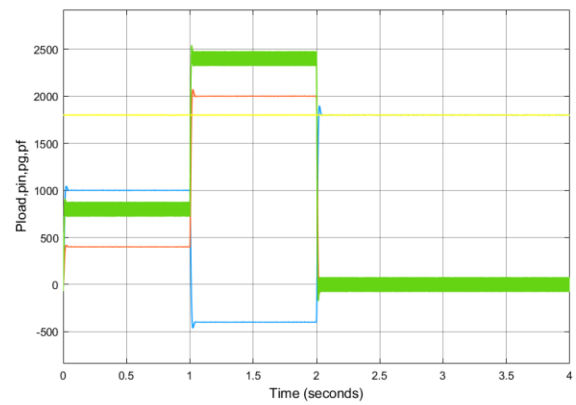


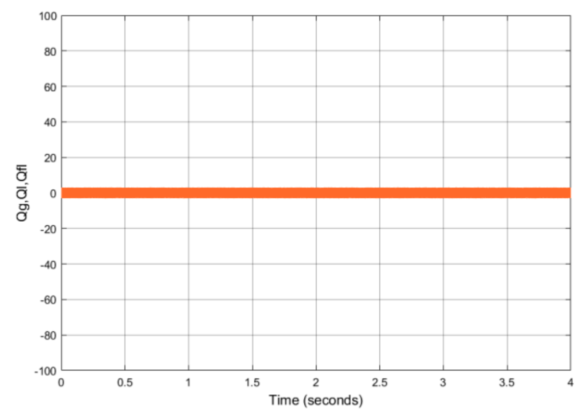












IV.CONCLUSION: The split-source inverter (SSI), which has fewer components and can operate as a full active power filter (F-APF), is suggested in this research for single-stage multi-functional grid-connected (MFGC) systems. Additionally, a strong control scheme based on SMC theory is created for the suggested system to accomplish a number of functions, such as grid-side reactive power compensation, harmonic elimination, and PV power generation. Additionally, the stability analysis and sliding surface choices have been examined to verify the system's high range of resilience and appropriate operation. In terms of DC input current regulation, DC link voltage regulation, grid current quality enhancement, power management, and transient and steady state performance, the obtained simulation and experimental findings validate the efficacy and dependability of the suggested control method. Additionally, the THD in both studies stays within the 5% IEEE standard limit in all working modes. Additionally, the SSI architecture is a great fit for these kinds of applications since it shows a smooth transition between the different operating modes, such as partial APF, genuine power injection, and complete APF. In order to increase controller performance during transitions between various operating modes, future research will concentrate on analyzing and improving the suggested control framework by using an adaptive law to dynamically change the control gains.

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