

Design and Analysis of High Gain DC-DC Boost Converter for Grid Connected Solar Photovoltaic System

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Abstract— This paper presents a high-gain DC-DC converter for a rooftop solar photovoltaic (SPV) system with a multi-functional grid-tied inverter. In order to achieve a smooth integration of roof-top SPV with the utility grid, a high gain DC-DC converter is required to boost up to a higher voltage gain, to reduce ripple voltage, and switching stress at the DC bus. Further, this higher gain DC voltage is converted into a three-phase AC voltage of the demanded utility grid by a multi-functionality grid-tied inverter (MFGTI). Hence for integrating the SPV with the utility grid, there are challenges to overcome, such as keeping the grid synchronized, and power quality issues under nonlinear load, & solar irradiation conditions. A modified synchronous reference frame (SRF) control technique is proposed to make the MFGTI capable to inject the active power from SPV into the utility grid. Simultaneously compensate the reactive power, and the current harmonics to improve the PF within the IEEE standard 519-2022. The proposed system is implemented using MATLAB®/Simulink software, and it is evaluated under various solar irradiation, and nonlinear load conditions.

Keywords— High gain DC-DC converter, solar photovoltaic (SPV), current harmonics, nonlinear load, MPPT, power quality

I. INTRODUCTION

Recent studies have shown that fossil fuels have a limited shelf life, negative environmental effects, and their highest price, all of these made the world move from fossil fuels to renewable energy sources (RESs). The RES such as solar photovoltaic (SPV), wind, geothermal, biomass, and hydropower are clean, low carbon, safe, highly efficient, and user-friendly. Among RES, the SPV power generation has quickly grown drastically compared to above mention RESs. The SPV has numerous benefits, such as lack of spatial restrictions, lower transmission and distribution costs, longer lifespan, ability to be scaled, less expensive maintenance, and no use of a turbine in its system [1]-[2]. In the past two decades, the SPV installation has multiplied in developed, and developing countries. Especially, China, the US, and India jointly account for 49% of the world's installed PV capacity, which is predicted to reach 3000 GW by 2030 after reaching 253 GW, 60.5 GW, and 40 GW, respectively [3].

Since, the number of residential building (RB) is increasing, this low voltage level roof-top SPV increase too. Thus, a high gain DC-DC converter is required to boost up to the higher gain DC voltage at DC-bus line. Furthermore, to use the converted high gain DC voltage for interfacing the low SPV system with utility grid at point of common coupling [2].

Many researchers across the globe have already worked on high gain, high efficiency DC-DC converters that are currently on the market that offer a relatively larger voltage gain. Among them, in [4] demonstrates an ultra- high gain switching capacitor DC-DC converter. It can function at low SPV voltage, but it is not suitable for three phase inverter. In reference [5], the author introduced a non-isolated high-step-up DC-DC converter with minimum switch voltage stress that can convert into higher voltage gain but it only functioned with a single phase inverter. According to [6] there is a high step-up couple inductor type high gain DC-DC converter, but its high voltage gain is not appropriate for interfacing with a three-phase inverter. In addition, its efficiency is not at maximum or low power levels, and its efficiency reduces when the power is raised. A coupled inductor-based isolated high gain, a high-efficiency DC-DC converter is detailed in [7], [8], and a coupled inductor-based high step-up converter with a soft switching approach is presented in [9]. In [10], a non-isolated high gain DC-DC converter is proposed but it is only applicable to maintain the medium voltage (MV), This DC-DC converter uses silicon carbide devices to increase the converter efficiency and maintain MV levels. In [11], introduced the resonant step-up (RS), which utilized an inductor and a capacitor to reach the step-up ratio. But achieving soft switching is a big challenge to reduce the turn-off, and reverse recovery losses. Moreover, the existence of parasitic elements has a high effect on DC-DC output voltage power transfer efficiency [12].

However, the previously mentioned proposed model on high gain DC-DC converters are appropriate for integration with a three phase- inverter, but still their results are shown inferior performance. Additionally, even at low power levels, these converters' efficiency levels are not particularly great when utilized for applications that require large voltage gain.

In response to the limitation of the mentioned high voltage gain DC-DC converter, this paper proposed a high gain boost DC-DC converter to achieve higher gain at the output with reduced the ripple voltage and switching stress effectively.

Further, power electronic inverters are used to integrate the generated high gain voltage of SPV at the DC bus with the utility grid. Due to increase of nonlinear loads in the present power system network causes injection of higher current harmonics, increase of reactive power burden which eventually reduces the power quality (PQ) of the system. In addition, integrating the SPV with the utility grid, there are lots of challenges to overcome, such as grid synchronization of SPV with utility grid by injecting active power along with the reduction in harmonic distortion, reactive power, and low power factor that will entirely impact on PQ [13]. Therefore, multi-functional grid tie inverter (MFGTI) control techniques to overcome of aforementioned problems. The control technique can effectively work on the grid synchronization along with power quality (PQ) issues. Moreover, MFGTI acts as an active power filter by mitigating the PQ issues along with grid synchronization of the SPV system under nonlinear load conditions. The grid synchronization will be worked based on the control techniques, such as synchronous reference frame (SRF) theory, ABC to DQ, Alpha to ABC, single phase power quality theory, and fuzzy power control theory [13]. These are the rest of the article which are organized as following sections: the system configuration is highlighted in section II. Besides, it highlights the operating modes of the proposed high gain DC-DC boost converter. Section III gives a detail of the proposed model design procedure. In section IV focuses on control techniques of MFGI, to show the procedure for finding the reference current for controlling the MFGTI. Section V highlights the result and discussion proposed model. And in section VI focuses on the conclusion of the proposed model.

II. SYSTEM CONFIGURATION

Figure.1 presents a proposed system which consist of SPV arrays, a high gain DC-DC converter, a MFGTI, an interfacing inductor, and non-linear loads.

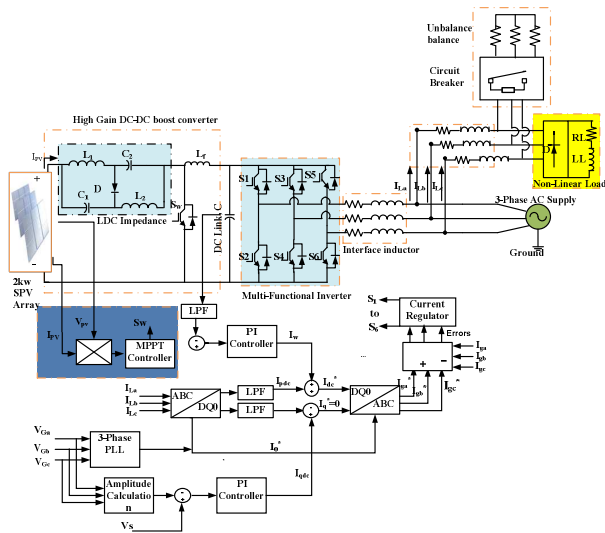


Fig.1 Block diagram of high gain DC-DC converter based grid connected SPV system

The rooftop SPV array which supplies a low DC voltage under solar irradiation condition is attached to the high gain DC-DC boost converter that converts the low DC voltage of the SPV to a higher DC voltage. In addition, the high gain DC-DC converter can extract the maximum power from SPV

by utilizing the P&O MPPT control technique. Then, the high-gain DC converter is coupled to MFGTI via the DC link capacitor. The SRF theory based on ABC to DQ control techniques and phase lock loop (PLL) implemented on MFGTI to interface the MFGTI with the utility grid, to compensate the reactive power, current THD within IEE standard limit, and improved power factor.

A. High Gain DC-DC Boost Converter Circuit Analysis

The proposed circuit is made of an LDC impedance network (which consist of two identical inductors and capacitors in parallel connection via one diode switch) in series with an SPV voltage source, and one insulated gate bipolar transistor (IGBT) switch in parallel to inductor at outer side[15]. The proposed circuit is able to convert the low DC voltage of SPV voltage (106.8V) to a higher gain DC voltage of 700V along with tracking the maximum power from SPV with the reduction in voltage ripples and switching stress.

Before initiating the analysis of the circuit, the following conditions need to consider.

- 1) All the circuits' parameters are ideal and IGBT selected as switch Sw.
- 2) The high gain converter operates at continuous conduction mode (CCM), and during off state of the switch the diode's current is in continuous.

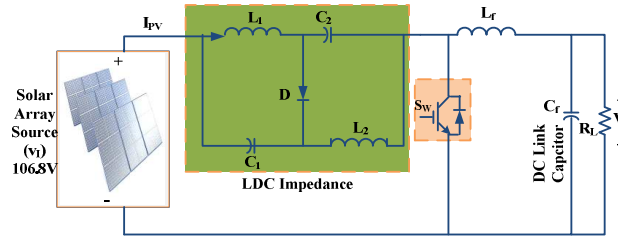


Fig.2 Circuit diagram of high gain DC-DC boost converter

A1. Operating Modes

According to equality of $L_1=L_2$, $C_1=C_2$ the following equations can be derived as,

$$\begin{cases} i_{L1} = i_{L2} = i_L \\ i_{C1} = i_{C2} = i_C \end{cases} \quad (1)$$

$$\begin{cases} v_{L1} = v_{L2} = v_L \\ v_{C1} = v_{C2} = v_C \end{cases} \quad (2)$$

Where v_L and i_L are for voltage and current of inductor and v_C i_C are for voltage and current of the capacitor of the circuit. According to the direction of the current in circuit components, five operating modes are possible, as shown in Fig.3. Based on circuit diagram of Fig.3 (a) the following equations can be derived by the KCL and KVL methods.

$$\begin{cases} i_i = i_L - i_C \\ i_D = i_L + i_C = 2i_L - i_i \end{cases} \quad (3)$$

$$\begin{cases} v_S = v_i + v_C - v_L \\ v_{Lf} = v_S - v_O \end{cases} \quad (4)$$

Mode 1: It is illustrated in Fig.3 (a), where switch S_w is turned on and diode D is acting as off state. Where the L_1 & L_2 are charged by the C_2 , C_1 , and v_i voltage source respectively, the load discharge the L_f . Hence, the current of the inductor (i_L) is positive and boosting linearly, but the

current in L_f (i_{Lf}) is positive and decreasing linearly. When the voltage across the IGBT switch is zero the following equation can be derived based on equation (4),

$$\begin{cases} v_L = v_i + V_C \\ V_{Lf} = 0 - V_O \end{cases} \quad (5)$$

Mode 2: It is illustrated in Fig.3 (b), in this mode the S_w is on, and D is off, but the inductor L_f is charged reversely via the C_f . Therefore, sign for the (i_{Lf}) indicated as negative and raising in the opposite way.

Mode 3: It is illustrated in Fig.3 (c), in this mode the S_w is off, and D is turned on, and the (i_{Lf}) sign is negative before S_w is off. Due to the series connection of v_i with LDC impedance network and inductor L_f , the L_f discharge the energy to voltage source and capacitors of LDC impedance network. Simultaneously, the capacitor C_1 & C_2 charged from inductor L_1 & L_2 randomly. So, the value pf (i_L) is positive, get decreased, and the value of (i_{Lf}) is negative and increasing randomly. To the end, the bellow formula is derived from equation (4),

$$\begin{cases} v_L = -V_C \\ V_{Lf} = V_S - V_O = V_i + 2V_C - V_O \end{cases} \quad (6)$$

Mode 4: It is illustrated in Fig.3 (d), in this mode the S_w is off, and D is turned on as well. In this mode the L_f and load is charged by the voltage source v_i and the inductor of LDC impedance network, at same time C_1 & C_2 are charging from L_1 & L_2 , respectively. Hence, (i_{Lf}) is positive and increasing linearly but (i_L) is reduced flatly. So, it make the equation 6 and resulting equation can be determined as,

$$i_{Lf} = i_L - i_c \quad (7)$$

The equation (7) states, whenever the current value of i_{Lf} is larger than the current value of i_L then mode four end up and current across the capacitor i_c will be negative.

Mode 5: It is illustrated in Fig.3 (e), the S_w and diode D are in same states as in mode four. According to above statement of i_c the C_1 & C_2 is discharging to inductor L_f and load, and the equation (6) & (7) will be derived.

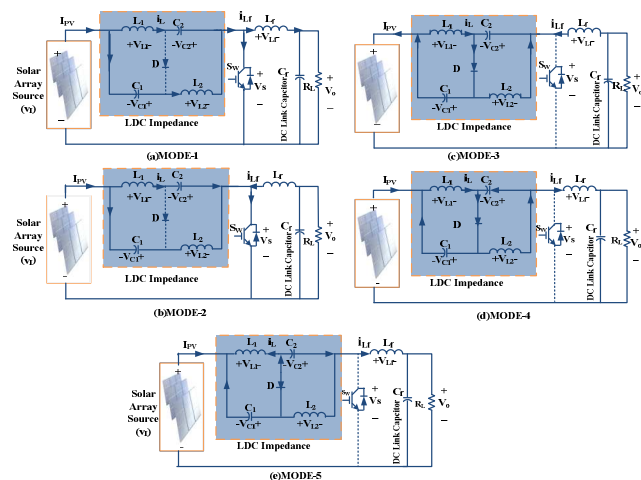


Fig.3 High gain DC-DC converter operating modes

B. Multi-Functional Grid Tie Inverter

The MFGI is made of six IGBT of anti-parallel diode switches and has the multi-functionality property to inject the

active power from SPV along with compensation of the reactive power and eliminate the current THD under different load conditions.

III. DESIGN OF PROPOSED SYSTEM

The proposed model shown in figure.1 is designed for SPV active power of 2kW. The design detail of each subsystem are described as following.

A. Design of Solar photovoltaic system

For generating the 2kW SPV power the proposed SPV requires 3 PV modules in parallel and three modules in series to form an SPV array.

B. Design of High Gain DC-DC boost Converter

The designed parameter details are given as bellow:

i. Calculation of Inductor

The inductor value of given proposed circuit in figure.1 is found as,

$$L_{1,L_2} = \frac{V_O(1-d)T_s}{\Delta I_L} \quad (8)$$

Where d is for duty cycle, and its value is calculated by $d = (1-V_i/V_O)$ is 0.847, and V_i and V_O are 106.8V, and 700V of the SPV array, respectively. ΔI_L is the current ripple of the output, its value considered as 5% of the input current of the PV (P_{SPV}/V_i), and it is computed as 0.9365A. T_s is the switching time period whose value is calculated by inverting the switching frequency ($T_s=1/15\text{KHZ}$), $T_s=66.6671\mu\text{s}$,

$$L_f = \frac{V_O(d)T_s}{\Delta I_{Lf}} \quad (9)$$

Here L_f is the inductor at load side, and ΔI_{Lf} is current ripple and its value calculated by the output current ($I_{Lf}=I_O=V_O/R_L$, $R_L=V_O^2/P_{SPV}=245\text{ ohm}$, the value of ΔI_{Lf} is calculated as 0.1425A.

ii. Calculation of Capacitor

The value of DC link capacitor is calculated as given bellow formula:

$$C_{DC} = \frac{(1-d)^2}{(1-2d)\Delta X_{CRL}F_s} \quad (10)$$

Here the value of ΔX_{CRL} is calculated by 5% of resistive load (RL).

C. Design of Multi Functional Grid Tied Inverter

The three phase inverter for a 328V line to line voltage, 2kW at 0.97 P.F lagging load is designed as bellow:

$$I_{rms} = \frac{VA}{3V_O} = \frac{P_O}{3(PF)V_O} \quad (11)$$

Where VA is for voltage ampere, and the rms value of load current is calculated based on equation (11) as 0.987A.

IV. CONTROL TECHNIQUES FOR GRID CONNECTED SPV

The proposed model consist of two control strategies.

- Control of high gain DC-DC boost converter is achieved using perturb and observation MPPT.

- ii. SRF theory based on ABC to DQ control techniques is used for calculating the reference current at AC side.

A. Control of High Gain DC-DC boost Converter

As maximizing electricity output and operating the SPV array at its utmost efficiency are extremely desirable thus, the grid-tied PV inverter operated using the maximum power point tracking algorithms[15]. For the proposed model, the P&O algorithm is used as they are less complex in implementation, simple, and robust in finding MPP during different hours of the day as solar radiation and temperature changes respectively[10].

B. Control of Multi-functional grid tied Inverter

The constant boosted-up DC voltage shall be converted into three-phase AC voltage via an MFGTI to feed active power to the utility grid and correct the PQ issues. To control the functionality of the MFGTI the proposed system used the SRF theory based on ABC to DQ control approach, to estimate the reference current of the AC main. This technique is based on transferring the load current synchronously in the DQ frame. The entire control system is shown in Fig.4 according to the control model the load current (I_{La} , I_{Lb} , I_{Lc}), PCC voltage (V_{ga} , V_{gb} , V_{gc}), and DC link bus voltage (V_{dc}) of MFGTI are sensed as feedback signals. Load current converted from ABC frame to DQ based on bellow matrix,

$$\begin{bmatrix} I_{Ld} \\ I_{Lq} \\ I_{L0} \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \quad (12)$$

Here $\cos\theta$ and $\sin\theta$ are calculated using the three phase lock loop (PLL), and PCC voltage (V_{ga} , V_{gb} , V_{gc}). The low pass filter (LPF) is used to filter the harmonics from reference current. The harmonic currents are obtained from the d axis and q axis of current.

$$I_{Ld} = I_{ddc} + I \quad (13)$$

$$I_{Lq} = I_{qdc} + I_{qac} \quad (14)$$

Using the LPF the AC components of the harmonics are filtered, and only the DC components are used in reference signal[2].

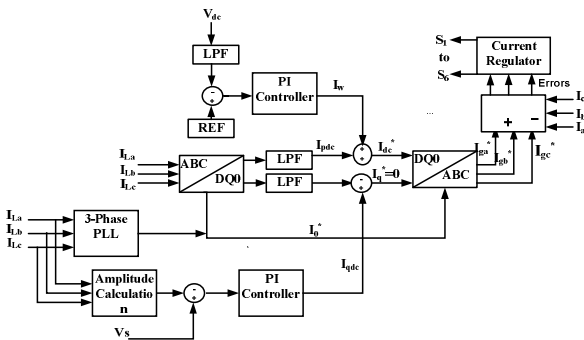


Fig.4 Block diagram of ABC to DQ controller of MFGTI

C. Unity PF control Proposed

Reactive power compensation is utilized for making unity PF.

To regulate the DC link voltage along to feed the losses of MFGTI (i_w) the AC mains should delivers the components of load current at direct axis along with its active components. The active power transfer for controlling DC link voltage, to compensate MFGTI losses which is provided by the DC bus PI controller. In order to remove the losses, the current component is stated as bellow by the PI controller [6],

$$i_w(k) = i_w(k-1) + K_{pd}(V_{de}(k) - V_{de}(k-1)) + K_{id}(V_{de}(k)) \quad (15)$$

Here $V_{de}(k)$ is an error voltage which is obtained from $V_{de}^{*(k)} - V_{de}^{(k)}$ of reference voltage (V_{dc}^*), and V_{dc} of DC link bus at k th sampling. K_{pd} , and K_{id} are called for the gain of DC-link voltage of PI controller.

The amplitude of reference AC current is calculated as,

$$I_d^* = I_{ddc} + I_w \quad (16)$$

The condition to obtain the active part, the main reference current should be in phase with the PCC voltage (V_{ga} , V_{gb} , V_{gc}). To obtain these reference currents the bellow matrix is implemented,

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} I_d^* \\ I_q^* \\ I_0^* \end{bmatrix} \quad (17)$$

In this reverse Park's transformation i_d^* value calculated as equation (16) and I_q^* and I_0^* are zero based on equation (17). In this way the value of I_a^* , I_b^* and I_c^* are calculated for controlling the MFGTI.

D. Zero Voltage Regulation Control

For regulating the voltage at PCC, AC main should transfer the exact direct axis components I^* with summation of quadrature axis current (I_{qdc}) along with output PI voltage controller (I_{qr}). The voltage PI controller will give the voltage error by comparing the AC main voltage (V_g) with its reference voltage (V_g^*). This error signal will be a reactive component of AC main current. The amplitude value of AC main voltage are calculated as,

$$V_g = \left(\frac{2}{3}\right)^{1/2} (V_{ga}^2 + V_{gb}^2 + V_{gc}^2) \quad (18)$$

The reactive current calculation is calculated as,

$$i_{qr}(k) = i_{qr}(k-1) + K_{pd}(V_{te}(k) - V_{te}(k-1)) + K_{iq}(V_{te}(k)) \quad (19)$$

Here, K_{pd} , and K_{iq} are the PCC voltage PI controller gain. The value of reference quadrature current is calculated as,

$$I_q^* = I_{qdc} - I_{qr} \quad (20)$$

V. RESULT AND DISCUSSION

Grid synchronization of SPV system with utility grid along with high gain DC-DC converter and MFGTI are modeled by MATLAB[®]/Simulink software.

The simulation result of the proposed system performance analysis is described under various solar irradiation, non-linear load in two stages.

Stages 1: The high gain DC-DC input and output simulation voltages shown in Fig.5. Therefore the Fig.5 verified that high gain DC-DC converter boosted the low SPV voltage of 106.8V into 700 V DC voltage with reduction in switching stress and ripple voltage.

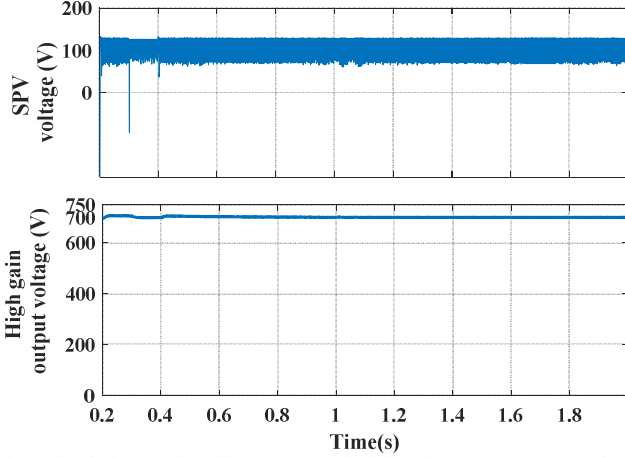


Fig.5 Simulation results of input SPV and High gain DC-DC output voltage

Stage2 proposed system: Fig.6, the simulated waveforms are three-phase grid voltage (V_g), grid current (I_g), load current (I_L), inverter current (I_{inv}), DC link voltage (V_{dc}), solar irradiation, and grid power factor (PF). These simulation results show the proposed system under various operation modes.

Mode I: Active harmonic filter (AHF) empower in this stage, the MFGTI is functioned as a power quality conditioner, the Fig.6 (b), and Fig.6(c) show that (I_g), and (I_L) current are similar at a time of 0.0s to 0.1s. When the AHF move on at 0.25s compensates for the harmonics, and reactive current of the nonlinear load. As a result, the utility grid currents become sinusoidal even when exposed to nonlinear loads continuously. While AHF mode condition, the SPV output power is always 0W. Based on such an assumption, the load's operational power need (2kW) supply from the grid.

Mode II: AHF+SPV MFGTI enabled: Instantaneously when the time shifted to 0.2s the SPV integrated with the utility grid and the active power start injection from the SPV to the utility grid based on solar irradiation conditions. The fig.5 (d) indicates that inverter current amplitude remarkably boosted when it moves from $t=0.2s$ to $0.3s$. In this mode of operation, the SPV unit injects 1850W of active power, and the grid will export the remaining load demand of $(2200-1850 = 350W)$. Therefore, this verified, how the SPV system and the utility grid can effectively control the active power.

Mode III: Solar insolation change: A grid-integrating SPV system is frequently exposed to periodic changes in the amount of solar insolation. The suggested model is kept through a rapid shift in solar insolation level from 1 kW/m^2 to 0.35 kW/m^2 at instant time of $t = 0.3s$ to $0.4s$ as illustrated in Fig.6 (f). This mode validates and emulates the MFGTI's potential for dynamic power transfer.

The voltage across the DC-bus capacitor remains intact and well-regulated within the permissible limit even when exposed to abrupt changes in solar insolation level, as shown in Fig. 6(e). Which proved the viability of the suggested

concept. When MFGTI does not turn on, the wave shape of grid current, and load current are same, which contains the total harmonic of 27.30% as shown in Fig.7 (a). By enabling the AHF mode of the MFGTI, it mitigates the current harmonic of utility grid current with reduced THD of 0.31 % as shown in Fig. 7(b) that complies with grid requirements, and it is within the IEEE standard.

Mode IV: unbalance load condition: Three-phase unbalanced loads have become increasingly prevalent in the power distribution system. Due to the flow of zero-sequence harmonic components, which caused by these loads, the neutral conductor exposed to the dangers of a higher voltage, and temperature.

To assure a flatly balanced, and grid current with the sinusoidal wave, the zero sequences harmonic current must be delivered in the three MFGTI outputs. This unbalance conditioning occurred at a time of 0.4s to 0.5s by applying a three-phase rectifier along with supplying RL load. Overall, the grid current maintained balance and pure sinusoidal which state and verifies the proposed three-phase MFGTI.

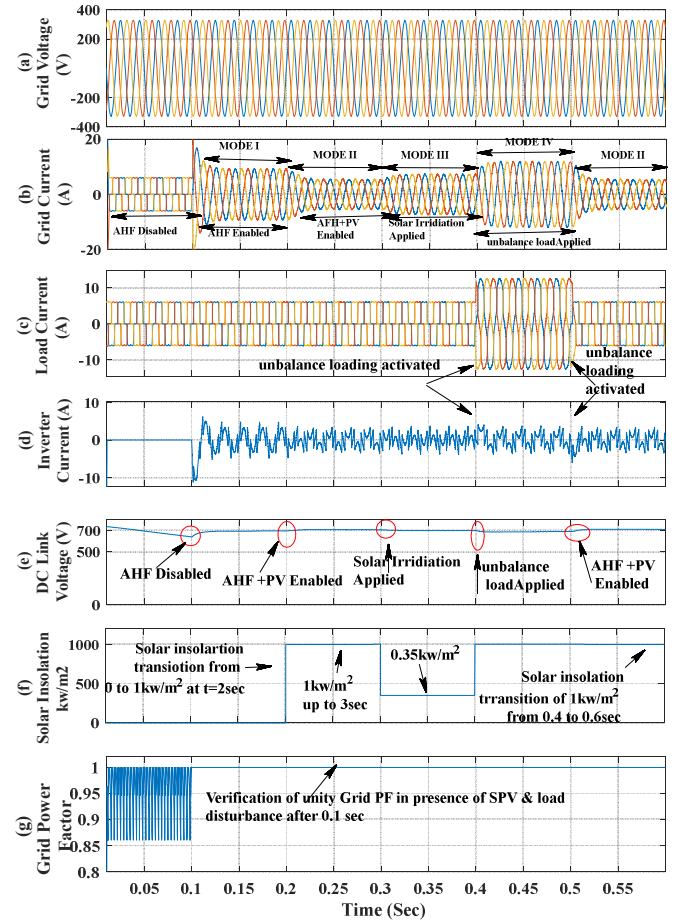


Fig.6 Simulation result under various mode operation: (a) Grid voltage,(b) Grid current,(c)Load current,(d)Inverter current,(e) DC link voltage,(f) Solar insolation, (g) Grid power Factor

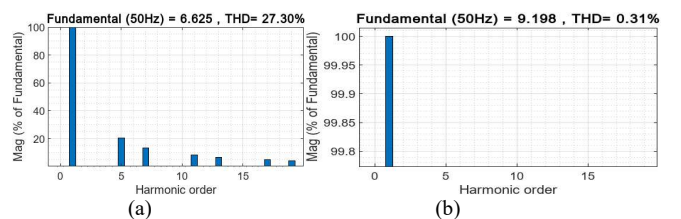


Fig.7 FFT analysis of THD (a) load current and (b) grid current

A. Comparative study

It is worthy to certify the high performance of SRF control theory compare to power balanced theory (PBT) for the proposed model. It is certified based on: (a) its effectiveness to predict the reference current in sinusoidal wave form & (b) capability to compile the THD within IEEE standard. This study superiority the SRF theory against the PBT which introduced in [16]. As it is obvious from Fig.8 (a) and (b), the proposed control technique implemented successfully and the reference current are completely in sinusoidal wave form under the various solar irradiation and unbalanced load condition, and its THD are accurately obtained within IEEE standard as shown in Fig. 7(b). However, the power balanced theory fail to give pure sinusoidal waveform under the unbalance load and solar irradiation condition.

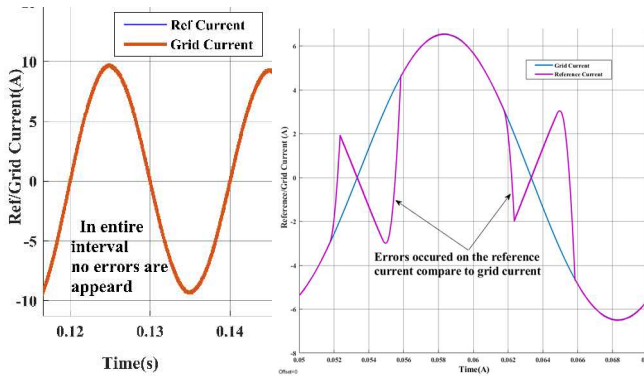


Fig.8 Comparative study (a) Ref current based on SRF Theory, (b) Ref current with PBT

VI. CONCLUSION

Synchronization of SPV system with utility grid, and solution to the power quality problems, and PF correction are achieved by utilizing the high gain DC-DC converter along with ABC to DQ control technique on MFGTI. High gain DC-DC converter utilized to boost up the low SPV voltage (106.8V) with less voltage ripples and switching stress to high gain DC voltage of 700V into the DC bus. Furthermore, to convert the DC bus voltage (700V) to the demanded three phase AC Voltage by the MFGTI. In order to operate the MFGTI for multi operation, the ABC to DQ control approach is implemented on MFGTI. ABC to DQ control approach can generate the reference AC main pulses for deriving the MFGTI switches effectively. By implementing SRF theory based on ABC to DQ control technique, the active power is injected from the SPV system to the utility grid with the reduction in current THD to 0.31% and with improved unity PF. It is worth mentioning that the above-mentioned issues are solved under various solar irradiation, nonlinear load conditions.

APPENDIX

SPV module details: $V_{MPP}=36.5V$, $I_{MPP}=6.9A$, $P_{MPP}=245.6W$, open circuit voltage (V_{OC}) = 44.8V and short circuit current (I_{SC}) 7.4A. High gain-DC-DC converter components' detail: $L_1=L_2= 6460.94 \mu H$, $C_1=C_2=1.2 \mu F$, coupling inductor $L_f=27.46 mH$, $C_{dc}=15001\mu F$ and DC-link voltage $V_{dc}= 700V$ and utility grid parameter $V_{LL}=328V$.

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