Research Article

Dual-Mode Photovoltaic Bidirectional Inverter Operation for Seamless Power Transfer to DC and AC Loads with the Grid Interface

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This paper develops the photovoltaic bidirectional inverter (BI) operated in dual mode for the seamless power transfer to DC and AC loads. Normal photovoltaic (PV) output voltage is fed to boost converter, but in space application, boost converter is not so preferable. To overcome this, buck and boost converters are proposed in this paper. Duty cycle to this converter is provided with the help of the outcome of the maximum power point tracking (MPPT) controller. This can be implemented by using perturbation and observation method. The MPPT will operate the switch between buck and boost modes. When the output voltage of a PV array is close to the dc bus voltage, then the bidirectional inverter can fulfill both rectification and grid connected mode. To control the power flow between dc bus and ac grid, a dc distribution system is used to regulate the dc bus voltage to a convinced level. Moreover, the bidirectional inverter must fulfill grid connection (sell power) and rectification (buy power) with power factor correction (PFC) to control the power flow between dc bus and ac grid. The simulations and hardware experimental results of a 2.5kVA circuit are presented to validate the performance of the proposed dual-mode seamless power transfer.

1. Introduction

Presently, world’s energy need is mostly supplied by the conventional energy resources, which are all having very limited storage sources on the Earth. The aspects like pollution, CO₂ emission, and global warming are deteriorating the environment. Hence, the new research era has been started with renewable energy sources like solar and wind. But with solar, wind power generation is not maintained constant due to the considering parameters like the variation in day-to-day temperature and irradiance. Overcoming these variations and meeting the required rated power of the PV system can be obtained the help of MPPT controller [1–4]. Normally, PV system output voltage is variable as well as smaller in magnitude compared to DC bus voltage. So, DC-DC boost converter is used to meet DC bus voltage. But in space applications, PV system output voltage may be lower than DC bus voltage. So, buck converter is used. These both operations can be overcome with the help of Buck-Boost converter, but the problem is with the negative output voltage and duty ratio variations. In buck mode, duty ratio varies from 0 to 0.5; boost mode duty ratio varies from 0.5 to 1. Avoiding this Buck or Boost converter is proposed in interfacing with MPPT controller. Whenever the PV system output voltage is more than the DC bus voltage, then the converter output is to be reduced (Buck) mode and duty ratio
Many photovoltaic cells are silicon based, but some other systems are going to exceed silicon photovoltaic. In the literature survey, PV-based power plants use the batteries for storage as well as an auxiliary input, but in proposed system, battery backup is not necessary. The PV output is not constant due to climatic conditions such as irradiance and temperature. Getting the constant DC output voltage and meeting the load requirement enhanced with DC-DC buck-boost converter with P&O algorithm [8–10]. The DC bus is fed to grid through bidirectional inverter (BI). The BI works in dual mode, i.e., grid connected mode and rectifier mode. If the PV generation is higher than the load requirement, then the BI injects surplus power into the ac grid, which is termed as grid connection mode (sell power) [11, 12]. On the contrary, the BI draws power from the ac grid to feed the load, which is termed as rectification mode (buy power). If the PV generation satisfies the load partially, then the seamless power transfer technique is implemented [13]. The seamless power transfer means that “unavailability of PV system generation on any one side, the grid takes care of the other side connected to critical loads and seamlessly transfers the real power through the DC bus.” The dual-mode photovoltaic bidirectional inverter is capable of operating either in grid connected mode (sell power) or rectification mode (buy power) with power factor correction (PFC) and the seamless power flow to fulfill the conditions like (a) if PV generation is not available and DC, AC loads are critical, then the total power is supplied from grid to the both loads; (b) if PV system output power satisfies DC loads partially, then the grid will provide full power to AC load, lasting power to DC load (seamless power transfer); (c) if PV system output power satisfies DC loads fully and AC loads partially, then the lasting power is supplied by grid (seamless power transfer); and (d) if DC and AC loads are satisfied with PV generation, the excess power is sent to grid through bidirectional inverter, i.e., grid connected mode (sell power).

2. Modelling and Simulation of PV System

Many photovoltaic cells are silicon based, but some other systems are going to exceed silicon photovoltaic cells with respect to cost and performance. The usage of equivalent electric circuits can help us to model the characteristics of a PV cell. This method is used for the implementations in MATLAB simulation [14, 15]. The same modelling technique is also applicable for modeling a PV string. Photovoltaic arrays convert sunlight into electricity directly. PV devices have nonlinear I-V characteristics with some parameters that need to be familiar from investigational data of practical devices. The accurate model for the PV device may be useful in the study of dynamic converters. A PV cell is basically a semiconductor diode [16, 17]. The prevalence of light on the cell generates charge carriers that invent an electric current, if the cell is short circuited. Basically, the PV spectacle is to be designed as the captivation of solar radiation and the generation and transports free carries at the p-n junction [18]. The rate of generation of electric carries depends on the occurrence light and the capacity of preoccupation of the semiconductor. The capacity of captivation mainly depends on the semiconductor bandgap on the replication of the cell surface, on electric mobility, on recombination rate, on the temperature, and on other factors [19]. The manufactory of PV devices always provide a set of observed data that may be used to obtain the accurate equation of the device I-V curve. Some manufactures also provide I-V curves obtained experimentally for dissimilar working conditions [20–22].

3. Buck-Boost Converter with MPPT

Normally, PV system output voltage is variable and smaller in magnitude compared to DC bus voltage. And load requirement is going to meet with the boost converter. But in space applications, due to climatic conditions, PV system voltage may be higher than DC bus voltage, then the buck converter is used. These both operations can be overcome with the buck-boost converter. To avoid this problem, a new method has been proposed called buck-boost converter. When photovoltaic output voltage \( V_{PV} \) is larger than the DC voltage \( V_{dc} \), then the MPPT is worked in reduced mode, i.e., buck mode of operation with switch \( M_1 \) and \( D_2 \). Otherwise, the MPPT will be functioned in boost mode of operation with switches \( M_1 \) and \( M_2 \) along with \( D_2 \). The proposed buck or boost DC-DC converter is illustrated in Figure 1.

Design of buck or boost converter is presented in Figure 2. The circuit parameters are expressed as \( L_{m} \) = inductance of inductor \( (H) \), \( R_{	ext{in}} \) = internal resistance of inductor \( (\Omega) \), PV voltage = \( V_{PV} \), PV current = \( I_{PV} \), DC bus voltage = \( V_{dc} \). DC load current = \( I_{dc} \), \( M_1 \) = IGBT switch for boost operation, \( M_2 \) = IGBT switch for the boost operation, \( C_{dc} \) = PV side capacitor, \( C_{dc} \) = DC side capacitor, \( i_{lm} \) = inductor current, \( V_{Lm} \) = voltage across the inductor, \( D_1 \), \( D_2 \) = diodes for operating in \( M_1 \), \( M_2 \) in OFF duty conditions, respectively, \( R_{M1} \), \( R_{M2} \) = ON state resistance of IGBTs, respectively, and \( V_{D1} \), \( V_{D2} \) = forward voltage drops across diodes. Inside the DC distribution system, the PV panel voltage \( (V_{PV}) \) is given as an input for the DC-DC converter and the output of converter is DC bus voltage \( (V_{dc}) \). If the voltage of a PV panels \( (V_{PV}) \) is much more than the bus voltage \( (V_{dc}) \), in this case, \( M_2 \) switch is turned off continuously and the operation of the converter should be in buck mode.

Mode 1: the IGBT switch \( M_1 \) is switched on as shown in Figure 2. And the analysis under buck mode to \( M_2 \) is always low, so this makes the diode \( D_2 \) to conduct always during buck mode. The magnetization of an inductance \( L_{m} \) is observed from the difference of voltages as \((V_{PV} - V_{dc})\) through power diode \( D_2 \).

\[
V_{Lm} = V_{PV} - i_{lm}R_{M1} - i_{lm}R_{M} - V_{D2} - V_{dc}. \quad (1)
\]
Mode 2: the $M_1$ (IGBT) is off as shown in Figure 2. The magnetization of an inductance $L_M$ is calculated from the output voltage $V_{dc}$ through the $D_1$ and $D_2$.

$$V_{Lm} = -V_{D1} - V_{D2} - V_{dc} - i_{Lm} R_M. \quad (2)$$

From Equations (1) and (2), duty ratio of the buck converter is calculated as follows:

$$D = \frac{V_{dc} + i_{Lm} R_M + V_{D2} + V_{D1}}{V_{PV} - i_{Lm} R_M + V_{D1}}. \quad (3)$$

From Equation (1), inductor voltage is calculated as follows:

$$L = \frac{V_{PV} - i_{Lm}(R_{M1} + R_M) - V_{D2} - V_{dc}}{\Delta I_{Lm}} \times DT_s. \quad (4)$$

Output capacitor during buck operation is as follows:

$$C = \frac{\Delta I_{Lm} \times DT_s}{2 \Delta V_{dc}}. \quad (5)$$

On the off chance, the voltage of the PV panel will be lower than the bus voltage, then the converter is made to be operated in boost mode. The $M_1$ switch is turned ON, continuously in the boost mode of operation. Mode 3: in mode 3, the $M_2$ is turned ON as depicted in Figure 2. The magnetization of an inductance $L_M$ is observed from the voltage of a PV panel through $M_1$ and $M_2$.

$$V_{Lm} = V_{PV} - i_{Lm}(R_{M1} + R_M) - V_{D2} - V_{dc}. \quad (6)$$

Mode 4: in mode 4, the $M_2$ switch is turned OFF as shown in Figure 2. The demagnetization of an inductance $L_M$ is calculated from the difference of voltages of PV panel and DC bus voltage through the $M_1$ switch and power diode $D_2$.

$$V_{Lm} = V_{PV} - i_{Lm}(R_{M1} + R_M) - V_{D2} - V_{dc}. \quad (7)$$

From Equations (6) and (7), the duty ratio of boost converter is calculated as follows:

$$D = \frac{V_{PV} - i_{Lp}(R_{M1} + R_{M2}) - V_{pm} - V_{D2}}{(i_{Lp} R_{M2} - V_{pm} - V_{D2})}. \quad (8)$$
allowed peak-tations are mentioned in Table 1.


current scheme, $M$ switching frequency $f_{sw}=15$ kHz, allowed peak-peak ripple $I_{sw} = 15$ kHz, allowed peak-peak ripple $V_{pp} = 2$ $V$. From the design parameters of buck and boost converters, individually out of which maximum values can be chosen for simulation as well as circuit design. The design parameters are available in Table 2.

DC-DC converter is worked in two modes of operation. When PV output is more than DC voltage, DC-DC converter is operated in buck mode. On the other hand, the DC-DC converter is operated in boost mode. Due to climatic conditions, DC-DC converter is functioned either buck or boost mode of operation performed with buck-boost transition.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Buck mode</th>
<th>Boost mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage ($V_{pv}$)</td>
<td>450 V</td>
<td>302 V</td>
</tr>
<tr>
<td>Output voltage ($V_{dc}$)</td>
<td>400 V</td>
<td>400 V</td>
</tr>
<tr>
<td>Input current ($I_{pv}$)</td>
<td>5.46 A</td>
<td>8.27 A</td>
</tr>
<tr>
<td>Output current ($I_{dc}$)</td>
<td>6 A</td>
<td>$I_{lm} = I_{pv}$</td>
</tr>
</tbody>
</table>

From Equation (6), inductance $L_M$ is observed as follows:

$$L = \frac{V_{pv} - i_{lp}(R_{M1} + R_{lp} + R_{M2})}{\Delta I_{lp}} DT_s.$$  

(9)

Output capacitor during boost operation is as follows:

$$C = \frac{I_{pm} \times DT_s}{\Delta V_{pm}}.$$  

(10)

From the above equations, the design parameters of buck-boost converter are obtained. The respective specifications are mentioned in Table 1.

Switch on state resistance $= R_{M1} = R_{M2} = 0.5 \Omega$  
switching frequency $f_{sw} = 15$ kHz, allowed peak-peak ripple for inductor current $= 0.5 \mu A$, allowed peak-peak ripple output voltage $= 2$ $V$. From the design parameters of buck and boost converters, individually out of which maximum values can be chosen for simulation as well as circuit design. The design parameters are available in Table 2.

### Table 2: Parameters of buck or boost converter.

<table>
<thead>
<tr>
<th>Parameter values</th>
<th>From buck mode</th>
<th>From boost mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L \geq 10.14$ mH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C \geq 52.99$ $\mu F$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{M1} = 451$ V</td>
<td>$I_{m1} = 6.25$ A</td>
<td></td>
</tr>
<tr>
<td>$V_{M2} = 401$ V</td>
<td>$I_{m2} = 8.52$ A</td>
<td></td>
</tr>
<tr>
<td>$V_{D1} = 453.125$ V</td>
<td>$I_{D1} = 6.25$ A</td>
<td></td>
</tr>
<tr>
<td>$V_{D2} = 395.74$ V</td>
<td>$I_{D2} = 8.77$ A</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2. Modified Perturb and Observe MPPT Controller

Modified MPPT algorithm is to calculate the differential power “ΔP” with the considerations of “ΔV” and “ΔI.” In case of conventional MPPT methods for iterations, there will be a chance of occurring of very large and very small differential power ΔP. Due to this, it creates the large changes in the magnitude of pulses with creating uneven changes in duty ratio. This produces more distortions in the outputs of the buck-boost converter. To overcome this, “ΔV” and “Δ I” are chosen to the modified MPPT algorithm. These “Δ V” and “Δ I” observe the power difference in a better way than the existed methods in order to manage the changes in the duty pulses with reducing the distortions in the outputs of the converter. Perturbation size of the algorithm is also chosen less than 0.01 seconds for a very keen observation while measuring the power differences at each iteration. The iteration process is continued as per the conditions given in the algorithm.

### 3.3. Simulation Results with Modified MPPT

From the MATLAB Simulink of modified MPPT model, the temperature and the irradiances are given as the inputs to the model at standard test conditions (STC). Each PV module has 60 cells to produce the 250-watt power. 10 modules are arranged in series to form an array. From simulation results, the module open-circuit voltage ($V_{oc}$) is about 37.6 volts, the short-circuit current ($I_{sc}$) is about 8.8 amps, and power is around 250 watts. Similarly, the $V_{oc}$ of array is 376 volts with $I_{sc}$ of 8.8 amps and the maximum power obtained at MPP is about 2500 watts. The results of PV array with modified MPPT model are obtained. I-V, P-V characteristic curves are presented in Figure 4. Practical I-V, P-V characteristic curves of PV module are measured with solar module analyzer as represented in Figure 5. Simulated and measured voltage, current, and power values of PV module and PV array are tabulated in Table 3.

### 4. Three-Phase Bidirectional Inverter

The circuit consists of bidirectional inverter (BI) linked between the solar system and AC grid. The input to bidirectional inverter is $V_{dc}$ sustained at consistent level. The bidirectional inverter is shown in Figure 6 which is worked for dual mode; when the PV generation is higher than the load requirement, the bidirectional inverter injects surplus power to the ac grid; on the contrary, the bidirectional
inverter draws power from the ac grid to compensate the load requirement.

The working of bidirectional inverter is explained with 3-Φ grid, which is connected to bidirectional inverter. Voltage from DC side equivalent circuit is shown in Figure 7. $V_L$ is the line to line voltage and $V_S$ is the bridge converter voltage controllable from the dc side. The general phasor diagram and phasor diagrams for both rectification mode and inverter operation at unity power factor (UPF) are depicted in Figures 7(a)–7(d).

The line current $i_L$ is adjusted by the voltage drop across the inductance $L$, by interlocking the two voltage sources (grid and bidirectional inverter). Power transfer between grid and bidirectional inverter is subjected to power angle “$\delta$” and amplitude of bidirectional inverter output voltage “$V_S$”, which indirectly controls the $\delta$ and amplitude of line current. In this way, the average value and sign of the dc current is subjected to control the proportional active power conducted through a bidirectional inverter. When $V_L > V_S$, then the power is taken from grid (rectification mode) but $V_L$ and $i_L$ are in phase as presented in Figure 7(b). When $V_S > V_L$, then the power is supplied to grid (inversion mode) but $V_L$ and $i_L$ are not in phase as shown in Figure 7(c). These two modes will be performed properly with the proper control techniques.

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**Figure 3:** Flowchart of the buck or boost mode transition.

**Figure 4:** Modified MPPT I-V and P-V characteristic curves of an array.

**Figure 5:** Measured I-V and P-V characteristic curves of PV module.
Table 3: Simulated and measured voltage, current, and power values of PV module and PV array.

<table>
<thead>
<tr>
<th>Parameter values</th>
<th>Simulated Module</th>
<th>Simulated Array</th>
<th>Measured Module</th>
<th>Measured Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power in watts</td>
<td>250</td>
<td>2500</td>
<td>169.8</td>
<td>1700</td>
</tr>
<tr>
<td>Maximum power point voltage ($V_{MPP}$) volts</td>
<td>30.23</td>
<td>302.3</td>
<td>24.62</td>
<td>246.2</td>
</tr>
<tr>
<td>Maximum power point current ($I_{MPP}$) amps</td>
<td>8.27</td>
<td>8.27</td>
<td>6.897</td>
<td>6.897</td>
</tr>
<tr>
<td>Open-circuit voltage ($V_{OC}$) volts</td>
<td>37.6</td>
<td>376</td>
<td>32.79</td>
<td>328</td>
</tr>
<tr>
<td>Short-circuit current ($I_{SCC}$) amps</td>
<td>8.8</td>
<td>8.8</td>
<td>7.443</td>
<td>7.44</td>
</tr>
</tbody>
</table>

Figure 6: Three-phase bidirectional inverter with control unit.

Figure 7: Equivalent circuit of grid connected bidirectional inverter with normal phasor diagram, rectifier mode phasor diagram, and inverter mode phasor diagram.
4.1. Control Strategies of Bidirectional Inverter. Classification and the bidirectional inverter control methods are categorized into 2 steps viz., voltage-based control and virtual flux control-based control method are analyzed in Figure 8.

High-power factor and sinusoidal input current waveforms are obtained with above control strategies. Among all control strategies, voltage-oriented control method is suitable for this research work and it requires the fixed switching frequency for easy design. And some of the parameters are listed below for the selection of the VOC method.

1. Direct power control has good p.f than VOC but drawback is with the constant switching frequency
2. A fixed switching frequency is required because it is easy for design and which has low sample frequency
3. A better p.f can be achieved with VF-DPC and that has lot of advantages with constant switching frequency

High dynamic and static performance can be obtained from voltage-oriented control (VOC) via an internal current control loop.

4.2. Voltage-Oriented Control (VOC). The voltage-oriented control is from the famous field-oriented control of induction machines. It assures a high dynamic and static performance. Since the output of bidirectional inverter (BI) be absolutely matched with grid, therefore, the control gate pulses for BI which controls the parameters of BI is the modulating signal. These modulating signals are obtained from 3-phase voltage and current is converted to synchronous dq rotating frame by using Park transformation. These outputs and \( V_{dc} \) are given to decoupled controller. The output of decoupled controller \( V_{d}^{*} \) and \( V_{q}^{*} \) is converted to \( V_{a}^{*} \), \( V_{b}^{*} \), and \( V_{c}^{*} \). The reference voltages generated gate pulses; those pulses are given...
4.2.1. Phase Locked Loop. The PLL is an important part in the grid connected systems. The main aim is to generate phase angle $\theta$ from grid voltage. For all dq-transformations, $\theta$ is used. By substituting $V_q$ to zero, then $V_d$ rotates synchronously with grid voltage vector. The proportional integral (PI) controller is used to adjust the $V_q$ to zero. The output of PI controller in grid angular frequency is integrated to yield the angle for the grid voltage and which is fed back to the abc-dq transformation to lock the dq synchronous reference frame with the grid voltage.

4.2.2. Decoupled Current Control. The control strategy for a decoupled current control is to control the active and reactive power of an inverter. And the inverter current is in individual axis. The active power loop is controlled by the dc link voltage. Then, the dc link voltage and the reactive power loop is controlled by the reactive component of the grid current. Perfect decoupling can be obtained by the proper design of the control. The major advantage of having two decoupled loops is neutralization of undesirable transients of reactive current caused by changes of active power and vice versa.

In VOC, the current reference for direct axis ($i_{d}^{*}$) is preferred as output power of inverter, while the current reference for quadrature axis ($i_{q}^{*}$) is preferred as the output reactive power of inverter. The $d$ and $q$ axis inverter currents are controlled by using two PI controllers; the PI controller brings the constant state error to zero between the reference currents ($i_{d}^{*}$ and $i_{q}^{*}$) and actual inverter currents ($i_{d}$ and $i_{q}$). The output voltage of inverter is in accordance to the mathematical model of grid-connected inverter is given by

$$V_{d}^{*} = V_{d} - k_{p}e_{d} - k_{i}I_{d} + \omega Li_{q}, \quad (11)$$

$$V_{q}^{*} = V_{q} - k_{p}e_{q} - k_{i}I_{q} - \omega Li_{d}, \quad (12)$$

where $V_{d}^{*}$ and $V_{q}^{*}$ are the dq components of inverter output voltage. $V_{d}$ and $V_{q}$ are the dq aspects of the park transformation of the grid voltage. Equations (11) and (12) mention about the robust connection of $d$ and $q$ axis. In decoupled controller, the cross-coupling terms are brought to the $d$ and $q$ axis with feed-forwarded terms such as voltages are further introduced to improve the overall performance of PI controller. The decoupled current controller $V_{d}^{*}$ and $V_{q}^{*}$ voltages are obtained. Then, $V_{d}^{*}$ and $V_{q}^{*}$ are transformed to abc form which were compared to actual phase voltages. The error will be reference to inner current loop. The inner loop develops the modulation signals in dq domain. The modulation signals are fed back to 3-phase voltage reference and fed to PWM, which drives the bidirectional inverter.

4.3. FPGA-Based Controller-Spartan-6. Spartan-6 FPGA-based controller for dc-dc converter and bidirectional inverter are presented in Figure 10. Hall-effect voltage and current transducers were used to sense line voltages, currents, dc bus voltage, pv voltage, and current in order to bring the voltage level of the controller to the level translators. Sineoidal signals were directly translated to digital form using bipolar ADC. VHDNL-based digital control is used for MPPT to the dc-dc converter and VOC for bidirectional inverter which is carried using PC and again with help of a level

**Figure 10:** FPGA-based Spartan-6 controller.
translator. The gating signals for dc-dc converter and bidirectional inverter were given to respective driver units.

5. Simulation and Experimental Validation

To verify the feasibility of bidirectional inverter with buck-boost MPPT controller for DC delivery systems, a Spartan-6 created hardware with designed parameters as shown in Figure 11. The specifications and components of the project are tabulated in Table 4. In PV system, the array is formed by 10 modules connected in series as depicted in Figure 11(a); parameters are listed in Table 4 and measured parameters from solar module analyzer are presented in Figure 11(b). Adjustable voltage is gained from PV system to keep the constant DC voltage at DC common coupling point. DC-DC buck-boost converter with MPPT is implemented. When solar output is more than the DC common coupling point, the voltage converter worked in buck mode by generating the required MPPT pulse to feed IGBT Switch M1. Otherwise, it will be operated in boost mode with switch M2. DC-DC converter with perturb and observe MPPT technique is used for getting constant DC voltage at DC bus. The performance of MPPT controller in simulation is from 0.9 sec to 1 sec when the converter is operated without MPPT and at time 1 sec MPPT is ON, then voltage and power will be increased and current gets decreased that the corresponding waveforms are available in Figure 12. Prototype plot is also validated as illustrated in Figure 13. Variations of values with and without MPPT are tabulated in Table 5.

The output voltage of a PV array is near to the DC bus voltage which changes with respect to the temperature and irradiance. During such cases, we generally prefer the buck-boost converter. The MPPT can attain smooth mode transition by succeeding the control flow as depicted in Figure 3. When \( V_{pv} \) is slightly lesser than \( V_{dc} \), then switch \( M_2 \) is OFF and the duty ratio of switch \( M_1 \) starts to decrease.

**Table 4: Prototype parameters and their values.**

<table>
<thead>
<tr>
<th>Component</th>
<th>Rating/make</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-DC converter IGBT ( M_1 ) and ( M_2 )</td>
<td>SKM100GAL1200T4</td>
</tr>
<tr>
<td>DIODE ( D_1 ) and ( D_2 )</td>
<td>C3D20060</td>
</tr>
<tr>
<td>PV capacitor ( C_{PV} )</td>
<td>2200 ( \mu F )</td>
</tr>
<tr>
<td>DC capacitor</td>
<td>2200 ( \mu F )</td>
</tr>
<tr>
<td>Inductor ( L_m )</td>
<td>10 ( \mu H )</td>
</tr>
<tr>
<td>Inductor ( L_s )</td>
<td>12 ( \mu H ) x3</td>
</tr>
<tr>
<td>Bidirectional inverter IGBTs (3)</td>
<td>SKM100GB1200T4</td>
</tr>
<tr>
<td>DC load</td>
<td>Rheostat 1000 watts</td>
</tr>
<tr>
<td>AC load</td>
<td>3-phase induction motor 1-hp, 415 V, 1.8 amps, and 1410 rpm</td>
</tr>
</tbody>
</table>
the duty ratio from 0.95. During this, current $I_{pv}$ will charge the capacitor $C_1$ and $V_{PV}$ is increased up to a higher level. Then, the boost to buck mode is attained. When $V_{pv}$ is slightly more than $V_{dc}$, then switch $M_1$ is switched ON and the duty ratio of switch $M_2$ starts to rise from 0.05. During this, converter is operated in boost mode. During morning hours up to 6 AM, the PV out is very less, but (AC and DC) loads required power will not be met. Then, the total load required power of (950 W) is to be completely taken from the grid. The bidirectional inverter acts as rectifier, and the corresponding voltage and current are in phase as shown in Figures 14(a) and 14(b). From 6 AM onwards, as the sun intensity increases, so at 10 AM, PV generation is also increased to about 330 W and remaining power is taken from the grid. Seamless power transferred between grid and loads is obtained. Similarly, at 11 AM, PV generation is 900 W and the remaining power is taken from the grid. At 12:40 PM, PV generation is 1500 W and DC and AC loads are satisfied and excess of 600 W power is fed to grid.
through bidirectional inverter, and the corresponding voltage and current waves are in out of phase that are represented in Figures 14(c) and 14(d).

The bidirectional inverter works in dual mode, i.e., grid-connected mode and rectifier mode. During the both conditions, the load must be critical. Power distribution between PV system, grid, and load is illustrated in Figure 15. From 0-0.8 sec, there is no PV generation, but to meet the load requirement, the total power is supplied from the grid. At 0.8 sec onwards, the PV generation starts, due to available

Figure 14: (a, b) Bidirectional inverter in rectifier mode (buy power) 950 W. (c, d) Bidirectional inverter in grid connected mode (sell power)-500 W.
irradiance and temperature. Then, the power is going to be reached up to 330 W at 1.5 sec; the remaining 600 W power is delivered by grid. From 1.5 sec, further increase of the PV generation takes place and power is reached to 900 W at to 2 sec; here also, the remaining power is taken from the grid. At 1.5 sec, again further increasing the PV generation power takes place and it reaches to about 1500 W at 2.5 sec. This power satisfies load requirement, and excess amount of power is given to grid. Power balance waveforms are presented in Figure 15 and the corresponding values are tabulated in Table 6.

Experimental readings are obtained from harmonic analyzer at different instants that are shown in Figure 14 and the corresponding values are noted in Table 7.

### Table 6: Simulated PV generation and grid power variations with constant load condition.

<table>
<thead>
<tr>
<th>Time in sec</th>
<th>PV generation (watts)</th>
<th>DC load (watts)</th>
<th>AC load (watts)</th>
<th>Simulated grid power (watts)</th>
<th>Mode of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.8</td>
<td>0</td>
<td>800</td>
<td>100</td>
<td>+950</td>
<td>Rectifier</td>
</tr>
<tr>
<td>0.8-1.5</td>
<td>330</td>
<td>800</td>
<td>100</td>
<td>+600</td>
<td>Seamless transfer</td>
</tr>
<tr>
<td>1.5-2.0</td>
<td>900</td>
<td>800</td>
<td>100</td>
<td>+98</td>
<td>Seamless transfer</td>
</tr>
<tr>
<td>2.0-2.5</td>
<td>1500</td>
<td>800</td>
<td>100</td>
<td>-500</td>
<td>Grid connected</td>
</tr>
</tbody>
</table>

### Table 7: Experimentally measured power, voltage, current, and power factor values at different instants.

<table>
<thead>
<tr>
<th>Time</th>
<th>PV generation (W)</th>
<th>DC load (W)</th>
<th>AC load (W)</th>
<th>Line voltage (V)</th>
<th>Line current (A)</th>
<th>Power (kW)</th>
<th>Power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 AM</td>
<td>0</td>
<td>800</td>
<td>100</td>
<td>308.2</td>
<td>1.880</td>
<td>0.950</td>
<td>0.99</td>
</tr>
<tr>
<td>10 AM</td>
<td>330</td>
<td>800</td>
<td>100</td>
<td>315.9</td>
<td>1.363</td>
<td>0.650</td>
<td>0.99</td>
</tr>
<tr>
<td>11 AM</td>
<td>900</td>
<td>800</td>
<td>100</td>
<td>310.3</td>
<td>0.522</td>
<td>0.091</td>
<td>1</td>
</tr>
<tr>
<td>12:40 PM</td>
<td>1500</td>
<td>800</td>
<td>100</td>
<td>312.2</td>
<td>0.970</td>
<td>-0.507</td>
<td>-0.96</td>
</tr>
</tbody>
</table>

6. Conclusions

This paper presents the photovoltaic bidirectional inverter which is operated in dual mode for the seamless power transfer to DC and AC loads with the grid interface. The bidirectional inverter controls the power flow between dc bus and ac grid by the regulating the dc bus common coupling voltage. The current is controlled in synchronous dq rotating frame and VOC is implemented to control active and reactive power as well as to control the current in \( d \) and \( q \) axis, respectively. PLL is used to make the rotating frame to synchronous frame with grid voltage by extracting the grid angle for synchronizing the inverter. As the PV array voltage is getting varied due to abnormal weather conditions, MPPT has been
incorporated for the dc-dc converter to obtain the dc voltage range around 580-600 V in order to meet the load requirement. Additionally, control laws to smooth out mode transition from boost to buck and vice versa. Power transfer between grid to DC bus (buy power mode) and power transfer between DC bus to grid (sell power) and seamless power transfer of overall inverter system has been implemented by meeting the requirement of DC and AC loads significantly. Experimental validations obtained from 2.5 kW, three-phase bidirectional inverter with the MPPT are analyzed clearly.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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