Solar PV based nanogrid integrated with battery energy storage to supply hybrid residential loads using single-stage hybrid converter

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Abstract: This study proposes a solar photovoltaic (PV) based nanogrid with integration of battery energy storage to supply both AC and DC loads using single-stage hybrid converter. A boost derived hybrid converter (BDHC) is used as a single-stage converter to supply the AC/DC hybrid loads. The BDHC reduces the number of conversion stages when compared to the conventional solar PV based systems to supply the AC/DC loads. A non-isolated buck–boost bidirectional DC–DC converter is used for charging and discharging of the battery to support the nanogrid. The power reference algorithm proposed in this study provides the proper utilisation of the solar PV in different operating conditions and uninterruptable power supply to the loads along with the battery storage management. A modulation scheme is implemented to operate the BDHC for generation of AC/DC hybrid outputs from a single input. The performance of the proposed system in different modes of operation has been evaluated using PSCAD simulation studies. A laboratory experimental setup is developed and control algorithms are implemented using LabVIEW based FPGA controller for verification of the results.

1 Introduction

The standalone DC nanogrids are increasing their popularity due to increase of renewable energy sources development. The standalone DC nanogrid systems are supported by DC distributed generators (DGs) like solar photovoltaic (PV) system along with energy storage device (ESD). The integration of energy storage system with renewable sources increases the reliability of the nanogrid system [1, 2]. The modern smart household appliances are hybrid in nature and require DC as well as AC supply [3, 4]. In typical DC nanogrid system, the power electronics converters are connected in parallel and are fed from the common DC bus to supply according to requirement of the loads [5–8]. The common DC bus is maintained constant by controlling all energy storage systems and renewable sources connected to the DC bus. The solar PV based DC nanogrid is popular because of its simpler installation and reliable power generation [8]. The large-scale solar PV system installation is uneconomical due to high installation cost and large energy storage capacity requirement. It is economical and efficient to install a small SPV system to supply necessary hybrid loads like LED lights/fans, laptops/mobile chargers, LED TVs and so on, available in smart hybrid buildings of the developing countries [4, 9]. Due to the intermittent nature of the solar PV system, the input varies over a wide range [10]. To regulate the input power and voltage of the solar PV, a dedicated DC–DC power electronics converter is used [11, 12]. This DC–DC power electronic converter interface extract the maximum power from the solar PV system [13–16].

In general, to address the intermittency of the renewable energy input and mismatch with the required load [15], the distributed energy sources are required for the consistent power supply to the loads [17]. In an off-grid or standalone applications, the solar PV system integrated with the energy storage systems acts as a DC DG for the DC nanogrid [18]. The power electronics converters are connected to this source to convert the available energy with high efficiency. The common DC bus provides energy for various converters connected in parallel to the DC bus to supply the loads [3, 12]. The converters connected at the DC bus require controllers to regulate their outputs according to load requirement (AC or DC) [19, 20]. Each dedicated converter of the hybrid load requires a separate control algorithm which increases the complexity of the control algorithm. Number of converters increases the passive elements along with more losses. To reduce this complexity, the hybrid converters are utilised which generates the multiple outputs with single-stage conversion. Switched boost converter and boost derived hybrid converters (BDHCs) are examples of single-stage hybrid converters to supply AC and DC loads simultaneously [21–23].

This paper proposes a solar PV system integrated battery energy storage to supply standalone residential DC nanogrid using single-stage hybrid converter. A BDHC is used as single-stage hybrid converter for simultaneous AC and DC outputs. A separate boost DC–DC converter is used to operate the solar PV with maximum efficiency. For energy balance in proposed system, a bidirectional DC–DC converter fed from battery energy storage is used [24]. A power balance control algorithm is proposed according to load requirement and availability of the power. The single-stage hybrid converter is derived by replacing the boost converter switch with a voltage source inverter (VSI) H-bridge structure. The BDHC converter is synthesised by connecting an inductor and a diode to the H-bridge at front and rear end, respectively [25, 26]. A modified unipolar sinusoidal pulse width modulation (SPWM) technique is used to operate BDHC converter. The proposed system performance is verified both through the simulation and experimental results.

The proposed solar PV system is viable and useful in small residential hybrid loads. It reduces the number of conversion stages when compared to the conventional solar PV based systems to supply AC/DC hybrid loads. The BDHC hybrid converter also addresses the problems like dead time circuit requirement and output voltage regulation of the VSI. The control strategy is less complex and more reliable to generate hybrid outputs from a single input with single-stage conversion. The power reference algorithm also provides the proper utilisation of solar PV in different operating conditions and provide uninterruptable power supply to the loads along with the battery storage.

2 Power flow control modes

For conventional solar PV applications involving AC and DC loads, distinct DC/AC and AC/DC converters are required.
involves more circuit elements and two-stage control. The proposed system using BDHC converter has single centralised controller as shown in Fig. 1, having single conversion stage. The proposed system has three distinct operating modes, i.e. (i) maximum power point tracking (MPPT) mode, (ii) power reference mode and (iii) battery supply mode. Fig. 2 illustrates the power flow in the three modes.

2.1 MPPT mode

The SPV system is able to supply more than the power required to the loads then the surplus power of SPV system is used to charge the ESD up to its upper limit of SOC. In this mode, the MPPT converter implements the MPPT algorithm and extracts maximum power from the SPV system. The extracted maximum power is supplied to the hybrid loads through the BDHC converter and stores the surplus power in ESD through battery converter. In the implementation of this mode, the MPPT converter controls the solar input and battery converter acts as buck converter to charge the ESD, and BDHC converter generates simultaneously, the AC and DC outputs to the hybrid loads. This power flow mode is shown in Fig. 2a.

2.2 Power reference mode

In the MPPT mode, the ESD reached to its upper limit of the SOC, and the battery converter operate in idle state. If the load power demand is less than the maximum power generated from the SPV system then the SPV array no need to operate at maximum power point (MPP). In this condition, the MPPT converter controls the solar input to operate at particular power reference. Hence, this mode is considered as power reference mode. The power reference is sum of the total load power demand. In this mode, the MPPT converter executes the power reference algorithm to extract load power demand from SPV system and BDHC converter supply the power to the hybrid loads [25, 26]. The schematic power flow diagram in power reference mode is shown in Fig. 2b.

2.3 Battery supply mode

The SPV array operates in this mode under two conditions. In condition-1 (Fig. 2c) solar power is insufficient to supply the load power demand; therefore the required extra power is supplied from the ESD. In this condition, the SOC should be greater than its lower limit. In this mode, the MPPT converter controls the SPV to operate at MPPT. The battery converter regulates the DC link capacitor voltage and gets discharged to feed the short of power. In condition-2, the SPV array is off (during night time) then the ESD will supply all the required load power demand. The power flow modes schematic representation is illustrated in Figs. 2c and d.

3 Operation of power converters

The proposed system consists of three types of power converters controlled by centralised controller. According to the requirement of power scenario, the controller generates required control signals for the respective power converter.

3.1 Operation of BDHC

The BDHC converter operates in three states as follows: (i) zero state condition, (ii) shoot through condition and (iii) power state condition. These conditions are illustrated in BDHC converter with direction of current flow in Fig. 3. Shoot through condition is obtained by turning on two switches of same leg of the full H-bridge topology ($G_1$–$G_4$). During this period, the inductor gets charged from DC bus and the DC output capacitor $C$ supplies power to the DC load. The diode $D$ is in off state and disconnects H-bridge from DC output capacitor. The AC output voltage is zero and AC current freewheels through the switches and diodes. Fig. 3a shows the schematic current flow diagram of shoot through condition.

In power state condition, the H-bridge of the BDHC operates as a conventional VSI. The inductor current gets distributed between AC and DC loads. The diode $D$ is in on state during this condition. The equivalent circuit of energy distribution is shown in Fig. 3b. To establish zero AC output state condition, all upper/lower switches of the inverter should be ON. In this state, the inductor discharges its stored energy to the DC load as well as DC capacitor through the diode $D$. Whereas AC output voltage is zero and AC current freewheels through the H-bridge diodes. The current flow diagram of zero state condition is shown in Fig. 3c.

3.2 Control algorithm for solar MPPT converter

The MPPT converter is a power electronic interface between the SPV array and DC bus. The MPPT converter controller executes two control algorithms according to operating modes. The first one is MPPT P&O control algorithm, which is used by the converter to extract maximum power from non-linear power characteristics of SPV array under different environmental conditions. The second algorithm is power reference algorithm, in which the controller extracts reference power from the SPV array. Fig. 4a shows the combined control logic for the MPPT converter in all operating modes. It can be seen from the schematic that when the PV power is greater than zero (day time) and ESD state of charge is defined in limit ($SOC_{upper} > SOC > SOC_{lower}$), the controller operates MPPT algorithm, and the maximum power point voltage ($V_{mpp}$) is calculated by two-step method to track the global maximum power. The calculated $V_{mpp}$ is compared with the actual PV voltage and the error is modulated through PI controller to generate switching pulses using triangular comparison method. If the ESD reaches to

![Block diagram representation of SPV system supplying AC and DC loads using the proposed single-stage BDHC](http://creativecommons.org/licenses/by-nc/3.0/)
its upper limit of SOC then the controller executes power reference algorithm with power reference equal to the total load power demand. Equation (1) represents the PV reference in power reference mode

\[
P_{PV\,ref} = P_{ac} + P_{dc}
\]  

3.3 Control algorithm for BDHC

A multi-output BDHC converter is utilised to convert input DC power into output DC and AC power, simultaneously. In modified unipolar PWM control algorithm, the shoot through signals are generated by comparing DC reference signals \( V_{ST} \) and \(-V_{ST} \) with carrier signal \( V_{tri} \) in positive and negative half cycles, respectively. A carrier-based PWM scheme is used to get switching pulses for AC output. When the carrier signal is greater than the AC reference modulation signal and less than shoot through signal, i.e. \(|V_m| < |V_{tri}| < |V_{ST}|\), the controller generates the signals for power state condition. As the required power is supplied by the SPV array and battery bank, the BDHC controller will work on same operating principle in all the modes. When there is insufficient power then the loads need to be reduced. Fig. 4b explains the modified unipolar PWM control algorithm for BDHC controller. The positive and negative references in the algorithm generate the switching pulses for the BDHC converter to give AC and DC outputs simultaneously from the input DC.
3.4 Control algorithm for non-isolated buck–boost converter

The charging and discharging of the battery is controlled by the non-isolated bidirectional DC–DC buck–boost converter. In MPPT mode, the battery will charge and the converter will work as buck converter. In battery supply mode, the battery converter acts as boost converter and discharges the required power. In power reference mode, the battery converter is in idle condition.

In all the modes, power reference to the battery is decided by the PV power and load demand. In order to increase the life cycle of the ESD, the controller enforces the battery to operate within SOC limits. Equation (2) represents the battery reference power in battery supply mode of the system. The control process to generate converter pulses is shown in Fig. 4c. In the charging state, the battery controller maintains the DC bus voltage and charges the ESD. Similarly, in discharging state, the battery controller extracts the reference power from the battery

\[ P_{B\text{ref}} = \begin{cases} 0, & \text{SOC} \geq \text{SOC}_{\text{upper}} \\ P_{\text{PV}} - P_{\text{ac}} - P_{\text{dc}}, & \text{SOC}_{\text{lower}} < \text{SOC} < \text{SOC}_{\text{upper}} \\ \end{cases} \]  

where \( P_{\text{PV}}, P_{\text{AC}}, P_{\text{DC}} \) are solar PV power, AC load power and DC load power, respectively. \( P_{B\text{ref}} \) and \( P_{\text{PVref}} \) are the reference powers for the battery controller and converter controller, respectively. The SOC is the state of charge of the battery and, \( \text{SOC}_{\text{upper}} \) and \( \text{SOC}_{\text{lower}} \) are the minimum and maximum limits of the SOC, respectively.

Table 1 explains the control logic implemented by the controllers in different modes. Real time variables from the system are feedback to the controller to generate power reference for the power converters.

The flow chart shown in Fig. 5 presents the mode selection algorithm for the power converters in the system to supply AC and DC loads. For reliable operation, the SOC of the battery bank is always monitored. The circuit parameters like solar PV power and DC and AC load powers, along with SOC of the battery decides the operating modes and generate the reference values for power converter controllers, in order to balance the power flow under all conditions.

From the flow chart, if solar PV power (\( P_{\text{PV}} \)) is more than the required load power (\( P_{\text{AC}} + P_{\text{DC}} \)) and battery SOC upper limit is reached, i.e. \( \text{SOC} \geq \text{SOC}_{\text{upper}} \), then battery will be in idle mode and PV operate in power reference mode. Similarly, if solar PV power (\( P_{\text{PV}} \)) is less than the required load power (\( P_{\text{AC}} + P_{\text{DC}} \)) and battery SOC lower limit is reached, i.e. \( \text{SOC} < \text{SOC}_{\text{lower}} \), then reduce the load to meet the solar PV power, otherwise if (\( \text{SOC} > \text{SOC}_{\text{lower}} \)), the battery supplies the deficient power to the loads. The upper and lower limits to the battery are provided to avoid the over-charging and deep-discharging conditions.

### Table 1: Controllers operation in different modes

| Mode          | Boost converter | BDHC input source | Buck–boost converter |
|---------------|-----------------|--------------------|---------------------|
| MPPT mode     | MPPT tracking   | SPV charge         | SPV idle state      |
| battery supply mode condition 1 | MPPT tracking | SPV + battery | discharge |
| battery supply mode condition 2 | idle state      | battery           | discharge |

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### 3.5 Comparison of the proposed system with conventional solar PV based DC nanogrid system

In the conventional solar PV based DC nanogrid system, the solar PV requires a DC/DC converter for MPPT [11, 14]. To supply the DC and AC loads it requires two separate DC/DC and DC/AC converters, respectively. Hence, the number of conversion stages and power electronic switches are more in the existing conventional DC nanogrids, and also the dead time requirement for the conventional VSI is necessary which will increase the complexity in the control algorithm. Whereas in the solar PV DC nanogrid system with the proposed BDHC, the number of conversion stages and power electronic switches will reduce, and the dead time circuit is no longer required. Therefore, the BDHC in
residential DC nanogrid system will reduce the conversion stages and complexity of the control algorithm. The comparison of the conventional solar PV based nanogrid system with the proposed solar PV based nanogrid system using BDHC is listed in Table 2.

### 4 Simulation results

The proposed control strategies and algorithms are verified using the PSCAD/EMTDC 4.5.1 ver software. The parameters of the proposed SPV system with battery bank are listed in Table 3. The total small household combined AC/DC load is considered 150 W. The SPV array operates, with 150 W output which is sum of AC and DC loads. From the simulation results it is observed that the solar PV maximum power is reduced when the radiation reduced to 500 W/m\(^2\). Under this condition, the solar PV array is considered 80%, the SPV array operates in power reference mode. When the battery bank is fully charged (or reached the specified limit of SOC), the controller of the solar boost converter implements the power reference mode. The reference power is calculated using (1), which is equal to the sum of the loads. The SPV array operates, with 150 W output which is sum of AC and DC loads. The DC bus voltage in every operating mode is shown in Fig. 7b. The zoomed view shows the state of charge of the battery. In MPPT mode, the solar PV operates at MPPT to feed the generated power to the DC bus of the system. The zoomed view shows the DC voltage is maintained constant in all the operating modes. The zoomed view of AC output in every operating mode is shown in Fig. 7b. The zoomed view shows the state of charge of the battery. In MPPT mode, the battery is charged through the extra power from the SPV array. When battery is fully charged, the battery will discharge to supply the loads and to maintain the DC bus voltage. In Fig. 7c at 2.5 s, the battery becomes fully charged, hence the power reference mode is on, and battery converter is in idle condition. At 5.0 s, the solar PV power is zero, therefore the battery supplies power to the BDHC converter.

### Table 3 Parameters of SPV system with battery bank

| Solar parameter | Radiation |
|-----------------|-----------|
| open circuit voltage (\(V_{oc}\)) | 27 V 26 V |
| short circuit current (\(I_{sc}\)) | 10 A 5 A |
| MPP voltage (\(V_{mpp}\)) | 21.6 V 21 V |
| MPP current (\(I_{mpp}\)) | 8 A 4 A |
| maximum power | 210 W 105 W |

| Other parameter | Value |
|-----------------|-------|
| battery | 12 V, 48 Ah |
| MPPT boost inductor (L) | 10 mH |
| DC link capacitor (C) | 2200 \(\mu\)F |
| battery converter inductor | 50 mH |
| switching frequency | 2000 Hz |

### Table 2 Comparison of the proposed system with conventional system

| S. No. | no. of switches | no. of converters | no. of conversion stages for loads | dead time requirement |
|--------|----------------|-------------------|-----------------------------------|----------------------|
| 1      | 6              | 3                 | 2                                 | yes                  |
| 2      | 3              | 2                 | 1                                 | no                   |

Fig. 5 Flow chart for selection of operating modes with the generation of reference value of power

Fig. 6 shows the simulated waveforms of \(I-V\) and \(P-V\) curves of SPV array and power tracking in different operating conditions. The MPPT algorithm tracks the maximum power from the SPV array under STC (1000 W/m\(^2\), 25°C). The zoomed view shows the tracking of actual solar PV power with peak value of characteristics. The SPV array is operating at MPP with 200 W of output power in MPPT mode.

When the battery bank is fully charged (or reached the specified limit of SOC), the controller of the solar boost converter implements the power reference mode algorithm. The reference power is calculated using (1), which is equal to the sum of the loads. The SPV array operates, with 150 W output which is sum of AC and DC loads. From the simulation results it is observed that the maximum power of the SPV array is 200 W, but because of power reference algorithm implementation, the SPV system is operating at 150 W. Fig. 6b illustrates the solar boost converter result, tracking 150 W power from the SPV array, depicted in \(P-V\) characteristics plot. The SPV array maximum power is decreased when the radiation reduced to 500 W/m\(^2\). The zoomed view shows the state of charge of the battery. The DC voltage is maintained constant in all the operating modes. The zoomed view shows the state of charge of the battery. In MPPT mode, the solar PV operates at MPPT to feed the generated power to the DC bus of the system. The zoomed view shows the state of charge of the battery. The DC bus voltage in every operating mode is shown in Fig. 7b. The zoomed view shows the state of charge of the battery. In MPPT mode, the battery is charged through the extra power from the SPV array. When battery is fully charged, the battery will discharge to supply the loads and to maintain the DC bus voltage. In Fig. 7c at 2.5 s, the battery becomes fully charged, hence the power reference mode is on, and battery converter is in idle condition. At 5.0 s, the solar PV power is zero, therefore the battery supplies power to the BDHC converter.
Fig. 7 shows the power balance of the SPV system in three different modes. In the MPPT mode, the solar PV operates at MPP with 200 W of power and supplies to the AC and DC loads (150 W), as well as battery banks (50 W). In power reference mode (2.5–5.0 s), the battery reaches to its maximum SOC limit, so the SPV system supply power to the AC as well as DC loads. In battery supply mode, the solar PV supplies no power hence only the battery supply power to the BDHC converter.

5 Experimental results

To validate the proposed control algorithm, a laboratory experimental prototype is developed. Agilent E4260 SAS (solar array simulator) is used as solar PV array. For battery backup, 12 V, 7 Ah batteries are used. Fig. 8 shows the laboratory prototype of the system. The IGBT based intelligent power module is used for power converter circuit to control the PV system. NI 7832R FPGA controller is used to implement the design algorithms and generate the pulses according to the operating modes. SCB-68 is used to supply gate signals to the power converters driver board. For MPPT, the input current and voltage of the SAS are monitored by

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**Table 4. Parameters of BDHC converter**

| Parameter       | Value      |
|-----------------|------------|
| input inductor  | 10 mH      |
| DC capacitor    | 1000 µF    |
| AC inductor 1   | 250 µH     |
| AC inductor 2   | 250 µH     |
| DC load         | 130 W      |
| AC load         | 20 W       |
| switching frequency | 2000 Hz  |

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Fig. 7d shows the power balance of the SPV system in three different modes. In the MPPT mode, the solar PV operates at MPP with 200 W of power and supplies to the AC and DC loads (150 W), as well as battery banks (50 W). In power reference mode (2.5–5.0 s), the battery reaches to its maximum SOC limit, so the SPV system supply power to the AC as well as DC loads. In battery supply mode, the solar PV supplies no power hence only the battery supply power to the BDHC converter.
the voltage and current sensors and given to the controller through analogue input pins. Table 4 describes the power circuit parameters.

Fig. 9 represents the \( P-V \) characteristics of SPV array used for the experimental validation and maximum power tracking from the SPV array characteristics using power reference based algorithm in MPPT mode as well as power reference mode. The cross point (×) represents the operating point of the SPV array. In MPPT mode, solar PV is operating at 200 W (maximum power of SPV characteristics) and supply to the loads. In power reference mode, the solar simulator is operating at 150 W which is equal to the load power.

Figs. 10a and b illustrate the PWM scheme of the BDHC converter. In general, the switches in the same leg of the H-bridge inverter are complementary. But in the BDHC converter it is in shoot through condition, i.e. the two switches may be on. From the switching pattern it is observed that in positive half cycle, the reference signal switches on S1 and S3, and switch S4 generate the shoot through mode. Similarly in negative half cycle, reference signal switches S2 and S4 on, and switch S2 generates the shoot through mode.

By using the power reference control algorithm along with the integration of battery storage device, the DC bus output voltage is maintained as constant in all possible operating modes. With constant 24 V DC bus as input, the single-stage hybrid converter supply to both AC and DC loads, simultaneously.

Fig. 11a shows the DC link capacitor voltage which is constant at 24 V. Fig. 11b shows the simultaneous AC and DC outputs of the BDHC converter with 24 V DC bus input. From the results it is observed that the DC output voltage is increased to 48 V and it acts as the input to the AC load. So, the peak value of the AC three-level output is equal to the DC output voltage which is equal to 48 V. Fig. 11c shows the AC and DC load voltages of the BDHC with resistive type of load. To understand the operation of the BDHC with non-linear load, a programmable AC/DC electronic load [Model 63802 (Chroma)] is used as AC non-linear load. The output waveforms of BDHC with non-linear AC load are shown in Fig. 11d.

The input source of the BDHC feed the AC load through the H-bridge of the hybrid converter and the AC filter. Simultaneously, it feeds the DC load through the diode and DC capacitor. It can be observed that the input current is divided between the H-bridge and the diode in different operating intervals of the BDHC. The sum of the H-bridge current and diode current is equal to the input inductor current. In the operating condition of BDHC shown in Fig. 3a, the complete input current is passed through the H-bridge. As shown in Fig. 3b, the input source current is divided between the diode and H-bridge, and in Fig. 3c the complete current is passed through the diode. Therefore, the H-bridge current and diode currents become discontinuous as shown in Figs. 12b and c. A step-up transformer can be used across the AC output to supply the common AC loads rated at distribution system voltage levels.

6 Conclusions

In this paper, a solar PV system integrated with battery energy storage feeds the 24 V DC nanogrid for small residential AC and DC hybrid loads. A power reference algorithm is proposed and implemented through the boost DC–DC converter for energy conversion from solar PV efficiently in different operating conditions. A modified unipolar SPWM method is implemented in single-stage hybrid BDHC converter for feeding power to the AC and DC loads, simultaneously. The battery storage system is controlled by non-isolated buck–boost converter using current and voltage control algorithms, in charging and discharging modes, respectively, for better reliability of the system. The operation of the proposed solar PV integrated battery storage system with single-stage BDHC hybrid converter is illustrated through the simulation results. A laboratory prototype of the system has been developed to verify the proposed system using LabVIEW FPGA digital controller. The proposed system has wider applicability in off-grid small residential loads.
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Fig. 11 Experimental waveforms
(a) DC link capacitor voltage,
(b) H-bridge output and DC output,
(c) AC and DC load waveforms for resistive load,
(d) AC and DC load waveforms for non-linear load

Fig. 12 Experimental waveforms
(a) Input inductor current,
(b) Current through H-bridge,
(c) Current through diode

DC micro grid system for future residential–rural electrification (no.24/20/2015-SWES (R&D)), is acknowledged.

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