A novel tri-capacity battery charger topology for low-voltage DC residential nanogrid

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Abstract
This study communicates a single-stage, 3-ɸ, rooftop solar photo voltaic (PV) and grid compatible tri-capacity battery charger (TBC) topology for a home-based low voltage direct current nanogrid (LVDC NG). The proposed architecture performs power factor correction drawing sinusoidal grid currents at unity power factor, single-stage rectification of 3-ɸ grid voltages and constant current mode battery charging simultaneously. The employed control scheme is experimentally validated on a 120 W scaled-down hardware prototype energising three lead-acid-based battery energy storage system (BESS) of nominal voltages 48/36/24 V and capacities 28/21/14 Ah, respectively. The obtained results affirm the effective operation of the LVDC NG under islanded/grid-to-battery and battery-to-grid modes. Further, an extension to the proposed work where the TBC functions charging a single BESS is put forward and validated adding merit to the proposed work.

1 | INTRODUCTION

With the uprising trend for direct current (DC) power consumption and tremendous technological development in solid-state power electronic components, DC distribution is gaining much focus and attention [1–6]. Distribution network operating on DC is reported to function at an improved efficiency (above 90%) [7], exhibit better stability with the absence of reactive elements and employs minimum converters between renewable sources and grid/loads. The nominal voltage level for the residential DC systems is proclaimed to be 48 V, as it is safe and harmless to humans even under direct contact [8]. Furthermore, it is reported that DC distribution offers nearly 15%–22% higher operating efficiency when compared to the conventional alternating current (AC) distribution system.

With electric vehicles (EVs) evolving as suitable alternatives to internal combustion engine vehicles [9, 10], it can be considered as special residential DC loads with charging mostly occurring at night-time at homes where EV could be plugged into the residential DC outlet for slow charging. Expecting huge deployment of EVs on the distribution network soon, various studies on charging topologies and control algorithms are being carried out [11–16].

A single-stage resonant charging topology for batteries with inherent power factor correction (PFC) is reported in [17]. However, with four diode bridge rectifier (DBR) units, the circuit design is complex. The authors in [18] present 1-ɸ unidirectional EV charger with a front-end PFC DC/DC stage, but the topology operates in discontinuous current conduction mode. A bidirectional 1-ɸ AC/DC converter for EV charging is proposed in [19], which consists of a half-bridge current source converter on the input side connected to a high-frequency transformer followed by the full-bridge converter (FBC). Though the proposed topology achieves soft switching without any additional component, the topology involves significant control and design complexity. A zero-voltage switching-based isolated DC/DC FBC is proposed in [20]. However, the circuit needs an additional front-end 1-ɸ AC/DC PFC boost converter and electromagnetic interference filter for functioning as an EV charger. A conventional phase-shift operated FBC connected to a full-bridge rectifier is proposed in [21], and an inductor-inductor-capacitor-based series resonant converter is reported in [22]. However, these topologies exhibit significant conduction loss due to the circulating current. Hence, a hybrid-type converter derived from the above converters is reported in [23–25]. However, the circuit part count is high. The authors in [26] present a pulse width modulation (PWM)-based resonant
FIGURE 1 Comparison of the proposed work with other literature findings

converter for onboard EV charging. However, the reported topology always operates under buck mode, thereby making it difficult to achieve battery discharge over the entire voltage range. A buck-boost-based cascaded converter topology proposed [27] for onboard EV charging consists of a buck and boost poles. However, the proposed control algorithm adds complexity, as each switch of the circuitry is controlled based on the input and output voltage relationship. A closed-loop bidirectional buck-boost DC/DC converter topology with an adaptive controller to minimise load shedding impacts and for improving power quality in an EV charging lot is proposed in [28]. The proposed topology, however, involves multiple converter stages leading to low efficiency. The authors in [29] report a modified Z-source-based EV charger with reduced power conversion stages. Although the proposed converter is a single-stage solar and grid compatible structure, the topology does not possess inherent PFC capability. A dual-stage EV charger with a front-end AC/DC stage consisting of two full-bridge voltage source converters (VSCs), cascaded to a bidirectional three-level asymmetrical VSC is proposed in [30]. Other popular reported EV charging topologies include a full-bridge DC/DC converter with interleaved boost stage [31], a dual active bridge converter cascaded to a front-end VSC [32, 33], modular multilevel topology [34] and so forth.

Though a wide variety of EV chargers are extensively discussed in the literature, low voltage DC nanogrid (LVDC NG)-based EV chargers are not reported. LVDC NG can be considered as an outcome of a bottom-up approach, more suited to remote and rural areas with preference to DC technology [35]. A concise definition of the NG is presented in [36] as a power distribution system for a small building/single house that can connect/disconnect from other power structures or grid through a gateway. Hence, an attempt has been made to develop a residential DC NG architecture for charging EVs and supplying DC loads. The proposed home-based tri-capacity battery charger (TBC) can be operated either as a 1-φ/3-φ system during grid-tied mode with inherent PFC or as a DC/DC converter system for power transfer while integrating solar PV array to the DC NG. The proposed system is devoid of a DBR unit and has a single boost inductor and output capacitor across each phase and provides boost/buck operation. A simple reconfigurable current control mechanism is also proposed. This design leads to less circuit and control complexity. Figure 1 projects the merits by comparing the part count and capabilities of the proposed TBC with EV charging topologies discussed in the literature and Table 1 presents the in-detail part count of the various topologies.

The study is organised as follows. Section 2 discusses the structure of the proposed rooftop LVDC residential NG. To predetermine the performance, mathematical models involved in developing the NG system are detailed in Section 3. Description of the control scheme is discussed in Section 4. Simulation and experimental results are presented in Sections 5 and 6, respectively. Section 7 concludes the study.

2 | SYSTEM DESCRIPTION

The design of a rooftop solar PV and grid compatible LVDC NG system for a single residential building is communicated in this study. The proposed LVDC NG system simultaneously performs PFC, single-stage rectification of 3-φ grid voltages and
TABLE 1 Comparison of the proposed tri-capacity battery charger with other topologies

| Reference topology | No. of stages | Power factor correction | No. of passive components | No. of semiconductor switches | No. of diode bridge rectifier circuits | SolarPV compatible | Battery-to-grid mode |
|-------------------|---------------|-------------------------|---------------------------|-------------------------------|---------------------------------------|-------------------|---------------------|
| Proposed          | 1             | ✓                       | 2                         | 4                            | √−                                    | ✓                 | ✓                   |
| 17                | 1             | ✓                       | 5                         | 6                            | 4                                     | x                 | x                   |
| 18                | 2             | ✓                       | 9                         | 6                            | 1                                     | x                 | x                   |
| 19                | 1             | ✓                       | 4                         | 8                            | −                                     | x                 | √                   |
| 20                | 2             | ✓                       | 10                        | 4                            | 1                                     | x                 | x                   |
| 21                | 2             | x                       | 6                         | 4                            | 1                                     | x                 | x                   |
| 22                | 2             | ✓                       | 6                         | 6                            | 2                                     | x                 | x                   |
| 23                | 2             | x                       | 6                         | 4                            | 1                                     | x                 | x                   |
| 24                | 2             | x                       | 6                         | 4                            | 1                                     | x                 | x                   |
| 25                | 2             | x                       | 7                         | 4                            | −                                     | x                 | x                   |
| 26                | 2             | x                       | 4                         | 8                            | −                                     | x                 | √                   |
| 27                | 2             | x                       | 5                         | 9                            | 1                                     | x                 | x                   |
| 28                | 1             | ✓                       | 6                         | 8                            | √−                                    | √                 | √                   |
| 29                | 2             | ✓                       | 7                         | 12                           | −                                     | √                 | x                   |
| 30                | 2             | ✓                       | 11                        | 15                           | −                                     | x                 | x                   |
| 31                | 2             | x                       | 6                         | 6                            | 2                                     | x                 | x                   |
| 32                | 1             | ✓                       | 3                         | 12                           | −                                     | x                 | x                   |
| 33                | 1             | ✓                       | 3                         | 12                           | −                                     | x                 | x                   |
| 34                | 1             | x                       | 6                         | 10                           | −                                     | x                 | x                   |

constant current (CC) charging of battery energy storage system (BESS). Figure 2(a) shows the proposed schema, which includes three low power rooftop solar PV arrays, three 1-Φ PWM modular boost rectifiers (PMBR), and three lead-acid-based BESS. The present work analyses the operation of the LVDC NG operating compatible with both solar PV or with grid supply, powering EV and residential DC loads through three bidirectional PMBR interface converter units. The proposed LVDC NG structure extracts solar power during the daytime, and during erratic solar power availability/night-time, it operates under grid-connected mode. In this work, the DC NG architecture is supported by three modular 0.5 kW solar panels. The DC NG loads are either 48/36/24 V energy-efficient electrical household appliances energised by three lead-acid-based BESS.

During the daytime, the solar PV-generated power charges the BESS through three modular PMBR operating as a DC-DC boost converter under CC charging mode. During nighttime/non-availability of solar PV power, the BESS charges through grid supply with the PMBR operating as a PFC rectifier drawing grid currents at unity power factor (UPF). The present study explores the dynamic operation of the proposed system under islanded/grid-to-battery (G2B) and battery-to-grid (B2G) modes. Further, an extension to the proposed work where the TBC functions charging a single BESS is put forward and validated adding merit to the proposed work. The topology includes two mode selector switches: Switch ‘S1’ to effect either grid-connected/islanded mode of operation and switch ‘S2’ to toggle between single/three BESS mode. The operation of the proposed TBC is experimentally validated on a scaled-down hardware prototype of 120 W energising three lead-acid-based BESS of capacities 28/21/14 Ah, respectively.

3 | MATHEMATICAL MODELLING OF NG COMPONENTS

The various subsystems are mathematically modelled to analyse the performance of the overall system. The corresponding electrical equivalent circuit of the proposed DC NG is shown in Figure 2(b). All equations mentioned in the mathematical modelling are for 1-Φ system. As the proposed topology is 3-Φ, four wire system at each phase operates independently during G2B/B2G and islanded modes with the effected modular control scheme.

3.1 | Modelling of the solar PV array

The $I_{P-I}$-$V_{P-I}$ curve of a practical single-diode solar PV cell model is adopted from [37] and is given by Equation (1):

$$I_{P-I} = I_{sh} - I_0 \left[ \exp \left( \frac{V_{P-I} + R_s I_{P-I}}{a V_T} \right) - 1 \right] - \frac{V_{P-I} + R_s I_{P-I}}{R_p}$$

(1)
FIGURE 2  low voltage direct current nanogrid (LVDC NG) architecture (a) proposed LVDC DC NG system schema, (b) electrical equivalent circuit diagram of the proposed DC NG

FIGURE 3  Performance graphs of the proposed tri-capacity battery charger topology (a) variation of grid currents, (b) variation of battery energy storage system (BESS) currents, and (c) variation of BESS voltages
where $i_{all}$ is PV-generated current; $I_D$ is saturation current; $V_J$ is thermal voltage of the solar PV array; $a$ is diode ideality constant; $R_s,R_p$ is equivalent series and parallel resistance, respectively. This model accurately operates in response to the irradiation and temperature changes in a day and can be modelled with fewer design parameters. Each 0.5 kW solar PV array has five 0.1 kW parallel-connected modules with an open-circuit voltage of 22 V and a short-circuit current of 5.92 A under standard irradiation and temperature test conditions of 1000 W/m² and 25°C, respectively.

### 3.2 Modelling of PMBR

To effect modelling of the PMBR module, the following assumptions are made.

1. The capacitor is large enough to allow the voltage across the capacitor to be approximately constant during one switching period.
2. All switches and reactive elements are ideal.

With 3Φ four-wire topology, each PMBR module functions independently as a 1Φ PFC boost rectifier. With three BESS, the individual converter current and voltage equations can be expressed as in Equations (2) to (7):

\[
\frac{di_{PMBR}}{dt} = \frac{v_n}{L_1} - \frac{V_{BEES}}{2L_1} (u_1 - u_2) \tag{2}
\]

\[
\frac{di_{PMBR}}{dt} = \frac{v_n}{L_2} - \frac{V_{BEES}}{2L_2} (u_1 - u_2) \tag{3}
\]

\[
\frac{di_{PMBR}}{dt} = \frac{v_b}{L_3} - \frac{V_{BEES}}{2L_3} (u_1 - u_2) \tag{4}
\]

\[
\frac{dV_{BEES}}{dt} = -\frac{1}{C_{DC}} \left[ i_{PMBR} u_1 - i_{PMBR} u_2 - \frac{V_{BEES}}{R_{BEES}} \right] \tag{5}
\]

\[
\frac{dV_{BEES}}{dt} = -\frac{1}{C_{DC}} \left[ i_{PMBR} u_1 - i_{PMBR} u_2 - \frac{V_{BEES}}{R_{BEES}} \right] \tag{6}
\]

\[
\frac{dV_{BEES}}{dt} = -\frac{1}{C_{DC}} \left[ i_{PMBR} u_1 - i_{PMBR} u_2 - \frac{V_{BEES}}{R_{BEES}} \right] \tag{7}
\]

where $v_n$, $v_b$, and $i_{PMBR}$, $i_{PMBR}$, $i_{PMBR}$ are the instantaneous grid voltages and grid currents, respectively; $V_{BEES}$ and $R_{BEES(i = 1,2,3)}$ are the terminal voltages and internal resistances of the BESS connected across the three phases; $I_{D(i = 1,2,3)}$ is the source inductance; $u_1$, $u_2$, $u_3$ (0 or 1) represent the logic state of the switches in the first and second legs of PMBR, respectively; switches in a single leg work complementarily. $C_{DC(i = 1,2,3)}$ are the capacitive filters connected at the output end of the corresponding PMBR units. Under single BESS mode, each PMBR module functions independently to charge the single BESS through a common capacitor $C_{DC}$ where $V_{BEES_1} = V_{BEES_2} = V_{BEES_3} = V_{BEES}$.

### 3.3 Modelling of BESS

The dynamics of the lead-acid BESS is adopted from [38] and is given by Equations (8) to (10):

\[
\frac{dS_{CBESS1}}{dt} = \frac{1}{C_{BEES1}} \left[ \frac{S_{CBESS1}}{R_{BEES1}} - I_{BEES1} \right] \tag{8}
\]

\[
\frac{dS_{CBESS2}}{dt} = \frac{1}{C_{BEES2}} \left[ \frac{S_{CBESS2}}{R_{BEES2}} - I_{BEES2} \right] \tag{9}
\]

\[
\frac{dS_{CBESS3}}{dt} = \frac{1}{C_{BEES3}} \left[ \frac{S_{CBESS3}}{R_{BEES3}} - I_{BEES3} \right] \tag{10}
\]

where $I_{BEES}$ and $S_{CBESS(i = 1,2,3)}$ represent the current and state of charge of the corresponding BESS; $C_{BEES(i = 1,2,3)}$ is the internal capacitance of the BESS. This simplified model accurately depicts the dynamic behaviour of the lead-acid battery and further neglects temperature and ageing effects, which do not have significant consequences in the operation of low power rated BESS. Under single BESS mode, with a single capacitor and a single battery $S_{CBESS1} = S_{CBESS2} = S_{CBESS3} = S_{CBESS}$.

### 3.4 Performance predetermination of the proposed TBC

The performance predetermination of the topology is carried out in MATLAB/Simulink environment using the above-developed mathematical models to analyse the operation of the proposed TBC over the entire load range. By varying the set reference BESS charging current, the corresponding behaviours of the TBC are noted down and sketched as shown in Figures 3(a)
FIGURE 5  Simulation results under islanded mode (a) solar PV irradiation and output voltage, (b) BESS1 voltage and current, (c) BESS2 voltage and current, and (d) BESS3 voltage and current.

FIGURE 6  Simulation results under grid-to-battery (G2B) mode (a) grid voltages, (b) grid currents.

to (c). Figures 3(a) and (b) show the drawn grid currents and corresponding BESS currents according to the set reference current. The actual grid currents drawn increase correspondingly with the increase in set reference charging current in concurrence with the employed control scheme. Figure 3(c) shows the voltages of the three BESS for the operating power range from 0.1 to 1 kW.

4  DESCRIPTION OF CONTROL SCHEME

A modular control scheme supporting the various modes of operation is envisaged for the proposed LVDC NG and is presented in Figure 4. The employed PMBR unit acts as an interface between the BESS, DC loads and the solar PV/grid.
FIGURE 7  Simulation results under G2B mode (a) \textit{r}' in-phase grid voltage and current, (b) \textit{BESS_1} voltage and current, (c) \textit{BESS_2} voltage and current, and (d) \textit{BESS_3} voltage and current

FIGURE 8  Simulation results under battery-to-grid (B2G) mode (a) \textit{r}' out-of-phase grid voltage and current, (b) \textit{BESS_1} voltage and current, (c) \textit{BESS_2} voltage and current, and (d) \textit{BESS_3} voltage and current
supply, operating as a DC-DC boost converter during the islanded mode, as a PFC boost rectifier during G2B mode and as a PFC buck inverter during B2G mode.

### 4.1 Control scheme for PMBR under mode-1 (islanded mode)

Under islanded mode, the switches $S_{2i}$ ($i = r, y, b$) in the corresponding phases are operated with each PMBR operating as a DC-DC boost converter transferring the PV-generated power to the three BESS. The control mechanism involves a proportional integral (PI) controller and PWM technique to regulate the BESS current in accordance with the reference value, thereby effecting the CC charging of BESS.

### 4.2 Control scheme for PMBR under mode-2 (G2B mode)

Under this mode, each PMBR module functions as a 1-Φ PFC boost rectifier transferring the grid power to the three BESS. The modular independent control effects CC charging of the BESS, drawing sinusoidal grid currents at UPF in the individual phases. The 3-Φ grid currents remain unbalanced owing to the different BESS capacities connected at the back end (28/21/14 Ah). For CC charging, the reference currents are generated with the required BESS charging current ($I_{\text{BESS}_{ref}}$), grid voltage and phase angle information ($V_{mi}, \sin \omega t_i$) as in Equations (11) to (13):

\[
i_{rPMBR}^* = \frac{2 \left( I_{\text{BESS}_{ref}} + V_{\text{BESS}1} \right)}{V_{mr}} \left( \sin \omega t_r \right) \quad (11)
\]
\[
i_{yPMBR}^* = \frac{2 \left( I_{\text{BESS}_{ref}} + V_{\text{BESS}2} \right)}{V_{my}} \left( \sin \omega t_y \right) \quad (12)
\]
\[
i_{bPMBR}^* = \frac{2 \left( I_{\text{BESS}_{ref}} + V_{\text{BESS}3} \right)}{V_{mb}} \left( \sin \omega t_b \right) \quad (13)
\]

The generated reference currents are compared with the actual converter currents and the current error is compared with a high-frequency carrier signal of 5 kHz that generates gate pulses for the corresponding PMBR units.

Under single BESS G2B mode, the same modular control is affected ($V_{\text{BESS}_1} = V_{\text{BESS}_2} = V_{\text{BESS}_3} = V_{\text{BESS}}$). With a common capacitor at the back end, the PMBR modules function independently to charge the single BESS drawing balanced sinusoidal grid currents at UPF.
4.3 | Control scheme for PMBR under mode-3 (B2G mode)

In grid-tied mode under the absence of EV and other DC NG loads, the BESS power can be exported back to the grid. Each PMBR module functions as a 1-Φ PFC buck inverter, and the modular control scheme effects BESS power export to the grid through all three phases. The reference currents are generated with the available BESS power \( P_{\text{BESS}} \) and grid phase angle information as in Equations (14) to (16).

\[
\begin{align*}
    i_{rPMBR}^* &= \frac{2 \ P_{\text{BESS}1}}{V_{mr}} \sin(wt_r) \\
    i_{yPMBR}^* &= \frac{2 \ P_{\text{BESS}2}}{V_{my}} \sin(wt_y) \\
    i_{bPMBR}^* &= \frac{2 \ P_{\text{BESS}3}}{V_{mb}} \sin(wt_b)
\end{align*}
\]

5 | SIMULATION RESULTS

The simulation is carried out in MATLAB/Simulink environment and the detailed system parameters used for simulation are shown in Table 2.

5.1 | Mode-1 (islanded mode)

The operation of the proposed TBC under islanded mode is tested under irradiation of 300 W/m². The corresponding PV array output voltage is 20 V as seen in Figure 5(a). The switches \( S_{2i} \) \( (i = r, y, b) \) in the corresponding phases are operated in this mode with each PMBR operating as a DC-DC boost converter transferring the PV-generated power to the three BESS. The charging curves of the three BESS are shown in Figures 5(b) to (d). The set reference current for the three BESS is 2 A and the employed modular control successfully regulates the battery currents to 2 A in all three phases. Figure 5(b) shows the battery voltage (48 V) and current (2 A*10 = 20 A) of BESS1. (The battery current is multiplied by a scale of 10 for visibility).

5.2 | Mode-2 (G2B mode)

Under this mode, each PMBR module functions as a 1-Φ PFC boost rectifier transferring the grid power to the three BESS. With the employed modular control scheme, the topology effects UPF operation in the individual phases but draws unbalanced grid currents corresponding to the connected different battery capacities (28/21/14 Ah). The corresponding grid voltages and currents are shown in Figures 6(a) and (b). The ‘r’ phase voltage and current shown in Figure 7(a) illustrates UPF operation. The BESS curves with the reference current set to 2 A are shown in Figures 7(b) to (d).

5.3 | Mode-3 (B2G mode)

Under this mode, each PMBR module functions as a 1-Φ PFC buck inverter transferring the BESS power to the grid. With modular control effected along the three phases and with different connected battery capacities, the topology effects BESS power export to the grid at UPF. The corresponding ‘r’ phase UPF operation with the voltage and current out-of-phase are shown in Figure 8(a). The BESS curves with the reference current set to 2 A are shown in Figures 8(b) to (d).
Mode-4 (G2B single BESS mode)

This mode is put forward as an extension of the proposed TBC topology. Under G2B single BESS mode (Figure 2(b)-dotted), the circuit is reconfigured to charge a single BESS through a common capacitive filter $C_{DC}$. This mode can be evoked either to charge a single higher capacity BESS or to achieve fast charging where the three PMBR modules function independently to charge the single BESS. With the effected modular control along the three phases and with a single connected battery (48 V 28 Ah—used for simulation and hardware), the topology effects UPF operation drawing sinusoidal balanced grid currents. The corresponding grid voltages and currents are shown in Figures 9(a) and (b). The battery curves are shown in Figure 9(c).

Figure 10 (a) to (c) represents power flow diagrams during the different modes of operation. Since PMBR operation is identical in all three phases, the power flow diagrams are shown along a single phase for each mode.

6 HARDWARE RESULTS

The experimental validation of the proposed TBC topology is carried out on a 120 W scaled-down hardware prototype energising three 12 V, 7 Ah series-connected lead-acid BESS of
nominal voltages 48/36/24 V. The setup is powered through a solar PV simulator during islanded mode and with a 3-phase auto-transformer with an output phase voltage of 15 V (rms) in grid-connected mode. Three Microchip dsPIC30F4011 micro-controllers are employed for realising the G2B/B2G control schemes separately for individual phases. LEM LV-25P and LA-20A hall-effect transducers sense the grid/BESS voltage and grid/BESS currents, respectively. The observed results captured on a two-channel digital storage oscilloscope (DSO) prove the effective functioning of the proposed system under islanded/G2B/B2G modes.

6.1 Mode-1 (islanded mode)

The solar simulator is set to emulate the test conditions of 300 W/m² at 25°C. The corresponding simulator output voltage according to the $IPV_{VPV}$ characteristic curve is 20 V as seen in Figure 11(a). A reference current of 0.2 A is set to verify the CC charging of the BESS during the islanded mode. The battery currents are seen to settle at 0.2 A, and the corresponding BESS curves are shown through Figures 11(b) to (d).

6.2 Mode-2 (G2B mode)

G2B mode is tested by supplying power from a 3-phase auto-transformer with 15 V (rms) as input to the three phases. A reference current of 0.2 A is set to verify the CC charging of the BESS during G2B mode. The employed modular control regulates the BESS current to 0.2 A in each phase and simultaneously effects UPF operation in the individual phases. The corresponding $r^\prime$ and $y^\prime$ phase grid voltages and currents captured on a two-channel DSO are shown in Figures 12(a) and (b), respectively.

6.3 Mode-3 (B2G mode)

Under B2G mode, the dsPIC30F4011 microcontrollers are flashed with the proposed control scheme with $IBESS_{ref}$ set to –0.2 A for each phase, and the operation of the PMBR modules is verified. The corresponding $r^\prime$ phase grid voltage out-of-phase with current can be verified through Figure 14(a), and the corresponding CC discharging of the three BESS can be verified through Figures 14(b) to (d).

6.4 Mode-4 (G2B single BESS mode)

The CC charging operation of the proposed TBC extension topology where the three PMBR modules charges a single BESS connected through a common capacitive filter $C_{DC}$ is validated.
FIGURE 14  Experimental results under B2G mode (a) $r'$ out-of-phase grid voltage and current, (b) BESS$_1$ voltage and current, (c) BESS$_2$ voltage and current, and (d) BESS$_3$ voltage and current

FIGURE 15  Experimental results under G2B single BESS mode (a) grid voltages, (b) grid currents, (c) $r'$ in-phase grid voltage and current, and (d) single BESS voltage and current
with 15 V (rms) input supply from a 3-φ auto-transformer, and the BESS reference current set to 0.3 A with each phase contributing 0.1 A to the BESS. The results observed are presented in Figure 15. Figures 15(a) and (b) show the corresponding grid voltages and currents of ‘r’ and ‘y’ phases, respectively. Figure 15(c) verifies the ‘r’ phase UPF operation, and Figure 15(d) shows the corresponding battery curves under G2B mode. The photograph of the hardware setup is attached for reference (Figure 16).

Thus, the operation of the proposed TBC topology under different modes is verified experimentally, and the results obtained are found analogous to the simulation results.

7 CONCLUSION

Thus, this study puts forth a single-stage solar PV and grid compatible LVDC residential DC loads/EV charging TBC topology in a home-based DC NG architecture with a simple control algorithm. The proposed architecture is suited to residential DC voltage levels of 48/36/24 V and can also be modified to operate at higher DC voltage levels up to 450 V for commercial EV charging stations. The proposed system functions drawing sinusoidal grid currents at UPF in both G2B and B2G modes, thereby ensuring low distortion of distribution network grid voltages, mitigating voltage fluctuations and power quality problems particularly considering the mass charging of EV occurring simultaneously at different households. Further, an extension to the reported work, where the TBC functions charging a single BESS, is put forward and validated adding merit to the proposed work. The results obtained through experimental validation on a scaled-down hardware prototype of 120 W energising three lead-acid-based BESS of capacities 28/21/14 Ah affirm the effective operation of the proposed TBC.

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APPENDIX A
Specifications of the solar PV array
(i) Model–12 V 100 W
(ii) Wattage–0.1 kW
(iii) Voltage at maximum power–18.2 V
(iv) Open-circuit voltage–22 V
(v) Current at maximum power–5.5 A
(vi) Short-circuit current–5.92 A
(vii) Number of series and parallel connected panels in 0.5 kW PV array = 1 and 5

Parametric design specifications of pulse width modulation modular boost rectifiers
Considering $V_{pk} = 15\sqrt{2}V$; $V_o = 48 V$; $f_s = 5 kHz$;
$P_o = 120 W$;$\Delta i = 3$; $\Delta v = 3$; $M = \frac{15\sqrt{2}}{48} = 0.4419$; $\delta = 1 - M = 0.5580$;
$L = \frac{V_{pk} (1 - M)}{2 f_s \Delta i M} = 1.1 \approx 1 mH$
$C = \frac{P_o}{2\pi f_s V_o \Delta v} = 26.5 \approx 30 \mu F$

Battery energy storage system (BESS) specifications
(i) BESS1–4 series 12 V 7 Ah lead-acid batteries.
(ii) BESS2–3 series 12 V 7 Ah lead-acid batteries.
(iii) BESS3–2 series 12 V 7 Ah lead-acid batteries.

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