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An Isolated Multiport Bidirectional DC-DC Converter for PV-Battery-DC Microgrid Applications

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Abstract—This paper proposes a new isolated, multiport, bidirectional DC-DC converter with the least number of switches for photovoltaic (PV)-battery-DC microgrid applications. The proposed converter is able to perform the maximum power point tracking (MPPT) control for the PV system when solar energy is available as well as control the charge and discharge of the battery with the PV system and the DC microgrid. Simulation and experimental studies are carried out and validate the proposed converter for simultaneous power management of a PV-battery system connected to a DC microgrid.

I. INTRODUCTION

Microgrids are becoming a promising technology for integrating distributed renewable energy systems and energy storage systems [1]. To integrate various renewable energy sources, such as photovoltaic (PV) systems and wind energy systems, and energy storage systems, such as batteries, into a microgrid, either a multiport converter for connecting multiple sources or an individual converter for each source can be used. A multiport converter is preferable to connect multiple sources to the grid or load due to their lower cost and higher power density.

A number of multiport converters have been proposed for renewable energy systems [2]-[9]. The multiport converter topologies can be classified into two categories: nonisolated topologies and isolated topologies. Nonisolated multiport converters are usually used in the applications which do not require galvanic isolation. In contrast, an isolated converter which contains a transformer is preferred for the applications which require galvanic isolation between the energy sources and the grid or load.

At some sites which are connected to a weak power grid or have no access to a power grid, renewable energy sources and energy storage systems are commonly used together. In

this case, a multiport bidirectional converter is preferable. The commonly used isolated multiport bidirectional DC-DC converters (BDCs) includes full-bridge [6] and half-bridge [7] topologies, which use two and four controllable switches for each port, respectively. However, the battery in [7] and [8] had to be charged and discharged within a switching period, i.e., the battery had to be charged and discharged with a high frequency, which is not desired from the perspective of the battery life. Recently, a new isolated three-port BDC was proposed for a PV-battery system [9]. That BDC used the least number of switches among all existing three-port BDCs, i.e., three switches for three ports, to realize the power management for the PV-battery system. The battery can be charged by the PV panel(s) and discharged to supply the load located on the high-voltage side (HVS) of the BDC. That BDC is preferable for standalone applications but is not sufficient for microgrid applications because the power flow between the LVS and HVS of the BDC is unidirectional, namely, the power can only be delivered from the primary side (LVS) to the secondary side (HVS) of the transformer.

This paper extends the work in [9] by adding two extra controllable switches on the secondary side of the transformer. The proposed BDC not only is capable of maximum power point tracking (MPPT) control for the PV system when solar energy is available, but also can charge the battery from the PV system and the DC microgrid. Therefore, the proposed BDC is suitable for both standalone and microgrid applications.

II. PROPOSED MULTIPORT BIDIRECTIONAL DC-DC CONVERTER

Fig. 1 shows the circuit diagram of the proposed isolated three-port BDC. It consists of a LVS circuit and a HVS circuit connected by a high-frequency transformer with the center tap on the secondary side. The LVS circuit consists of a unidirectional port (Port 1) connected to a PV system and a bidirectional port (Port 2) connected to a battery. The HVS circuit consists of the secondary winding of the transformer connected to the switches S_3 and S_4 , a low-frequency LC filter, and Port 3, which can be connected to a DC load or a

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Fig. 1. Proposed isolated, three-port, bidirectional DC-DC converter.

DC microgrid. Among the switches, S_1 is called the main switch because it not only controls the amount of power generated from the PV system connected to Port 1 (P_1), but also changes the direction of the current flowing through the transformer. The transformer's turn ratio is defined as $n = N_p/N_s$, where N_p and N_s are the numbers of turns of the primary and secondary windings, respectively. To simplify the analysis, all capacitances in the circuit are assumed sufficiently large such that the voltages across them within a switching period are constant.

The power flow between the LVS and the HVS is bidirectional; the solar power can be used to charge the battery and supply the load in the DC microgrid. In most applications $n < 1$ and, thus, the converter has two operating modes: 1) boost mode, where the power flows from the LVS to the HVS; and 2) buck mode, where the power flows from the HVS to the LVS. According to the possible directions of the power flow of the proposed converter in the two operating modes, there are four different operating scenarios for the converter, as illustrated in Fig. 2.

Scenario 1: the battery is charged by the PV system.

Scenario 2: the energy generated by the PV system is delivered to the DC microgrid.

Scenario 3: the battery is discharged to supply power to the DC microgrid.

Scenario 4: the battery is charged by the power from the DC microgrid.

As indicated in Fig. 2, Scenarios 1, 2 and 3 occur in the boost mode while Scenario 4 is in the buck mode. The power management of the battery is independent of the operating mode of the converter, namely, the battery can be charged or discharged in either the boost or buck mode. Therefore, the operation of the buck-boost converter in Port 2 shown in Fig. 1 is not analyzed together with that of Port 1. The following two subsections analyze the operation of Port 1 with the HVS in the two different modes.

A. Boost Mode

In this mode, the switch S_1 is active, while the switches S_3 and S_4 are inactive but their internal diodes form a rectifier on the HVS. The converter has two operating stages depending on the state of the switch S_1 . The equivalent circuits and steady-state waveforms of the two operating stages of the converter (without Port 2) are shown in Figs. Fig. 3 and Fig. 4, respectively.

Stage 1: $t \in [t_1, t_2]$ (see Fig. 3), during which S_1 is on. Fig. 3(a) shows the equivalent circuit in this stage, where the inductor L_1 stores energy, and the capacitor C_s discharges through the transformer and the switch S_1 . The voltage across the primary side of the transformer, v_p , is negative, which forces the conduction of the internal diode of the switch S_4 on the HVS. The energy stored in the capacitor C_s is delivered to the HVS through the internal diode of the switch S_4 .

Stage 2: $t \in [t_1, t_2]$, during which S_1 is off. On the LVS, v_p has a positive value in this stage; the energy stored in L_1 during Stage 1 is delivered to the HVS through the transformer and charges the capacitor C_s at the same time. The current through the HVS flows from the internal diode of the switch S_4 to that of the switch S_3 .

The differential equations in both stages are the same as those in [10].

Fig. 2. Possible power flow directions in the two operating modes of the converter.

Fig. 3. The steady-state waveforms of the proposed converter (without Port 2) in the boost mode.

Fig. 5. The steady-state waveforms of the proposed converter (without Port 2) in the buck mode.

Fig. 4. The equivalent circuits of the proposed converter (without Port 2) in the boost mode. (a) Stage 1 and (b) Stage 2.

B. Buck Mode

In this mode, the switch S_1 is inactive, while S_3 and S_4 are active; the power is delivered from the HVS to the LVS. Fig. 5 and Fig. 6 show the steady-state waveforms and the equivalent circuits of the converter (without Port 2) for four different operating stages. As shown in Fig. 5, the gate signals of the switches S_3 and S_4 (S_3^* and S_4^* , respectively) are complementary with each other to avoid their commutation.

Stage 1: $t \in [t_1, t_2]$ (see Fig. 5), during which the switch S_3 is off and S_4 is on ($S_3^* = 0$ and $S_4^* = 1$). Fig. 6(a) shows the equivalent circuit in this stage. When S_4 is on, the voltage of the secondary side of the transformer, v_s , is positive; then the internal diode of the switch S_1 is on and v_p is clamped to $-V_{cs}$. The direction of the current i_p is positive. The energy is delivered from the HVS to the LVS and is stored in the capacitor C_s . The stored energy will further charge the battery through the buck-boost circuit connected to Port 2 as shown in Fig. 1.

Stage 2: $t \in [t_2, t_3]$, during which S_3 and S_4 are off ($S_3^* = 0$ and $S_4^* = 0$). Fig. 6(b) shows the equivalent circuit in this stage. The current through the inductor L , i_{dc} , charges the parasitic capacitor of the switch S_4 , and the following equation is held.

$$v_{ds4} + 2 \cdot v_s = v_{ds3} \quad (1)$$

where v_{ds3} and v_{ds4} are the voltages across the switches S_3 and S_4 , respectively; v_s is the voltage across the secondary side of the transformer. As indicated by (1), if v_{ds4} increases, v_{ds3} decreases since v_s is a constant value, i.e., $v_s = -v_{cs}/n$. Particularly, when $v_{ds4} = -2v_s$, $v_{ds3} = 0$, which provides the ZVS condition for the switch S_3 .

Assume that the parasitic capacitor of the switch S_4 is fully charged within time Δt and its peak voltage is $2v_{cs}/n$, then

$$C_{oss} = \frac{i_{dc}(t_2) \cdot \Delta t / 2}{2v_{cs} / n} \quad (2)$$

where C_{oss} is the parasitic capacitance of the switch S_4 . According to (2), Δt can be calculated as:

$$\Delta t = \frac{4C_{oss} \cdot v_{cs}}{n \cdot i_{dc}(t_2)} \quad (3)$$

Then the ZVS of the switch S_3 can be achieved if Δt is less than the time duration of this stage, namely,

$$\frac{4C_{oss} \cdot v_{cs}}{n \cdot i_{dc}(t_2)} < t_3 - t_2 \quad (4)$$

Fig. 6. The equivalent circuits of the proposed converter (without Port 2) in the buck mode. (a) Stage 1; (b) Stage 2; (c) Stage 3; and (d) Stage 4.

Inequality (4) indicates that a large current through the inductor L is preferable for the switch S_3 to achieve the ZVS.

Stage 3: $t \in [t_3, t_4]$, during which S_3 is on and S_4 is off ($S_3^* = 1$ and $S_4^* = 0$). Fig. 6(c) shows the equivalent circuit in this stage. The conduction of S_3 leads to $v_p = v_{cs}$ such that

the volt-second balance of the transformer is held. $i_p = 0$ and no power flows between the HVS and the LVS.

Stage 4: $t \in [t_4, t_5]$, during which S_3 and S_4 are off ($S_3^* = 0$ and $S_4^* = 0$). Fig. 6(d) shows the equivalent circuit in this stage. Similar to the analysis in Stage 2, the ZVS of the switch S_4 can be achieved. Once the switch S_4 is turned on at time t_5 , Stage 4 switches to Stage 1.

III. SIMULATION RESULTS

Simulation studies are carried out in MATLAB/Simulink to validate the proposed isolated multiport BDC connected to a PV panel and a battery. The PV panel is SunWize SW-S110P, which has the open-circuit voltage (V_{oc}) and the short-circuit current (I_{sc}) of 22 V and 6.3 A, respectively. The nominal voltage and rated capacity of the battery are 7.5 V and 5600 mAh, respectively. A 24 V DC voltage source is used to emulate the DC microgrid in Fig. 2. The switching frequency is 100 kHz. The transformer turn ratio is $n = 5:7$. The perturbation and observation (P&O) MPPT algorithm [11] is implemented in the boost mode to control the PV panel's output power.

In the first test, the operation of the battery is changed from Scenario 1 to Scenario 3 instantaneously in the boost mode. Fig. 7(a) shows the power response of the battery. The battery first works in Scenario 1, where the energy is extracted from the PV panel. At the 30th ms, the power reference of the battery is step changed from -24 W to 24 W, where the negative and positive signs represent that the battery works in the charge and discharge modes, respectively. As shown in Fig. 7(a), the measured battery power reaches 24 W quickly within 1.5 ms. Fig. 7(b) shows the ideal maximum power point (MPP) and the actual power output of the PV panel as well as the power delivered to the HVS. The measured PV power and the ideal MPP (41.6 W) are on top of each other, which validates the effectiveness of the MPPT control using the P&O algorithm and the proposed converter. The power delivered to the HVS is changed from 16 W to 62 W within 20 ms, which is longer than the response time of the battery (1.5 ms) shown in Fig. 7(a).

In the second test, the solar energy is not available and the converter works in the buck mode to charge the battery using the power from the DC microgrid (i.e., Scenario 4). As shown in Fig. 8(a), the battery reference power is changed from -12 W to -24 W at the 30th ms; and the measured battery power follows the step change within 2 ms. The power supplied by the HVS is automatically adjusted to -24 W within 20 ms. Theoretically, the power supplied by the HVS should be the same as that absorbed by the battery. However, during the power transient, there is deficient power as depicted in the shadow area in Fig. 8(a), which is provided by the energy stored in the capacitor C_s . Fig. 8(b) shows the voltage response of the capacitor C_s . The voltage drops from 16.64 V to 16.08 V, which indicates that the energy stored in the capacitor C_s is released to charge the battery.

(a)

(b)

Fig. 7. Power responses in the boost mode when the battery operation changes from Scenario 1 to Scenario 3 instantaneously. (a) Battery power; (b) PV power and power delivered to the HVS.

(a)

(b)

Fig. 8. System responses in the buck mode (Scenario 4). (a) Battery power and power supplied by the HVS; (b) voltage response of the capacitor C_s .

IV. EXPERIMENTAL RESULTS

The system simulated is constructed in hardware to further validate the proposed converter via experimental studies. Fig. 9 shows the prototype of the whole system. It consists of the proposed BDC, which is connected to the SunWize SW-S110P PV panel, the battery, and a DC microgrid simulator, and an eZdsp F2818 control board. The battery consists of four Samsung ICR18650-28A rechargeable lithium-ion cells, where two cells are connected in series to form a pack and the two packs are connected in parallel. The nominal voltage, maximum charging current, and nominal capacity of the battery are 7.5 V, 5.6 A, and 5600 mAh, respectively. The DC microgrid simulator includes a TENMA DC voltage source and a Kikusui

Plz664WA programmable DC electronic load working in the constant voltage mode. The control algorithm is implemented in a TMS320F2812 DSP located on the eZdsp F2812 control board. Other parameters of the system are the same as those used in the simulation.

Fig. 10 shows the experimental results in Scenarios 1 and 2, where the PV panel and the battery work in the MPPT mode and charge mode, respectively. As shown in Fig. 10(a), the power generated by the PV panel is 41.18 W in the steady state. The switch S_{20} is active and the negative battery current ($i_{bat} = -1.25$ A) indicates that the battery works in the charge mode. Fig. 10(b) shows the power-voltage (P-V) characteristic curve of the PV panel, which was derived by measuring the step response of the voltage (v_1) and current (i_1) of PV panel when it is connected to Port 1. During the

Fig. 9. The prototype of the overall system.

transient, v_1 increases from zero to V_{oc} , which changes the operating point of the PV panel. The P-V characteristic curves can be assumed constant within every three minutes since it was a clear day. As shown in Fig. 10(b), the MPP of the PV panel is 41.86 W, which is slightly higher than 41.18 W measured 90 seconds earlier, as shown in Fig. 10(a). Such a small deviation was caused by the P&O MPPT algorithm in which the duty cycle varies slightly along the optimal duty cycle from time to time. Therefore, the PV panel has achieved its MPP in the boost mode.

Fig. 11 shows the experimental results in Scenario 3, where no solar energy is available. The switches S_1 and S_{21} are active. The positive current of the battery indicates that it is discharged. The voltage of the HVS is 24.1 V, which is slightly higher than that of the DC microgrid simulator of 24 V.

Fig. 12 shows the steady-state waveforms of the LVS voltage and current of the transformer and the current of the battery when the converter works in Scenario 4. As shown in Fig. 12, when the switch S_4 is on, $v_p < 0$ and $i_p > 0$, the capacitor C_s is charged by the voltage source located on the HVS; when the switch S_4 is off, $i_p = 0$. The negative battery current indicates that the battery is charged.

Fig. 13 shows the gating signals (PWM₃ and PWM₄) and the drain-to-source voltage (v_{ds3} and v_{ds4}) waveforms of the switches S_3 and S_4 . The drain-to-source voltages of the switches S_3 and S_4 drop to zero before their gate signals are applied. Therefore, the switches S_3 and S_4 are turned on under the ZVS condition in Scenario 4. These results validate the theoretical analysis in Section II.

V. CONCLUSION

A new isolated, three-port, bidirectional DC-DC converter with the least number of switches has been proposed for PV-battery-DC microgrid applications. The proposed converter has been used for integrating a PV panel and a battery to a DC microgrid in this paper. Simulation

Fig. 10. Experimental results in Scenarios 1 and 2 of the boost mode. (a) The steady-state voltage, current, and power waveforms of the PV panel and the current of the battery; (b) the P-V curve of the PV panel.

Fig. 11. The experimental results in Scenario 3.

Fig. 12. The steady-state voltage and current waveforms of the primary side of the transformer and the current of the battery in Scenario 4.

(a)

(b)

Fig. 13. ZVS of the switches S_3 and S_4 in Scenario 4. (a) PWM₃ and v_{ds3} ; (b) PWM₄ and v_{ds4} .

and experimental results have shown that the converter is not only capable of MPPT for the PV panel when there is solar radiation, but also can control the charge/discharge of the battery. Particularly, the bidirectional power flow between the LVS and the HVS is suitable for microgrid applications.

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