An integrated four port bidirectional dc-dc converter for photovoltaic energy harvesting systems

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Abstract In this paper, an integrated four port DC-DC converter with bidirectional power transfer capability is proposed for connecting two photovoltaic sources with an energy storage element to a dc load. This converter achieves high power density due to its integrated structure and device sharing feature among the ports. Adopted PWM and secondary side phase-shifting control eliminates the circulating current and its associated conduction losses and minimizes the current ripple at input ports. Further, it simplifies the complexity of control by decoupling the control variables of input and output ports. Working of the converter under different operating conditions are verified with a 500-W experimental prototype.

key words: dc-dc converter, multiport converter, renewable energy harvesting

Classification: Power devices and circuits

1. Introduction

Efficient energy harvesting from renewable sources become unavoidable due to the fast depleting conventional fossil fuel sources. But when there is a need for continuous power supply to the load, these renewable energy-based power generation systems become less reliable because of their intermittent nature[1, 2, 3]. In this case, multiple sources along with storage have to be used to maintain the continuous power supply to the load. For connecting multiple sources and storage either multiple converters or an integrated multiport converter can be used. An integrated multiport converter proved to be more efficient than the multiple converter structure because of its simplified structure and centralized control[4, 5, 6, 7]. Recently various topologies of multiport converters have been reported in the literature because of their increasing merits. They can be classified as non-isolated[8, 9, 10], fully-isolated[11, 12, 13] and partially-isolated topologies[14, 15, 16]. Partially-isolated topologies are gaining importance these days because of the simplified structure and improved power density features. The focus of this paper is mainly on the partially-isolated multiport topology which uses a single winding transformer to isolate multiple input ports with the load port. Many three port partially-isolated converters can be seen in literature and they are derived by either combined dc-linking and magnetic coupling technique[17] or by the integration of non-isolated circuits into isolated circuits[18, 19, 20]. These three-port converters have only one source port and a storage port, supplying a load port. Since they depend on only one source, reliability is less. A four-port converter with two source ports has been reported in [21]. It is derived by integrating non-isolated buck/boost circuits into a phase-shifted full-bridge circuit and here two source ports are formed by sharing the switching legs of the primary bridge circuit. This converter uses PWM and primary phase-shift control, in which the duty cycle adjustment of primary bridge switching legs are used for maximum power tracking of the sources and battery power management. And phase-shift between gate pulses of primary switching legs are used for output voltage regulation. This primary phase shift control results in the coupling of control variables of source and load ports[22, 23]. Further, in primary phase-shifting operation, the switching legs cannot be operated with 180° phase difference which results in increased current ripple at the input ports. And this converter allows only unidirectional power transfer between the source and load port. To overcome these effects of primary side phase shifting, secondary side phase shifting has been introduced. The application of this technique can be seen in some two port converters[24, 25, 26, 27] and three port converters[28, 29, 30]. In this paper, a modified four port bidirectional converter is formed by replacing the diodes in the secondary side with controllable switches. This inclusion of controllable switches allows the transfer of phase shift control to the secondary side while allowing bidirectional power transfer between source and load ports. Shifting of phase shift control to the secondary side decouples the control variables of the duty cycle and output voltage. Hence, in this converter, the duty cycle adjustment of primary bridge switching legs is used for maximum power tracking and battery management alone and not for output regulation. And phase shift between gate pulses of the primary and secondary switches are used to regulate the output voltage and power flow direction. This decoupling of control variables of input and output ports simplifies the control complexity. The secondary phase-shifting allows the switching legs at the primary side to be operated with 180°

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phase difference without any further phase shift, because of which the current ripple at the PV ports can be significantly reduced [29, 30]. Unlike primary phase shift control, this secondary phase shift control eliminates the circulating current during the freewheeling interval and reduces the related conduction losses. Also, the inclusion of controllable switches at the secondary side eliminates the losses due to diode reverse recovery current. This reduction of losses, significantly improves the power transfer efficiency from PVs to load when compared to primary phase shift control.

2. Proposed four port bidirectional dc-dc converter

As illustrated in figure (1), the mosfets $Q_1$, $Q_3$ forms a bridge which is connected to another bridge formed by mosfets $Q_5$, $Q_8$ through a high frequency transformer. This set-up is equivalent to a phase-shifted full bridge circuit. $L_{hf}$ is the total leakage inductance plus required external inductance of the high frequency transformer and it determines the maximum power transferred between primary and secondary side ports. By adding inductors and diodes to the switching legs of the primary side, two boost converter sections are formed. Diodes are used to block the power flow into the PVs when battery is charged from load side. Mosfets $Q_1$ and $Q_2$, inductor $L_{B1}$ with diode $D_{B1}$ forms one boost converter. And mosfets $Q_3$ and $Q_4$, inductor $L_{B2}$ with diode $D_{B2}$ forms another boost converter. These boost converter sections connect the two PV sources to the battery. In this integration of boost circuits with the full-bridge circuit, primary side active devices are shared by both the boost and phase-shifted full-bridge converters, which results in the reduction of component count when compared to the conventional cascaded structure. The conventional cascaded structure depicted in [21] uses eight controllable switches in primary side other than diodes and passive devices, whereas this integrated structure uses only four controllable switches due to sharing which improves the power density. This proposed circuit is capable of feeding a stand-alone dc-load or a dc-bus.

Fig. 1. The proposed four-port bidirectional dc-dc converter

3. Working principle of the converter

Boost converters section: With PV sources as input and battery as output, this section of converter is equivalent to a boost converter. Maximum power of the sources $PV_1$ and $PV_2$ are tracked by adjusting the duty cycle of switching legs $D_1$ and $D_2$ respectively. Operational waveforms of this section are given in figure (2). The voltage conversion ratio of this section is same as a boost converter

$$V_B = \frac{V_{PV1}}{1 - D_1} = \frac{V_{PV2}}{1 - D_2}. \quad (1)$$

Where, $V_B$ is the voltage across the battery and $V_{PV1}$ and $V_{PV2}$ are the voltages. $D_1$ and $D_2$ are duty ratios of primary side switching legs.

![Fig. 2. Waveforms of boost section](image)

Full bridge with secondary phase-shift control section: From battery to load the converter is equivalent to a voltage fed full bridge converter with secondary phase-shift control. The phase difference between the switching pulses of primary and secondary bridge switches, represented as “$\phi$” is used to control the amount and direction of power transfer between battery and load. The duty cycle of primary side switches is determined by MPPT or battery power management control blocks. The duty cycle of secondary side switches is fixed to 0.5$T_s$. The voltage conversion ratio of this section is given by

$$m = \frac{V_O}{nV_B}. \quad (2)$$

Where, $n$ is the turns ratio of high frequency transformer, $V_O$ is the output voltage.

The equation that represents the amount of power flow between the load and battery port is given by,

$$P = \frac{nV_BV_O(1 - \phi)}{2\pi^2 f_s L_{hf}}. \quad (3)$$

Where $f_s$ is the switching frequency. The power flow direction is determined by the sign of the phase shift angle “$\phi$”. When the switching instants of primary side switches are leading when compared to secondary side switches, then the phase shift is considered as positive and power flows from primary to secondary side. When switching instants of secondary switches are leading, then the phase shift is considered as negative and power flows from secondary to primary side. The operational waveforms of this section is shown in figure (3) and figure (4).
4. Proposed secondary phase shift control

The maximum power tracking of PV sources, charging and discharging control of battery, and regulation of load are considered as control objectives to achieve power management of different ports of the converter. MPPT controller employs Perturb and Observe algorithm to calculate the duty cycle change required to track maximum power of PVs. Battery charging control provides CC and CV charging control of battery. Battery charging control operates in parallel with MPPT controls and competes for the minimum to acquire control over the duty cycle of primary side switches. The load voltage regulation is done by controlling the phase shift between the primary and secondary switches with a simple voltage control loop. The battery discharge controller monitors the state of charge of the battery, and when it reaches the minimum level it will shut down the load or changes the power flow direction by varying the phase shift angle and allows the battery to be charged by the connected dc bus or grid.

5. Possible power transfer modes

Depending on the availability of PV power, the converter is capable of working in the following power transfer modes. 

**Mode 1**: when there is surplus PV power, the battery will get charged from PV sources and the load will also be supplied by the PV sources.

**Mode 2**: when there is no sufficient power from the PVs to meet alone the load requirements, battery discharges along with PVs to supply the load.

**Mode 3**: when there is zero power from the PVs, the battery alone will discharge to supply the load.

**Mode 4**: In case when the converter is working in mode-3 and the battery state of charge reduces to its permissible level, the converter will enter this mode. Here the battery will be stopped from discharging and it is allowed to get charged from the load side dc bus.

| Mode | PV sources | Battery | Power flow direction |
|------|------------|---------|---------------------|
| 1    | MPPT       | Charging| Primary to secondary |
| 2    | MPPT       | discharging | Primary to secondary |
| 3    | NA         | discharging | Primary to secondary |
| 4    | NA         | Charging  | secondary to primary |
6. Experimental results

To verify the working of the proposed converter and its control strategy, experimental prototype of 500 W was developed and control signals are generated using a digital control platform RT lab-OP4510 with the parameters shown in table (2). The inductor currents of the boost converter sections at steady state is given in Figure (7). For a positive phase shift, the primary and secondary bridge voltages and the corresponding output voltage are given in figure (8). For the same phase shift, the secondary inductor current and voltage are given in figure (9). Figure (10) shows that for changes in load current, battery current compensates without changing the output voltage. And figure (11) shows that for changes in PV currents, again battery current changes without affecting the output. From figures (10) and (11), it is clear that the source side and load side control is decoupled from each other. The comparison of PV to load power transfer efficiency for the primary phase shift and secondary phase shift control obtained from same testing conditions are given in figure (12). These tested waveforms and results proves the validity and working of the converter with the adopted secondary phase-shift control.

![Fig. 7. Steady state waveforms of boost converter](image)

![Fig. 8. Primary (Vab) and secondary side (Vcd) phase shifted voltages with corresponding output voltage](image)

![Fig. 9. Secondary side inductor current and voltage for primary to secondary side power transfer](image)

![Fig. 10. Battery current change for load current change](image)

![Fig. 11. Battery current change for changes in PV current](image)

7. Conclusion

A modified four port bidirectional converter is proposed for interfacing two PV sources and a battery to a dc load. The device sharing feature of this integrated converter reduces the component count and improves the power density. The adopted secondary phase shift control simplifies the control design complexity by decoupling the control variables of source and load side ports. Also, the secondary phase-shift control reduces the current ripple at PV ports by allowing the primary switching legs to be operated with 180° phase difference. The power losses related to the circulating current during the freewheeling stage is reduced and reverse recovery loss of diodes are eliminated in secondary phase.
shift control. The reduction of power losses effectively improves the power transfer efficiency from PV to load when compared with the primary phase-shifting technique. Test results of the 500-W experimental prototype validate the effectiveness and working of the converter for different input and output conditions.

References

[1] LI. Yunwei, et al.: “Overview of control, integration and energy management of microgrids,” Journal of Modern Power Systems and Clean Energy 2(2014)212(DOI:10.1007/s40565-014-0063-1).

[2] De la Fuente, et al.: “Photovoltaic power system with battery backup with grid-connection and islanded operation capabilities,” IEEE transactions on industrial electronics 60 (2013) 1571 (DOI: 10.1109/TIE.2012.2196011).

[3] SN.Motapon, et al.: “A comparative study of energy management schemes for a fuel-cell hybrid emergency power system of more-electric aircraft,” IEEE transactions on industrial electronics 61 (2014) 1320 (DOI: 10.1109/TIE.2013.2257152).

[4] [4] M. Mihai, : “Multitop converters - a brief review,” International Conference on Electronics, Computers and Artificial Intelligence Papers (2015) 27 (DOI: 10.1109/ECAI.2015.7301246).

[5] H.Tao, et al.: “Multitop converters for hybrid power sources,” IEEE Power Electronics Specialists Conference Papers (2008) 3412 (DOI: 10.1109/PESC.2008.4592483).

[6] W.Jiang, et al.: “Multitop Power Electronic Interface—Concept, Modeling, and Design,” IEEE Transactions on Power Electronics 26 (2011) 1890 (DOI: 0.1109/TPEL.2010.2093583).

[7] H.Tao, et al.: “Family of multitop bidirectional DC-DC converters,” IEEE Proceedings - Electric Power Applications Papers (2006) 451 (DOI: 10.1049/ip-fecha.20050362).

[8] K.P. Savitha, et al.: “Multi-port DC-DC converter for DC microgrid applications,” IEEE International Conference on Power Systems Papers (2016) 1 (DOI:10.1109/ICPES.2016.7584018).

[9] H. Matsuo, et al.: “Characteristics of the multiple-input DC-DC converter,” IEEE Transactions on Industrial Electronics 51 (2004) 25 (DOI: 10.1109/TIE.2004.825362).

[10] Wu.Hongfei, et al.: “A family of non-isolated three-port converters for stand-alone renewable power system,” IECON Annual Conference of the IEEE Industrial Electronics Society Papers (2011) 1030 (DOI:10.1109/IECON.2011.6193337)

[11] H.Tao, et al.: “Three-Port Triple-Half-Bridge Bidirectional Converter With Zero-Voltage Switching,” IEEE Transactions on Power Electronics, 23 (2008) 782 (DOI: 10.1109/TPEL.2007.915023).

[12] H.Krishnaswami, et al.: “Three-Port Series-Resonant DC-DC Converter to Interface Renewable Energy Sources With Bidirectional Load and Energy Storage Ports,” IEEE Transactions on Power Electronics, 24 (2009) 2289 (DOI: 10.1109/TPEL.2009.2022756).

[13] A.Ajam, et al.: “Soft-switching method for multiport DC/DC converters applicable in grid-connected clean energy sources,” IET Power Electronics, 8 (2015) 1246 (DOI: 10.1049/iet-pel.2014.0592).

[14] J.Zeng, et al.: “An isolated three-port bidirectional DC-DC converter for photovoltaic systems with energy storage,” IEEE Industry Applications Society Annual Meeting Papers (2013) 1 (DOI:10.1109/IAS.2013.6682520).

[15] J.Zeng, et al.: “An isolated multiport bidirectional DC-DC converter for PV-battery-DC microgrid applications,” IEEE (ECCE) Papers (2014) 4978 (DOI:10.1109/ECCE.2014.6954084).

[16] W.Li, et al.: “PWM Plus Phase Angle Shift (PPAS) Control Scheme for Combined Multiport DC/DC Converters,” IEEE Transactions on Power Electronics, 27 (2012) 1479 (DOI: 10.1109/TPEL.2011.2163826).

[17] H.Tao, et al.: “Multi-input bidirectional DC-DC converter combining DC-link and magnetic-coupling for fuel cell systems,” IAS Annual Meeting. Conference Record Papers (2005) 2021 (DOI:10.1109/IAS.2005.1518725).

[18] Ay-Atrash, et al.: ‘Boost-integrated phase-shift full-bridge converter for three-port interface,” IEEE Power Electronics Specialists Conference Papers (2007) 2313 (DOI:10.1109/PESC.2007.4342371).

[19] M.C.Mira, et al.: “Analysis, Design, Modeling, and Control of an Interleaved-Boost Full-Bridge Three-Port Converter for Hybrid Renewable Energy Systems,” IEEE Transactions on Power Electronics , 32 (2017) 1138 (DOI: 10.1109/TPEL.2016.2549015).

[20] H.Xiao, et al.: “A ZVS Bidirectional DC-DC Converter With Phase-Shift Plus PWM Control Scheme,” IEEE Transactions on Power Electronics , 23 (2008) 813 (DOI: 10.1109/TPEL.2007.915188).

[21] H.Wu, et al.: “Multiport Converters Based on Integration of Full-Bridge and Bidirectional DC–DC Topologies for Renewable Generation Systems,” IEEE Transactions on Industrial Electronics , 61 (2014) 856 (DOI: 10.1109/TIE.2013.2254096).

[22] Z.Qian, et al.: “Modeling and Control of Three-Port DC/DC Converter Interface for Satellite Applications,” IEEE Transactions on Power Electronics, 25 (2010)637 (DOI: 10.1109/TPEL.2009.2053925).

[23] C.Zhao, et al.: “An Isolated Three-Port Bidirectional DC-DC Converter With Decoupled Power Flow Management,” IEEE Transactions on Power Electronics , 23 (2008) 2443 (DOI: 10.1109/TPEL.2008.2002056).

[24] W.Li, et al.: “Secondary-Side Phase-Shift-Controlled ZVS DC/DC Converter With Wide Voltage Gain For High Input Voltage Applications,” IEEE Transactions on Power Electronics , 28 (2008) 5128 (DOI: 10.1109/TPEL.2013.2334290).

[25] T.Mishima, et al.: “Practical Evaluations of a ZVS-PWM DC–DC Converter With Secondary-Side Phase-Shifting Active Rectifier,” IEEE Transactions on Power Electronics, 26 (2011) 3896 (DOI: 10.1109/TPEL.2011.2132146).

[26] H.Wu, et al.: “A Family of Soft-Switching DC–DC Converters Based on a Phase-Shift-Controlled Active Boost Rectifier.”
[27] H. Xiao, et al.: “A ZVS Bidirectional DC–DC Converter With Phase-Shift Plus PWM Control Scheme,” IEEE Transactions on Power Electronics, 30 (2015) 657 (DOI: 10.1109/TPEL.2014.2308278).

[28] M. Asgari Moqaddam, et al.: “PWM plus secondary-side phase-shift controlled full-bridge three-port bidirectional converter for application in MVDC distribution networks,” Power Electronics Drive Systems Technologies Conference Papers (2017) 178 (DOI: 10.1109/PEDSTC.2017.7910318).

[29] J. Zhang, et al.: “PWM Plus Secondary-Side Phase-Shift Controlled Soft-Switching Full-Bridge Three-Port Converter for Renewable Power Systems,” IEEE Transactions on Industrial Electronics, 62 (2015) 7061 (DOI: 10.1109/TIE.2015.2448696).

[30] H. Wu, et al.: “Secondary-Side-Regulated Soft-Switching Full-Bridge Three-Port Converter Based on Bridgeless Boost Rectifier and Bidirectional Converter for Multiple Energy Interface,” IEEE Transactions on Power Electronics, 31 (2016) 4847 (DOI: 10.1109/TPEL.2015.2473002).