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Bidirectional Battery Charger for PV Using Interleaved Fourport DC-DC Converter

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Abstract

In this paper, a four-port bidirectional dc-dc converter is proposed for grid-interactive photovoltaic (PV) system application. The four-phase topology is suitable for residential pumping, aerospace power requirements. The control of battery and different capacities of PV modules are naturally decoupled. In addition, the port interface with PV is current type which can implement maximum power point tracking (MPPT) and soft switching under wide variation of PV terminal voltage. Finally, simulation results are proposed to verify the power control in different operation modes.

***Keywords**: dc-dc converter, integrated three-port, grid- interactive, MPPT, soft-switching*

1. Introduction

Grid-interactive PV systems with battery have been reported for peak power shaving and backup power [1-3]. Recently, it has also been reported to provide a solution to improve the power quality of the grid. The small energy storage integrated with residential PV systems can effectively reduce the over voltage caused by reverse power flow to maintain the power quality of the grid. Moreover, the battery- integrated PV systems can perform a key power quality function, including reactive power compensation and harmonic cancellation [7-8]. Integrated multi-port bidirectional dc-dc converter has been proposed for PV system with battery backup [9-10] due to the advantages of low cost and high efficiency. However, the presented converters are not able to charge the battery from the grid. Moreover, the control of battery and PV is coupled therefore the operation of PV and battery will affect each other. In this paper, a four-port converter for grid- interactive PV system is developed based on a interleaved boost bidirectional dc-dc converter [11-13]. The four-phase interleaved topology is suitable for higher MPP-tracking converters, operating range has to be limited to the voltage less than the MPP voltage when the output voltage or current control is active [1]. However, a multiport converter is complex and there are more design challenges, e.g. The control structure. The advantages of using multi-port structure is that the primary source only needs to be sized according to the average power consumed by the load for a specific power application, and all three ports are capable of bidirectional power flow so battery can be charged from PV and the grid as well. In addition, the PV port can implement MPPT and achieve soft switching under wide variation of PV voltage. Therefore, the high efficiency will be maintained.

2. Research Method

Figure 1 shows the topology of multiphase interleaved four-port dc-dc converter. This converter was proposed in [14] with detailed description of open-loop operation principle. In this paper, this converter is applied to grid-interactive PV system to achieve integrated MPPT and bidirectional battery charge/discharge function. Three-phase Y-Y type high frequency transformers are used to boost the PV voltage and provide galvanic isolation between grid side and PV/battery side. The battery is connected to the primary side dc link. The voltage of battery changes slowly, so the primary side dc-link voltage can keep constant. The PV is connected to the current source low voltage dc port.

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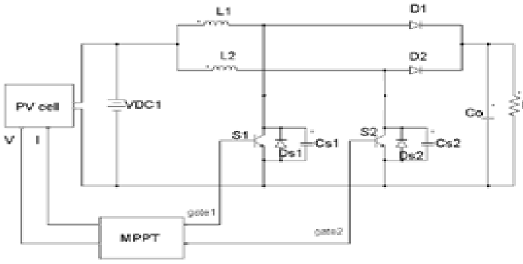

Figure 1. Topology of multiphase interleaved one-port dc-dc converter

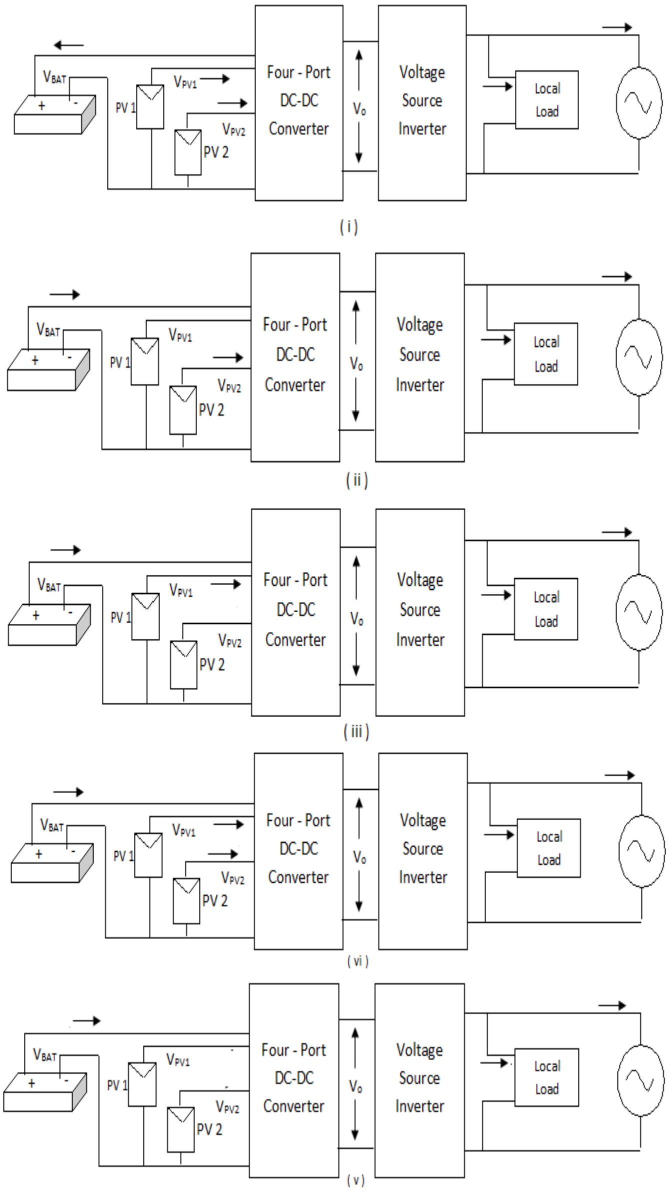

Figure 2. Modes of various operation for proposed method

All of the three ports are bidirectional and a diode is added to the PV port for protection. Because the terminal voltage of PV array varies quickly and frequently with different solar irradiation level, the dc low voltage port with current source has the advantage to implement both MPPT and soft switching. There are two control variables of this integrated dc-dc converter. Duty cycle D is used to realize MPPT control of PV, and phase shift angle φ is used to regulate the total power by PV and battery. The PV and battery power control are naturally decoupled, which will be further described in the following. Figure 2 shows the three selected typical operation modes of the grid-interactive PV system with battery. In mode I, when the solar irradiation is low, the power generated by PV cannot satisfy the load power requirement so that the battery will discharge and provide power to the load. The power flow is shown in (i), where Pload =Ppv +Pbat. Figure 2 (v) gives the power flow of mode III that there is no power generated by PV at night or cloudy day, and only battery supports the load, i.e. Pload = Pbat. There are more modes for grid-connected combined operation. For example, the battery can be charged during night when the price of utility electricity is low.

Additionally, the PV can provide power to battery, load or grid depending on the different condition. Figure 3 shows the proposed control algorithm of grid- interactive PV system using a three port dc-dc converter. The output current Io of dc-dc converter is controlled by phase shift angle φ, and duty cycle is used to realize MPPT. For the stand-alone mode, the phase shift angle φ is controlled by voltage controller and battery current Ibat is determined by the PV power and load requirement. When the PV power is low, the battery discharges and provides part of power to the load. When the PV power is high, the excess power will charge the battery. For the grid-connected PV system, the battery current Ibat is more flexible and determined by state of charge (SOC) management. If the battery is fully charged, the extra PV power will send back to the grid. The average model of the converter is developed to analyze its steady state and dynamic performance. Because each phase of proposed topology is symmetrical [11], the modeling of three-phase converter can be treated as the model of single-phase half-bridge dc-dc converter.

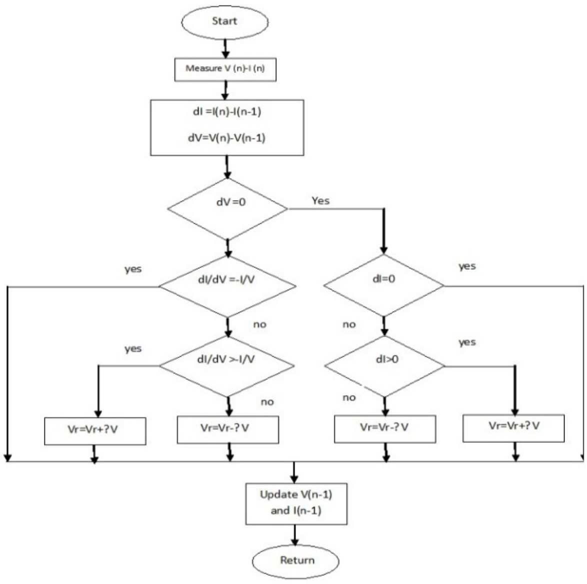

Figure 3. Flow Diagram of Incremental Conductance Algorithm

The state variables are the dc inductor current iL dc, the primary side dc- link voltage Vd, and the output voltage vo. The state equation is given as,

$$\mathrm{L}\frac{\mathrm{dIldc}}{\mathrm{dt}} = \mathrm{Vin} - \mathrm{DVd} \quad (1)$$

$$\mathrm{Cd}\frac{\mathrm{dVd}}{\mathrm{dt}} = \mathrm{Dildc} - \mathrm{io1} \quad (2)$$

$$\mathrm{C\Phi}\frac{\mathrm{dV\Phi}}{\mathrm{dt}} = -\mathrm{V\Phi}/\mathrm{Rl} - \mathrm{i\Phi1} \quad (3)$$

Since the power of each phase is:

$$P0 = Vd2\Phi(4\pi - \frac{3\Phi}{18\pi wl}) \quad (4)$$

The average value of io1 referred to the primary side is,

$$i01 = P0/Vd\Phi(4\pi - \frac{3\Phi}{18\pi wl}) \quad (5)$$

Since the dc-link voltage keeps constant level, according to Equation (2), the output power Po is just related to the phase shift angle. The terminal voltage of PV changes in a wide range under different ambience, and the duty cycle D in steady state. Under different solar irradiation and temperature, the PV voltage of maximum power point Vpm is different. The duty cycle D is regulated by MPPT controller using incremental conductance method [15] to achieve Vpm and MPP. The flow chart of MPPT controller is presented in Figure 3. For the battery power, Pbat can be expressed by, Pbat = VbatIbat= Vbat (Vbat-Vd) / Rbat = Vbat DVpv / Rbat. Since Po= Ppv + Pbat = Vpv Ipv + Vbat Ibat = f (φ), the total power of PV and battery can be controlled by phase shift angle φ.

3. Results and Analysis

Simulation in Matlab-Simulink is used to verify the performance of proposed system. The integrated MPPT function and battery charge/discharge operation, as well as the system transients between different modes are selected in simulation and experimental results to evaluate the controller performance. Figure 6 and Figure 7 show the simulation results in the condition of varied solar irradiation. The PV 1 panel has the following specifications: under 1000W/m2 irradiation, the maximum power point is Vm = 54.7V and Im = 5.58A; the open circuit voltage Voc is 64.2V and short circuit current Isc is 5.96A. 5*66 PV panels are connected in parallel to generated power up to 3KW and the PV 2 panel has the following specifications: under 1000W/m2 irradiation, the maximum power point is Vm = 54.7V and Im = 5.58A; the open circuit voltage Voc is 64.2V and short circuit current Isc is 5.96A. 5*66 PV panels are connected in parallel to generated power up to 3KW. The battery pack's voltage is 50V and output voltage is 58.89V. At first, when the irradiation is low, both PV and provide power to the load, i.e. mode I. When the irradiation is high, the power generated by PV not only supports the load but also charges the battery, which is mode II. During cloudy day or night, Ppv is 0, and battery provides all the power to the load. For the grid-connected system, the battery current can be controlled by SOC management. In Figure 6, when the battery is almost full, the current decreases to 1.5A. The excessive power from PV is sent back to the grid. The three-phase bidirectional dc-dc converter is using ATMega micro digital controller. The parameters of PV array are: Vpm = 40V, Voc = 48V, Imp=5*5.4A, Isc = 5*5.8A. The primary side dc link is connected to a 12V battery pack. Figure 6 shows the experimental results of mode change. The Po is fixed 50W. The PV power is from 50W down to 0W and battery is from charging mode to discharging mode. It can be seen that, the total output power is provided by battery and the output current is not affected during the mode transient. Figure 7 shows the experimental results when the PV terminal voltage changes from 400V to 500V, i.e. the solar irradiation is from 200W/m2 to 1000W/m2. The power from PV will increase and that from battery will decrease. When the PV power is higher than requirement, the battery is charged by PV. Figure 8 and 9 shows experimental results of the load changing with different PV voltage. The experimental results illustrate that the power exchange can be realized among three ports and output power is not affected by the dynamic power distribution between PV and battery since it is controlled by phase shift angle. For four-port converter, the switches can also satisfy the ZVS conditions if small dc inductors are utilized and the voltages on both sides of the transformer are matched. The parameters used for simulating the proposed algorithm. The simulation results are obtained as follows (e.g. Figure 6, 7, 8, 9)

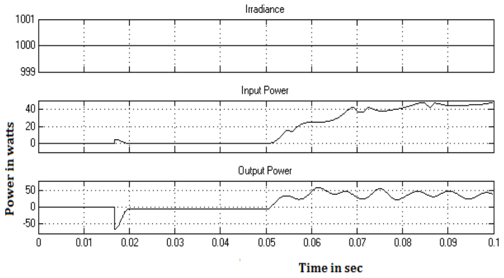

Figure 6. Irradiance, Input & Output power graph for PV panel

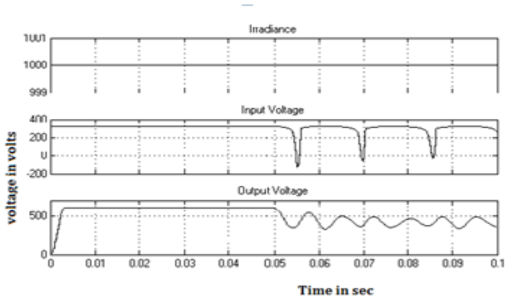

Figure 7. Irradiance, Input & Output Voltage graph with time in seconds

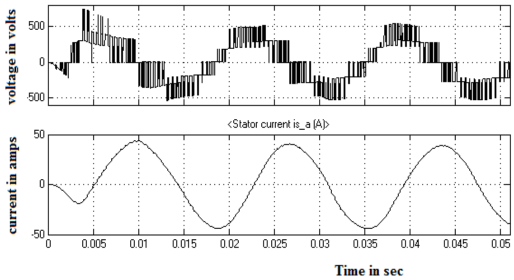

Figure 8. Input voltage and current for motor with time in seconds

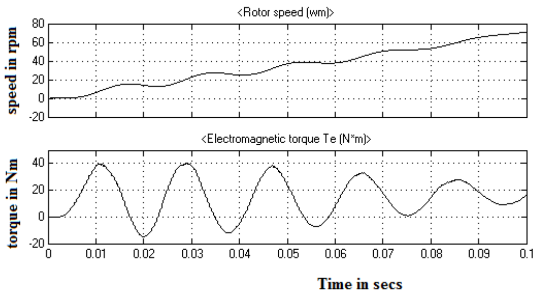

Figure 9. Characteristics of motor speed and torque

In this section, it is explained the results of research and at the same time is given the

4. Conclusion

In this paper, a four-port different capacities of PV system with battery using interleaved bidirectional dc-dc converter was proposed. The high frequency transformers provide voltage boost capability and galvanic isolation. PV and battery interfacing with different type of ports can realize MPPT and soft switching under wide variation of PV voltage. The two control variables, duty cycle and phase shift angle, can be controlled independently to realize MPPT and power flow between energy sources and load. The benefit of bidirectional power flow is helpful to manage the SOC of battery in grid- connected mode. Simulation and experimental results verified the principles.

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