ANALYSIS, DESIGN, MODELING, AND CONTROL OF AN INTERLEAVED-BOOST FULL-BRIDGE THREE-PORT CONVERTER FOR HYBRID RENEWABLE ENERGY SYSTEMS

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ABSTRACT

The design, modeling and control of a three-port (TPC) isolated dc-dc converter based on interleaved-boost-full-bridge with pulse-width-modulation and phase-shift control for hybrid renewable energy systems. In the proposed topology, the switches are driven by phase-shifted PWM signals, where both phase angle and duty cycle are controlled variables. The power flow between the two inputs is controlled through the duty cycle, whereas the output voltage can be regulated effectively through the phase-shift. The primary side MOSFETs can achieve zero-voltage switching (ZVS) operation without additional circuitry. Additionally, due to the ac output inductor, the secondary side diodes can operate under zero current switching (ZCS) conditions. In this work, the operation principles of the converter are analyzed and the critical design considerations are discussed. The dynamic behavior of the proposed ac inductor based TPC is investigated by performing state-space modeling. Moreover, the derived mathematical models are validated by simulation and measurements. In order to verify the validity of the theoretical analysis, design and power decoupling control scheme, a prototype is constructed and tested under the various modes, depending on the availability of the renewable energy source and the load consumption. The experimental results show that the two decoupled control variables achieve effective regulation of the power flow among the three ports.

Keywords: Energy storage, phase-shift and duty cycle control, renewable energy, state-space modeling, three-port converter

1. INTRODUCTION

In order to fulfill different system requirements, various hybrid system configurations and converter topologies have been proposed and investigated. In applications where galvanic isolation is required, there are basically two categories classified as: multiple-converter conversion and multiple-port conversion. In the multiple converter configurations, power converters are connected in parallel or in series in order to couple the energy sources and loads. By contrast, multiple-port power conversion systems can have high power density and low cost, due to the fact that some components and circuits in various power ports, such as transformers, rectifiers and output filters, can be shared as a common part along the power conversion path. Therefore, multiple-port converters have been receiving increased attention in recent years. A general solution to obtain an isolated multiple-port converter is to adopt the magnetic coupling method, where various input power sources can be coupled with transformer windings or independent transformers. In this solution, the multiport converter can be constructed from the basic high frequency switching cells, including the half-bridge (HB), full-bridge (FB), boost-half-bridge (BHB) and their combinations, according to the system constraints imposed by the features of the input power sources. Based upon this
principle, a number of three-port (TPC) bidirectional dc-dc converters, which can fully isolate the various power ports and control the power flows into/out of each port.

Renewable power systems, which are capable of harvesting energy from, for example, solar cells, fuel cells, wind, and thermo-electric generators, are found in many applications such as hybrid electric vehicles, satellites, traffic lights, and powering remote communication systems. Since the output power from renewable sources is stochastic and the sources lack energy storage capabilities, energy storage systems such as a battery or a super capacitor are required to improve the system dynamics and steady-state characteristics. A three-port converter (TPC), which can interface with renewable sources, storage elements, and loads, simultaneously, is a good candidate for a renewable power system and has recently attracted increased research interest. Compared with the conventional solutions that employ multiple converters the TPC features single-stage conversion.

Three port converters are found to be better than conventional systems which uses multiple converters. Because of its advantages such as superior system efficiency, faster response, fewer components, compact packaging and unified power management. A dual active bridge topology is found to be commonly popular among the bi-directional DC-DC converters that uses two half bridges or two full bridges in the high frequency transformer that has phase shift control ensuring in zero voltage switching and flexible power flow control. A high efficiency Zero Voltage Switching (ZVS) multiinput converter directly utilized the current-source type applying for both input power sources. This method offers a reduction in conduction loss of switches in the dual-power-supply state depending on the designed Pulse Width Modulation (PWM) signals and series-connected input circuits. In order to achieve turn-on ZVS of the switches, an auxiliary circuit with a small inductor functioning in the Discontinuous Conduction Mode (DCM) was used. It is possible to remove the huge reverse-recovery current of the output diode through auxiliary inductor which is connected to Scotty diode. An interleaved method that can alleviate the output voltage ripple of the two-input inductor currents is proposed. Thus, this converter was beneficial to convert two power sources of different voltages to a single DC-bus voltage. This converter can be used both in single as well as dual power supply states. A two-input power converter that has a ZVS for hybrid Fuel Cell and battery power system. However, this converter could neither deliver a bi-directional functionality nor could boost the input voltage, despite having well developed circuit efficiency.

2. RELATED WORKS

In [1], FredeBlaabjerg, Zhe Chen, and SoerenBaekhoejKjaer et al presents The global electrical energy consumption is rising and there is a steady increase of the demand on the power capacity, efficient production, distribution and utilization of energy. The traditional power systems are changing globally, a large number of dispersed generation (DG) units, including both renewable and nonrenewable energy sources such as wind turbines, photovoltaic (PV) generators, fuel cells, small hydro, wave generators, and gas/steam powered combined heat and power stations, are being integrated into power systems at distribution level. Power electronic, the technology of efficiently processing electric power, plays an essential part in the integration of the dispersed generation units for good efficiency and high performance of the power systems. This paper reviews the applications of power electronics in the integration of DG units, in particular, wind power, fuel cells and PV generators. The main advantages of using renewable sources are the elimination of harmful emissions and the inexhaustible resources of the primary energy. However, the main disadvantage, apart from the higher costs, e.g., photovoltaic, is the uncontrollability.
In [2] Zhe Chen, Josep M. Guerrero, and FredeBlaabjerg et al presents The power electronic applications for wind energy systems. Various wind turbine systems with different generators and power electronic converters are described, and different technical features are compared. The electrical topologies of wind farms with different wind turbines are summarized and the possible uses of power electronic converters with wind farms are shown. Finally, the possible methods of using the power electronic technology for improving wind turbine performance in power systems to meet the main grid connection requirements are discussed. Power electronic, being the technology of efficiently converting electric power, plays an important role in wind power systems. It is an essential part for integrating the variable-speed wind power generation units to achieve high efficiency and high performance in power systems. Even in a fixed-speed wind turbine system where wind power generators are directly connected to the grid, thyristors are used as soft-starters. The power electronic converters are used to match the characteristics of wind turbines with the requirements of grid connections, including frequency, voltage, control of active and reactive power, harmonics, etc.

In [3] Wenping Zhang, Dehong Xu, Xiao Li, Ren Xie, Haijin Li, Dezhi Dong, Chao Sun et al presents Due to the long cold start time and slow dynamics of proton exchange membrane (PEM) fuel cell (FC) stack, operating modes transfer control strategy for fuel cell uninterruptible power supply (FC-UPS) is different from the traditional uninterruptible power supply (UPS) system. In this paper, a seamless transfer control strategy, which is suitable for FC-UPS, is proposed. The power conversion architecture of FC-UPS is presented with the characteristic analysis of PEMFC and the requirements of UPS. Then, the scheme of the seamless transfer control strategy is investigated. The proposed seamless transfer control strategy is not only capable of guaranteeing the uninterruptible load voltage, but also protecting FC against the power demands beyond its allowable bandwidth during the transition for long lifespan and safety. Finally, the control scheme has been verified on a 10-kW FC-UPS prototype. The lead-acid or Ni–Cd battery is generally employed in UPS.

In [4] Haimin Tao, Andrew Kotsopoulos, Jorge L. Duarte et al presents Multiport dc–dc converters are particularly interesting for sustainable energy generation systems where diverse sources and storage elements are to be integrated. This paper presents a zero-voltage switching (ZVS) three-port bidirectional dc–dc converter. A simple and effective duty ratio control method is proposed to extend the ZVS operating range when input voltages vary widely. Soft-switching conditions over the full operating range are achievable by adjusting the duty ratio of the voltage applied to the transformer winding in response to the dc voltage variations at the port. Keeping the volt-second product (half-cycle voltage-time integral) equal for all the windings leads to ZVS conditions over the entire operating range. A detailed analysis is provided for both the two-port and the three-port converters. Furthermore, for the three-port converter a dual-PI-loop based control strategy is proposed to achieve constant output voltage, power flow management, and soft-switching. The three-port converter is implemented and tested for a fuel cell and super capacitor system.

In [5] Yaow-Ming Chen, Yuan-Chuan Liu, and Feng-Yu Wu et al presents A multi-input dc/dc converter based on the flux additively is proposed in this paper. Instead of combining input dc sources in the electric form, the proposed converter combines input dc sources in magnetic form by adding up the produced magnetic flux together in the magnetic core of the coupled transformer. With the phase-shifted pulse width-modulation (PWM) control, the proposed converter can draw power from two different dc sources and deliver it to the load individually and simultaneously. The operation principle of the proposed converter has been analyzed in detail. The output voltage regulation and power flow control can be achieved by the phase-shifted PWM control. A prototype converter with two different dc voltage sources has been successfully implemented. Computer simulations and hardware
experimental results are presented to verify the performance of the proposed multi-input dc/dc converter. Transformers in different varieties of converters are used to deliver the electric power from the primary side to the secondary side to meet the desired voltage and current requirements as well as to provide the electric isolation for the application.

3. PROPOSED SYSTEM

The design, modeling and control of a three-port (TPC) isolated dc-dc converter based on interleaved-boost-full-bridge with pulse-width-modulation and phase-shift control for hybrid renewable energy systems. In the proposed topology, the switches are driven by phase-shifted PWM signals, where both phase angle and duty cycle are controlled variables. The power flow between the two inputs is controlled through the duty cycle, whereas the output voltage can be regulated effectively through the phase-shift. The primary side MOSFETs can achieve zero-voltage switching (ZVS) operation without additional circuitry. Additionally, due to the ac output inductor, the secondary side diodes can operate under zero current switching (ZCS) conditions.

4. THREE PORT CONVERTER TOPOLOGY

A three-port energy management system includes a primary source and storage, and single-stage power conversion between any two of the three ports is possible. Having the two energy inputs, the instantaneous power can be redistributed in the system in a controlled manner, which results in improvement of system dynamics and reliability. Another advantage of using a three-port system is that the primary source only needs to be sized according to the average power consumed by the load, not necessarily to the peak power. This operation is economically beneficial since per watt cost of the primary source is usually high, and thus it makes sense to operate the primary source at the maximum power.

5. THREE PORT CONVERTER TOPOLOGY

The maximum possible power flow is determined by the leakage (and externally added) inductance. This circuit can be operated with soft-switching, provided that the operating voltage at each port is kept near constant. However, when the port operating voltage varies widely, such as with super capacitors, the soft-switched operating range will be reduced. In a method has been proposed to extend the soft-switching range by adjusting the duty ratio of the voltage (a rectangular-pulse wave) inversely proportional to the operating voltage of the port.
6. CIRCUIT DESCRIPTION

The studied topology in Fig. 1 consists of two input inductors, $L_1$ and $L_2$, an ac inductor $L_{ac}$, four power MOSFETs $M_1$–$M_4$, and a high-frequency transformer with a turns ratio of 1:$n$. The ac inductor, which is the sum of the leakage inductance and the auxiliary inductance, is the power interface element between primary and secondary sides of the transformer. Switches $M_1$, $M_2$, and $M_3$, $M_4$ are driven with complementary gate signals with a dead band. $V_1$ and $V_2$ represent the input voltages; $iL_1$ and $iL_2$ are defined as the input inductor currents; $v_{ab}$ is the voltage between the midpoints of the bidirectional interleaved boost switching legs, and $iL_{ac}$ is the current of the secondary side winding. In order to decouple the two inputs $V_1$ and $V_2$ and regulate the output voltage accurately, both the duty cycle and the phase-shift angle are adopted as the control variables simultaneously. The duty cycle of the power switches is used to adjust the power among the two independent sources, and the phase-shift angle between the midpoints of the full bridge is employed to regulate the power flow to the output port.

Through the phase shift with duty cycle control, and according to the availability of the renewable energy source and the load demand, the proposed converter can operate in various operating modes: in DI mode when the load demand is higher than the available power from the renewable energy source and the energy storage element delivers the extra energy to the load; in DO mode when the input power is higher than the load power demand and the energy storage element balances the power by storing the excess energy; and in SISO mode when power transfers between the two inputs or from one of the inputs to the output port.

7. INTERLEAVED TOPOLOGIES

Using interleaved topologies, the proposed basic bidirectional switching cells can be used for higher power applications (greater than 10 kW, for example). We have presented in a three-port three-phase TAB converter topology which is an extension of the single-phase TAB topology. As shown in Fig. this circuit consists of three inverter stages operating in a six-step mode with controlled phase shifts. The three bridges are interconnected by a three-
port three-phase symmetrical transformer, and the inductors in the circuit represent the leakage inductances of the transformer (and external inductors if necessary). The transformer can be either in Y-Y or in Δ-Δ connection. Note that coupling of the windings is between the ports and there is no Interphase coupling. As indicated in the figure, windings marked with the same symbol are coupled. The major advantage of the three-phase version is the much lower VA rating of the dc side filter capacitors.

8. CONTROL STRATEGY

A feedback control structure was used for each operating mode of the converter topology. The objective is to regulate the load voltage and prevent load transitions from affecting the operation of the converter. A multi-loop control scheme was described here. It simultaneously regulates the PV power to achieve the MPPT, or battery charging control and the output voltage. Control diagram of the three port converter is shown in the Fig 6. Multi objective control architecture is implemented to regulate different power ports.

9. STATE-SPACE MODELING

State-space average modeling of the proposed TPC is presented. This technique to modeling switching dc–dc converters, which results in a dynamic linear model in terms of state-space equations, is used in this study. Due to the inherent sampling process of switched-mode converters, averaged models can accurately predict the behavior up to half of the switching frequency. If precise modeling beyond the switching frequency is required, i.e., in self-oscillating control schemes, a discrete-time approach for modeling switched-mode controllers can be used.
It can be observed that the ac inductor charge and discharge always depend on the converter input voltage $V_2$, the converter output voltage $V_O$, and the phase-shift angle, whereas voltages $V_1$ and $V_2$ are regulated by the duty cycle. Therefore, the proposed topology can be dynamically modeled as two individual converters: a bidirectional interleaved boost converter (BIBC), which balances the power flow within the two input sources, and a PSFB converter or single active-bridge converter, which delivers the power to the load through the ac inductor. As a result, the proposed converter offers independent controllability by using duty cycle and phase shift as control variables and reutilizes the primary-side switches to regulate the two power flows. The high integration of the two structures in a TPC results in a topology with lower component number and higher power density than multiple-converter systems. Moreover, as previously discussed, in the completely demagnetized case the energy transferred to the output port does not depend on the converter duty cycle; therefore, the two control variables, phase shift $\Phi$ and duty cycle $D$, are completely decoupled.

10. POWER FLOW REGULATION AND CONTROL

At the renewable energy port, either voltage or current can be selected to be regulated depending on the type of the selected renewable energy source. At the energy storage port, constant voltage (CV) and constant current (CI) regulators are implemented, and at the output port, voltage regulation is performed. In order to control the power among the two inputs and the load and thereby balance the power between the different energy sources, two control loops are active at any time. The output port regulation loop is employed to regulate the load voltage by the phase-shift angle $\Phi$. On the other hand, assuming $V_1$ is the renewable energy source such as fuel cells or PVs, the voltage or current is controlled by the duty cycle $D$. The power from the other input $V_2$ as an energy storage unit, for example, a battery or a super capacitor, is controlled depending on the power at the renewable energy source and the output load power demand. Therefore, the energy management and control scheme can be summarized in the following way. The system is always set to control the renewable energy source and in the case of a PV application, to maximize the power delivered to the system through a maximum power point tracking algorithm (MPPT). If the renewable input power is smaller than the required power at the output port, the storage unit will compensate the power difference automatically. On the other hand, if the input power is bigger than the power required at the load terminal, the energy surplus is used to charge the energy storage element by inverting the power flow direction at this port.
11. CONCLUSION

An isolated soft-switched TPC to interface with hybrid renewable energy systems is presented. Its operating principle and design considerations are discussed and verified by simulation and experimental results. In order to control the power flow between the different ports, a duty cycle and phase-shift control scheme is adopted. The duty cycle is used to control the power flow between the two independent sources, whereas the phase-shift angle is employed to regulate the output voltage. The state-space modeling and control of the proposed TPC operating in completely demagnetized and fully magnetized mode is presented. The mathematical model is validated by simulation as well as experimental measurements of the plant and line-to-output transfer functions. The advantage of the proposed topology is that it can be dynamically modeled as individual converters, which makes it possible to design a control strategy with totally uncoupled control variables. This fact makes this topology a very interesting solution in renewable energy applications where an energy storage element is required, since full reutilization of the converter primary-side switches is achieved, without having a negative impact in the controllability of the converter. By selecting the renewable source and the energy storage voltages $V_1$ and $V_2$ to require a duty cycle approximately to 0.5 the phase-shift value range can be fully utilized. Experimental results demonstrate that the proposed energy/power management solution achieves effective control of the power flow among the input, bidirectional and output ports.

REFERENCE


