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Operating modes and practical power flow analysis of bidirectional isolated power interface for distributed power systems

Huiqing Wen [a,b,*], Bin Su [c]

[a] Dept. of Electrical and Electronic Eng., Xi'an Jiaotong-Liverpool University, Suzhou, China
[b] State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an, China
[c] Hangzhou Electric Power Bureau, State Grid Corporation of China, Hangzhou, China

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ABSTRACT

Due to the intermittent nature of the renewable energy sources including photovoltaic and wind energy, the energy storage systems are essential to stabilize dc bus voltage. Considering the discharge depth of super-capacitors and energy-storage batteries, the bidirectional isolated power interface will operate for a wide range of voltage and power. This study focuses on in-depth analysis of the dual-active-bridge dc–dc converter that is controlled by the dual-phase-shift scheme to improve the conversion efficiency in distributed power system. The power flow of each operating mode with dual-phase-shift control is characterized based on a detailed analysis of the effects of "minor parameters", including the deadtime and power device voltage drops. The complete output power plane of the dual-active-bridge converter with dual-phase-shift control is obtained and compared with experimental results. The optimal operating mode is determined according to the practical output power range and the power flow characteristics. Experimental evaluation shows the effectiveness of the proposed power flow model with dual-phase-shift control and significant efficiency improvement using the optimal mode of dual-phase-shift compared with the conventional phase shift control.

1. Introduction

Distributed power systems are showing more advantages compared with the centralized configuration with the growing penetration of distributed generators (DGs). The advantage of the system stability was revealed in [1]. The research in [2] shows that distributed power systems can minimize the energy losses through optimization. By using the distributed optimal power flow, distributed power systems can improve the control robustness [3]. The advantage of cost reduction was shown in [4]. Besides, the advantage of design flexibility and reliability in islanding detection was illustrated in [5]. Considering the intermittent nature of the renewable energy sources including photovoltaic (PV) and wind turbine, the energy storage systems (ESS) are essential to stabilize the dc bus voltage. For instance, battery banks were used for dispatching intermittent renewable sources [6]. The technical and economic design of photovoltaic and battery energy storage system was shown in [7]. In [8], the characteristics of fuel cells and other electrochemical energy storage system were illustrated. In [9], the hydrogen storage system for a renewable Microgrid was analyzed. Besides, a hybrid storage system for electric vehicles was discussed in [10]. A typical configuration of DC distributed power system normally includes modular energy storages and high-efficiency power interfaces [11]. Among them, bidirectional dc–dc converters are essential to accommodate the charge/discharge operations of ESS and balance the power generation and load demands [12]. Various bidirectional isolated DC–DC topologies have been proposed. For instance, a multilevel cascade PWM converter was used for battery energy storage system [13]. A push-pull PWM converter was discussed in [14]. A current-fed resonant converter was used to interface with DC Microgrid [15]. The topology of Dual Active Bridge (DAB) has drawn significant attention. DAB converter is used to interface energy storage system in Microgrid [16]. The application for the power distribution system was discussed in [17]. It can provide the propulsion power and balance energy transfer between various dc voltage levels in hybrid electric vehicle [18]. It can be used for large proton exchange membrane (PEM) fuel cells as power conversion interfaces [19]. The main advantages of the DAB converter have been discussed widely. For instance, the research in [20] revealed its advantage of bidirectional power flow capability. The research in [21] showed its

* Corresponding author at: Dept. of Electrical and Electronic Eng., Xi'an Jiaotong-Liverpool University, Suzhou, China. Tel.: +86 (0)512 8188 0477; fax: +86 (0)512 8188 0445.
E-mail address: Huiqing.Wen@xjtlu.edu.cn (H. Wen).

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Nomenclature

V_1	magnitude of the transformer primary voltage	D_2	lag phase-shift ratio with EDPS
V_2	magnitude of the transformer secondary voltage	k_1	voltage drops ratio across the primary side
N	transformer turns ratio	k_2	voltage drops ratio across the secondary side
C_1	input capacitor	M	deadtime ratio in half switching period
C_2	output capacitor	P_{in_HL}	average input power for heavy-load conditions
L_s	leakage inductor	P_{o_HL}	average output power for heavy-load conditions
d	voltage conversion ratio	P_{in_LL}	average input power for light-load conditions
D_1	leading phase-shift ratio with EDPS	P_{o_LL}	average output power for light-load conditions

feature of modular structure. The feature of compact design was discussed in [22]. The inherent soft switching characteristics were discussed in [23]. The research in [24] revealed its feature of output voltage ripple minimization. The advantage of high efficiency was mainly discussed in [25]. The advantage of electrical stresses reduction was mainly discussed in [26].

The power interface for distributed power systems has to operate for a wide range of voltage and power considering the operating features of batteries and ultracapacitors. For instance, the battery voltage in an automotive typically ranges from 11 to 16 V, while the power train voltage is between 240 and 450 V. The operating power ranges from 20% to the rated power [18]. The typical operating voltage range of ultracapacitors is between 28 V and 45 V, the load power varies between 16% and the rated power [27]. Correspondingly, two major design challenges must be considered and solved:

(1) *Practical output power range:* DAB converters are usually controlled by the conventional phase-shift (CPS) technique that both bridges are modulated with the same switching frequency and constant 50% duty ratio [18]. The phase shift determines directly the power flow direction and the amplitude of the output power. However, the maximum phase shift ϕ_{max} is limited to avoid large circulating current during power conversion. The minimum phase shift ϕ_{min} is constrained by rise and fall times of MOSFETs. Normally, the practical operating phase shift ϕ varies between 0.03 p.u. and 0.125 p.u. [27]. Thus, the output power range that can be transferred is different from the theoretical value especially considering the effects of deadtime and the device voltage drops, which are referred as "minor parameters" in this paper. For instance, the experimentally obtainable minimum power with the maximum input voltage in [27] accounts for only 58.33% of the rated power. Besides, a lower P_o is not practically achievable. Furthermore, in this case, the output voltage can no longer be regulated. However, the effects of "minor parameters" are usually ignored in traditional power flow model [24].

(2) *Efficiency:* In DAB converter, the polarity of the inductor current i_L is not always the same as the primary voltage v_{T1} in a certain period. It's the same case for the current i_L and the secondary voltage v_{T2}. When the voltage conversion ratio is different from unity, CPS might result in low conversion efficiency due to the loss of the soft-switching capability [28]. CPS also results in high reactive power [29]. In [25], the research indicates that the reactive power with CPS control is inherent, and is the main factor contributing to large peak current and system loss.

To address these issues, a Dual-phase-shift (DPS) control strategy was proposed in [25] to eliminate the reactive power and therefore minimize the DAB converter conduction losses. Although the basic operating principle and reactive power with DPS are introduced in [25], the power characteristic of DPS control and its effectiveness in efficiency improvement are not fairly evaluated due to two control variables and multiple operating modes. For instance, in the experimental comparison of conventional CPS, DPS control and model-based phase-shift control (MBPS) [30], the efficiency improvement with DPS is not as good as expected in [25]. In [31], the power characterization of the DAB DC–DC Converter with DPS control was analyzed. However, it chooses only two modes that are insufficient to represent the complete operating range of DAB [32]. Furthermore, the effectiveness of DPS in efficiency improvement has not been addressed [31]. In [33], four operating modes with DPS control were analyzed. However, it adopts the conventional power flow model, where the effects of "minor parameters", such as deadtime and the device voltage drops, will not be considered. Thus, obvious discrepancies observed in experiments could not be explained correctly. In fact, similar to CPS, using the DPS control, the effects of "minor parameters" become more significant especially for energy storage systems applications, where DAB converters link with low-voltage high-current battery side with high-voltage DC link bus.

On this basis, this study aims the in-depth analysis of the power flow characteristic of each operating mode with DPS control and the effects of "minor parameters" including the deadtime and power device voltage drops, which are commonly neglected in previous studies. The complete output power plane of the DAB converter with DPS control is presented. Three output power regions are classified, such as the high-power, middle-power and low-power region. The possible operating modes for each region are specified. A systematical analysis about the effects of "minor parameters" on the power characteristics of DAB converter is conducted and the accurate power flow models with DPS control are developed and verified by the experimental results. With the new power flow model, the optimal operating mode for each output power region is selected and the optimal phase-shift pairs are also determined. The potential of DPS in the efficiency improvement are evaluated for different output power regions. Experimental evaluation shows the effectiveness of the proposed power flow model with DPS control and significant efficiency improvement using the optimal mode of DPS compared with the CPS control.

2. Operating modes with DPS control

In order to address the limitation of conventional phase-shift control, a Dual-phase-shift (DPS) control strategy is proposed to improve the conversion efficiency for a wide range of voltage and power. Fig. 1 shows the schematic circuit of the DAB converter, which typically consists of two full bridges that are interconnected through a high frequency transformer T_r. The primary side full bridge includes $Q_{11} \sim Q_{14}$ and the secondary side full bridge consists of $Q_{21} \sim Q_{24}$. The widely adopted control is the conventional