The Review and Analysis of the Impact of Dc-Dc Converters on Wind Power Generation

Yuanhang Yang

Department of Electrical Engineering and Electronics, University of Liverpool, Liverpool, L69 7ZG, United Kingdom

Y.Yang258@student.liverpool.ac.uk

Abstract. As wind energy has become an integral part of the ongoing energy transition, the scale of offshore wind farms and wind turbines continuously increases, and each turbine is expected to reach higher power capacity. This requires advanced DC/DC converters to meet stringent operational demands. This paper reviews the performance of Single Active Bridge (SAB), Dual Active Bridge (DAB), and modular DC/DC converters in wind turbine systems. These topologies have evolved from the simpler SAB to more complex DAB and modular configurations such as input-parallel output series (IPOS) and input-series output-parallel (ISOP) structures. As well as, this paper summarizes and compares both the advantages and disadvantages of different topologies in terms of efficiency, modularity, and control flexibility. Finally, it emphasizes the suitability of these topologies for future wind energy applications and proposes the promising potential of neural network control and adaptive regulation for power sharing and fault tolerance in modular systems.

Keywords: Wind Power, Wind Turbine, Dual Active Bridge, DAB

1 Introduction

As global demand for clean energy continues to increase, wind power is gradually becoming a cornerstone of the transition to a sustainable energy structure. According to statistics, in 2008, the global newly installed wind power capacity reached 27 GW, with the cumulative installed capacity growing to 120.8 GW [1]. In order to enhance the integration level and overall cost-effectiveness of offshore wind systems, increasing numbers of studies and projects are adopting medium-voltage direct current (MVDC) collection systems and high-voltage direct current (HVDC) transmission solutions. These solutions are widely considered a cost-effective technology path to reduce costs [2]. In this context, DC/DC converters with high power handling capabilities, high voltage step-up ratios, and reliability requirements have become essential components for energy conversion within wind turbines.

The structure of DC/DC power converters used in wind power systems has evolved from the Single Active Bridge (SAB) to the Dual Active Bridge (DAB), and further to

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modular series-parallel inverter configurations with higher power density and stronger modularity capabilities.

The initial SAB structure, due to its simple topology and low implementation cost, was widely used in early DC wind power or small-to-medium power applications. However, with active switches only on the input side and passive diode rectification on the output side, its energy flow direction is limited, and the control freedom is relatively low. This structure is more

suitable for unidirectional power flow systems, but is not ideal for complex systems that require bidirectional power flow or high dynamic response [3].

As the SAB inverter no longer meets the demands of the new equipment for high control capabilities and bidirectional energy flow, DAB topology has gradually become mainstream. The DAB features a dual-bridge structure, with active control on both sides, allowing bidirectional power transfer between the input and output. It also enables power regulation, soft switching, and better adaptability to varying voltage ratios through phase-shift modulation.

In the past decade, as the capacity of wind power systems has increased, the demand for high power and high voltage outputs has grown, leading to increased stress on inverters. To alleviate pressure on inverters, researchers have proposed multimodule converter structures, such as the widely used IPOS (Input-Parallel Output-Series) and ISOP (Input-Series Output-Parallel) configurations [4].

Overall, the trend of wind power systems evolving towards higher capacity, higher voltage, and modularity is reflected in the transition of topologies from SAB to DAB, and further to multi-module DAB-IPOS/ISOP structures. This progres- sion highlights the growing demand for power converter performance, control flexibility, and system maintainability in modern wind power applications. The following sections will first define the converter requirements from the perspectives of current converter power and the voltage handling capacity, as well as safety. The advantages and disadvantages of different topologies will then be systematically reviewed and compared from the perspective of energy efficiency, volume, and modu- larity. Finally, the paper will summarize the applicability and advantages of different topologies in practical applications.

2 Requirment for Converter

2.1 Power rating requirement for DC/DC Converters

According to the research conducted by W.Chen[5], the average rated power of global wind turbines has already reached or exceeded 10 MW. As the capacity of individual turbines continues to increase, the power handling capability of DC/DC converters must be enhanced accordingly. Research indicates that a DC/DC converter with a power rating of at least 15 MW is necessary to achieve clear cost-effectiveness in a fully DC system [6]. Therefore, to meet the demands of next-generation wind power systems, future high-voltage DC converters used in wind farms should have a power handling capacity of no less than 15 MW.

2.2 Voltage setting for DC/DC converters

The input voltage of the DC/DC converter depends on the DC voltage output of the generator-side rectifier [5]. Most mainstream wind power systems have an output voltage of 690 V AC on the generator side, which rectifies to approximately 1–1.2 kV DC. Some high-end models provide outputs of 3.3–4 kV AC, which rectifies to 4–6 kV DC. Therefore, considering the current turbine structures and future voltage enhancement trends, it is recommended to set the input voltage for DC/DC converters used in MVDC systems to 2–6 kV DC to ensure compatibility with a variety of wind turbines. The output voltage is directly related to the construction efficiency and safety of the medium-voltage DC (MVDC) or high-voltage DC (HVDC) collection grid. The DC bus voltage level for offshore wind power systems is typically set between 30–60 kV, with some scenarios reaching 80 kV or higher [5]. Therefore, to accommodate the expanding offshore wind farms in deep-sea and long-distance applications, and to ensure voltage compatibility with HVDC systems, the output voltage for current high-voltage DC/DC converters is recommended to be in the range of 40–60 kV DC.

2.3 Safety and topology requirements

High-voltage DC systems pose significant safety risks to personnel, making electrical isolation a key design priority. Employing an isolated DC/DC converter topology not only enables high voltage step-up ratios but also offers electrical isolation, fault tolerance, and electromagnetic compatibility advantages [5]. These converters can meet the dual demands of safety and reliability for high-power, high-voltage wind power systems without compromising system efficiency. As such, the trend in future DC/DC converter design will favor isolated topologies.

3 Review and Analysis of Different Converter Topologies

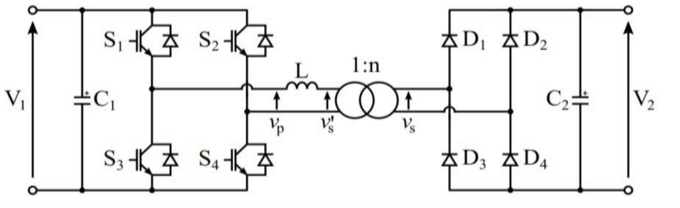

Fig. 1. The structure of single active bridge converter (Picture credit: Original)

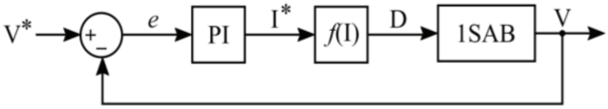

Fig. 2. The control system of SAB [7]

As shown in Fig 1, the development trend of DC-DC inverters has progressed from the Single Active Bridge (SAB) to the Dual Active Bridge (DAB), and now to modular inverters. This section will introduce each of these structures and provide a comparative analysis of their performance, control characteristics, and application scenarios.

3.1 Review and Analysis of SAB converter

The Single Active Bridge (SAB) operates by alternately driving the transistors S1 S4 and S2 S3 on the primary side to generate a square wave voltage. The duty cycle determines the conduction time of S3 and S4, thereby controlling the width of the voltage pulses and the amount of power transferred from the input bridge to the output bridge. The secondary side uses a passive rectifier diode bridge, simplifying the control structure.

This converter can operate in either Continuous Conduction Mode (CCM) or Discontinuous Conduction Mode (DCM), depending on factors such as leakage inductance, voltage ratio, and duty cycle. In CCM, soft switching can be achieved by paralleling capacitors across the switches, which reduces switching losses. However, when the output power is low, the system enters DCM, causing the soft-switching capability to be lost. In this case, the parallel capacitors may increase turn-off losses instead [3].

The basic control structure of the SAB involves a proportional-integral (PI) controller, which is shown in Fig 2 [7]. This controller uses a transfer function to set the required current based on the voltage error, which can be de- signed to control either the input or output voltage. Most wind power systems operate in partial load conditions. Early on, high-frequency control methods, such as variable frequency control, were used to achieve zero-voltage switching (ZVS) and reduce losses. However, there is ongoing debate regarding the trade-off between higher losses and simpler control with constant frequency control, which is easier to implement. In 2007, an experiment tested the losses of the SAB circuit under different wind speeds [3]. Under different control methods, the loss varies at different wind speeds. Experimental results indicate that the loss characteristics of diodes and IGBTs vary under different control strategies and wind speeds. Variable frequency control, when combined with appropriate capacitance, tends to reduce diode losses compared to constant frequency control. For IGBTs, variable frequency control is more effective at higher wind speeds, whereas constant frequency control exhibits more consistent losses across varying conditions. Overall, converter losses under variable frequency control range from approximately 3.2% to 3.8% of the input power, while constant frequency control results in slightly higher but more stable losses, ranging from 3.8% to 4.1% [3]. The difference between the two control modes is relatively small, suggesting that the choice should be based on specific device characteristics and operational requirements.

Ultimately, it was concluded that for large-scale wind power applications, which do not continuously operate at full power, DCM control is more economical and practical, as it does not require soft-switching capacitors and reduces the complexity of control and filter inductance requirements. Additionally, the SAB inverter features a compact structure, high efficiency (superior to DAB under partial load), and does not require synchronized control of the output bridge, making it suitable for deployment in confined spaces such as wind turbine nacelles [3]. However, the SAB inverter also has its drawbacks. When operating in DCM, current stress is higher, which increases transmission losses, and it cannot support bidirectional power transfer [8]. The SABs single-point structure means that any fault can impact the entire system, and when operating in DCM, turn-off losses increase significantly under low power conditions [3]. Furthermore, the SAB, when operating in DCM, cannot effectively support high load currents, which limits its use in high-power scenarios. This also results in the SAB's limited modularity and scalability. In contrast, the DAB inverter can handle higher load currents in such conditions, making it superior to the SAB in terms of modularity [9].

3.2 Review and analysis of DAB converter

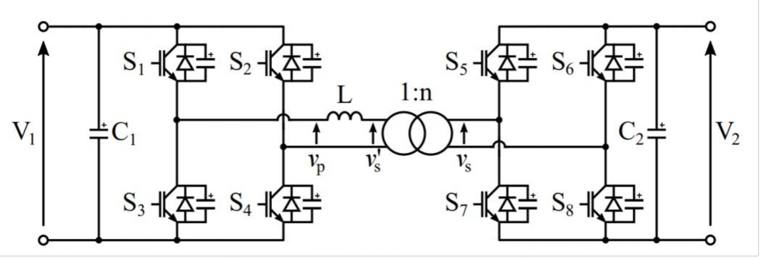

Fig. 3. The structure of dual active bridge[9]

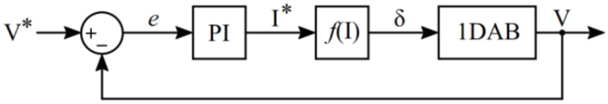

Fig. 4. The control system of DAB[7]

The structure of the Dual Active Bridge (DAB) is shown in the fig 3. The control principle and topology of the DAB are similar to those of the Single Active Bridge (SAB), with the key difference being the active bridge on the auxiliary equipment. This allows the DAB to support bidirectional power flow. Like the SAB, the leakage inductance of the DAB transformer is utilized for power transfer, which results in a more compact overall design [9]. As can be seen in fig 4, the operation of the DAB is as follows: First, the DAB generates a square wave voltage on both bridges, with the voltage phase angle shifted. The phase angle determines the direction of power transfer, and the duty cycle of the two pairs of switches on each bridge is half the switching period [7]. The DAB operates only in Continuous Conduction Mode (CCM), achieving soft switching through the use of capacitors connected in parallel with each switch [10].

A cost-effective all-DC wind farm requires a DC/DC converter with a 15 MW high power handling capability to accommodate the rated values of future wind turbines [5]. This presents a significant challenge for individual DAB inverters. According to the research by L. Max and T. Thiringer, the modularity advantages of the DAB inverter are presented, proposing a series/parallel modular structure (CDAB), demonstrating that the DAB configuration has the potential to meet the growing demands of wind power systems for higher power and voltage output. This compensates for the weakness in modularity and the limited application range of the SAB. Furthermore, the redundancy and reliability of the DAB were verified, leading to the conclusion that the DAB supports fault-tolerant operation in modular units, addressing the drawback of the SAB's single-point structure, where a fault impacts the entire system.

However, the Dual-Active Bridge (DAB) topology also presents certain drawbacks. Due to the large number of components and high system complexity, this structure leads to significantly increased overall cost and physical dimensions. This issue is particularly critical in offshore wind power applications, where the internal space within turbine nacelles is extremely limited and installation conditions are highly constrained. Nevertheless, the three-phase DAB system alleviates the pressure of installing the converter in such confined environments.

A 10 MW rated output power was used to evaluate six configurations based on differ- ent IGBT generations with varying thermal characteristics [11]. The total volume and weight of each configuration were analyzed and compared. The results show that, under the same 10 MW output, single-phase systems consistently exhibit larger overall volumes, ranging from approximately 120,000 cm^3 to 100,000 cm^3. In contrast, the three-phase systems demonstrate significantly reduced volumes, falling within the range of approximately 90,000 cm^3 to 80,000 cm^3, achieving a volume reduction of about 33%. In terms of total weight, the single- phase systems range between 250 kg and 240 kg, whereas the three-phase systems weigh around 200 kg, representing a weight reduction of over 20%.

These findings clearly indicate that, while maintaining the same 10 MW power output, the three-phase DAB structure not only offers advantages efficiency but also performs significantly better in terms of critical physical parameters such as volume and weight. This greatly enhances its deployability and maintainability in space-constrained environments such as wind turbine nacelles. Therefore, the three-phase topology is more suitable for practical offshore wind turbine applications where installation space is limited.

According to the research by F. Corti et al [12], the various phase-shift-based control strategies for DAB converters were analyzed, including Single Phase Shift (SPS), Extended Phase Shift (EPS), Double Phase Shift (DPS), and Triple Phase Shift (TPS). The results highlighted the significant advantages of DPS and TPS control strategies over basic SPS control, particularly in terms of expanding the Zero Voltage Switching (ZVS) operating range and reducing circulating currents. Notably, DPS maintains high efficiency under light load conditions, while TPS further extends the soft-switching range and optimizes conduction losses.

A simulation study of the DAB converter using DPS control was conducted by R. K. Singh et al [13]. The results indicated that DPS effectively eliminates circulating currents, with conversion efficiency rising from 89.6% in SPS mode to 93%. Additionally, when the internal and external phase shift angles are unequal, maximum power transfer can be achieved, further showcasing the benefits of dual-degree-of-freedom control.

Compared to the Single Active Bridge (SAB) converter, which commonly uses fixed-frequency control strategies, the DAB's phase-shift control offers superior performance in dynamic adjustment, soft-switching range, and adaptability to varying load conditions. The DAB converter not only performs better in terms of efficiency but also enables more flexible power regulation and a wider soft-switching operating range, making it suitable for applications requiring higher efficiency and dynamic performance.

3.3 Review and analysis of modular DAB structure

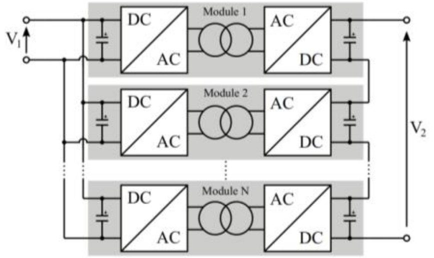

Fig. 5. The structure of modular converter[13]

Currently, common cascaded connection topologies include four forms: Input-Series Output-Series (ISOS), Input-Series Output-Parallel (ISOP), Input-Parallel Output-Parallel (IPOP), and Input-Parallel Output-Series (IPOS) [4]. Among these, the IPOS connection topology is the most widely used for high-power and high-voltage step-up applications in wind energy systems. The structure is shown in fig 5. According to research by R. K. Singh and Y. Pal[13], a modular wind energy system architecture based on the IPOS structure is proposed. Multiple small power three-phase DAB converters are installed in each wind turbine, with parallel connection on the input side and series connection on the output side, creating a medium-voltage direct current (MVDC) collection system. The simulation, performed in four typical operating conditions using PLECS, including full-rated power generation, unbalanced power under varying wind speeds, multiple turbines operating partially, and the worst-case scenario with only one turbine operating, showed that the system maintained a stable 18 kV bus output voltage. Moreover, the system achieved current distribution balance between turbines and demonstrated good dynamic response capability under various load and dynamic conditions.

The research introduced a Neural Network (NN) control strategy for power sharing and fault isolation between multi-module DAB converters under the IPOS structure

[14]. The system included four parallel DAB modules, and the tests were conducted under power reversal, load change, and DC fault conditions. The results showed that with the NN controller, the power distribution error was controlled within 2%, and module faults were quickly identified and isolated without interrupting the system operation.

In conclusion, the IPOS structure offers several advantages, including strong modular scalability, lower voltage and power stress per module, redundancy, and fault tolerance, making it ideal for high-power, high-voltage wind DC collection systems. However, challenges arise, particularly in the control complexity of the modular DAB structure, especially in power scheduling and redundancy switching [14]. Furthermore, J. G. Hayes et al. compared the losses of SAB, DAB, and their cascaded versions (CSAB, CDAB) at a 15 MW wind turbine with an 80 kV output voltage. The results showed significant performance differences across the configurations. The converter losses are mainly composed of transformer losses as well as switching and conduction losses in the semiconductor components [7].

The SAB configuration exhibits the lowest losses among the four configurations, with losses ranging from 0.5% to 1.1%, mainly due to the low losses of the diodes used in the rectifier. SAB is particularly suitable for applications that require unidirectional power flow.

The DAB configuration provides bidirectional power flow but incurs higher losses, ranging from 1.2% to 1.8%, due to switching losses in the IGBTs and core losses caused by the fixed duty cycle. Nonetheless, DAB has the advantage of bidirectional power flow.

The CSAB configuration, which cascades multiple SAB units, has efficiency similar to the standalone SAB, with losses ranging from 0.6% to 1.2%. Although it requires more modules, CSAB offers higher reliability with only a modest increase in losses, making it a viable option for future wind turbine applications.

The CDAB configuration, which cascades multiple DAB units, has losses ranging from 1.3% to 2.0%. These losses are slightly higher, primarily due to the increased number of switches in the cascaded configuration and the larger trans- former core volume. However, it still provides bidirectional power flow and higher reliability.

In summary, while the SAB and CSAB configurations perform best in terms of efficiency, maintaining losses below 1.5%, they only support unidirectional power flow. On the other hand, DAB and CDAB configurations are better suited for applications requiring bidirectional power flow. Moreover, regardless of whether SAB or DAB topologies are used, power losses significantly increase when modular connections are employed, although modular structures enhance the overall power handling capability of the converter. The CSAB and CDAB configurations strike a balance between reliability and efficiency, making them more suitable for large-scale, high-power wind DC collection systems, especially where redundancy and fault tolerance are critical.

3.4 Comprehensive analysis

As wind energy systems move towards larger capacities, higher voltage ratings, and modular designs, DC-DC converter topologies have evolved from SAB to DAB, and further to modular DAB configurations like IPOS-DAB. These topologies offer distinct advantages in terms of structural complexity, power density, control flexibility, and adaptability. The following provides a summary of the advantages and disadvantages of each topology through Table 1.

Table 1. Comparison of SAB, DAB, and modular converter structures (IPOS)

Indicator	SAB	DAB	Modular (IPOS)
Structural Complexity	Simple	Complex	Complex
Conversion Efficiency	High (0.5%-1.2%)	Medium (1.2%-1.8%)	Medium
Control Flexibility	Low, Fixed Control	High, Supports ZVS/DPS	High, Adaptive
Redundancy	Poor, System Shutdown on Failure	Medium, Fault Isolation Supported	High, Fault-Tolerant
Applicable Power	Low (5MW)	High (Above 15 MW)	High (Above 15 MW)
Bidirectional Power Flow	No	Yes	Yes
Modularity	Limited	High	Very High
Installation Suitability	Small Systems	Large Systems	Large Systems

4 Conclusion

This paper reviews and analyzes the performance of Single Active Bridge (SAB), Dual Active Bridge (DAB), and modular converters. By examining past research, it compares the advantages and disadvantages of SAB, DAB, and modular converters. Overall, for applications requiring small power converters, both the SAB and DAB structures are suitable, each with its own advantages and disadvantages. Compared to DAB, the SAB offers lower volume, mass, and transmission losses, and simpler control strategies. However, it cannot provide fine-tuned regulation or bidirectional power flow, and its modularity is limited, making it more suitable for low- precision, small power applications. On the other hand, DAB provides greater control flexibility and bidirectional power flow capability, making it suitable for high-power and finely regulated applications. DAB achieves soft-switching through phase-shift modulation, reducing switching losses. It offers stronger modularity, supporting higher power, but at the cost of increased system size and weight, which makes it more difficult to install in confined wind turbine nacelles.

For applications requiring large power converters, modular converter structures such as IPOS and ISOP are appropriate. These modular structures enhance the converter's power handling capability, improve redundancy, and increase scalability, making them suitable for large-scale wind energy systems that can meet high power demands and improve system reliability. The downside is the increase in system size, and regardless of whether SAB or DAB is modularized, losses will increase. Additionally, the signal control of modular converters becomes more complex, and both the installation within nacelles and the implementation of signal control pose significant challenges.

Simultaneously, Neural Network (NN) controllers and adaptive control strategies are important research directions for the future. Intelligent control can dynamically adjust power scheduling, load sharing, and fault isolation, enhancing system adaptability and fault tolerance.

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