Analysis, Comparison and Selection of DC-DC Converters for a Novel Modular Energy Conversion Scheme for DC Offshore Wind Farms

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Abstract— **Offshore wind farms provide benefits over onshore farms in terms of the amount of generated energy and environmental impact. Cost efficient energy transmission is one of the challenges of such installations. In this context, direct connection of DC wind turbines to the transmission line is a promising solution. This paper proposes a novel energy conversion scheme for the direct connection of the DC wind turbines to the transmission line. In addition, a brief comparison between two DC-DC converters is presented to establish the most suitable topology for the modular DC-DC converter required by the proposed energy conversion scheme.**

Keywords—DC collection network, modular DC-DC converter, series resonant converter, phase-shifted full-bridge converter

I. INTRODUCTION

In 2020, wind energy will play a key role in providing 15% of the generated electricity in the European Union [1]. Thereafter, it is expected that the 30% of the total wind power generation will come from offshore wind farms [1]. Due to the steadier and higher speed wind in offshore sites, higher power extraction than in onshore farms is possible. In addition, the lower environmental impact of offshore wind farms allows the installation of larger turbines than in onshore farms [2].

Despite the advantages, installation of offshore wind farms involves a series of challenges that increases their complexity. Life expectancy is threatened by the salty, corrosive and humid environment [3]. In addition, the accessibility to offshore installations for maintenance or reparation works is more difficult than in onshore wind farms. Furthermore, the transmission of the generated energy through submarine cables is challenging. Depending on the distance and the transmitted power, a high voltage alternating current (HVAC) or a high voltage direct current (HVDC) transmission system can be used [4]. As a reference for subsea and underground cable systems, 80 km is generally considered as the boundary distance above which a HVDC transmission system is preferred [5-6].

If HVAC transmission lines are used, the capacitive behaviour of the long submarine cables increases the amount of circulating reactive current. This leads to additional power cable losses, so, the longer the transmission distance the higher the power losses [5]. On the other hand, with HVDC transmission lines, there is no circulating reactive current. Consequently, better transmission line utilization is achieved [7]. Furthermore, HVDC links require smaller right of ways (power corridors) than their HVAC counterparts due to their smaller diameter and the use of two cables instead of three [8].

In the near future, farther from shore and bigger wind farms are expected. Therefore, HVDC transmission systems will play a key role in offshore installations.

Currently, all installed offshore wind farms with HVDC transmission systems have an alternative current (AC) collection network to connect all the wind turbines [9], Fig. 1. Then, the collected energy is transmitted by the HVDC system. In addition to circulating reactive currents, the AC grid collector needs a sizable offshore platform to shelter a bulky AC transformer [10]. This increases installation costs.

Recent research has focused on substituting AC collection networks by a direct current (DC) equivalent. The use of DC collection networks may improve overall system efficiency (no reactive currents through the cables) and reduce space requirements (elimination of the bulky line frequency AC transformers) [10].

Although different DC collection systems have been proposed [10-15], the parallel connection of DC wind turbines is promising and provides an effective DC collection network solution [10]. In this layout, all the DC wind turbines are connected in parallel directly to the transmission line. Thus, offshore platforms are no longer required, consequently saving an estimated 15-20% of the total infrastructure costs [10].

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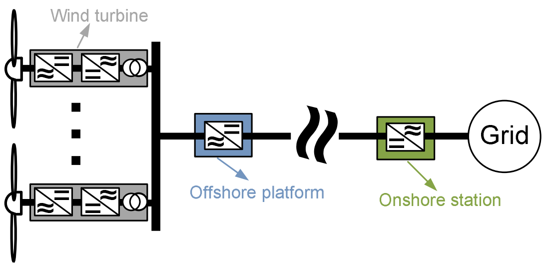

Fig. 1. Conventional offshore wind farm with a HVDC transmission system.

The lack of a standard converter that operates as a DC-DC transformer is the main challenge of this proposal. This converter must be able to boost the turbine side low DC voltage up to the level required for transmission. In addition, the DC-DC transformer must compete in terms of reliability and efficiency, with the AC transformer [16].

Thus, in the first part of the paper, different DC wind farm configurations are described. In the second part, a novel modular energy conversion scheme which allows the direct connection of the DC wind turbines to the HVDC transmission line is proposed. Analysis and comparison of DC-DC converters is presented and finally, the best suited DC-DC converter for the proposed modular energy conversion scheme is selected.

II. OFFSHORE WIND FARMS WITH DC COLLECTION NETWORKS

Generally, two types of DC collection networks can be identified: centralized and dispersed [11]. Centralized DC collection networks operate at lower voltages than the transmission voltage. Consequently, an intermediate DC-DC transformer is required on the offshore platform. The dispersed DC collection grid operates at transmission voltage levels, therefore, no intermediate DC-DC transformer and offshore platform are required.

A. Centralized DC collection networks

Two types of centralized DC networks can be found in the literature.

Fig. 2 shows an example of a centralized DC collection network, which is formed by parallel connection of the DC buses of the generator side rectifiers. Although few converters are used to construct this DC network, the low DC grid voltage, limited by commercially available semiconductor voltage ratings, obliges high cable currents. As a consequence, the required cable sections make the cable expensive [11].

Fig. 3 shows an alternative configuration of a centralized DC collection network with an intermediate DC-DC transformer at each wind-generator. This additional stage reduces system efficiency and reliability, however, the collection grid DC voltage can be boosted to tens of kV to reduce cable power losses, hence cable cross section and costs are reduced [11].

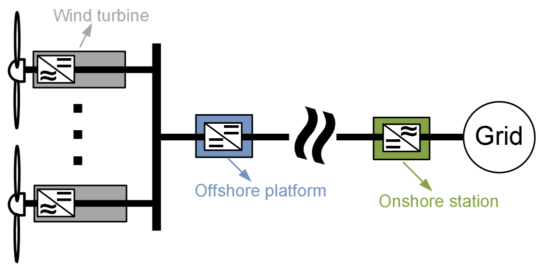

Fig. 2. Centralized DC collection network without turbine side DC-DC converter.

As mentioned, the main drawback of the centralized DC networks is the intermediate DC-DC transformer on the offshore platform to boost the DC grid voltage to the transmission voltage. This converter must manage the power from the wind farm and its failure will jeopardize the entire energy extraction from the wind farm.

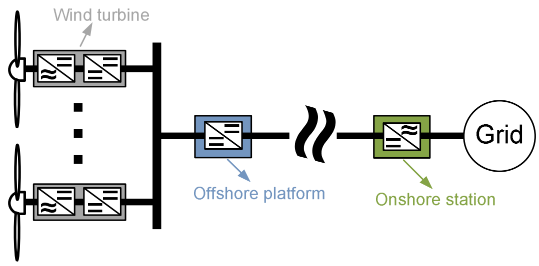

Fig. 3. Centralized DC collection network with turbine side DC-DC converter.

B. Dispersed DC collection networks

The most important characteristic of the dispersed DC collection network is the absence of an intermediate DC-DC transformer. Therefore, the offshore platform is not necessary, thereby reducing installation costs [14].

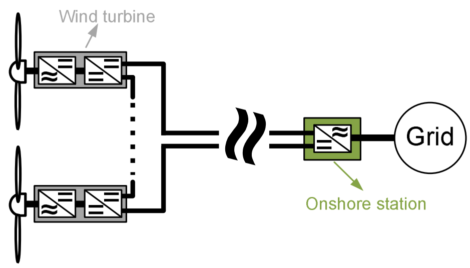

Fig. 4. Series connected dispersed DC collection network.

Two different types of dispersed DC grids can be found in the literature. First, the output stage of DC wind turbines can be connected in series to reach the required transmission voltage, Fig. 4. A rectifier and DC-DC transformer are built into the turbine. In order to connect wind turbines in series, the output stage DC-DC transformers must provide galvanic isolation.

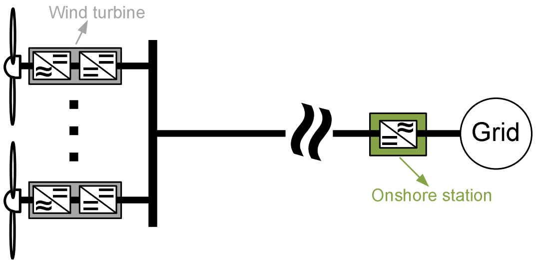

Fig. 5. Parallel connected dispersed DC collection network.

The extracted power difference between the series connected wind turbines makes converter design and control difficult [14]. This is the main drawback of this type of dispersed DC collection network.

Second, the DC wind turbine output stages can be parallel connected [10], Fig. 5. Due to the parallel connection, the turbine control remains simple compared to the series connected wind turbine scheme. In addition, unlike the series connected wind turbine scheme, failure of one turbine should not significantly affect the behaviour of the other turbines.

However, in order to directly connect DC wind turbines to the transmission line, the DC-DC transformer must boost the low rectifier side voltage to the transmission voltage. Thus DC-DC converter design is a challenge.

In summary, due to the characteristics of parallel connected DC wind farms, such a scheme should provide benefits to future offshore wind farm installations.

III. Proposed Modular Energy Conversion Scheme for Parallel Connected DC Collection Networks

Fig. 6 shows the proposed modular energy conversion scheme for parallel connected DC collection networks. The energy conversion scheme is composed of several single phase power stacks. Each stack is formed by a rectifier and a modular DC-DC converter with several conventional input-parallel output-series (IPOS) connected DC-DC converters. The IPOS connection of single DC-DC converters avoids parallel or series connection of switching devices. Thus, the complexity of a single converter design is reduced. Fig. 6 shows the power stacks are series connected to enable direct connection of the wind turbine to the transmission lines. Depending on the number of power stacks and the number of DC-DC converters in each stack, the converter can operate at any input and output voltage level. Additionally, with a large number of DC-DC converters, the proposed modular energy conversion scheme can continue delivering full power even if some modules fail (inherent internal fault management against module failure) [16].

Despite the simplicity of passive rectifiers, active rectifiers are preferred due to its better control range and waveforms quality. In addition, the constant DC bus voltage leads to an optimal DC-DC converter design. If a passive rectifier is used, the DC bus voltage varies with wind speed that may result in suboptimal DC-DC converter design, especially, in term of passive elements' sizes. Here, single phase H-bridge (HB) converters are proposed as rectifiers. Thus, the considered control scheme maintains a constant DC bus voltage for the HB converter which leads to an optimal DC-DC converter design.

When a conventional DC-DC converter is used to boost the low DC bus voltage to the transmission voltage, its switching devices must be connected in series to achieve required voltage blocking capabilities. This increases the converter complexity and reduces reliability.

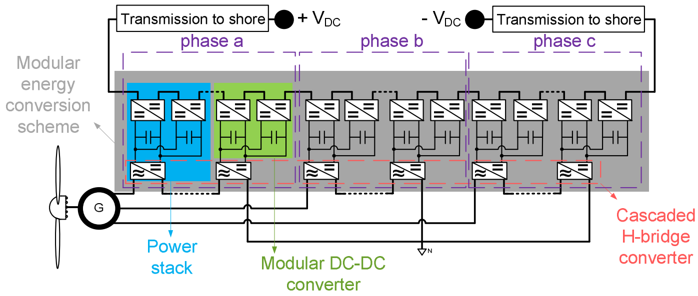

Fig. 6. Proposed modular energy conversion scheme.

Considering the crucial role of the DC-DC converter stage in the proposed wind energy conversion system, it is necessary to conduct comprehensive analysis that may aid in selection of a suitable DC-DC converter for an efficient modular energy conversion scheme with small volume and light weight.

Amongst several DC-DC converters, only the DC-DC converters that provide galvanic isolation are suitable for the IPOS connection. Among the hard switched converters, the low switch number of the half bridge converter makes it a viable topology. However, for a given output power, its large energy storage requirements (in the passive components) make it bulkier and less attractive than other converter topologies. Some papers proposed the use of dual active bridge converters, however, simple and reliable converter structures are preferred in offshore wind generation, even if bidirectional energy flow control capability is not utilized. The full-bridge isolated-boost converter is an efficient converter which does not require bulky passive elements. However, auxiliary switching aid circuits are needed for safe operation, and this increases converter complexity. The single active bridge (SAB) and the phase-shifted full-bridge (PSFB) converters show good trade-off between efficiency and passive element energy storage. Both converters are candidates for the proposed modular energy conversion scheme. As the SAB and PSFB converters are comparable structures, for simplicity, this paper only considers the PSFB converter.

Alternatively, resonant DC-DC converters can achieve high efficiency levels, so they are also considered in this comparison. In order to reduce the number of passive components, only resonant converters that include the leakage inductance of the medium frequency transformer (MFT) in the resonant tank are considered. The series resonant (SR) and the LLC resonant converters are candidates for this application. However, preliminary results for the LLC converter indicate that the required relatively low magnetizing inductance make this converter poorer than the series resonant converter in terms of efficiency and stored energy.

Consequence, in following sections, the phase-shifted full-bridge converter and the series resonant converter will be analysed and compared to find the most suitable converter for the proposed application.

A. Description of the compared DC-DC converters

The SR and the PSFB converters have similar structures. The input DC bus voltage is inverted and applied to the primary of the medium frequency transformer. The series resonant converter has a capacitor which resonates with the MFT leakage inductance. In the output stage, the series resonant converter has a filter capacitor while the phase-shifted full-bridge converter has an LC filter.

The phase-shifting [13] modulation scheme used by the PSFB converter shown in the Fig. 7 enables switch zero voltage switching (ZVS) turn on. Also, this modulation scheme leads to negligible switching losses in the diode rectifier. In order to avoid transformer saturation, the control scheme must guarantee that the average voltage applied to MFT is zero (no DC injection).

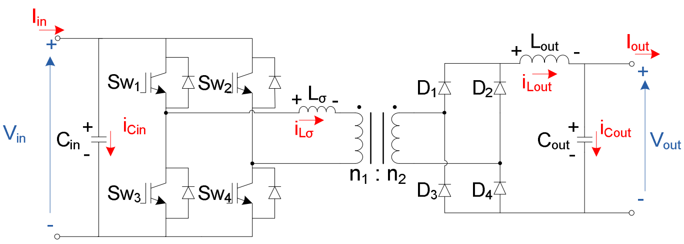

Fig. 7. Phase-shifted full-bridge converter.

The converter output voltage (V_{out}) in Fig.7 depends on the input voltage (V_{in}), the number of turns (n_1, n_2), and the effective duty cycle (δ_{eff}). It can be expressed as [17]:

$$V_{out} = 2 \cdot V_{in} \cdot \delta_{eff} \cdot \frac{n_2}{n_1} \tag{1}$$

From Eq. (2), the effective duty cycle depends on the duty cycle (δ), the leakage inductance (L_σ), the switching frequency (f_{sw}), the input power (P_{in}) and the input voltage (V_{in}). If the transformer has a low leakage inductance, the effective duty cycle is maximized and the required turn ratio can be minimized.

$$\delta_{eff} = \delta - L_\sigma \cdot \left(\frac{2 \cdot P_{in} \cdot f_{sw}}{V_{in}^{\ 2}} \right) \tag{2}$$

The output filter inductance (L_{out}) is based on the desired output current ripple (Δi_{out}) as:

$$L_{out} = \frac{V_{out} \cdot (0.5 - \delta_{eff})}{f_{sw} \cdot \Delta i_{out}} \tag{3}$$

Finally, the output filter capacitance (C_{out}) is based on the desired output voltage ripple (Δv_{out}) and the output current ripple (Δi_{out}) as:

$$C_{out} = \frac{\Delta i_{out}}{16 \cdot f_{sw} \cdot \Delta v_{out}} \tag{4}$$

On the other hand, the SR converter shown in Fig. 8 excites the resonant tank (composed by L_σ and C_r) at a switching frequency (f_{sw}) slightly higher ($f_{sw} \approx f_r$) than the resonant frequency (f_r). Thus, as shown in Fig. 9, the resonant tank provides near load independent unity gain. At this frequency, the switches operate in a zero voltage switching mode, that is, IGBT turn-on losses and diode turn-off losses are negligible and only IGBT conduction and turn-off losses contribute to converter losses.

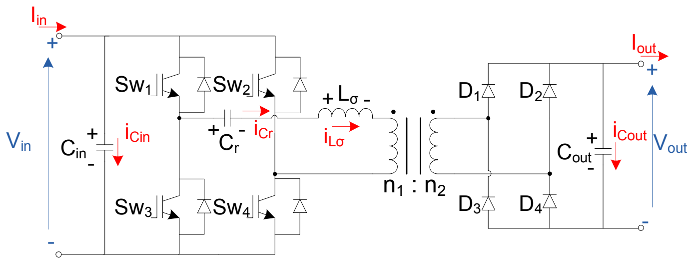

Fig. 8. Series resonant converter.

At resonance, the passive elements stored energy is low [18]. If the duty cycle is changed, the fundamental voltage applied to the MFT primary is controlled by the duty cycle. Thus, the output voltage can be controlled. The transformer turn ratio determines the output voltage for a given duty cycle.

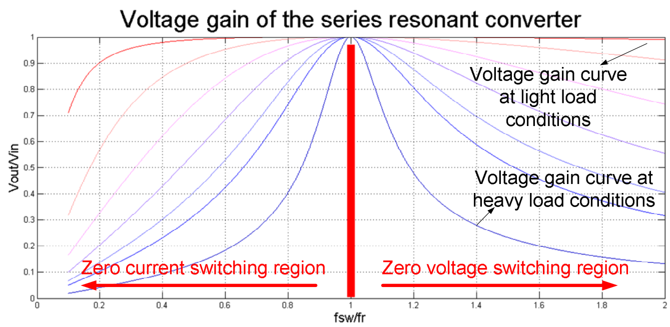

Fig. 9. Voltage gain of the series resonant converter.

The resonance frequency (f_r) is determined by the resonant capacitor (C_r) and the leakage inductance of the transformer (L_σ).

$$f_r = \frac{1}{2 \cdot \pi \cdot \sqrt{C_r \cdot L_\sigma}} \tag{5}$$

The input capacitance (C_{in}) has been calculated considering the instantaneous active power through the single phase HB rectifier. Compared to a three phase rectifier, single phase rectifiers have a second harmonic current component that leads to higher DC bus capacitance requirements.

$$C_{in} \approx \frac{V_{\max HB} \cdot I_{\max HB}}{4 \cdot \pi \cdot V_{in} \cdot \Delta v_{cin} \cdot f_{generator}} \quad (6)$$

B. Comparison of the DC-DC converter cells

As part of an energy generation system, DC-DC converter efficiency is an important aspect. In addition, due to the limited space available for the wind turbines dedicated for offshore wind farms, the volume required by each converter must be considered. The two converter characteristics in Table 1 are designed to have similar efficiencies, power losses and cooling system volumes. Thus, it is considered that the main volume difference between the compared converters results from the bulk of passive components. As a first approach, the volume of passive components is assumed related to their stored energy.

Only semiconductor power losses have been considered. Average conduction power loss (P_{cond}) depends on the semiconductor switch on-state resistance and threshold voltage drop (r_d, V_{th}) and the current flow in the switching device (I_{rms}, I_{ave}).

$$P_{cond} = r_d \cdot I_{rms}{}^2 + V_{th} \cdot I_{ave} \quad (7)$$

Average switching losses depends on the switched current (i_{sw}), switched voltage (v_{sw}), switching frequency (f_{sw}), and the energy loss characteristic provided by the manufacturer (A_{sw}, B_{sw}, C_{sw}) for the 100FIT test voltage (V_{100FIT}).

$$P_{sw} = \sum_{n=1}^{x} \frac{v_{sw}(n)}{V_{100FIT}} \cdot \left(A_{sw} \cdot i_{sw}(n)^2 + B_{sw} \cdot i_{sw}(n) + C_{sw}\right) \cdot f_{sw} \quad (8)$$

The considered generator is a 10MW, 6.6kV permanent magnet synchronous generator (PMSG). The comparison is for different transmission voltages, thus, a wider tendency portrait of the compared converters can be evaluated. For the comparison, the output stage rectifier diodes are 6.5 kV diodes (V_{100FIT} = 3.6 kV). Using such rectifier diodes, Table 1 shows the number of DC-DC converters to achieve the required redundancies per phase. Also the required voltage and current ratings of the input stage IGBTs, for different transmission voltages, is shown.

From Table 1, the number of required DC-DC converters by each topology at each transmission voltage is the same. But the IGBTs must conduct approximately twice current in the series resonant converter. This high current leads to higher tank capacitor (C_r) stress. Therefore, for long durability (life expectancy), this passive component must be carefully designed.

Due to low rated power, power loss and cooling requirements per module, low power DC-DC converters can operate at higher switching frequencies than high power converters. Increased switching frequency leads to smaller passive components, thus, the stored energy per converter is reduced.

TABLE I. CHARACTERISTICS OF THE DC-DC CONVERTERS

	Transmission voltages				
	50 kV	***100 kV***	***300 kV***	***400 kV***	***640 kV***
Total number of power stacks	12	15	21	27	30
Total number of DC-DC converters	24	45	105	135	210
Number of power stacks per phase	4	5	7	9	10
Number of DC-DC converters per phase	8	15	35	45	70
Number of DC-DC converters per power stack	2	3	5	5	7
Number of redundant power stacks per phase	1	1	1	1	1
Input DC bus voltage of the DC-DC converters	1833 V	1375 V	916 V	687 V	611 V
IGBT voltage and current ranges (SR converter)	3.3 kV 800 A	3.3 kV 800 A	1.7 kV 300 A	1.7 kV 300 A	1.2 kV 225 A
IGBT voltage and current ranges (PSFB converter)	3.3 kV 400 A	3.3 kV 400 A	1.7 kV 150 A	1.7 kV 150 A	1.2 kV 100 A
Efficiency of the SR converter	98,76%	98,36%	98,77%	98,92%	98,49%
Efficiency of the PSFB converter	98,77%	98,33%	99,10%	98,95%	98,48%

In Table 1 and Fig. 10, the transmission voltage increase leads to a higher number of DC-DC converters. As a consequence, the rated power of the required converter is lower and the stored energy is reduced. In Fig. 10 the SR converter stores more energy than the PSFB converter for a similar efficiency. Thus, the series resonant converter has bulkier passive components than the phase-shifted full-bridge converter.

Although both converters are suitable for this application, based on lower passive component stresses, lower current rate of switching devices, and lower volume required by the PSFB converter, the phase-shifted full-bridge converter is the preferred choice for the DC-DC converters.

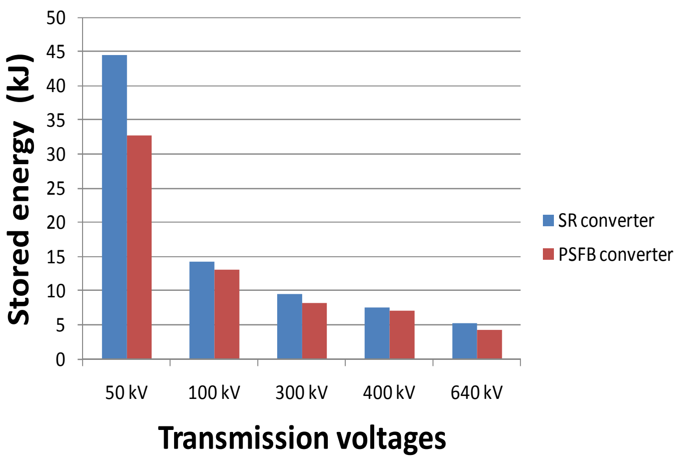

Fig. 10. Stored energy by each energy convertion scheme at each transmission voltage.

IV. CONCLUSION

In this paper, a novel modular energy conversion scheme for offshore wind farms was presented. Its high modularity allows operation at any generator and transmission voltage using standard power stacks. Redundant stacks can be added to increase converter reliability.

A key component of the proposed conversion scheme is the DC-DC converter. High efficiency and low volume requirements are desirable for offshore wind farms connection. Qualitative analysis was used to reduce the pool for choices to between series resonant and the phase-shifted full-bridge converters. The detailed quantitative comparison of these two converters shows that the phase-shifted full-bridge converter is better suited for the proposed modular energy conversion scheme than the series resonant converter.

Future research will focus on the design, control and reliability analysis of the proposed energy conversion topology. In addition, the cost of the proposed solution will be evaluated and compared with existing solutions.

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