Power Electronic Converters Review for Wind Turbine Applications: State of Art, Reliability and Trends

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***Abstract*--Wind energy has recently became the most promising renewable energy. The global cumulative installed wind power capacity increased dramatically to reach 627GW in 2019. In order to handle the growing size and more stringent grid codes, researchers have developed and improved many converters topologies. Some of these converters are commercialized while others are still in development. This paper presents the state-of-the-art of the power converters usable in wind turbine applications, an overview of the most interesting converters topologies and their efficiency in Wind Turbine Systems (WTS). As reliability became essential in WTS, especially in offshore turbines, a detailed study on the reliability of the static converters used in WTS with a comparison analyse of the most reliable configurations and their fault tolerant ability. The study shows the importance of the choice of the power converter topology in the overall reliability of WTS.**

Keywords- Power Electronic Converters; Wind turbine; reliability; trends.

I. INTRODUCTION

Unlike the fossil fuel energy, with renewable energies, it is possible to produce electricity without harming the environment. In the last decade, with global awareness of climate warming, electricity production from the energy renewable has come under increasing attention. In 2019, the power production from renewables energies has reached 2530GW, it is about a third of total installed electricity capacity. Wind power is the second most renewable energies installed in the word with 627GW which represents 21% of global energy renewable electricity production [1].

The used technology in wind turbine applications has changed since the power capacity penetration has grown dramatically to reach, for example, 14% of all electric energy consumption in Europe and 41% of all electric energy consumption in Denmark [2]. The first configuration used in wind turbine applications was a fixed-speed Squirrel-Cage induction Generator (SCIGs) directly connected to the grid.

Recently, as the power capacity of the wind turbines increases, regulating the frequency and the voltage in the grid becomes a very important issue, the technology has developed toward variable speed. Permanent Magnet Synchronous Generator (PMSG) connected to the grid through a power converter shows nice properties like high efficiency, small size, and low maintenance; hence, it is a nice choice for wind turbine applications.

The purpose of this paper is to give an overview of recent converters technologies used in WTS. On other hand, as reliability is a major challenge in WTS, a comparative study about reliability of those converters is presented.

In section II, an overview of existing technology market developments of wind power generation. In section III, the most used wind turbine configurations and currents promising power converters topologies for WTS are presented. In section IV, the reliability of WTS components is analyzed. In section V, as they constitute one of major source of failure, a study about reliability of power converters used in WTS is presented. Finally, the conclusions are presented in section VI.

II. WIND TURBINE SYSTEMS

The wind power installed capacity is growing significantly since 1999 to reach 58 GW installed only in 2019. Therefore, the cumulative installed wind power capacity increased exponentially from 6100 MW in 1996 to 627 GW in 2019. Estimation predicts that this number would reach 2015 GW in 2030. Approximately 10 countries have more than 83% of all cumulative installed wind power capacity in the world, including 5 countries in Europe (Germany, Spain, UK, France, Italy), 2 in the Asia-Pacific (China, India), 2 in North America (US, Canada) and 1 in Latin America (Brazil), [1]. This dominance is shown in Figure 1 and it's obvious that countries with high technology advancements have a higher growth rate and higher penetration of wind power electricity. The large turbine presents a lot of advantages. They allow capturing a high power with low installation and maintenance costs compared to the small turbines. Hence, the size of the commercial wind turbine has greatly increased in the last decade as presented in Figure 2. The largest wind turbine reported in 2020 is 12MW with a diameter of 220 m (General Electric Haliade-X 12MW), and it is will be commissioned in 2021.

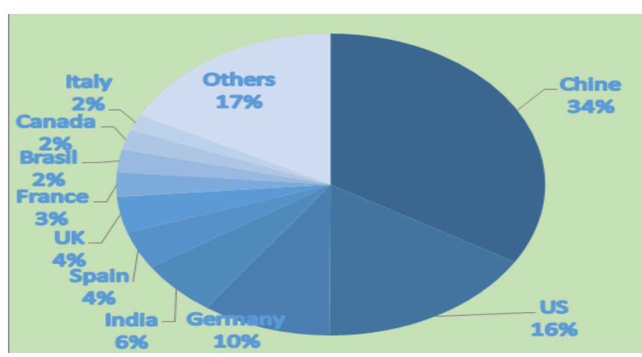

Figure 1. Renewable wind energy capacity in the word [1].

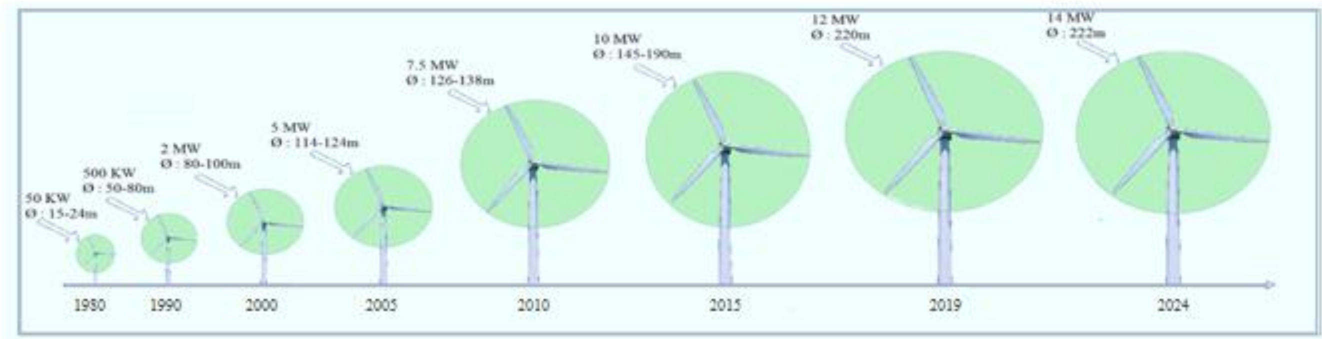

Figure 2. Evoluion of wind turbine size since 1980 .

Siemens Gamesa has announced that they are developing 14 MW wind turbine with a rotor diameter of 222 m. It announced that the turbine will be available in 2024 [3]. Denmark based wind turbine company Vestas remained the world's largest wind turbine manufacturer and supplier in 2018 [4], due to its wide geographic diversification strategy and strong performance in the U.S. market.

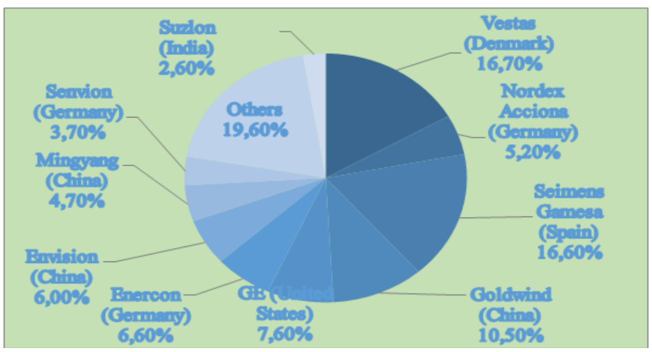

Figure 3. Top 10 Wind turbine suppliers market share in 2018 [4].

The top 10 wind turbine manufacturers in the world are shown in Figure 3. The world's largest wind turbine companies account for over 75% of the global installed capacity every year, and their industrial dominance is expected to continue over the future.

III. WIND TURBINE CONCEPTS AND CONVERTERS TOPOLOGIES

Depending on the types of generator, power converters and speed control, most wind turbine can be classified into following four types:

- Type 1: Fixed-speed wind turbine systems;
- Type 2: Semi-variable speed wind turbine with variable rotor resistance;
- Type 3: Variable speed wind turbine with partial-scale converter;
- Type 4: Variable speed wind turbine with a full-scale converter.

All those wind turbine technologies have been used and commercialized in the last 30 years. Due to their efficiency the two last configurations are the most dominant technologies in the market. The power converters is one of the most important components of Wind Turbine System (WTS). The main objective of the power converters is to ensure the generator speed variation control in the turbine system. To accomplish this purpose, different topologies of converter have been proposed in the literature in the last decades. Recently, with the growing wind turbine penetration, these converters have to fulfil several technical requirements. The converter cost is an important factor, since it represents approximately 7%~8% of the global cost of the wind turbine system [8][9]. The cost of maintenance must also be as low as possible to reach less expensive and competitive energy compared with the others sources of energy, reliability is also an important element in the choice of the converters. The efficiency of the converters is also very important, especially in high power wind turbines where even, 1% efficiency improvement can save thousands of dollars over a period of a few years [19]. The output power quality of the converters is a primordial in the comparison between the different topologies. The output voltage should be as close as possible to the sinusoidal shape with low total harmonic distortion (THD) and small filter for a better converter [12][17]. The power converters can be classified as direct and indirect according to the different stages of the conversion. Overall, the indirect Back-to-Back (BTB) converters technology is the most used in the wind turbine applications [10].

A. *Two-levels Voltage Source Converter* (*2L-VSC*)

The two-levels voltage source converters are the most widely used converters on the market. For its simple, configuration this technology is mastered and well established in the field of wind energy conversion. It is considered a dominant topology used in around 90% of the wind turbines with power less than 0.75 MW. As illustrated in Figure 4, the Voltage Source Rectifier (VSR) and the Voltage Source Inverter (VSI) are back-to-back and are connected to a dc-link capacitor. This dc-link ensures the decoupling between the generator and the grid, therefore transient in the generator do not appear on the grid side. The VSR controls the torque and speed of the generator, while the VSI controls the voltage of the dc-link and the reactive power of the grid.

The VSR and the VSI are generally made with low-voltage transistors (LV-IGBT) arranged in a matrix. The switching frequency of VSR and VSI are fixed between 1 and 3 kHz to achieve low witching loss and high power density [5].

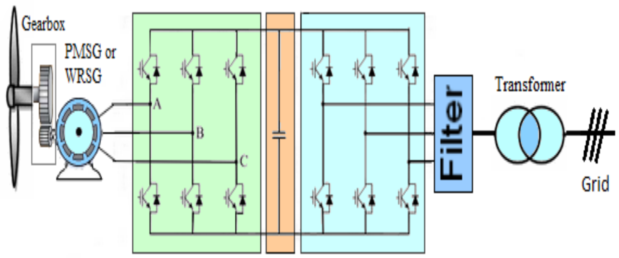

Figure 4. BTB based on the two-levels voltage source converter.

B. Parallel two-levels Voltage Source Converter (2L-VSC)

To achieve high current capacity, two or more VSC converters can be connected in parallel depending on the power required. As illustrated in Figure 5, two VSC modules are connected in parallel to reach a power of 1.5 MW corresponding to type 4 of the wind turbines. For type 3 of the wind turbines, connecting two modules in parallel can achieve a power of 5 MW. This configuration allows a wide margin for redundancy operation. To improve the system efficiency in the case of under production one or more converter modules can be put out of service. The redundancy of the converters allows to the wind turbine to continue operating at reduced capacity in the case of a fault in the converters, after the faulty module is isolated. In the Gamesa G128, more than 6 power converters are connected in parallel to reach a nominal power of 4.5 MW [11]. However, the major disadvantage is that a large number of modules lead to the complexity control and congestion of the system.

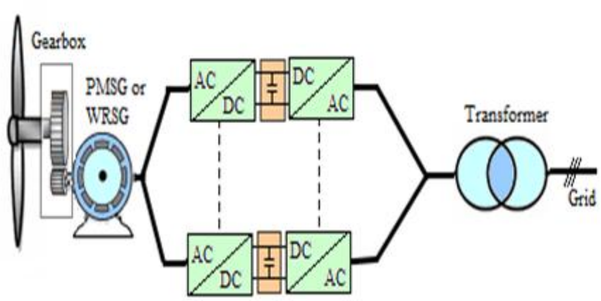

Figure 5. WTS with parallel connected BTB Two-levels VSCs

C. Three-levels Neutral-Point Clamped Converter (3L-NPC)

Another solution that has been widely studied in the literature for type 4 of the wind turbines is the three-levels Neutral Point Clamped converter (NPC). In this configuration, an arrangement of four power switches per leg, clamped with diodes to a midpoint of the dc-link. With this configuration, each power device has to block only half of the total converter voltage then the power of the converter can be doubled [13]. The output phase voltage of the converter contains three-levels leading to a reduced voltage variations dv/dt and electromagnetic interference compared to the 2L-VSC converters [12][13][16][20]. The main drawback of 3L-NPC is that the power switches do not have symmetric losses, forcing a derating of the devices. As shown in Figure 6, NPC converters enable medium voltage operation, and commercial wind turbines reached 6 MW rated power without connecting serial or parallel switching devices. These converters are installed and marketed with the "Multibrid M5000" wind turbine [6][22].

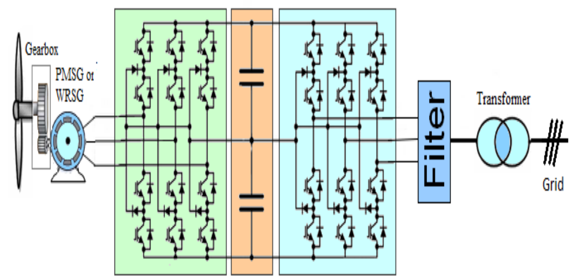

Figure 6. Three-levels Neutral-Point Clamped Converter (3L-NPC) .

D. Three-levels Active Neutral-Point Clamped Converter (3L-ANPC)

The Active Neutral Point Clamp (ANPC) converters, illustrated in figure 7, have a structure almost identical to the NPC converters, the diodes are replaced by Insulated Gate Bipolar Transistor (IGBT) switches. Although more active switches are used, that allowing more redundancy to maintain the frequency and the same switching losses in all the IGBT switches, [6][12][23][24]. In similar operations, BTB 3L-ANPC converters are capable of handling 32% higher power (up to 7.12 MW) and 57% higher switching frequency (1650 Hz) compared to 3L-NPC BTB converters. This configuration has been applied more recently in the field of MV drives and can also be used in the wind turbine system sector [18]. Vestas, one of the leading manufacturers, is currently studying this power converter topology, [19].

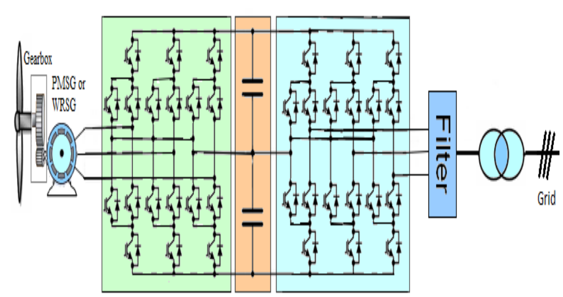

Figure 7. Three-levels Active Neutral-Point Clamped Converter (3L-ANPC).

E. Three-levels Flying Capacitor Converter (3L-FC)

The configuration of the Flying Capacitor converter (FC) is similar to the NPC converter, where the clamping diodes

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are replaced by the floating capacitors. The concept of FC was introduced in the early 1970, and was introduced into machines drives applications in the 1990. The converter generates additional voltage levels while reducing voltage stress on the drive [14]. The power switches, setting an FC between two devices, is illustrated in Figure 8. Each pair of switches with an FC constitutes a power cell.

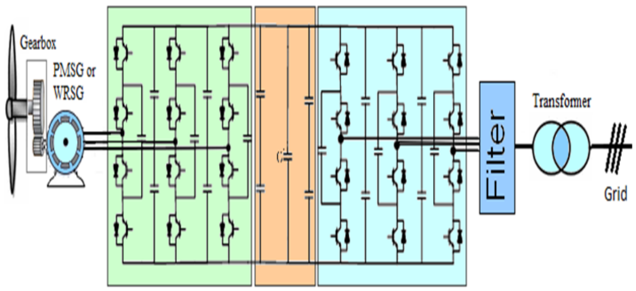

Figure 8. Three-levels Flying Capacitor Converter (3L-FC)

The most important difference with the NPC topology is that the FC has a modular structure and additional cells can be connected, increasing the number of voltage levels of the converter and the power rate.

The advantages of the flying capacitor multilevel converter are flexible switch mode, high protection ability to power devices, to control active power and reactive power conveniently [25][26]. The 3-levels configuration has found a practical application, but has not yet found a commercial success in wind turbines.

IV. WIND TURBINE SYSTEM RELIABILITY

Recently, with the orientation of wind energy manufacturers towards offshore wind turbines, the issue of the reliability of wind systems has become a major preoccupation for what it generates maintenance costs caused by accessibility limited of wind farms. This problem has been extensively studied in literature to identify a major failure in wind systems. Researchers have conducted surveys of the reliability of wind systems at various wind sites around the world to identify the most common faults in these systems [27-31]. According to a study published by the University of Kassel, Germany in 2006 [27], based on the recovery of maintenance data from a 13 years (1993-2006) on a wind power site Germany, the power converters is a leading cause of failure in wind system as shown in Figure 9. Another study [28], shows that the use of maintenance data recorded for 11 years in a field of 650 wind turbines in Germany allowed researchers to identify the main causes of failures on this site. The conclusions given in [28] show that the defects in the converters represent a large part of these defects. They are ranked in 3rd position just behind the faults in the electrical system control and the mechanical defects in the rotor.

More recently, in 2016, a study of the City University of Hong Kong on two wind farms in China [29], the researchers found different results: -The first project, which contains 61 wind turbines of 1.5 MW, with data recovered over a period of 4 years between 2009 and 2013, the result shows that electrical systems (converters) account for 14% of the failures. The control of the wind system accounts for the largest share of these defects with 35% of total defects recorded over this period. The second project contains a small number of wind turbines, 46 wind turbines, but with a power greater than that of the first project, 2 MW by a wind turbine. The analysis of maintenance data over a period of two years show that electrical systems (converters) account for 26% of failures, equal to failures rate found in the control system.

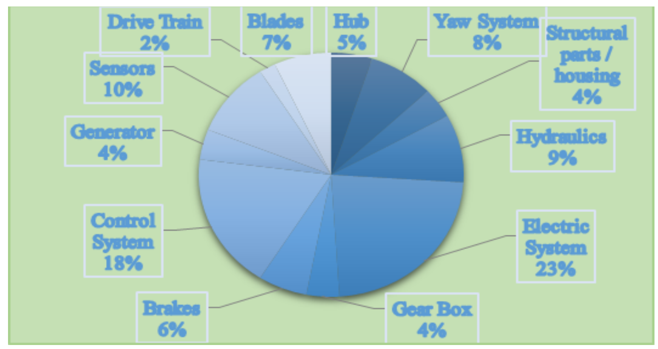

Figure 9. Share of main components of total number of failures [27].

The wind turbines designed in 2000 are generally based on fixed or semi-variable speed technology, different from the technology generally used this last decade based on the synchronous machine with variable speed. It can be noted that the zone of the installation of these fields also plays an important role in the rates of defects of the components. Another point that can be made is that the reliability of wind turbines systems depends on the reliability of the used components and experience of the manufacturers. However, despite the difference in the failure rates between the different components of the wind system, which can be found in the different studies, the defects in the converters are considered as a major element in the shut-down of the service in the almost all of these studies.

V. CONVERTERS RELIABILITY IN WIND TURBINES APPLICATIONS

In the following, a deep analysis of the different reliability studies carried out on wind turbines around the world is proposed. The purpose of this analysis is to find a link between the different systems used in wind turbines and the failure rate in power converters. This study will allow us to identify the causes of failures in power converters and to propose the solutions and topologies to be used to improve the reliability of wind turbine systems. In [28] and [30], the results of the data recovered on the wind farms, affirm that, contrary to that is widespread in the literature, the failures in the systems with direct drive permanent magnet synchronous generator (PMSG) are more significant to those with indirect drive doubly-fed induction generator (DFIG). In their conclusions, the authors ask questions about the usefulness of the systems based on PMSG generators with the number of failures recorded, while it is supposed to improve the reliability of wind turbines systems. In the same study of the

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TABLE I. COMPARISON OF BTB CONVERTERS TOPOLOGIES FOR HIGH POWER WIND TURBINES [6].

	2L-VSC	Parallel 2L-VSC	3L- NPC	3L-ANPC	3L-FC
Typical Power	0.75 MW	5.0 MW	3.0-12.0 MW	3.0-12.0 MW	3.0-12.0 MW
Number of Converters	1	6	1	1	1
Number of Switches	12	72	24	36	24
Switching devices	LV-IGBT	LV-IGBT	MV-IGBT/ICGT	MV-IGBT/ICGT	MV-IGBT/ICGT
Diodes	0	0	12	0	0
Capacitors	0	0	0	0	6
Device voltage Stress	V_{dc}	V_{dc}	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$
Reliability of System	++	+++	+++	+++	++
Redundancy	No	Yes. Module redundancy	No	No	No
Advantages	Simple and matured technology	Redundancy	Low harmonic Matured technology	Low harmonic Equal loss distribution	Low harmonic
Disadvantages	Limited Power	Complex control	Unequal loss distribution	A large number of switches	Complex control
Technology status	Highly Mature	Highly Mature	Well established	Research Only	Research Only
Power Density	Moderate	Low	High	High	High

University of Columbia [30], the failure rates in the electrical converters used in the case of the two systems (Geared/ Direct drive) are studied and compared. The failures at the converters are greater in the case where the system is based on direct drive technology. In another study [31], maintenance data from 2220 turbines were studied to determine the failure rate in the various components of these systems. The wind turbines studied are modern types, with power ranging between 1.5 MW to 2 MW. They are divided into two groups, depending on the training configuration. The first group is made up of 1800 turbines based on the DFIG generators. The second group consists of 400 turbines equipped with the PMSG generators. It should be noted that the converters used in the two configurations belong to the same manufacturer, which will allow us to analyse and compare the failures of these converters for each configuration. The comparison between the failure rates of the power converters of the two systems illustrated in Figure10 shows that the converter in the direct drive system with PMSG generators presents annual failure rate of 0.593 which is approximately four times more than the failure rates recorded in the system based on the DFIG generators.

To answer the questions on the number of significant failures recorded in PMSG generators systems compared to systems based on the DFIG generators, asked by the authors in, [28][30].

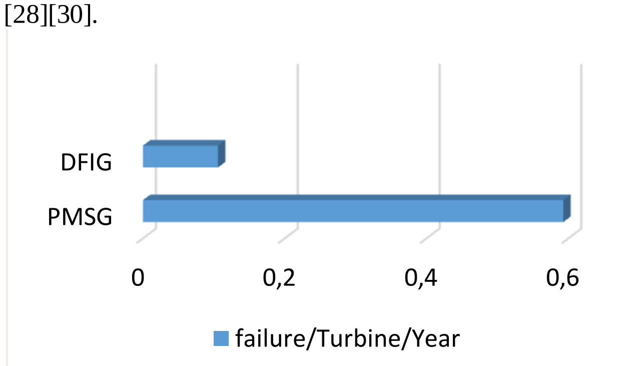

Figure 10. Annual failure rate [31].

This difference is mainly due to the increase in failures in power converters. Knowing that for the same power value of a turbine, the used converter in the PMSG systems must have a power three times higher than that of the converter used in DFIG systems, since in the latter case, the power supplied via the converter represents only part of the overall power supplied by the turbine. Since the maximum power of a two-levels converter does not exceed 750 kW, to increase the powers in PMSG systems, manufacturers tend to put in

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parallel several two-levels converters as presented in Figure 5, which generates the increase of the number of switches and proportionally the number of failures in the system. Figure 11 illustrates a comparison between the failures of converters recorded in two studies [30][31] with turbines of different powers. It is noted that the increase in the power of the turbine generates the increase in the difference between failure rates between the DFIG systems and the PMSG systems, due to the paralleling of two-levels converters to achieve the desired power.

In the literature, the reliability of the power converters is linked only to the redundancy of the system, something which could be sufficient in the case of onshore wind turbines. Furthermore, in offshore wind turbines where for economic and production reasons, the reliability requirement is more important any source of failure must be considered.

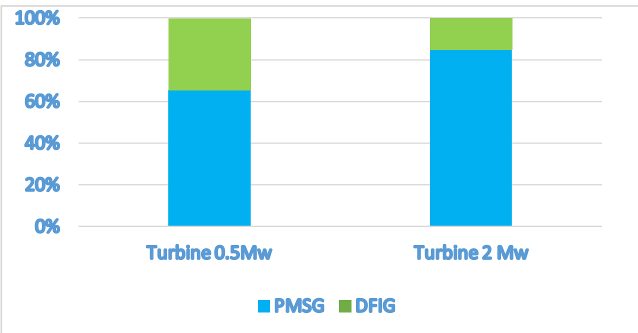

Figure 11. Converters failures rates based on the power of the turbine.

Therefore, in this study the analysis of several maintenance data from different wind farms around the world, allowed us to identify the importance and the need to take into account the number of switches used in the converters as a criterion for the reliability of energy conversation systems. Moreover, the choice of the most reliable converter topology is depending on the power of the application. In Table I, an example of reliability of converters for a 5 MW wind turbine, in this case the paralleling of 2-level converters do not offer higher reliability since the number of switches which are fragile components becomes very important and decrease the reliability of the whole system. Multilevel converters, especially modified 3-level NPC converter with redundant arm [32][33][34] can be the most suitable for this application, as they present redundancy and low number of switches.

VI. CONCLUSION

The global production capacity of wind turbines has been steadily increasing over the past ten years, and as a result the penetration rate has risen dramatically, which imposes more requirements and constraints on the design of the wind turbines systems. This paper gives a summary of the latest technologies and industrial solutions used in the field of wind turbines. The paper shows the importance of power converters in the performance and efficiency of the wind turbines systems. Several topologies of converters are studied in the literature. However, only a few topologies are used today in the real industry applications. The choice of the converters is important in the global wind turbines systems. The two-levels converters are most used but with the current trend towards systems with high power levels and high voltage levels, multilevel converters, especially three-levels NPC converters represent the most suitable system. For reliability of the power converters issues, the failures at the level of converters are proportional to the number of switches used in the energy conversion system. The majority of recent studies claim that, contrary to popular belief, failures in systems based on PMSG generators are greater than those in systems based on the DFIG generators. In our study, we explain the reasons which are mainly due to the significant increase in failures in the power converters system. However, systems based on the PMSG generators remain the most reliable for onshore wind turbines since the downtime caused by a failure at the converters is significantly lower than that caused by a failure of the gearbox.

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