Reliability and Performances of Power Electronic Converters in Wind Turbine Applications

Aimad Alili, Mamadou Baïlo Camara, Brayima Dakyo and Jacques Raharijaona
GREAH Laboratory, University of Le Havre Normandy
Le Havre, France
Email: Alili.aimad@univ-lehavre.fr,camaram@univlehavre.fr,brayima.dakyo@univ-lehavre.fr,
jacques.raharijaona@univ-lehavre.fr

***Abstract*-The reliability of wind turbines system (WTS) is becoming a key issue as the penetration rate of wind energy is continuing to grow in the last decades. The reliability of a wind turbine is the reliability of all the components and sub-systems that compose the entire system. In this paper, we present a study of the wind turbines structures, currently used components and technologies. A review of wind turbine maintenance data from multiple wind turbines firms installed in different countries and different climatic zones. The study aims to identify the most critical components of the different technologies used in WTS and the effect of the wind turbine structure on the global failure rate of the WTS. We focus on two of the most used configurations in WTS (Variable speed wind turbine with partial-scale converter and Variable speed wind turbine with a full-scale converter) and the power converters associated with these configurations. These converters represent one of the most fragile components according to the data of major reliability studies. The comparison between the reliability rate of the different WTS topologies show the importance of the choice of the configuration and power converter topologies to ensure the availability of WTS.**

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

I. INTRODUCTION

In order to reduce the dependence of their countries on fossil fuels and to increase the production of electricity by clean energy. Government investment in renewable energies is increasing. Therefore, the renewable energy production is growing worldwide, in 2020, the global production capacity has reached 2799 GW, it is about a third of total installed electricity capacity. Wind power is the second most renewable energies installed in the word with 733 GW, which represents 26% of global energy renewable electricity production [1][2].

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 [3]. The first configuration used in wind turbine applications was a fixed-speed Squirrel-Cage Induction Generators (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. Manufactures are moving toward variable speed Permanent Magnet Synchronous Generator (PMSG) connected to the grid through a power converter. This configuration 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 the other hand, as reliability is a major challenge in WTS, a comparative study about the reliability of the 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 the major sources of failure, a study about the 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 93 GW installed only in 2020. Therefore, the cumulative installed wind power capacity increased exponentially from 6100 MW in 1996 to 733 GW in 2020. 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) [2]. This dominance is shown in Figure 1 and it is obvious that countries with high technology advancements have a higher growth rate and higher penetration of wind power electricity.

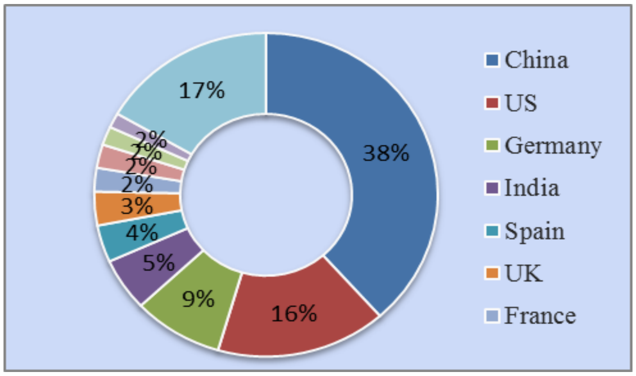

Figure 1. Renewable wind energy capacity in the word.

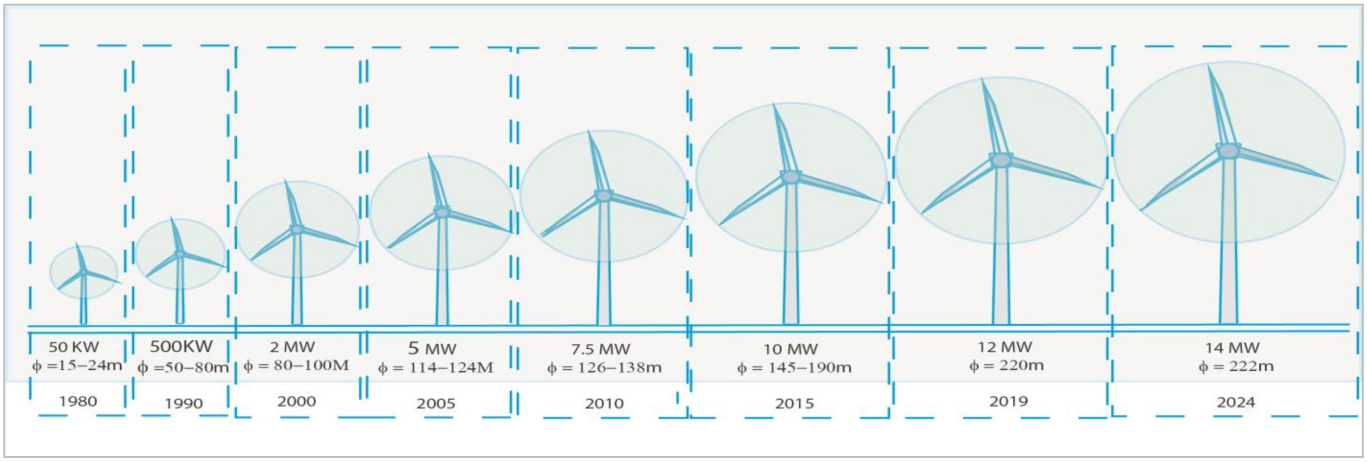

Figure 2. Evoluion of wind turbine size since 1980.

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 2021 is 12MW with a diameter of 220 m (General Electric Haliade-X 12 MW), and it will be tested to operate at 13MW. 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 [4].

Denmark based wind turbine company Vestas remained the world’s largest wind turbine manufacturer and supplier in 2018 [5], due to its wide geographic diversification strategy and strong performance in the U.S. market.

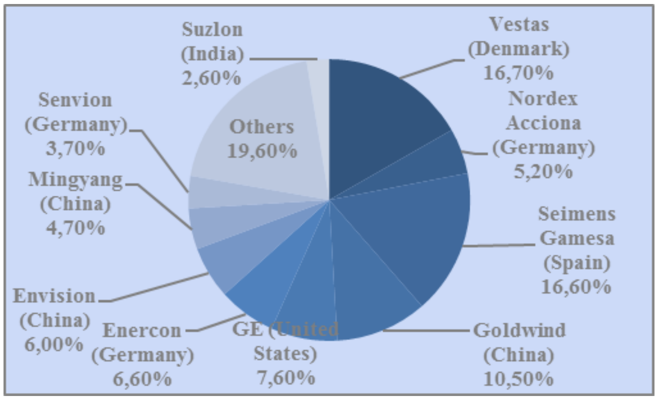

Figure 3. Top 10 wind turbine suppliers market share in 2018 [5].

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

A. Wind turbine concepts

Depending on the types of generator, power converters and speed control, most wind turbine structures 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 these 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. In the following, these two wind turbine concepts are going to be exposed.

1) Variable Speed Wind Turbine with a partial-scale converter

Variable speed wind turbine with the partial-scale converter is generally associated with a doubly fed induction generator (DFIG), the typical configuration of this technology is shown in Figure 4. The induction generator is directly connected to the grid and the rotor is interfaced through a back-to-back power electronic converter. The converter system includes two AC/DC-based Voltage Source Converters (VSCs) connected by a DC-bus voltage. The power converter controls the rotor frequency and thus the rotor speed. Typically, the variable speed range is +30% around the nominal speed [7][8]. The main advantage is that only a part of the power production is fed through the power electronic converter. Hence, the nominal power of the power electronics converter system can be less than the nominal power of the wind turbine. In general, the nominal power of the converter is about 30% of the wind turbine power. The gearbox is essential in this type of configuration. Some commercial solutions using this technology are Repower 6M, 6.0 MW; Bard 5.0, 5 MW; Senvion 6.2m 126; General electric GE.6-82.5 and Acconica AW-100/ 3000, 3 MW; Shanghai el W3600/122, 3.6MW; Nordex N80,1.5-2.5MW; Sinovel, 3MW [21].

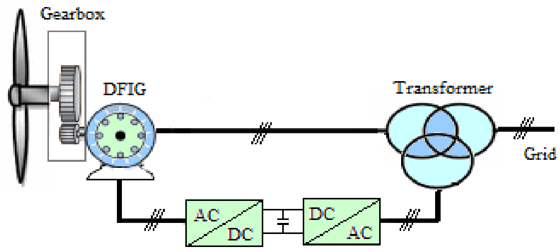

Figure 4. Variable-speed wind turbine with a partial-scale converter

2) *Variable Speed with a Full-scale Converter*

A variable speed wind turbine partial-scale converter is shown in Figure 5. In this configuration, the wind turbine uses a full-scale power converter between the generator and grid to enhance performance. Since all the generated power has to pass through the power converter, the power converter must be rated the same as generator capacity, which involves increasing the size, cost, and complexity of the system. However, the wind energy conversion efficiency is highest in this turbine compared to other types of turbines and the gearbox can be eliminated by using a high pole synchronous generator [13].

The PMSG, SCIG, and Wound Rotor Synchronous Generator (WRSG) have all been used in this type of configuration. However, due to the reduced losses, weight, and noise, the PMSGs are most commonly adopted and they are becoming the best seller technology in the wind energy market. Manufactures are commercialized several models of wind turbines based on PMSG full-scale technology: Goldwind GW140/3000; Enercon E126, 7.5 MW; Siemens Gamesa SG 8.0-167 DD, 8 MW; General electric Haliade 150, 6MW; Multibrid M5000, 5 MW; Adwen AD 5-135 and Vestas V-112, 3 MW [7][20].

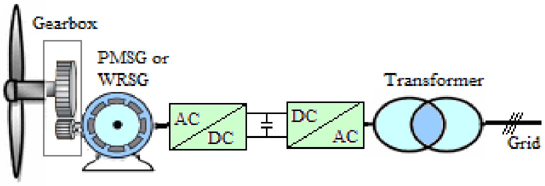

Figure 5. Variable speed wind turbine with a full-scale converter

B. *Converters For Wind Turbine System*

The power converter 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 [9][10]. 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 [20]. 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 [13][16][18]. 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) converter technology is the most used in the wind turbine applications [11].

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

The two-level 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 6, the Voltage Source Rectifier (VSR) and the Voltage Source Inverter (VSI) are back-to-back and are connected to a DC-bus capacitor. This DC-bus 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 [6].

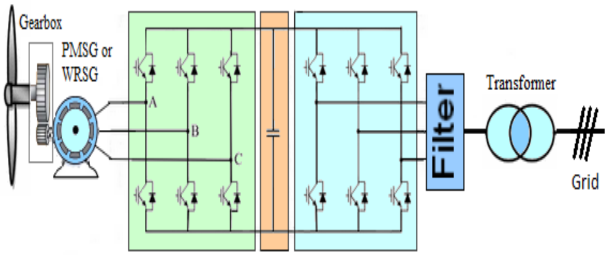

Figure 6. BTB based on the two-levels voltage source converter.

2) 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 7, 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 redundant operation. To improve the system efficiency in the case of underproduction, one or more converter modules can be put out of service. The redundancy of the converters allows 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 [12]. However, the major disadvantage is that a large number of modules lead to the complexity control and congestion of the system.

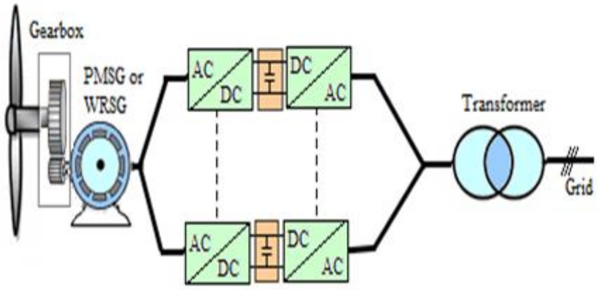

Figure 7. WTS with parallel connected BTB Two-levels VSCs

3) 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 [14]. 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 [13][17][21][22]. 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 8, 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 [7] [23].

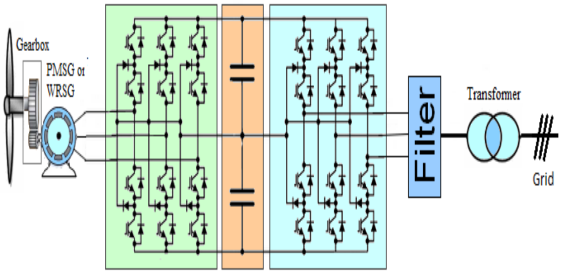

Figure 8. Three-levels Neutral-Point Clamped Converter (3L-NPC) .

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

Active Neutral Point Clamp (ANPC) converters illustrated in Figure 9 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 [7][13][24][25]. 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 [19]. Vestas, one of the leading manufacturers, is currently studying this power converter topology [20].

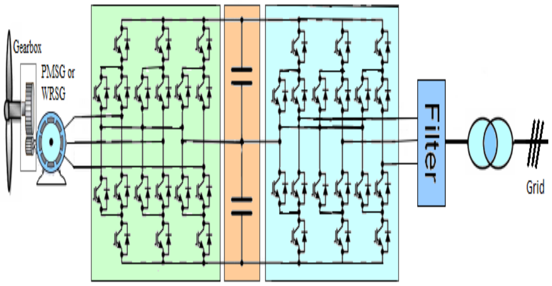

Figure 9. Three-levels Active Neutral-Point Clamped Converter (3L-ANPC).

5) 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 are replaced by the floating capacitors. The concept of FC was introduced in the early 1970, and was introduced into machine drives applications in 1990. The converter generates additional voltage levels while reducing voltage stress on the drive [15]. The power switches, setting an FC between two devices, are illustrated in Figure 10. Each pair of switches with an FC constitutes a power cell.

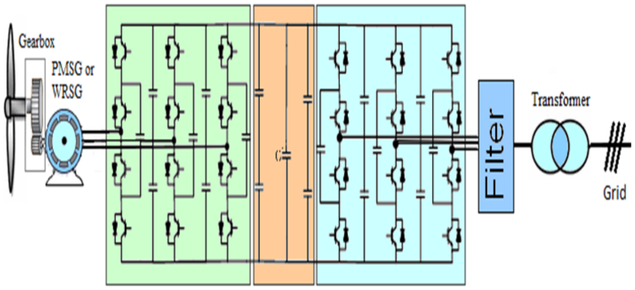

Figure 10. Three-levels Flying Capacitor Converter (3L-FC)

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 [26][27]. 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 due to the maintenance costs caused by limited accessibility of wind farms. This problem has been extensively studied in literature [28-33].To identify the major cause of 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:

- CIRCE

CIRCE is a research project on the reliability of wind systems conducted by the University of Zaragoza in Spain. SCADA data are collected over a period of three years on different wind farms, the totality of wind turbines studied is close to the 4300 onshore wind turbines of variable power between 0.3 and 3 MW. Two wind turbines configurations, geared and direct drive technologies are studied in the study. Data from the reliability analysis of the 23 wind farms included in this research are published in [34].

- CWEA

The CWEA study is carried out in China over a period of two years between 2010 and 2012. The data are published in [35] where the data analysis of 640 wind turbines with a power between 1.5 and 6 MW is presented. In this study, only the critical faults are considered, and the published data do not allow to differentiate the types of technologies used in these wind turbines.

- LWK

In [35] the LWK project data are presented. The data are collected over a period of 13 years from onshore wind sites in northern Germany. In total, the maintenance data of 643 wind turbines of power varying between 0.2 to 2 MW per wind turbine are exploited in this study. The reliability of wind power systems of both geared and direct drive concepts is studied and the failure rate of different components is exposed.

- Huardian project

The study includes maintenance data from 26 wind farms located in China. These sites are made up of 1313 wind turbines of different technology type and of unspecified power. The study is published in [36], failures are presented as a percentage, which makes it difficult to use the data.

- EPRI

Electric Power Research Institute (EPRI) based in the USA is at the initiative of this project. The data come from maintenance data from various wind farms in California. The number of wind turbines exploited in the study is small (290 wind turbines) of very low power, which varies between 0.04 to 0.6 MW. The technology of the wind turbines studied is very old, due to the fact that the study was carried out between the years 1986 and 1987. The study is published in [37].

TABLE I. WIND TURBINE SYSTEM COMPONENTS

Subsystem	Assembly	Subsystem	Assembly
Rotor system	Blade Hub Air brake Pitch system	Hydraulic system	Hydraulic system
		Yaw system	Yaw system
		Control system	Control system Sensors Data acquisition system
Drive train	Shafts and bearings Mechanical brake	Electrical system	Converter Transformer Electrical protection and switchgear
Gearbox	Gearbox		
Generator	Generator	Structure	Tower Foundations
Other	Other		

- ELforsk/Vindstat

The study was published in [38], it is based on the recovery of maintenance data from wind farms in Sweden. It comprises 723 onshore wind turbines with a capacity of 0.055 to 3 MW monitored between 1997 and 2004. The study provides the failure rate and downtime of the various wind turbine components for the period studied.

- Muppandal

This study is based on maintenance data from the Muppandal wind farm in southern India. The data are published in [39], where an analysis of the performances, failure and reliability of 15 wind turbines with a power of 225 kW are presented. The recovery of maintenance data is over a period of 4 years between 2000 and 2004.

- NEDO

The study is conducted by Japanese New Energy and Industrial Technology Development Organization (NEDO) and published in [40]. The study took place over a period of one year between 2004 and 2005. The number of wind turbines included in this study is 924 turbines. Only, faults with a downtime, greater than 72 h are considered as a failure in this study. This explains the very low failure rate of the various components of a wind power system, and makes any comparison with other reliability studies subjective.

- WMEP

WMEP (Wissenschaftliches Mess- und Evaluierungsprogramm) is a German project on the reliability of wind power systems. The data are published in [41], the study started in 1989 over a period of 17 years. The number of wind turbines contained in the study is 1500 wind turbines of different technologies and power varying between 0.03 MW and 1.8 MW. The study is rich in information, it allows us in particular to have the failure rate and the downtime of different wind turbine components over a long period of time.

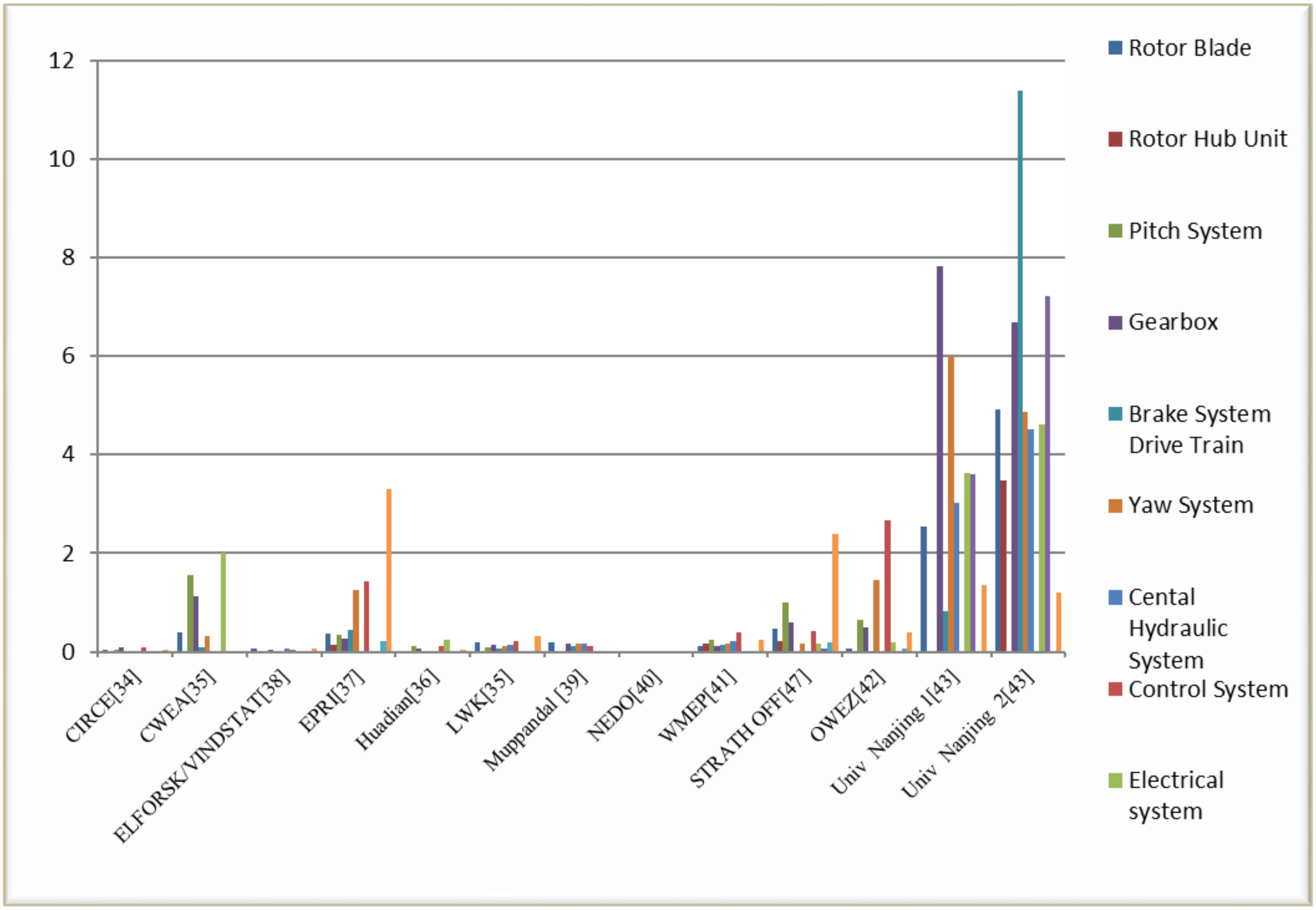

Figure 11. Wind turbine reliability study comparison [35-43].

- University of Strathclyde

In [47], 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.

- OWEZ

Offshore Wind farm Egmond Aan Zee (OWEZ) is an offshore wind farm launched in 2007 in Netherlands. The site is made up of 36 Vestas V90 wind turbines, with a power of 3 MW per turbine. The maintenance data are published annually by NoordzeeWind and are analyzed in [42].

- University of Nanjing

In 2016, a study by the City University of Nanjing on two wind farms in China [43]: 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 second project contains a few numbers of wind turbines, 46 wind turbines, but with a power greater than that of the first project, 2 MW by a wind turbine.

Figure 11 shows the results of the most relevant studies published in the literature and obtained from data recovery at different wind turbine sites around the world [34-43]. The distribution of wind turbine system components over the different subsystems is presented in Table I. The results show that the defect distribution rate varies between the different studies and this is mainly due to two reasons: the location of the wind turbines studied: the climatic regions can have considerable effects on the reliability of certain components. The second reason is the technology used in the different wind turbines, the reliability of the wind systems is also related to the manufacturers and the importance given to the reliability of the components during the development phase.

In this section, we focus on the result of some of majors studies. According to a study published by the University of Kassel, Germany in 2006 [44], based on the recovery of maintenance data for 13 years, the power converters are a leading cause of failure in a wind system as shown in Figure 12. Another study [45], shows that the use of maintenance data LWK allowed researchers to identify the main causes of failures on this site. The conclusions given in [45] 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 electric system control and the mechanical defects in the rotor.

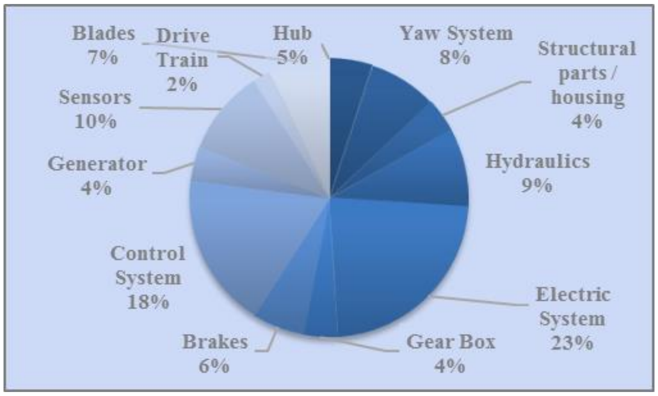

Figure 12. Share of main components of total number of failures [44].

More recently, in 2016, in the study [43], the researchers found different results: for the first project, 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. In the second project, the analysis of maintenance data over a period of two years shows that electrical systems (converters) account for 26% of failures, equal to failures rate found in the control system.

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 turbine 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 based 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 [45] and [46], 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 turbine systems. In the same study of the University of Columbia [46], the failure rates in the 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 presented in [47], 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 includes 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 analyze 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 Figure 13 shows that the converter in the direct drive system with PMSG generators presents an 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.

TABLE II. COMPARISON OF BTB CONVERTERS TOPOLOGIES FOR HIGH POWER WIND TURBINES [7].

	2L-VSC	**Parallel 2L-VSC**	**3L- NPC**	**3L- NPC-modified**	**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	3.0-12.0 MW
Number of converters	1	6	1	1	1	1
Number of switches	12	72	24	32	36	24
Switching devices	LV-IGBT	LV-IGBT	MV-IGBT/ICGT	MV-IGBT/ICGT	MV-IGBT/ICGT	MV-IGBT/ICGT
Diodes	0	0	12	16	0	0
Capacitors	0	0	0	0	0	6
Device voltage stress	V_{dc}	V_{dc}	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$	$V_{dc}/2$
Reliability of system	++	+++	+++	++++	+++	++
Redundancy	No	Yes. Module redundancy	No	Yes. Leg redundancy	No	No
Advantages	Simple and matured technology	Redundancy	Low harmonic matured technology	Low harmonic redundancy	Low harmonic Equal loss distribution	Low harmonic
Disadvantages	Limited power	Complex control	Unequal loss distribution	Unequal loss distribution	A large number of switches	Complex control
Technology status	Highly mature	Highly Mature	Well established	Research only	Research only	Research only
Power density	Moderate	Low	High	High	High	High

In [32], Koutoulakos presented a study of 643 WTs in Schleswig Holstein (LKW) Germany. The wind turbines are either fixed or variable speed configuration, and geared or with the direct drive concept. The study includes a data failure rates per turbine per year for different wind turbine sizes. We divided the WTs into two groups based on power (0.5 to 0.6 MW group and around 1 MW group). Reliability data of the various wind turbine components are separately analyzed to identify critical subassemblies of each topology. The comparison of geared and direct drive topologies shows that; the larger WTs had longer downtimes and higher cost. In Figure 14, the result shows that the electric failures in the direct driven wind turbine are more frequent for the two groups.

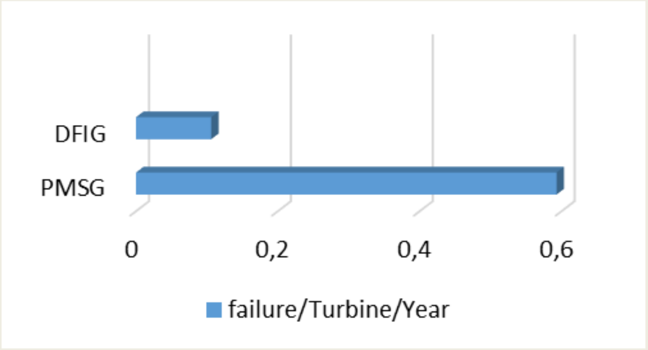

Figure 13. Annual failure rate [47].

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, [45][46].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 parallel several two-level converters as presented in Figure 5. This solution enables to increase the number of switches and proportionally to the number of failures in the system. Figure 14 illustrates a comparison between the failures of converters recorded in three studies [32][46][47] 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 need of paralleling the two-level converters to achieve the desired power.

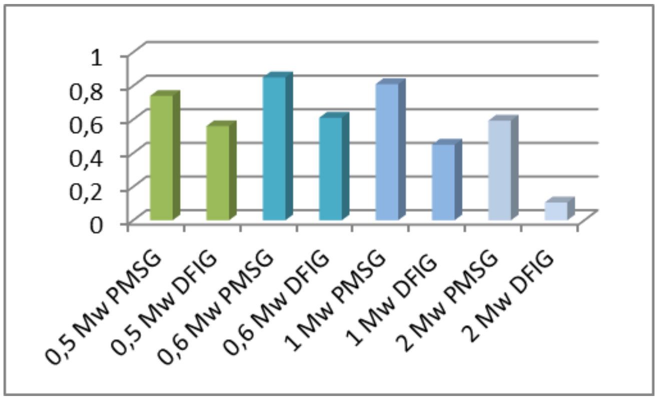

Figure 14. Converters failures rates based on the power of the turbine [32][46][47].

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 economy and production reasons, the reliability requirement is more important, any source of failure must be considered.

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 II, an example of reliability of converters for a 5 MW wind turbine, in this case the paralleling of 2-level converters does not offer higher reliability since the number of switches, which are fragile components becoming very important and decrease the reliability of the whole system.

Several attempts to develop methods to ensure continuity of service in converters have been developed in the literature. These methods can be classified into two categories, the one that uses hardware redundancy and the one that has no hardware redundancy. The first solution ensures continuity of operation in the nominal mode without power reduction while the second solution envisaged aims a degraded mode of the converter, which certainly continues to operate, but with lower power.

The hardware redundancy generally requires the use of other additional components, it was used for the 2-VSL converters in [51-55]. The most popular technique is based on the addition of a redundant arm can be activated when a fault is detected in one of the converter arms, this arm will be isolated using triacs or fuses. The same solution is used in [48-50] for NPC converters with the addition of an NPC redundant arm or FC redundant arm, as illustrated in Figure 15. Similar strategy is also used for ANPC converter as shown in [56-57].

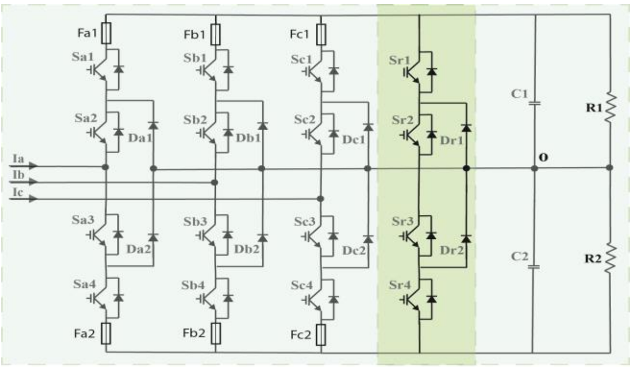

Figure 15. Redundant NPC Converter

On the other hand, in order to improve converters reliability and availability, various controls strategies to improve the system response in case of defects without hardware redundancy were studied. In [58-59], the authors proposed a control method using voltage vector redundancy for a Neutral Point Clamped (NPC) inverter. Similar approaches that do not require additional components are applied for other three-level topologies, such as the T-type converter [60], the active NPC converter [61-63].

VI. CONCLUSION

This paper presents the current technologies used in wind power systems and those may be a possible solution for WTS in the near future. A particular focus has been placed on power converters, as they are one of the most important components in the energy conversions in wind power systems. The other important point that we mention in this study is the reliability of wind power systems, a study of the various research and data available in the literature on the reliability of wind power systems is presented. Then an analysis and a comparison of the reliability between the different topologies used in wind power systems have been developed. This analysis allows us to observe:

-The data from different studies on the reliability of the component of wind turbine systems may be different and it is mainly due to: the different meteorological conditions of the wind turbines firms studied ; the different manufacturers and the importance that they give to the reliability in their designing processes; and the definition that researchers give to failure. For example, in the NEDO study, only breakdowns, which cause 72 hours of downtime are considered as failure, it explains the low rates of failures in this study.

-The choice of the converters is important in the global wind turbines systems. The two-level 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 converter issues, the failures at the 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 failures 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 converter systems. 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.

In the literature very few studies allow access to components maintenance data according to the structure of the studied wind turbines, most of this research separates the studied wind turbines only according to their power. Except these information are important for comparative analyzes and to deduce more reliable conclusions.

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