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Open-circuit switch fault tolerant wind energy conversion system based on six/five-leg reconfigurable converter

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ABSTRACT

In this paper, an FPGA-controlled fault tolerant back-to-back converter for DFIG-based wind energy conversion application is studied. Before an open-circuit failure in one of the semiconductors, the fault tolerant converter operates as a conventional back-to-back six-leg one. After the fault occurrence in one of the switches, the converter will continue its operation with the remaining five healthy legs. Design, implementation, simulation and experimental verification of a reconfigurable control strategy for the fault tolerant six/five leg converter used in wind energy conversion are discussed. The proposed reconfigurable control strategy allows the uninterrupted operation of the converter with minimum affection from an open-circuit switch failure in one of the semiconductors. Software reconfiguration is also necessary in PWM signal generation unit, to assure that proper gate signals are calculated and generated based on the actual five-leg structure Simulations and experimental tests are carried out and the results are presented and compared. They all confirm the capability of the studied reconfigurable control and proposed fault tolerant architecture in ensuring the system's service continuity.

1. Introduction

Wind energy is a very fast growing type of renewable energy with a growth rate of more than 20% for installed wind turbines from 2008 to 2013 [1]. One of the most widely used structures in currently installed wind turbines is the doubly-fed induction generator (DFIG). A DFIG-based wind energy conversion systems needs a power converter with reduced rating, compared to other variable-speed turbines with series power converters. In fact, here the power converter has to handle a fraction of the output rated power (around 30%) in steady state condition [2].

The most common power electronic converter used in DFIG-based WECS is the two-level back-to-back converter. This topology is also commonly used in many other applications such as electrical drives and uninterruptible power supplies (UPS). Nevertheless, this type of converter is sensitive to its switches' failures. Any failure in the power converter will decrease the system performance and may propagate to other parts of the system. Therefore, once a fault occurs, the system operation has to be stopped. This is not desirable in renewable power units, because it results in financial losses. This is especially true for wind turbines, since they are usually installed in remote areas, mainly offshore, and their maintenance is time consuming and costly [3]. Therefore, reliability and the capability of continuity of service are compulsory in such applications [4,5]. On the other hand, power converters are in fact one of the most fragile parts of a WECS [5], and have the highest failure rate after pitch control [6]. While some works are reported on the fault prognosis for the pitch system [6], diagnosis of stator and rotor fault of the DFIG [7], and diagnosis for machines bearing failures [8], little work is done on the fault diagnosis and fault-tolerant operation of the converter of a WECS itself.

The first step in reacting to a switch failure in the converter is to detect quickly its occurrence, and also to localize it. Fault detection schemes for power electronic converters are discussed in several papers. In [9,10] fault detection schemes are presented for some multilevel converters. Gate signal monitoring is used in [11] for the detection of IGBT failures. An observer-based method is used in [12] to detect the fault in the converter sensors. A fault diagnosis method

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for open-circuit failures in matrix converters is proposed in [13]. An adaptive neuro fuzzy interface algorithm is presented in [14] for detection of open circuit failures in grid-connected single phase inverters that uses inverter's output currents for fault detection. A sliding mode observer is used for fault detection in the multicell converter presented in [15]. A very fast FPGA-based fault detection using a "time and voltage criterion" is presented in [16,17]. It is capable of detecting the fault and its location in a few tens of microseconds. In fact, FPGA can run these tasks very quickly, thanks to its parallel architecture. Therefore it appears to be a very suitable choice for implementation of the real-time fault detection schemes [17].

Once the fault is diagnosed and its location determined, proper modifications must take place in the hardware of the fault-tolerant converter, as well as in the digital control part. Several reconfigurations for different fault-tolerant converters are presented in [18,19]. A fault-tolerant multicell converter is proposed in [15]. A fault-tolerant matrix converter is studied in [20]. In [21,22], three-phase inverter topologies with and without a redundant leg are studied. It is demonstrated that there is in fact the possibility to have a generalized control and fault detection scheme for a fault-tolerant six-leg back-to-back converter without redundancy. In such a topology and after a fault, the conventional six-leg converter operates with five legs and continues to supply the load. The five-leg converter topology is already proposed for applications such as AC/AC converter for a three-phase induction motor drive [23,24], control of two three-phase machines [25] and reversible fault-tolerant AC motor drive systems [26]. Its application in a DFIG-based WECS is investigated and compared to a back-to-back six-leg converter in [27].

In this paper, a six-leg back-to-back fault-tolerant converter without redundancy in WECS with DFIG is studied. Suitable fault-tolerant control strategy is presented and it is shown that such a fault tolerant system (FTS) might be interesting and efficient for this application.

In the following, first an introduction to fault-tolerant operation is presented in section II. The proposed FTS and reconfigurable back-to-back converter, in terms of architecture and control strategy, are also discussed in this section. Simulation results are provided in section III to demonstrate the performances of the studied system. The experimental set-up which allows validating the whole study of the DFIG-based WECS in faulty condition is investigated in the same section. All simulation and experimentation results are then discussed. Finally, some conclusions on this work are provided in section IV.

2. Proposed fault-tolerant system

2.1. General approaches to fault tolerant systems

There are two general approaches in order to make a system fault-tolerant, either with or without redundancy. In a FTS with redundancy, after fault detection and upon reconfiguration, the faulty part is removed and replaced by the redundant one. In this case, the system structure is unchanged after the reconfiguration and thereby the same operation capability can be guaranteed after a single fault occurrence. However, redundancy in not always necessary and in some cases a degraded performance may be acceptable after a fault. In these cases, a suitable reconfiguration might be enough to assure the minimum required performance. Fig. 1 shows the general outline of FTS. The redundant part and its switching mechanism are shown with dashed boundaries in this figure, as they are not present in FTSs without redundancy. This approach is taken here to propose an FTS without redundancy, based on a 6/5leg reconfigurable converter.

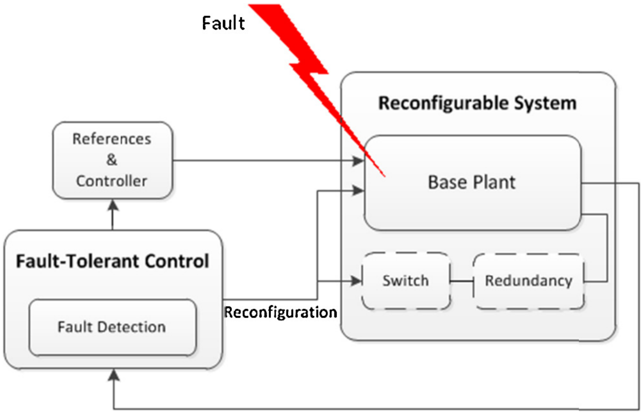

Fig. 1. General presentation of a fault tolerant system.

2.2. 6/5 leg converter topology

Fig. 2 shows the studied FTS. In this case, no redundant part (switch and driver) is used. Reconfiguration in the hardware (converter) is done by using bidirectional switches (TRIACs here), which makes possible to transform the converter structure from six to five-leg. In normal (pre-fault) operation of the converter, the converter is a conventional back-to-back and the three bidirectional switches are all open. Once a fault has been detected, the fault tolerant control (FTC) switches on the suitable TRIAC to reconfigure the converter's topology, and the converter stays in the 5-leg mode until the maintenance. Software reconfiguration is also necessary in PWM signal generation unit, to assure that proper gate signals are calculated and generated based on the actual structure, as will be explained later in this section.

There are different options for the bidirectional switches used in this structure. Any solid state bidirectional switch such as TRIACs, an IGBT associated to a diode bridge or common collector or common emitter connection of two IGBTs can be chosen [28]. In this study, TRIACs are used in order to remain cost-optimized.

It should be noted that the voltage producing capability in the five-leg converter is lower than in the six-leg converter. It means that with the same dc-link voltage, smaller three-phase voltages at the AC terminals can be produced, compared to the six-leg converter [27]. Also the current rating in the shared leg of the converter is larger than in the other legs. Therefore, when designing the fault-tolerant converter, careful considerations must be taken into account to have the desired performance after reconfiguration, either by increasing the dc-link voltage or by changing the control strategy to decrease the required voltages [24,29,30]. A proper current rating of the shared leg has to be also consisdered. These studies can be found in an earlier contribution [27], where for a WECS with DFIG, different schemes for the minimization of the required dc-link voltage in post-fault mode are discussed.

2.3. Reconfigurable control of the converter

Any conventional PWM method can be used for the control of the (pre-fault) six-leg converter. Upon the fault detection and reconfiguration, the faulty leg is disconnected by putting the two gate signals to zero, and one of the remaining healthy legs will be shared between the two sides of the converter. Among the several PWM approaches studied in the literature for this 5-leg post-fault topology, the method proposed in [23,26] seems simpler for practical implementation, and also it produces less harmonics. Therefore this approach is adopted here. First, voltage reference signals $v_{xi}^*(x \in \{a, b, c\}, i \in \{1, 2\})$ for the two sides of the converter are calculated using the proper methods depending on the