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Five-leg converter topology for wind energy conversion system with doubly fed induction generator

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ABSTRACT

In this paper, application of a five-leg converter in Doubly Fed Induction Generator (DFIG) for Wind Energy Conversion Systems (WECS) is investigated. The five-leg structure and its PWM control are studied and performances are compared with the classical six-leg topology. The main drawback of five-leg converter with respect to the six-leg back-to-back converter is the need to increase the dc-link voltage for the same operation point, i.e. the same powers in case of WECS. So, different methods for the reduction of the required dc-link voltage in the five-leg case are studied. The five-leg converter is used to replace the conventional six-leg one, with the same ability. For the performance evaluation of this structure and its fully digital controller in a more realistic and experimental manner, Hardware in the Loop experiments is carried out. It is shown that efficient control of active and reactive powers and dc-link voltage is performed. Hardware in the Loop results demonstrate the high performance of the proposed fully digital control which is implemented on an Altera FPGA target.

1. Introduction

Wind energy is the fastest growing type of renewable energy. One can notice an average growth rate of about 30% for installed wind turbines in the past 10 years. At the end of 2020, the installed capacity of wind turbines is expected to be around 1900 GW [1]. For European wind energy association, the goal is to produce 26–34% of the electricity of Europe from wind in 2030 [2]. Global market of wind energy is clearly expanding steadily, and consequently the technologic competition in this area has been accelerated.

The most widely used structure in currently installed wind turbine is the Doubly Fed Induction Generator (DFIG)-based wind turbine. One of its major advantages over other variable-speed turbine structures with a series converter is the reduced rating of the power electronic converter. The maximum power that the power converter has to handle in steady state condition is reduced to a fraction (20–30%) of the output rated power [3].

On the one hand, repairing a Wind Energy Conversion Systems (WECS) is a very time-consuming process [4], and actually, in most cases, the repairing is scheduled annually [5]. Therefore, continuity of service and reliability are mandatory for such applications. This is again more important for islanded smart or micro grids where wind power has a major role, and the higher reliability of the converter of wind turbine is highly recommended.

On the other hand, five-leg converter topology has been proposed for drive applications such as independent control of two three-phase motors [6], fault tolerant reversible AC motor drive systems [7] and AC/AC supply of a three-phase induction machine [8]. It has been shown that this converter topology could give satisfactory results in such applications. Moreover, it has better performances over other component-minimized topologies like 9-switch converter [9] and half-bridge-based converters [7]. In [9], it is shown that in this topology, the switches rating and losses are lower compared to 9-switch converter. In [7] it is stated that in contrary to the half-bridge-based converters, there is no AC current flowing through dc link capacitors in the five-leg converter, and also the required dc-link voltage can be minimized. Finally, the use of a reduced number of power devices leads to higher converter reliability compared with the conventional back-to-back six-leg topology.

However, as far as DFIG based WECS is concerned, the application of a five-leg converter topology and the study of the suited control and dc-link voltage minimization have never been reported in the literature. We think that such a converter topology might be interesting and efficient for this purpose.

In this paper, a five-leg converter-based structure as the back-to-back converter of a DFIG based wind turbine is studied. It is shown that it might have some benefits compared to conventional six-leg

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"back-to-back" converters. In the next section, the overall system under study is explained. Moreover, control of the DFIG, the dc-bus voltage and the five-leg converter is developed. In the third section, a comparative study of five-leg and six-leg converter topologies in WECS with DFIG is presented. Also different schemes for the minimization of the required dc-link voltage in the five-leg converter for wind application are discussed. Two PWM patterns for five-leg converter are studied in the forth section. Finally, Hardware in the Loop (HIL) experiments are presented for a 3 MW WECS, based on a FPGA-based HIL platform, developed in our laboratory [10].

2. Five-leg converter in WECS with DFIG

The structure and control of a WECS with DFIG fed by a five-leg converter is different from the conventional scheme with six-leg converter, but there are also some similarities. A conventional WECS with a six-leg converter is shown in Fig. 1. The stator is directly connected to the grid, and the rotor is connected through a back-to-back (six-leg) converter to the mains. This converter allows controlling the dc-link voltage, the input power factor, and also controls the DFIG (electromagnetic torque and stator power factor).

Different methods for controlling WECS with DFIG are suggested in the literature [11–13]. In [11] a discrete power control for DFIG is presented. In [12] a modulated hysteresis current controller is used to control the rotor currents. The classical DFIG control consists of calculating the suitable voltage references for each three-leg converter. Then, by using PWM control units, the suited gate signals for switches are computed. For the Rotor Side Converter (RSC) voltage references calculation, a grid-voltage oriented method is used [13]. The reference frame is chosen so that the q-axis component of the stator flux vector is null. In this reference frame, the electromagnetic torque (T_e) and the stator reactive power (Q_s) are related to q and d axis components of the rotor currents and are expressed by:

$$T_e = -p\frac{(mL_m)}{L_s}\varphi_{sd}i_{rq} \tag{1}$$

$$Q_s = V_{sq}\varphi_{sd}L_s - V_{sq}\frac{(mL_m)}{L_s}i_{rd} \tag{2}$$

$$V_{rq} = R_r i_{rq} + \frac{(\sigma L_r \mathrm{d}i_{rq})}{\mathrm{d}t} - \sigma L_r\omega_r i_{rd} + \frac{(\omega_r mL_m)}{L_s}\varphi_{sd} \tag{3}$$

$$V_{rd} = R_r i_{rd} + \frac{(\sigma L_r \mathrm{d}i_{rd})}{\mathrm{d}t} - \sigma L_r\omega_r i_{rq} \tag{4}$$

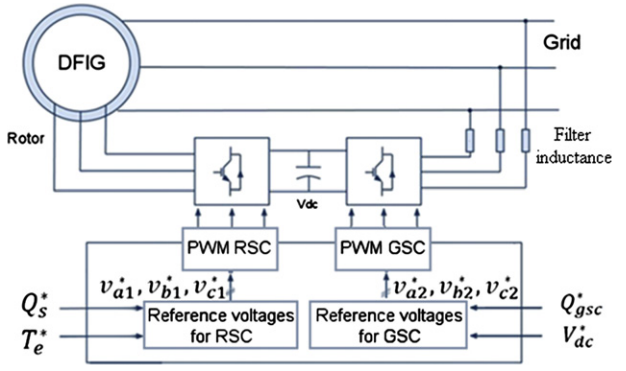

Fig. 1. Conventional WECS with DFIG based on a six-leg converter.

By using PI controllers and by applying feed-forward compensation terms, the control of torque and reactive power is performed. Fig. 2 shows the block diagram of the RSC control [13].

The grid-side converter (GSC) is normally controlled in order to regulate the dc-bus voltage and provide unity power factor at the point of connection to grid. This is done using another well known grid-voltage oriented control for the three-phase controlled rectifiers [13,14].

Two sets of voltage references obtained from these control schemes are normally sent to the two respective PWM blocks in conventional systems, as is shown in Fig. 1.

However, for a five-leg converter the procedure is different. For the proposed scheme with a five-leg converter, as the converter topology is different, the PWM control must be changed. Fig. 3 shows the proposed WECS with DFIG based on a five-leg converter. Since the number of legs is reduced, the number of output control signals should be reduced too. Therefore a modified and suited PWM scheme for five-leg converter must be used. However, the voltage references generation units remain the same in five- and six-leg cases. Thus, with an appropriate PWM method, the generation of the two desired set of three-phase voltages at grid and rotor sides is possible. The PWM method is explained later in Section 4.

3. Comparison of five-leg and six-leg converters in WECS with DFIG

DFIG systems based on five-leg and conventional back-to-back converters may be compared in different ways. However, notice that in our work both are supposed to produce the same active power.

In [15], general $3n$-leg and $(2n+1)$-leg converters topologies are compared. It is demonstrated that in component-minimized converters there is a limit on the sum of the voltages on the two sides of converter (in this case, rotor side and grid side) for a given dc-bus voltage. Let us consider a six-leg converter with a dc-link voltage equal to V_{dc}. Such a converter can produce three-phase sinusoidal voltages with a maximum peak phase voltage of V. The modulation index M is defined as $2\,V/V_{dc}$. So, the peak value of the phase-to-phase voltage will be:

$$V_{ll} = M\sqrt{3}V_{dc}/2 \tag{5}$$

Consequently, the maximum of the modulation signal is $2/\sqrt{3}$, because the produced line-to-line voltage cannot be larger than V_{dc}.

For the five-leg converter, the peak value of line-to-line voltage between legs j_1 and i_2 can be written as:

$$V_{j1} - V_{i2} = V_{j1} - V_c + V_c - V_{i2} = V_{jc(1)} + V_{ic(2)} \tag{6}$$

where subscripts 1 and 2 point to two different sides of the converter (rotor side and grid side). In the other words, the peak

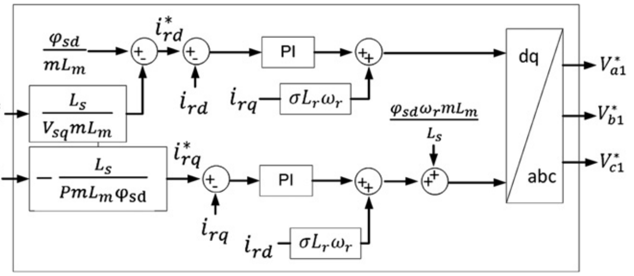

Fig. 2. RSC control [13].