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A review of design consideration for Doubly Fed Induction Generator based wind energy system

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ABSTRACT

In the design of a Doubly Fed Induction Generator (DFIG), the electrical, dielectric, magnetic, thermal, and mechanical considerations are essential in the design. The generator speed, rotor and stator windings, core, rotor slots, and the insulation system must also be considered for practical designs as wind turbines in the range of 2 MW. In this paper, the conflicting design requirements reconciled for the construction DFIGs with high reliability and efficiency in the wind farm applications.

1. Introduction

Today, significant attention is drawn to utilizing renewable energies such as wind power to avoid using fossil fuels for electric power generation [1–5]. Wind power uses the power of wind air flow through wind turbines to mechanically generate electrical power. The generators used for wind turbines are divided into two types; fixed speed and adjustable speed generators [6–9]. The fixed speed types have more expensive mechanical structures [10,11], especially in high rated powers. The adjustable speed generators often operate for up to 5 MW [12,13], among which the directly coupled type have significant problems [14,15]. Utilizing the wind power plant with variable wind speed has some advantages comparing to the fixed wind speed ones [16–19]. Although the constant speed power plants are directly connected to the grid [20,21], and the broader range of energy is covered, have a higher mechanical stress and noise. The adjustable speed power plants have less mechanical stresses, and noise that makes these generators more desirable [22–24]. Today, the cost-effective power converters and efficient control of speeds are possible that have created a large market for DFIGs [25–27].

Synchronous Generators (SG) [28,29] and DFIGs [30,31] can be regarded as one of the most functional generators in wind turbines [32–35]. Utilizing a DFIG for wind turbines has the following advantages [31]: (a) producing the maximum power at variable speeds [36,37]. (b) The ability to control the active and reactive power with combining the power electronic converters that lead to lower losses and higher efficiency [38,39]. Adjusting the power factor is achievable at lower costs. In four quadrant converter operation, the active and reactive power can be controlled [40,41]. (c) These generators have inexpensive inverters since they are typically controlled by a ratio of at least 25% p.u whereas they are at the rate of ±30% around the synchronous speed. These converters are 25% smaller than the ones utilized in the SGs that have made them more expensive. (d) The price of the inverter's and EMI's (electromagnetic interference) filters are also lower. The DGIFs require less maintenance and have natural protection against short circuits and instant overloads [32,42,43]. A DFIG can supply power with steady voltage and frequency while the rotor turns with a different speed [44–46]. Today, almost 99% of the wind turbines' generators use the power converters because of cost advantage. Over 70% of the wind turbines are operated with wound rotor DFIGs [47] in 2009. The overall capacity of all wind turbines installed worldwide by the end of 2017 reached 539,291 MW [48].

1.1. Problem statement and description

In this paper, the problem of the design of DFIG is investigated. In this regrad, the generator speed, stator winding, rotor windings, core and slots of the rotor/stator, load variation, and the insulation system are studied in the design of the generator. These parameters impact the efficiency, reduce the cost, repair and maintenance periods, and extending the lifetime operation of the wind generating

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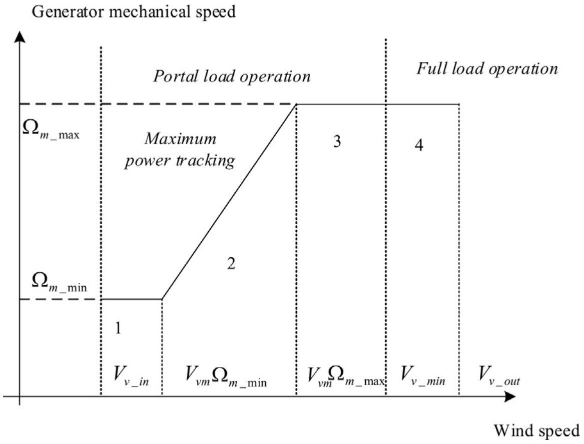

Fig. 1. The regions of the wind and the generator speeds.

systems. The structure of the paper is as follows: in Section 2 the rated speed and its variations along with its relationship with other factors are discussed. The winding type, ratio, connection, and the turn's number of stator/rotor winding are investigated in Section 3. The core and stator/rotor slots issues are considered in Section 4. In Section 5 of the paper presents the design of the insulation, the criteria for selection of the insulation systems, and also the insulation classes. Finally, a conclusion is given in Section 6.

2. Speed in the wind turbine generator

In wind turbines operation, the following design parameters play important roles; (a) minimum speed, (b) maximum speed, and (c) rated speed [49]. The minimum speed is defined when the generator's turning speed gets almost around the resonance frequency of the tower (near to 0.5 Hz). The resonance frequency must be avoided since in the low-speed range vibration mechanical structure can occur. The maximum speed is based on the mechanical structure limitation because of failure. A high rate of speed can result in excessive stress on the blades and turbine shaft. The nominal speed occurs when the turbine is working in the maximum aerodynamic efficiency. These three regions are shown in Fig. 1.

As an example, some design set the minimum speed of a 2 MW generator in a range of 900, 1000, 1125 and 1500 rpm in the design and construction of the production. The maximum speed of these generators is considered as 1500, 1800, 1875, 1900 and 2000 rpm for this specific application. The nominal speeds have been around 1500, 1487, 1650, 1660, 1680, 1750 and 1980 rpm. According to these data, the rated speed can be determined around 1600–1700 rpm for a 2 MW generator.

The designer must consider the limitation of speed operation and efficiency. Moreover, the designer should take into account the effect of speed selection on the total structure of the generator or its parameters so that the most efficient speed can be selected.

As the size of machine increases, it will result in higher cost for the machine. In standards ranges, finding a group of machine outputs with similar frame size is used for design. The output coefficient of an AC rotating machine (C) and rated torque (T) are [50]:

$$C = \frac{kVA}{D^2 L n_s} \rightarrow T \propto \frac{kVA}{n_s} \tag{1}$$

In which, D is the diameter of the machine and L is the length. kVA is the power developed by the armature. The size of the active and functional parts of the machine depends mainly on D^2L, and the rated torque is in relation with D^2L. Therefore, the output coefficient has a relationship with rated torque per unit volume. The volume of active and functional parts of the machine, the size, and usually the price decrease as the speed and the output coefficient increase.

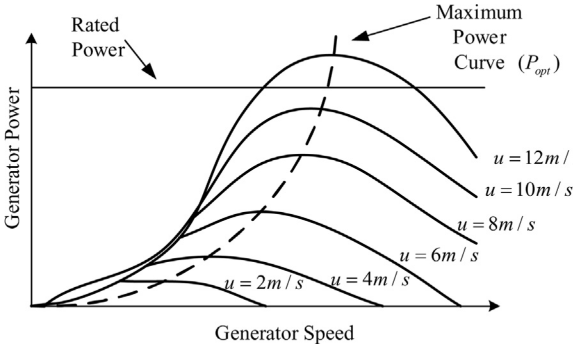

Fig. 2. The DFIG efficient power at various speeds [52,54].

Since the output coefficient is proportional to the multiplied values of the electrical and magnetic loadings, using the highest possible values for the particular loads in designing is desirable. However, utilizing sizeable specific load values can have a reverse effect on the machine operating characteristics including, efficiency, temperature and power factor. So since the volume and the price are not the only essential design factors of the machine, the designer needs to analyze the influence of the total loads on the machine's operation. Since the active mass volume of the machine varies in a reverse relation to the rated speed (D^2L α 1/Rated speed), the maximum operating speed has to be selected. The rotor mechanical stresses limit the maximum speed. However, speed is not the only design factor which has to be considered. The synchronous speed of an AC machine is determined through the number of poles and the feeding (or the line) frequency. For a specific number of poles, the armature frequency varies in direct relationship with the rotor speed and the iron losses of the armature increases as the frequency increases.

Losses and their distribution within a machine are other factors which determine the temperature rise and the efficiency. As an example (and approximately), if the speed of a motor with 1500 rpm rotating speed in a specific volume is to be designed for 1600 rpm, the active volume mass will get 1.066 times smaller. Due to this volume reduction, a price reduction is followed. On the other hand, this layout needs smaller air gaps and a motor with narrower slots. Therefore an increase in leakage flux and mechanical stresses results.

The wind speed variations and the generator power need to be considered. The wind speed and (the rotor speed) the blades speed are related to the generator speed. In a DFIG, the mechanical power and speed are defined as [51,52]:

$$P_{mech} = \frac{1}{2}\rho\pi R^2 u^3 C_p(\theta, \lambda) \tag{2}$$

in which, ρ is the air density (kg/m^3), R is the radius (m), πR^2 is the swept area (m^2), u is the wind speed (m/s) and $C_p(\theta, \lambda)$ is the aerodynamic functionality which depends on the blades (pitch) angles (θ) and tip speed ratio (λ). If θ is equal zero, in this case C_p is only function in λ, and λ is function of rotor mechanical speed, rotor radius of blade and wind speed as follows [53].

$$C_p(\lambda) = \frac{60.04 - 4.69\lambda}{\lambda} e^{\left(\frac{-21+0.735\lambda}{\lambda}\right)} + \frac{0.0068\lambda}{1 - 0.035\lambda}, \quad \lambda = \frac{\omega_r R}{u} \tag{3}$$

where ω_r is the rotational speed (rad/s). Fig. 2 shows the efficient power of DFIG in various speed ranges. The more precise presentation of this characteristics is shown in Fig. 3.

The power and the wind speed relationship show that the power output is a function of the cube of wind speed. For a 2 MW generator of a wind turbine with a wind speed reduction from 9 to 7 m/s