Electrical Power and Energy Systems 70 (2015) 61–69

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A control scheme for improving the efficiency of DFIG at low wind speeds with fractional rated converters

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ARTICLE INFO

Article history:
Received 21 May 2014
Received in revised form 12 January 2015
Accepted 31 January 2015
Available online 21 February 2015

Keywords:
Wind energy conversion system
Variable speed generator
Doubly fed induction generator
Extending speed range
Stator short circuited operation

ABSTRACT

This study proposes a scheme for extending the low speed range of operation of a Doubly Fed Induction Generator (DFIG) without down grading the efficiency. Also, only fractional rated converters are employed. The technique involves two operational modes for the generator. When the rotor speed is between 70% and 130% of the synchronous speed, the machine is operated in the normal Doubly Fed Induction Generator (DFIG) mode and when the rotor speed falls below 70%, it is operated in Stator Short Circuited (SSC) mode. The switch-over from the DFIG mode to the SSC mode is carried out at a threshold speed to maintain the efficiency of generator with the same fractional rated converters. The computer simulations on a typical DFIG (250 kW) in Matlab/Simulink environment illustrate that the range of efficiency improvement is from zero to 15%. Further, the experimental results on a 2.3 kW DFIG set up are also illustrated to demonstrate the efficacy of the scheme.

Introduction

With the depleting natural resources, increase in energy demand and global warming, exploitation of renewable energy sources is growing at a fast pace since last decade. Of the renewable energy sources, wind energy is attractive options as 100 kW–8 MW wind turbines are commercially available.

An overview and comparison of wind turbine generators are presented in [1–3]. Variable speed wind turbines have increased energy capture compared to fixed speed wind turbines. Among the variable speed wind turbines DFIGs are widely used due to the advantages such as four quadrant operation, decoupled power control, fractional rated converters and reduced mechanical stresses [4–7]. As the operating speed of DFIG is limited to 30% above and below synchronous speed, the rating of power converters used are typically 30% of the machine rating.

Studies [8–10] presented the steady state analysis of DFIG for wide speed operation. The rotor voltage is linearly proportional to the slip (0.49 p.u. for a wind speed of 5 m/s at a slip of 0.47) while the aspect of efficiency is not examined [8]. The active power delivered is controlled by varying the angle between the stator and rotor voltages and magnitude of rotor voltage [9]. Increased rating of the power converter is implied at speeds below 70% of synchronous speed [10].

Maximum Power Point Tracking (MPPT) scheme [11] was independent of the turbine parameters and air density where the peak power points in the P–ω curve corresponds to $dP/d\omega = 0$ while [12] presented the implementation of speed mode control for tracking the peak wind power. In [13] MPPT was implemented using characteristic power curve. The optimal power reference curve was obtained by finding the optimal mechanical power and generator speed for a given wind speed.

Generally, the efficiency of induction generator is low at low wind speeds. Efficiency of induction generator, synchronous generator and PMSG were compared in [14] for different wind speeds. The efficiency of induction generator is lower compared with that of other machines, particularly at low rotor speeds. A method to calculate losses, power and efficiency of wind turbine generator systems with DFIG [15] reported the efficiency of a 5 MW DFIG to be just 50% near the cut-in speed. This is primarily due to the predominance of constant magnetizing current, in spite of low winding currents. An approach to determine the optimal rotor voltage for extracting maximum power at any wind velocity ensuring steady state stability of the generator was discussed in [16].

Different methods to improve efficiency and power factor of induction motor are presented in [17–21]. One of the techniques for extending the speed range of induction generator included pole changeable [5,22,23] stator winding. The stator is wound for two windings with different pairs of poles [5]. At lower speeds the

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http://dx.doi.org/10.1016/j.ijepes.2015.01.032
0142-0615/© 2015 Published by Elsevier Ltd.

Nomenclature

$\bar{v}_s$	stator voltage space vector
$\bar{i}_s$	stator current space vector
$\bar{i}_r$	rotor current space vector
P_s, Q_s	stator active and reactive powers
R_s, R_r	stator and rotor phase winding resistances referred to stator
L_{ls}, L_{lr}	stator and rotor phase winding inductances
L_m	magnetizing inductance
ω_s	angular frequency of stator voltage
ω_m	angular speed of rotor (electrical)
P_m	mechanical power
v_w	wind velocity
s	slip

winding with the higher pole pairs was used and at rated and higher speeds the winding with lower pole pairs was used. While this arrangement increases the efficiency at lower speeds, it is suitable only for constant speed wind turbines and moreover the size of machine is large to accommodate twin pole pair arrangement. In [24] a pole changing method for DFIG with cyclo-converter on rotor side was presented. Although the speed range is extended, the effects of this on power output and efficiency were not addressed and the complexity in implementation of cyclo-converter is extensive. Variable speed generators with full rating converters [25] can operate in full speed range i.e. down to cut in speed. However, the cost of the power converters is very high.

In an offshore application [26], the DFIG was operated at rated V/f through an HVDC link and the power converters on rotor side are rated for 5% of machine rating. Using this scheme the efficiency of the system at lower wind speeds was improved. But the disadvantage of the scheme is that the number of converters required for control is higher. In another study [27], the induction generator was operated in doubly fed mode at nominal speeds and as a singly fed induction generator at lower speeds. Though the lower speed efficiency is improved, issues such as the basis for switching over from one mode to another, the ratings of the power converters employed, and MPPT, have not been discussed.

Extending the speed range with limited rating converters while maintaining the efficiency of the generator has not received adequate attention so far. The main disadvantage with DFIG is that it requires higher rated power converters at lower speeds. Hence, with fractional rated converters the operating speed range of DFIG is limited to 70–130% around synchronous speed. In the present work a strategy is proposed for an efficient extended low speed operation, extracting the maximum power with fractional rated converters, thereby significantly reducing the size and cost of the converters. At lower speeds the mechanical power available is less. Therefore, a MPPT algorithm is proposed in which the total copper loss is minimized while the tracking maximum power from the wind turbine by switching operation to the SSC mode. The method involves determining the optimum value of the slip for a rotor speed. Further, from the optimum slip the rotor voltage and frequency are determined. At normal and high speeds (say 0.7–1.3 p.u. of synchronous speed), the Wound Rotor Induction Machine (WRIM) is operated in doubly fed (DFIG) mode (Fig. 1a). The Rotor Side Converter (RSC) is controlled to extract the maximum power from the wind and the Grid Side Converter (GSC) is used to maintain the dc link voltage. At lower speeds (below 0.7 p.u.), the stator is short circuited (Fig. 1b) while the rotor is connected to grid through the converters to transfer the power from RSC to the grid through GSC. The RSC is operated to extract the maximum power from the wind while keeping the rotor voltage within limits (30% of stator nominal voltage) and the GSC is used to maintain the dc link voltage constant.

This paper is organized as follows. In Section 'Wind turbine characteristics' the concept of maximum power tracking is explained. Theoretical analysis for two modes of operation viz., the DFIG mode and the SSC mode and the respective control strategies are discussed in Section 'Steady state model'. Section 'Results and discussion' describes the simulation and experimental results.

Wind turbine characteristics

The output power from the wind turbine [13] is expressed as

$$P_m = 0.5\pi\rho C_p R^2 V_w^3 \tag{1}$$

where ρ is air density, C_p is the power coefficient, R is the radius of wind turbine.

Optimum tip speed ratio and optimum power [13] for the wind are given by

$$\lambda_{opt} = \frac{\omega_{opt} R}{V_w} \tag{2}$$

$$\text{and } P_{opt} = K_{opt}\omega_{opt}^3 \tag{3}$$

$$\text{where } K_{opt} = \frac{0.5\pi\rho C_{p\max} R^5}{\lambda_{opt}^3}$$

ω_{opt} is the rotor speed at which turbine power for certain wind speed is maximum and $C_{p\max}$ is the maximum power coefficient. The dynamic equation of wind turbine is expressed as

$$\frac{d\omega_m}{dt} = \frac{1}{J}[T_m - T_L - B\omega_m] \tag{4}$$

where J is the turbine inertia, B is the friction coefficient, T_m is torque developed by the turbine, T_L is the torque due to load and ω_m is the rotor speed.

Steady state model

Steady state models of WRIM are developed for predicting the performance in DFIG mode and SSC mode. In both DFIG and SSC modes the RSC is used to extract maximum power from the wind.

Steady state analysis – DFIG mode of operation

Fig. 1a shows the schematic diagram of DFIG. Tracking maximum power from the wind and controlling of stator side active and reactive power is carried out via RSC. Power factor at the grid is maintained through the GSC. Fig. 2a shows the per-phase equivalent circuit of DFIG referred to stator. The equations governing steady state operation are given by

$$V_s - R_s I_s = j\omega_s\varphi_s \tag{5}$$

$$V_r - R_r I_r = js\omega_s\varphi_r \tag{6}$$

$$\text{where } \varphi_s = L_{ls}I_s + L_m I_m \tag{7}$$