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A stator voltage switching strategy for efficient low speed operation of DFIG using fractional rated converters

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A B S T R A C T

This paper presents a scheme for extending low speed operation of a wind driven Doubly Fed Induction Generator (DFIG) with limited rating converters (30%). In this scheme, a low voltage is applied to the stator at rotor speeds below the normal range (0.7 p.u.) while the nominal voltage is applied when the rotor speed is above this range. The switch-over to a lower stator voltage below a threshold speed facilitates to maintain the operational efficiency with the same fractional rated converters. Simulations results of a typical 250 kW DFIG in Matlab/Simulink environment reveal that, a lower stator voltage increases the generator efficiency at lower speeds without exceeding (limited) rating of the rotor side power converter. Typically the speed range is extended by 20% when reduction in voltage is 42%. With a 250 kW generator the energy harvested over one year is increased by 61.1 MWh with the proposed scheme. The scheme is simple, economical and can be implemented through speed sensor and contactors. Experiments on a laboratory test set up demonstrate the efficacy of the proposition.

1. Introduction

Large scale Wind Energy Conversion Systems (WECS) using variable-speed generators are popular due to many advantages, including maximized power capture, reduced mechanical stress on the turbine, and reduced acoustic noise [1]. Asynchronous generators are more common for variable speed WECS because of smaller size, lower cost and low maintenance [3].

Among the variable speed asynchronous generators [4,5], the variable speed concept with partial scale converters is economically viable due to the versatile four quadrant operation of DFIG with decoupled power control in sub-synchronous and super-synchronous speed ranges [1], reduced rating of power converters, DC bus capacitor and the line side inductor [2]. The steady state analysis of DFIG in both sub and super-synchronous speeds has been widely reported [6–10].

Various schemes reported for DFIG control include direct torque control, direct power control, sensorless operation [11], vector control with a position sensor [12], stator flux oriented vector control of DFIG with and without position sensor [13], use of hysteresis controllers without position sensor [14], and DPC strategy [15,16] in the grid flux reference frame without position sensors.

The Maximum Power Point Tracking (MPPT) method is the key to improve efficiency and energy extraction in the wind turbine system [17–19]. In Ref. [17] the MPPT method through the characteristic power curve is presented and performance of wind turbine with MPPT power control is explained. An analytical approach was suggested [19] to determine the rotor current commands for maximum mechanical power and minimum loss based on generator speed.

Efforts were made to improve the efficiency of induction motor under light loads by changing the stator winding connection [20–22]. Most of the over sized induction motors operate with low efficiency and power factor under light loads [20]. The most common method for improving the efficiency and power factor of induction motors at light loads is to reduce the stator voltage by switching the stator winding connection from delta to star. In Ref. [21] a multi-step air gap flux regulation method is implemented with a star-delta switchable stator winding connection, thereby improving the efficiency and power factor over an extended speed range. In Refs. [23,24] the pole changing method is employed to extend the speed range of the induction motor.

A few studies focused on improving energy extraction by extending the speed range of generator. Pole changing method is employed for speed extension in standalone wind driven self

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Nomenclature

$\bar{v}_s$	stator voltage space vector
$\bar{i}_s$	stator current space vector
$\bar{v}_r$	rotor voltage space vector
$\bar{i}_r$	rotor current space vector
$\bar{\varphi}_s$	stator magnetizing flux space vector
P_s,Q_s	stator active and reactive power
R_s,R_r	stator and rotor phase winding resistances
L_s,L_r	stator and rotor phase winding inductances
L_m	magnetizing inductance
ω_e	angular frequency of stator flux
ω_m	angular speed of rotor (electrical)
P_m	mechanical power
v_w	wind velocity

Subscripts

d,q	synchronous reference frame

Superscripts

e	synchronous reference frame
s	stationary reference frame
*	reference value

excited induction generator [30]. In Ref. [25] the rotor is supplied through a cyclo-converter and the range of speed is extended by changing the number of pairs of poles in stator. Although the speed range is widened, the effects of this on the power output and the generator efficiency have not been explained. Complexity in implementation using a cyclo-converter, aspects of smooth transition between two sets of pole pairs, also need consideration.

While most studies in literature considered zero to 30% slip range, wider speed operation is also reported, although with an increased rating of the rotor side converters [4]. Since the reactive power demand of the DFIG and also the rating of power converters increase proportionately with slip, it is a common practice to restrict the maximum slip to about 30%. To facilitate larger slip operation with the same 30% rated converters, a technique involving slackening of the zero reactive power constraint on stator side was proposed [26]. However the issue of decaying generator efficiency at low speeds was not looked into. Another study [27] reported an operating speed range of 50–90% of the synchronous speed with improved efficiencies up to 95%. Conventional DFIG operation for normal wind conditions and stator short circuited mode at lower wind speed are considered. In Ref. [28] the DFIG is operated at rated V/f using the power converters rated for 5% of machine rating, but the disadvantage is that number of converters required is higher.

The aspect of extended low speed operation at moderate efficiencies with limited rating converters has not been addressed adequately by researchers so far. This study presents a technique for extending the speed range while maintaining a reasonable efficiency of the generator with the same limited rating converters in the rotor circuit. In general, the DFIG operation below 70% of the synchronous speed is marked by low efficiency due to increased reactive power demand of the generator accompanied by increased losses. Also the converters need to be rated higher. Even with higher rated converters the efficiency is poor below a certain speed. It is possible to improve the efficiency at low speeds by reducing the stator voltage thereby decreasing the excitation requirement. This fixed, lower voltage can be provided through a tapping on the stator side transformer. At normal and high speeds (i.e. higher mechanical power) nominal stator voltage operation can be pursued, giving the nominal efficiencies.

Broadly speaking, the choice of lower stator voltage depends on the new maximum slip under consideration. Since most transformers have the provision of tappings, such a voltage switch-over does not warrant any design modifications or additional cost. Further, since the speed is a slowly changing variable, a speed sensor along with a contactor based voltage switching is adequate for real time implementation. The scheme is simple and economical in implementing and yields greater annual returns through increased energy harvesting.

The proposed scheme is verified through MATLAB simulations on a 250 kW wind turbine and also through simulations and experiments on a 2.3 kW laboratory test bench using Altera cyclone II FPGA controller. Results demonstrate the feasibility of moderately efficient extended speed operation with the limited rating converters.

This paper is organized as follows. Detailed mathematical modeling of a doubly fed induction machine including iron losses is described in section 2. Further the decoupled control of DFIG with RSC and GSC are explained in section 2. Maximum Power Point Tracking from the wind is explained in section 3. Section 4 describes the proposed scheme of extended low speed operation of DFIG. In the first case study, the simulation results of a 250 kW wind driven DFIG are presented and in the second case, the simulation and test results for a 2.3 kW laboratory DFIG are illustrated in section 5.

2. Mathematical modeling

Fig. 1 shows the schematic diagram of DFIG system. Rotor Side Converter (RSC) is used to control active and reactive power of the generator and also to track the maximum power from the wind. The Grid Side Converter (GSC) is used to maintain DC link constant. Transformers are used to step down the voltage at stator side and rotor side.

2.1. Modeling of DFIM

Fig. 2a shows the spatial distribution of stator voltage, stator flux and rotor currents in different reference frames. Stator voltage and stator flux are considered along $_q$ and $_d$-axes in the synchronous reference frame respectively. Fig. 2b shows the per phase equivalent circuit of induction machine.

The stator and rotor voltages in synchronous reference frame, can be expressed as

$$\bar{v}_s^e = R_s\bar{i}_s^e + \frac{d\bar{\varphi}_s^e}{dt} + j\omega\bar{\varphi}_s^e, \tag{1}$$

$$\bar{v}_r^e = R_r\bar{i}_r^e + \frac{d\bar{\varphi}_r^e}{dt} + j(\omega_e - \omega_m)\bar{\varphi}_r^e, \tag{2}$$

For higher rated machines the iron loss component can be neglected. But in smaller rating machines it cannot be neglected. So iron loss component is considered for modeling (laboratory machine). The iron loss component of the machine is modeled as a resistance in parallel to the mutual magnetizing inductance as shown in Fig. 2b.

The resistance $_{Rfe}$ provokes an active current consumption ($_{ife}$) but does not contribute to flux. The flux is created by the current flow through the magnetizing and leakage inductances. Hence, in the synchronous reference frame the stator and rotor fluxes are given by