

Control of doubly-fed reluctance generators for wind power applications



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ARTICLE INFO

Article history:

Received 18 September 2014

Received in revised form

6 May 2015

Accepted 15 June 2015

Available online xxx

Keywords:

Control

Doubly-fed machines

Reluctance generators

Wind power

ABSTRACT

The paper deals with flux and voltage vector oriented control of a transpiring brushless doubly-fed reluctance generator (BDFRG) technology for grid-connected wind turbines. The BDFRG features the low operation & maintenance costs by using a fractional inverter, and offers the high reliability of brushless structure at competitive performance to its popular slip-ring companion, the doubly-fed induction generator (DFIG). The relative experimental results for the two parameter independent speed and reactive power control algorithms have successfully verified the simulation studies on a custom-built machine for various loading profiles.

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1. Introduction

A conventional doubly-fed induction generator (DFIG) has been a widely adopted choice for geared wind turbines where variable speed ranges of 2:1 or so allow the converter to be downsized to about 25–30% of the machine rating with obvious cost reduction implications [1–5]. However, reliability and maintenance issues of brush gear remain one the major DFIG concerns [4,5]. Brushless doubly-fed generators (BDFGs) [6–9] may be an economical solution to these well-known DFIG limitations. Apart from additional cost benefits of brushless design, another important functional advantage of the BDFG over DFIG is the superior fault-ride-through capability [10] without the need for protective crowbar circuitry to by-pass the partially-rated converter. This salient BDFG feature is afforded by the proportionally larger leakage inductances and consequently lower fault current levels compared to the DFIG [11–13]. The previous favorable properties have stimulated increasing attention to the BDFG and medium-scale prototypes have been built [10,14] with large 2 MW designs proposed [7] as a

potential DFIG replacement in wind power applications.

Unlike the traditional DFIG, the BDFG has two standard, sinusoidally distributed, stator windings of different pole numbers and applied frequencies, and a rotor with half the total number of stator poles. The primary (power) winding is tied to the supply grid directly, and the secondary (control) winding through a bi-directional IGBT converter normally in ‘back-to-back’ configuration [15]. The BDFG rotor can take the two distinct forms: (1) modern reluctance (i.e. BDFRG in Fig. 1) [7,16], and (2) ‘nested’ cage (i.e. BDFIG) [8,14]. A large-scale BDFRG has been shown to be able to perform comparably to the DFIG [7] as well as to provide the higher efficiency [17] with simpler dynamic modeling and control than the BDFIG cousin [8,18]. Similarly to the DFIG [5,19–21], the primary reactive power and torque can be controlled in an inherently decoupled manner with the BDFRG [6,22] in contrast to the BDFIG [8,18].

Scalar V/f control [6], primary voltage-oriented (vector) control (VC) [6], direct torque and flux [7] or reactive power [23] control (DTC), direct power control (DPC) [25], and sliding mode control [9] have been developed for the BDFRM(G). Although intellectually interesting, the work in Refs. [6,9] is purely theoretical in nature and of questionable viability. Several stator frame based DT(P)C methods have been experimentally validated with a shaft-position sensor [23,25] or sensor-less speed regulation [7]. However, the preliminary results for no-load operation of a small-scale BDFRM have been produced, but actually more useful speed control of the

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Nomenclature

$v_{p,s}$	primary, secondary winding phase voltages [V]
$i_{p,s}$	primary, secondary winding currents [A]
$R_{p,s}$	primary, secondary winding resistances [Ω]
$L_{p,s,ps}$	primary, secondary and mutual 3-phase inductances [H]
$\lambda_{p,s}$	primary, secondary winding flux linkages [Wb]
λ_{ps}	mutual flux [Wb]
$\omega_{p,s}$	primary, secondary winding frequencies [rad/s]
ω_{rm}	rotor angular velocity [rad/s]
ω_{syn}	synchronous speed = ω_p/p_r [rad/s]
P_m	mechanical (shaft) power [W]
$P_{p,s}$	primary, secondary mechanical power [W]
T_e	electro-magnetic torque [Nm]
P, Q	primary real [W] and reactive [VAR] power

loaded BDFRG has not been clearly demonstrated in Refs. [7,23,25]. In addition, all these DT(P)C schemes have the familiar disadvantages of hysteresis control such as variable switching rates and higher sub-harmonic contents to be of any notable practical use from a power quality point of view. Furthermore, the approach in Ref. [7] turns out to be sensitive to machine parameter knowledge uncertainties and poor performance has been reported.

No publication with real-time implementation of VC or true primary flux (field)-oriented control (FOC) has subsequently appeared, nor has any quantitative comparative control analysis been made, in the BDFRM(G) literature to date. This paper is an attempt to fill this gap with a comprehensive evaluation of VC and FOC by both computer simulations and laboratory tests under different speed and/or loading conditions of the example BDFRG including those typically encountered in wind energy conversion systems (WECS). The results presented should be of immediate interest not only to the BDFG research community but also to broad academic and industrial circles dealing with the DFIG wind energy sector given the model and control analogies of the two machines to be highlighted in the following despite the conceptually different operating principles.

2. Space-vector theory

The BDFRM(G) dynamic model in rotating reference frames (Fig. 2), using motoring convention and standard notation for the primary and secondary winding quantities, can be represented as

[22]:

$$\left. \begin{aligned} v_p &= R_p i_p + \frac{d\lambda_p}{dt} = R_p i_p + \frac{d\lambda_p}{dt} \Big|_{\theta_p=\text{const}} + j\omega_p \lambda_p \\ v_s &= R_s i_s + \frac{d\lambda_s}{dt} = R_s i_s + \frac{d\lambda_s}{dt} \Big|_{\theta_s=\text{const}} + j\omega_s \lambda_s \\ \lambda_p &= L_p \underbrace{(i_{pd} + j i_{pq})}_{i_p} + L_{ps} \underbrace{(i_{sd} - j i_{sq})}_{i_{sm}^*} \\ \lambda_s &= L_s \underbrace{(i_{sd} + j i_{sq})}_{i_s} + L_{ps} \underbrace{(i_{pd} - j i_{pq})}_{i_{pm}^*} \end{aligned} \right\} \quad (1)$$

where $L_{p,s,ps}$ are the 3-phase self and mutual inductances, $\omega_{p,s}$ are the applied angular frequencies (rad/s) to the respective winding, whereas $i_{sm} = i_s$ and $i_{pm} = i_p$ in Eq. (1) are the magnetically coupled (i.e. magnetizing) currents from the complementary machine side of the same magnitude but modulated frequency [22].

The flux equations above, and the other fundamental steady-state relationships for the machine, can be written as follows [22]:

$$\lambda_p = \underbrace{L_p i_{pd}}_{\lambda_{pd}} + \underbrace{L_{ps} i_{sd}}_{\lambda_{pq}} + j \cdot (L_p i_{pq} - L_{ps} i_{sq}) \quad (2)$$

$$\lambda_s = \lambda_{sd} + j \cdot \lambda_{sq} = \sigma L_s i_s + \underbrace{\frac{L_{ps}}{L_p} \lambda_p}_{\lambda_{ps}^*} \quad (3)$$

$$\omega_{rm} = \frac{\omega_p + \omega_s}{p_r} = \left(1 + \frac{\omega_s}{\omega_p}\right) \cdot \omega_{syn} = (1 - s) \cdot \omega_{syn} \quad (4)$$

$$T_e = \frac{3p_r}{2} (\lambda_{ps_d} i_{sq} - \lambda_{ps_q} i_{sd}) \quad (5)$$

$$P_m = T_e \cdot \omega_{rm} = \underbrace{\frac{T_e \cdot \omega_p}{p_r}}_{P_p} + \underbrace{\frac{T_e \cdot \omega_s}{p_r}}_{P_s} = P_p \cdot \left(1 + \frac{\omega_s}{\omega_p}\right)_{-s} \quad (6)$$

where $s = -\omega_s/\omega_p$ is the 'generic' slip, $\sigma = 1 - L_{ps}^2/(L_p L_s)$ is the leakage factor defined as with conventional induction machines, λ_{ps}

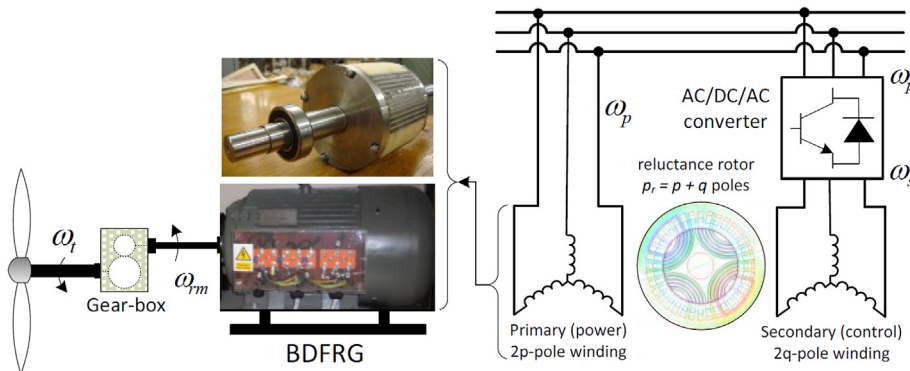


Fig. 1. A simplified schematic of the BDFRG wind turbine drive train.

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