Energy Conversion and Management 81 (2014) 120–132

Contents lists available at ScienceDirect

Energy Conversion and Management

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

# High-efficiency control of brushless doubly-fed machines for wind turbines and pump drives

Sul Ademi, Milutin Jovanovic *

*Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, UK*

ARTICLE INFO

*Article history:*
Received 9 June 2013
Accepted 11 January 2014
Available online 4 March 2014

*Keywords:*
Wind power
Brushless
Doubly-fed machines
Control

ABSTRACT

The paper is concerned with vector control of a promising brushless doubly-fed reluctance machine (BDFRM) technology for generator and drive systems with limited adjustable speed ranges such as wind turbines or pump-alike installations. The BDFRM has been receiving increasing attention because of the low capital and operation and maintenance costs afforded by the partially-rated power electronics and the high reliability of brushless construction, while offering performance competitive to its well-known slip-ring counterpart, a doubly-fed induction machine. The comprehensive comparative studies have evaluated the performance of two robust control algorithms by computer simulations and experimentally on a custom-made BDFRM under the maximum torque per inverter ampere conditions for improved efficiency of electro-mechanical energy conversion.

© 2014 Elsevier Ltd. All rights reserved.

## 1. Introduction

Brushless doubly-fed machines (BDFMs) have been considered as a reliable, cost-effective candidate for wind generators and centrifugal or axial pump (fan, compressor) devices [1–11], which have traditionally been served by a wound-rotor induction machine either with a controllable external resistance in the rotor circuit or operated in a doubly-fed slip power recovery mode (DFIM) [12–17]. In these applications, where only a limited variable speed capability is required (e.g. typically, a 2:1 range or so around the synchronous speed [2,6,18]), the BDFM would retain the DFIM cost benefits of using a smaller inverter (e.g. around 25% of the machine rating), contributing further with higher reliability and maintenance-free operation by the absence of brush gear.

The BDFM has two standard stator windings but of different applied frequencies and pole numbers, unlike the DFIM. The primary (power) winding is grid-connected, and the secondary (control) winding is normally supplied from a bi-directional power converter. A BDFM reluctance type (Fig. 1), the brushless doubly-fed reluctance machine (BDFRM) [1–6], appears to be more attractive than its 'nested' cage rotor form, the brushless doubly-fed induction machine (BDFIM) [7–10,19]. This preference has been mainly attributed to the prospect for higher efficiency [3] with simpler modeling and control[1] associated with the BDFRM cage-less rotor of similar design to that of a modern synchronous reluctance machine [23–25]. However, the BDFM rotor must have half the total number of stator poles to provide the rotor position dependent magnetic coupling between the stator windings, a pre-requisite for the torque production [1,4].

In light of the recently introduced grid codes requiring wind turbines to stay on-line and provide reactive power support for voltage recovery under faulty conditions, another important BDFM merit is the seemingly superior low-voltage-fault-ride-through (LVFRT) capability to the DFIM [26–29]. It has been shown that, owing to relatively large leakage inductances and thus lower fault current levels, the LVFRT of the BDFIM may be accomplished safely without a crowbar circuitry, and with the higher operating stability as well as the lower cost grid integration [30,31]. These potential LVFRT performance advantages over the DFIM can be carried over to the BDFRM featuring the leakage reactance values of the same order as the BDFIM.

Various control strategies[2] have been developed for the BDFRM over the years including scalar control [2,36], primary flux (field) oriented control (FOC) [2,20,36], direct torque control [5,36], torque

[1] Field-oriented control of the primary reactive power and electromagnetic torque is inherently decoupled in both the BDFRM [20] and DFIM [21], but not in the BDFIM [8,10,22].

[2] A good literature review on control of the BDFIM can be found in [7–10,31,32], and of the DFIM in [33–35].

* Corresponding author. Tel.: +44 191 2273016.
*E-mail addresses:* sul.ademi@northumbria.ac.uk (S. Ademi), milutin.jovanovic@northumbria.ac.uk (M. Jovanovic).

http://dx.doi.org/10.1016/j.enconman.2014.01.015
0196-8904/© 2014 Elsevier Ltd. All rights reserved.

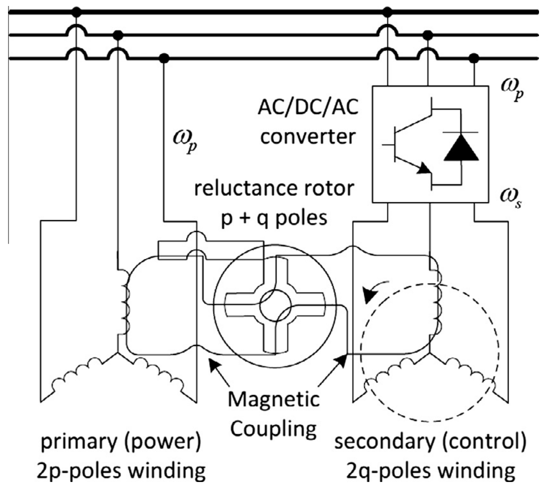


**Fig. 1.** A conceptual diagram of the converter-fed BDFRM.

and reactive power control [37,38], and direct power control [39]. Although a comparative analysis of these control methods has been partly made in [36] (and more detailed for the DFIM in [35]), to the best knowledge of the authors, no similar study has been reported specifically on FOC vs primary voltage oriented control[3] (VC), and there has been no practical work published on VC of the BDFRM. The most likely reason is that the two terms (FOC/VC) have often been interchangeably used to indicate the same control approach despite the quite distinctive meanings as elaborated in [40] taking the stator flux/voltage oriented control analogies for the DFIM as an example.

The fact is that with a proper selection of the reference frames, the two popular control techniques indeed become very similar in nature and dynamic response, especially with larger machines of lower resistances [6,18]. Nevertheless, they have clear conceptual differences and performance trade-offs to be pointed out in this paper using the maximum torque (power) per inverter ampere (MTPIA) strategy [1,2,25] as a ground for their comparison on a custom built BDFRM prototype. The rational behind looking at this particular control property is the potential efficiency gain that can be achieved by reducing both the secondary winding copper and inverter switching losses [1,2]. A wind turbine as a prime mover in generating, and a pump-alike load in motoring mode of the BDFRM, both having the same shape torque-speed characteristic, have been selected as case studies. Extensive realistic simulation studies taking into account the usual practical effects (e.g. transducers' DC offset, noise in measurements, and a four-quadrant power converter model with space-vector PWM) are presented to support the discussions. The simulated motoring operation of the BDFRM is also experimentally validated and a good correlation of the results is demonstrated.

## 2. Dynamic model

The underlying control principles can be better understood by having a closer insight into the space vector theory and unusual torque producing mechanism of the BDFRM [4,41]. Assuming motoring convention and using standard notation, the BDFRM model in rotating $d-q$ reference frames can be represented as [4]:

[3] Voltage oriented control (VOC) is commonly being referred to simply as vector control (VC) in the literature, though, both VOC and FOC can be classified as broad sub-categories of the latter.

$$\left.\begin{aligned}
\underline{v}_p &= R_p\underline{i}_p + \frac{d\underline{\lambda}_p}{dt} = R_p\underline{i}_p + \left.\frac{d\underline{\lambda}_p}{dt}\right|_{\theta_p\text{const}} + j\omega_p\underline{\lambda}_p \\
\underline{v}_s &= R_s\underline{i}_s + \frac{d\underline{\lambda}_s}{dt} = R_s\underline{i}_s + \left.\frac{d\underline{\lambda}_s}{dt}\right|_{\theta_s\text{const}} + j\omega_s\underline{\lambda}_s \\
\underline{\lambda}_p &= L_p\underbrace{(i_{pd}+ji_{pq})}_{\underline{i}_p} + L_{ps}\underbrace{(i_{sd}-ji_{sq})}_{\underline{i}^*_{sm}} \\
\underline{\lambda}_s &= L_s\underbrace{(i_{sd}+ji_{sq})}_{\underline{i}_s} + L_{ps}\underbrace{(i_{pd}-ji_{pq})}_{\underline{i}^*_{pm}}
\end{aligned}\right\} \tag{1}$$

The above flux equations can be manipulated to:

$$\underline{\lambda}_p = \underbrace{L_pi_{pd}+L_{ps}i_{sd}}_{\lambda_{pd}} + j\cdot\underbrace{(L_pi_{pq}-L_{ps}i_{sq})}_{\lambda_{pq}} \tag{2}$$

$$\underline{\lambda}_s = \underbrace{\sigma L_si_{sd}+\lambda_{ps_d}}_{\lambda_{sd}} + j\cdot\underbrace{(\sigma L_si_{sq}+\lambda_{ps_q})}_{\lambda_{sq}} = \sigma L_s\underline{i}_s + \underbrace{\frac{L_{ps}}{L_p}\underline{\lambda}^*_p}_{\underline{\lambda}_{ps}} \tag{3}$$

where the primary and secondary winding are denoted by the subscripts 'p' and 's' respectively, $\sigma = 1 - L^2_{ps}/(L_pL_s)$ is the leakage factor, and $\lambda_{ps}$ is the primary flux linking the secondary winding (i.e. the mutual flux linkage). The definitions of the 3-phase self ($L_{p,s}$) and mutual ($L_{ps}$) inductances can be found in [4,23].

The fundamental angular velocity relationship for the electro-mechanical energy conversion in the machine with $p_r$ rotor poles and $\omega_{p,s} = 2\pi f_{p,s}$ applied frequencies (rad/s) to the respective $>2p$-pole and $2q$-pole windings (Fig. 1) is [4]:

$$\begin{aligned}
\omega_{rm} &= \frac{\omega_p+\omega_s}{p_r} = \frac{(1-s)\cdot\omega_p}{p+q} = (1-s)\cdot\omega_{syn} \\
&\iff n_{rm} = 60\cdot\frac{f_p+f_s}{p_r}
\end{aligned} \tag{4}$$

where the generalized slip is $s = -\omega_s/\omega_p$, and $\omega_{syn} = \omega_p/p_r$ is the synchronous speed (for $\omega_s = 0$ i.e. a DC secondary) as with a $2p_r$-pole wound rotor synchronous turbo-machine. Notice that $\omega_s > 0$ for 'super-synchronous' operation, and $\omega_s < 0$ at 'sub-synchronous' speeds (i.e. an opposite phase sequence of the secondary to the primary winding). It is interesting that the two speed modes of the BDFRM are equivalent to a $2p_r$-pole induction machine in generating ($s < 0$) or motoring ($s > 0$) regimes, and that the speed can be expressed in the same generic form in terms of the slip despite the quite distinct operating principles [4].

The machine instantaneous torque, and the rotor movement (i.e. the acceleration torque) taking into account friction terms, can be expressed as follows [4]:

$$\begin{aligned}
T_e &= \frac{3p_rL_{ps}}{2L_p}(\lambda_{pd}i_{sq}+\lambda_{pq}i_{sd}) = \frac{3p_r}{2}(\lambda_{ps_d}i_{sq}-\lambda_{ps_q}i_{sd}) \\
&= \frac{3p_r}{2}(\lambda_{pd}i_{pq}-\lambda_{pq}i_{pd})
\end{aligned} \tag{5}$$

$$T_a = J\cdot\frac{d\omega_{rm}}{dt} = T_e - T_L(\omega_{rm}) - F\cdot\omega_{rm} \tag{6}$$

Some important observations should be made about (1)–(3). While all the $\omega_p$ rotating vectors in the primary voltage and flux equations are in $\omega_p$ frame, the corresponding secondary counterparts, including the $\lambda_{ps}$ components in (5), are rotating at $\omega_s$ and are in $p_r\omega_{rm} - \omega_p = \omega_s$ frame according to (4) and the BDFRM theory in [4]. Note also that $\underline{i}_{sm} = \underline{i}_s$ and $\underline{i}_{pm} = \underline{i}_p$ in (1) are the magnetically coupled currents from one machine side to the other of the same magnitude but different frequency to the originating current vectors [4]. Given that $\lambda_p$ and $\lambda_{ps}$ in (5) are approximately constant by the primary winding grid connection, torque control can be achieved through the secondary $dq$ currents in the $\omega_s$ frame.

Using (4), one can easily derive the mechanical power equation showing individual contributions of each BDFRM winding:

Download English Version:

https://daneshyari.com/en/article/763972

Download Persian Version:

https://daneshyari.com/article/763972

Daneshyari.com