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A novel sensorless speed controller design for doubly-fed reluctance wind turbine generators

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ABSTRACT

A brushless doubly-fed reluctance generator has been seen by research communities as a potential solution to higher operation and maintenance costs associated with the compromised reliability of brush compartment of conventional doubly-fed induction generators, while offering comparable performance and similar cost benefits of using a partially-rated power electronic converter in wind power applications. A new flux vector oriented encoder-less scheme for speed and inherently decoupled torque and reactive power control has been proposed and successfully experimentally verified on a small machine prototype by emulating the typical torque-speed operating characteristics of ordinary horizontal-axis wind turbines. The obtained test results have clearly indicated the excellent controller response and disturbance rejection abilities over the entire speed range of interest.

1. Introduction

Brushless doubly-fed generators (BDFGs) have been considered as a possible alternative to traditional doubly-fed induction generators (DFIGs) for wind energy conversion systems (WECS) with limited speed ranges [1]. As members of the same slip power recovery family of machines, both the BDFG and DFIG can be supplied by a proportionally smaller inverter being usually around 30% of their rating [2]. Such cost advantages over the main competitor on the wind power market, the bulky and expensive multi-pole wound rotor or permanent-magnet synchronous generators (SGs) with fully-rated power converters, are accompanied by the DFIG reliability issues of brush gear, which entails regular maintenance and may be an obstacle for its long-term use [3].

The concern for the DFIG's future has been further reinforced with the introduction of the national grid codes and stringent regulations for wind turbines to meet in order to stay on-line and provide the necessary ancillary services during abnormal operating conditions [4]. In response to this initiative and to satisfy the stipulated low-voltage-fault-ride-through (LVFRT) requirements, enormous research has been subsequently undertaken and many hardware and/or software solutions proposed in an attempt to handle DFIG faults in a LVFRT compliant manner [5]. For example, computer simulations in [6] have shown that a new controllable protection device may secure better damping of the drive train speed oscillations and faster voltage recovery than most of the prevailing schemes. Similar studies have been done and benefits claimed for a super-capacitor energy storage system described in [7]. Despite these efforts, the insufficiently rated DFIG power modules are generally unable to cope with the rotor transient over-voltages and/or currents while simultaneously producing the reactive power for voltage support, as concluded in [8]. However, the SGs can accomplish this with their full-scale converter and other desirable operating characteristics during voltage dips as detailed in [9]. The cost vs size trade-offs for power electronics render the LVFRT performance of DFIGs inferior to SGs according to the comparisons in [10].

The BDFG may be able to overcome the aforementioned DFIG drawbacks, thus many low to medium-scale prototypes have been recently built, the biggest one recorded to date in [11]. A 2 MW design for wind turbines has also been suggested [12]. As the name reiterates, brushes and slip rings are eradicated, hence the more reliable and maintenance-free operation [3]. These favorable properties should be particularly appealing for off-shore wind turbines, where the DFIG running costs can be considerable [1]. Another essential BDFG merit is the distinguishing LVFRT capability, which can be accomplished safely without protective crowbar circuitry for the machine-side converter owing to the relatively higher leakage inductances and lower fault current levels compared to the DFIG [13].

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Nomenclature

$v_{p,s}$	primary, secondary winding phase voltages [V]	p_r	number of rotor poles
$i_{p,s}$	primary, secondary winding currents [A]	ω_{rm}	rotor angular velocity $= \omega_r/p_r$ [rad/s]
$R_{p,s}$	primary, secondary winding resistances [Ω]	θ_{rm}	rotor angular position $= \theta_r/p_r$ [rad]
$L_{p,s}$	primary, secondary 3-phase self-inductances [H]	ω_{syn}	synchronous speed $= \omega_p/p_r$ [rad/s]
L_m	3-phase mutual inductance [H]	P_m	mechanical (shaft) power [W]
σ	leakage factor (constant) $= 1 - L_m^2/(L_pL_s)$	$P_{p,s}$	primary, secondary mechanical power [W]
$\lambda_{p,s}$	primary, secondary winding flux linkages [Wb]	T_e	machine electro-magnetic torque [Nm]
λ_m	mutual flux [Wb]	T_L	prime mover or load (shaft) torque [Nm]
$\theta_{p,s}$	primary, secondary frame angular positions [rad]	P, Q	primary real [W] and reactive [VAr] power
$\omega_{p,s}$	primary, secondary winding frequencies [rad/s]		

The BDFG contains two ordinary, distributed 3-phase stator windings of different applied frequencies and pole numbers, with a rotor having half the total number of stator poles to produce the shaft position dependent magnetic coupling between the windings required for the torque production. The primary (power) winding is grid connected, while the secondary (control) winding is supplied through a fractional dual-bridge converter in 'back-to-back' configuration for bi-directional power flow (Fig. 1). The BDFG with a modern reluctance rotor form is known as the Brushless Doubly-Fed Reluctance Generator (BDFRG) in Fig. 1 [14]. Whereas, the so called Brushless Doubly-Fed Induction Generator (BDFIG) has a special 'nested' cage rotor structure [15]. By the absence of the rotor windings, the BDFRG offers the prospect for higher efficiency than the equivalent BDFIG as experimentally demonstrated in [16]. Furthermore, it has simpler dynamic modeling with lower machine parameter dependence and inherently decoupled control of torque and reactive power [17]. The same merits can be credited to the DFIG [18]. In contrary, the BDFIG model and control are rather involved to reflect the three-winding arrangement [19]. The emphasis of this paper therefore contemplates on the BDFRG as a prominent forthcoming technology.

The current scope of BDFRG(M) control comprises the following categories: scalar control (SC), vector control (VC), direct torque and secondary flux control (DTC), direct torque and primary reactive power control (DTQC), direct power control (DPC), and sliding mode control (SMC). The SC principles established in [20] are intellectually interesting, but have been left unproven in practice. The same holds for the preliminary non-linear SMC attributes discussed in [21]. On the other hand, an original model-based DTC approach has been put forward and experimentally validated using a shaft position sensor for speed control in [22]. Additionally, an angular velocity observer based upgrade of this method for sensorless operation of the BDFRM can be found in [20]. However, whether implemented in sensor or sensorless mode, the DTC algorithm in [22] is sensitive to inductance knowledge and λ_s estimation inaccuracies so that poor proof of concept results for an unloaded BDFRM have only been reported.

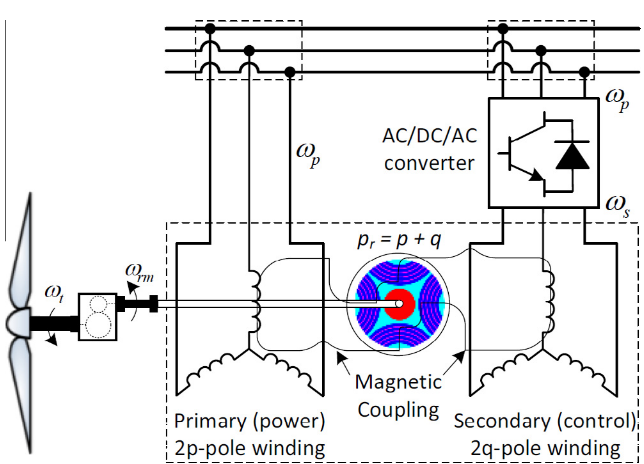

Fig. 1. A conceptual diagram of the BDFRG based wind energy conversion system (WECS).

The preceding DTC shortcomings have been eliminated and much improved response obtained by replacing λ_s with Q as a control variable in the parameter independent DTQC scheme presented in [23]. Similar performance enhancements have been achieved by applying the DPC alternative [24]. The downside of these contributions is that fixed loading conditions of the BDFRG (M) considered are of little interest to the target WECS or reversible pumped storage units [25]. Although robust and easy to implement in a stator frame without having to know the rotor position or speed [26], the DTQC and DPC are of hysteresis ('bang-bang') type and suffer from usual variable switching frequencies and higher flux (torque) ripples, unlike, in this sense, the superior VC. Besides, they both require an encoder solely for the speed regulation, and the sensor use is under-utilized from this point of view compared to the VC where it also serves for torque control.

VC with voltage space-vector orientation (VOC) or flux (field) vector orientation (FOC) has been a widely adopted option in industrial and academic circles for various adjustable speed drive and generator systems, including WECS [27]. As such, it has been intensively investigated for commercial DFIGs as surveyed in [4]. The theoretical considerations of the VC concept for the emerging BDFRG substitute in [20] have not been supported by true measurements. Further important advances have been thereafter made in [28], and the follow-up research by the authors, with the comparative development of the two robust VOC and FOC methods for typical variable speed and/or loading conditions of the small-scale BDFRG(M) in the end WECS or pump-type applications emulated in a laboratory environment. The maximum torque per inverter ampere performance of the two schemes have been assessed experimentally for the BDFRM, and by simulation analyses of the BDFRG [28]. The latter have been fully verified by the test results presented in [29]. A significant extension to this work appears in [30] where the reactive power response and disturbance rejection abilities of the controllers for the BDFRG have been evaluated. Realistic computer simulations of the VOC and FOC studies on a 2 MW BDFRG turbine with optimum tip-speed-ratio have been published in [31]. A good review of this and other maximum power point tracking (MPPT) strategies has been conducted in [32].

The BDFG works referenced above almost exclusively rely on the rotor position information for closed-loop speed control. Sensorless operation would be desirable as shaft encoders bring many limitations in terms of cost, maintenance, sturdiness, and cabling requirements [33]. The latter deficiency may be particularly severe with DFIG turbines where regular brush servicing can pose a grow-