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Wind power applications of doubly-fed reluctance generators with parameter-free hysteresis control

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ABSTRACT

The development and practical implementation aspects of a novel scheme for fast power control of the doubly-fed reluctance generator with a low-cost partially-rated converter, a promising brushless candidate for limited speed ranges of wind turbines, are presented in this paper. The proposed concept is derived from the fundamental dynamic analogies between the controllable and measurable properties of the machine: electro-magnetic torque and electrical power, and flux and reactive power. The algorithm is applied in a stationary reference frame without any knowledge of the machine parameters, including rotor angular position or velocity. It is then structurally simpler, easier to realize in real-time and more tolerant of the system operating uncertainties than model-based or proportional-integral control alternatives. Experimental results have demonstrated the excellent controller response for a variety of speed, load and/or power factor states of a custom-built generator prototype.

1. Introduction

A brushless doubly-fed generator (BDFG) may be an attractive solution to reliability and maintenance issues of carbon brushes and slip-rings with a conventional doubly-excited induction generator (DFIG) while offering competitive performance and the same economic benefits of partial power electronics [1]. For a typical speed ratio of 2:1 in wind energy conversion systems (WECS), the converter derating can be about 75% of the machine itself [2]. In this sense, both the BDFG and DFIG are preferable to heavy and expensive multi-pole wound rotor synchronous generators (SGs) or permanent-magnet generators (PMGs) with fully-rated converters, which are not only costly but more prone to failures undermining the otherwise high reliability of their dedicated wind turbines, gear-less technologies in particular [3]. Another concern for the manufacturers of large PMG units is the risk management of market volatility, availability and payable price premiums of the rare earth magnets (e.g. NdFeB) deployed [4].

With the increasing penetration of distributed generation, the challenging requirements have been imposed by the grid integration codes for the reactive (and real) power support to be provided by WECS to help preserve the transient stability during network disturbances (e.g. voltage sags) [5]. Putting these preventive measures in place has revealed another important BDFG potential, the superior low-voltage-ride-through (LVRT) characteristics owing to the inherently higher impedances and thus lower fault currents relative to the equivalent DFIG [6]. This salient BDFG property could facilitate to a great deal the design of hardware and software protection for the LVRT compliant fractionally-rated converter, decreasing so the supplementary system complexity and cost of DFIG installations [7]. DFIG turbines are known to have LVRT weaknesses and many interesting solutions have been recently proposed to find improvements [8]. The latest rigorous review of the extensive research done on this subject has been published in [9]. However, tangible practical advances are yet to be made in this direction for the DFIG to become comparable to the PMG, which is amenable to fulfilling the LVRT obligations due to the use of a full-power converter and favorable low voltage capability curves as demonstrated by the WECS field tests presented in [10].

In order to eliminate brushes for reliable and maintenance-free operation, the BDFG has evolved as a self-cascaded inside-out version of the DFIG [11]. This means that the rotor (secondary or control) winding, usually fed from two standard IGBT bridges in bi-directional ('back-to-back') arrangement to allow both super and sub-synchronous speeds in either machine mode, has been moved to the stator and placed together with the grid-connected (primary or power) winding but of different pole number (Fig. 1). The necessary magnetic interaction between the two windings for the torque production is achieved through the rotor with half the total num-

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Nomenclature

$v_{p,s}$	primary, secondary winding phase voltages [V]	$\omega_{p,s}$	primary, secondary winding frequencies [rad/s]
$e_{p,s}$	primary, secondary winding back-emf [V]	p, q	primary, secondary winding pole-pairs
$i_{p,s}$	primary, secondary winding currents [A]	p_r	number of rotor poles $= p + q$
$R_{p,s}$	primary, secondary winding resistances [Ω]	ω_{rm}	rotor angular velocity $= d\theta_{rm}/dt$ [rad/s]
$L_{p,s}$	primary, secondary 3-phase self-inductances [H]	θ_r	rotor 'electrical' angular position $= p_r\theta_{rm}$ [rad]
L_m	3-phase mutual inductance [H]	ω_{syn}	synchronous speed $= \omega_p/p_r$ [rad/s]
σ	leakage factor (constant) $= 1 - L_m^2/(L_pL_s)$	P_m	total mechanical (shaft) power [W]
$\lambda_{p,s}$	primary, secondary winding flux linkages [Wb]	$P_{p,s}$	primary, secondary mechanical power [W]
λ_m	mutual flux [Wb]	T_e	machine electro-magnetic torque [N m]
$\theta_{p,s}$	primary, secondary flux vector angular positions [rad]	P, Q	primary real [W] and reactive [VAr] power

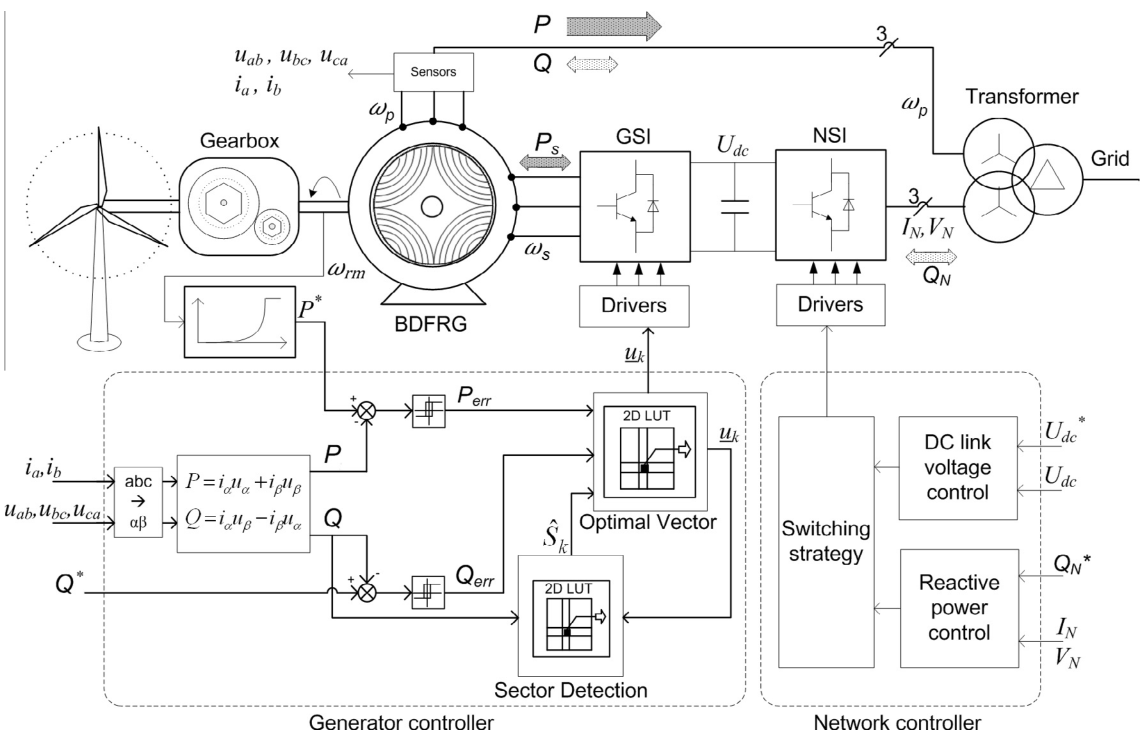

Fig. 1. A simplified structural diagram of the BDFRG wind turbine with maximum power point tracking and sensorless hysteresis primary power control of the generator side inverter (GSI).

ber of the stator poles [12]. Therefore, for the same number of rotor poles and a given line frequency, the DFIG synchronous speed would be twice that of the BDFG making it naturally a medium-speed machine and avoiding the need for a high-speed gear stage of the vulnerable 3-stage gearbox in WECS [1]. From this point of view, the BDFG could bring higher efficiency and reliability as well as running costs savings in these applications, and especially off-shore [13].

The BDFG reluctance rotor type, the Brushless Doubly-Fed Reluctance Generator (BDFRG in Fig. 1), has several advantages over its 'nested' cage counterpart, the Brushless Doubly-Fed Induction Generator (BDFIG) [12]. Experiments have shown that the BDFRG can be more efficient than the BDFIG of the same stator frame [14]. In addition, the cage-less rotor allows the fewer parameter dependent dynamic modeling, and intrinsically decoupled control of torque and primary reactive power of the BDFRG, unlike the BDFIG [15]. Similar BDFRG attributes are shared by the DFIG [16]. In contrast with the BDFRG or DFIG, the BDFIG has fairly complicated and heavily parameter sensitive model-based vector control [17]. Severe robustness compromises can be affiliated with direct torque controllers for this machine as well [18].

Several 6/2-pole BDFRGs in a kW range have been built, one of which rated at 1.5 kW considered in this paper, and the other to note being a 4 kW counterpart reported in [19]. The more sizeable example recorded in the open literature is a 16 kW, 8/4-pole [12]. One should also mention a 42 kW, 6/2-pole machine studied in [20]. The biggest prototype made so far seems to be a 6/4-pole, 100 kW [21]. An original 2 MW, 6/2-pole design for wind turbines has also been proposed [22].

Research paths on control of other machines have been largely pursued in the BDFRG case over the last decade or so. Although intellectually appealing, the non-linear sliding mode control theory developed in [23] has not been applied in practice to be able to judge on its viability. On the other hand, a stator frame executed

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