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Low voltage ride-through of DFIG and brushless DFIG: Similarities and differences

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ABSTRACT

The brushless doubly fed induction generator (BDFIG) has been proposed as a viable alternative in wind turbines to the commonly used doubly fed induction generator (DFIG). The BDFIG retains the benefits of the DFIG, i.e. variable speed operation with a partially rated converter, but without the use of brush gear and slip rings, thereby conferring enhanced reliability.

As low voltage ride-through (LVRT) performance of the DFIG-based wind turbine is well understood, this paper aims to analyze LVRT behavior of the BDFIG-based wind turbine in a similar way. In order to achieve this goal, the equivalence between their two-axis model parameters is investigated. The variation of flux linkages, back-EMFs and currents of both types of generator are elaborated during three phase voltage dips. Moreover, the structural differences between the two generators, which lead to different equivalent parameters and hence different LVRT capabilities, are investigated.

The analytical results are verified via time-domain simulations for medium size wind turbine generators as well as experimental results of a voltage dip on a prototype 250 kVA BDFIG.

1. Introduction

With increasing penetration of wind energy into electrical power systems, many countries have introduced connection Grid Codes to regulate the effect of wind farms on the grid. One of the most important and demanding requirements of these codes deals with the low voltage ride-through (LVRT) capability of wind turbines (WTs). LVRT arises as Grid Codes require WTs to remain connected during grid voltage dips according to a pre-determined curve. For example, LVRT characteristics of the German Transpower Grid Code are shown in Fig. 1 [1]. According to this Grid Code, WTs must tolerate voltage dips from the highest value of the three line voltages with a profile above the bold line of Fig. 1, i.e. in the gray region, without disconnecting.

The most widely installed modern variable speed WTs employs the doubly fed induction generator (DFIG). Using the DFIG in WTs provides a degree of variable speed operation, when using partially rated bi-directional converter and associated filters. The disadvantage of the DFIG is its unavoidable use of brush-gear and slip-rings, which reduce reliability [2].

The brushless DIFG (BDFIG) has been proposed as an alternative to the DFIG in variable speed WTs. The BDFIG retains the main benefits of DFIG without brush-gear or slip-rings, leading to higher reliability and less maintenance.

Extensive analytical investigations have been made into the LVRT capability of DFIG including methods to improve its performance. FACTS devices [3], supercapacitor energy storage [4], series grid-side converter [5], crowbar and static transfer switches [6], energy capacitor systems [7], series dynamic resistors [8], dynamic voltage restorers [9,10] and controller modifications [11–16] have all been suggested to improve DFIG LVRT capability.

On the other hand, many aspects of the BDFIG or more generally the Brushless Doubly Fed Machine (BDFM), such as steady-state modeling [17] and analysis [18], dynamic modeling [19,20] and control [21–23] have been studied in the literature and BDFIG LVRT performance has been studied using crowbar and series dynamic resistors [24].

The DFIG has been used in WTs since late 1980s and many WT manufacturers have wide experience of its operation and control. It appears that if BDFIG is analyzed and controlled in a similar way, it would facilitate the understanding of its LVRT behavior. Additionally, the control systems proposed for enhancing LVRT capability of DFIG can also be used for BDFIG, albeit with some modifications.

At the current stage of BDFIG design, due to the relatively lower torque densities predicted for BDFIGs compared to conventional

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Nomenclature

p	pole number
N_r	number of BDFIG rotor circuits
v	voltage
i	current
λ	flux linkage
e	back electro-motive force
R	winding resistance
L	self inductance
L_l	leakage inductance
M	mutual inductance
T	torque
ω	angular speed
Q	reactive power
J	inertia
K_s	shaft stiffness
D	shaft damping coefficient
γ	shaft twist angle
δ	winding damping factor

Subscripts and superscripts

s	DFIG stator
r	rotor
p	BDFIG power winding
c	BDFIG control winding
e	electrical
m	mechanical
$'$	transient
0	steady-state (pre-fault)
b	base

induction machines [18], a BDFIG could be larger than a DFIG of the same rating and speed. However, experiments on an actual medium scale BDFIG show satisfactory steady state and dynamic performance [25], which could be improved further with advances in design.

As the BDFIG has a complex air gap flux, this paper aims to facilitate BDFIG LVRT analysis similar to a DFIG by presenting the equivalences between the BDFIG and DFIG. Moreover, their LVRT capability will be compared, reflecting the effect of inherent features in such generators on their equivalent parameters.

The structure of the paper is as follows: Section 2 explains the modeling and control of both generators; Section 3 elaborates their LVRT performance, using a *dq* model, in which variations of flux linkages and EMFs are analyzed; and also compares their LVRT capabilities taking into account the differences between their parameters; in Section 4, simulation results are presented to verify the analysis; and finally in Section 5, experimental results of a severe voltage dip at terminals of a 250 kVA BDFIG is presented to verify analysis and simulations.

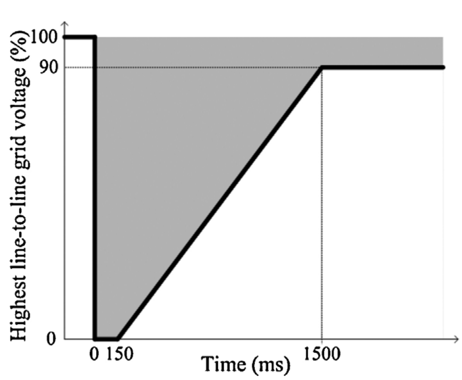

Fig. 1. German Transpower Grid Code LVRT curve [1].

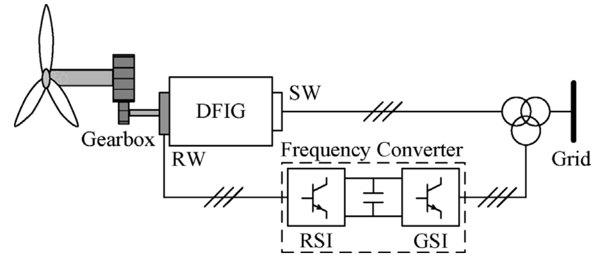

Fig. 2. WT with DFIG.

2. Principles of DFIG and BDFIG

A WT with DFIG is illustrated in Fig. 2. The generator is a wound rotor induction machine, in which the rotor winding (RW) is connected, via brush gear and slip rings, to a bi-directional, partially rated converter and its stator winding (SW) and the converter are connected to the grid in parallel. The converter consists of two inverters connected back-to-back via a DC link capacitor. The rotor side inverter (RSI) controls the rotor speed and stator reactive power, while the grid side inverter (GSI) controls the DC link voltage to remain essentially constant.

The BDFIG, on the other hand, has two stator windings while its RW is shorted, not requiring brush-gear or slip-rings. As can be observed in Fig. 3, one of the stator windings, the power winding (PW), is connected directly to the grid while the other, the control winding (CW), is connected to the grid via a partially rated converter. The converter is identical to that used in the DFIG, except the inverters need to be named machine side inverter (MSI) and grid side inverter (GSI).

The PW and CW have different pole pair numbers to avoid direct electromagnetic coupling between them. This difference is selected to be greater than 1 to prevent unbalanced magnetic pull on the rotor [26]. The RW should be designed such that in addition to direct coupling with each stator winding, it establishes cross coupling between the PW and CW. In fact, the rotor acts as an interface between the two stator windings and associates their different pole number fields together. To satisfy this requirement, the number of rotor circuits or pole pairs, N_r, should be related to the stator winding pole numbers as:

$$N_r = p_p + p_c \tag{1}$$

The most popular rotor structure proposed so far for the BDFIG is the nested-loop rotor, in which each nest represents one circuit [26]. The RW produces a magneto-motive force (MMF) in response to each of the PW or CW MMFs, which has space harmonic content orders of p_p and p_c as well as other undesired higher orders. In this way, the p_p pole pair MMFs from the PW and RW

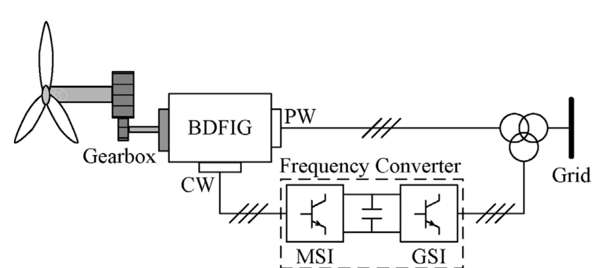

Fig. 3. WT with BDFIG.