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Mathematical modeling and analysis of brushless doubly fed reluctance generator under unbalanced grid voltage condition

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ABSTRACT

The brushless doubly fed reluctance generator (BDFRG) can be an attractive choice for wind power application where mostly located at remote areas with unbalanced grid voltages, however there is not any study on the BDFRG under this condition up to now. In this paper, a mathematical model for the BDFRG under unbalanced grid voltage condition has been developed. Its equivalent circuit in *dq* reference frames has been extracted, and the torque and power equations have been derived, all based on the positive and negative sequence components. Also, a real-time separation method has been proposed to separate the BDFRG positive and negative sequences. The developed model and equations express the basis of the BDFRG operation under unbalanced grid voltage condition. The proposed model is simulated in MATLAB/Simulink software and the accuracy of the proposed model and equations has been validated by comparison with simulation results of an existing BDFRG model under balanced condition, which has already been experimentally verified in the literature.

Introduction

Nowadays, brushless doubly fed reluctance generator (BDFRG) has been proposed as a potential alternative to the existing solutions for wind power applications [1–8]. The main reason of this increasing interest could be found in the reasonable cost and high reliability of the BDFRG because of its brushless structure [3,9]. On the other hand, its comparative performance with other generators such as doubly fed induction generator (DFIG) [10] and brushless doubly fed induction generator (BDFIG) [9,11] leads to consideration of the BDFRG as a suitable choice for wind power application.

The BDFRG uses partially-rated converter in wind power applications like other doubly fed generators [1–3]. In addition, the absence of rotor cage makes it more efficient [4] and easier to control [3] in comparison with the BDFIG. Also, elimination of brushes and slip rings in its structure ensures high reliability and low maintenance cost of the BDFRG in comparison with DFIG, which are especially important to off-shore plants [12].

The BDFRG has two sinusoidal distributed three-phase windings in its stator with different pole pairs and supply frequencies. A reluctance rotor with P_r salient poles can make a magnetic coupling between the primary (with P_1 pole pairs) and secondary (with P_2 pole pairs) [2]. The primary is directly connected to the grid while the secondary is connected through a back to back converter. The BDFRG connection to the grid is shown in Fig. 1 [12], and Fig. 2 illustrates its structure.

In literature, different methods have been proposed to control of the BDFRG under balanced condition. These methods can be classified into following categories: scalar control [16–19], field orientation control (FOC) [20–28], direct torque control (DTC) [23,29–34] and direct power control (DPC) [12,35]. A comparative analysis of these control methods can be found in [36]. All of these methods are designed to control of the BDFRG under balanced condition, whereas, wind power plants are often installed in rural and remote areas which weak grid with unbalanced voltages is usual [37–39]. This caused to some problems in wind generator such as unbalanced currents, localized heating in the generator stator, electrical torque and power pulsations and stress on the mechanical parts [37,38]. Consequently, wind generator may has to be disconnected from the grid to avoid mentioned problems [40]. However, these problems can be compensated by using proper control methods. So, the study of wind generator under unbalanced grid voltage condition and design of a suitable control method is very important. However, there is not any study on the BDFRG under unbalanced grid voltage condition until now. This paper aims to fill this gap by presenting a new model for the BDFRG under unbalanced grid voltage condition.

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Nomenclature

P_r	salient poles of rotor
P_1, P_2	pole pairs of primary and secondary
ω_r	electrical angular velocity of rotor
ω_p, ω_s	angular frequency of primary and secondary
R_p, R_s	resistance of primary and secondary
L_p, L_s	inductance of primary and secondary
L_{ps}	primary to secondary mutual inductance
J	inertia of BDFRG
dq	stationary reference frame
dq_p	rotating reference frame at ω_p for primary
dq_s	rotating reference frame at ω_s for secondary
${dq_p}^+$	rotating reference frame at ω_p for primary positive sequence
${dq_p}^-$	rotating reference frame at $-\omega_p$ for primary negative sequence
${dq_s}^+$	rotating reference frame at ω_s for secondary positive sequence
${dq_s}^-$	rotating reference frame at $\omega_r + \omega_p$ for secondary negative sequence
$\boldsymbol{v}$, $\boldsymbol{i}$, $\boldsymbol{\lambda}$	voltage, current and flux space vectors
$\boldsymbol{x}$	a space vector which can be $\boldsymbol{v}$, $\boldsymbol{i}$ or $\boldsymbol{\lambda}$
$\boldsymbol{x_p}$	primary space vector in dq_p reference frame
$\boldsymbol{x_s}$	secondary space vector in dq_s reference frame
$\boldsymbol{x_{p_s}}$	primary space vector in dq reference frame
$\boldsymbol{x_{s_s}}$	secondary space vector in dq reference frame
x_{p1}, x_{p2}	moduli of positive and negative sequences of $\boldsymbol{x_p}$
x_{s1}, x_{s2}	moduli of positive and negative sequences of $\boldsymbol{x_s}$
θ_{xp^+}, θ_{xp^-}	initial angular positions of positive and negative sequences of $\boldsymbol{x_p}$
θ_{xs^+}, θ_{xs^-}	initial angular positions of positive and negative sequences of $\boldsymbol{x_s}$
$\boldsymbol{x_p^+}$, $\boldsymbol{x_p^-}$	positive and negative sequence components of $\boldsymbol{x_p}$ in the dq_p^+ and dq_p^- reference frames
$\boldsymbol{x_s^+}$, $\boldsymbol{x_s^-}$	positive and negative sequence components of $\boldsymbol{x_s}$ in the dq_s^+ and dq_s^- reference frames
x_{pd}^+, x_{pd}^-	real parts of $\boldsymbol{x_p^+}$ and $\boldsymbol{x_p^-}$
x_{pq}^+, x_{pq}^-	imaginary parts of $\boldsymbol{x_p^+}$ and $\boldsymbol{x_p^-}$
x_{sd}^+, x_{sd}^-	real parts of $\boldsymbol{x_s^+}$ and $\boldsymbol{x_s^-}$
x_{sq}^+, x_{sq}^-	imaginary parts of $\boldsymbol{x_s^+}$ and $\boldsymbol{x_s^-}$
x_{pd}, $\bar{x}_{pd}$	real part of $\boldsymbol{x_p}$ and its mean value
x_{pq}, $\bar{x}_{pq}$	imaginary part of $\boldsymbol{x_p}$ and its mean value
x_{sd}, $\bar{x}_{sd}$	real part of $\boldsymbol{x_s}$ and its mean value
x_{sq}, $\bar{x}_{sq}$	imaginary part of $\boldsymbol{x_s}$ and its mean value
P_p, P_{p_av}	three-phase active power of primary and its average value
$P_{p\_\cos2}$, $P_{p\_\sin2}$	oscillating part coefficients of three-phase active power of primary
Q_p, Q_{p_av}	three-phase reactive power of primary and its average value
$Q_{p\_\cos2}$, $Q_{p\_\sin2}$	oscillating terms of three-phase reactive power of primary
P_s, P_{s_av}	three-phase active power of secondary and its average value
$P_{s\_\cos2}$, $P_{s\_\sin2}$	oscillating terms of three-phase active power of secondary
Q_s, Q_{s_av}	three-phase reactive power of secondary and its average value
$Q_{s\_\cos2}$, $Q_{s\_\sin2}$	oscillating terms of three-phase reactive power of secondary
T_e, T_{e_av}	electrical torque and its average value
$T_{e\_\cos2}$, $T_{e\_\sin2}$	oscillating part coefficients of electrical torque
BDFRG	brushless doubly fed reluctance generator
BDFIG	brushless doubly fed induction generator
DFIG	doubly fed induction generator
VUF	Voltage Unbalance Factor
FFT	Fast Furriery Transform

The first step in design of a proper control method for a wind generator under unbalanced grid voltage condition is to obtain the generator equations under this condition. In this paper, the dynamics, torque and power equations of the BDFRG under unbalanced grid voltage condition are derived and its operation is analyzed. The derived equations, which are in the positive and negative sequences, describe the BDFRG behavior under unbalanced grid voltage condition. They can also be basis of different methods for control of the BDFRG in the future. The proposed model is simulated in MATLAB/Simulink and the derived equations accuracy have been validated by comparing with the existing BDFRG model under balanced condition [5,41], which has already been experimentally validated in [6,12,22,27,28,31,32].

The rest of this paper is arranged as follows: The BDFRG mathematical model under balanced condition is expressed in Section "The BDFRG mathematical model under balanced condition". In Section "The BDFRG mathematical model under unbalanced grid voltage condition", a new mathematical model for the BDFRG under unbalanced grid voltage condition is proposed, and the required positive and negative dq reference frames are defined. Also, an equivalent circuit for the negative sequence is extracted. The BDFRG power and torque equations, based on the positive and negative sequence components, are developed in Section "Power and torque equations". In Section "Real-time sequence separation", a method for the real-time separation of the BDFRG positive and negative sequences is proposed. Finally, the accuracy of the proposed model and equations for the BDFRG under unbalanced grid voltage condition are checked in Section "Model validation".

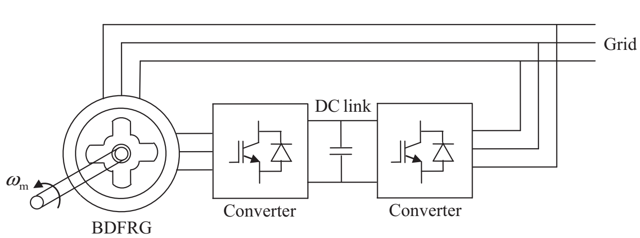

Fig. 1. The connection of the BDFRG to the grid.

The BDFRG mathematical model under balanced condition

The space vector model for the BDFRG is as follows [5,41]:

$$\boldsymbol{v_p} = R_p\boldsymbol{i_p} + \frac{d\boldsymbol{\lambda_p}}{dt} + j\omega_p\boldsymbol{\lambda_p} \quad (1)$$

$$\boldsymbol{v_s} = R_s\boldsymbol{i_s} + \frac{d\boldsymbol{\lambda_s}}{dt} + j(\omega_r - \omega_p)\boldsymbol{\lambda_s} = R_s\boldsymbol{i_s} + \frac{d\boldsymbol{\lambda_s}}{dt} + j\omega_s\boldsymbol{\lambda_s} \quad (2)$$

$$\boldsymbol{\lambda_p} = L_p\boldsymbol{i_p} + L_{ps}\boldsymbol{i_s^*} \quad (3)$$

$$\boldsymbol{\lambda_s} = L_s\boldsymbol{i_s} + L_{ps}\boldsymbol{i_p^*} \quad (4)$$

where R_p, R_s, L_p, L_s and L_{ps} are respectively primary resistance, secondary resistance, primary inductance, secondary inductance and primary to secondary mutual inductance. $\boldsymbol{x_p}$ and $\boldsymbol{x_s}$ are the primary and secondary space vectors in the reference frames rotating at ω_p and ω_s, respectively. ω_p, ω_s and ω_r are the angular frequency of the