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Modeling, control and fault diagnosis of an isolated wind energy conversion system with a self-excited induction generator subject to electrical faults

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ABSTRACT

In this paper, a contribution to modeling and fault diagnosis of rotor and stator faults of a Self-Excited Induction Generator (*SEIG*) in an Isolated Wind Energy Conversion System (*IWECS*) is proposed. In order to control the speed of the wind turbine, while basing on the linear model of wind turbine system about a specified operating point, a new Fractional-Order Controller (*FOC*) with a simple and practical design method is proposed. The *FOC* ensures the stability of the nonlinear system in both healthy and faulty conditions. Furthermore, in order to detect the stator and rotor faults in the squirrel-cage self-excited induction generator, an on-line fault diagnostic technique based on the spectral analysis of stator currents of the squirrel-cage *SEIG* by a Fast Fourier Transform (*FFT*) algorithm is used. Additionally, a generalized model of the squirrel-cage *SEIG* is developed to simulate both the rotor and stator faults taking iron loss, main flux and cross flux saturation into account. The efficiencies of generalized model, control strategy and diagnostic procedure are illustrated with simulation results.

1. Introduction

The recent technological developments of the wind turbine systems focus on maintenance cost reduction [1–3], production capacity improvement [4,5], control stability and operational reliability [6–8]. The use of an induction machine as a generator in almost all types of these systems [9,10] as in isolated wind energy conversion system justifies the importance of the supervision of their normal operations. A variety of faults can occur within the induction machine [11], such as the rotor cage malfunctions and the stator phase unbalance, that may result in a complete breakdown if the progress of the fault is not detected.

Generally, the fault diagnosis method consists of creating the real fault into the physical system, and evaluating its effect on different measured variables. Such approach can be dangerous for the generator and may lead to the destruction of the wind turbine. Therefore, adequate models of the induction machine for studying the behavior of the wind energy conversion system are needed and remain an effective tool to predict the performance of the IWECS under fault conditions.

The classical dynamic models incorporating the effect of saturation in the magnetic circuit of the *SEIG* which are based on stationary reference frame d–q axes theory as in [12–16] suppose that both stator and rotor windings are symmetric. In these models, the equivalent resistance matrix is diagonal and the equivalent inductance matrix is symmetric. These models are simple for simulation but they cannot reflect any asymmetries due to stator or rotor faults.

In the literature, other analytical models of induction machines are still the most common choices for the emulation of stator and rotor faults [17–19]. The simplest method to simulate a stator fault is to insert an additional resistance in series to one phase stator winding in order to cause a stator phase unbalance. While emulating a rotor fault, the classical model takes into account the individual conductors in the rotor cage using R–L series circuits, with current loops defined by two adjacent rotor bars connected by portions to the end ring. When a broken rotor bar fault is considered, the corresponding bar resistance value is assumed to be high value to force the current in the bar to zero [20]. Therefore, for squirrel-cage self-excited induction generator, a model with N_r rotor bars takes into account the nonlinearity of the magnetic circuit characteristic of the machine. This approach

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leads to a very complicated transient model. Such a model is quite complex and its computer simulation becomes very long. So, it will not be used in this work.

In this paper, a new model based on stationary frame *d–q* of the *SEIG* incorporating the effect of stator and rotor asymmetries (due to faults) is developed. The effects of iron losses, main flux and cross flux saturation are also incorporated in the model. The model supposes that stator resistances are not equal. This situation is equivalent to a dissymmetry winding due to faults in the *SEIG* stator such as the inter-turn short circuit. The rotor is decomposed to N_r loops. For a healthy rotor, the rotor loops are identical and have the same parameters that make this model similar to the classical *d–q* model, but when a rotor fault occurs, some loops are affected. In this condition, the equivalent resistance of the rotor in the two axes *d–q* model is not diagonal, making this model more generalized than the classical *d–q* model.

Fault diagnosis allows the detection and the identification of any deviation of the operating parameters from their normal or expected values [21,22]. Most popular methods of induction machine condition monitoring use the steady-state spectral components of the current variables [23,24]. In this paper, in order to diagnosis the stator and rotor faults in the *SEIG*, we use a diagnostic procedure based on the stator current analysis using *FFT* algorithm that has the ability to identify and isolate certain frequency components of interest [25].

Recently, application of fractional calculus in the control area is increasingly used [26–30]. In comparison with the classical order controllers, the fractional order controllers have a potential to improve the control performance [27], and increase the system robustness because of extra real parameters involved [31]. In this paper, according to the imposed three tuning constraints, to guarantee control performance and the robustness to the loop gain variations, a new fractional order controller (Fractional Order Proportional, Integral, Derivative and Integrator order Derivative $PI^{\alpha}D^{\mu}D$) is proposed and designed for the fixed-speed operation of wind turbines by adjusting the blade-pitch angle.

The paper is organized as follows. The model of the system represented by Fig. 1 (*SEIG*, actuator and turbine) is developed in Section 2. The pitch control design, based on proposed fractional-order $PI^{\alpha}D^{\mu}D$ controller, is represented in Section 3. The diagnosis procedure is represented in Section 4. The simulation results are given in Section 5. The conclusion is given in Section 6.

2. Modeling of the system

2.1. Modeling of the squirrel-cage SEIG

2.1.1. Stator modeling taking into account stator fault

The dynamic model for the stator windings of the three-phase squirrel cage induction generator is developed and the relevant volt–ampere equations are:

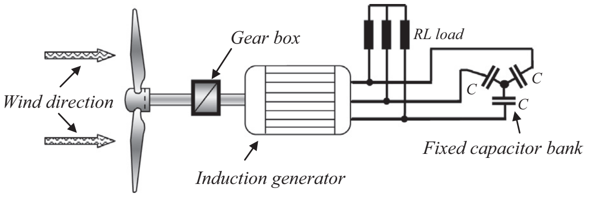

Fig. 1. Basic schema: *SEIG* with a capacitor excitation system driven by a wind turbine.

$$-V_s = R_s I_s + \frac{d\phi_s}{dt} \tag{1}$$

$V_s = [V_{sa}, V_{sb}, V_{sc}]^T$ is the stator voltage vector; $I_s = [i_{sa}, i_{sb}, i_{sc}]^T$ is the stator current vector; $R_s = diag[R_{sa}, R_{sb}, R_{sc}]$ is an 3 by 3 stator resistance matrix; $\phi_s = [\phi_{sa}, \phi_{sb}, \phi_{sc}]^T$ is a stator flux vector.

With the Park transformation (P_s), the voltage equations for the stator windings can be written as:

$$-V_{sdq} = P_s R_s P_s^{-1} I_{sdq} + P_s \frac{d\left(P_s^{-1}\phi_{sdq}\right)}{dt} = R_{SDQ} I_{sdq} + \frac{d\phi_{sdq}}{dt} + \omega_s \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \phi_{sdq} \tag{2}$$

where R_{SDQ} is the equivalent resistance matrix and is given by:

$$R_{SDQ} = P_s R_s P_s^{-1} = \begin{bmatrix} R_{ds} & R_{sdq} \\ R_{sdq} & R_{qs} \end{bmatrix},$$
$$P_s = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \tag{3}$$

To emulate a stator phase unbalance, we insert an additional resistance R_d in series to one phase stator winding ($R_{sa} = R_s + R_d$).

2.1.2. Rotor modeling taking into account rotor fault

A squirrel-cage rotor is often modeled by N_R meshes, as shown in Fig. 2. Each mesh is substituted by an equivalent circuit representing the resistive and inductive nature of the cage [32,33].

From the rotor cage equivalent circuit represented by Fig. 2, the electric equation of the *j*-th loop can be defined as:

$$0 = (R_{b(j)} + R_{b(j-1)} + 2R_e)i_j - R_{b(j-1)}i_{j-1} - R_{b(j)}i_{j+1} + \frac{d\phi_{rj}}{dt} \tag{4}$$

Expression of ϕ_{rj} is given by:

$$\phi_{rj} = (L_{rp} + 2(L_b + L_e))i_j + \sum_{\substack{k=1 \\ k \neq j}}^{N_r} M_{rr} i_{rk} + \sum_{k=1}^{3} M_{rjsk} i_{sk} - L_b i_{(j-1)} - L_b i_{(j+1)} \tag{5}$$

Thus, the rotor electric equations can be written as:

$$0 = RI_r + \frac{d}{dt}\phi_r$$
$$\phi_r = [\phi_{r1}, \phi_{r2}, \ldots, \phi_{rN_r}]$$
$$I_r = [i_{r1}, i_{r2}, \ldots, i_{rN_r}] \tag{6}$$

where R is the equivalent rotor loop resistance matrix, its expression is given by:

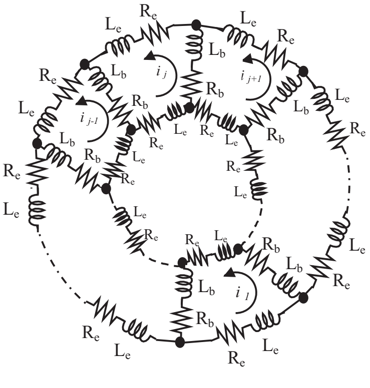

Fig. 2. Rotor cage equivalent circuit.