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Modelling and Fault Diagnosis of Stator Inter-Turn Short Circuit in Doubly Fed Induction Generators

Qian Lu, Timofei Breikin and Hong Wang

Control System Centre, School of Electrical and Electronic Engineering the University of Manchester, PO. Box 88, Manchester, M60 1QD, UK. (Qian.Lu@postgrad.manchester.ac.uk).

Abstract: In this paper, a dynamic state space model of a DFIG with stator inter-turn short circuit fault is proposed. This model can quantitatively describe the fault at any level in any single phase. Both healthy and faulty conditions can be simulated by using this model. Base on this model, an observer based fault detection and diagnosis (FDD) scheme is developed, which can not only provide a rapid detection when fault occurs but also give an accurate diagnosis of the fault position and level. In order to ensure the observer stability under a wide rang of the speed variation of DFIGs, a time varying Kalman like gain supplied with measured rotor speed is applied to the observers. Moreover, an exponential adaptive observer is employed to provide a desirable estimation of fault level. The simulation results demonstrate the effectiveness of this approach in detecting and diagnosing the faults under both stationary and speed varying operations. The latter is particularly important for fault detection of wind turbine DFIGs.

Keywords: DFIG, inter-turn short circuit, state space model, FDD, observer.

1. INTRODUCTION

The doubly fed induction generators (DFIG) are currently the most widely used generators in wind power generation. It has significant advantages over the other generators, such as variable speed constant frequency (VSCF) operation, low mechanical stresses, and high system efficiency (Holdsworth, 2003). Practically, wind turbine generators are commonly situated in the areas that are remote and difficult to access, hence a reliable condition monitoring and self fault diagnosis is crucial in reducing the down time costs and avoiding expensive repairs. The inter-turn short circuit fault is reported to be one of the most common electrical faults in induction machines including DFIG, which occurs between two wires within one phase as a result of insulation deterioration (Amirat, 2009). Since this type of fault is always characterized by remarkable low faulty currents, it is difficult to be detected, especially in early stages. Therefore, in the past decade, a large amount of research efforts are attracted to the studies of modelling and fault detection for this small initial fault (Amirat, 2009; Lu, 2009).

Modelling of DFIGs with the inter-turn short circuit fault is the first step in the development of FDD schemes. Based on the multi-circuit theory, a two-axis transient model for induction machine with stator turns fault was proposed in (Tallam, 2002), and similar work is also reported in (Arkan, 2005). This model can quantitatively represent the fault level, while it fails to characterize the faulted phase. Nevertheless, the healthy condition can not be represented by this model as well. In this paper, based on their work, a state space model of DFIGs is developed. This proposed DFIG faulty model can represent the inter-turn short circuit fault at any level in any single phase, besides it can represent both faulty and healthy conditions of DFIGs. This model is presented in a standard state space form, which is important as it provides a base for observers and controllers design in the purpose of fault detection and fault tolerant control.

There are many existing techniques, which have been used for the fault detection of DFIGs (Douglas, 2003). The most popular one for detecting inter-turn short circuit faults is the machine current signature analysis (MCSA) in terms of analyzing the steady state spectra of the stator line currents (Joksimovic, 2000). However, this technique can only be applied to the stationary analysis and it is very sensitive to the changes of operation conditions such as speed or load variations. Therefore this method is not suitable for the fault detection of wind power generation. Wavelet analysis is stated to be an effective non-stationary fault detection technique (Gritli, 2009). Nevertheless, this technique is unable to locate the faults position and diagnosis the faults level. To overcome the limitation of above techniques, an observer based FDD scheme is proposed in this paper, which can determine both the fault position and level. Additionally, this approach is can be applied for non-stationary fault detection due to online property of observer based methods. In order to ensure the reliable fault detection and precise estimation of fault level under a wide range of speed variation, a time varying Kalman like gain is employed to the observer design. This scheme is also implemented on a closed-loop controlled DFIG to illustrate its effectiveness in detecting the fault under varying speed operation.

The outline of this paper is given as follows. In section 2, the three-axis and two-axis dynamic models of the DFIG with inter-turn short circuit fault are derived, based on which a state-space model is proposed. Based on this model, an observer based FDD scheme is developed in section 3. The simulation results are presented in section 4, with a conclusion given in section 5.

2. ANALYTICAL MODEL OF DFIGs WITH INTER-TURN SHORT CIRCUIT IN STATOR

The stator winding configuration of a DFIG with an inter-turn short circuit fault in phase 'a' is shown in Fig. 1. A transient model for this fault scenario has been proposed in (Tallam, 2002), in which the fault level is represented by a model parameter μ . In this paper, in order to characterize the faulted phase, another model parameter f_x is introduced to describe the fault position. The DFIG model in both the natural abc reference frame and d-q reference frame are firstly derived. Moreover, a state space model is proposed, which is the base for the following observer based FDD.

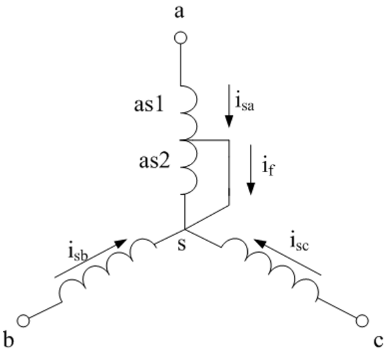


Fig. 1. Stator winding configuration with the inter-turn short circuit fault in phase 'a'.

2.1 Model in Natural abc Reference Frame

A DFIG model in natural abc reference frame is derived to describe the inter-turn short circuit fault at any level in any single phase of stator. In this model, the fault position parameter f_x is defined as below for three cases that fault occurs in phase 'a', 'b' and 'c', respectively.

$$f_a = [1\ 0\ 0]^T,\ f_b = [0\ 1\ 0]^T,\ f_c = [0\ 0\ 1]^T .$$

The fault level parameter μ denotes the fraction of the shorted winding. The voltage and flux linkage model equations in matrix form are given as

$$\begin{bmatrix} V_{abc\_s} \\ V_{abc\_r} \\ v_f \end{bmatrix} = \begin{bmatrix} R_s & 0_{3\times3} & -\mu R_s f_x \\ 0_{3\times3} & R_r & 0_{3\times1} \\ \mu R_s f_x^T & 0_{1\times3} & -\|\mu R_s f_x\| \end{bmatrix} \begin{bmatrix} I_{abc\_s} \\ I_{abc\_r} \\ i_f \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_{abc\_s} \\ \lambda_{abc\_r} \\ \lambda_f \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \lambda_{abc\_s} \\ \lambda_{abc\_r} \\ \lambda_f \end{bmatrix} = \begin{bmatrix} L_{ss} & L_{sr} & -\mu L_{ss} f_x \\ L_{rs} & L_{rr} & -\mu L_{rs} f_x \\ \mu L_{ss} f_x^T & \mu L_{sr} f_x^T & -\mu L_{DD} \end{bmatrix} \begin{bmatrix} I_{abc\_s} \\ I_{abc\_r} \\ i_f \end{bmatrix} \quad (2)$$

Among these equations, the resistance and inductance matrices are given as

$$R_s = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix},\ R_r = \begin{bmatrix} r_r & 0 & 0 \\ 0 & r_r & 0 \\ 0 & 0 & r_r \end{bmatrix}.$$

$$L_{ss} = \begin{bmatrix} L_s & -\frac{1}{2}M_s & -\frac{1}{2}M_s \\ -\frac{1}{2}M_s & L_s & -\frac{1}{2}M_s \\ -\frac{1}{2}M_s & -\frac{1}{2}M_s & L_s \end{bmatrix} \quad L_{rr} = \begin{bmatrix} L_r & -\frac{1}{2}M_r & -\frac{1}{2}M_r \\ -\frac{1}{2}M_r & L_r & -\frac{1}{2}M_r \\ -\frac{1}{2}M_r & -\frac{1}{2}M_r & L_r \end{bmatrix}$$

$$L_{sr} = M_{sr} \begin{bmatrix} \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r & \cos(\theta_r + \frac{2\pi}{3}) \\ \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) & \cos\theta_r \end{bmatrix}$$

$$L_{rs} = L_{sr}^{\ T}$$

The stator, rotor and faulty circuit 'as2' self inductances are defined as

$$L_s = L_{ls} + M_s ,\ L_r = L_{lr} + M_r ,\ L_{DD} = L_{ls} + \mu M_s .$$

By referring the rotor parameters to the stator the mutual inductances become equal:

$$M_s = M_r = M_{sr}$$

The corresponding electromagnetic torque is

$$T_e = P(I_{abc\_s}^T \frac{\partial L_{sr}}{\partial \theta_r} I_{abc\_r} + \mu f_x^{\ T} i_f \frac{\partial L_{sr}}{\partial \theta_r} I_{abc\_r}) \quad (3)$$

2.2 Model in d-q Reference Frame

Transforming the model equations (1) and (2) into a stationary d-q reference frame (stator fixed d-q reference frame), a DFIG model in d-q variables is derived as follows, with the fault position parameter f_x defined as

$$f_a = [1\ 0]^T,\ f_b = \begin{bmatrix} -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}^T,\ f_c = \begin{bmatrix} -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}^T .$$

The voltage and flux linkage model equations are given as

$$\begin{bmatrix} V_{dq\_s} \\ V_{dq\_r} \\ v_f \end{bmatrix} = \begin{bmatrix} R'_s & 0_{2\times2} & -\frac{2}{3}\mu r_s f_x \\ 0_{2\times2} & R'_r & 0_{2\times1} \\ \mu r_s f_x^T & 0_{1\times2} & -\mu r_s \end{bmatrix} \begin{bmatrix} I_{dq\_s} \\ I_{dq\_r} \\ i_f \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_{dq\_s} \\ \lambda_{dq\_r} \\ \lambda_f \end{bmatrix} + [\Omega] \begin{bmatrix} \lambda_{dq\_s} \\ \lambda_{dq\_r} \\ \lambda_f \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} \lambda_{dq\_s} \\ \lambda_{dq\_r} \\ \lambda_f \end{bmatrix} = \begin{bmatrix} L'_{ss} & L'_{sr} & -\frac{2}{3}\mu L'_{ss} f_x \\ L'_{rs} & L'_{rr} & -\frac{2}{3}\mu L'_{rs} f_x \\ \mu L'_{ss} f_x^T & \mu L'_{sr} f_x^T & -\mu L_{DD} \end{bmatrix} \begin{bmatrix} I_{dq\_s} \\ I_{dq\_r} \\ i_f \end{bmatrix} \quad (5)$$

among which, the modified resistance and inductance matrices are given as

$$R'_s = \begin{bmatrix} r_s & 0 \\ 0 & r_s \end{bmatrix},\ R'_r = \begin{bmatrix} r_r & 0 \\ 0 & r_r \end{bmatrix}.$$

$$L'_{ss} = \begin{bmatrix} L_s & 0 \\ 0 & L_s \end{bmatrix},\ L'_{rr} = \begin{bmatrix} L_r & 0 \\ 0 & L_r \end{bmatrix},\ L'_{sr} = \begin{bmatrix} L_m & 0 \\ 0 & L_m \end{bmatrix},\ L'_{rs} = L'^{\ T}_{sr} .$$

The stator, rotor and faulty circuit 'as2' self inductances for this model are defined as

$L_m = \frac{3}{2} M_s$, $L_s = L_{ls} + L_m$, $L_r = L_{lr} + L_m$, $L_{DD} = (L_{ls} + \mu \frac{2}{3} L_m)$.

The corresponding electromagnetic torque is

$$T_e = PL_m (\frac{3}{2} I_{dq\_s} \times I_{dq\_r} + \mu f_x i_f \times I_{dq\_r}) \tag{6}$$

2.3 State Space Model

It is difficult to design the observers or controllers directly based on the above models presented in voltage and flux equations. Therefore, it is necessary to convert them into a state space form. By taking the currents as state variables, model equations (4) and (5) can be organized into a standard state space form. To obtain this form, the inverse of the inductance matrix in (5) has to be calculated firstly. However, when $\mu = 0$ that represents the healthy condition, the inductance matrix is non-singular. To solve this problem, μi_f is taken as one of the state variables instead of i_f , in which case the inductance matrix becomes singular for any μ . In this way, the derived state-space form is able to represent both faulty and healthy conditions. Since resistance in the insulation break is 0 for most insulation materials, the voltage v_f for the short circuit loop can be regarded as 0. Therefore, state space model can be derived as

$$\begin{cases} \dot{x} = (A_c + A_{\omega_r} \omega_r) x + (B_c + B_\theta \theta) u \\ y = Cx \end{cases} \tag{7}$$

where, the state, input variables and output measurements are $x = \begin{bmatrix} i_{sd} & i_{sq} & i_{rd} & i_{rq} & \mu i_f \end{bmatrix}^T$, $u = \begin{bmatrix} u_{sd} & u_{sq} & u_{rd} & u_{rq} & 0 \end{bmatrix}^T$, and $y = \begin{bmatrix} i_{sd} & i_{sq} & i_{rd} & i_{rq} \end{bmatrix}^T$.

For notation simplification, by defining

$$\theta = \frac{\mu}{2\mu - 3} \tag{8}$$

$D = L_s L_r - L_m^2$, and $J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$, the coefficient matrices can be reduced into

$$A_c = \frac{1}{D} \begin{bmatrix} -L'_{rr} R'_s & L'_{sr} R'_r & \frac{2}{3} r_s L_r f_x \\ L'_{sr} R'_s & -L'_{ss} R'_r & -\frac{2}{3} r_s L_m f_x \\ 0_{1\times2} & 0_{1\times2} & 0 \end{bmatrix} + \frac{1}{L_{ls}} \begin{bmatrix} 0_{2\times2} & 0_{2\times2} & -\frac{2}{3} r_s f_x \\ 0_{2\times2} & 0_{2\times2} & 0_{2\times1} \\ 0_{1\times2} & 0_{1\times2} & -r_s \end{bmatrix}$$

$$A_{\omega_r} = \frac{1}{D} \begin{bmatrix} L_m^2 J & L_r L_m J & -\frac{2}{3} L_m^2 J f_x \\ -L_s L_m J & -L_s L_r J & \frac{2}{3} L_s L_m J f_x \\ 0_{1\times2} & 0_{1\times2} & 0 \end{bmatrix} \quad B_c = \frac{1}{D} \begin{bmatrix} L'_{rr} & -L'_{sr} & 0_{2\times1} \\ -L'_{sr} & L'_{ss} & 0_{2\times1} \\ 0_{1\times2} & 0_{1\times2} & 0 \end{bmatrix}$$

$$B_\theta = \frac{1}{L_{ls}} \begin{bmatrix} -2 f_x f_x^T & 0_{2\times2} & 0_{2\times1} \\ 0_{2\times2} & 0_{2\times2} & 0_{2\times1} \\ -3 f_x^T & 0_{1\times2} & 0 \end{bmatrix} \qquad C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

3. STATOR INTER-TURN SHORT CIRCUIT FAULT DIAGNOSIS

In previous section, a state space model for a DFIG with stator inter-turn short circuit fault is proposed. In present of the time varying rotor speed, this model is a multiple-input and multiple-output (MIMO) linear time varying (LTV) system with two unknown parameters f_x and μ .The purpose of FDD is to generate an alarm signal when a fault occurs and diagnose the fault position and fault level by estimating parameter f_x and μ . Based on the proposed state space model, an observer based FDD scheme is developed in this paper, which is consisted of three steps as shown in Fig. 2 .

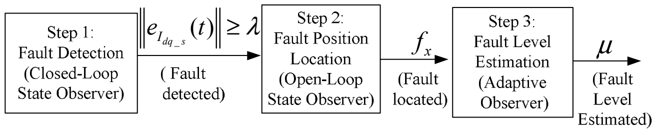


Fig. 2. Observer based FDD scheme.

3.1 Step 1: Fault Detection

It is stated that the observer based fault detection is very effective in detecting the sensor and actuator faults (Isermann, 2006). Actually the inter-turn short circuit fault can be considered as an actuator fault as the model described in (7). Hence in this section a close-loop state observer is (Luenberger observer) is applied to detect fault. However, it is impossible to design the observer directly based on model (7) as the fault position parameter f_x is unknown. Therefore, model (7) needs to be modified firstly. By analyzing the model equation (7), it can be seen that the fault current i_f is governed by the following dynamics.

$$\frac{d}{dt}(\mu i_f) = -\frac{r_s}{L_{ls}} \mu i_f - \frac{1}{L_{ls}} \frac{3\mu}{2\mu - 3} f_x^T V_{dq\_s} \tag{9}$$

After the system enter into steady state, equation (9) becomes

$$\mu i_f = -\frac{1}{r_s} \frac{3\mu}{2\mu - 3} f_x^T V_{dq\_s} \tag{10}$$

By substituting it into (7), the model can be reduced into

$$\begin{aligned} \frac{d}{dt} \begin{bmatrix} I_{dq\_s} \\ I_{dq\_r} \end{bmatrix} &= A_H \begin{bmatrix} I_{dq\_s} \\ I_{dq\_r} \end{bmatrix} + B_H \begin{bmatrix} V_{dq\_s} \\ V_{dq\_r} \end{bmatrix} + \frac{1}{r_s} \frac{2\mu}{2\mu - 3} \frac{1}{D} \begin{bmatrix} -L'_{rr} R'_s + L_m^2 J \omega_r \\ L'_{sr} R' - L_s L_m J \omega_r \end{bmatrix} f_x f_x^T V_{dq\_s} \\ &= A_H \begin{bmatrix} I_{dq\_s} \\ I_{dq\_r} \end{bmatrix} + B_H \begin{bmatrix} V_{dq\_s} \\ V_{dq\_r} \end{bmatrix} + \frac{1}{r_s} \frac{2\mu}{2\mu - 3} A_H \begin{bmatrix} f_x f_x^T V_{dq\_s} \\ 0_{2\times1} \end{bmatrix} \end{aligned} \tag{11}$$

The parameter matrices in above model are

$$A_H = A_{c\_H} + A_{\omega_r\_H} \omega_r \tag{12}$$

$$A_{c\_H} = \frac{1}{D} \begin{bmatrix} -L'_{rr} R'_s & L'_{sr} R'_r \\ L'_{sr} R'_s & -L'_{ss} R'_r \end{bmatrix} \quad A_{\omega_r\_H} = \frac{1}{D} \begin{bmatrix} L_m^2 J & L_r L_m J \\ -L_s L_m J & -L_s L_r J \end{bmatrix}$$

$$B_H = \frac{1}{D} \begin{bmatrix} L'_{rr} & -L'_{sr} \\ -L'_{sr} & L'_{ss} \end{bmatrix} \qquad C = I_{4\times4} \; .$$

Based on this modified model, a well known close loop state observer (Luenberger observer) is constructed as

$$\begin{cases}\dot{\hat{x}} = A_H\hat{x} + B_H u + K(y - C\hat{x}) \\ \hat{y} = C_H x\end{cases} \tag{13}$$

where, estimated states, input signals and prediction outputs are defined respectively as

$$\hat{x} = [\hat{I}_{dq\_s}\ ,\ \hat{I}_{dq\_r}]^T\ ,\ u = [V_{dq\_s}\ ,V_{dq\_r}]^T\ \ \hat{y} = [\hat{I}_{dq\_s}\ ,\ \hat{I}_{dq\_r}]^T$$

Comparing (13) and (11), the estimation error equations are

$$\frac{d}{dt}\begin{bmatrix} e_{I_{dq\_s}} \\ e_{I_{dq\_r}}\end{bmatrix} = (A_H - KC)\begin{bmatrix} e_{I_{dq\_s}} \\ e_{I_{dq\_r}}\end{bmatrix} - \frac{1}{r_s}\frac{2\mu}{2\mu - 3}A_H\begin{bmatrix} f_x f_x^T V_{dq\_s} \\ 0_{2\times1}\end{bmatrix} \tag{14}$$

The fault detection can be readily carried out by observing the stator current residuals $e_{I_{dq\_s}}$ as follows

$$\begin{cases}\left\|e_{I_{dq\_s}}(t)\right\| < \lambda;\ \text{no fault occurs} \\ \left\|e_{I_{dq\_s}}(t)\right\| \geq \lambda;\ \text{fault has occured}\end{cases} \tag{15}$$

This is the well known observer based fault detection. $\lim_{t\to\infty} e_{I_{dq\_s}}(t) = 0$, only when $\mu = 0$ that means no fault occurs. The residuals $e_{I_{dq\_s}}$ therefore can provide a reliable fault detection regardless of where the fault occurs.

3.2 Step 2: Fault Position Location

To locate the fault position after the alarm has been generated, the feedback loop of the state observer (13) is opened. In this way, the residuals $e_{I_{dq\_s}}$ are reduced into the following equation after the observer enters into steady state.

$$e_{I_{dq\_s}} = \frac{1}{r_s}\frac{2\mu}{2\mu - 3} f_x f_x^T V_{dq\_s} \tag{16}$$

It can be observed that the residuals $e_{I_{dq\_s}}$ are decided by fault position parameter f_x . For the three cases that fault occurs in phase 'a', 'b' and 'c', $f_x f_x^T$ are computed as

$$f_a f_a^T = \begin{bmatrix}1 & 0 \\ 0 & 0\end{bmatrix}, f_b f_b^T = \begin{bmatrix}\frac{1}{4} & -\frac{\sqrt{3}}{4} \\ -\frac{\sqrt{3}}{4} & \frac{3}{4}\end{bmatrix}, f_c f_c^T = \begin{bmatrix}\frac{1}{4} & \frac{\sqrt{3}}{4} \\ \frac{\sqrt{3}}{4} & \frac{3}{4}\end{bmatrix}$$

Therefore, the fault position can be located by comparing d and q components of the stator current residuals referring to following relations

$$\begin{cases}\dfrac{e_{I_{q\_s}}}{e_{I_{d\_s}}} = 0 & \text{fault in phase 'a'} \\ \dfrac{e_{I_{q\_s}}}{e_{I_{d\_s}}} = -\sqrt{3} & \text{fault in phase 'b'}\ . \\ \dfrac{e_{I_{q\_s}}}{e_{I_{d\_s}}} = \sqrt{3} & \text{fault in phase 'c'}\end{cases} \tag{17}$$

3.3 Step 3: Fault Level Estimation

After fault position has been located, in order to estimate the fault level online, a well known online parameter estimation method (adaptive observer) is applied. Since the parameter f_x is known after the fault has been located, the model (7) can be used for observer design with a little modification as

$$\begin{cases}\dot{x} = A(t)x + B_c u + \Psi(t)\theta \\ y = Cx\end{cases} \tag{18}$$

where, $A(t) = A_c + A_{\omega_r}\omega_r(t)$, $\Psi(t) = B_\theta\left[V_{sd}(t), V_{sq}(t)\right]^T$, with $B_\theta = \frac{1}{L_{ls}}\left[-2f_x f_x^T, 0_{2\times2}, -3f_x\right]^T$, θ is obtained from μ as (8).

In practice, DFIGs are predominantly running under varying speed condition. In model (18), the rotor speed $\omega_r(t)$ can be consider as a time varying parameter while can be measured by in real time. Therefore this model is a MIMO line time varying system. For this type of system, a global exponential adaptive observer has been proposed in (Zhang, 2002) to estimate the states and unknown parameter simultaneously. In order to employ this observer to estimate parameter θ , two assumptions have to be satisfied firstly, according to theorem 1 in (Zhang, 2002).

Assumption 1: Assume that there exists a matrix $K(t)$ so that the system

$$\dot{\eta}(t) = (A(t) - K(t)C(t))\eta(t) \tag{19}$$

is exponentially stable.

Assumption 2: $\Psi(t)$ is persistently exciting.

In this work, to fulfil the assumption 1**,** a time-varying Kalman like gain $K(t)$ is designed as:

$$\begin{cases}K(t) = S(t)^{-1}C^T\Sigma \\ \dot{S}(t) = -\rho S(t) - A(t)^T S - SA(t) + C^T\Sigma C,\ S(0) > 0\end{cases} \tag{20}$$

where, ρ is a sufficiently large positive constant and Σ is a positive definite matrix. By using this Kalman like gain, the exponential stability of (19) can be easily proofed by selecting Lyapunov candidate function as $V = \eta(t)^T S(t)\eta(t)$ (Besancon, 2006). Assumption 2 is also satisfied by system (18) as the stator voltages are exciting at all time when DFIG is running.

Therefore for a system given in the form of (18), by using a time varying Kalman like gain as (20), an exponential adaptive observer exists, whose structure is as follows

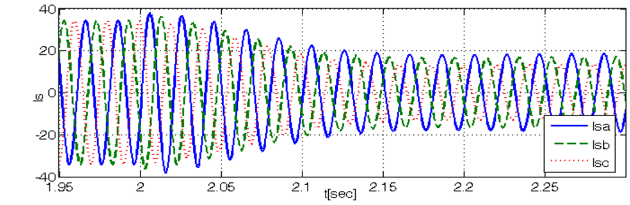
$$\begin{cases}\dot{\Upsilon}(t) = (A(t) - K(t)C)\Upsilon(t) + \Psi(t) \\ \dot{\hat{x}} = A(t)\hat{x} + B_c u + \Psi(t)\hat{\theta} + \left[K(t) + \gamma_\theta\Upsilon(t)\Upsilon^T(t)C^T\right][y - C\hat{x}] \\ \dot{\hat{\theta}} = \gamma_\theta\Upsilon^T(t)C^T[y - C\hat{x}]\end{cases} \tag{21}$$

where, γ_θ is a positive constant.

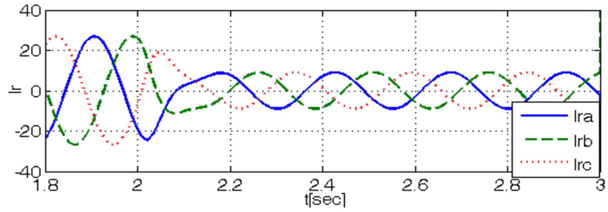
Remark: The time varying Kalman like gain (20) is also implemented to the close loop state observer (13) to ensure its stability under a wide rang of the speed variation.

4. SIMULATION RESULTS

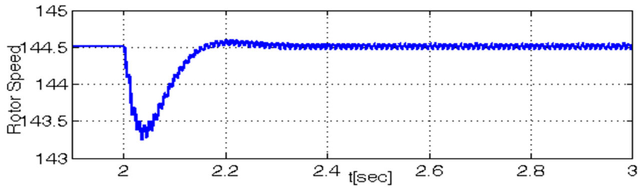
A transient behaviour of DFIG from the normal condition to a 1% inter-turn short circuit fault at t=2 is simulated by using the proposed state space model. The parameters of the simulated DFIG model are reported in Appendix. The simulation results are given in Fig. 3. As it shown, the stator and rotor currents both decrease when short circuit fault occurs. The stator current becomes unbalanced and the current in phase ‘a’ is bigger the other two. The asymmetry of the stator currents causes a fluctuation in the rotor speed at high frequency. The steady state stator currents for the cases that fault occurs in phase ‘a’, ‘b’ and ‘c’ is shown in Fig. 4. It can be seen that the current in faulted phase is the biggest.



(a) Stator current signature.

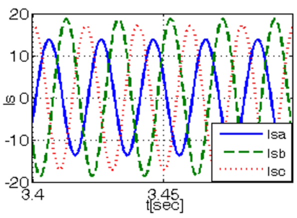


(b) Rotor current signature.

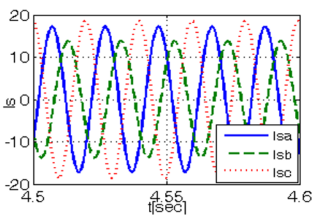


(c) Rotor speed.

Fig. 3. Transient behaviours from normal condition to a 1% inter-turn short circuit fault.



(a) 1% fault in phase ‘b’



(b) 1% fault in phase ‘c’

Fig. 4. Stator current signature for inter-short circuit fault in phase ‘b’ and ‘c’.

The effectiveness of this proposed observer based fault diagnosis scheme is validated through simulation tests performed by different faults scenarios and operation conditions. This fault diagnosis scheme is firstly tested on a DFIG operating at stationary condition with constant rotor voltages (V_r = 8.3 V at f_r = 3 Hz) and a constant load torque (T_{load} = -250 Nm). A 2% inter-turn short circuit fault is applied at 2 sec and develops into 4% at 3sec. The FDD results are given in Fig. 5. As it shown, the fault can be rapidly detected by observing the norm of stator current residuals. After the fault has been detected, the feedback loop of the state observer is opened at 2.2 sec. The fault can be located by comparing $e_{I_{d\_s}}$ and $e_{I_{q\_s}}$ referring to the relations described in (17). At 2.5 sec, the adaptive observer is activated and produces an accurate estimation of the fault level μ. The stator current residual signatures for different cases that fault occurs in phase ‘a’, ‘b’ and ‘c’ are given in Fig. 6. This figure shows that the simulation results are in good agreement with the relations described in (17).

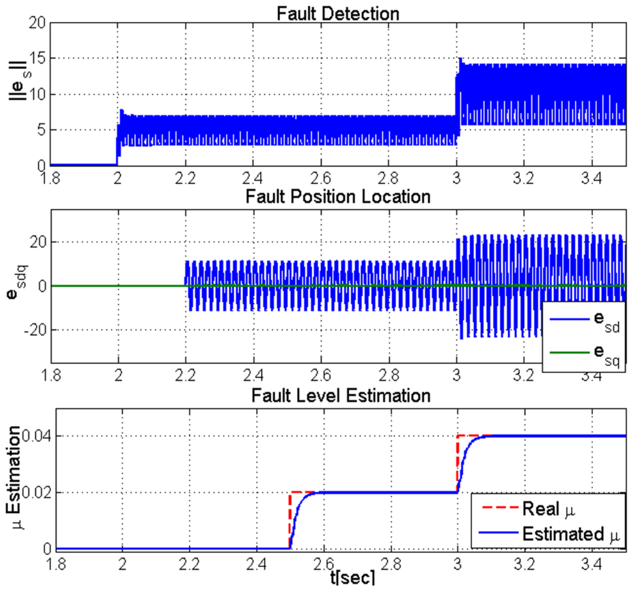


Fig. 5. FDD for an inter-turn short circuit phase in phase ‘a’.

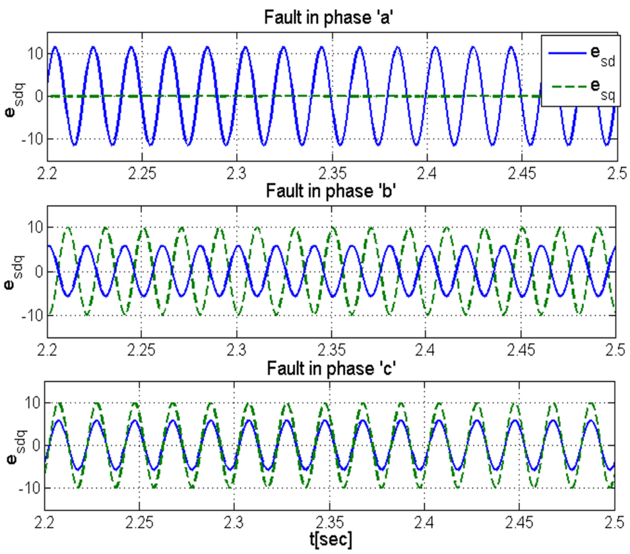


Fig. 6. The stator current residual signatures for the cases that fault occurs in phase ‘a’, ‘b’ and ‘c’.

This FDD scheme is also tested on a faulty DFIG under varying speed operation. A speed variation from subsynchronous region to super-synchronous region is performed by applying a stepwise load torque (T_{load} changes from -230Nm to -300Nm at t=2s) to the generator running under decoupled DQ control. A 1% inter-turn short circuit is applied at t=1s. The maximum power extraction control strategy is employed to adjust the active power setting point, and the reactive power setting point is set as zero. The generator output active and reactive powers in this whole process are shown in Fig. 7. The corresponding rotor speed variation is presented in Fig. 8. It can be seen that the short circuit fault causes a minor decrease in the rotor speed and the active power output. The fault level estimation is given in Fig. 9. It shows that the estimation of μ is not affected by the speed variation.

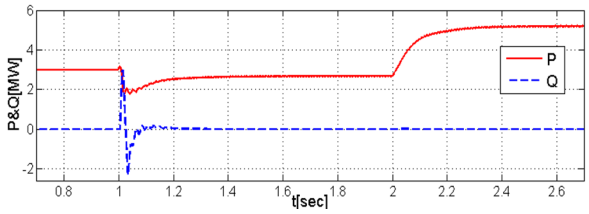


Fig. 7. Output active and reactive power.

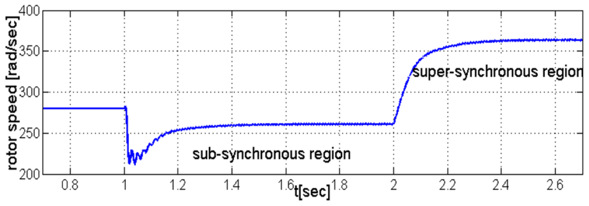


Fig. 8. Rotor speed.

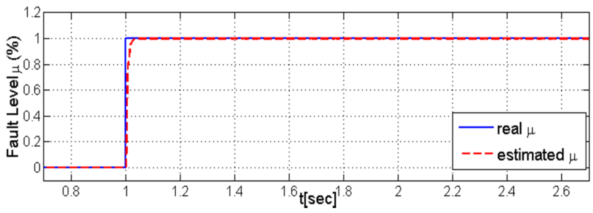


Fig. 9. Fault level estimation under varying speed operation.

CONCLUSIONS

In this paper, a state space model of DFIGs with stator inter-turn short circuit fault has been proposed. This model allowed for the simulations of different fault scenarios and operation conditions. Moreover, the fault position and level can be quantitatively described by two model parameters. Based on this model, an observer based FDD scheme has been proposed, which was completed within three steps using three different observers. The validity of this scheme on diagnosing the fault at different levels in different phases has been demonstrated through simulation tests. This scheme has been also tested under speed varying operation. It was shown that the applied exponential adaptive observer with a time varying gain is able to provide a good estimation of level under a wide rang of speed variation.

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Appendix

Machine Parameters:

rated stator frequency: $f_s = 50$ Hz;

rated stator phase voltage: $V_s = 130$ V;

mutual inductance: $L_m = 44.2$ mH;

stator leakage inductance: $L_{s\sigma} = 673.97$ μH;

rotor leakage inductance: $L_{r\sigma} = 490.60$ μH;

stator resistance: $R_s = 45$ mΩ;

rotor resistance: $R_r = 66.5$ mΩ;

machine inertia: $J = 0.4$ kg/m^2;

number of pole pairs: $P = 2$.