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Fault Diagnosis and Fault-Tolerant Control of Wind Turbines via Sliding Mode Control

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Abstract: This paper studies the problem of fault estimation using adaptive fault diagnosis observer method for a DFIG based wind turbine system. This adaptive fault estimation algorithm is proposed to enhance the rapidity and accuracy performance of fault estimation. Tn particular, an electrical fault scenario, the DFTG winding short circuit fault, is considered due to its high occurrence rates. Based on the fault estimation information, a fault compensator is designed based on fault information provided by the fault diagnosis scheme to guarantee the stability of the system, and it incorporates with a traditional controller to provide an online fault compensation of winding short circuit faults. Finally, the implementation of the proposed approach and the results obtained from its application to the DFTG based wind turbine system are presented to illustrate the efficiency of the proposed methodology.

Keywords: Wind Generator, Short Circuit, Adaptive Observer; Fault Estimation, Fault Diagnosis, Fault Compensation.

I. INTRODUCTION

In the last decades, with increases in energy demands, black-outs, and environmental concerns regarding global warming, renewable electricity sources have been one of the most growing industries in the field of electricity production [1, 2]. Recently, penetration rate of wind energy has reached significant levels in many countries [3]. In recent years, doubly-fed induction generator (DFIG), as a variable speed generator, has attracted a wide interest for application with wind energy. Using DFIG could achieve many advantages such as operation over a wide range of rotor speeds and decreasing the amount of power carried by the converter with substantial reduction in converter cost [4-6]. However, DFIG suffers from high sensitivity to grid disturbances, especially grid current faults which could lead to local or system wide instabilities [7-11]. So, there is a need to improve the ability of wind turbines to remain connected to the electricity grid even with grid faults in order to provide the support needed by the system after the fault is cleared. Several studies have been carried out in order to achieve the inquired systems reliability, especially for DFIG-based wind turbine conversion system. Among these, one of the most commonly used schemes for fault diagnosis and fault tolerant control, are related to adaptive observer-based approaches [12-17]. The aim of this paper is to analyze model-based fault estimation schemes and develop adaptive observer techniques to diagnose DFIG single-phase short circuit faults especially within stator windings, and also use the estimated states to reconstruct the controller so as to compensate the effects of faults.

The contents of this paper are as follows. Firstly, a mathematical model of the DFIG with respect to singlephase short circuit faults within stator windings is proposed. Secondly, based on this proposed fault model, an adaptive observer based fault diagnosis scheme is proposed which allows online diagnosing of the fault level and location. Next, based on the proposed fault diagnosis scheme, a fault compensator is developed and integrated to the system, which is able to provide an online compensation of any possible winding short circuit faults. Finally, simulation results are presented and show that this fault compensator can highly reduce the oscillations in the electromagnetic torque, output power and some other electrical quantities in the presence of short circuit faults.

II. SYSTEM MODELING

The winding short circuit fault, especially within stator windings, is one of the most common faults in electric machines including DFIGs. This fault may occur within one phase or sometimes in several phases simultaneously. In this work, we denote the former case: the single-phase fault. In this section, we aim to develop a mathematical model of DFIG with respect to the single-phase short circuit fault within stator windings. When a short circuit fault occurs, the stator windings currents become asymmetrical, and an obvious increase can be observed in the current of the faulted phase. This is because the effective impedance of the faulted phase is reduced by the short circuit. The modeling strategy is to consider the short circuit loops as some additional circuits placed in parallel to the original winding circuits of DFIG, and then represent the electrical and magnetic relationships among all these circuits by using circuit theory. The sequence component decomposition is a widely used technique dealing with the structural asymmetry problems of the electric machines [18, 19]. In this section, a common sinusoidal signal decomposition technique is introduced. By using this technique, the single-phase fault model proposed is transformed into a state-space model representation and the fault is formulated into an additive fault current.

The mathematical models for the single-phase short circuit fault, within stator windings, in the d-q coordinates after applying the sequence component decomposition are developed and given as follows:

Positive sequence model

$$\begin{cases} V_R^{+} = r_{sl}\left(i_s^{+} - i_f^{+}\right) + \dfrac{d}{dt}\Psi_s^{+} + j\omega_s\Psi_s^{+} \\ V_r^{+} = r_r i_r^{+} + \dfrac{d}{dt}\Psi_r^{+} + j(\omega_s - \omega_r)\Psi_r^{+} \end{cases} \quad (1)$$

$$\begin{cases} \Psi_s^{+} = l_{sl}(i_s^{+} - i_f^{+}) + M\, i_r^{+} \\ \Psi_r^{+} = l_r i_r^{+} + M\left(i_s^{+} - i_f^{+}\right) \end{cases} \quad (2)$$

Negative sequence model

$$\begin{cases} V_R^{-} = r_{sl}\left(i_s^{-} - i_f^{-}\right) + \dfrac{d}{dt}\Psi_s^{-} - j\omega_s\Psi_s^{-} \\ V_r^{-} = r_r i_r^{-} + \dfrac{d}{dt}\Psi_r^{-} - j(\omega_s + \omega_r)\Psi_r^{-} \end{cases} \quad (3)$$

$$\begin{cases} \Psi_s^{-} = l_{sl}(i_s^{-} - i_f^{-}) + M\, i_r^{-} \\ \Psi_r^{-} = l_r i_r^{-} + M\left(i_s^{-} - i_f^{-}\right) \end{cases} \quad (4)$$

Where:

$V_R^{+}, V_R^{-}, V_r^{+}, V_r^{-}$ **:** represent the positive-sequence and negative sequence phasors of the stator and rotor voltages, respectively.

$i_s^{+}, i_s^{-}, i_r^{+}, i_r^{-}$ **:** represent the positive-sequence and negative sequence phasors of the stator and rotor currents, respectively.

$\Psi_s^{+}, \Psi_s^{-}, \Psi_r^{+}, \Psi_r^{-}$: are the positive-sequence and negative sequence phasors of the stator and rotor fluxes, respectively.

i_f^{+}, i_f^{-} **:** are the positive-sequence and negative sequence phasors of the fault current, respectively.

For the purpose of fault diagnosis, we aim to develop state-space representations of the mathematical faulty DFIG model.

III. CONVENTIONAL ADAPTIVE FAULT ESTIMATION OBSERVER DESIGN

The design of a conventional adaptive observer is developed as shown in Fig.1, to estimate fault variables, in order to diagnose the single-phase short circuit appearing within stator windings, taking into consideration the sequence component decomposition technique. The observer is constructed as follows:

$$\begin{cases} \dot{\hat{x}}^{\pm}(t) = A\hat{x}^{\pm}(t) + Bu^{\pm}(t) + B_f\hat{i}_f^{\pm}(t) + L(y^{\pm}(t) - \hat{y}^{\pm}(t)) \\ \hat{y}^{\pm}(t) = C\hat{x}^{\pm}(t) \\ \dot{\hat{i}}_f^{\pm}(t) = \Gamma^{-1}B_f P(x^{\pm}(t) - \hat{x}^{\pm}(t)) \end{cases} \quad (5)$$

Where $\hat{x}^{\pm}(t)\in\mathbb{R}^4$the state is vector of the 0 bserver and y $\hat{y}^{\pm}(t)\in\mathbb{R}^4$is the output vector of the observer. $\hat{i}_f^{\pm}(t)\in\mathbb{R}^2$is the estimation of the fault $i_f^{\pm}(t)$are th e parameters $L\in\mathbb{R}^{4\times4}, P\in\mathbb{R}^{4\times4}$, and $\Gamma\in\mathbb{R}^{2\times2}$to be designed. Since it has been assumed that the pair (A, C) is observable, the observer gain matrix L can be selected such that (A -LC) is a stable matrix.

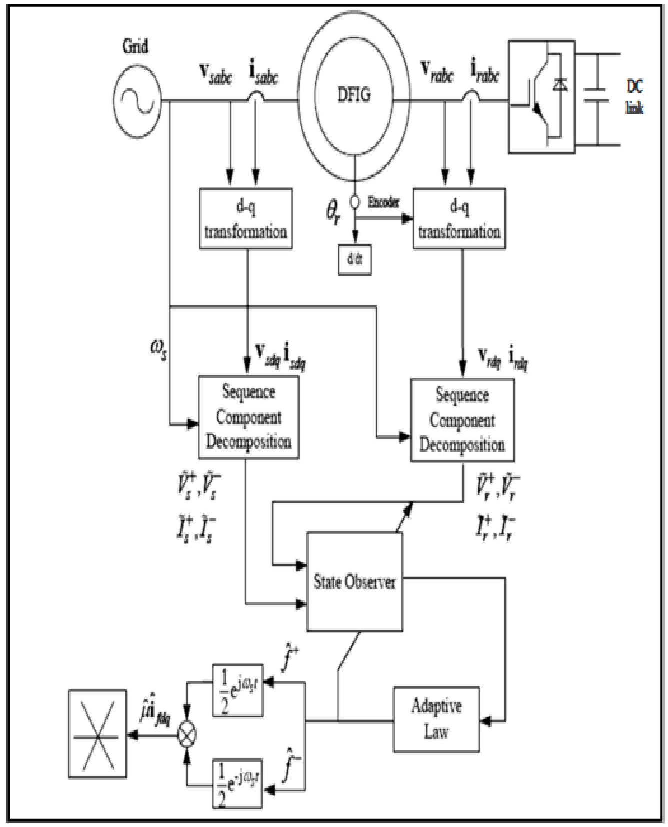

Fig.1. Schematic diagram of adaptive observer based fault diagnosis for single-phase short circuit fault.

Denote

$$\begin{cases} e_x(t) = x(t) - \hat{x}(t) \\ e_f(t) = f(t) - \hat{f}(t) \end{cases} \quad (6)$$

Then the estimation error dynamic system can be obtained as

$$\begin{cases} \dot{e}_x(t) = (A - LC)e_x(t) + B_f e_f(t) \\ \dot{e}_f(t) = -\Gamma^{-1}B_f^T P e_x(t) \end{cases} \quad (7)$$

IV. FAULT COMPENSATION

For a closed-loop controlled DFIG wind turbine under the conventional control strategy, since the measured outputs (currents) are fed to the controller to adjust the system target outputs (electromagnetic torque and output power), any asymmetries in the currents can ultimately lead to the oscillations in the electromagnetic torque, and the increase in the magnitude of oscillations in the output power. In order to reduce the above mentioned effects on a closed-loop controlled DFIG wind turbine system, a fault compensator is proposed as shown in Fig.2, and it is combined with a conventional controller, such that the oscillations in the torque can be removed and the oscillation amplitude in output power can be reduced.

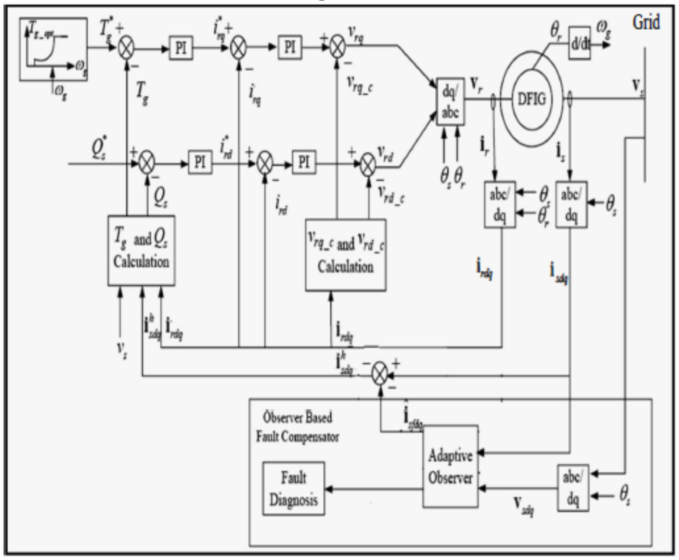

Fig.2. Conventional closed-loop control with the fault compensator.

This compensator is constructed based on the estimated unknown states i_{fd}^+, i_{fq}^+, i_{fd}^-, and i_{fq}^- provided by the adaptive observers given in the last section, in order to eliminate the influence of short circuit faults on the closed-loop controlled system. Therefore, an additive relationship of the healthy and faulty system output currents can be proposed, which IS given as: $i_{sd} = i_{sd}^h + i_{fd}, i_{sq} = i_{sq}^h + i_{fq}$ Where i_{sd}^h and i_{sq}^h denote the healthy currents components, i_{fd} and i_{fq} denote the faulty currents components. The healthy currents components can thus be obtained by subtracting these estimated faulty currents components from the currents measurements, and used for the closed-loop control.

VI. CONCLUSIONS

In this paper, an adaptive observer technique for a model-based fault diagnosis was developed in order to improve the reliability of DFIG stator windings short circuit fault within wind turbine systems. Then, an active fault tolerant scheme was synthesized based the fault information provided by the fault diagnosis scheme. For this purpose, a fault compensator was designed, and then used to correct the current measurements and reference signals. This fault compensator was validated on a closed-loop controlled DFIG wind turbine system, and the simulation results showed that it can highly reduce the oscillations in the electromagnetic torque, output power and other output electrical quantities aroused by winding short circuit faults.

VI. SIMULATION RESULTS

The simulation studies are carried out in the Matlab/Simulink environment. Before presenting the main results of faults estimation, it is crucial to mention that, the observer is activated at t=2sec after the DFIG reaching the steady state, and thereafter a short circuit fault is applied to stator phase 'a' at t=2,5sec. Figs. 3 to 6 present the real values of the faults $(i_f^+(t), i_f^-(t))$ and their estimations.

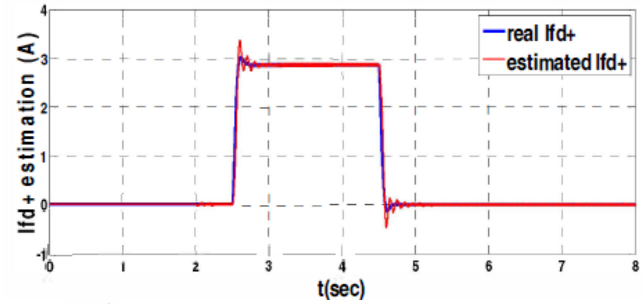

Fig.3. I_{fd}^+ estimation using conventional adaptive observer.

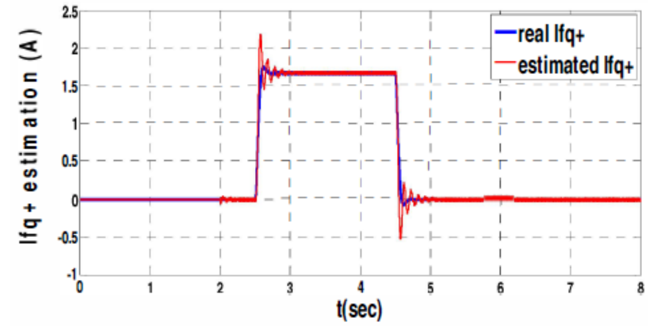

Fig.4. I_{fq}^+ estimation using conventional adaptive observer.

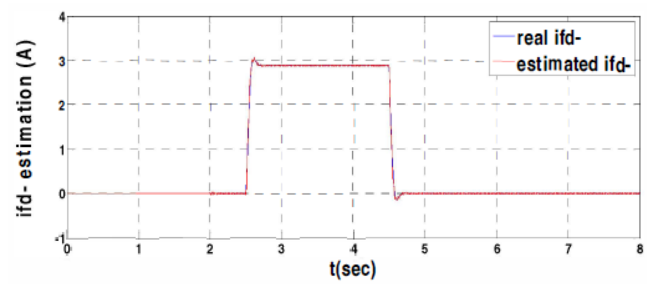

Fig.5. I_{fd}^- estimation using conventional adaptive observer.

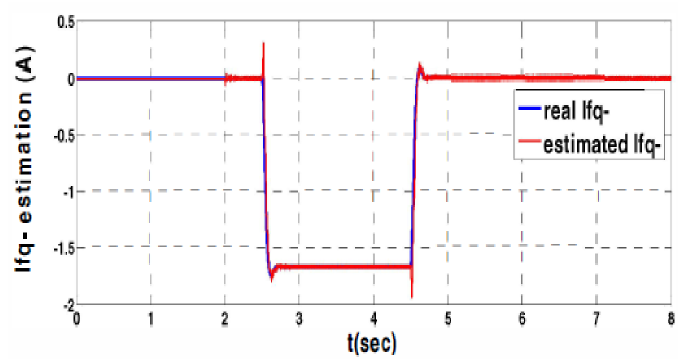

Fig.6. I_{fq}^- estimation using conventional adaptive observer.

The adaptive observer based fault diagnosis scheme is firstly employed to provide an online diagnosis of the short circuit faults, and meanwhile estimate faulty currents components. These components are then utilized in the fault compensator to remove the influences of the fault. To compare the performance of the DFIG wind turbine system before and after the fault compensation, and to see the improvements of using the fault compensator on the output variations, simulations results are demonstrated as shown in Figs.7 to 10:

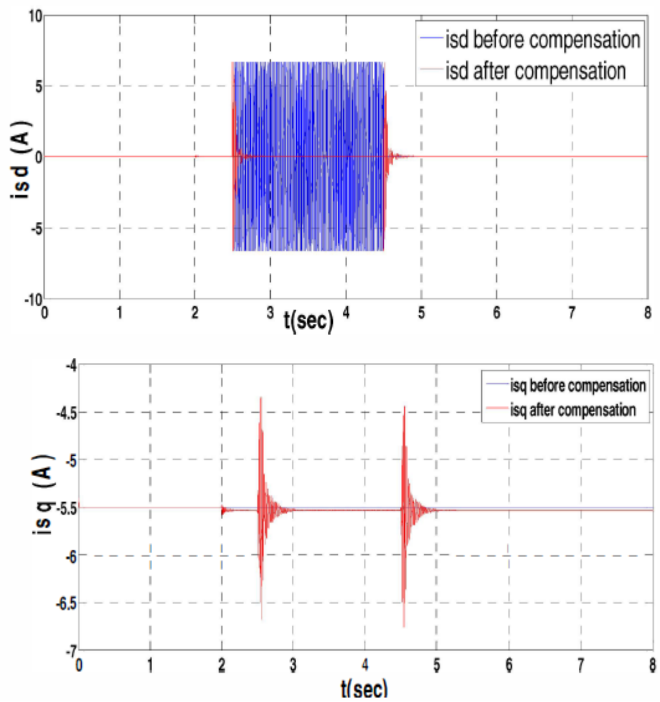

Fig.7. Stator currents compensation.

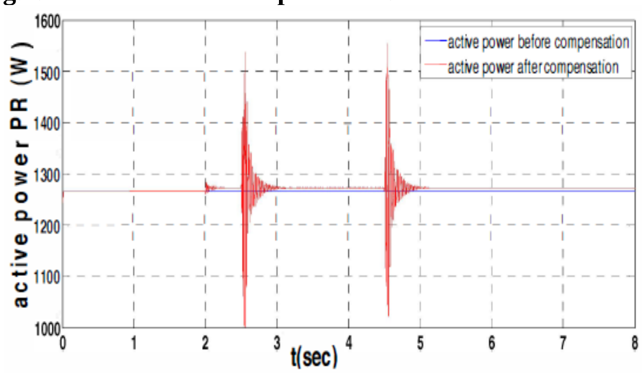

Fig.8. Active power compensation.

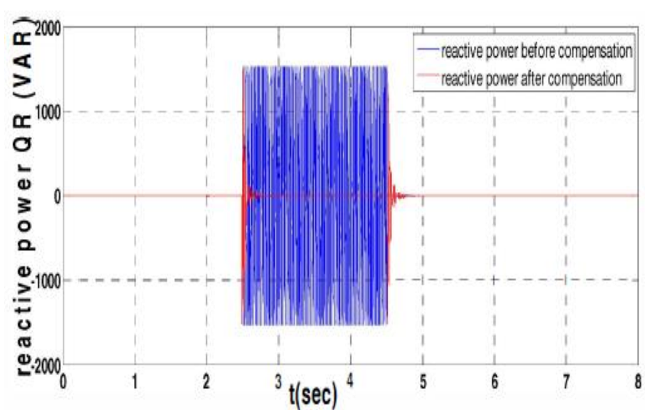

Fig.9. Reactive power compensation.

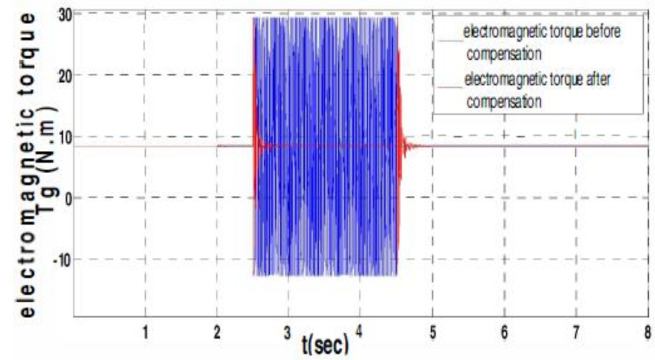

Fig. 10. Electromagnetic torque compensation.

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