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Current Sensor Fault Diagnosis for Doubly-fed Wind Generator Control System

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Abstract: Aiming at the improvement of operation reliability, the study present a sensor fault diagnosis method for the doubly-fed wind generator control system. Firstly, a double-fed wind generator modeling method on consideration of unknown input disturbance is presented. The designs of Luenberger observer and sliding mode observer are following. The former is in order to change the nonlinear system into a linear time-invariant one and the latter for the elimination of the influence of unknown input disturbance in fault diagnosis. Finally, an observers-based sensor fault diagnosis method is proposed and its effectiveness is verified through experiments with different types of sensor faults.

Key words: Fault detection, state observers, robust residual, doubly-fed generator

INTRODUCTION

The operation of generator set is becoming more dependent on various control system with continuous improvement of capacity of wind generator and its degree of automation. Accuracy of process parameters measurements is the key for ensuring reliable operation of wind generating system. Sensor is used for measurements of all types of process parameters. It may cause directly malfunction of control system or serve accidents in case there is a fault on sensors (such as current sensor) that are important for functions of wind generating control system. Therefore, development of sensor fault diagnosis in wind generating system is a very important actual demand.

Fault detection and isolation has been studied for more than three decades and many approaches have been proposed to solve this problem (Frank, 1990; Hwang *et al*., 2010; Sun *et al*., 2011; Liu *et al*., 2011; Ng *et al*., 2007; Zhao and Hou, 2012). There also have been many achievements on fault diagnosis of wind generator set in nowadays. However, most of them are study on drive systems of the generator set such as gearbox and shaft system (Ribrant and Bertling, 2007; Chinchilla *et al*., 2006; Xie and Jiao, 2010; Yang *et al*., 2008; Hameed *et al*., 2009; Wang and Guo, 2007; Dinkhauser and Fuchs, 2009) while there are only a few of studies on fault diagnosis of sensor in wind generating system. A direct torque control based fault diagnosis and reconstruction method for doubly-fed position sensor is puts forward in (Abdellatif *et al*., 2009). It assured the continuously stable operation of the devices. Li *et al*. (2011) proposed an observer based disturbance filtering unit design method and establishes an adaptive threshold based sensor fault diagnosis model. However, the influences of input error and disturbance on system are not taken into consideration in this model.

Kai Rothenhagen and Friedrich W. Fuchs published a study with regard to bilinear observer based doubly-fed generator fault detection (Rothenhagen and Fuchs, 2006). In the study, the decoupling of rotational speed was realized by separation of doubly-fed generator systems. This study represents a new modeling method considering the influences of rotational speed measuring error and disturbance on system based on (Rothenhagen and Fuchs, 2006) so that the system model is more accurate. The influence of rotational speed is isolated by the use of Luenberger observer. For the influence of rotational speed disturbance which is considered based on this work, this study designs a sliding mode observer in combination with the performance of sliding mode observer eliminating the influence on disturbance to system. Finally, current sensor fault detection of doubly-fed wind generating system is achieved.

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SYSTEM DESCRIPTION

The doubly-fed wind generating system given by (Rothenhagen and Fuchs, 2006):

$$\begin{cases}\dot{x} = Ax + Bu \\ y = Cx\end{cases} \tag{1}$$

where, $x = [x_1 \quad x_2 \quad x_3 \quad x_4]^T = [i_{ds} \quad i_{qs} \quad i_{dr} \quad i_{qr}]^T$ is state vector, i_{ds}, i_{qs}, i_{dr} and i_{qr} are d-q coordinate components of stator and rotor voltage, respectively. $u = [u_{ds}\ u_{qs}\ u_{dr}\ u_{qs}]^T$ is input vector. y(t) is output vector. The system matrix A, the input matrix B and the output matrix C are given, respectively, as follows:

$$A = \begin{bmatrix} -\frac{R_s}{\sigma L_s} & \omega + \frac{L_{sr}^2\omega_r}{\sigma L_s L_r} & \frac{L_{sr}R_r}{\sigma L_s L_r} & \frac{L_{sr}\omega_r}{\sigma L_s} \\ -(\omega + \frac{L_{sr}^2\omega_r}{\sigma L_s L_r}) & -\frac{R_s}{\sigma L_s} & -\frac{L_{sr}\omega_r}{\sigma L_s} & \frac{L_{sr}R_r}{\sigma L_s L_r} \\ \frac{L_{sr}R_s}{\sigma L_s L_r} & -\frac{L_{sr}\omega_r}{\sigma L_r} & -\frac{R_r}{\sigma L_r} & \omega - \frac{\omega_r}{\sigma} \\ \frac{L_{sr}\omega_r}{\sigma L_r} & \frac{L_{sr}R_s}{\sigma L_s L_r} & -(\omega - \frac{\omega_r}{\sigma}) & -\frac{R_r}{\sigma L_r} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & -\frac{L_{sr}}{\sigma L_s L_r} & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & -\frac{L_{sr}}{\sigma L_s L_r} \\ -\frac{L_{sr}}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_r} & 0 \\ 0 & -\frac{L_{sr}}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_r} \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where, R_s and R_r are stator winding resistances and rotor winding resistances, respectively, L_s and L_r are stator equivalent self-inductances and rotor equivalent self-inductances in d-q coordinate, respectively. L_{sr} denotes the main inductance. ω is the synchronous electric rotational speed, ω_r is the electric rotational speed of rotor:

$$\sigma = 1 - \frac{L_{sr}^2}{L_s L_r}$$

In the study, it proposes to new state-space equation in d-q coordinate system of doubly-fed wind generator to be as below. This takes into account the actual application analysis and the fact that rotational speed disturbance shall be considered during modeling:

$$\begin{cases}\dot{x}(t) = Ax(t) + Bu + Dd(t) \\ y(t) = Cx(t)\end{cases} \tag{2}$$

where, dt = $\Delta\omega_r$ is the unknown bounded nonlinear function, representing rotational speed error and unknown input disturbance of generator system which are collectively referred to as unknown input disturbance. It is assumed that the unknown input disturbance is a bounded function such that $\|d(t)\| \le \rho$, where ρ is a known function. D is the known disturbance distribution matrix:

$$D = \begin{bmatrix} 0 & \frac{L_{sr}^2}{\sigma L_s L_r} & 0 & \frac{L_{sr}}{\sigma L_s} \\ -\frac{L_{sr}^2}{\sigma L_s L_r} & 0 & -\frac{L_{sr}}{\sigma L_s} & 0 \\ 0 & -\frac{L_{sr}}{\sigma L_r} & 0 & -\frac{1}{\sigma} \\ \frac{L_{sr}}{\sigma L_r} & 0 & \frac{1}{\sigma} & 0 \end{bmatrix}$$

FAULT DIAGNOSIS SCHEME

As can be seen from Eq. 2, A contains the electric rotational speed of rotor ω_r as a variable input parameter which means that the system is nonlinear. Therefore, matrix A is split up into following two parts (Rothenhagen and Fuchs, 2006; Bennett, 1998):

$$A = A_s + A_r\omega_r \tag{3}$$

where, the first item A_3 is irrelevant with ω_r:

$$A_s = \begin{bmatrix} -\frac{R_s}{\sigma L_s} & \omega & \frac{L_{sr}R_r}{\sigma L_s L_r} & 0 \\ -\omega & -\frac{R_s}{\sigma L_s} & 0 & \frac{L_{sr}R_r}{\sigma L_s L_r} \\ \frac{L_{sr}R_s}{\sigma L_s L_r} & 0 & -\frac{R_r}{\sigma L_r} & \omega \\ 0 & \frac{L_{sr}R_s}{\sigma L_s L_r} & -\omega & -\frac{R_r}{\sigma L_r} \end{bmatrix}$$

$$A_r = \begin{bmatrix} 0 & \frac{L_{sr}^2}{\sigma L_s L_r} & 0 & \frac{L_{sr}}{\sigma L_s} \\ -\frac{L_{sr}^2}{\sigma L_s L_r} & 0 & -\frac{L_{sr}}{\sigma L_s} & 0 \\ 0 & -\frac{L_{sr}}{\sigma L_r} & 0 & -\frac{1}{\sigma} \\ \frac{L_{sr}}{\sigma L_r} & 0 & \frac{1}{\sigma} & 0 \end{bmatrix}$$

For Eq. 2, the sliding mode observer and Luenberger observer are designed as follows:

$$\begin{cases} \dot{\hat{x}}(t) = (A_s + A_r\omega_r)\hat{x}(t) + Bu + L_1(y(t) \\ \quad - \hat{y}(t)) + L_2\omega_r(y(t) - \hat{y}(t)) + Dv \\ \hat{y}(t) = C\hat{x}(t) \end{cases} \tag{4}$$

where, "^" indicates estimate value of relevant variable, L_1 and L_2 are matrixes to be designed. v is input signal of the sliding mode variable structure, expressed as:

$$v = \begin{cases} -\rho\dfrac{Fe_y}{\|Fe_y\|} & \text{if} \quad e_y \neq 0 \\ 0 & \text{if} \quad e_y \neq 0 \end{cases} \tag{5}$$

Define $e = \hat{x}-x$ as the state estimation error and $e_y = \hat{y}-y$ as the output estimation error.

It can be obtained from Eq. 2-4 that:

$$\dot{e} = (A_s - L_1C)e + (A_r - L_2C)\omega_r e + D(v - d(t)) \tag{6}$$

It can be known from calculation that (A_3, C) is observable. It implies that there is a matrix L_1 which enables $A = A_3-L_1C$ to be stable matrix. And there's a Lyapunov equation as below:

$$A_1^T P + PA_1 = -Q \tag{7}$$

where, P and Q are all symmetrical positive definite matrixes.

If select a matrix L_2 so that $A_r-L_2C = 0$. Then, the influence of rotational speed of motor ω_r is isolated and the original nonlinear system is changed to be linear time-invariant system. In this case, it can be obtained from Eq. 6 that:

$$\dot{e} = A_1e + D(v - d(t)) \tag{8}$$

The convergence of the above observer is guaranteed by the following proof.

Proof: Consider the following Lyapunov function:

$$V = e^TPe \tag{9}$$

Along the trajectory of systems Eq. 8, the derivative of the Lyapunov function with respect to time is:

$$\dot{V} = \dot{e}^TPe + e^TP\dot{e} = e^T(A_1{}^TP + PA_1)e + 2e^TPD(v - d(t)) \tag{10}$$

Select F that enables $PD = C^TF^T$, then:

$$2e^TPD(v - d(t)) = 2(FCe)^T(v - d(t)) \tag{11}$$

Therefore:

$$2e^TPD(v - d(t)) \leq -2\|Fe_y\|(\rho - \|d\|) \tag{12}$$

In conclusion, the following can be obtained:

$$\dot{V} \leq -e^TQe \tag{13}$$

So, $\lim\limits_{t\to\infty} e = 0$.

This completes the proof.

When a sensor fault occurs, state equation of system is changed to be the following:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu + Dd(t) \\ y(t) = Cx(t) + Ef(t) \end{cases} \tag{14}$$

where, f(t) denotes sensor fault and E is the distribution matrix of fault:

$$f(t) = \begin{bmatrix} f_{ds}(t) \\ f_{qs}(t) \\ f_{dr}(t) \\ f_{qr}(t) \end{bmatrix}, E = \begin{bmatrix} \varepsilon_1 & 0 & 0 & 0 \\ 0 & \varepsilon_2 & 0 & 0 \\ 0 & 0 & \varepsilon_3 & 0 \\ 0 & 0 & 0 & \varepsilon_4 \end{bmatrix}$$

Where:

$$\varepsilon_i = \begin{cases} 1 & \text{There is a fault} \\ 0 & \text{There is no fault} \end{cases} \quad i = 1, 2, 3, 4$$

The residual signal is defined as:

$$r(t) = e_y\text{-}Ef \tag{15}$$

- There is no fault on the sensor, i.e., f(t) = 0

It can be known from dynamic state error Eq. 6 that, e can still converge to zero field due to above design although there is unknown input disturbance d(t), so the residual $r(t)\approx 0$.

- There is fault on the sensor, i.e. $f(t) \neq 0$

It can be known from Eq. 15 that, at the moment when there is a fault the residual will change to -Ef(t) from zero field. In conclusion, the occurrence of a fault of sensor can be indicated by that the residual deviates from zero fields.

SIMULATION STUDY

The parameters of 2MW doubly-fed wind generator will be used for simulation test and its main parameters are shown in Table 1.

In view of that the stator current sensor in d-q coordinate occur incipient faults and abrupt faults, Fault detection is carried out based on two different situations. The purpose is to verify feasibility and effectiveness of fault detection scheme designed. Simulation test is implemented using MATLAB7.1. The electric rotational speed of rotor in simulation test is $\omega_r = 376.8$ rad sec^{-1}, the input voltage of stator is set to be 690 V and the frequency is 50 Hz, the voltage of rotor is set to be 690 V and the frequency is 12 Hz. $\Delta\omega_r$ is simulated using noise signal and its amplitude is 30. Parameters of observer are designed to be $\rho = 1000$. Pole of matrix L_3 is configured at [-10 -30 -50 -20] using the method adopted and the matrix L_3 is:

$$L_s = \begin{bmatrix} 30 & 314 & -0.0016 & 0 \\ 314 & 20 & 0 & -0.0016 \\ 0.0018 & 0 & 50 & 314 \\ 0 & -0.0048 & -314 & 10 \end{bmatrix}$$

It can be obtained from A_r-$L_r C = 0$ that:

$$L_r = \begin{bmatrix} 0 & -1.0005 & 0 & -0.0252 \\ 1.0005 & 0 & 0.0252 & 0 \\ 0 & 0.0200 & 0 & -0.0005 \\ -0.0200 & 0 & 0.0005 & 0 \end{bmatrix}$$

It can be obtained from $PD = C^T F^T$ that:

$$F = \begin{bmatrix} 0 & 0.0250 & 0 & -0.0012 \\ -0.0167 & 0 & 0.0002 & 0 \\ 0 & 0.0008 & 0 & -0.0001 \\ -0.0005 & 0 & 0.0001 & 0 \end{bmatrix}$$

There are incipient faults on the sensor:

Table 1: Main parameters of doubly-fed wind generator

Parameters	Values
Rated power (MW)	2
Rated voltage (V)	690
Rated frequency (Hz)	50
Rated rotational speed (r min^{-1})	1200
Stator resistance (pu)	0.0062
Stator leakage (pu)	0.0625
Rotor resistance (pu)	0.0096
Rotor leakage (pu)	0.0787
Mutual inductance of stator and rotor (pu)	3.1276
No. of pole-pairs	2

$$f_{ds}(t) = f_{dr}(t) = f_{qr}(t) = \begin{cases} 0 & t < 3s \\ e^{0.5t} & t \geq 3s \end{cases}, \; f_{qs}(t) = 0$$

The waveform of d axis stator current residual r_1 and that of q axis stator current residual r_2 in this situation are as shown in Fig. 1-2, respectively.

There are incipient faults and abrupt faults on the sensor:

$$f_{ds}(t) = f_{dr}(t) = \begin{cases} 0 & t < 3s \\ e^{0.5t} & t \geq 3s \end{cases}$$

$$f_{qs}(t) = f_{qr}(t) = \begin{cases} 0 & t < 3s \\ 3 & t \geq 3s \end{cases}$$

The waveform of d axis stator current residual r_1 and that of q axis stator current residual r_2 in this situation are as shown in Fig. 3-4, respectively.

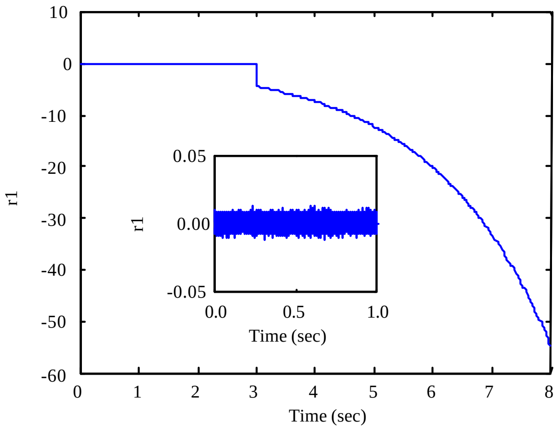

Fig. 1: d axis stator current residual

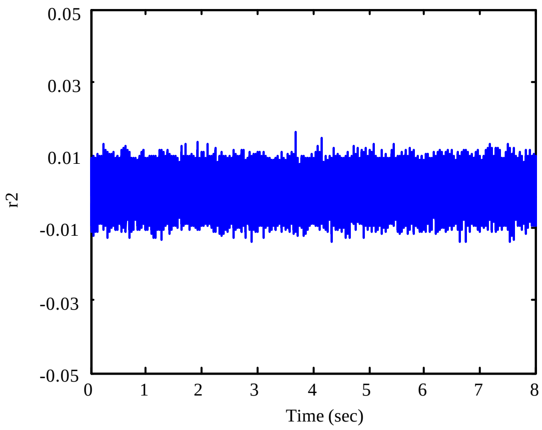

Fig. 2: q axis stator current residual

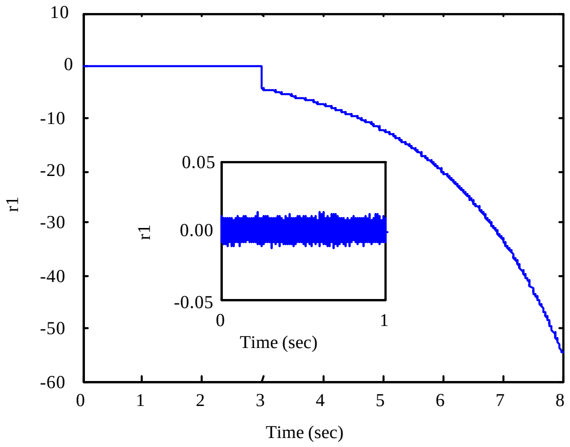

Fig. 3: d axis stator current residual

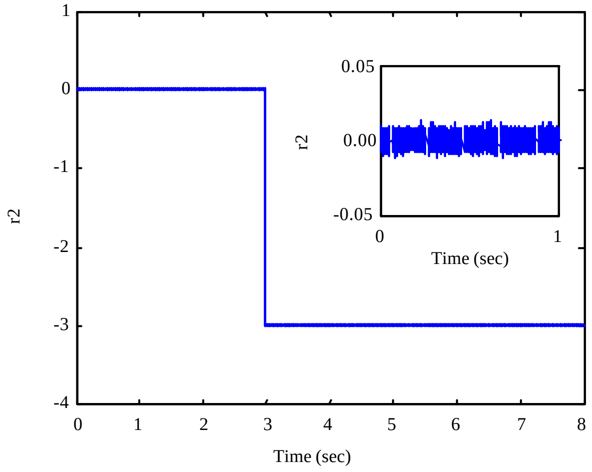

Fig. 4: q axis stator current residual

It can be known from waveforms of above simulation test that, residual r will stay at zero field when no fault is incurred no matter if both of d axis stator current and q axis stator current fail or only either of them fails and the residual r will significantly deviate from zero field during the period when fault is occurring. Therefore, it demonstrates that the observer designed can detect effectively the fault incurred.

CONCLUSION

Decoupling of rotational speed of system can be realized by separation of doubly-fed generator system based on bilinear observer. Meanwhile, fault detection of doubly-fed wind generator can be carried out when there are both rotational speed measurement error and disturbance, by application of two Luenberger observers at the same time in combination with sliding mode observer. It can be demonstrated by simulations of different fault conditions that, the fault diagnosis method presented in this study can detect well various current sensor fault situations.

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