Fault-tolerant control of doubly-fed induction generators under voltage and current sensor faults

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ABSTRACT

This paper presents a Kalman filter-based fault-tolerant control (KFFTC) strategy for a doubly-fed induction generator (DFIG) under voltage and current sensor faults. Based on the independent time-varying models of stator voltages, stator currents, and rotor currents, six Kalman filters are designed in parallel to estimate voltage and current components in the presence of measurement noise. The sensor faults are detected and isolated based on the residuals calculated from observations obtained by sensors and estimations provided by Kalman filters. The faulty measured signals are then replaced by the estimated signals derived from corresponding Kalman filters. The faulty measured signals are then replaced by the estimated signals derived from corresponding Kalman filters. The faulty measured signals are then replaced by the estimated signals derived from corresponding Kalman filters. The faulty measured signals are then replaced by the estimated signals derived from corresponding Kalman filters. The faulty measured signals are then replaced by the estimated signals derived from corresponding Kalman filters.

1. Introduction

The limited reserves of fossil fuel resource and increasing awareness of environment pollution have significantly promoted the development of renewable energy. Wind energy is a cost-effective and environmentally friendly resource which has received considerable attention in the past decade \cite{1,2}. With the advantages of small converter rating, high energy efficiency, and full power control capability, the doubly-fed induction generator (DFIG)-based wind turbines have been widely used in modern wind energy conversion systems (WECSs). Traditional vector control (VC) scheme \cite{3–6} is broadly applied in the control of commercial DFIGs. In the VC scheme, the independent regulation of active and reactive powers of DFIG is achieved by the decoupled control of rotor-current loops.

A DFIG-based wind turbine is fragile to electrical, mechanical, and sensor faults \cite{7}, which will deteriorate system performance and lead to unscheduled shutdown of the system. Fault-tolerant control (FTC), which consists of fault detection and isolation (FDI) and system reconfiguration, is considered as an effective technique to improve system’s reliability. Fault-tolerant power converter topologies have been presented to ensure the non-stop operation of DFIG under electrical faults, such as short- and open-circuit failures \cite{8,9} and power grid faults \cite{10,11}. A wide range of publications have addressed the FDI of DFIG with mechanical faults, including bearing damage \cite{12}, inter-turn fault \cite{13}, and air-gap eccentricity \cite{14}.

Sensor fault is another major cause of failure of DFIG system, and it is gaining great interests to prevent damage and reduce downtime of the system. A sensor fault has an enormous impact on the operation of DFIG since the control performance of VC highly relies on the feedback signals measured by sensors. Electrical and mechanical faults are usually straightforward, but sensor faults are unequivocal due to the complicated configuration of control system. Recent literatures have investigated various FTC strategies for DFIG-based wind turbine in the case of sensor faults. Significant amounts of works have been performed on the wind turbine with rotor-speed and pitch-angle sensor faults using fuzzy observer \cite{15,16}, interval observer \cite{17}, extended-order observer \cite{18}, and more recent works can be found in \cite{19}. Nevertheless, the dynamic characteristics of DFIG, and the voltage and current sensor faults are not considered.

Authors in \cite{20} have proposed a predictive model-based current sensor FTC strategy for the WECS with DFIG. However, additional current sensors are required to attain hardware redundancy, which increases system cost and complexity. In \cite{21–23}, various FTC strategies were developed based on Luenberger observers for the DFIG operating under the condition of current sensor faults. Ref. \cite{21} focuses on the FDI of stator-current sensor faults, while the rotor-current sensor faults and system reconfiguration are not taken into account. In \cite{22,23}, fault residuals were generated by current state observers to...
Nomenclature

$\overrightarrow{V}_s$, $\overrightarrow{V}_r$ stator, rotor voltage vectors
$\overrightarrow{i}_s$, $\overrightarrow{i}_r$ stator, rotor current vectors
$\overrightarrow{A}_s$, $\overrightarrow{A}_r$ stator, rotor flux vectors
$R_s$, $R_r$ stator, rotor resistances
$L_s$, $L_r$ stator, rotor inductances
$L_{sl}$, $L_{rl}$ stator, rotor leakage inductances
$L_m$ mutual inductance
$\omega_s$, $\omega_r$, $\omega_{slp}$ synchronous, rotor, slip speeds
$\theta_s$, $\theta_r$, $\theta_{slp}$ stator-voltage, rotor, slip angles
$P_s$, $Q_s$ stator active, reactive powers
$T_e$ electromagnetic torque
$p$ differential operator
$k_{pi}$, $k_{pi}$ proportional, integral gains of j-th controller

Kalman filters

$X_s$, $U_s$, $Z_s$ state, input, output vectors
$A_s$, $B_s$, $H_s$ system, control, observation matrices
$W_s$, $V_s$ process, measurement noises
$Q_s$, $R_s$ covariance matrices of process, measurement noises
$K_s$, $P_s$ Kalman gain, covariance matrices
$T_s$, $v_s$ sampling period, stator-voltage magnitude

Fault-tolerant control

$R_f$, $R_t$ fault residuals
$T_f$ time period of fault detection and isolation
$R_{hs1}^{sv}$, $R_{hs2}^{sv}$ fault detection thresholds
$R_{vs1}^{sc}$, $R_{vs2}^{sc}$, $R_{vs3}^{sc}$ fault isolation thresholds
$f^s$, $f^q$, $f^{sv}$ fault flags

Subscripts

d, q synchronous d-, q-axis components
a, b, c stationary phase-a, phase-b, phase-c components
k sampling period counter

Superscripts

\begin{align*}
\sqrt{} & \quad \text{matrix transpose} \\
\wedge & \quad \text{estimated value} \\
sva, svc & \quad \text{phase-a, phase-c SVKF components} \\
sca, scc & \quad \text{phase-a, phase-c SKKF components} \\
rca, rcc & \quad \text{phase-a, phase-c RCKF components}
\end{align*}

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detect and isolate stator-current and rotor-current sensor faults. Faulty current measurements were replaced by the estimations provided by respective observer to reconfigure the closed-loop control system. In [24], stator voltages were treated as unknown disturbances, and an disturbance observer was designed to calculate residuals and generate replacement signals for DFIG in the case of stator-voltage sensor faults.

All the above observer-based FTC strategies of DFIG can isolate sensor faults, but fail to determine which sensor is faulty. In addition, either voltage or current sensor faults are covered. Moreover, Luenberger observers with fixed gains are designed for the time-varying dynamics of DFIG, which cannot guarantee the convergence of observers and closed-loop stability. Furthermore, measurement noise is not considered in the design of observers, which degrades their performance. The well-known Kalman filter shows outstanding performance in dealing with the problem of estimating states of linear time-varying systems with process and measurement noises, and it has been applied to the sensor FTC of wind turbine [25], gas turbine [26], linear dc motor [27], and permanent-magnet synchronous motor drive [28].

This paper deals with the aforementioned issues and proposes a Kalman filter-based fault-tolerant control (KFFTC) strategy for the VC-controlled DFIG with voltage and current sensor faults. With the employment of the three-phase sinusoidal model, two stator-voltage Kalman filters (SVKFs) are developed in parallel to estimate the magnitude and angle of stator voltages without involving current measurements. The DFIG model is decoupled into stator-current and rotor-current dynamics, and two stator-current Kalman filters (SKKFs) and two rotor-current Kalman filters (RCKFs) are then designed to obtain the estimations of stator-current and rotor-current components, respectively. Residuals are generated based on voltage and current Kalman filters, and an FDI logic is presented to detect the sensor faults and isolate the faulty sensor. During the occurrence of single-phase sensor fault, the remaining healthy sensor is employed by corresponding Kalman filter to provide accurate replacement signals for reconfiguration of DFIG system. Simulation and experimental studies are conducted on a grid-connected DFIG system to demonstrate the feasibility and effectiveness of the proposed KFFTC strategy.

The rest of this paper is organized as follows. The DFIG model and VC scheme are presented in Section 2. Section 3 describes the design of voltage and current Kalman filters. Section 4 illustrates the proposed KFFTC strategy. Simulation and experimental results are presented in Sections 5 and 6, respectively. Conclusions are drawn in Section 7 and appendix is presented thereafter.

2. Conventional vector control of DFIG

2.1. DFIG model

The equivalent circuit of a DFIG described in the synchronous rotating reference frame is depicted in Fig. 1, in which $\overrightarrow{V}_s$, $\overrightarrow{V}_r$ are stator and rotor voltage vectors, $\overrightarrow{I}_s$, $\overrightarrow{I}_r$ are stator and rotor current vectors, $\lambda_s$, $\lambda_r$ are stator and rotor flux vectors, $R_s$, $R_r$ are stator and rotor resistances, $L_{sl}$, $L_{rl}$ are stator and rotor leakage inductances, $L_m$ is mutual inductance, $L_s = L_{sl} + L_{su}$, $L_r = L_{rl} + L_{ru}$ are stator and rotor inductances, $\omega_s$, $\omega_r$ are synchronous and rotor speeds. From Fig. 1, the stator and rotor fluxes of DFIG are given by [3–6]

\begin{align*}
\lambda_{sd} &= L_{isd} I_s + L_{im} I_d, \quad \lambda_{sq} = L_{isq} I_s + L_{im} I_q \\
& \quad \lambda_{rd} = L_{ird} I_r + L_{im} I_d, \quad \lambda_{rq} = L_{irq} I_r + L_{im} I_q
\end{align*}

(1)

and the stator and rotor voltages are expressed as [3–6]

\begin{align*}
& \omega_s \lambda_{sd} - \omega_r \lambda_{rd} = v_{sd} \\
& \omega_s \lambda_{sq} - \omega_r \lambda_{rq} = v_{sq}
\end{align*}

\begin{align*}
& \omega_s \lambda_{sd} + \omega_r \lambda_{rd} = v_{rd} \\
& \omega_s \lambda_{sq} + \omega_r \lambda_{rq} = v_{rq}
\end{align*}

(2)

(3)

(4)

where $p$ is differential operator, $\omega_{s0} = \omega_s - \omega_r$ is slip speed, subscripts d and q represent d- and q-axis components, respectively. The stator active power $P_s$, stator reactive power $Q_s$, and electromagnetic torque $T_e$ are represented by

![Fig. 1. Equivalent circuit of a DFIG.](https://example.com/fig1.png)
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