Electrical Power and Energy Systems 98 (2018) 48–61

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

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

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ARTICLE INFO

Keywords:
Doubly-fed induction generator
Voltage and current sensor faults
Kalman filter-based fault-tolerant control

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 filter to reconfigure the control system of DFIG during the sensor faults. Simulation and experimental studies undertaken on a grid-connected DFIG system reveal that the KFFTC strategy is able to correctly detect the sensor faults and isolate the faulty sensor, and it ensures the fault-tolerant operation of DFIG under the conditions of stator-voltage, stator-current, and rotor-current sensor faults.

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 [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 [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 [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 [8,9] and power grid faults [10,11]. A wide range of publications have addressed the FDI of DFIG with mechanical faults, including bearing damage [12], inter-turn fault [13], and air–gap eccentricity [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 [15,16], interval observer [17], extended-order observer [18], and more recent works can be found in [19]. Nevertheless, the dynamic characteristics of DFIG, and the voltage and current sensor faults are not considered.

Authors in [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 [21–23], various FTC strategies were developed based on Luenberger observers for the DFIG operating under the condition of current sensor faults. Ref. [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 [22,23], fault residuals were generated by current state observers to

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https://doi.org/10.1016/j.ijepes.2017.11.028
Received 23 March 2017; Received in revised form 25 September 2017; Accepted 20 November 2017

Nomenclature

$\vec{v}_s$, $\vec{v}_r$	stator, rotor voltage vectors
$\vec{i}_s$, $\vec{i}_r$	stator, rotor current vectors
$\vec{\lambda}_s$, $\vec{\lambda}_r$	stator, rotor flux vectors
R_s, R_r	stator, rotor resistances
L_s, L_r	stator, rotor inductances
L_{ls}, L_{lr}	stator, rotor leakage inductances
L_m	mutual inductance
ω_s, ω_r, ω_{slip}	synchronous, rotor, slip speeds
θ_s, θ_r, θ_{slip}	stator-voltage, rotor, slip angles
P_s, Q_s	stator active, reactive powers
T_e	electromagnetic torque
p	differential operator
k_{pj}, k_{ij}	proportional, integral gains of j-th controller

Kalman filters

X_k, U_k, Z_k	state, input, output vectors
A_k, B_k, H_k	system, control, observation matrices
W_k, V_k	process, measurement noises
Q_k, R_k	covariance matrices of process, measurement noises
K_k, P_k	Kalman gain, covariance matrices
T_s, v_s	sampling period, stator-voltage magnitude
θ_{s0}	initial value of stator-voltage angle
σ_s, σ_r	leakage factors of stator-, rotor-current loops

Fault-tolerant control

R_1, R_2	fault residuals
T_f	time period of fault detection and isolation
R_{th1}^{sc}, R_{th1}^{rc}	fault detection thresholds
R_{th2}^{sv}, R_{th2}^{sc}, R_{th2}^{rc}	fault isolation thresholds
f^{sv}, f^{sc}, f^{rc}	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

$\top$	matrix transpose
$\wedge$	estimated value
sva, svc	phase-a, phase-c SVKF components
sca, scc	phase-a, phase-c SCKF components
rca, rcc	phase-a, phase-c RCKF components

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 (SCKFs) 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 $\vec{v}_s$, $\vec{v}_r$ are stator and rotor voltage vectors, $\vec{i}_s$, $\vec{i}_r$ are stator and rotor current vectors, $\vec{\lambda}_s$, $\vec{\lambda}_r$ are stator and rotor flux vectors, R_s, R_r are stator and rotor resistances, L_{ls}, L_{lr} are stator and rotor leakage inductances, L_m is mutual inductance, $L_s = L_{ls} + L_m$, $L_r = L_{lr} + L_m$ are stator and rotor inductances, ω_s, ω_r are synchronous and rotor speeds. From Fig. 1, the stator and rotor fluxes of DFIG are given by [3–6]

$$\lambda_{sd} = L_s i_{sd} + L_m i_{rd},\quad \lambda_{sq} = L_s i_{sq} + L_m i_{rq} \tag{1}$$

$$\lambda_{rd} = L_r i_{rd} + L_m i_{sd},\quad \lambda_{rq} = L_r i_{rq} + L_m i_{sq} \tag{2}$$

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

$$v_{sd} = R_s i_{sd} + p\lambda_{sd} - \omega_s \lambda_{sq},\quad v_{sq} = R_s i_{sq} + p\lambda_{sq} + \omega_s \lambda_{sd} \tag{3}$$

$$v_{rd} = R_r i_{rd} + p\lambda_{rd} - \omega_{slip} \lambda_{rq},\quad v_{rq} = R_r i_{rq} + p\lambda_{rq} + \omega_{slip} \lambda_{rd} \tag{4}$$

where p is differential operator, $\omega_{slip} = \omega_s - \omega_r$ 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

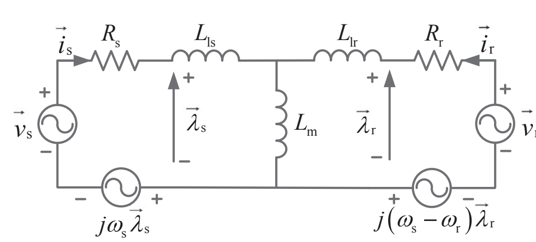

Fig. 1. Equivalent circuit of a DFIG.