Fault-tolerant Control of a Wind Turbine with a Squirrel-cage Induction Generator and Rotor Bar Defects

Wind turbines are usually installed on remote locations and in order to increase their economic competence malfunctions should be reduced and prevented. Faults of wind turbine generator electromechanical parts are common and very expensive. This paper proposes a fault-tolerant control strategy for variable-speed variable-pitch wind turbines in case of identified and characterised squirrel-cage generator rotor bar defect. An upgrade of the torque control loop with flux-angle-based torque modulation is proposed. In order to avoid or to postpone generator cage defects, usage of pitch controller in the low wind speed region is introduced. Presented fault-tolerant control strategy is developed taking into account its modular implementation and installation in available control systems of existing wind turbines to extend their life cycle and energy production. Practical implementation aspects such as estimation of variables used in control and estimate errors are considered and respected in operation, as well as fault-induced asymmetries. Simulation results for the case of a megawatt class wind turbine and the identified rotor bar fault are presented.

Key words: Wind turbine control, Torque control, Generator fault-tolerant control, Nonlinear estimation, Asymmetric field-oriented control

1 INTRODUCTION

Aspiration for finding adequate substitute for conventional fossil fuel power systems has a great impact on today political and economic trends and guidelines. Combining different branches of science and engineering, wind energy is one of the fastest-growing renewable energy sources with an average growth rate of 26% in last 5 years [1]. It is green, inexhaustible, everywhere available but unreliable with poor power quality and as a result – expensive.

The challenge is to make wind turbine control system capable of maximising the energy production and the produced energy quality while minimising costs of installation and maintenance.

Wind turbines are usually installed at low-turbulent wind remote locations and it is important to avoid very costly unscheduled repairs. In order to improve reliability of wind turbines, different fault-tolerant control (FTC) algorithms have been introduced [2], focused mainly on sen-
sor, inverter and actuator faults. Focus here is on generator electromechanical faults, which are besides gearbox and power converters faults the most common in wind turbine systems [3]. Many installed wind turbines have squirrel-cage induction generator (SCIG) and about 20% to 30% of machine faults are caused by defects in rotor cage [4].

Rotor bar defect is caused by thermal fatigue due to cyclic thermal stress on the endring-bar connection which occurs because of different thermal coefficients of bars and lamination steel. As presented in [5, 6], a monitoring system that is able to detect a developing bar defect is designed based on current signature analysis and offers the possibility to switch from preventive to predictive maintenance and thus to significantly reduce costs.

Focus of this paper is to research and develop a fault-tolerant extension of the wind turbine control system that prevents the identified rotor bar defect from spreading. We introduce a fast control loop for flux-angle-based modulation of the generator torque, and a slow control loop that ensures the generator placement at a point that enables the fast loop to perform correctly and keeps the electrical energy production optimal under emergency circumstances.

The basic concept of the generator FTC is proposed in [7]. Here we further improve the idea and develop the algorithm by considering practical implementation aspects such as how state estimation techniques are combined with the derived FTC strategy. State estimation error is anticipated in the FTC in order to guarantee safe operation in its presence. Unscented Kalman filter approach is chosen for estimation of variables that are needed in wind turbine generator torque control because of its proficient ability to cope with hard nonlinearities. A paper that concerns with influence of parameter variation on machine control and their estimation is presented in [8].

Occurred rotor bar fault introduces changes in classical mathematical model of the induction machine. A method for modeling changes in machine leakage inductance is proposed and the fault influence is respected in the control. The method presents an upgrade of conventional fundamental-wave approach in machine modeling and control. A similar work related with asymmetries caused by a stator inter-turn fault can be found in [9].

This paper is organized as follows. The basic control strategy for a variable-speed variable-pitch wind turbine is presented in Section 2 along with normal wind turbine operating maps. In Section 3 a mathematical model of an SCIG is given explaining the theoretical basis used to form a control system extension. Estimation of machine variables used for torque control is described in Section 4. A fault-tolerant approach and control algorithm are proposed and presented in Section 5. They enable wind turbine operation in emergency state with estimation error taken into account. Section 6 concerns with changes of the SCIG model due to occurred fault. Section 7 provides MATLAB/Simulink simulation results obtained with the proposed fault-tolerant control strategy.

2 WIND TURBINE CONTROL SYSTEM

Variable-speed variable-pitch wind turbine operating area is parted into two regions (see Fig. 1): low-wind-speed region (region I), where all the available wind power is fully captured and high-wind-speed region (region II) where the power output is maintained constant while reducing the aerodynamic torque and keeping generator speed at the rated value.

![Fig. 1. Ideal power curve with maximum $P_N$ and power curve due to developed fault with maximum $P_{NB}$](image)

The ability of a wind turbine to capture wind energy is expressed through a power coefficient $C_P$, which is defined as the ratio of extracted power $P_t$ to wind power $P_V$:

$$C_P = \frac{P_t}{P_V}. \quad (1)$$

The maximum value of $C_P$, known as Betz limit, is $C_{P_{\text{max}}} = 0.593$. It defines the maximum theoretical capability of wind power capture. The real power coefficient of modern commercial wind turbines reaches values of about 0.48 [10]. Power coefficient data is usually given as a function of the tip-speed-ratio $\lambda$ and pitch angle $\beta$ (Fig. 2). Turbine power and torque are given by [11]:

$$P_t = C_P(\lambda, \beta)P_V = \frac{1}{2}\rho_{\text{air}}R^2\pi\rho_{\text{air}}R^2\pi C_P(\lambda, \beta)V^3, \quad (2)$$

$$T_t = \frac{P_t}{\omega} = \frac{1}{2}\rho_{\text{air}}R^2\pi C_Q(\lambda, \beta)V^2, \quad (3)$$

where $C_Q = C_P/\lambda$, $\rho_{\text{air}}$, $R$, $V$ and $\omega$ are torque coefficient, air density, radius of the aerodynamic disk of a wind turbine, wind speed and the angular speed of blades, respectively, and $\lambda = \frac{\omega R}{V}$.

Since the goal is to maximise the output power in low-wind-speed region, wind turbine must operate such that the power coefficient $C_P$ is at its maximum value (or near it). This is achieved by maintaining $\lambda$ and $\beta$ on values that ensure $C_P = C_{P_{\text{max}}}$ [10–12], see Fig. 2. Therefore the
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3 MATHEMATICAL MODEL OF AN INDUCTION MACHINE

There are several approaches in modelling an induction machine [13]. One of the most common is the representation of machine stator and rotor phases in the two-phase common rotating \((d, q)\) coordinate system, which is suitable for field-oriented control application. A rotor-based field-oriented control (ROFC) implies that the common rotating \((d, q)\) frame is aligned with rotor flux linkage:

\[
\vec{\psi}_r = \psi_{rd} + j\psi_{rq},
\]

and the complex value of \(\vec{\psi}_r\) becomes a scalar \(\psi_{rd}\).

Mathematical model of a squirrel-cage induction machine used for ROFC can be represented with the following equations [13]:

\[
u_{sd} = k_s i_{sd} + L_d \frac{di_{sd}}{dt} + \left( \frac{L_1}{T_r} - L_s \right) i_{mr} - \omega_c L_d i_{sq},
\]

\[
u_{sq} = R_s i_{sq} + L_d \frac{di_{sq}}{dt} - \omega_c (L_l - L_s) i_{mr} + \omega_l L_l i_{sd},
\]

where \(u_{sd,q}\) are stator voltages in \(d\) and \(q\) axes, \(i_{sd,q}\) are stator currents, \(i_{mr}\) is the rotor magnetizing current. Parameter \(T_r = \frac{L_r}{R_s}\) is the rotor time constant, parameters \(L_r, L_s\) and \(L_m\) are rotor, stator and mutual inductance, respectively, \(R_s\) and \(R_a\) are rotor and stator resistances, \(L_l = (L_s - \frac{L_r^2}{L_l}), k_s = (R_s - \frac{L_r^2}{L_l} + \omega_c).\) Variable \(\omega_c = 2\pi f\) denotes the speed of machine magnetizing flux rotation with respect to the stator, where \(f\) is the frequency of voltage supplied by the inverter. Terms with \(\omega_c\) in (6) and (7) represent the machine back-electromotive force (EMF).

ROFC equations are given by:

\[
i_{mr} = \frac{\psi_{rd}}{L_m},
\]

\[
i_{sd} = i_{mr} + T_r \frac{di_{mr}}{dt},
\]

\[
\omega_{sl} = \omega_c - \omega_l,
\]

\[
T_g = \frac{3}{2} \frac{L_d^2}{L_r} i_{mr} i_{sq} = k_m i_{mr} i_{sq},
\]

where \(\omega_{sl} = \frac{\omega_{rd} - \omega_{rl}}{T_r}\) is the slip speed calculated as a difference between the magnetic flux rotation speed \(\omega_c\) and real rotor mechanical speed \(\omega_l\) multiplied by the number of stator pole pairs \(p\). The variable \(\omega_{sl}\) with its sign dictates whether the asynchronous machine is in the motor or in the generator operating regime.

Relation (11) is the key equation for ROFC of an induction machine. Following from (9), the magnetizing current vector \(i_{mr}\) is not suitable for fast control action influencing torque because of the time lag \(T_r\). Therefore it is kept constant in the sub-nominal speed operating region and \(i_{mr} \triangleq i_{sd} \triangleq i_{sda}\) is implied, where \(i_{sda}\) is the rated value of \(d\)-current corresponding to the rated flux value. Torque is controlled only by \(q\) stator current component \((i_{sq})\).

Relations (6) and (7) show that \(d\) and \(q\) coordinates are not fully decoupled for the case of voltage-controlled machine (Fig. 4) and changing the voltage value in one axis.

**Fig. 2. Power a) and torque b) coefficients for an exemplary 700 kW variable-speed variable-pitch wind turbine**

- **Fig. 3. Control system of a variable-speed variable-pitch wind turbine**

- **Fig. 4. Schematic of the mathematical model of a squirrel-cage induction machine for ROFC**

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where $k_g = k_m i_{sdn}$, $k_e = L_s i_{sdn}$ and $T_0$ is the torque starting point for the transient. Notice that back EMF supports torque reduction and aggravates torque restoration. Fast transients with $T_1$ and $T_2$ are needed for achieving the maximum possible power production with proposed fault-tolerant control. However, in digital control implementation torque in the next discretization step must not exceed desired reference value. Therefore the value of $T_1$ (absolute value of which is by far greater than one of $T_2$) is limited with:

$$T_1 = T_0 - (T_0 - T_d) \frac{\tau}{T_s},$$

where $T_d$ is the desired torque value and $T_s$ is the sample time.

4 ESTIMATION OF FIELD-ORIENTED CONTROL VARIABLES

Field-oriented control and its derivatives require precise machine magnetizing flux position and it is impossible to measure it in asynchronous machines. If the flux position used in calculations deviates from the real flux position, ($d, q$) coordinate system becomes unaligned and relation (8) is no longer valid, which introduces error and mathematical model discrepancy. In the sequel we propose an estimation method for obtaining FOC variables based on the unscented Kalman filter (UKF) algorithm.

4.1 Stochastic machine model

For the implementation of estimation algorithm, a stochastic nonlinear mathematical model is required. Therefore, the model from Section 3 is augmented to include process and measurement noise $v$ and $n$, respectively:

$$\frac{di_{sd}}{dt} = \frac{1}{T_l} u_{sd} + \frac{1}{L_i} \Delta u_{sd} - k_m i_{sd} + v_1,$$

$$\frac{di_{sq}}{dt} = \frac{1}{T_l} u_{sq} + \frac{1}{L_i} \Delta u_{sq} - R_s i_{sq} + v_2,$$

$$\frac{di_{mr}}{dt} = \frac{1}{T_r} (i_{sd} - i_{mr}) + v_3,$$

$$\frac{d \rho}{dt} = p \omega_0 + \frac{1}{T_r} i_{sq} + v_4,$$

where $\rho$ is the flux angle. Described model can be generally represented as:

$$\dot{x} = F_c(x, u, v),$$

where $x = [i_{sd} \quad i_{sq} \quad i_{mr} \quad \rho]^T$ is the state vector, $u = [u_{sd} \quad u_{sq} \quad \omega_0]^T$ is the input vector and $F_c(\cdot)$ is a vector function. Stator currents are usually measured in electric machines and measurement vector is therefore chosen as $y = [i_a \quad i_b + i_c]^T$ (the sum $i_a + i_b + i_c = 0$ holds), generally represented as:

$$y = H(x, n).$$
The measurement vector is related with $d, q$ coordinate system through inverse Clark’s and Park’s transforms [13]:

$$
i_a = i_{sd} \cos \rho - i_{sq} \sin \rho + n_1,$$

$$
i_b = i_{sd} \left( -\frac{1}{2} \cos \rho + \frac{\sqrt{3}}{2} \sin \rho \right) +$$

$$+ i_{sq} \left( \frac{1}{2} \sin \rho + \frac{\sqrt{3}}{2} \cos \rho \right) + n_2. \quad (28)$$

Control scheme for FOC with UKF and corresponding input and measurement vectors is presented in Fig. 5.

![Fig. 5. Field-oriented control loop with unscented Kalman filter (UKF)](image)

### 4.2 Unscented Kalman filter algorithm

The UKF represents a novel approach for estimations in nonlinear systems and provides better results than extended Kalman filter (EKF) in terms of mean estimate and estimate covariance [14]. The core idea of UKF lies in unscented transformation, the way of propagating Gaussian random variables (GRV) through a nonlinear mapping. The unscented transformation is performed using so-called sigma points, a minimal set of carefully chosen sample points that enables better capturing of mean and covariance of GRVs than simple point-linearization of the mapping: posterior mean and covariance are accurate to the second order of the Taylor series expansion for any nonlinear function.

An attractive feature of UKF is that partial derivatives and Jacobian matrix (like in EKF) are not needed and continuous-time nonlinear dynamics equations are directly used in the filter, without discretization or linearization. Computational effort of UKF with carefully implemented algorithm can be similar to that of the EKF. More information can be found in [14] and [15] while different applications of UKF are presented in [16, 17]. The UKF algorithm is given in the sequel.

#### 4.2.1 Initialization and time update

In order to choose a proper set of sigma points, the estimated state vector $\hat{x}_k$ in a discrete time-instant $k$ is augmented to include means of process and measurement noise $\bar{v}$ and $\bar{u}$, forming the vector $\hat{x}_k^n$:

$$\hat{x}_k^n = \mathbb{E}(x_k^n) = \begin{bmatrix} \hat{x}_k^T & \bar{v} & \bar{u} \end{bmatrix}^T,$$

where $\mathbb{E}(\cdot)$ denotes the expectance. Covariance matrix $\mathbf{P}_k$ is also augmented accordingly and $\mathbf{P}_k^n$ is formed:

$$\mathbf{P}_k^n = \mathbb{E}\left( (x_k^n - \hat{x}_k^n)(x_k^n - \hat{x}_k^n)^T \right) = \begin{bmatrix} \mathbf{P}_k & 0 & 0 \\ 0 & \mathbf{R}^v & 0 \\ 0 & 0 & \mathbf{R}^u \end{bmatrix}, \quad (30)$$

where $\mathbf{R}^v$ and $\mathbf{R}^u$ are process and measurement noise covariance matrices, respectively. Time update algorithm starts with the unscented transformation and by forming the sigma points matrix $\mathbf{X}_k^n$:

$$\mathbf{X}_k^n = \begin{bmatrix} \hat{x}_k^n & \hat{x}_k^n + \sqrt{\mathbf{P}_{k}^{v}} & \hat{x}_k^n - \sqrt{\mathbf{P}_{k}^{v}} & \hat{x}_k^n + \sqrt{\mathbf{P}_{k}^{u}} & \hat{x}_k^n - \sqrt{\mathbf{P}_{k}^{u}} \end{bmatrix}. \quad (31)$$

Variable $\sqrt{\mathbf{P}_{k}^{v}}$ is the lower-triangular Cholesky factorization of matrix $\mathbf{P}_k^v$ and $\gamma = \sqrt{L + \lambda}$ is a scaling factor. Parameter $L$ is the dimension of augmented state $x_k^n$ and parameter $\lambda$ determines the spread of sigma points around the current estimate, calculated as:

$$\lambda = \alpha^2 (L + \kappa) - L. \quad (32)$$

Parameter $\alpha$ is usually set to a small positive value e.g. $10^{-4} < \alpha \leq 1$ and $\kappa$ is usually set to 1. There are $2L + 1$ sigma points used for transformation, which correspond to dimension of vector $\mathbf{X}_k^n = \left((\mathbf{X}_k^{x})^T \ (\mathbf{X}_k^{u})^T \ (\mathbf{X}_k^{v})^T\right)^T$.

Time-update equations used to calculate prediction of states $\hat{x}_{k+1}$ and state covariance $\mathbf{P}_{k+1}$ as well as prediction of outputs $\hat{y}_{k+1}$ are:

$$\mathbf{X}_{i,k+1|k} = \mathbf{F}_d \left( \mathbf{X}_{i,k} \mathbf{u}_k, \mathbf{X}_{i,v} \right), \quad i = 0, ..., 2L, \quad (33)$$

$$\hat{x}_{k+1} = \sum_{i=0}^{2L} W_k^{(m)} \mathbf{X}_{i,k+1|k},$$

$$\mathbf{P}_{k+1} = \sum_{i=0}^{2L} W_k^{(c)} \left( \mathbf{X}_{i,k+1|k} - \hat{x}_{k+1} \right) \times$$

$$\left( \mathbf{X}_{i,k+1|k} - \hat{x}_{k+1} \right)^T, \quad (35)$$

$$\mathbf{Y}_{i,k+1|k} = \mathbf{H} \left( \mathbf{X}_{i,k+1|k}, \mathbf{X}_{i,v} \right), \quad i = 0, ..., 2L, \quad (36)$$

$$\hat{y}_{k+1} = \sum_{i=0}^{2L} W_k^{(m)} \mathbf{Y}_{i,k+1|k}, \quad (37)$$

where $i$ is an index of columns in vector $\mathbf{X}_k^n$ (and $\mathbf{X}_k^{x}$, $\mathbf{X}_k^{u}$, $\mathbf{X}_k^{v}$) starting from zero value. Weights for mean and covariance calculations are given by:

$$W_k^{(m)} = \frac{1}{2L + \alpha},$$

$$W_k^{(c)} = \frac{1}{(2L + \alpha)(2L + \alpha + 1)} + \left( 1 - \alpha^2 + \beta \right), \quad (38)$$

$$W_k^{(i)} = \frac{\lambda}{2L + \alpha}, \quad i = 1, ..., 2L.$$
For Gaussian distributions, $\beta = 2$ is optimal.

4.2.2 Measurement update

Once required covariance and cross-covariance matrices are computed by employing unscented transformation, the measurement update algorithm is performed in the same way as in classical EKF:

$$
P_{\tilde{y}_{k+1}} = \sum_{i=0}^{2L} W_i^{(c)} \left( Y_{i,k+1} - \tilde{y}_{k+1} \right) \times \left( Y_{i,k+1} - \tilde{y}_{k+1} \right)^T,
$$

$$
P_{\tilde{x}_{k+1}} = \sum_{i=0}^{2L} W_i^{(c)} \left( X_{i,k+1} - \tilde{x}_{k+1} \right) \times \left( Y_{i,k+1} - \tilde{y}_{k+1} \right)^T,
$$

$$
K_{k+1} = P_{\tilde{x}_{k+1}} P_{\tilde{y}_{k+1}}^{-1},
$$

$$
\hat{x}_{k+1} = \tilde{x}_{k+1} + K_{k+1} \left( y_{k+1} - \tilde{y}_{k+1} \right),
$$

$$
P_{\tilde{x}_{k+1}} = P_{\tilde{x}_{k+1}} - K_{k+1} P_{\tilde{y}_{k+1}} K_{k+1}^T,
$$

where $P_{\tilde{y}_{k+1}}$ is output covariance matrix, $P_{\tilde{x}_{k+1}}$ is cross-covariance matrix, $K_{k+1}$ is Kalman gain matrix, $\hat{x}_{k+1}$ are posterior states and $P_{\tilde{x}_{k+1}}$ is posterior covariance.

5 FAULT-TOLERANT CONTROL

Previous sections have described most widely adopted wind turbine control strategies, as well as mathematical model of the generator. This section is dedicated for further improvement of control strategies in order to disable or to postpone generator fault development and to achieve maximum energy production under emergency conditions at the same time. For now, detected generator fault triggers a turbine safety device and leads to a system shut-down. Whole unscheduled repair process requires significant amounts of money and the situation is even worse for off-shore wind turbines, not to mention opportunity costs of turned-off wind turbine.

To avoid thermal stress of the defected rotor bar, currents flowing through it should be less than currents flowing through the healthy ones. The magnitude of currents in rotor bar is sinusoidal and it is determined by the machine magnetic flux. Speed at which the flux rotates along the rotor circumference is the generator slip speed defined with (10). Flux position with respect to the rotor is denoted with $\theta$. The flux affects the damaged rotor bar only on a small part of its path as it moves along the circumference, whereas this path part is denoted with $\Delta\theta = \theta_2 - \theta_1$, see Fig. 6. Our primary goal is to reduce the electrical and thermal stress reflected through currents and corresponding generator torque in that angle span to the maximum allowed safety value $T_{gf}$. The value $T_{gf}$ is determined based on fault identification through machine fault monitoring and characterisation techniques, together with flux angles $\theta_1$ and $\theta_2$ [5]. Related topic, focused on stator winding inter-turn short circuit faults and periodically modulated stator flux is proposed in [18] and [19].

Torque is therefore modulated based on the machine flux angular position with respect to the damaged part as shown in Fig. 6. When the flux in angle $\theta$ approaches the angle span $\Delta\theta$, the torque is reduced to the maximum allowed value $T_{gf}$ defined with a fault condition. After the flux passes it, the torque is restored to the right selected value $T_{gf}$. The value $T_{gf}$ is determined such that the average machine torque is maintained on the optimum level, taking into account the machine constraints. Procedure is then periodically executed, with period equal $\pi$ (or $\pi$ in time domain), since the flux influences the faulty part with its north and south pole in each turn.

Using the described FOC algorithm with decoupling procedure the generator is modelled as first-order lag system, as mentioned in Section 3. Torque transients from Fig. 6 are therefore defined as exponential functions, decrease and increase respectively:

$$
T_{g_1}(t) = e^{-\frac{\theta}{\tau}} \left( T_{gf} - T_1 \right) + T_1,
$$

$$
T_{g_2}(t) = T_2 - e^{\frac{\theta}{\tau}} \left( T_2 - T_{gf} \right).
$$

Slip speed of the generator is defined as

$$
\omega_{sl}(T_g(t)) = \frac{d\theta}{dt},
$$

from which the angle is obtained:

$$
\theta(t) - \theta(0) = \int_0^t \omega_{sl}(T_g(t)) \, dt = \int_0^t kT_g(t) \, dt.
$$

Desired $T_{gf}$ is reached with transient (44) at certain time $t_1$ and desired $T_{gf}$ is reached with transient (45).
at certain time $t_{on}$:
\[
T_{gf} = e^{\frac{-\tau_g}{T_g}} (T_{g,off} - T_1) + T_1, \quad (48)
\]
\[
T_{g,off} = T_2 - e^{\frac{-\tau_g}{T_g}} (T_3 - T_{gf}). \quad (49)
\]

The angle span which has passed during the torque reduction determines the angle $\theta_{off}$ at which the transition has to start in order to reach the torque $T_{gf}$ at angle $\theta_1$ due to the finite bandwidth of the torque control loop. In the same way, torque restoration transient determines the angle $\theta_{on}$ at which the torque $T_{g,off}$ is fully restored. Finally, $\theta_{off}$ is derived from (18), (47) and (48):
\[
\theta_{off} = \theta_1 - k\tau (T_{g,off} - T_{gf} - T_1 \ln a), \quad (50)
\]
where $\ln a = \ln \frac{T_{gf} - T_1}{T_{g,off} - T_1}$. In the same way, $\theta_{on}$ is obtained as:
\[
\theta_{on} = \theta_2 + k\tau (T_{gf} - T_{g,off} - T_2 \ln b), \quad (51)
\]
where $\ln b = \ln \frac{T_2 - T_{g,off}}{T_2 - T_{gf}}$.

If the torque value $T_{g,off}$ can be restored at some angle then the following relation holds:
\[
\theta_{on} - \theta_{off} \leq \pi. \quad (52)
\]

Putting (50) and (51) into (52), the following is obtained for condition (52):
\[
-k\tau (T_1 \ln a + T_2 \ln b) \leq \pi - \Delta \theta. \quad (53)
\]

Because of large inertia of the whole drivetrain, generator and blade system, described torque oscillations (reduction and restoration) are barely noticeable on the speed transients, such that the wind turbine shaft perceives the mean torque value:
\[
T_{av} = \frac{1}{\tau_\pi} \int_0^{\tau_\pi} T_g dt. \quad (54)
\]

Mean value of the generator torque from Fig. 6 is then given by:
\[
T_{av} = \frac{\pi - 2k\tau (T_1 \ln a + T_2 \ln b)}{k\tau_\pi}, \quad (55)
\]
with
\[
\tau_\pi = \pi - \Delta \theta + k\tau (T_1 \ln a + T_2 \ln b) = \frac{\Delta \theta}{kT_{gf}}, \quad (56)
\]

By applying torque (and corresponding $q$-current) references $T_1$ and $T_2$ from (18), (19), it is ensured that the generator spends the least possible time in reduced torque area.

Equation (52) (or (53)) is not satisfied if the speed $\omega_g$ is large enough (or if there is a large rotor path under fault influence). In that case the torque modulation is given with Fig. 7 and peak torque $T_g$ is attained at angle $\theta^*$:
\[
\theta_2 - \pi + k\tau (T_{gf} - T_g^* - T_2 \ln b^*) = \theta_1 - k\tau (T_g^* - T_{gf} - T_1 \ln a^*), \quad (57)
\]
where $\ln a^* = \ln \frac{T_{gf} - T_1}{T_2 - T_{gf}}$, and $\ln b^* = \ln \frac{T_2 - T_{gf}}{T_2 - T_{gf}}$. Values $T_g^*$ and $\theta^*$ can be obtained from:
\[
k\tau (T_1 \ln a^* + T_2 \ln b^*) = \Delta \theta - \pi, \quad (58)
\]
\[
\theta^* = \theta_1 - k\tau (T_g^* - T_{gf} - T_1 \ln a^*). \quad (59)
\]
\[\text{Fig. 7. Torque modulation due to a fault condition when } T_{g,off} \text{ cannot be restored}\]

Mean value of the generator torque from Fig. 7 (i.e. in case when (52) is not satisfied) is now given by
\[
T_{av} = \frac{\pi - k\tau (T_1 \ln a^* + T_2 \ln b^*)}{k\tau_\pi}, \quad (60)
\]
with
\[
\tau_\pi = -\tau (\ln a^* + \ln b^*) + \frac{\Delta \theta}{kT_{gf}}. \quad (61)
\]

Concludingly, if (53) is fulfilled, the resulting average torque is given with (55); if not, then the resulting average torque is given with (60). On the boundary, i.e. for equality in (52) or (53), both (55) and (60) give the same torque $T_{av}$, such that $T_{av}(\omega_g)$ is continuous. The maximum available torque $T_{g,off}$ is the nominal generator torque $T_{gn}$. Replacing $T_{g,off}$ in (55) with the nominal generator torque $T_{gn}$ gives the maximum available average torque under fault characterised with $\Delta \theta$ and $T_{gf}$. Fig. 8 shows an exemplary graph of available speed-torque points under machine fault, where the upper limit is based on relations (53), (55) and (60) with $T_{g,off} = T_{gn}$. Dashed area denotes all available average generator torque values that can be achieved for certain generator speed.

From Fig. 8 it follows that up to the speed $\omega_{g1}$, it is possible to control the wind turbine in the faulty case without
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Algorithm 1 Fault-tolerant control algorithm, slow loop

I. If $T_{gref}' \leq T_{gf}$, disable the fast loop and pass $T_{gref}'$ to the torque controller;

II. Compute $T_{g,nonf}$ from (18), (19), (55) and (56) such that $T_{av}(\omega_g) = T_{gref}'$; if $T_{g,nonf} > T_{gn}$, set $T_{g,nonf} = T_{gn}$;

III. If (53) is fulfilled set $\theta_{start} = \theta_{off} \mod \pi$ and $\theta_{end} = \theta_{on}$ else compute $\theta^*$ from (59) and set $\theta_{start} = \theta^* \mod \pi$, $\theta_{end} = \theta_{2}$ and $T_{g,nonf} = T_{2}$;

IV. Compute $\omega_{g1}$ as a speed coordinate of the intersection point of $T_{av}(\omega_g)$ and of the normal wind turbine torque controller characteristics, compute $\omega_1 = \omega_{g1}/n_s$ and set $\omega_{ref} = \omega_1$.

Algorithm 2 Fault-tolerant control algorithm, fast loop

I. On the positive edge of logical conditions:

- $\theta > \theta_{start}$ set $T_{gref} = T_1$,
- $\theta > \theta_1$ set $T_{gref} = T_{gf}$,
- $\theta > \theta_2$ set $T_{gref} = T_2$,
- $\theta > \theta_{end}$ set $T_{gref} = T_{g,nonf}$.

Fig. 8. Available torque-speed generator operating points under fault condition (shaded area). Full line is the achievable part of the wind turbine torque-speed curve under faulty condition. Dash-dot line is the healthy machine curve.

Fig. 9. a) Control system of wind turbine with fault-tolerant control strategy. b) Enlarged fault-tolerant control block.

5.1 Uncertainties

Considering practical aspects of the algorithm implementation, a look-up table with $T_{g,nonf}$ values can be used. Exponential torque transients can be approximated with straight lines for lower computational efforts as in [7]. The real generator stator current measurements used for UKF correction procedure are noisy and the model used for estimation may deviate from the real generator system. Proposed fault-tolerant control algorithm is based on the accurate information about machine magnetizing flux position $\theta$. Therefore, if $\theta$ is not correct, the torque is not reduced appropriately on the faulty part $\Delta \theta$ and rotor-bar defect tends to spread further on.

To overcome the problem, faulty part $\Delta \theta$ can be redundantly extended to ensure the proper torque reduction in the faulty machine section, making the FTC algorithm robust on the error of flux position estimate. For that purpose we propose to include the flux position uncertainty obtained from the estimation algorithm and state covariance matrix in $\theta_{off}$ and $\theta_{on}$ calculations procedure. Faulty part $\Delta \theta$ is extended by $\pm 3 \sigma_\theta$, where $\sigma_\theta$ is a square root of

\[ \begin{align*}
\sigma_\theta &= \text{square root of } \text{variance in } \theta \text{ estimates} \\
\end{align*} \]
the variance of machine flux position estimate \( \hat{\theta} \) extracted from the covariance matrix in (43). Probability that the true flux position is within the presumed interval is:

\[
p(\theta \in \left[ \hat{\theta} - 3\sigma_\theta, \hat{\theta} + 3\sigma_\theta \right]) = 99.73\%.
\] (62)

Another feature of the presented FTC algorithm is that torque reduction at point \( \theta_{off} \) always starts at a fixed time step dictated by the sample time \( T_s \). Therefore, it may miss the intended angle of \( \theta_{off} \) and begin at some point \( \theta_{off} + \Delta \theta_{T_s} \). Depending on the sample time value this feature can have a noticeable effect as well. Following from (46), \( \Delta \theta_{T_s} \) is calculated as:

\[
\Delta \theta_{T_s} = \omega_{sd}T_s = kT_s\mod(T_s)T_s.
\] (63)

In the same manner, uncertainty of the fault detection algorithm can also be taken into consideration, formed as a variance \( \sigma_\theta \). All of described uncertainties are included in \( \theta_{off} \) and \( \theta_{on} \) calculations with corrected values of \( \theta_1^c \) and \( \theta_2^c \):

\[
\theta_1^c = \theta_1 - 3\sigma_\theta - \Delta \theta_{T_s} - 3\sigma_\theta,
\] (64)

\[
\theta_2^c = \theta_2 + 3\sigma_\theta + \Delta \theta_{T_s} + 3\sigma_\theta.
\] (65)

That way, equations (50) and (51) with \( \theta_1^c \) and \( \theta_2^c \) remain unchanged.

6 CONTROL OF AN INDUCTION MACHINE WITH ROTOR ASYMMETRIES

In Section 3 a widely-adopted and well-tested RFOC algorithm is described. It is based on so-called fundamental wave machine model approach, which assumes ideal and sinusoidal distribution of magnetizing flux in the machine air-gap. It provides very good results and satisfying performance of the machine but neglects inherent asymmetries due to machine physics and geometry.

Because of occurred rotor bar defect, newly formed asymmetries are introduced inside machine rotor phases. They are reflected on the system performance in terms of vibrations, as well as current and torque oscillations. The diagnostics method for locating and characterisation of the rotor bar defect proposed in [5, 6] is based on observation of this newly arisen system performance.

This section is dedicated for further improvement of system performance and smooth operation of the slightly asymmetric generator. Rotor bar defect causes very small change in resistance \( R_r \) and inductance \( L_r \) of the whole rotor cage, but has a noticeable impact on the leakage inductance \( L_l \). In order to respect asymmetries in machine control we propose an extension of the previously described RFOC algorithm based on the variable leakage inductance observation.

For symmetric machine the leakage inductance is the same for all phases and so far the \( L_l \) was implied to be a constant parameter. Due to occurred asymmetry in the machine, the leakage inductance is no longer the same for all phases and can be represented with a complex value denoted with \( L_{l,t} \). It is composed of a scalar offset value \( L_{off,t} \) and a complex value \( L_{mod,t} \). The offset value represents the symmetric part while complex value includes induced asymmetry with its magnitude and spatial direction. More about this approach can be found in [5, 6]. In common \((d, q)\) reference frame leakage inductance \( L_{l,t} \) is represented as:

\[
L_{l,t} = L_{off,t} + L_{mod,t}, \quad L_{mod} = L_{mod} e^{j2\gamma}.
\] (66)

The angle \( \gamma = \omega_{sl}t + \varphi \) corresponds to the current location of the rotor bar defect with respect to the magnetizing flux. The frequency is doubled due to effects of both north and south magnetic field poles per single flux revolution period. Both \( L_{mod} \) and \( \gamma \) are provided from the fault monitoring and characterisation technique.

The leakage inductance can be represented with:

\[
L_{l,t} = L_{ld} + j\cdot L_{iq},
\] (67)

where \( L_{ld} = L_{off,t} + L_{mod,\cos(2\gamma)} \) and \( L_{iq} = L_{mod,\sin(2\gamma)} \).

By putting it into stator and rotor voltage equations (6) and (7) and by performing linear transformations of equalities, the following relations are obtained:

\[
u_{sd} = k_a i_{sd} + L_a \frac{d i_{sd}}{dt} + \frac{L_{iq}}{L_{ld}} R_s i_{sq} - \frac{L_{iq}}{L_{ld}} u_{sq} - \omega_e L_a i_{sq} + \left( \frac{L_a}{T_r} - \frac{L_s}{T_r} \right) i_{mr} + \omega_e L_{l,t} L_s i_{mr},
\] (68)

\[
u_{sq} = R_s i_{sq} + L_a \frac{d i_{sq}}{dt} - \left( \frac{L_{iq}}{L_{ld}} R_s + \frac{L_{iq}}{L_{ld}} L_s \right) i_{sd} + \frac{L_{iq}}{L_{ld}} u_{sd} + \omega_e L_{l,t} L_s i_{sd} + \frac{L_{iq}}{L_{ld}} L_s i_{mr} - \omega_e (L_a - L_s) i_{mr},
\] (69)

where \( k_a = (R_s - \frac{L_s}{T_r} - \frac{L_a}{T_r}) \) and \( L_a = \left( L_{ld} + \frac{L_s^2}{L_{rd}} \right) \). In the same way as in symmetric FOC, the decoupling method is applied. By introducing correction voltages \( \Delta u_{sd} \) and \( \Delta u_{sq} \), fully decoupled relations are derived:

\[
u_{sd} + \Delta u_{sd} = k_a i_{sd} + L_a \frac{d i_{sd}}{dt}, \quad (70)
\]

\[
u_{sq} + \Delta u_{sq} = R_s i_{sq} + L_a \frac{d i_{sq}}{dt}.
\] (71)
where
\[
\Delta u_{sd} = \frac{L_{iq}}{L_{ld}} u_{sq} \left( \frac{L_{iq}}{L_{ld}} R_s i_{sq} + \omega_c L_a i_{sq} - \left( \frac{L_s}{T_r} - \frac{L_0}{T_r} \right) i_{mr} - \omega_c L_a i_{mr} \right) - \frac{L_{iq} L_s}{L_{ld} T_r} i_{mr} + \omega_c (L_a - L_s) i_{mr},
\]
(71)
\[
\Delta u_{sq} = -\frac{L_{iq}}{L_{ld}} u_{sd} + \left( \frac{L_{iq}}{L_{ld}} R_s + \frac{L_{il}}{L_{ld}} \frac{L_a}{T_r} \right) i_{sd} - \frac{L_{iq} L_s}{L_{ld} T_r} i_{mr} + \omega_c (L_a - L_s) i_{mr}.
\]
(72)

Equations (68)-(73) represent the mathematical model of an asymmetric induction machine. With complex leakage inductance from (66) and (67), influence of the rotor bar defects and asymmetry, the leakages from (68) to (73), influence of the rotor and stator asymmetry. With complex leakage inductance from (66) and (67), influence of the rotor bar defects and asymmetry, the leakages from (68) to (73), influence of the rotor and stator asymmetry.

In the same manner, PI controller parameters are chosen with integral time constants \( T_{idn} = \frac{L_a}{k_a} \) for d-current, \( T_{idn} = \frac{L_a}{k_a} \) for q-current. With index \( a \) controller parameters in case of detected asymmetry are denoted. PI controller gain \( K_{va} \) is selected with respect to desired transient velocity and inverter constraints. Control system block scheme remains the same as in Fig. 4. The way of detecting the true value of transient leakage inductance \( L_{il,t} \) under asymmetric machine conditions determines how much is the system performance improved with the new FOC algorithm.

7 SIMULATION RESULTS

This section provides simulation results for a 700 kW MATLAB/Simulink variable-speed variable-pitch wind turbine model with a two-pole 5.5 kW SCIG scaled to match the torque of 700 kW machine. Generator parameters are: \( L_s = 0.112 \) H, \( L_m = 0.11 \) H, \( R_s = 0.3304 \) Ω, \( R_r = 0.2334 \) Ω and PI controller gain is \( K_{va} = 1 \). Turbine parameters are: \( C_{p_{max}} = 0.4745 \), \( R = 25 \) m, \( \lambda_{opt} = 7.4 \), \( \omega_n = 29 \) rpm, \( T_{in} = 230.5 \) kNm with gearbox ratio \( n_s = 105.77 \). Maximum voltage supplied to one phase is \( U_{imax} = \frac{2}{3} U_{dc} = 467 \) V. Fault is simulated between flux angles \( \theta_1 = \frac{\pi}{2} \) and \( \theta_2 = \frac{\pi}{2} + \frac{\pi}{6} \), with \( T_{gf} = 0.5 T_{gf} \) and presented fault-tolerant control algorithm is applied. Larger sample time is generally more suitable for Kalman filter but here is chosen to fulfill requirements of FOC and fast FTC loop as \( T_s = 400 \) µs. Results in Fig. 10 show how the wind turbine behaves in healthy and faulty condition for a linear change of wind speed through the entire wind turbine operating area. As a result of FTC, new nominal operating point is \( (\omega_{q1}, T_{av}(\omega_{q1})) \) (Fig. 8) and pitch control is activated sooner than in healthy machine conditions.

Fig. 11 shows the fault-tolerant control system reaction to the fault that is identified at \( t = 50 \) s for the case when the average generator torque under fault \( T_{av}(\omega_q) \) can be equal to the required torque \( T_{gf} \) for the incurred speed \( \omega_q \), i.e. the optimum speed-torque point is for the occurred fault in the dashed area of Fig. 8, above the line \( T_{gf} \). A turbulent wind flow based on the Kaimal model is used in the simulations. Fig. 11 also shows that proposed FTC strategy introduces additional wind turbine speed oscillations that influence the whole wind turbine system. A conventional method for avoiding wind turbine resonant frequencies [10–12] can be applied in this case as well. In particular, the torque modulation occurs with frequency of about 2 Hz for rated slip value and contributes to material fatigue. Therefore, the proposed FTC algorithm is to be preferably used only as an emergency reaction until next scheduled overhaul. However, in presented simulations we used a rather serious fault case with \( T_{gf} \) being half of rated torque value. In practice, the fault development can be characterised at early stage and \( T_{gf} \) is expected to be much closer to \( T_{gf} \) and oscillations would be less pronounced.

Fig. 12 shows the fault-tolerant control system reaction to the fault identified at \( t = 50 \) s for the case when the incurred healthy machine speed-torque operating point falls out of the dashed area of Fig. 8. In this case blade pitching is used in the faulty condition to bring the speed-torque operating point into \( (\omega_{q1}, T_{av}(\omega_{q1})) \). Simulations are also performed on a wind turbine with detailed struc-
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Fig. 11. Generator torque modulation and wind turbine speed when $T_{g, \text{non}f} < T_{g,n}$. Fault occurs at 50 s.

Fig. 12. Generator torque modulation and wind turbine speed when $T_{g, \text{non}f} = T_{g,n}$. Fault occurs at 50 s.

Fig. 13. Wind turbine structural loads for the case of normal operation and applied FTC (dash-dot line), a) presents the bending torque at tower top, b) is $y$-axis deflection of a blade, with 1 m distance from the blade root, c) is the nacelle deflection in $y$-axis.

Fig. 14. Flux angle estimation error and variance $\sigma^2_\theta$
8 CONCLUSION

This paper introduces a fault-tolerant control scheme for variable-speed variable-pitch wind turbines with a squirrel-cage induction generator. We focus on generator rotor bar defect that can be characterised at early stage of development. Presented method is used as an autonomous control reaction to diagnosed fault in order to avoid wind turbine shut-down. Results show that simple extension of the conventional wind turbine control structure prevents the fault propagation while power delivery under fault is deteriorated as less as possible compared to healthy machine conditions. State estimation errors and fault-introduced asymmetries are respected in operation as well.

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