Fault-tolerant Control of Permanent Magnet Synchronous Generator in Wind Turbines

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Abstract:

Increase of wind turbine availability is one of the main goals in wind energy research trends. The paper concerns with avoiding wind turbine shut-down under generator stator insulation degradation. We propose a fault-tolerant control that modulates the machine magnetic flux and reallocates the electrical stress from faulty to healthy generator stator parts, and extracts the maximum available power in the faulty operation under a strict condition of stopping further fault propagation. The algorithm is set for the case of 700 kW wind turbine with direct-drive permanent magnet synchronous generator but can be applied for any other type of generator as well. Proposed method is suitable for a wide range of generator operation and fault conditions, from early stage of fault-development to inter-turn short circuit. The method is also conceived as a modular extension to the conventional wind turbine control system. Simulation results are obtained and possible wind turbine operating area under different stage of fault is mapped.

1. Introduction

Increase by 18% in 2010 of direct-drive wind turbine (WT) concepts and announcements of new 7-8 MW WTs [1] makes it evident that permanent magnet synchronous generator (PMSG) is the future trend in wind energy. However, some of the previous gearbox problems will be transferred to the generator, which already has a fault frequency about 10 times greater than equivalent-power industrial machines [2]. Raising concerns for generator availability are to be expected and a lot of effort is currently put into development of new diagnostic methods. Motivated by this we propose a fault-tolerant control (FTC) for generator electromechanical faults.

With the goal of increasing the total efficiency of wind energy extraction and market competence, FTC for increase of WT availability emerged as a promising area of research. Different strategies are proposed, mostly based on redundancies of sensors and electronic components, and control algorithm is used to evaluate the trustworthiness of each [3]. Focus here is on generator electromechanical faults, which are besides gearbox and power converters faults the most common in wind turbine systems [2].

About 30% to 40% of electric machine faults are related to stator insulation [2], [4]–[7]. Some of the most common causes are moisture in the insulation, winding overheating or vibrations [8]. Modern voltage-source inverters also introduce additional voltage stress on the inter-turn insulation caused by the steep-fronted voltage surge.

Built on available diagnostic methods, we isolate the fault and reallocate the generator stress such that the fault propagation is stopped and the generator is operating safely in the fault presence. Specifically, we consider stator winding faults such as insulation degradation that will evidently cause inter-turn (within the same phase), phase-to-phase (between two different phases) or phase-to-ground short circuits. Researches in public domain [4]–[7] show that emergence of this kind of faults occurs gradually and can be detected on-line before they are fully developed to catastrophic proportions. This gives an opportunity for an autonomous reaction of the control algorithm to protect the generator and enable the safe operation under occurred fault until the scheduled maintenance takes place. The FTC is used to modulate generator electromechanical variables in a way that the main cause of rapid fault spreading is removed but also that maximum possible power production in the faulty conditions is maintained.

In our recent work, we proposed FTC of squirrel-cage induction generator for rotor-cage defect [9] and stator inter-turn short circuit [10]. Here we make a contribution to the PMSG with specific distinctions of synchronous operation and permanent magnetic flux but also extend the FTC possibilities for early insulation degradation stage of fault development. The method can be applied to any variable-speed variable-pitch wind turbine, regardless of the generator type.

The paper presents conventional control algorithms of wind turbine (Section 2.) and field-oriented control (FOC) of PMSG (Section 3.). Fault-tolerant control theory, developed algorithm, achievable PMSG and WT operation and an extension of conventional control structure are elaborated in Section 4. Simulation results are presented in Section 5., performed on a 2 MW PMSG with power and torque scaled to match the 700 kW direct-drive WT aerodynamics. Finally, the Section 6. provides conclusions.

2. Wind turbine control system

Modern variable-speed variable-pitch wind turbines operate in two different regions. One is so-called low-wind-speed region where torque control loop adjusts the generator torque to achieve the desired wind turbine rotational speed in order to make the power production optimal. The other region is high-wind-speed region where the power output is maintained constant while reducing the aerodynamic torque and keeping generator speed at the rated value. For this task a blade-pitch control loop is responsible. Both control loops are shown in Fig. 1

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:

$$C_P = \frac{P_t}{P_V}. \tag{1}$$

The maximum value of C_P, known as Betz limit, is $C_{Pmax} = \frac{16}{27} = 0.593$. 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 [11]. Power coefficient data is usually given as a function of the tip-speed-ratio λ and pitch angle β (Fig. 2). Turbine power and torque are given by [12]:

$$P_t = C_P(\lambda,\beta)P_V = \frac{1}{2}\rho R^2 \pi C_P(\lambda,\beta)V^3, \tag{2}$$

$$T_t = \frac{P_t}{\omega} = \frac{1}{2}\rho R^3 \pi C_Q(\lambda,\beta)V^2, \tag{3}$$

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

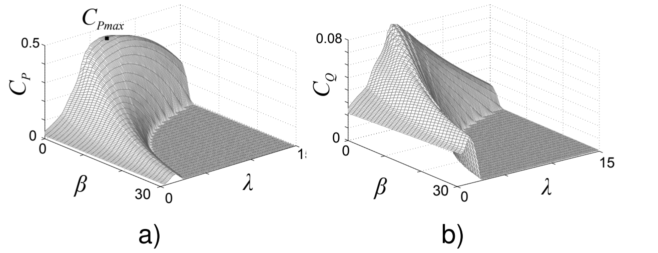

Figure 2: Power a) and torque b) coefficients for an exemplary 700 kW variable-pitch turbine.

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. This is achieved by maintaining $\lambda = \lambda_{opt}$ and $\beta = \beta_0$ on values that ensure $C_P = C_{Pmax}$. Therefore the generator torque and consequently the aerodynamic torque is determined by:

$$T_g^* = \frac{1}{2\lambda_{opt}^3}\rho\pi R^5 C_{Pmax}\omega^2 = K_\lambda \omega^2. \tag{4}$$

Uppercase '*' denotes reference values. This way the wind turbine operating points in low wind speed region are located at the maximum output power curve, called C_{Pmax} locus. For more information about wind turbine modeling and control system design see [11], [12].

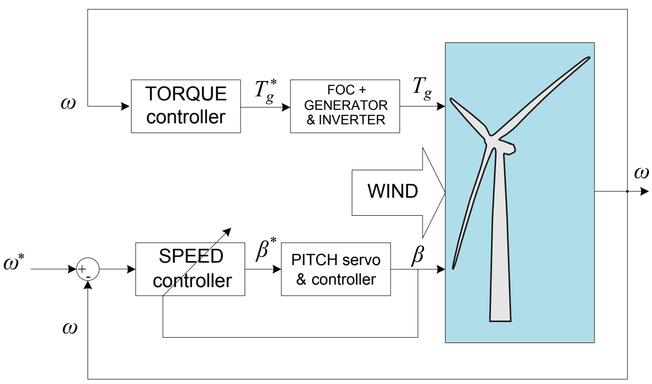

Figure 1: Control system of a variable-speed variable-pitch wind turbine.

3. Generator model and control

Common approach in modeling and control of permanent magnet synchronous machine is to use the mathematical model represented in a two-phase (*d,q*) coordinate system that rotates with supply voltage speed ω_e and is aligned with *d*-axis permanent magnet rotor flux (rotor flux vector $\bar{\psi}_r$ is set to constant ψ_r). The general model is described with:

$$u_{sd} + \Delta u_{sd} = R_s i_{sd} + L_{sd}\frac{di_{sd}}{dt}, \tag{5}$$

$$u_{sq} + \Delta u_{sq} = R_s i_{sq} + L_{sq}\frac{di_{sq}}{dt}. \tag{6}$$

Variables $u_{sd,q}$ are stator phase voltages in (*d,q*) coordinate system, $i_{sd,q}$ are stator phase currents, L_{sd} and L_{sq} are stator inductances in *d* and *q* axes. For the case of non-salient machine (magnets are attached to the rotor exterior), two inductances are equal, $L_{sd} = L_{sq}$. Parameter R_s is the stator resistance. Voltages Δu_{sd} and Δu_{sq} are called decoupling or correction voltages:

$$\Delta u_{sd} = L_{sq}\omega_e i_{sq}, \tag{7}$$

$$\Delta u_{sq} = -L_{sd}\omega_e i_{sd} - \psi_r \omega_e, \tag{8}$$

which ensure that the voltage value in one axis is not affected by the voltage in other. The rotor flux ψ_r is created by permanent magnets and, for the purpose of controller design, it is commonly assumed to be constant (in fact it is dependent on the magnet temperature). The flux perceived by stator is dependent on currents that flow through stator windings:

$$\psi_{sd} = L_{sd} i_{sd} + \psi_r, \tag{9}$$
$$\psi_{sq} = L_{sq} i_{sq}, \tag{10}$$

and affect the stator flux amplitude $\psi_s = \sqrt{\psi_{sd}^2 + \psi_{sq}^2}$. Machine electromagnetic torque is given by:

$$T_g = \frac{3}{2} p \left[\psi_r i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq} \right], \tag{11}$$

where p denotes the number of pole pairs. The torque is controlled only by *q* stator current component, whereas the *d* component is set to zero in order to reach the maximum possible torque range. The above-rated speed operation can be achieved by controlling the i_{sd} with negative values.

A non-salient machine is considered in the sequel due to simplicity reasons for deriving the fault-tolerant control laws and stator inductance is set to $L_{sd} = L_{sq} = L_s$.

Machine model given by (5) and (6) is suitable for proportional-integral (PI) controller design. If integral time constants $T_I = L_s/R_s$ and gain K_r are chosen, closed loop dynamics can be represented as a first-order lag system with transfer function:

$$\frac{i_{sd}(s)}{i_{sd}^*(s)} = \frac{i_{sq}(s)}{i_{sq}^*(s)} = \frac{1}{1 + \tau s}, \tag{12}$$

where τ is a time constant defined with $\tau = \frac{L_s}{K_r}$. Described conventional control method is called field-oriented control. For more information about machine modeling and FOC please refer to [13].

4. Fault-tolerant control

The new and intact insulation in healthy generator conditions is negatively affected by the voltage derivative that arises from the pulse-width modulation. However, once degraded, the insulation has pronounced resistive character and is rapidly damaged further with the stator voltage amplitude [5], i.e., the voltage amplitude becomes dominant to voltage derivative contribution in insulation degradation and is proportional to inter-turn currents through degraded insulation that result in local over-heating. Therefore, in order to stop the fault development, induced voltage in the generator stator windings needs to be restricted and kept under some safe value K obtained from the machine diagnostics. To this aim, the K restriction is to be imposed on stator flux time-derivative, which is the main contribution to the induced stator voltage. In the three-phase coordinate system (*a,b,c*) stator voltage equation is defined with:

$$u_{sx} = i_{sx} R_s + \frac{d\psi_{sx}}{dt} \approx \frac{d\psi_{sx}}{dt}, \tag{13}$$

where x denotes one of the phases. The goal for suppressing the fault is formed as a restricted value of flux derivative:

$$\left| \frac{d\psi_{sx}}{dt} \right| \leq K. \tag{14}$$

The magnetic flux is generated with permanent magnets on the rotor and can be considered constant as described before. However, the magnetic flux perceived by stator windings from (9) and (10) can be reduced with adequate stator currents such that permanent magnet flux is dissipated in the air-gap instead of closing through stator coils. This feature is commonly used in the above-rated-speed operation, known as the flux-weakening method. We utilize this possibility to form a FTC and to restrict the flux derivative.

Approach with globally weakened flux in the below-rated-speed operation can be used to avoid the fault propagation, but it reduces the power production unnecessarily (Fig. 3). Theoretical maximum of power production in faulty operation and boundary condition for fault suppressing is the case when flux derivative reaches the exact value of K:

$$\left| \frac{d\psi_{sx}}{dt} \right| = K. \tag{15}$$

Arising from this condition, the flux is modulated to obtain a triangular waveform with slope value of K such that its derivative is equal to fault restriction coefficient:

$$\begin{aligned} \psi_{sa}(t) &= Kt, & t \in [-\tfrac{\pi}{2\omega_e}, \tfrac{\pi}{2\omega_e}] + \tfrac{2k\pi}{\omega_e}, \\ \psi_{sa}(t) &= -Kt + K\pi, & t \in [\tfrac{\pi}{2\omega_e}, \tfrac{3\pi}{2\omega_e}] + \tfrac{2k\pi}{\omega_e}. \end{aligned} \tag{16}$$

Generally, the stator flux is considered sine-wave (in the fundamental-wave approaches, such as FOC) with amplitude $|\psi_s|$, angular frequency ω_e and phase offset φ_x. The flux in phases $x = a, b, c$ is represented with:

$$\psi_{sx}(t) = |\psi_s|(t) \sin(\omega_e t + \varphi_x), \tag{17}$$

and relation $|\psi_s| = \sqrt{\psi_{sd}^2 + \psi_{sq}^2}$ holds.

Following from (15) and (17), an appropriate flux amplitude envelope is chosen to achieve the triangular waveform (for phase *a* with $\varphi_a = 0$):

$$|\psi_s|(t) = \frac{\frac{K}{\omega_e} \omega_e t}{\sin(\omega_e t)}, \tag{18}$$

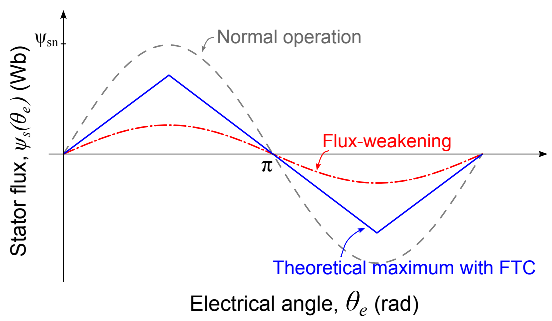

Figure 3: Angle-dependent stator flux waveforms for healthy generator and faulty generator with FTC.

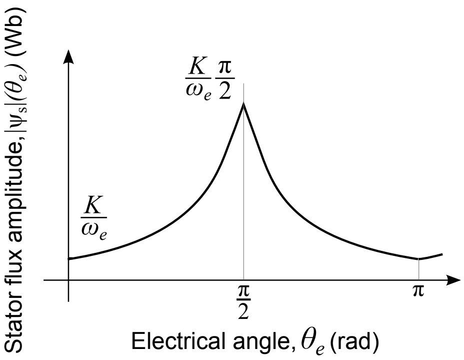

Figure 4: Electrical-angle-dependent stator flux amplitude modulation for FTC.

where $\omega_e t = \theta_e$ is the electrical angle used for (*d,q*) transformations. The minimum absolute value is at angles $\omega_e t = 0, \pi, ...$, and maximum at $\omega_e t = \pi/2, 3\pi/2...$:

$$\begin{array}{rcl} |\psi_s|(0) & = & \frac{K}{\omega_e}, \\ |\psi_s|\left(\frac{\pi}{2}\right) & = & \frac{K}{\omega_e}\frac{\pi}{2}. \end{array} \tag{19}$$

The FTC is used to calculate stator currents that modulate the stator flux amplitude based on the instantaneous flux position, with twice the frequency of the desired waveform, as shown in Fig. 4. As the *q*-current is responsible for maintaining the constant torque, the *d*-current from (9) is used to achieve corresponding $|\psi_s|(t)$. Note that targeted flux amplitude is in fact a time-sequence of *sinc* functions, which ultimately results in a triangular waveform when multiplied with sine magnetic flux distribution generated by permanent magnets rotation. With modulated stator flux amplitude, the stator flux rate of change and consequently the induced voltage in stator windings are restricted and the fault development is stopped or greatly delayed.

Proper values of i_{sd} are chosen to achieve the triangular form in Fig. 3 while taking into account: *(i)* $|i_s|$ must not exceed predefined nominal value i_{sn}, *(ii)* desired machine torque and corresponding i_{sq}, *(iii)* the maximum flux restriction (rated value ψ_{sn}) due to saturation. If the i_{sd} is set to a minimum allowed value, which corresponds to minimum value of stator flux $\psi_{s,min}$, the FTC is acting as a simple flux weakening. In order to achieve full rated current i_{sn} and thus the maximum possible operating area of the faulty generator, i_{sd} is set to follow an equivalent trajectory as $|\psi_s|(t)$. This allows the i_{sq} modulation as a counterpart from $i_s = \sqrt{i_{sd}^2 + i_{sq}^2}$ and thereby larger possible mean torque value. The i_{sq} modulation also introduces additional torque oscillations and undesirable increase of WT structural loads but extends the possible operation by about notable 40% more power as the simulations performed show.

For a time-variable flux amplitude envelope $|\psi_s|(t)$, the flux derivative for fault suppression is defined with:

$$\frac{d\psi_{sx}(t)}{dt} = \frac{d|\psi_s|(t)}{dt}\sin(\omega_e t) + |\psi_s|(t)\omega_e\cos(\omega_e t) \leq K, \tag{20}$$

where the derivative of amplitude envelope from (18) is:

$$\frac{d|\psi_s|(t)}{dt} = K\frac{\sin(\omega_e t) - \omega_e t\cos(\omega_e t)}{\sin^2(\omega_e t)}. \tag{21}$$

Note that two parts in (20) are related to $\sin$ and $\cos$, which is in fact the restriction (14) presented in (*d,q*) rotating coordinate system. Both parts can be therefore individually considered for K restriction:

$$\begin{array}{rcl} \frac{d|\psi_s|(t)}{dt} & \leq & K, \\ |\psi_s|(t)\omega_e & \leq & K, \end{array} \tag{22}$$

and maximum boundary values follow:

$$\frac{d|\psi_s|(t)}{dt}\sin(\omega_e t) = \left\{ \begin{array}{ll} 0, & \omega_e t = 0 \\ K, & \omega_e t = \frac{\pi}{2} \end{array} \right. , \tag{23}$$

$$|\psi_s|(t)\omega_e\cos(\omega_e t) = \left\{ \begin{array}{ll} K, & \omega_e t = 0 \\ 0, & \omega_e t = \frac{\pi}{2} \end{array} \right. . \tag{24}$$

On the other hand, the fastest achievable transient of i_{sd} is determined with inverter limitation. Considering the worst case scenario and a typical value of DC-link voltage U_{dc} in wind turbines, even the maximum stator flux derivative at $t = \frac{\pi}{2\omega_e}$ is achievable and this issue is not explicitly treated in the derived FTC. The FTC algorithm is given in the Algorithm 1.

Algorithm 1 Fault-tolerant control for PMSG

1. Obtain corresponding mean value of *q*-current, $i_{sq,mean}$ from (4) and (11) with torque reference T_g^* and current speed ω; obtain corresponding mean value of *d*-current, $i_{sd,mean}$ from $i_{sq,mean}$ and i_{sn};
2. Obtain $\psi_{s,min}$ from (19); if obtained $\psi_{s,min} \geq \psi_{sn}$ for current ω, no FTC is needed: set $i_{sd}^* = 0$, $\omega^* = \omega_n$ and go to Step 8, otherwise continue on Step 3;
3. Calculate minimum value of *d*-current, $i_{sd,min}$ from $\psi_{s,min}$; calculate mean value of stator flux, $\psi_{s,mean}$ from $i_{sq,mean}$ using (9) and (10);
4. If calculated $\psi_{s,mean} < \psi_{s,min}$, apply flux weakening: set $i_{sd}^* = i_{sd,mean}$, $i_{sq}^* = i_{sq,mean}$, $\omega^* = \omega_C$ and go to Step 8, otherwise continue on Step 5;
5. Find maximum value for the modulation $\psi_{s,max}$ from (18) with $\psi_{s,min}$ and $\psi_{s,mean}$;
6. Obtain current value of $|\psi_s|(t)$ with $\psi_{s,min}$ and $\psi_{s,max}$ from (18), aligned with stator flux angle from $\arctan(\psi_{sq}/\psi_{sd})$;
7. Determine current references i_{sd}^* and i_{sq}^* with i_{sn} and obtained $|\psi_s|(t)$; set $\omega^* = \omega_C$;
8. Pass calculated i_{sd}^* and i_{sq}^* to FOC; pass ω^* to pitch controller;
9. **Initialization:** Set $\omega_C = \omega_n$ and execute steps 1–5 until $\psi_{s,max} \leq \frac{k}{\omega_e}\frac{\pi}{2}$ from (19). Decrease ω_C by small value ϵ_ω at each iteration; set ω^* equal to the obtained ω_C at the last iteration.

Step 9 needs to be performed only once per certain K, steps 1–5 once per modulation period and steps 6–8 at each sample time instant (or only step 8 if no flux modulation is required). The algorithm requires fairly low computer resources with summations, divisions, sine and square root calculations. It can be even more simplified by using look-up tables, such as e.g. $\omega_C(K)$ or slightly more complex $i_{sd}^*(K, \omega_e, \theta_e)$ for $\theta_e \in \{0, \frac{\pi}{2}\}$.

Using the described method, an exemplary graph of available speed-torque points under machine fault is shown in Fig. 5. Normal operation of the healthy generator is bounded with rated machine torque T_{gn} and rated speed ω_n and pitch control is responsible to keep the operating point between boundaries. The curve denoted with *Optimum power* represents optimal operating points of wind turbine at which the power factor coefficient C_p and power production is at maximum value, (4). The flux weakening is applied between 'A' and 'B' points and flux modulation between 'B' and 'C'. The closer the WT operation is to point 'C', the more expressed are the torque oscillations. In the faulty state, optimum power production can be followed to the edge of possible generator operating area and blade pitching is used to keep the WT at new rated point denoted with 'C'. For the case of diagnosed fault, shaded area denotes all available generator torque values that can be achieved for certain generator speed. Generator torque denoted with T_f is the largest available torque that can be achieved under fault condition, wherein the mean torque value is considered for the flux modulation part. Interventions in classical variable-speed variable-pitch wind turbine control that ensure fault-tolerant operation are given in Fig. 6 (red blocks).

Desired generator torque reference T_g^*, dictated by the wind turbine torque control loop (4), determines adequate mean value of i_{sq}. Remaining part of the current is the maximum allowed value of i_{sd}, which determines

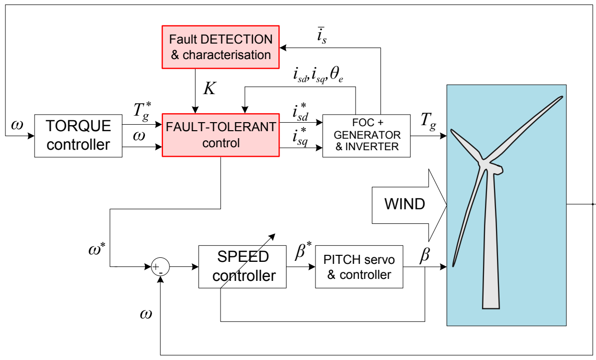

Figure 6: Control system of wind turbine with fault-tolerant control strategy.

the maximum possible reduction of stator flux ψ_{sd}. This feature is also dependent on the generator type, size and permanent magnet flux since the stator flux can only be reduced to the minimum value of $\psi_{s,min} = -L_{sd}i_{sn} + \psi_r$, as follows from (9). This is one limit for the WT operating area with FTC and corresponding product of $|\psi_s|(t)\omega_e$ – the other is WT speed and the minimum meaningful cost effectiveness of available power, both of which are related to the stage of fault development. However, megawatt class WTs offer very wide area of operation depending on the value of K, as presented in Fig. 7.

If there is a short-circuit between turns of the same phase, permanent magnets and variable magnetic flux induce voltage in the shorted turn and, due to very small resistance, cause very high current that develops the fault rapidly. By constraining the flux derivative, the current in shorted turn is restricted as well. Therefore, the proposed method works both for the insulation degradation and inter-turn short circuit cases and can be applied to any stage of the fault development. The stage of fault is dictated only by the coefficient K, which usually falls in the interval (10% ÷ 100%) of the rated product $\omega_{en}\psi_{sn}$ (see Fig. 7).

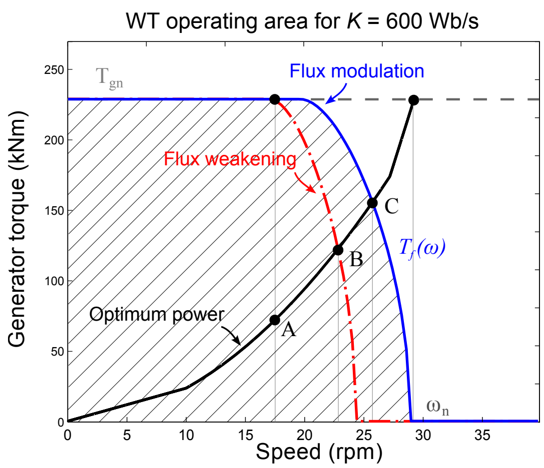

Figure 5: WT operating area for healthy generator case and faulty with $K = 600$ Wb/s (value of $K = 1070$ Wb/s corresponds to the healthy generator).

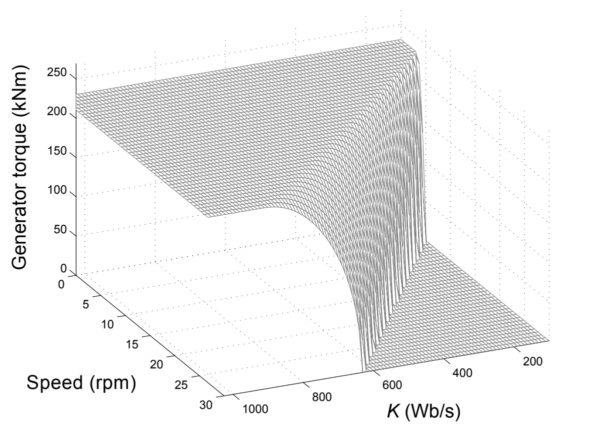

Figure 7: WT operating area for different stages of fault development, expressed through the K coefficient.

5. Simulation results

This section provides simulation results for a 700 kW MATLAB/Simulink variable-speed variable-pitch WT model with a 2 MW PMSG. The focus is on electric variables, which are related to a 2 MW generator but parameters and transients are comparative to any megawatt-class wind turbine. On the other hand, the aerodynamic model differs significantly for various types and sizes of WTs and therefore the generator is scaled to match the torque and power of a 700 kW machine. Simulations are performed on an ideal PMSG model presented in Section 3 with the goal of observing electrical transients and possibilities for stator flux modulation and FTC. Inverter dynamics are therefore neglected due to minor influence on the observed problem. Generator and aerodynamic parameters are given in tables 1 and 2.

Table 1: Generator parameters used in simulations.

Description	Parameter	Value
Rated power	P_n	2 MW
Rated frequency	f_n	12.64 Hz
Number of pole pairs	p	32
Stator resistance	R_s	0.01 Ω
Stator inductance in *d*-axis	L_{sd}	3 mH
Stator inductance in *q*-axis	L_{sq}	3 mH
Permanent magnets flux	ψ_r	12.9 Wb

Table 2: Wind turbine parameters used in simulations.

Description	Parameter	Value
Rated power	P_{tn}	700 kW
Maximum power factor	C_{Pmax}	0.47
Blades disc radius	R	25 m
Optimum tip-speed-ratio	λ_{opt}	7.4
Rated speed	ω_n	29 rpm
Rated torque	T_t	230.5 kNm
Total moment of inertia	J_t	780 000 kgm^2

Simulations are performed for the case of $K = 600$ Wb/s and faulty phase *a*. Figure 8 shows the *d*-current component responsible for flux modulation. Due to reduced tracking capability of PI controllers used in FOC, a time lag occurs between the reference and response of the i_{sd}. The lag causes unsymmetrical flux derivative and results in overshoot of the imposed limit, as shown in Fig. 9 (dash-dot line, denoted as PIs). Simple solution for the problem is to set K to a lower value to ensure redundancy.

Here we apply simple predictive controller from [14] to overcome the problem. Triangular flux waveform is presented in Fig. 10 and its derivative never exceeds the limit K, as shown in Fig. 9. Drops of flux derivative at peak values can be removed by including anticipated rapid stator flux angle changes in the predictive controller. Figure 9 also shows comparison with phase voltage (dashed line), where the approximation (13) is justified. Targeted flux magnitude modulation is shown in Fig. 11.

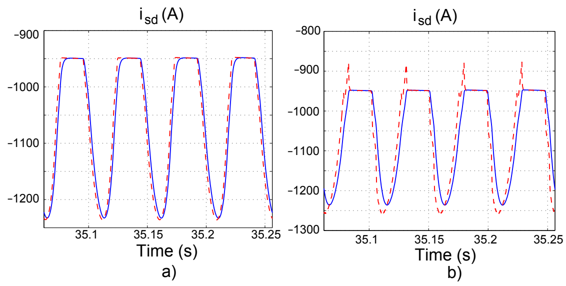

Figure 8: Direct current component i_{sd} for case of: a) conventional PI control, b) predictive control. Dashed is the reference value.

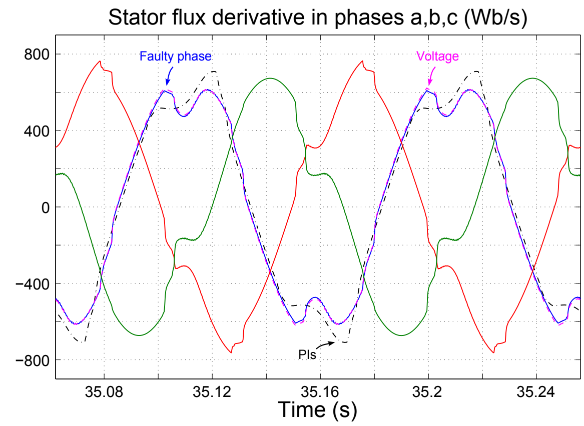

Figure 9: Stator flux derivative in phase coordinates. Dashed is the phase voltage in the targeted (faulty) phase.

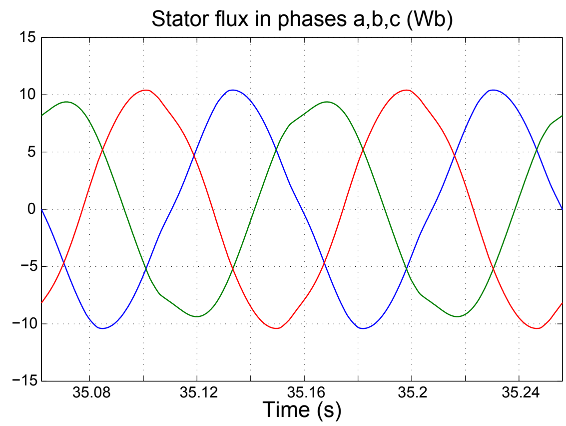

Figure 10: Stator flux in phase coordinates.

The generator electromechanical fault is reflected in stator voltages and currents (Fig. 12), and thereby as periodical changes in power production, which are further on rectified to DC-link, then inverted back and filtered by grid-side converter. The DC-link capacitor also acts as a power buffer that smoothes the power production oscillations.

Mechanical variables of WT for the case of normal

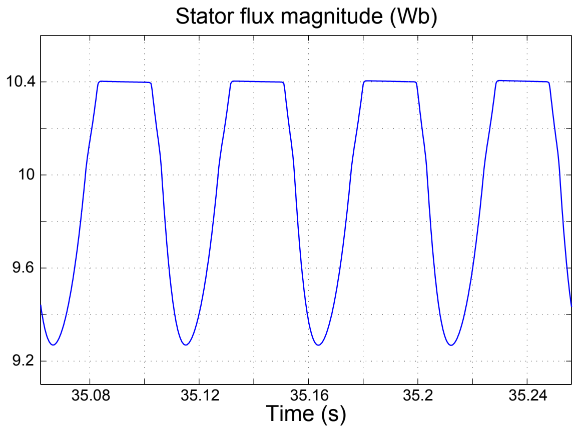

Figure 11: Stator flux amplitude envelope modulation, $|\psi_s|(t)$.

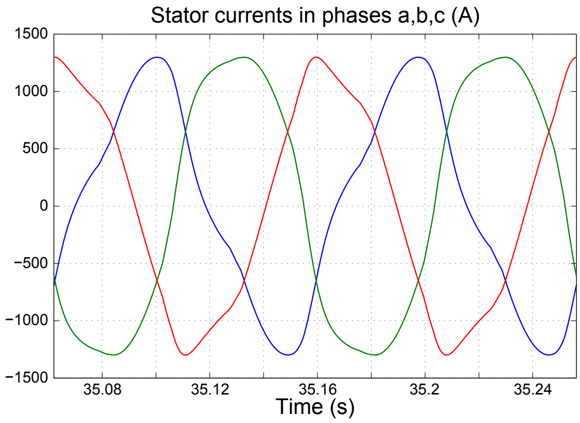

Figure 12: Stator phase currents.

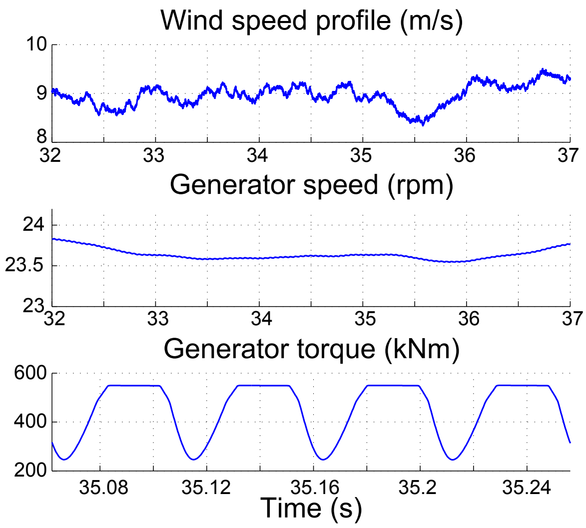

Figure 13: Wind speed and WT operating point.

turbulent wind and applied FTC are shown in Fig. 13. Torque oscillations due to applied i_{sd} and i_{sq} currents modulation are evident, but because of very large moment of inertia of WT rotor disc, the effect is barely noticeable in WT speed. The mean value of torque is kept on the same value as for the case of healthy generator and given operating point, which makes the generator behave identically from the outer WT control loops perspective, only with reduced operating range.

Depending on the diagnostic method sensitivity, the FTC can achieve a wide scope of generator operation, from inter-turn short circuit and from about 30% to almost intact power production, i.e., it can be applied permanently or only temporarily for avoiding the wind turbine shut-down and power production opportunity costs until the next scheduled repair. The FTC is designed as an extension of conventional WT control and algorithm inputs are stator flux derivative constraint imposed by the machine monitoring subsystem, speed and currents measurements, i.e., only already available sensors are required for the implementation. It is important to point out that FTC keeps the operation below rated values of generator variables – they are just shaped and reallocated properly to achieve fault-tolerant operation. This relaxes increased generator iron losses due to non-sine waveforms and increased harmonic composition caused by FTC, as well as torque oscillations influence on structural loads.

6. Conclusions

Results show that generator insulation faults can be stopped from spreading with proper modulation of magnetic flux perceived by stator and safe operation in the presence of the fault can be achieved. We further show how power production can be safely maximized in the faulty conditions. Added market value of proposed control algorithms lays in the fact that they are conceived as cheap, efficient and modular software upgrades to the existing classical generator control algorithms and whole wind turbine control strategy, without any mechanical interventions. The nature of upgrades allows the fault-tolerant control to be easily incorporated in new concepts, but also in already available and working wind turbines with various types of generators. Moreover, the method can be applied for any inverter-fed AC electric machine, regardless of size and application.

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