Fault-tolerant Control of Wound Rotor Synchronous Generator in Wind Turbines

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Abstract—The paper concerns with increasing wind turbine availability by avoiding the shut-down under generator stator insulation degradation. Field-oriented control algorithm is derived for the wound rotor synchronous generators in wind turbine and further extended to achieve safe operation in the stator fault presence. The fault-tolerant control restricts the magnetic flux time derivative and thereby the stator voltage, which is the main cause for rapid fault development in the degraded stator insulation conditions. The method ensures maximum power production and wide wind turbine operation for different developed fault stages. The algorithm is set for the case of 700 kW wind turbine with direct-drive wound rotor synchronous generator but can be applied for any other type of generator as well.

Index Terms—Wind Turbine Control, Wound Rotor Synchronous Generator, Field-oriented Control, Fault-tolerant Control

I. INTRODUCTION

Increase by 18% in 2010 and new announcements of large power direct-drive wind turbines (WT) [1] makes it evident that such a concept is the future trend in wind energy, mainly related to usage of permanent magnet synchronous generators (PMSGs). However, some companies opted for wound rotor synchronous generator (WRSG) type because of the long building tradition, easier manufacturing and far cheaper design, with proven value for very large powers. The concept is a mature technology used for a long time in hydro power plants, suitable for easy control of active and reactive power delivery.

Because of the marginal applications so far, the control of wound rotor synchronous machine concept with stator fully decoupled from the grid by a power converter is a topic tapped only with few of the research groups [2]–[4]. Highly dynamic performance and exploitation of best possible torque range of such machines is an imperative in WTs. The first contribution of the paper is the adjustment of field-oriented control (FOC) widely used in PMSGs to WRSG with independent excitation based on proportional-integral (PI) controllers in rotor flux coordinates with introduced decoupling of variables.

Direct-drive generators in WTs absorb some of the previous gearbox problems and have a fault frequency about 10 times greater than equivalent-power industrial machines [5]. Lots of effort is currently put into development of new diagnostic methods for insulation faults detection [6]–[8]. Motivated by this, we propose a fault-tolerant control (FTC) for generator electromechanical faults that avoids WT shut down and en-

ables safe operation, conceived as a modular extension of FOC and WT control.

About 30% to 40% of electric machine faults are related to stator insulation [5]–[8]. Some of the most common causes are moisture in the insulation, winding overheating or vibrations [9]. Modern voltage-source inverters also introduce additional voltage stress on the inter-turn insulation caused by the steep-fronted voltage surge.

Building 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 eventually causes inter-turn, phase-to-phase or phase-to-ground short circuits.

Researches show that emergence of this kind of faults occurs gradually and can be detected on-line before they are fully developed to catastrophic proportions, i.e., phase-to-phase or phase-to-ground short circuits [6]–[8]. This gives an opportunity for an autonomous reaction of the control algorithm to protect the generator and enable safe operation under occurred fault. The FTC is used to modulate generator electromechanical variables in a way that the main cause of rapid fault spreading is removed but also the maximum possible power production in faulty conditions is maintained. Generator stator flux linkage is therefore modulated in a way that its time derivative and consequently the induced voltage in a faulty phase are kept restricted under a maximum allowed value specified by the generator diagnostics.

In our recent work, we proposed FTC of squirrel-cage induction generator for stator inter-turn short circuit [10] and PMSG insulation degradation [11]. Here we make a contribution to the WRSG with specific distinctions of synchronous operation and excitation-generated flux. The method can be applied to any electrical machine, regardless of the size and purpose.

Conventional control algorithms of wind turbine and FOC of WRSG are presented in Section II. Fault-tolerant control theory, developed algorithm, achievable WT operation and an extension of conventional control structure are elaborated in Section III. Simulation results are presented in Section IV, whereas the simulations are performed on a 700 kW direct-drive WT aerodynamics with corresponding WRSG. Finally, the Section V provides conclusions.

II. WIND TURBINE CONTROL SYSTEM

A. Turbine control

Modern variable-speed variable-pitch wind turbines operate in two different regions. One is the so-called low-wind-speed region where torque control loop adjusts the generator torque to achieve 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 keeping the aerodynamic torque and generator speed at the rated value. For this task a blade-pitch control loop is responsible.

To achieve optimum power production in the low-windspeed region, wind turbine operates at the maximum value of power factor $C_P = C_{Pmax}$ by maintaining the optimum value of the tip-speed-ratio, $\lambda = \lambda_{opt}$. The power factor C_P defines how much power is extracted from the wind. Generator torque reference is calculated from:

$$T_g^* = \frac{1}{2\lambda_{opt}^3} \rho_{air} \pi R^5 C_{Pmax} \omega^2 = K_\lambda \omega^2, \qquad (1)$$

where ρ_{air} is air density, R is aerodynamic disc radius and ω is rotational speed. For more information about wind turbine modeling and control system design see [12].

B. Generator control

Electrical subsystem sketch of direct-drive WT concept with WRSG suitable for FOC is shown in Fig. 1. Common approach in modeling and control of electrical machines used for FOC design is a 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 of the rotor flux (rotor flux vector $\bar{\psi}_r$ is set to constant $\psi_{rd} = \psi_f$). The general model without damper windings is described with:

$$u_{sd} = R_s i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_e \psi_{sq}, \qquad (2)$$

$$u_{sq} = R_s i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_e \psi_{sd}, \tag{3}$$

$$u_f = R_f i_f + \frac{d\psi_f}{dt},\tag{4}$$

where $u_{sd,q}$ are stator phase voltages in (d,q) coordinate system, u_f is the excitation voltage, $i_{sd,q}$ are stator phase currents, i_f is the excitation current, R_s is the stator resistance and R_f is the rotor resistance. Flux linkages are described



Fig. 1. Wind turbine electrical subsystem with WRSG.

with:

$$\psi_{sd} = L_{sd}i_{sd} + L_{md}i_f,\tag{5}$$

$$\psi_{sq} = L_{sq} i_{sq},\tag{6}$$

$$\psi_f = L_{md}i_{sd} + L_f i_f. \tag{7}$$

The flux perceived by stator is comprised of (5) and (6), whereas $\psi_s = \sqrt{\psi_{sd}^2 + \psi_{sq}^2}$ holds. Parameters $L_{sd,q}$ and are stator inductances, L_{md} is mutual inductance in *d*-axis and L_f is the rotor inductance. For the case of cylindrical rotor poles, stator inductances are approximately equal, $L_{sd} \approx L_{sq}$.

Model used for controller design is formed from (2)-(7):

$$u_{sd} + \Delta u_{sd} = R_s i_{sd} + L_{ls} \frac{di_{sd}}{dt} + \frac{L_{md}}{L_f} u_f - \frac{L_{md}}{L_f} R_f i_f,$$
(8)

$$u_{sq} + \Delta u_{sq} = R_s i_{sq} + L_{sq} \frac{di_{sq}}{dt},\tag{9}$$

$$u_{f} = R_{f}i_{f} + L_{lf}\frac{di_{f}}{dt} + \frac{L_{md}}{L_{sd}}(u_{sd} + \Delta u_{sd}) - \frac{L_{md}}{L_{sd}}R_{s}i_{sd},$$
(10)

where $L_{ls} = \left(L_{sd} - \frac{L_{md}^2}{L_f}\right)$ and $L_{lf} = \left(L_f - \frac{L_{md}^2}{L_{sd}}\right)$. Decoupling or correction voltages are:

$$\Delta u_{sd} = L_{sq} \omega_e i_{sq},\tag{11}$$

$$\Delta u_{sq} = -L_{sd}\omega_e i_{sd} - L_{md}\omega_e i_f,\tag{12}$$

which ensure the back-electromotive force cancelation and linear machine model. Machine electromagnetic torque is given by:

$$T_g = \frac{3}{2}p \left[L_{md} i_f + (L_{sd} - L_{sq}) i_{sd} \right] i_{sq}, \tag{13}$$

where p denotes the number of pole pairs. The maximum possible torque range is achieved when the machine is fully magnetized with rotor excitation current i_f and d stator current component is set to zero, since $L_{md} \gg (L_{sd} - L_{sq})$ in (13). This enables full rated stator current range to be used for i_{sq} and torque control, and generator operates only as an active power source.

Machine model given by (8)-(10) is suitable for controller design. We opt for a conventional multiple-input and multipleoutput (MIMO) controller design approach with decoupling controllers [13] since the model is coupled through rotor and stator currents. The model is represented with following transfer functions:

$$G_{ff} = \frac{I_f(s)}{U_f(s)} = \frac{K_{ff}(1 + T_{ff}s)}{(1 + T_{p1}s)(1 + T_{p2}s)},$$
(14)

$$G_{fd} = \frac{I_f(s)}{U_{sd}(s) + \Delta u_{sd}} = \frac{K_{fd}s}{(1 + T_{p1}s)(1 + T_{p2}s)},$$
 (15)

$$G_{df} = \frac{I_{sd}(s)}{U_f(s)} = G_{fd},\tag{16}$$

$$G_{dd} = \frac{I_{sd}(s)}{U_{sd}(s) + \Delta u_{sd}} = \frac{K_{dd}(1 + T_{dd}s)}{(1 + T_{p1}s)(1 + T_{p2}s)},$$
 (17)

$$G_{qq} = \frac{I_{sq}(s)}{U_{sq}(s) + \Delta u_{sq}} = \frac{K_{qq}}{1 + T_{qq}s},$$
(18)

where corresponding system gains $(K_{ff}, K_{fd}, K_{dd}, K_{qq})$ and time constants $(T_{ff}, T_{dd}, T_{p1}, T_{p2}, T_{qq})$ are derived from (8)-(10).

With $T_{p2} \gg T_{p1}$ and by ignoring the system zero, main controllers are suitable for PI form and magnitude optimum approach:

$$R_{ff} = K_{rf} \frac{1 + T_{Ifs}}{T_{Ifs}}, \quad R_{dd} = K_{rd} \frac{1 + T_{Ids}}{T_{Ids}}, \tag{19}$$

$$R_{qq} = K_{rq} \frac{1 + T_{Iq}s}{T_{Iq}s},$$
 (20)

while MIMO decoupling is performed accordingly:

$$R_{fd} = -\frac{G_{fd}}{G_{ff}}, \quad R_{df} = -\frac{G_{df}}{G_{dd}}.$$
 (21)

Since the MIMO control law is influenced both by internal variables and system output, faster response of variables is achieved. Parameters of PI controllers are selected: $T_{If} = T_{Id} = T_{p2}$, $T_{Iq} = T_{qq}$ with corresponding magnitude optimum gains K_{rf} , K_{rd} and K_{rq} . Whole control structure is shown in Fig. 2. Block denoted with *variable estimation* is a model-based observer with included stationary to rotary frame transformations. The representative FOC concept is given here and for more information about machine modeling and control please refer to [14].

C. Flux-weakening

The above-rated speed operation, i.e., the flux-weakening is performed to keep the machine at rated power and can be achieved by reducing i_{sd} , i_{sq} or i_f . Choosing the optimum flux-weakening method is dependent on machine parameters, uppermost with L_{sq}/L_{sd} ratio. For the case of WT generator types with large number of salient poles, large diameter and small length (hydro generators), reduction of i_{sd} and i_{sq} currents is more efficient approach since the ψ_{sq} takes the dominant part in ψ_s . For the case of fast rotating, cylindrical generators with small diameter and large length (turbo generators), ψ_{sd} is dominant and the flux-weakening is more efficient with reduction of i_f current.

III. FAULT-TOLERANT CONTROL

The stator insulation is usually modeled as a realistic, highfrequency capacitance, with the current flow caused by voltage time derivative, i.e., the insulation is negatively affected by the pulse-width modulation. However, once degraded, the insulation has pronounced resistive character and is rapidly damaged further by the inter-turn currents, which are dependent on stator voltage amplitude [7]. 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, represented in phase coordinates as:

$$u_{sx} = i_{sx}R_s + \frac{d\psi_{sx}}{dt} \approx \frac{d\psi_{sx}}{dt},$$
(22)



Fig. 2. MIMO controller and field-oriented control of a wound rotor synchronous generator.

where x denotes one of the phases (a, b, c). The goal for suppressing the fault in phase x is formed as:

$$\left|\frac{d\psi_{sx}}{dt}\right| \le K.$$
(23)

The magnetic flux perceived by stator windings from (5) and (6) can be reduced with adequate stator currents without affecting the generator torque building current i_{sq} such that rotor flux is dissipated in the air-gap instead of closed through stator coils. This feature is commonly used in machine control as the flux-weakening method in the above-rated-speed operation. We utilize this possibility to form a FTC and to restrict the flux time derivative in WRSG.

Approach with globally reduced voltage and weakened flux in the below-rated-speed operation can be also 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 time derivative reaches the exact value of K:

$$\left|\frac{d\psi_{sx}}{dt}\right| = K.$$
(24)

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

$$\psi_{sx}(t) = K(t + \varphi_x), \ t \in \left[-\frac{\pi}{2\omega_e}, \frac{\pi}{2\omega_e}\right] + \frac{2k\pi - \varphi_x}{\omega_e}, \ (25)$$
$$\psi_{sx}(t) = -K(t + \varphi_x - \pi), \ t \in \left[\frac{\pi}{2\omega_e}, \frac{3\pi}{2\omega_e}\right] + \frac{2k\pi - \varphi_x}{\omega_e},$$

where φ_x are (a, b, c) phase offsets $\{0, \frac{\pi}{3}, -\frac{\pi}{3}\}$, respectively.

Generally, the stator flux is considered sine-wave (in the fundamental-wave approaches, such as d, q model) with amplitude $|\psi_s|$, angular frequency ω_e and phase offset φ_x . The



Fig. 3. Electrical-angle-dependent stator flux waveforms for healthy generator and faulty generator with FTC.

flux in phases x = a, b, c is represented with:

$$\psi_{sx}(t) = |\psi_s|(t)\sin(\omega_e t + \varphi_x). \tag{26}$$

To achieve the triangular waveform, an appropriate flux amplitude envelope is chosen, following from (24) and (26) (for phase *a* with $\varphi_a = 0$):

$$|\psi_s|(t) = \frac{\frac{K}{\omega_e}\omega_e t}{\sin(\omega_e t)},\tag{27}$$

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 $\omega_e t = \pi/2, 3\pi/2...$:

$$\begin{aligned} |\psi_s|(0) &= \frac{K}{\omega_e}, \\ |\psi_s|\left(\frac{\pi}{2}\right) &= \frac{K}{\omega_e}\frac{\pi}{2}. \end{aligned}$$
(28)

The modulated flux is shown in Fig. 4. The minimum value corresponds to safe operation for the faulty case addressed by constant flux weakening and rest of the magnitude modulation is to extract the maximum possible power production under the safety constraint. The peak value of modulation is restricted by the rated value of stator flux ψ_{sn} . The modulation is performed with twice the frequency of magnetic flux rotation.

The magnetic flux is generated with rotor excitation and is kept constant in the normal operation. The torque (13) is comprised of dominant mutual product of i_f and i_{sq} . This allows the i_{sd} to handle the flux modulation to achieve corresponding $|\psi_s|(t)$ and perform FTC. For the case of salient pole machine, slight variations in the torque due to changing of i_{sd} are compensated with i_{sq} to achieve smooth operation.



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

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 rotor windings 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 i_{sd} is kept at the minimum allowed value, which corresponds to minimum value of stator flux $\psi_{s,min} = K/\omega_e$, the FTC is acting as a simple fluxweakening.

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

$$\frac{d\psi_{sx}(t)}{dt} = \frac{d|\psi_s|(t)}{dt}\sin(\omega_e t) + |\psi_s|(t)\omega_e\cos(\omega_e t) \le K,$$
(29)

where the time derivative of amplitude envelope from (27) is:

$$\frac{d|\psi_s|(t)}{dt} = K \frac{\sin(\omega_e t) - \omega_e t \cos(\omega_e t)}{\sin^2(\omega_e t)}.$$
 (30)

By substituting (27) in (29) and (30), it follows that the fault suppression goal with theoretical maximum of power production in faulty operation is achieved as (24) is fulfilled for any $\omega_e t$.

The feasibility of $|\psi_s|(t)$ from (27) is also dependent on the fastest achievable transients of i_{sd} , i_{sq} and i_f , 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 time derivative at $t = \frac{\pi}{2\omega_e}$ is achievable and this issue is not explicitly treated in the derived FTC.

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 WT operating points where the power factor coefficient C_p and power production is at maximum value, (1). The flux-weakening is applied between 'A' and 'B' points and flux modulation between 'B' and 'C', where power production at 'C' is about 25% greater than at 'B'.

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. Interventions in classical variable speed variable pitch wind turbine control that ensure fault-tolerant operation are given in Fig. 6 (red blocks). Variable β denotes pitch angle.

The control of WRSG offers lots of freedom and optimization approaches are suitable for determining required currents for a wide range of attainable torques and speeds. Appropriate



Fig. 5. WT operating area for healthy generator case and applied FTC with K set to 600 Wb/s (rated value is at 1025 Wb/s).

values of i_{sd} and i_{sq} for flux-weakening we obtained by using a two-loop iterative approach with different values of stator and excitation currents covering all possible operating region, and with the goal of torque maximization under the constraint of rated product $\psi_{sn}\omega_{en}$ (rated voltage). The same iterative approach is then extended for different values of constrained product $\psi_{s}\omega_{e}$, i.e., the fault condition K. Simple look-up tables were formed: $T_{gA}(K)$, $T_{gB}(K)$, $T_{gC}(K)$ and $\omega_C(K)$, where point 'B' corresponds to the minimum value and 'C' to the mean value of achievable flux modulation (27). With this approach, the on-line part of FTC algorithm is trivial, consisting only of simple algebraic relations that require fairly low computer resources, as given in the Algorithm 1.

If there is a short-circuit between turns of the same phase, variable magnetic flux induces voltage in the shorted turn and, due to very small resistance, causes very high current that develops the fault rapidly. By constraining the flux time 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



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

Algorithm 1 Fault-tolerant control for WRSG

- 1. Obtain T_a^* from (1) for current ω ;
- 2. If T_g^* falls in the interval below 'A', the generator is operating in the safe area and no FTC is needed: calculate i_{sq}^* from (13), set $i_{sd}^* = i_{sdn}$, $i_f^* = i_{fn}$, $\omega^* = \omega_n$ and continue to step 5;
- If T^{*}_g falls in the interval between 'A' and 'B', apply fluxweakening: obtain i_{sd_min} and i_{sq_min} that correspond with ψ_{s,min} for current ω; set i^{*}_{sd} = i_{sd_min}, i^{*}_{sq} = i_{sq_min}, i^{*}_f = i_{fn}, ω^{*} = ω_C and continue to step 5;
- 4. If T^{*}_g falls in the interval between 'B' and 'C', introduce torque modulation: obtain |ψ_s|(t) from (27) for current stator flux angle and calculate i^{*}_{sd} = |ψ_s|(t)/ψ_{s,min} · i_{sd_min}; maintain smooth torque by calculating adequate i^{*}_{sq} from i_{sd_min} and i_{sq_min} by using (13); set i^{*}_f = i_{fn} and ω^{*} = ω_C;
- 5. Pass i_{sd}^* , i_{sq}^* and i_f^* to FOC; pass ω^* to pitch controller;

fault is dictated only by the coefficient K, which usually falls in the interval (10% ÷ 100%) of rated product $\psi_{sn}\omega_{en}$.

IV. SIMULATION RESULTS

This section provides simulation results for a 700 kW MATLAB/Simulink variable-speed variable-pitch WT model. Simulations are performed on an ideal WRSG model presented in Section II 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 parameters are given in Table I. The generator is scaled to match the 700 kW WT with aerodynamical torque of 230 kNm and speed of 29 rpm. Since WT dynamics are by far slower than generator transients, results are presented in time scale that correspond to four modulation periods and appear as a steady-state operation.

Simulations are performed for the case of K = 600 Wb/s and the phase *a* is targeted by flux modulation and FTC. Figure 7 shows the MIMO controller performance and manipulated currents for flux modulation. Reduced PI controller tracking capability introduces time lags between reference values and responses for i_{sd} and i_{sq} . The figure also shows that

 TABLE I

 GENERATOR PARAMETERS USED IN SIMULATIONS.

Description	Parameter	Value
Rated power	P_n	1800 kVA
Rated voltage	U_n	1250 V
Rated frequency	f_n	13.5 Hz
Number of pole pairs	p	30
Stator resistance	R_s	0.022 Ω
Stator inductance in <i>d</i> -axis	L_{sd}	12.18 mH
Stator inductance in q-axis	L_{sq}	8.53 mH
Stator mutual inductance	L_{md}	10.46 mH
Rotor inductance	L_{f}	12.65 mH
Rotor resistance	R_{f}	1.24 Ω
Rated excitation voltage	U_f	800 V

rapid change in *d*-current has minor influence on excitation current i_f due to the decoupled controller.

The stator flux waveform deviates slightly from the targeted triangular waveform (Fig. 8) due to machine rated flux restrictions and controller tendency to achieve the reference values of FOC variables. The fault restriction is fully satisfied as stator flux time derivative in faulty phase never exceeds the imposed limit of K, as shown in Fig. 9. Further improvement may be achieved by eliminating the tracking lag of currents with e.g. predictive controller, where the reference values are known for the forthcoming modulation period (by considering a constant ω during the modulation period).

Stator currents, shown in Fig. 10, introduce higher harmonics but the issue is not reflected on the power delivered to the grid due to back-to-back power converter between the generator and the grid. Since the goal of FTC is to tamper solely electrical variables, torque and speed are influenced only by system coupling and PI controller imperfections, as shown in Fig. 11, which makes the generator behave identically from the outer WT control loops perspective (only with reduced operating range).



Fig. 7. FOC currents i_{sd} , i_{sq} and i_f . Dashed lines denote reference values.



Fig. 8. Stator flux in phase coordinates.



Fig. 9. Stator flux time derivative in phase coordinates. Dashed line denotes the K constraint.



Fig. 11. Generator speed and torque.

V. CONCLUSIONS

Field-oriented control of wound rotor synchronous generator offers fast dynamics and wide torque operation. Generator insulation faults can be stopped from rapid spreading by restricting the stator flux time derivative and thus by removing the cause for fault development. Safe operation of wind turbine can be achieved with maximized power production in the faulty conditions. Proposed control algorithms 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 and for any type of generator. Moreover, the modular approach means the concept can be applied with minor modifications to any inverter-fed AC electric machine operated by field-oriented control, regardless of size and application. Machine safe operation is maintained regardless of the fault, only with reduced operating range due to the voltage restriction and slightly slower possible transients for smaller machines, depending on the fault severity.

ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no 285939 (ACROSS), from the "Centre of Excellence for Structural Health" (CEEStructHealth) supported by the EU under contract IPA2007/HR/16IPO/001-040513, and from the Republic of Croatia Proof of Concept Grant Fund for Researchers through project "Proof of Concept for Wind Turbine Generator Faulttolerant Control" (PoC-WTGFTC), grant no PoC5_1_108.

REFERENCES

- [1] Renewable Energy Policy Network for the 21st Century (REN21), "Renewables 2013", Global status report, 2013.
- [2] A. K. Jain, V. T. Ranganathan, "Modeling and Field Oriented Control of Salient Pole Wound Field Synchronous Machine in Stator Flux Coordinates", *IEEE Transactions on Industrial Electronics*, vol. 58, no. 3., pp. 960–970, Mar. 2011.
- [3] M. Imecs, C. Szabo, I. I. Incze, "Stator-Field-Oriented Vectorial Control for VSI-Fed Wound-Excited Synchronous Motor", *International Aegean Conference on Electrical Machines and Power Electronics, ACEMP*, pp. 303–308, 2007.
- [4] J. Bocker, J. Janning, H. Jebenstreit, "High Dynamic Control of a Three-Level Voltage-Source-Converter Drive for a Main Strip Mill", *Transactions on Industrial Electronics*, vol. 49, no. 5, pp. 1081–1092, Oct. 2002.
- [5] Z. Daneshi-Far, G. A. Capolino, H. Henao, "Review of Failures and Condition Monitoring in Wind Turbine Generators", XIX International Conference on Electrical Machines - ICEM 2010, 2010.
- [6] G. Stojičić, G. Joksimović, M. Vašak, N. Perić, T. M. Wolbank, "Increasing Sensitivity of Stator Winding Short Circuit Fault Indicator in Inverter Fed Induction Machines", 15th International Power Electronics and Motion Control Conference, EPE-PEMC ECCE Europe 2012, pp. DS2a.10-1–7, 2012.
- [7] J. Yang, J. Cho, S. B. Lee, J. Yoo, H. D. Kim. "An Advanced Stator Winding Insulation Quality Assessment Technique for Inverter-Fed Machines", *IEEE Transactions on Industry Applications*, vol. 44, no. 2, pp. 555–564, 2008.
- [8] T. Boileau, N. Leboeuf, B. Nahid-Mobarakeh, F. Meibody-Tabar: "Synchronous Demodulation of Control Voltages for Stator Interturn Fault Detection in PMSM", *IEEE Transactions on Power Electronics*, vol. 28, no. 12, pp. 5647–5654, 2013.

- [9] A. H. Bonnet and C. Yung, "Increased efficiency versus increased reliability", *IEEE Industry Applications Magazine*, vol.14, no.1, pp. 29-36, 2008.
- [10] V. Lešić, M. Vašak, N. Perić, G. Joksimović, T. M. Wolbank. "Faulttolerant Control of a Wind Turbine with Generator Stator Inter-turn Faults", *Automatika*, vol. 54, no. 1, pp. 89–102, 2013.
- [11] V. Lešić, M. Vašak, G. Stojčić, T. M. Wolbank, "Fault-tolerant Control of Permanent Magnet Synchronous Generator in Wind Turbines", *European Wind Energy Association 2014 Annual Event, EWEA*, pp. 6, 2014.
- [12] L. Y. Pao and K. E. Johnson, "Control of Wind Turbines: Approaches, Challenges, and Recent Developments", *IEEE Control Systems Magazine* vol. 31, no. 2, pp. 44-62, 2011.
- [13] B. A. Ogunnaike, W. Harmon Ray, Process Dynamics, Modeling, and Control, Oxford University Press, ISBN 0-195-09119-1, 1994.
- [14] W. Leonhard, Control of Electrical Drives, Berlin, Germany: Springer Verlag, ISBN 3-540-41820-2, 2001.

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