Influence of Wind Turbine Generator Fault-tolerant Control on Power Production Quality

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Abstract

Renewable energy sources bring to fore the significance of power electronics and corresponding control. The topic of wind turbine fault-tolerant control has emerged as a promising line of research for improving their market competence. The paper presents summarized control of wind turbine converter with a fault-tolerant control extension for generator electromechanical faults, based on a proper modulation of the stator magnetic flux. The modulation also introduces hard periodic oscillations in the stator currents and generator output power. Simulation results obtained with a Matlab-Simplorer co-simulation and detailed power converter model show that DC-link capacitor and corresponding control algorithm act like an energy buffer that suppress the influence of generator stator oscillations on currents passed to the grid and maintain the high quality of power production. Following from the results, the generator and grid side controls are justified to be considered as two independent problems.

1 Introduction

Development of renewable energy sources introduced new challenges in the whole power electronics area, from converter topologies and design, manufacturing solutions to control algorithms. Because of stochastic nature of wind and sun, the task of adequate quality of produced energy has almost entirely become a concern of power converters. Everlasting struggle for trade-off between power quality and converter switching losses has never been so much expressed and the significance of power filters is becoming increasingly important.

After a huge breakthrough and an average growth rate of 26% in last 5 years, wind energy today is a well-tested technology with total world installed capacity of approximately 283 GW by the end of 2012 [1]. Remote locations are best suitable for wind turbine (WT) operation because of low-turbulent and strong winds. This introduces difficult and expensive maintenance procedures and rises availability concerns. Due to turbulent nature of the wind and frequent dynamic changes in the operation, WT generator failure frequency per year is about 10 times greater than of equivalent industrial electrical machines [2].

In order to fulfil demanding requests for high WT availability, a fault-tolerant control (FTC) line of research was set. 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]. In our past work we proposed a fault-tolerant control procedure for rotor-bar fault of a squirrel-cage induction generator (SCIG) [4] and for the stator inter-turn insulation fault that can be applied on both synchronous and asynchronous electrical machines [5]. Observed faults cover about 70% of electrical machine faults [6].

Both FTC procedures enable safe operation of the wind turbine system in the presence of corresponding generator electromechanical fault while harvesting as much energy as possible from the faulty generator. Stator FTC is based on a modulation of magnetic flux in such way that its derivative and corresponding induced voltage in the faulty phase are kept under the maximum allowed value imposed by the fault detection algorithm. Consequently, current that flows through degraded insulation would not cause further fault propagation. The flux modulation requires stator phase currents that differ from their fundamental sine-wave shape as in normal operation. In short, they strengthen and weaken the magnetic field in the machine air-gap depending on the current flux position and thereby cause variations in the output energy that is further on passed to the grid through a three-phase AC/DC/AC, back-to-back converter.

Connection of a wind turbine system to the grid is a complex task. Rapid development of bigger and larger power-scale wind turbines through last 30 years was in fact aggravated by technological limitations of power converters. Today the overall cost of the power electronics is about 7% of the whole wind turbine [7]. Even specially designed doubly-fed induction generator was introduced to overcome this problem. Because of stochastic wind, WT output power exhibits unceasing fluctuations. On the other hand, grid power is required to be of flawless quality with constant frequency and minimum harmonic distortion. The only way to achieve this goal is to fully exploit the power converter possibilities with well-designed control structure.

Focus here is to investigate the impact of proposed FTC on output power quality, and generally the coupling of generator and grid side voltage waveforms. The main issue is that modulation frequency of stator phase currents and therefore the frequency of output power oscillations is twice of the flux rotational speed. This should be handled by the DC-link capacitor and corresponding control system.

The paper is organized as follows. The mathematical model of a WT converter and conventional control algorithms are presented in Section 2. A fault-tolerant approach and control algorithm that enables wind turbine operation under stator insulation fault is briefly described in Section 3. Section 4 focuses on the simulations results and power quality analysis. Conclusions are given in Section 5.

2 Wind turbine converter model and control

Back-to-back converter consists of a rectifier, DC-link and inverter where power can flow in both directions. Both rectifier and inverter part are fully controllable and can operate as one and the other. In wind turbines, they are called grid-side and generator-side converters. In electric drives community, controllable grid-side part is also referred to as 'active rectifier' or 'active front end', while the generator-side is often referred to simply as the 'drive'.

The basic topology is presented in Fig. 1. Variables $\bar{u}_g$ and $\bar{i}_g$ are grid three-phase voltage and current vectors, respectively, $\bar{u}_{g\_PWM}$ is the vector of fundamental PWM voltage components, R_g and L_g are grid resistance and inductance, R_{gf} and L_{gf} are grid filter resistance and inductance. DC-link capacitor is denoted with C_{dc} and $\bar{u}_s$ and $\bar{i}_s$ are generator stator phase voltages and currents, respectively. The converter interconnects two AC electrical systems and allows power flow in both directions. The DC-link and corresponding capacitor filters the DC voltage and also acts as a power buffer that decouples generator from the grid. It enables grid and the generator to operate at different frequencies and attenuates most of the power fluctuations caused by stochastic wind. Grid filter is used to reduce harmonic distortion caused by pulse-width modulation (PWM).

The basic topology from Fig. 1 can be extended with an LCL filter for the grid-side part, or by introducing additional filter or boost DC/DC converter in the DC-link. Also, a multi-level converter is the usual topology for medium and high power applications. Generator-side filter is often used as a voltage derivative filter to extend the life cycle of the stator insulation.

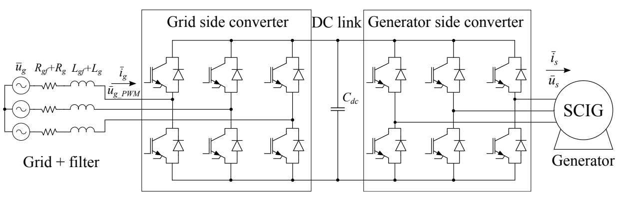

Figure 1. Back to back power converter topology in wind turbines.

From the control viewpoint, basically all the main topologies can be reduced to mathematical model of the converter presented in Fig. 1, which is therefore considered in the sequel. The WT output power can be controlled with the aim of feeding the main grid, stand-alone loads or a micro-grid.

2.1 Generator-side converter

Task of control of the generator-side converter is to ensure adequate generator operating point, demanded by the outer control loop and maximum power point tracking (MPPT). This is mainly referred to the field-oriented control (FOC) or direct torque control (DTC) and their derivatives, which are in charge of balancing between generator torque and wind turbine aerodynamical torque, and of ensuring the optimum power production trajectory tracking [4,5,7].

A very common mathematical model of an AC squirrel-cage induction machine represented in the two-phase (d,q) rotating coordinate system and with rotor flux linkage aligned with the d-axis (rotor flux vector $\bar{\psi}_r$ is set to ψ_{rd}) is described:

$$u_{sd} + \Delta u_{sd} = k_s i_{sd} + L_l \frac{\mathrm{d}i_{sd}}{\mathrm{d}t}, \tag{1}$$

$$u_{sq} + \Delta u_{sq} = R_s i_{sq} + L_l \frac{\mathrm{d}i_{sq}}{\mathrm{d}t}, \tag{2}$$

with $L_l = (L_s - \frac{L_m^2}{L_r})$ and $k_s = (R_s - \frac{L_l}{T_r} + \frac{L_s}{T_r})$. Variables $u_{sd,q}$ are stator phase voltages in (d,q) coordinate system, $i_{sd,q}$ are stator phase currents, L_s, L_r and L_m are stator, rotor and mutual inductances, respectively. Parameters R_s and R_r are stator and rotor resistances and $T_r = \frac{L_r}{R_r}$ is the rotor time constant. Voltages Δu_{sd} and Δu_{sq} are called decoupling or correction voltages:

$$\Delta u_{sd} = \frac{1}{T_r}\frac{L_m^2}{L_r} i_{mr} + \omega_e L_l i_{sq}, \tag{3}$$

$$\Delta u_{sq} = -\omega_e \frac{L_m^2}{L_r} i_{mr} - \omega_e L_l i_{sd}, \tag{4}$$

which ensure that the voltage value in one axis is not affected by the voltage in other. The rotor flux is created by the magnetizing current i_{mr} and ω_e is the frequency of voltage supplied to the stator. A rotor field-oriented control (RFOC) equations from which the AC machine model (1)-(4) is derived are:

$$i_{mr} = \frac{\psi_{rd}}{L_m}, \tag{5}$$

$$i_{sd} = i_{mr} + T_r \frac{\mathrm{d}i_{mr}}{\mathrm{d}t}, \tag{6}$$

$$\omega_{sl} = \omega_e - p\omega_g, \tag{7}$$

$$T_g = \frac{3}{2} p \frac{L_m^2}{L_r} i_{mr} i_{sq} = k_m i_{mr} i_{sq}, \tag{8}$$

where $\omega_{sl} = \frac{i_{sq}}{T_r i_{mr}}$ is the slip speed, ω_g is the mechanical speed, p denotes the number of pole pairs and T_g is the electromagnetic torque. The torque is controlled only by q stator current component because magnetizing current vector i_{mr} is dependent on the time lag T_r and is therefore kept constant in the sub-nominal speed operating region. Whole control structure

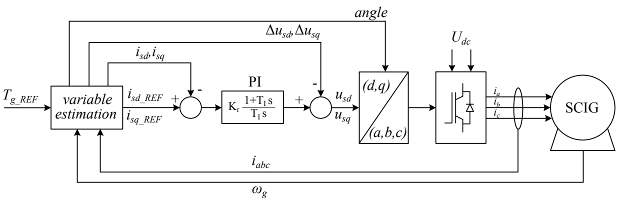

Figure 2. Field-oriented control loop.

is shown in Fig. 2. If a generator-side filter is used, the filter inductance is simply added to L_s and used in (1)-(4).

Converter and PWM delays are commonly modeled as:

$$G_d = \frac{1}{1+1.5T_s \cdot s}, \tag{9}$$

where T_s is controller sample time. Machine model given by (1) and (2) with delay (9) is suitable for proportional-integral (PI) controller design with *magnitude optimum* approach. PI integral time constants are therefore $T_{Id} = L_l/k_s$ for d-current, $T_{Iq} = L_l/R_s$ for q-current and the gain $K_{rd,q} = L_l/3T_s$ for both d and q currents. For more information about machine modeling and FOC please refer to [8].

2.2 Grid-side converter

From the control aspect of grid-side converter, there are two main issues in WT power systems. First is to maintain the constant level of DC-link voltage, which always tends to change due to variable generator power production. Second is control of the AC power injected to the grid by ensuring desired phase and amplitude of grid-side filter currents. As a consequence, more or less active or reactive power is transferred from the generator to the grid. Usual way to achieve desired AC power and DC-link voltage control is with so-called voltage-oriented control (VOC), or direct-power control (DPC), similar to the generator control [9].

With an analogy to FOC, variables in VOC are also transferred to (d,q) coordinate system and mathematical model of the grid and corresponding filter are given by (R_g and L_g are negligible):

$$u_{d\_PWM} + \Delta u_{gd} = R_{gf} i_{gd} + L_{gf}\frac{\mathrm{d}i_{gd}}{\mathrm{d}t}, \tag{10}$$

$$u_{q\_PWM} + \Delta u_{gq} = R_{gf} i_{gq} + L_{gf}\frac{\mathrm{d}i_{gq}}{\mathrm{d}t}, \tag{11}$$

where u_{d,q_PWM} are fundamental components of voltage supplied by PWM, $u_{gd,q}$ and $i_{gd,q}$ are grid voltages and currents, respectively. Decoupling voltages are:

$$\Delta u_{gd} = -\omega L_{gf} i_{gq} - u_{gd}, \tag{12}$$

$$\Delta u_{gq} = \omega L_{gf} i_{gd} - u_{gq}, \tag{13}$$

where u_{gq} is set to zero value by phase-locked loop (PLL) control.

Controller design procedure is performed in the same as in FOC, by applying the magnitude optimum rules on (9),(10) and (11). Parameters of PIs in d and q axes are therefore chosen:

$$T_{Iid,q} = \frac{L_{gf}}{R_{gf}}, \qquad K_{rid,q} = \frac{L_{gf}}{3T_s}. \tag{14}$$

With this approach, both grid current control loops can be approximated by first-order lag system:

$$G_{ci} \approx \frac{1}{1+3T_s \cdot s}. \tag{15}$$

2.2.1 DC-link voltage control

Control of DC-link voltage and current control loop are implemented in cascaded control: a slower outer DC voltage loop and a fast internal current loop. The voltage value is therefore maintained by the AC current and power balancing between generator and the grid. If more power is passed to the grid than produced by the generator the DC-link voltage value is falling, and vice versa. Since the two loops operate at different dynamics they can be considered decoupled.

Power balance condition between generator power $P_{generator}$ and grid power P_{grid} is defined with:

$$P_{dc} = P_{generator} - P_{grid}, \tag{16}$$

and by substituting the relation for capacitor power P_{dc} the condition takes the form suitable for obtaining the transfer function:

$$\frac{\mathrm{d}u_{dc}}{\mathrm{d}t} = \frac{1}{u_{dc}C_{dc}} P_{generator} - \frac{1}{u_{dc}C_{dc}} P_{grid}. \tag{17}$$

By performing linearization around $u_{dc} = U_{dc}$, $P_{generator} = P_{0,generator}$ and $P_{grid} = P_{0,grid}$, where the generator and grid powers are considered balanced and equal $P_{0,generator} = P_{0,grid}$ in steady-state operation, the DC-link voltage transfer function is obtained:

$$\frac{\Delta u_{dc}(s)}{\Delta P_{grid}(s)} = -\frac{1}{sU_{dc}C_{dc}}, \tag{18}$$

where $P_{grid} = \frac{3}{2} U_{gd} i_{gd}$ (assuming u_{gq} is set to zero by PLL and $u_{gd} = U_{gd}$ is constant grid voltage). With (15) and (18), parameters of PI controller are chosen by following the *symmetrical*

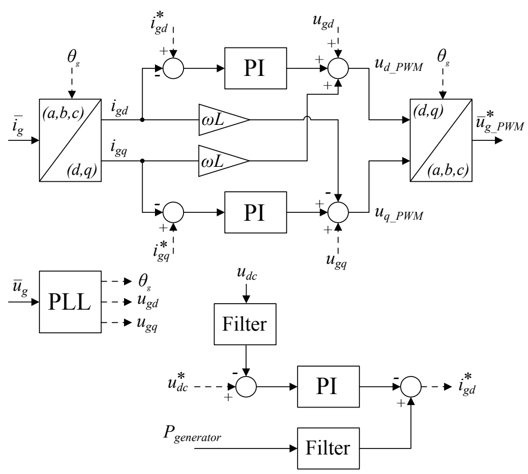

Figure 3. Basic voltage-oriented control loop.

optimum approach:

$$T_{I,dc} = 12T_s, \qquad K_{r,dc} = \frac{U_{dc}C_{dc}}{9U_{gd}T_s}. \tag{19}$$

A complete voltage-oriented control block scheme, including PLL, current control and DC-link control, is presented in Fig. 3. Dashed arrows are VOC internal variables. Optional active and reactive power control loops with corresponding PI controllers can also be included to extend the basic control structure. For the case of investigation of FTC influence on power quality, VOC is set to generate only active power with i_{gd} while reactive power generation is excluded and $i_{gq} = 0$ A. Instantaneous generator output power value is used as a feed-forward signal. Active generator power and DC-link voltage filters in Fig. 3 are used to lower the influence of generator power fluctuations. For more information about grid-side converter modeling and VOC please refer to [10].

3 Fault-tolerant control

Some of the most common causes of stator insulation faults are moisture in the insulation, winding overheating, or vibrations. Modern voltage-source inverters also introduce additional voltage stress on the inter-turn insulation caused by the steep-fronted voltage surge [6].

In the three-phase coordinate system (a,b,c) stator voltage equation is defined with:

$$u_{sx} = i_{sx}R_s + \frac{d\psi_{sx}}{dt} \approx \frac{d\psi_{sx}}{dt}, \tag{20}$$

where x denotes one of the phases. 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 [11], 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:

$$\left|\frac{d\psi_{sx}}{dt}\right| \leq K. \tag{21}$$

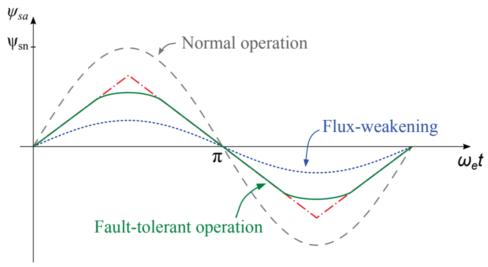

Figure 4. Stator flux waveforms for healthy and faulty machine.

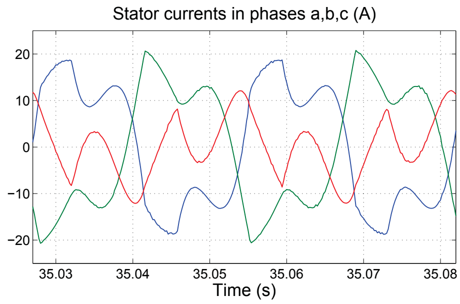

Figure 5. Generator stator currents with applied fault-tolerant control.

The value K is determined based on fault identification procedure through machine fault monitoring and characterization techniques [11,12]. Following from (20) this restricts the induced voltage in faulted turns and, in the case of inter-turn short circuit, also the circulating currents responsible for local overheating. Generally, the stator flux is considered sinewave (in the fundamental-wave approaches, such as FOC), denoted as 'Normal operation' in Fig. 4. In order to stop the fault from spreading, the obvious approach is to lower the amplitude of magnetic flux to achieve some safe value. This approach is in fact a flux-weakening method, commonly applied to electrical machines when operating above the rated speed ('Flux-weakening' in Fig. 4). However, this degrades the power production considerably and unnecessary.

In [5] we showed that about 30% more power is extracted from a faulty generator if a proper flux modulation is imposed, rather than simple flux reduction. This is achieved for the case when flux derivative is aimed to reach exactly the imposed value of K restriction, i.e., for the case of triangular waveform of the flux with included generator restrictions (saturation, slip etc.). The targeted flux waveform is denoted as 'Fault-tolerant operation' with full line in Fig. 4.

Whole approach and the step-by-step algorithm is elaborated to details in [5] and goes out of the scope of this paper. Here, the output power quality of WT with faulty generator and applied FTC with the described flux modulation is observed. Currents that shape the flux in triangular waveform and at the same time maintain desired smooth torque and speed are shown in Fig. 5. The harmonic composition of the currents is very undesirable and by far unacceptable for the strict grid regulations. However, the currents are rectified and inverted back by the grid-side converter and filtered before connection to the grid. The analysis of grid currents is performed in the next section.

4 Simulations and results

Whole control structure (Fig. 6), including FOC, FTC, VOC and wind turbine controllers, is implemented in the Matlab/Simulink 2010b environment, as well as wind turbine aerodynamics [4,5,7]. Electrical system, grid, AC/DC/AC converter, PWMs and the generator are implemented in the Simplorer 7.0, a professional software for power electronics created by Ansys Inc. and widely used in industry. The two simulation tools are connected with real-time communication using SIM2SIM Simplorer link interface and Simulink

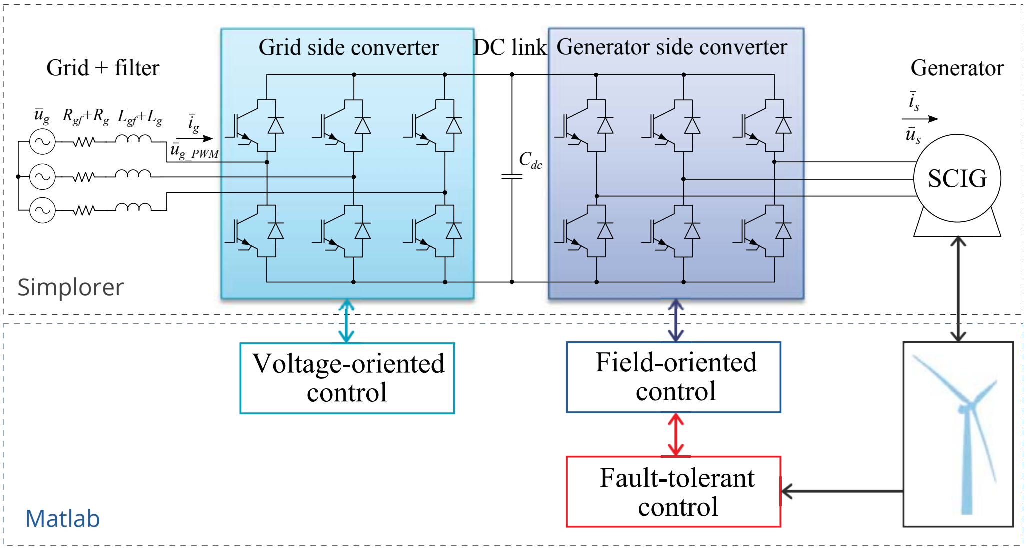

Figure 6. Simulation scheme with denoted Simplorer and Matlab part.

Table 1. Simulation parameters.

Parameter	Value	Parameter	Value
L_s	0.112 H	L_{gf}	20 mH
L_r	0.112 H	R_{gf}	0.2 Ω
L_m	0.11 H	C_{dc}	500 μF
R_s	0.3304 Ω	U_{dc}	700 V
R_r	0.2334 Ω	U_g	$230\sqrt{2}$ V
T_r	0.48 s	$K_{r,PLL}$	2
p	1	$T_{I,PLL}$	0.01 s
K_r	6.82	K_{ri}	33.33
T_{Id}	0.0074 s	T_{Ii}	0.1 s
T_{Iq}	0.0125 s	$K_{r,dc}$	0.5978
J	0.5666 kgm^2	$T_{I,dc}$	0.0024 s

S-function. The co-simulation is suitable for complex control algorithms and detailed power switches (IGBTs) analysis. In addition, it can be easily modified for different levels of complexity for power switches (such as advanced IGBT or thermal dynamics) or control methods (PIs, optimal control, advanced estimation techniques etc.).

Generator used in simulations is a 5.5 kW SCIG and 700 kW WT aerodynamics are down-scaled to match the machine torque. Simulation parameters are given in Table 1. Power converter switches are equivalent-line-modeled with forward voltage of 0.8 V, 1 mΩ bulk resistance and 100 kΩ reverse resistance. Diodes are also equivalent-line-modelled with forward voltage of 1.2 V, 1 mΩ bulk resistance and 100 kΩ reverse resistance. Sample time used in Simplorer simulation is $T_{sp} = 2 \cdot 10^{-6}$ s and in Matlab simulation (sample time for controllers) is $T_s = 2 \cdot 10^{-4}$ s. Frequency of the PWM carrier voltage (switching frequency) is chosen $f_s = 1$ kHz. Normal wind turbine operation is simulated from 0 s to 0.6 s simulation time and the FTC algorithm is applied afterwards.

Figure 7 shows mechanical and electrical powers of the generator (before scaling) in normal operation. Mechanical power is obtained with $T_g \cdot \omega_g$ and electrical with $\frac{3}{2}(u_{sd}i_{sd} + u_{sq}i_{sq})$. Since an ideal, fundamental-wave generator model is used in simulations, difference between mechanical and electrical power is caused only by stator and rotor heat losses. Powers shown in figures are presented with positive signs. This is a characteristic for wind turbine system viewpoint. Variables related to the grid and electric machine are presented with negative signs for power consumption and positive for power generation.

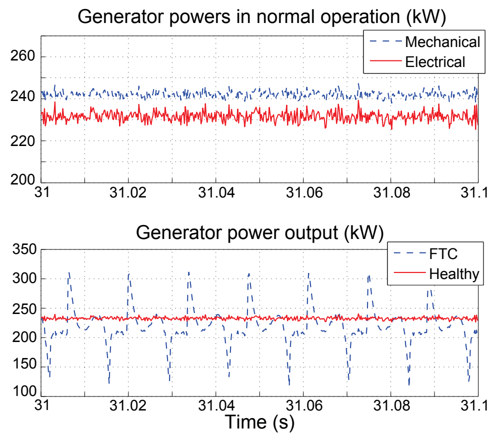

Figure 7. Generator input power and output power for for healthy and faulty conditions.

Figure 7 also shows generator power production (electrical power) for normal and FTC applied operation. The mechanical power is kept at the same value by FTC as in normal operation under the same conditions. However, output power fluctuation caused by FTC is evident. Period of oscillations correspond to doubled frequency of the machine flux ($\omega_e = 229$ rad/s for simulated operating point) and corresponds to the period of performed flux modulation.

Influence of FTC algorithm on grid converter is shown in figures 8 and 9. Since DC-link is acting also as a power buffer between the generator and the grid, it is expected that FTC and power fluctuations are greatly reflected on it. However, it may be observed that differences in currents in Fig. 9 are barely visible and FTC has only a small influence on power production quality.

Harmonic spectrum is presented in Fig. 10. The quality of output power is often expressed by total harmonic distortion (THD) factor. The THD factor for grid currents in normal operation with inductive filter and VOC is 2.51 %. For the case of faulty generator conditions and applied FTC, the THD factor is 2.95 %. This occurs due to variations in DC-link voltage.

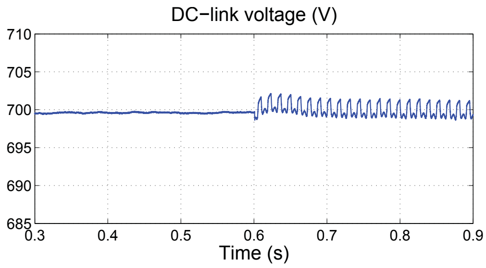

Figure 8. DC-link voltage for healthy and faulty generator conditions.

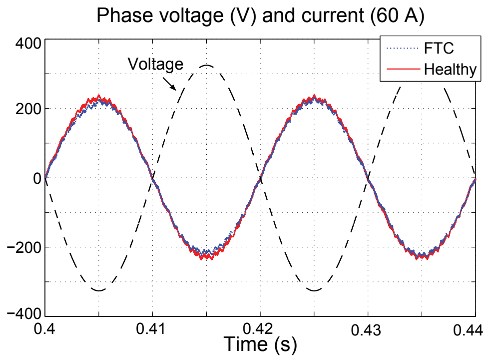

Figure 9. Power injected to the grid for healthy and faulty generator conditions. Current measurement is scaled by factor 60 and shown in the 0.4 ÷ 0.44 time scale.

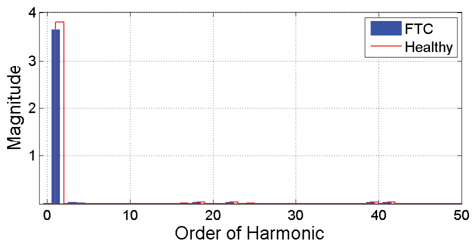

Figure 10. Harmonics spectrum of grid currents for healthy and faulty generator conditions.

5 Conclusions

Generator insulation faults can be stopped from spreading with proper modulation of stator magnetic flux and safe operation in the presence of the fault can be achieved. Wind turbine generator is fully decoupled from the grid by a back-to-back converter with own separate control of grid-side and generator-side parts. Because of the decoupling, the power variations caused by the fault-tolerant control are only slightly reflected on the power passed to the grid in the terms of barely noticeable increase of THD. Simulation results show that negative phenomena caused by the fault-tolerant control are almost entirely attenuated by the DC-link and high quality of output power is maintained. Furthermore, results show that back-to-back power converter gives outstanding possibilities and WTs are ready to adopt new and more complex control algorithms.

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