# Dually Fed Permanent Magnet Synchronous Generator Condition Monitoring Using Stator Current

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**Summary**

As the number of installed wind turbines steadily increase in the world, better and more efficient maintenance procedures are needed. Condition monitoring is one method which increases the efficiency of maintenance as it provides information on the current state of the turbine, which in turn determines when and what type of maintenance is needed. This paper presents an extension of a previously derived method that is able to detect generator winding faults as well as faults in the mechanical part of the drive train. The method is here applied on a setup consisting of a generator with dual windings connected to two completely isolated, individual controlled inverters. Furthermore, the investigated method includes the use of an observer system for estimating the generator rotor position and generator speed, extending the original method to a sensorless operation. The observer system consists of a flux observer and a phase looked loop. The simulated model is based on data from a direct driven wind turbine generator in the MW range. Since the machine in this paper is dually fed, faults in the electrical system are more easily detected by comparing the outputs from both converters, which under normal conditions are identical. With the knowledge on how the observer is constructed and how it reacts to parameter errors, it is shown that the resulting effects of the phase looked loop during an electrical fault can be utilized when determining in which part of the generator the fault has accorded, without the need to look at the two different outputs individually. It is also shown that mechanical imbalances are detectable but nothing is gained by having a system consisting of two sets of separated electrical windings compared to a system with a single electrical winding. Differentiating between electrical and mechanical faults is possible by observing the frequency content in the monitored quantities, as mechanical faults creates and oscillation at the generators mechanical rotating frequency where electrical faults frequency content is a multiple of the generators electrical frequency.

**Introduction**

Wind power production is steadily increasing in the world, where the first generation turbines had a fixed speed and was directly connected to the grid. Then the variable speed wind turbines became the more dominant type because of it offers less mechanical stress in the turbine. However, there is no rigid standard topology for wind turbines. One can choose between different types of generators such as electrically excited synchronous machine, permanent magnet synchronous machine, induction machine or the doubly fed induction machine. Additionally, direct drive or a gearbox can be used. The most common turbine today is the doubly fed induction machine with a gearbox [1]. This setup uses power converters connected to the machines rotor circuit which enables a limited variable speed range, where the limited range is sufficient for wind turbine applications. However, this setup has some drawbacks compared to a wind turbine using a full power converter. The biggest advantage of using a full power converter is the grid code compliance. By using full power converters connected back-to-back the turbine effectively becomes decoupled from the grid, enabling full control of the turbine regardless of grid conditions. Selecting a direct drive turbine removes the potential risk of gearbox failure, which is a large and heavy component and costly to exchange if it fails. Gearboxes are one of the more common components to fail in a wind turbine [2]. If the gearbox is removed there is one less component that can fail; on the other hand, for turbines with direct drive the generator fail rate is higher compared to geared turbines [2]. This motivates the need for efficient fault identification and health monitoring.

By utilizing the measurement system a full power converter provide, online analysis of the drive train's health status can be performed. This paper presents an extension of the method developed in [3] for fault detection to be used on a simulation model of a dually fed generator consisting of two separated sets of windings connected to two isolated converters. The possibility of utilizing the proposed method in a sensorless environment, where an observer system is used to estimate the generator rotor position and generator speed, is investigated. The observer system consists of a flux observer and a phase locked loop (PLL). The system modeled is based on data from a 4.1 MW direct drive permanent magnet machine wind turbine, designed for offshore applications.

**Drive train models**

The modeled generator is a three phase machine with surface mounted permanent magnets that can be represented by the following equations:

$$v_a = R_s i_a + \frac{d\lambda_a}{dt}, \qquad v_b = R_s i_b + \frac{d\lambda_b}{dt}, \qquad v_c = R_s i_c + \frac{d\lambda_c}{dt} \tag{1}$$

$$\lambda_a = \left(L_{s_\lambda} + L_{s_m}\right) i_a - \frac{L_{s_m}}{2}(i_b + i_c) + \omega_{el}\psi_{pm}\cos(\omega_{el} t) \tag{2}$$

$$\lambda_b = \left(L_{s_\lambda} + L_{s_m}\right) i_b - \frac{L_{s_m}}{2}(i_a + i_c) + \omega_{el}\psi_{pm}\cos(\omega_{el} t - \frac{2\pi}{3}) \tag{3}$$

$$\lambda_c = \left(L_{s_\lambda} + L_{s_m}\right) i_c - \frac{L_{s_m}}{2}(i_a + i_b) + \omega_{el}\psi_{pm}\cos(\omega_{el} t + \frac{2\pi}{3}) \tag{4}$$

where $v_i$ is phase voltage, $R_s$ is the stator resistance, $i_i$ is phase current, $\lambda_i$ is flux linkage , $L_{s_\lambda}$ is the stator leakage inductance, $L_{s_m}$ is the stator magnetizing inductance, $\omega_{el}$ is the electrical rotational speed of the generator and $\psi_{pm}$ is the flux linking from the permanent magnets. As the modeled generator has two sets of insolated windings, there is an additional identical set of above voltage equations, i.e. the generator is in total supplied with six voltages while the rotor position and rotor speed are equal in all equations.

The two parts of the modeled generator are individually controlled by inverters governed by cascade connected controllers. The controllers are implemented in a dq- coordinate system aligned with the rotor magnetic field. As such the generator model presented above is transformed in to an equivalent dq-model in order to derive the current controller. An open loop torque controller calculates the reference current. The current error (difference between reference current and actual current) is feed to the discrete current controllers. The current controller calculates the voltages references to the generator, see Figure 1. The torque reference is a lookup table with the generator speed as input.

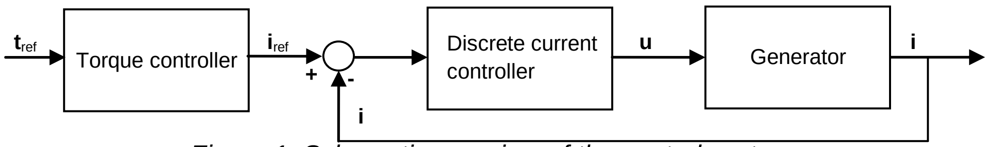


*Figure 1. Schematic overview of the control system*

For the a permanent magnet the machine with a known rotor position the generator torque can be calculated as

$$T_{pmsm} = \frac{3}{2} np\, i_q \psi_{pm} \tag{5}$$

where $np$ is the number of pole pairs and $i_q$ is the q-current, which represents the active current. The $i_q$ reference to be used in the controller is calculated using equation (5), and as this paper only considers the machine side of the back-to-back topology the reactive current $i_d$ reference is set to 0. Reactive power on the machine side is used for field weakening which is not utilized in this paper. The actual machine torque is calculated using equation (5), where the actual three phase generator currents are used to acquire the actual $i_q$.

The mechanical drive train is modeled as a twomass model without self damping, defined using the following equations:

$$J_{turbine}\frac{d\omega_{rotor}}{dt} = T_{load} - K_s\alpha - K_d\frac{d\alpha}{dt} - B\omega_{turbine} \tag{6}$$

$$J_{generator}\frac{d\omega_{generator}}{dt} = K_s\alpha + K_d\frac{d\alpha}{dt} - B\omega_{generator} - T_{generator} \tag{7}$$

$$\frac{d\alpha}{dt} = \omega_{turbine} - \omega_{generator} \quad (8)$$

$$\Theta_{generator} = \int \omega_{generator} \quad (9)$$

where $J$ is the inertia, $\omega$ denotes the mechanical rotational speed, $T$ is the torque, $K_s$ is the shaft stiffness, $K_d$ is the self damping constant, $B$ is friction constant, $\alpha$ is the shaft displacement angle in radians and $\Theta_{generator}$ is the generators rotor mechanical position in radians. As seen from the equations above the shared torque of the two inertias are $K_s\alpha + K_d\frac{d\alpha}{dt}$. $T_{wind}$ acts as the accelerating torque and $T_{generator}$ acts as the breaking torque. In the model used in this paper, the mechanical shaft has a high stiffness but is poorly damped. If the shaft is excited by a torque step, the two masses will cause a misalignment between the two ends of the shaft, as the two masses have different speeds initially. As the shaft stiffness is high, the speed difference between the two masses will be small. Since the shaft has poor damping any speed difference in the two masses will result in an oscillation in the speed in one of the masses compared to the other, before reaching a steady state. Figure 2 shows a schematic overview of the modeled drive train, with the information exchange between each part of the models.

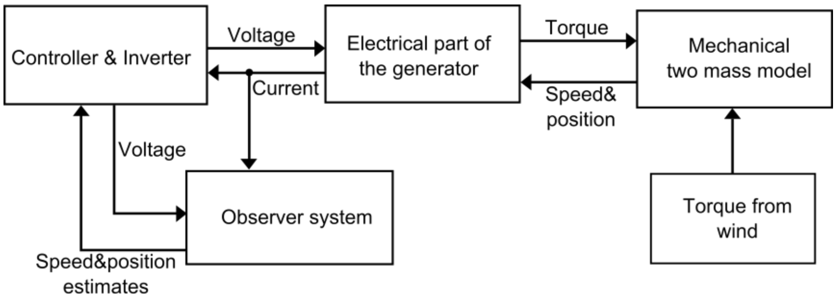


*Figure 2. Schematic overview of the drive train setup*

**Methods used**

As explained in [3], by using the steady-state torque equation for a non-salient pole synchronous machine it can be shown that

$$T_{generator} \propto \frac{\omega_{generator}}{X_a} \quad (10)$$

where $\omega$ is the mechanical speed and $X_a$ is the synchronous reactance. Since equation (10) is derived during steady state conditions, and therefore utilizes that the load, load angle and flux in the machine are constant.

From this relation it is possible to define a quantity $C$ to be uses for monitoring the drive train condition in real time as

$$C = \frac{T_{generator}}{\omega_{mechanical}} \quad (11)$$

The generator torque can be easily obtained through calculation using equation (5) and the mechanical speed of a wind turbine is typically measured. The speed can also be estimated, which removes the dependence of speed sensors. The speed and rotor position can be estimated using an observer system. The observer system consists of a flux observer and a PLL. The PLL consists of a PI-controller that uses an estimated rotor position error as input to calculate an estimated rotor speed. From this estimated speed the rotor position can be estimated by integration. The rotor position error is defined as the difference between rotor position calculated from the flux observer and the estimated rotor position from the phase locked loop. The rotor position calculated from the flux observer utilizes both αβ- and dq-currents. The flux observer is governed by the following equations:

$$\underline{\lambda_{dq}} = L_d i_d + jL_q i_q + \Psi_{pm} \quad (12)$$

$$\underline{\lambda_{\alpha\beta}} = \left(L_d i_d + jL_q i_q + \Psi_{pm}\right)e^{j\theta_{rotor}} \tag{13}$$

where $\theta_{rotor}$ is the electrical rotor position in radians. As the generator in this paper has surface mounted magnets the $L_d$ and $L_q$are equal, i.e. $L_d = L_q = L_{s_{dq}}$ the above equations can be rewritten as:

$$\underline{\lambda_{\alpha\beta}} = L_{s_{dq}}\underline{i_{\alpha\beta}} + \Psi_{pm}e^{j\theta_{rotor}} \tag{14}$$

$$\angle\left(\underline{\lambda_{\alpha\beta}} - L_{s_{dq}}\underline{i_{\alpha\beta}}\right) = \angle\Psi_{pm}e^{j\theta_{rotor}} \tag{15}$$

$$\hat{\theta}_{rotor} = \tan^{-1}\frac{\lambda_\beta - L_{s_{dq}}i_\beta}{\lambda_\alpha - L_{s_{dq}}i_\alpha}. \tag{16}$$

where $\hat{\theta}_{rotor}$ is the estimated rotor position. $\lambda_{\alpha\beta}$ is obtain from

$$\underline{V_{\alpha\beta}} = R_s\underline{i_{\alpha\beta}} + \frac{d\underline{\lambda_{\alpha\beta}}}{dt} \tag{16}$$

$$\underline{\lambda_{\alpha\beta}} = \int(\underline{V_{\alpha\beta}} - R_s\underline{i_{\alpha\beta}})\,dt. \tag{17}$$

This estimation method requires true current and voltage values to give the true value. For a small drift in either current of voltage will cause integrator problems. In [4] there is a proposed drift compensator which uses the phase locked loop calculated rotor position to estimate $\underline{\lambda_{\alpha\beta}}$ by using equation (13), stated again for clarification.

$$\underline{\hat{\lambda}_{\alpha\beta}} = \left(L_d\hat{\imath}_d + jL_q\hat{\imath}_q + \Psi_{pm}\right)e^{j\widehat{\theta_{rotor}}} \tag{18}$$

where $\hat{\imath}_d$ and $\hat{\imath}_q$ are calculated using $\hat{\theta}_{rotor}$ as the transformation angle. The estimated flux is then compared with the flux estimated through the observer. The difference is the error sent to the phase locked loop and the resulting output is fed back to the original calculation of the flux, see Figure 3. This forces the two calculated rotor fluxes to converge into an equal value. The phase locked loop calculated rotor position is then used in the generators current controller and when calculating the quantity $C$.

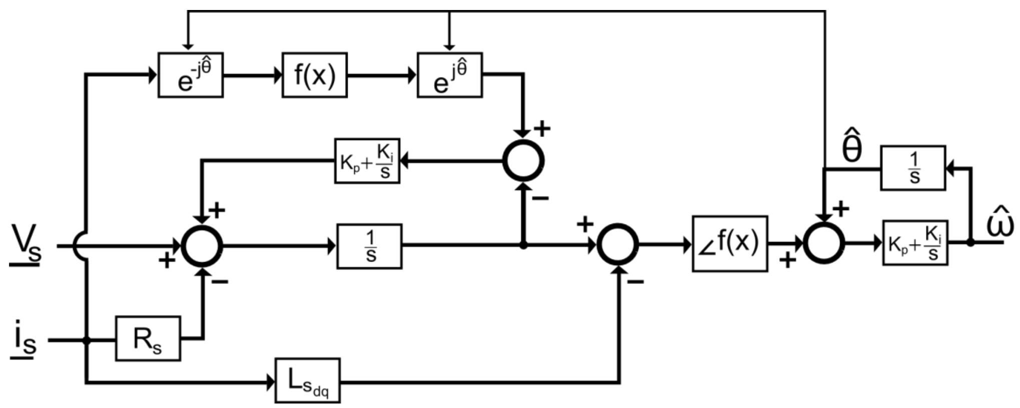


*Figure 3. Schematic sketch of the observer system.*

During steady state the observer system works properly and the estimated and actual speed are equal; however, during dynamic changes the estimated speed can start to oscillate due to the much shorter time constant of the electrical system compared to the mechanical time constant. The oscillations can be reduced by filtering the estimated rotor speed [5], but since this paper is only considering constant load and speed, a method of reducing any oscillations will not be discussed.

**Simulation results**

In this section, the observability of small interwinding faults and mechanical faults by monitoring the defined quantity $C$ is presented. The response in $C$ from identical electrical faults using actual quantities and estimated quantities will be compared. The response from different severness, as well as faults in different phases will be presented. As the modeled system uses two independent electrical systems, the benefit of monitoring the difference between the quantities $C$ from each system is also presented.

The simulations were performed using Matlab Simulink using model parameters that cannot be disclosed due to confidentiality issues. However, usable generic parameters can be found in [6]. The generator is modeled using a state space representation, the controllers are programmed in C and are in the discrete time domain. The torque calculation and the observer system are in continuous time using the mathematical block in Simulink, as shown in Figure 3.

The simulations were performed with a constant load torque, $T_{load}$, at a speed close to rated speed. An electrical interwinding fault in phase *a* in the machine is simulated by a stepwise reduction of the inductance value. A mechanical imbalance is modeled as a sinusoidal torque variation in the load torque at the turbine's mechanical rotation frequency, during a mechanical fault the total load torque is described by equation (19).

$$T_{load} = T_{wind} + T_{fault} \sin \Theta_{generator} \tag{19}$$

An interwinding fault changes the electrical impedance of the affected stator's phase inductance, which alters the current, the magnetic flux and torque contribution from that phase. Figure 4 shows the simulated response in $C$ when there is a fault in one phase, in only one of the two set of windings, by 0.1% while using actual rotor position and actual speed. The reduction makes the electrical system unbalanced, resulting in a negative sequence component superimposed on the original criteria. The characteristic of a negative sequence is its frequency at twice that of the fundamental frequency. The negative sequence component becomes visible in the quantity $C$ after the fault, indicating that there is an asymmetry in the generator. The small change in inductance only imposes a very small variation in the generator torque, too small for affecting the speed and as a result the impact in $C$ is very small, as seen in Figure 4 where the amplitude of the oscillation is about $2 * 10^{-5}$ per units compared to the pre-fault value.

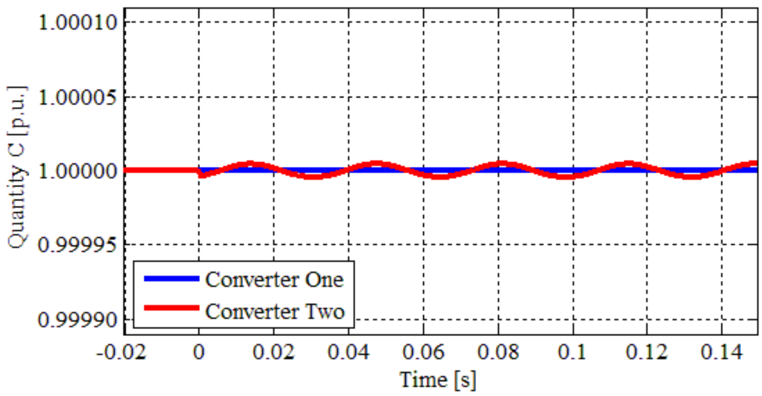


*Figure 4.The quantity $C$ when using actual rotor position and speed.*

Using the observer system to estimate the speed during a simulation with an identical setup gives a larger amplitude variation in $C$ as well as a small positive error offset in the oscillation. The difference is due to the parameter sensitivity of the phase locked loop. It is still using the initial values of the inductances when calculating the generator speed and as the inductances change the phase looked loop will thus perform a calculation error. The phase looked loop used in this paper is not designed to operate during unbalanced conditions and cannot cope with the negative sequence oscillation in currents. The offset and the amplitude changes when using a phase looked loop, show in Figure 5. The amplitude changes due to the error in estimating the speed, as the estimated speed also oscillates and amplifies the faults effect on the quantity $C$.

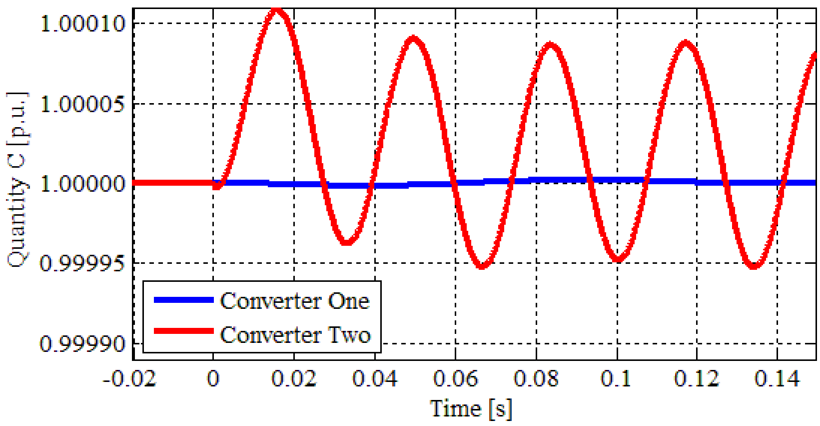


*Figure 5.The quantity $C$ using estimated rotor position and speed.*

The amplitude of the oscillations is still very small in comparison to pre-change value of $C$, therefore it is more efficient to monitor the difference between the two quantities $C$ from the different converters, see Figure 6. The simulation shows that in a noise free environment any difference between the two parts is detectable.

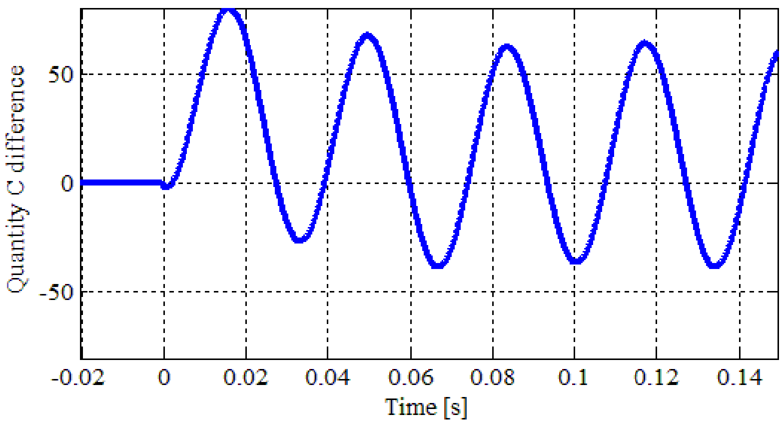


*Figure 6. The absolute difference between the two quantities $C$*

If there are identical faults on both sets of windings, the difference method cannot be utilized as identical faults impose identical variations in the quantity $C$, both in phase and amplitude. However, the probability of having identical faults on both sets of windings at the same time is small, making the strategy of monitoring the difference in both quantities a useful tool for identifying electrical faults in the generator. The amount of inductance lost affects the amplitude of the oscillation whereas which of the generator's phase is altered affects the oscillations phase shift in $C$. These effects are shown in Figure 7 and 8, where in Figure 7 the inductance is reduced twice as much for one set of windings but both is applied the same corresponding generator phase in the two sets of windings. In Figure 8 the magnitude of the inductance loss is identical for both sets of winding but applied to different corresponding generator phases.

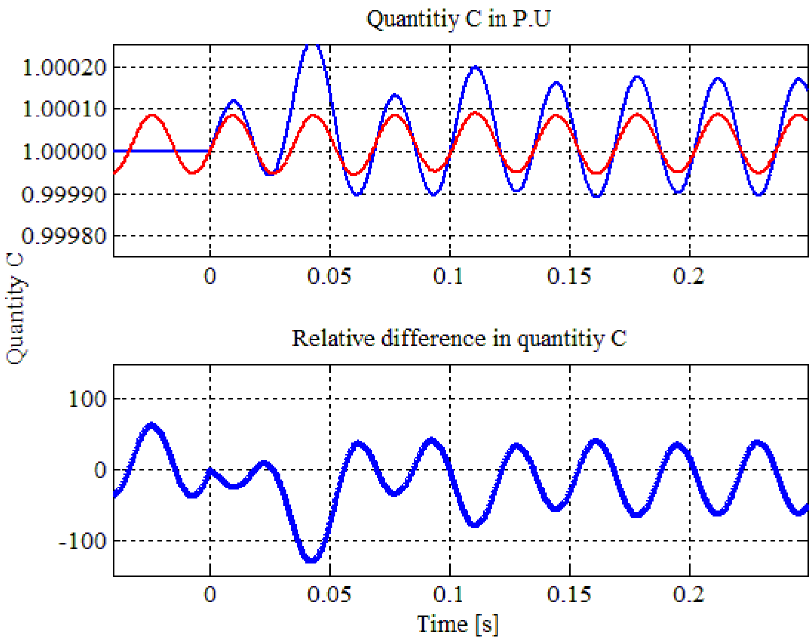


*Figure 7. Different amount of inductance is lost but on same corresponding generator phase.*

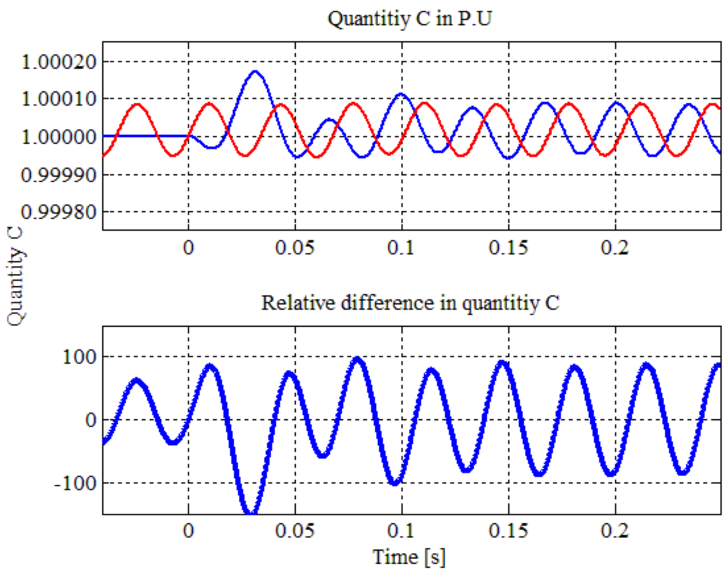


*Figure 8. Identical amount of inductance lost but in different corresponding generator phases.*

The offset created by the phase locked loop can be utilized when looking at the difference in order to identify which set of windings is faulty. The difference is defined as

$$C_{difference} = C_{winding1} - C_{winding2}. \tag{19}$$

Both quantities have a positive offset for a reduction in induction. By looking at the sign of the average value of the difference the faulty winding can be identified, eliminating the need to monitor the quantities individually for identifying electrical faults. This is shown in Figure 9 where the difference average first is positive but then becomes negative as the oscillations of quantity $C$ for the second winding is larger (due to a larger loss of inductance) and it is thus the dominating quantity.

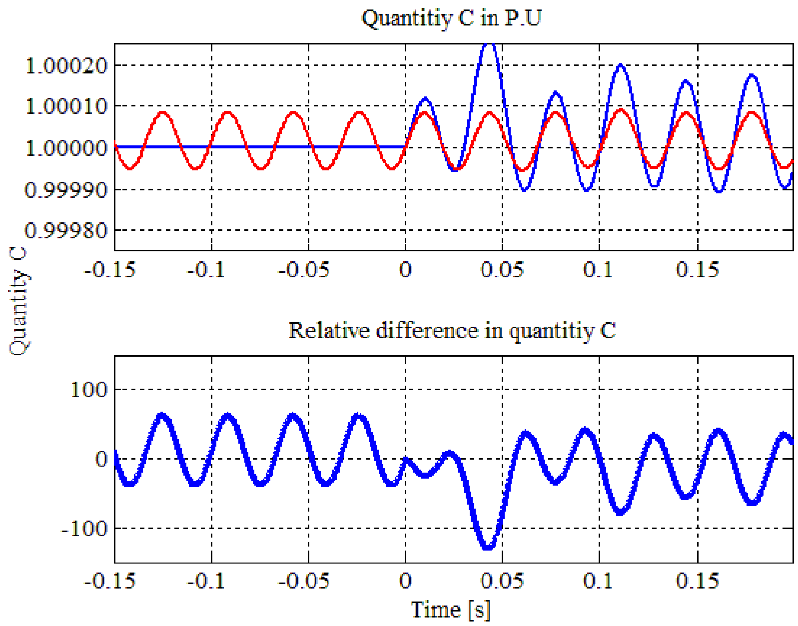


*Figure 9.The offset in difference can be used to determine which part of generator is affected.*

Mechanical unbalances can also be detected by looking at the quantity $C$. An unbalanced mechanical fault will also create an oscillation in $C$ but at the generators mechanical rotating frequency. This mechanical unbalance is visible in the quantities $C$ from both of electrical systems, were both are equally affected as they share the mechanical system and the observer system is independent of the mechanical properties as is only uses electrical quantities. For these types of faults the advantage of having two independent quantities cannot be utilized in a similar manner as for the electrical faults. Figure 10 shows both quantities but as they are identical they completely overlap and appear to be only one single line. However, having two systems provides a method of verification and increase reliability and robustness of the detection of mechanical faults.

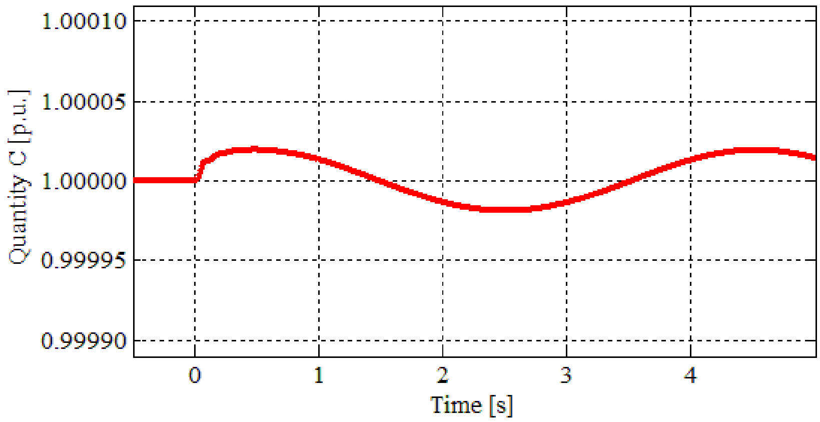


*Figure 10. The impact of a mechanical fault on both quantities.*

**Conclusions**

In this paper an extension of the method proposed in [3] to be in sensorless mode using an observer system consisting of a flux observer and a PLL. The method was then applied to a dually fed system model, where the electrical parts are governed individually. It has been shown that monitoring the difference between the methods defined quantity $C\ (= T_{generator}/\omega_{mechanical})$ generated from the two individual electrical systems can be a useful tool for detecting electrical faults. With the knowledge on how the observer system is designed and is affected by parameter errors, it can beneficially be utilized in the analysis of the fault response in the quantity $C$. Having a dually fed system does not provide any additional information to this method for detecting mechanical faults compared to a singly fed system.

**Future work**

Further investigate if the proposed method can be a viable tool to detect other types of faults and if it is possible to use in real-time operation during dynamic behavior of the system. The simulated results will be compared to laboratory results where measurement noises are present, in order for verifying the accuracy of the method during sensorless operation. If proven successful in the lab, the method will be tested using measurements from a real turbine installation.

**Acknowledgements**

The authors would like to acknowledge Swedish Energy Agency and Swedish Wind Power Technology Centre their aid with funding and the authors would also like to acknowledge ABB, General Electric and Göteborg Energi for their aid with funding and for providing data used the models.

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