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Dynamic load on a Francis turbine runner from simulations based on measurements

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Abstract. The frequency of the Nordic power grid has become more volatile during recent years. This gives rise to two effects in synchronous machines. Firstly, as grid frequency changes the rotational speed of synchronous machines must change likewise. Secondly, the Nordic grid uses speed droop operation extensively as the primary governing; hence the power produced is a function of the grid frequency. These two coupled effects will lead to the runner and axle on synchronous machines having to cope with a varying level of torque. Even if the unit is supposedly operating at steady state via a fixed set point for the production, the influence of the varying grid frequency is that the torque is not steady at all. Recent years' new high head Francis runners in Norway have shown a tendency towards experiencing fatigue to a greater extent than what seem to be the case for new runners decades ago. Leading to this paper, measurements have been made of the rotational speed; generator power; main servo motor position and grid frequency at a Francis turbine unit. Based on these measurements simulations that include the hydraulic domain have then been performed. From these simulation results a property is constructed which is intended as a qualitative measure of the material stresses induced in the rotating masses of the unit, and is representative of the dynamical loads on the material of the rotating masses. The work is a part of a longer term goal, namely identifying the stress oscillations in a Francis turbine runner operating at speed of rotation oscillating because of grid frequency variations.

1. Introduction

The state of the electric energy system in the Nordic grid is in constant change, and steady state conditions are, if ever occurring, rare. Fluctuations on production side and on demand side of the system are perpetual perturbations to the system, and along with inherent dynamical responses as well as a large range of timescales present in the physics involved, the system is never fully balanced. A primary governing mechanism is a necessity in an electrical energy system to ensure that there is means of obtaining a balance between production and consumption in a short time scale, i.e. to ensure that small and rapid changes are dealt with, preventing black out due to normal incidents occurring.

The primary governing mechanism in the Nordic grid is speed droop operation, and until recent there has been no automatic secondary governing mechanism either; the speed droop operation has been a sufficient measure for ensuring acceptable operation conditions in the electrical grid. The speed droop operation is basically increasing the production at power producing units when the grid frequency decreases, because a decreasing frequency means that consumption is higher than the production. In this way a new dynamic balance is found. The Transmission System Operator (TSO) is responsible for setting the maximum value for the speed droop, and the value is currently set to 6%. The mathematical expression for the speed droop, b_p , is



$$b_p = \frac{\Delta f / f_{nom}}{\Delta P / P_{nom}} \quad (1)$$

where Δf is the change in grid frequency, f_{nom} is the nominal frequency, i.e. 50Hz in the Nordic region, ΔP is the change in power at the power plant and P_{nom} is the nominal power at said power plant. Setting a value for b_p then defines how much the power produced should change given a change in the frequency.

The last decade the quality of the frequency of the electrical grid in the Nordic region has gone down to the extent that the implementation of a new market for automatic secondary governing was established in 2013 by the TSOs in the Nordic region. The decreasing quality can be seen in Figure 1.

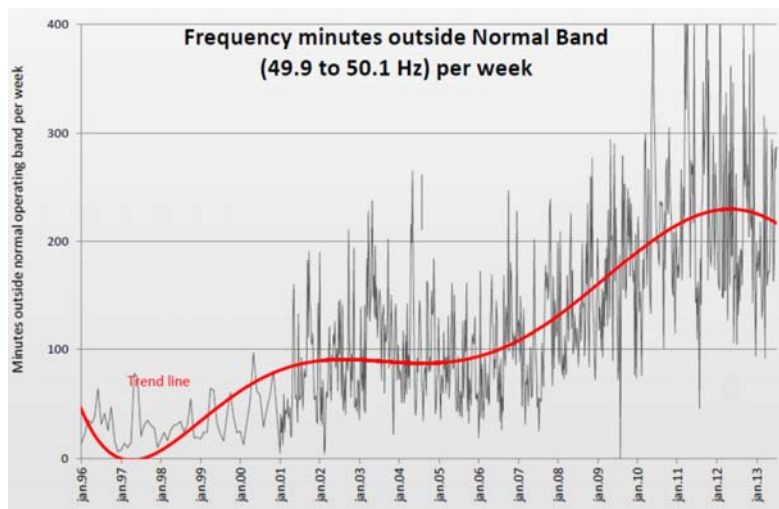


Figure 1: The grid quality represented as minutes outside the normal band, from [1].

The market is providing so-called “Frequency Restoration Reserves” (FRR) to the system, a mechanism for relieving the primary governing so that it can handle new imbalances to come [2].

This paper is focusing on a different aspect of varying grid frequency, namely the fact that synchronous machines have to match their rotational speed to the instantaneous grid frequency. The consequence of this is that the rotating parts of a hydro power turbine unit is decelerating and accelerating due to variations in the grid frequency. Since a change in angular velocity is due to a net torque, the grid frequency variations are imposing an oscillating net torque on the rotating parts. Also, the speed droop operation is increasing the torque purely by increasing the production when the rotational speed decreases, an effect also present at constant rotational speed. But then again the rotational speed is decreasing, so the torque will increase because of this as well. All in all the rotating parts of the turbine unit is experiencing a lot of torque oscillations, and the materials are dealing with these oscillations by increasing the stresses in the materials. This is interesting because what seems to be the trend the later years is that new runners are showing signs of fatigue to a much greater extent than the old runner did. Several high head Francis replacement runners in Norway have broken down quite rapidly after commissioning the recent years. The reason for this is unknown and probably complex, including effects of Rotor Stator Interactions (RSI) and resonance frequencies in the runner. Still, these rather fast oscillations are superimposed on slower oscillations such as the effect of varying grid frequency. This justifies an investigation of these slower oscillations.

This paper is presenting both measurements and simulations performed on an existing power plant. Measurements have been made of the grid frequency at the power plant and the mA measurement loop signal of rotational speed; guide vane apparatus and generator power. These are the signals which go to the power plant control room. No measurements have been made on the hydraulic domain; however that is why the simulations have been made. The measured grid frequency is used as an input to the clamps of a synchronous generator in a model of the power plant which simulates hydraulic, mechanical, magnetic and electric domains. From these simulations the differential torque acting to

accelerate or decelerate the rotating part is found and used as a measure of the dynamical loads on the rotating part of the turbine unit.

2. Methodology

This section is describing the methodology used to obtain the results presented in this paper. The results are obtained by coupling measurement results from a power plant and simulations using Matlab. These two different elements are presented below. Finally, this section describes how the key element of this paper, the torque oscillations on the rotation part of the turbine unit, is extracted from the simulations.

2.1. Measurements performed at the power plant

The measurements performed on the power plant are quite simple and crude, except for the grid frequency measurement which is highly accurate. It has been measured using a National Instrument (NI) module which can measure directly on the mains 230V which then is used to measure the grid frequency. For the three other measured properties their respective 0-10 mA measurement loop was broken and a 500 Ohm precision resistance was introduced in series configuration and a -5.0 - 5.0V NI module was used to log the voltage signal. All these measurements were performed at 250 Hz logging frequency, and they were averaged over one second and written to file. The software used to log and average the signals is Labview and an in-house generic logging program. As stated above the grid frequency measurement is highly accurate, this is because it is a direct measurement, counting cycles per second thus in no need for any calibrations. The other measurements are not that accurate, however they are never used as an input to the simulations, they are used to see if there are load changes occurring other than speed droop operation (planned changes in the power production) and as comparison for the simulations. The values written to file are un-calibrated voltage values, which afterwards are manipulated to give a qualitative representation of the behaviour of the measured quantity. The measurement setup has been logging for almost three months from October 2013 to January 2014, giving a lot of information about the grid frequency for the entire measurement period. However, the power plant has not been producing power the entire period; only the last month of the logging period has been with production of power. Still, a lot of interesting things have been recorded, amongst these several emergency shut downs due to a storm and the following start-up of the machine.

A search has been made within the grid frequency measurements in order to find the largest variations for different time scales. Several significant dips of the frequency have been found, where the time before the frequency starts to recover is typically 6-8 seconds. The frequency is then rapidly recovered after a few seconds, and this is in accordance with the response from hydro power plants to a fall out of generation somewhere in the electrical system, knowing that the typical and classical dimensioning value for the very important hydro power parameter ratio T_a/T_w equals 6 (Acceleration time for the rotating masses divided by the acceleration time for the water). However, it is the longer time scales that are interesting for the work presented here, more specifically the events that cause the frequency to go from one of the limits to the other limit in a relatively steady manner. For the work presented here a search has been made looking for a period of 500 seconds which maximizes the sum of the gradient of the frequency time series; i.e. quantitatively searching for the 500 second time interval where the frequency changes most. The speed droop setting at the power plant is 6%.

2.2. Simulations performed on the basis of grid frequency time series

Using the Method Of Characteristics (MOC), a model of the power plant is numerically constructed using MatLab and in-house code. The MOC is constructed as suggested in Wylie et. al. [3], using a staggered grid both for computational speed and for reducing numerical noise [4]. The model is fully elastic, allowing for the presence of elastic waves known as the “water hammer”. The tunnels and pipes are divided into an appropriate number of sub-divisions ensuring that the time increment in the simulations is a constant and that the length, wave propagation speed and time increment is in accordance to each other for the entire hydraulic system. The layout of the power plant can be seen in Figure 2.

The hydraulic domain of the rotating part of the turbine unit is modelled using a turbine model developed by Torbjørn K. Nielsen [5]. The model represents a turbine characteristic dependent on the rotational speed, discharge and head, and is partly based on the Euler turbine equation. A simple

model of a voltage governor in a generator is also used, as well as a governing equation where a PI-governor is present. All in all, seven equations are solved using a solver that makes use of a multidimensional Newton's method to find the seven unknown variables that need to be determined. These seven variables are: Angular velocity; flow through the turbine, opening degree of the guide vane apparatus; the electrical current at the generator terminals; the phase angle between rotor and stator magnetic field; the magnetic flux; and the generator voltage. It's in these equations that the grid frequency enters as an input, and where the rest of the parameters have to adjust to the fluctuation in the grid frequency. Some of these equations are necessary momentary balances, while other equations are differential equations which are integrated using Euler integration in which the desired value to be determined for the present time step then appears.

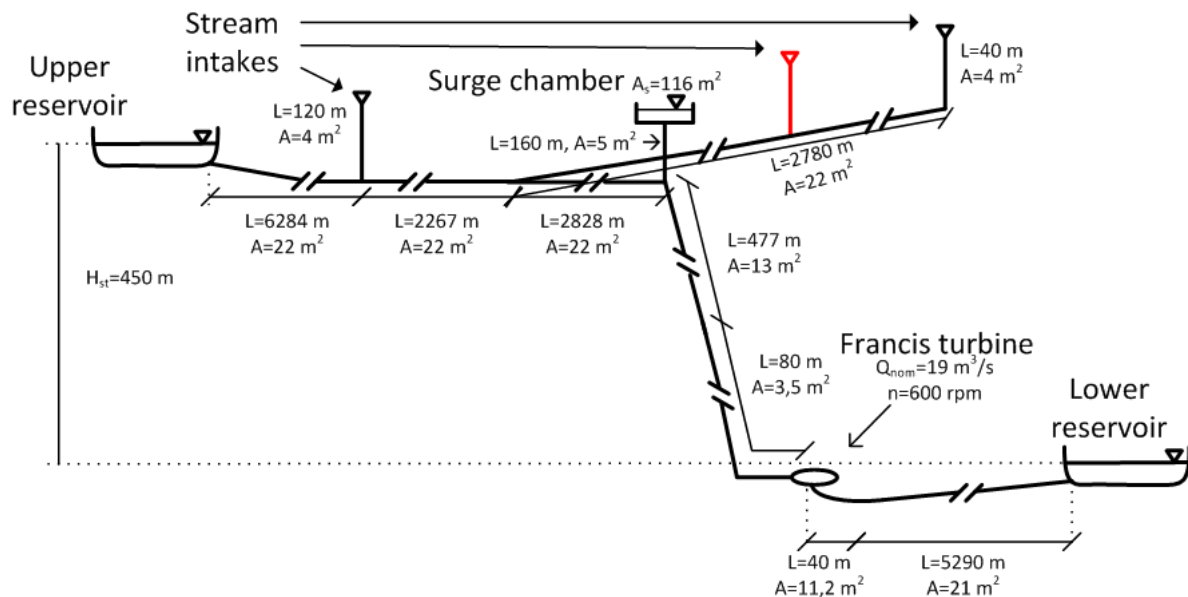


Figure 2: Layout of the power plant, the stream intake drawn in red is omitted in the simulations

2.3. Torque oscillations

The hydraulic power resulting in hydraulic torque is trying to accelerate the rotating masses. The magnetic power resulting in magnetic torque acting on the rotor from the stator is trying to bring the rotating masses to a haul. If there is a balance between these torques the rotating mass is at constant rotational speed. However, a change in either of these two will make the rotational speed change. The magnetic torque acting on the rotating mass from the generator stator is a function of the angle δ in a rotating reference between the magnetic fields of the rotor and stator; if the angle is zero no power is transmitted from the rotor to the stator and the magnetic torque is zero as well. The power, and the torque, increases as the angle increase up to a certain point where it starts to decrease; the generator is in danger of “slipping”. The source to a change in this angle may come from both energy domains on each side of the rotating mass of the turbine. The angle can decrease because the torque from the hydraulic side is reduced (the rotor field is leading over the stator field in a synchronous generator) due to dynamics or an operational set point change. This will cause the rotational speed to momentarily decrease and the angle is reduced until a new balance is obtained because the magnetic torque reduces when the angle is reduced.

However, the grid frequency can also be the source of a change in the angle. If the grid frequency increases, the stator magnetic field is experiencing acceleration and is catching up to the rotor magnetic field. The angle then decreases and the magnetic torque is reduced allowing for the rotor to accelerate because the hydraulic torque now is higher than the magnetic torque. This acceleration occurs until a new equilibrium is obtained, this time at a higher rotational speed and of course synchronous to the grid frequency yet again.

The torques which act to accelerate or decelerate the rotating mass can be extracted from the simulation results. The torque acting to accelerate the runner from the hydraulic domain, $T_{hydraulic}$, is given as

$$T_{hydraulic} = \frac{\rho g H Q \eta_h}{\omega} \quad (2)$$

where ρ is the water density, g is the gravitational acceleration, H is the net head over the runner, Q is the flow through the runner, η_h is the hydraulic efficiency and ω is the angular velocity of the runner. The torque acting to decelerate the runner is the torque acting on the rotor of the generator which is a function of the magnetic angle between the rotor and stator magnetic fields which can be approximated as a sine [6]. The torque, herein called $T_{magnetic}$, can be found as

$$T_{magnetic} = T_{nom} \frac{\sin \delta}{\sin \delta_{nom}} \quad (3)$$

where T_{nom} and δ_{nom} , are the nominal torque and magnetic angle, respectively; δ is the varying magnetic angle in a rotating frame of reference following the rotating masses causing the torque to change. There is one more torque which is participating in the speed change of the rotational mass, and that is one which is dependent on the time rate of change of the magnetic angle. This one is a regulatory mechanism built into the generator and is meant to dampen the oscillations in the magnetic angle. This torque is a dampening torque, $T_{dampening}$, which stabilize the rotor and is described by

$$T_{dampening} = m_d \frac{d\delta}{dt} \quad (4)$$

where m_d is a constant linking the magnitude of torque to the magnitude of the time derivative of the magnetic angle.

All these torques are balanced by the shear stresses in the rotating mass, and must be absorbed in equal amount on all parts of the rotating mass. If the material is thin the stresses are high, and this is the case for the runner vanes because these vanes are deliberately made thin to reduce relative velocities inside the runner, minimizing frictional losses.

The torques are summed in Newton's 2nd law for rotational motion to give the value of the change of angular momentum with time;

$$J \frac{d\vec{\omega}}{dt} = \sum \vec{T} \quad (5)$$

or in scalar form
$$J \frac{d\omega}{dt} = T_{hydraulic} - T_{magnetic} - T_{dampening} \quad (6)$$

where J is the mass moment of inertia. The first torque on the right hand side is an accelerating torque, the second is a decelerating torque and the third one is accelerating or decelerating according to the change in the magnetic angle. For steady state conditions the accelerating and decelerating torques are the same, and the stresses in the material will be according to this torque level. However, the non-stationary problem is not as simple to analyse because the torques are not the same, and what will the torque level in the material be? Clearly the vector sum of torques cannot be used (describing the speed changes of the rotor) since it will be zero for steady state conditions, and we know that the stresses in a rotor transmitting power is not. The steady state torque is equal to the torques acting on the ends of the rotor, and a property that catches both steady state value and the dynamics attributing to the change of torques on the ends is the constructed property T_{stress}

$$T_{stress} = \frac{T_{hydraulic} + T_{magnetic}}{2} + T_{dampening} \quad (7)$$

$T_{dampening}$ is zero at steady state conditions, so adding this is not affecting the steady state validity of the expression. Given the expressions for these torques above it is a simple procedure to extract this information from the simulation results. The hydraulic and magnetic torques are variables that are explicitly used in the simulations, whereas the dampening torque is easily post-calculated from the

time series of the magnetic angle. As a side note, it is thought that T_{magnetic} on a prototype in operation could be found from high quality electrical power measurements subtracted the generator losses.

3. Results

Two different cases have been simulated; one is the 500 second period where the grid frequency increases most, the other is the 500 second period where the grid frequency decreases most. The search for these extremes has been within the measurement results for the last month of the logging where the power plant has been producing power. Both the periods with maximum increase and decrease in grid frequency was found on the same day, December 20th 2013. The maximum increase occurred at approx. 0538 AM and the maximum decrease occurred at approx. 2058 PM. The grid frequency for the entire date is shown in Figure 3.

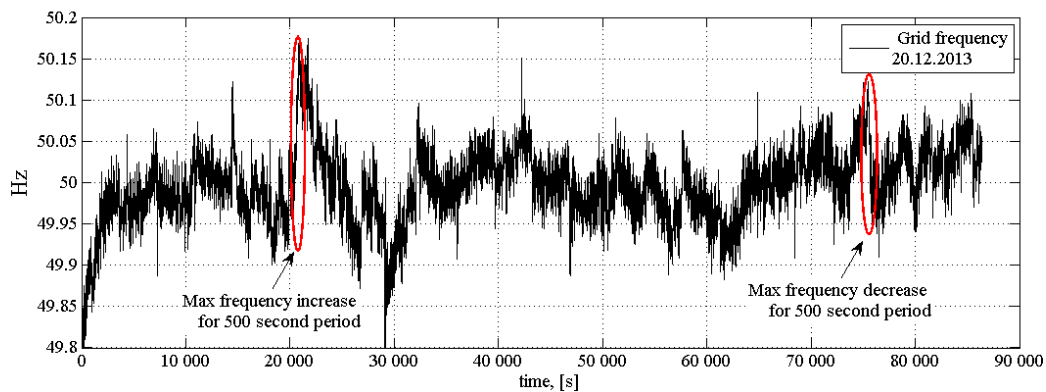


Figure 3: The grid frequency measured on 20.12.2013

When simulating these 500 second periods it has actually been simulated for 700 seconds; 200 second prior to the objective period. the reason for this is that there isn't steady state conditions when the objective period his occurring, so in order to have a somewhat realistic simulation of the objective period the initial conditions for this period should contain all residual dynamics from the previous operation. This is ensured by simulating these additional seconds prior to the objective period.

3.1. Increasing frequency

The measured frequency of the 500 second period where increase was highest can be seen in Figure 4. The normalised simulated power, guide vane opening angle and the rotational speed of the unit can be seen in Figure 5. Figure 6 is showing the constructed T_{stress} given by equation (7) normalized by the mean value of T_{stress} for the 500 second period.

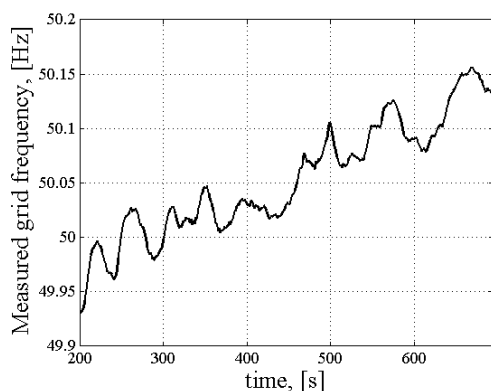


Figure 4: Period of measured increasing grid frequency

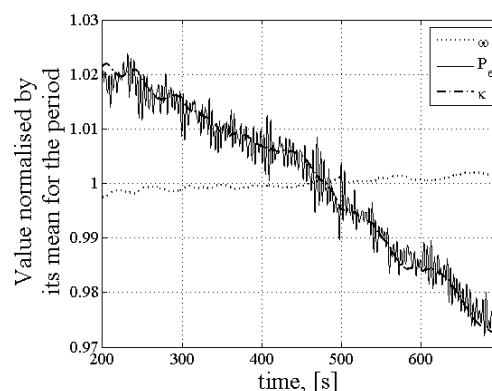


Figure 5: Normalised simulation results

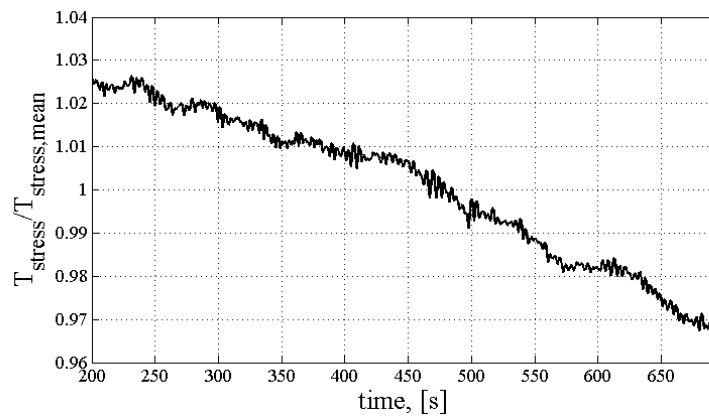


Figure 6: Normalised T_{stress} for the case of increasing frequency

3.2. Decreasing frequency

The measured frequency of the 500 second period where decrease was highest can be seen in Figure 7. The simulated power, guide vane opening angle and the rotational speed of the unit can be seen in Figure 8. Figure 9 is showing the constructed T_{stress} given by equation (7), normalized by the mean value of T_{stress} for the 500 second period.

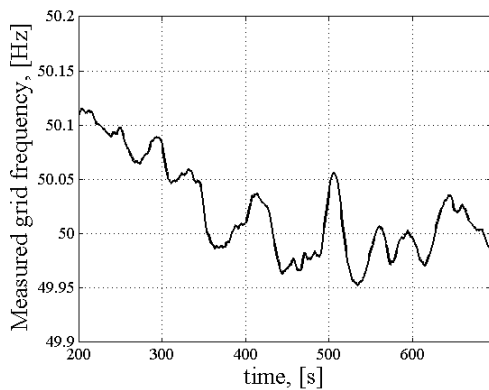


Figure 7: Period of measured decreasing frequency

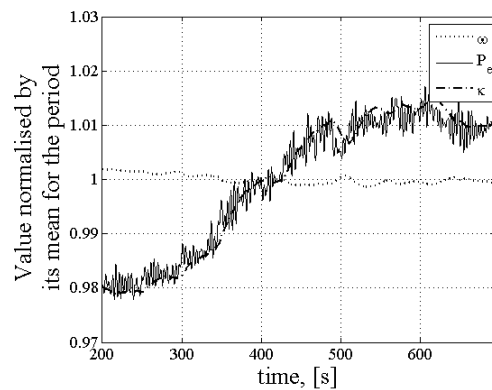


Figure 8: Normalised simulation results

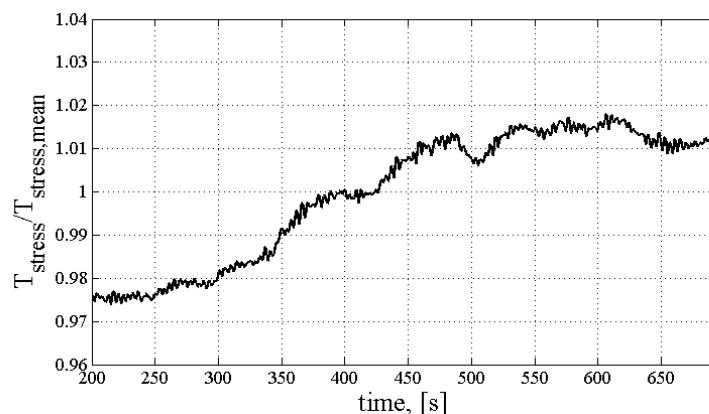


Figure 9: Normalised T_{stress} for the case of decreasing frequency

4. Discussion

First it should be verified that the values for the measured properties are qualitatively similar to the simulated results for the same properties. It's sufficient to show this for one of the cases presented, and the decreasing frequency is chosen. Figure 10 is showing normalized power, rotational speed and guide vane opening based on voltage value from measurements as well as the same properties from

simulations. The best match between the simulations and the measurements is for the rotational speed. This is not a big surprise because both the simulations and the actual rotational speed has a very strong link to the grid frequency, which is an input to the simulations and have been measured with high accuracy. The voltage measurements are post-calibrated by subtracting their mean value, dividing this result by the standard deviation of the measurement time series, multiplying with the corresponding simulation result standard deviation and then adding the mean of the simulated results; in effect scaling measurement voltage values to simulated values.

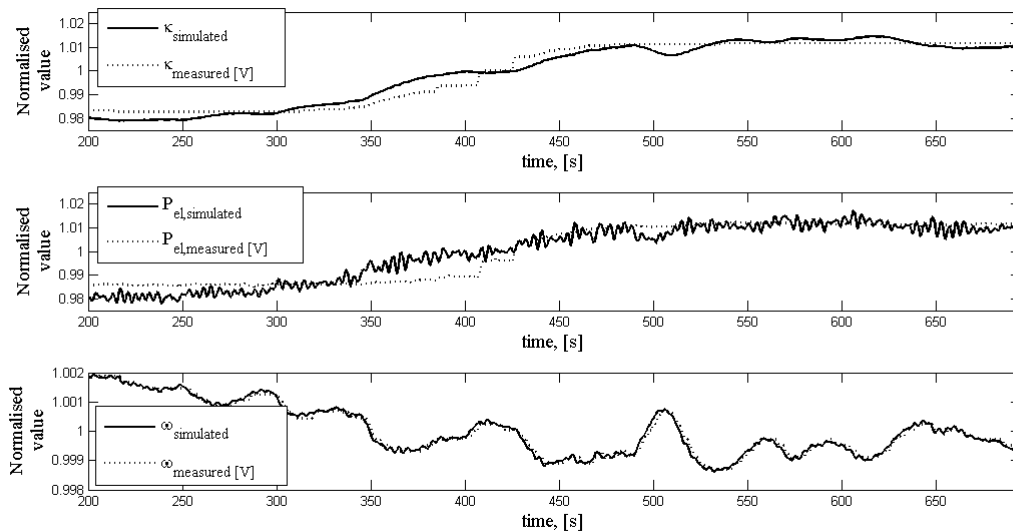


Figure 10: Comparisons between simulations and measurements

4.1. The case of increasing grid frequency

For the case of the increasing grid frequency we first point out that the frequency is changing with approximately 0.2 Hz, going from slightly below nominal value to well above the allowed value for steady state operation. For a transient, however, the acceptable deviation is within 49.5 and 50.5 Hz, so this is still an operation deemed acceptable, and not an unusual incident. Further one can see in Figure 6 that the value T_{stress} is decreasing, meaning that the rotating mass is relieved; the overall trend is due to the reduction of rotational speed, and then there are a lot of smaller ripples due to the oscillations in the magnetic angle δ . The decrease in T_{stress} is not far from 6% over the period, and the trace for T_{stress} looks very much like the trace for $P_{\text{el,simulated}}$.

4.2. The case of decreasing grid frequency

For the case of decreasing frequency the frequency change is slightly above 0.15 Hz for the period. This is not an unusual change for the frequency, and a more severe change is observed in the time series presented in Figure 3, seen around 28000 seconds into the series. This is however considered incidental, and is one of the cases mentioned earlier where the frequency is recovered after a few seconds. For the presented case, the value for T_{stress} increases by approximately 4%. Again, the trace for T_{stress} look very much like the trace for $P_{\text{el,simulated}}$.

4.3. General discussion

The traces for T_{stress} for both cases look very much like the trace for $P_{\text{el,simulated}}$. There is no load set point change occurring in these simulations and the variation in $P_{\text{el,simulated}}$ is strictly because the speed droop is used to such high extent in the operation. The trend of the trace is determined by the speed droop operation, and the small ripples seen are the effect of the dynamic between the rotor and stator magnetic fields, i.e. the magnetic angle oscillations.

Assuming steady frequency at nominal value will not take into consideration the effects presented herein. So, what is shown here is a real effect that comes in addition to the typical effects investigated by RSI and other dynamical investigations assuming steady frequency. Even if the effect is limited and

of a longer time scale than what is considered the appropriate time scale for fatigue mechanisms, it should only be neglected when found negligible, which require investigations.

5. Conclusions

The grid frequency in the Nordic grid is far from being steady, it varies much and relatively fast. This changes the rotational speed on synchronous machines, as well as the production, which is changed inversely to the frequency due to the primary governing principle known as speed droop. The effect of this is that the torque acting on the rotating masses is also varying, and this torque must be balanced by shear stresses induced in the material of the rotating masses. Not quantifying the magnitudes of the shear stress, the value of the torque variations have been quantified using simulations based on measurements of grid frequency. Simulations of normal operation avoiding extreme incidents show that this torque variation is in the range of 5% of the set point value. Not a high value per se, but the dynamic load on the runner due to this is additional to the loads due to RSI and draft tube oscillations. For this reason it can be concluded that one should not disregard this effect.

6. Further work

The work will be continued by further investigation of the torsional stresses on the runner using a Finite Element Method approach on a given geometry of a Francis runner. The ultimate goal for this work is to perform a transient RSI simulation to quantify the variations in stress and seek to have these verified on model and prototype runners.

7. Acknowledgements

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