FREQUENCY SUPPORT BY SYNTHETIC INERTIA FROM VARIABLE SPEED WIND TURBINES

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Abstract – This paper investigates the possibilities for frequency support by synthetic inertia from variable speed wind turbines. A model for representing synthetic inertia in PSS/E (Power System Simulator for Engineering) has been developed. It allows the user to relatively simple implement different control strategies to find the most suitable strategy for a particular power system. Furthermore, it can be used regardless of the existence of wind turbine models in the power system model and is connected separately to any arbitrary bus in the power system.

The results from the simulations show that the frequency nadir is reduced when implementing frequency support by synthetic inertia from wind turbines. As the wind power integration increases the frequency nadir is further improved when wind turbines can provide synthetic inertia. Regarding recovery, the results indicates that in order to minimise the risk of an under-frequency event the energy should be taken during a frequency overshoot and/or distributed in time, i.e. not all wind power plants should recover at the same time. However, these studies of synthetic inertia provided by wind turbines are still in the early stage and further work will be performed.

Keywords – Synthetic Inertia; Frequency support; Ancillary service; Active power; Wind turbines; PSS/E, User Model,

INTRODUCTION

As the amount of wind power in power systems increases, the proportion of connected synchronous machines will decrease during periods of high wind power generation. Since, many wind turbines does not increase their active power output during under-frequency events their inertia constant could be considered to be zero. Therefore the stability of the power system may be reduced due to decreasing rotating mass of synchronous generators if replacing hydropower by wind power. This will deteriorate the ability to maintain the desired power system frequency during events of sudden large power loss. By installing wind power turbines with capability to improve stability of system frequency by synthetic inertia the trend of reduced system stability when increasing wind power generation can be counteracted. Synthetic inertia is a concept to temporarily extract the rotational energy stored in the turbine as active power during under-frequency events by additional control functions in the wind turbine controller. It is expected that provision of synthetic inertia by wind turbines allows further expansion of wind power plants in power systems with high density of wind power generation but also in power systems with higher share of conventional power plants, e.g. hydro and nuclear power plants. Increasing the quantity of renewable energy sources correlates with the overall objective of reducing greenhouse gas emissions. The studies in this paper aim to demonstrate possibilities to provide frequency support in the Nordic power system by synthetic inertia from variable speed wind turbines. This project is on-going and is funded by the Smart Grid Gotland project [1].

Simulations in a reduced model of the Nordic power system, N32, which only contains conventional power plants have been performed. The model represents an equivalent of the Swedish mainland and the neighbouring countries Finland, Norway and eastern Denmark. The total power generation in the Nordic model is 15 900 MW of which 9 440 MW has been made eligible for wind power integration. The total load is 15 500 MW. The dynamic studies are performed with the software tool PSS/E (Power System Simulator for Engineering) version 33.

Studies to analyse how synthetic inertia may influence system frequency have among others been investigated by Energiforsk and Vattenfall R&D in Sweden. The results of these studies are summarized in [2] and [3]. A report handling some underlying theory in the field has previously been written within Vattenfall “unpublished” [4]. Furthermore, field experiences from wind turbines offering synthetic inertia can be found in [5] and [6].

BACKGROUND

Various events in the power system can occur which cause a frequency deviation. Since wind power is an intermittent power source dependent on the wind speed, changes in the wind climate will directly affect the power output. The greater the amount of wind power generation, the greater the impact of variable wind speed on the power system and this might cause a frequency drop. An additional event that can cause a frequency drop is disconnection of a large production unit, e.g. nuclear power plant, or loss of a transmission line.

Previous studies have been performed in the N32 model and an island power system with 168 MW wind power generation representing the Island of Gotland on the Swedish east coast. The results show that wind turbines can contribute to frequency support through supply of active power as synthetic inertia in the event of a frequency dip. For further results refer to [3] and [7].

An analysis of the inertia constant H for wind turbines has been performed in order to estimate a value of energy available for synthetic inertia. Assume that moment of inertia, J, for a 2-3MW wind turbine is 1×10^7 kgm^2. Thus, the rotational energy E_{kin} can be calculated with the following formula.

$$E_{kin} = \frac{1}{2} \cdot J \cdot \omega^2 \qquad (1)$$

Where ω is the rotational speed. Thereafter, the inertia constant H is given by the following equation.

$$H = \frac{E_{kin}}{S_{rated}} \qquad (2)$$

Where S_{rated} is the rated power of the wind turbine. Calculation of the current value of H for a 3 MW wind turbine with hourly average operational data values during ten month in 2015 is given in Figure 1. The result shows that the inertia constant is maximum approximately 4.7 sec in the operational interval.

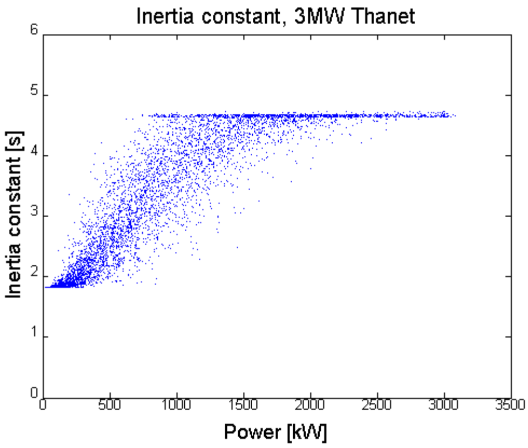

Figure 1. Inertia constant as a function of power generation for a 3MW wind turbine.

Even though the inertia constant for wind turbines could be estimated to maximum 5 sec, which can be compared to 3-4 sec for hydropower, the rated power for hydropower plants in the Nordic power system is significantly higher than wind power plants. This gives a higher amount of available rotational energy in the present power system with large share of hydropower plants. Thus, high amount of available power for synthetic inertia from wind power require a high penetration of installed wind power capacity, particularly when the capacity factor for wind power is considerably lower than for hydropower. Additionally, there are rotational speeds of the turbines that should be avoided as these give rise to heavy vibrations and resonance of the tower. If a turbine ends up in that area it may be necessary to temporarily exclude the turbine to avoid the risk of breakdowns. This means that the estimation of synthetic inertia availability from wind turbines need to be individually analyzed. However, power extraction from directly connected synchronous machines are dependent on the frequency deviation, which is not necessary for a variable speed wind turbine where the governor can be constructed independently of the grid frequency. Therefore the frequency has to drop to a significantly lower level before a hydropower plant delivers the same amount of power for frequency support as a wind turbine can per installed MW.

MODELLING OF SYNTHETIC INERTIA

In the previous work described in [2] and [6], a PSS/E user model written in the programming language FORTRAN, representing synthetic inertia has been developed. The synthetic inertia model is connected at the same connection point in the Nordic power system model as the synchronous generator, which generation the wind turbine partly is replacing. The generation from the modelled wind turbine is the sum of the contribution from synthetic inertia and generation form the wind turbine.

The model is used together with a Python program that let the user decide e.g. wind power penetration in the power system model, scaling of inertia on the conventional generation and options for recovery. It can be used regardless of the existence of wind turbine models in the power system model and is connected separately to any arbitrary bus in the power system model containing a production unit. In the on-going work, the user model has been further developed including e.g. additional options for injection of synthetic inertia and possibility to divide the power system in areas with individual setting for synthetic inertia.

Focus in the on-going work is tuning of the frequency derivative dependent power output characteristic for synthetic inertia, both for activation and deactivation. The time constant and amplification during power output mode has also been collaborated upon. Frequency limits and/or frequency derivative limits are options for activation and deactivation of the present characteristic. Calculation of the frequency derivative is shown in Figure 2. where f is the frequency in the power system, K_d is the amplification, T is the time constant and df/dt is the frequency derivative.

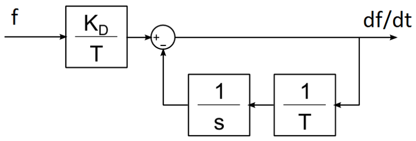

Figure 2. Calculation of frequency derivative for the frequency derivative dependent characteristic.

The additional power output P_{SI} from synthetic inertia is given as follows.

$$P_{SI} = -HP_{\max} \cdot \frac{df}{dt}\frac{1}{f} \qquad (3)$$

Where $P_{\max}$ is maximum power output from the wind turbine, df/dt is the frequency derivative and f is the frequency in the power system. Notice that the value for H is updated each time step depending on the rotational speed. When the frequency decreases, P_{SI} starts to increase due to the negative derivative of frequency. It continues to increase until the frequency variation becomes zero. For further description of the user model, see [3] and [7].

For all simulations the inertia constant H for wind power plants is 5 sec and maximum output power including synthetic inertia from the wind turbines is 1.1 pu of rated power during 8 sec. When quantifying a certain amount of wind power in the simulations it is assumed that 100% of rated power is achieved.

Two different characteristics for injection of synthetic inertia have been studied. These are the C2 characteristic, giving $P_{SI} = P_{\max}$ at activation and then decreases linearly until reaching $P_{SI} = 0$ when all energy is delivered, independently of the frequency deviation or derivative as long as deactivation criteria not are reached. The other characteristic is frequency derivative dependent where the additional power output is proportional to the frequency derivative. In order to create a frequency drop a generation loss of 500 MW is simulated in each simulation.

RESULTS

In recent studies concluded in [2] it has been shown that high initial power output is the most beneficial when reducing the frequency nadir. In order to compare the static C2 characteristic to a more dynamic one the df/dt characteristic has been further developed. In Figure 3 and Figure 4 the frequency and synthetic inertia response in Nordic 32 is illustrated with 40% of wind power. The green and blue curves in Figure 4 represents the C2 and df/dt characteristic respectively. Even with greater time constant and high amplification it is more beneficial to counteract the frequency nadir with characteristic C2.

In Figure 5 the frequency response is depicted for the initial power generation in N32 without wind power and together with different levels of wind power with synthetic inertia. The blue curve represents the case without wind power (no synthetic inertia) and the green, red and turquoise curves represents 20, 40 and 60% of wind power with synthetic inertia. The under-frequency deviation from 50 Hz is reduced from 0.4 Hz to approximately 0.3 Hz.

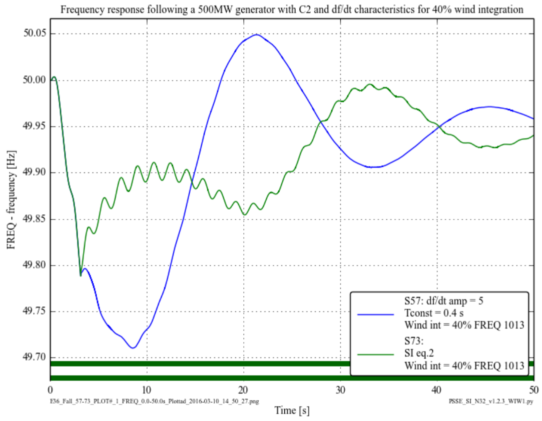

Figure 3. Frequency response after 500 MW generator trip for C2 and df/dt characteristics with amplification of 5 and time constant 0.4 sec.

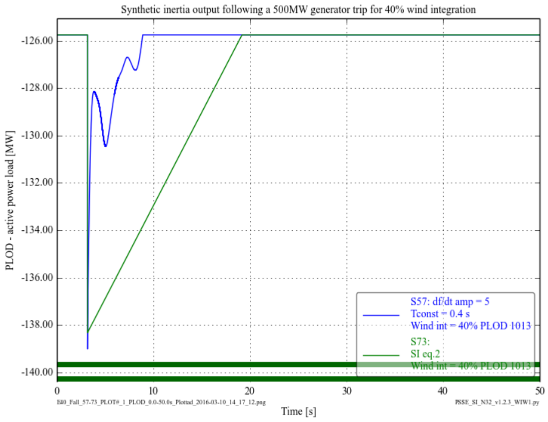

Figure 4. Synthetic inertia response for C2 and df/dt characteristics after 500 MW generator trip.

when introducing frequency support from wind turbines. With higher amount of wind power the frequency nadir can be further reduced. This is due to the increased inertia constant H in the power system when introducing wind turbines with synthetic inertia.

Furthermore, for the case with 40% of wind power the synthetic inertia response and recovery (green curve) is illustrated in Figure 6 together with the frequency (blue curve). Additional simulations in N32 studying different recovery time and frequency situations in the grid show that in order to not create another under-frequency event due to power loss during the recovery phase, it is beneficial to recover most of the energy during the overshoot short after the synthetic inertia output created with df/dt characteristic, see Figure 7. Distribute the recovery in time for different wind power plant in the power system and increase the recovery time could also counteract the risk of creating a frequency drop.

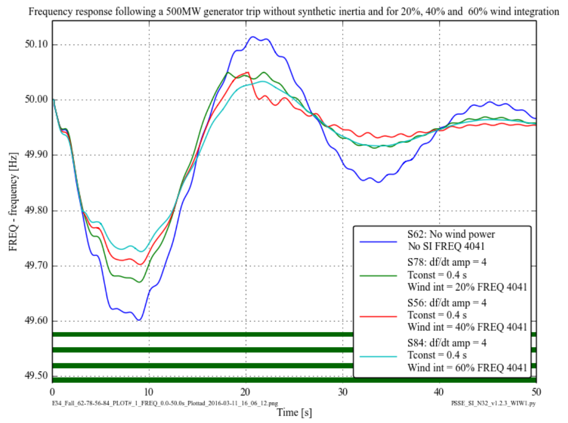

Figure 5. Frequency response during 500 MW generator trip without wind power and with synthetic inertia for 20, 40 and 60% of wind power.

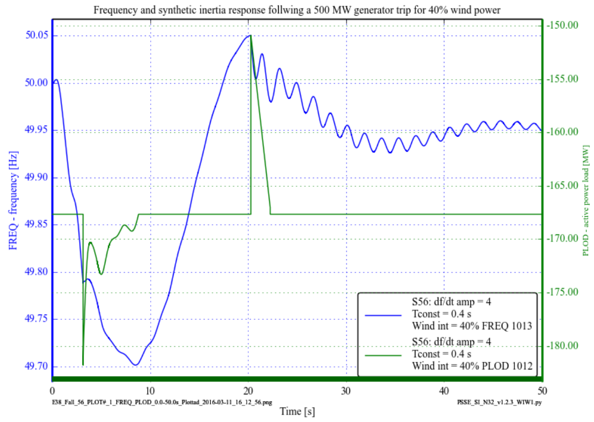

Figure 6. Frequency and synthetic inertia response for 40% wind power during 500 MW generator trip.

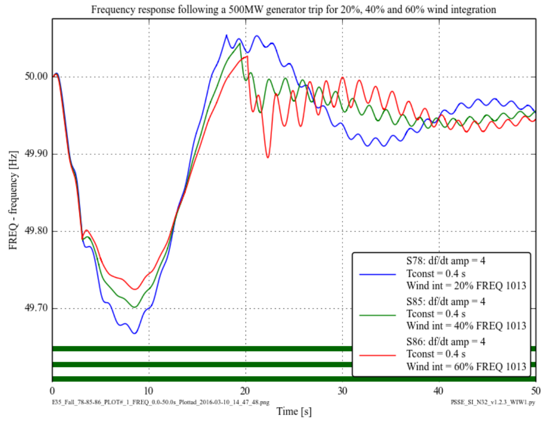

Figure 7. Frequency response after 500 MW generator trip and recovery during frequency overshoot.

At nominal power the blade pitch is used to not accelerate the blade exceeding nominal rotational speed, thus less amount of the energy in the wind is used for power generation. This has also been proved during field measurements presented in [6]. When pitching the blades the power decreases because the torque of the turbine decreases as the angle of attack becomes less optimal. Due to that it should be noted that the risk for power reduction during recovery is distinguished during operation at nominal power, since the blade pitch could be used to accelerate the turbine to nominal rotational speed again.

CONCLUSIONS

Studies in the N32 model of the Nordic power system shows that the frequency nadir could be remarkably reduced due to additional active power output during an under-frequency event.

The frequency deviation from 50 Hz during trip of a 500 MW generation unit is reduced from 0.4 Hz to approximately 0.3 Hz when introducing frequency support from wind turbines. The frequency nadir is further reduced when increasing the amount of wind power. After synthetic inertia output simulations analysing recovery period are performed. In order to minimise the risk of creating another frequency drop, due to loss of power generation, it is beneficial to recover most of the energy during an overshoot short after the synthetic inertia output with df/dt characteristic. The recovery could also be distributed in time after deactivation of synthetic inertia.

The studies are in the early stage, i.e. further simulations analysing the behaviour in the power system and development of the synthetic inertia model is necessary.

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