INERTIAL SUPPORT FROM VARIABLE SPEED WIND TURBINES

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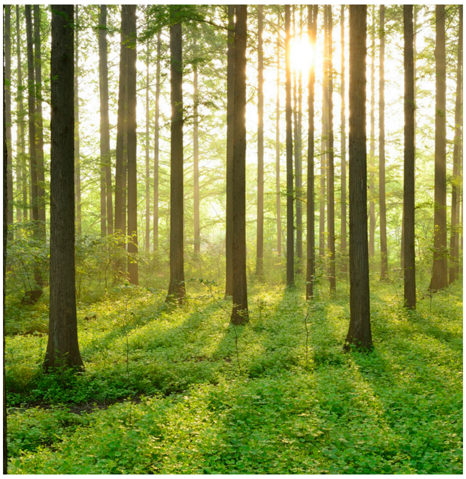

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Inertial Support from Variable Speed Wind Turbines

Inertial support strategies using wind turbines for low-inertia power system with high penetration of wind power

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Förord

"Inertial support from Wind Turbines" är ett projekt finansierat av Energiforsk och Energimyndigheten genom programmet Vindforsk.

En utmaning för framtidens elproduktion är att upprätthålla en stabil nätfrekvens utan den roterande massan som kärnkraften bidragit med.

Projektets syfte är att studera mängden kinetisk energi som kan utnyttjas från ett vindkraftverk med variabelt varvtal samt hur denna energi kan stödja frekvensstabiliteten i elnätet.

Ett resultat är en ny kontrollstrategi för vindkraftverk som kan användas för att stabilisera nätfrekvensen. Vidare undersöks möjligheten att komplettera likspänningsledet med ett Li-batteri som kan utnyttjas vid låga vindar för att stabilisera frekvensen vid behov.

Projektet har utförts av Chalmers Tekniska Högskola med Peiyuan Chen som projektledare.

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Reported here are the results and conclusions from a project in a research program run by Energiforsk. The author / authors are responsible for the content and publication which does not mean that Energiforsk has taken a position.

Sammanfattning

I ett framtida elnät där flertalet kärnkraftverk och andra fossila produktionsanläggningar stängts ner kommer det naturliga energilagret, i form av kinetisk energi, från synkrongeneratorer att minska avsevärt. Detta naturliga energilager är avgörande för att vidhålla frekvensstabiliteten i elnätet vid stora effektbortkopplingar. Vindkraftverk har kinetisk energi lagrad i sina turbiner, men denna används inte i deras standard utförande på grund av de kraftelektroniska omvandlarna i verken. Projektets huvudsyfte är att studera mängden kinetisk energi som kan utnyttjas från ett vindkraftverk med variabelt varvtal under stora effektbortkopplingar samt hur denna energi kan stödja frekvensstabiliteten i elnätet.

Ett resultat från projektet är en ny kontrollstrategi för vindkraftverk med variabelt varvtal. Denna kontrollstrategi låter vindkraftverket under kontrollerade former extrahera delar av sin kinetiska energi för att stödja frekvensstabiliteten i elnätet. I en fall studie baserad på det nordiska elnätet ger den föreslagna strategin 5,2 % mindre frekvensavvikelse än den mest lovande strategin beskriven i litteraturen som efterliknar frekvenssvaret från en traditionell synkrongenerator. År 2015 fanns i genomsnitt ca 2,2 GWs kinetisk energi att extrahera från vindkraften i Sverige. Då vindhastigheten är mycket låg går även den kinetiska energin ner till noll. För att alltid kunna leverera stöd till frekvensstabiliteten har därför möjligheterna med ett extra energilager, installerat i likspänningslänken hos de kraftelektroniska omvandlarna, studerats. I en fallstudie på ett 3,6 MW vindkraftverk kapabelt att leverera 10 % av sin installerade effekt (360 kW) från ett energilager resulterade i en uppskattad energilagerskostnad på 90 tkr för ett Li-ion batteri (billigast av de undersökta lagringsteknologierna). Med en sådan energilagring kan ett vindkraftverk alltid ge 10 % extra kraft, i relation till toppeffekten, för att stödja nätfrekvensen oberoende av vindförhållandena.

Summary

If a significant amount of nuclear power plants and fossil-fuel based thermal power plants are closed down in an electrical grid, the natural energy storage from the rotating mass of the synchronous generators in these power plants will also disappear from the grid. This natural energy storage is crucial in maintaining a stable grid frequency in case of power disturbances. Variable speed wind turbines have energy from their rotating turbines (referred to as the kinetic energy), however, it is not utilized to support the grid frequency in its default setting because of the power-electronic converters. Thus, the main aim of the project is to find out how much kinetic energy that can be extracted from variable speed wind turbines to support grid frequency during a disturbance such as an outage of a big generator in the system.

Among the results obtained in the project, a new control strategy is proposed for the variable speed wind turbine to extract its kinetic energy to support the grid frequency. In the case study analysed, the proposed strategy gives the lowest frequency nadir, and 5.2% less frequency deviation than the state-of-the-art strategy that mimics the behaviour of a traditional synchronous machine. Furthermore, at the system-wide level in 2015, an average of about 2.2 GWs of kinetic energy can be extracted from all variable speed wind turbines installed in Sweden. However, there are occasions when this value goes down to 0 at very low wind speeds. The possibility of installing an additional energy storage inside (on the dc-link of) a wind turbine is also evaluated. A case study on a 3.6 MW variable speed wind turbine shows that in order to provide 10% of the rated power (360 kW) from the energy storage, Li-ion battery is the cheapest among the three evaluated options, with the estimated cost of about 90 kSEK. With such an energy storage, a wind turbine will always be able to provide 10% extra power, on top of its normal power output, to support the grid frequency irrespective of wind conditions.

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1 Background and Motivation

Renewable energy resources, especially wind energy, have become a significant part of the generation system in the majority of the electrical power systems. According to the Directive 2009/28/EC on renewable energy, the EU will reach a 20% share of energy from renewable sources by 2020. Furthermore, after the Fukushima nuclear disaster in 2011, several European countries have taken actions to phase out their nuclear power plants, e.g. Germany has shut down eight of its nuclear power plants and been planning to close the remaining ones by 2022. Consequently, in order to balance the electricity demand within the EU and be less dependent on external energy supplies, the EU has to resort to renewable energy sources, such as wind, solar and biofuel, as the main long-term energy solution.

During large disturbances, kinetic energy stored in turbine-generator systems plays a major role in maintaining power system stability by momentarily absorbing or injecting power from or to the grid. The lack of such kinetic energy or the so-called system inertia may lead to frequency instability or even blackout in a power system when subject to a significant disturbance. However, the phase-out of synchronous machines such as nuclear power plants reduces such system inertia drastically. Furthermore, the renewable energy sources, which are usually power-electronic interfaced, do not respond with inertia support during a disturbance. Therefore, it is a challenging task to maintain a sufficient level of system inertia to secure the operation of future power system with high penetration of non-synchronous renewable generations. A number of previous work has been carried out to evaluate the technical capability for variable speed wind turbines to provide fast support to the grid frequency from the kinetic energy stored in their rotating mass [1]-[13]. However, little work has been done to analyse the uncertainty of wind turbines in providing such a grid support. Furthermore, the typical way of controlling the wind turbine to provide such a service is to mimic the behaviour of a traditional synchronous machine. However, a power-electronic converter can regulate the power production from a wind turbine at a much faster speed than the traditional control of a synchronous machine. Thus, does it exist a better control strategy for the wind turbine to provide grid frequency support than simply to mimic the synchronous machine? This project is to look into these issues, to provide corresponding clarifications and to evaluate possible solutions.

2 Project Aim

The main aim of the project is to find out how much kinetic energy that can be extracted from wind turbines to support grid frequency during a disturbance such as an outage of a big generator in the system. An additional aim is to find out if an energy storage is connected inside a wind turbine to assist the control of the grid frequency, what the size of the energy storage is required and how much it costs.

In order to achieve these aims, this project has looked into the following questions.

1. How often do big disturbances occur in the Nordic power system?
2. How much kinetic energy is released from synchronous machines during a grid disturbance? Is this sufficient to keep the grid frequency within the acceptable levels?
3. How much kinetic energy can be extracted from wind turbines? What are the limitations for wind turbines to provide such a grid service?
4. Is it better for a wind turbine to mimic/emulate the behaviour of a traditional synchronous machine during a grid frequency disturbance or is there a better alternative?
5. There will be no kinetic energy from a wind turbine if the wind does not blow and the turbine does not rotate. In this case, one option is to connect a small energy storage inside the wind turbine to provide grid frequency support when necessary. How much energy storage is needed and how much does it cost?

3 Project Results and Discussions

The project results are published in one PhD thesis [1], one project report [2], two journal articles [3], [4] and a peer-reviewed conference paper [5]. Two additional journal articles are also under preparation. The main results from the project are summarized below with corresponding discussions.

Four years (2006, 2013-2015) of data have been collected from three phasor measurement units (PMUs) installed in the Nordic power system, and these supply us with about 1577 million frequency measurement data points per year per PMU. From these data, it has been found out that there are on average 17.5 major disturbances (when the grid frequency goes down below 49.8 Hz) per year in the Nordic power system. The minimum grid frequency (frequency nadir) can go down to 49.4 Hz at the lowest. On average, the **rate of the change of frequency (RoCoF)** is around -0.1 Hz/s, and it takes about 8.7 sec for the frequency to drop from 50 Hz to its minimum value (frequency nadir). In the dataset analysed, as the grid frequency nadir never goes down below 49.4 Hz, it indicates that the current system handles one single big disturbance in a satisfactory way. However, the main concern is that if this is still the case in 10 years, in further future or in the case when nuclear and fossil fuel based thermal units are completely taken out of production. As the power system evolves, e.g. Sweden is closing down two reactors in Ringhals (1750 MW) and one in Oskarshamn (1100 MW), but Finland is building a new 1600 MW nuclear generator and another one of 1200 MW, and there are many more high voltage dc (HVDC) cables built between the Nordic system and the continental European power system, etc., the number of major disturbances are expected to change (most likely to increase). With the knowledge of the statistics of the current system behaviour, we can evaluate what should be done in order to maintain or even improve the system behaviour for a future scenario of the power system. Furthermore, these statistics also give us a good idea about how often and for how long the fast grid frequency support is needed in the current Nordic system. These statistics do not only serve as good references for evaluating the frequency stability of the future power system, but also provide guidelines for system operators on what to request from wind turbines if they are controlled to provide fast frequency support in the Nordic system, such as how often per year this functionality of grid frequency support may be needed and how long this support should last.

The largest generator in the Nordic system is the nuclear reactor Oskarshamn 3, which has a size of about 1400 MW. If we lose this generator suddenly, the production loss needs to be compensated immediately from the kinetic energy stored in the rotating mass of all the remaining synchronous generators in the system, including hydro, nuclear and other thermal power plants. In the meanwhile, the hydro power plants will also slowly open its water gate to increase the power outputs to compensate this production loss. Based on the assumptions of a given hydro power plant behaviour and other system characteristics, it is estimated that on average about 3 GWs of kinetic energy must be at standby to prevent the grid frequency from falling down below 49 Hz in the case of a production loss of 1400 MW. This estimate, however, does not include consumption forecast error and variations and wind power forecast error and variations, which may require more or less standby kinetic energy depending on if the grid frequency goes below or above 50 Hz.

On the other hand, based on the data that we have collected, it is estimated that the standby kinetic energy that stored in the rotating mass of hydro, nuclear and thermal generators in the Nordic system ranges between 117 GWs and 304 GWs. The kinetic energy tends to be low during the summer period, and high during the winter period. This level of kinetic energy seems to be much higher than what is needed, i.e. only around 3 GWs. However, only if the system frequency drops from 50 Hz to 0 can all of this kinetic energy be utilized. A more suitable measure is to estimate how much kinetic energy is released from the synchronous generators if the frequency drops from 50 Hz to 49 Hz, which is the minimum requirement by the system operator. Consequently, the standby kinetic energy that can be utilized from synchronous generators is reduced to values between 4.6 GWs and 12 GWs, which is still sufficient to fulfil the need of 3 GWs, even though the margin is drastically reduced. In an estimated scenario of 2025, even though the nuclear power plants in Sweden is reduced by about 2850 MW, the nuclear power plants in Finland will be increased by 2800 MW. Thus, the available kinetic energy from nuclear power plants can be assumed to remain more or less similar to today. However, if the future political decision in Finland leans towards the decommissioning of nuclear power plants, then we need to re-evaluate this safety margin. Nevertheless, it is of interests to know how much kinetic energy can be extracted from variable speed wind turbines installed in the Nordic system. This, however, depends on what type of control strategies to be implemented in these wind turbines.

Therefore, different control strategies have been looked into of variable speed wind turbines to provide fast frequency support to the grid by extracting kinetic energy (or referred to as inertial power) from their rotating masses. This control strategy is referred to as the 'controlled inertial response' in our work. This is also known as the emulated inertia or synthetic inertia in the literature. There are existing commercial products that equip variable speed wind turbines with this 'controlled inertial response' functionality, such as ENERCON and GE. ENERCON's solution is to provide a pre-defined power pattern for providing extra inertial power to the grid, and this power provision is rather fast in the beginning, but may have a risk of causing a second frequency dip when the wind turbines try to re-gain its rotational speed after a certain time. On the other hand, GE's solution is to mimic the behaviour of a traditional synchronous machine. One disadvantage of this approach is that the provision of inertial power from wind turbines ramps up rather slowly and depends on the local measurement of the RoCoF. Furthermore, the estimation of this RoCoF, especially at the initial stage of a system disturbance, is rather tricky in the sense that the value is sensitive to the sampling rate of the grid frequency, e.g. the value may almost halved if the sampling rate reduces from 10 samples per second to 1 sample per second. However, if the sampling rate is too high, it may capture erroneous values due to fast transients or noises. Thus, to improve the two main existing control strategies, a new control strategy to extract inertial power from wind turbines is proposed in the thesis [1]. The proposed strategy is shown in Figure 1, and consists of activation criterion, support phase, transition criterion, recovery phase, and reconnection criterion. The main idea is that once the wind turbine is activated to provide inertial power support to the grid, e.g. based on a local frequency measurement or a communication signal, the support power ramps up fast to a given value without relying on the estimation of the grid RoCoF at the initial stage of the grid frequency swing, which is rather tricky to estimate as described above. But the control strategy monitors the grid RoCoF continuously and use this information to determine when to transit to the recovery phase to re-gain its rotational speed. Once the recovery phase finishes, the controller switches back to its original controller that aims at capturing the maximum wind energy. This approach combines the advantages of the two approaches used by ENERCON and GE. A detailed discussion of this proposed control strategy is described in the PhD thesis [1]. In a simple 50% hydro 50% wind system, it is shown that the proposed control strategy provides the best grid frequency support, as shown in Figure 2. The 'f-independent algorithm' is similar to the ENERCON approach while the 'f&df/dt-dependent algorithm' is similar to the GE approach. The proposed strategy gives the lowest frequency nadir, and 5.2% less frequency deviation than the 'f&df/dt-dependent algorithm' and 15.5% less frequency deviation than the 'f-independent algorithm'. More studies are conducted and can be found in the PhD thesis [1].

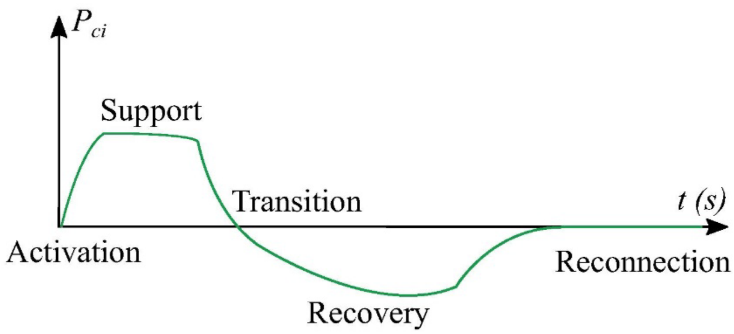

Figure 1 A conceptual graph showing the proposed control strategy of a variable speed wind turbine for providing fast power support to the electrical grid.

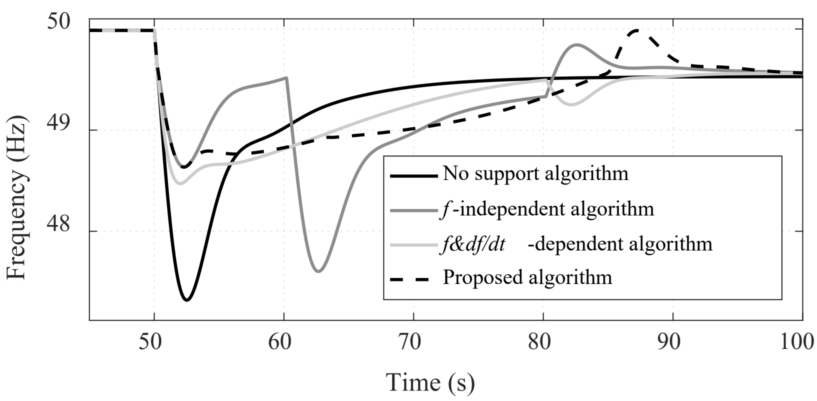

Figure 2 Grid frequency response under different control strategies of providing kinetic energy to the grid from variable speed wind turbines.

A detailed study is conducted in another report [2] at Chalmers to evaluate the aggregated inertial support from wind turbines installed in Sweden. The main results show that if every wind turbine is providing 10% of its rated power on top of its normal power output, then all the variable speed wind turbines in Sweden in 2015 can provide on average about 2.2 GWs of kinetic energy to support the grid frequency. For about 87% of the time, these wind turbines can provide the same or more kinetic energy than the biggest nuclear generator (Oskarshamn 3) in Sweden can do when the grid frequency goes down from 50 Hz to 49 Hz. However, there are occasions when the total aggregated kinetic energy that can be extracted from all these wind turbines goes down to 0 or a very small value during very low wind speed periods. So does the system aggregated wind power production during this period. This makes the fast frequency support from wind turbines a much less reliable means for the grid operator during the long-term planning stage, even though this frequency support functionality is still valuable from the short-term operational perspective, such as day-ahead or hourly ahead, when there is a more accurate forecast of wind speed in the system. In the case of 10% inertial power support from wind turbines, the total kinetic energy that can be potentially extracted from all the wind turbines in the Swedish system is rather linearly proportional to the total wind power production in the Swedish system.

In order to provide a firm fast frequency support from wind turbines, one option evaluated in [1] is to install a small energy storage inside (on the dc-link of) the wind turbine. The evaluated energy storage include lead-acid battery, Li-ion battery and super-capacitor bank. A case study on a 3.6 MW variable speed wind turbine shows that in order to provide 10% of the rated power (360 kW) from the energy storage, Li-ion battery is the cheapest among the three options, with 72 cells connected in series to form one string and with 5 parallel strings in total. The total size of the energy storage is 93 dm^3 with the total weight of 176 kg. The estimated cost is 90 kSEK. With such an energy storage, a wind turbine will always be able to provide 10% of extra power, on top of its normal power output, to support the grid frequency irrespective of wind conditions.

4 Conclusions

This project has successfully quantified the capability and limitation of variable speed wind turbines to provide inertial support to the electrical grid in the case of frequency disturbances. The main limitations include wind speed, minimum turbine rotor speed and converter rating. A new control strategy (inertial response strategy) to extract kinetic energy from the variable speed wind turbine is proposed in the project. In the case study analysed, the proposed strategy gives the lowest frequency nadir, and 5.2% less frequency deviation than the state-of-the-art strategy, which is to mimic the behaviour of a traditional synchronous machine.

Furthermore, from the four year's frequency data measurement, it is found out that there are on average 17.5 major disturbances per year in the Nordic power system, and it takes about on average 8.7 sec for the frequency to drop from 50 Hz to its minimum value (frequency nadir). During a major disturbance, the amount of kinetic energy released from synchronous machines in the Nordic system ranges between 4.6 GWs and 12 GWs, which is sufficient in the current system to keep the grid frequency within acceptable ranges. However, this kinetic energy is expected to decrease in the future with more renewable power generators and less nuclear and fossil-fuel based thermal power plants.

Moreover, on average about 2.2 GWs of kinetic energy can be extracted from all variable speed wind turbines installed in Sweden in 2015. However, there are occasions when this value goes down to 0 at very low wind speeds. This makes it difficult for the system operator to rely on the wind turbines solely to provide a constant level of inertial power support during the stage of their long-term system planning. Nevertheless, the inertial power support from wind turbines is still valuable during the short-term operational planning such as the day-ahead planning.

Finally, the possibility of installing an additional energy storage inside (on the dc-link of) a wind turbine is also evaluated to provide a firm power support to the grid frequency. A case study on a 3.6 MW variable speed wind turbine shows that in order to provide 10% of the rated power (360 kW) from the energy storage, Li-ion battery is the cheapest among the three evaluated options, with 72 cells connected in series to form one string and with 5 parallel strings in total. The total size of the energy storage is 93 dm^3 with the total weight of 176 kg. The estimated cost is about 90 kSEK. With such an energy storage, a wind turbine will always be able to provide 10% of extra power, on top of its normal power output, to support the grid frequency irrespective of wind conditions.

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