Sub synchronous Resonance problems in Power Systems with large penetration of Wind Generation: A Review

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Abstract

Power system experiences severe problems while integrating large scale wind power, which is produced in a stochastic behavior due to natural wind fluctuations. The rapid power fluctuations from the large scale wind farms introduce several challenges to reliable operation and contribute to deviations in the planned power generation which may lead to power system control problems. One of the challenges of large-scale integration of wind farms in transmission networks is the need for increased transmission capacity to transport bulk amount of wind power.

Analysis of the effect of various factors, such as the level of series compensation power output and rating of wind farms, location of faults in wind farm connected to a series connected network is an important and necessary. Series compensation is an established means of enhancing the power transfer capability of existing transmission lines and is being increasingly considered for integrating large wind power plants. However, series compensated transmission lines may cause sub-synchronous resonance (SSR) in turbine-generators, which can lead to electrical instability at sub-synchronous frequencies and potential turbine-generator shaft failures. Sub-synchronous oscillations between wind turbines and a series capacitor in the transmission network results in significant damage to the wind turbines. The mitigation of SSR by various FACTS devices such as STATCOM is an important aspect to investigate, this leads to study the impact of wind penetration on SSR.

Major areas of studies need to be carried out: Load Flow studies, Stability studies (Rotor Angle, Frequency and voltage) and sizing and allocation of reactive power sources.

Key words: Wind penetration- Sub synchronous resonance- Stability- STATCOM

1.0 Introduction

The stability of the power system is affected by large penetration of wind generators. Modeling of wind generators for analysis plays an important role to obtain accurate response of the impact on the power system stability.

In power systems where a significant part of the power generation comes from wind turbines, system operation issues become a challenge due to the variations in the available wind power. In an off-shore wind farm, the power fluctuations can be much more intense than from the aggregated
wind power production on land, due to the geographically distributed nature of wind production. With an increase of off-shore wind farms, wind power fluctuations may introduce several challenges to reliable power system operation and thus leading to may lead to power system control issues.

Recognizing the importance of RE systems in meeting the growing energy demand, and reducing carbon emissions, wind generators are being installed and thus the penetration levels of wind energy into the grid is increasing rapidly. The large scale grid integration of wind generation challenges power system operation are mainly due to its variable output and limited predictability, which may lead to stability problems.

The operation of power system is becoming challenging specially due to large penetration of wind generation. The operation and structure of distribution system is changing with the integration of wind generation. Among the new issues, there is the question of stability of distribution systems in the presence of a large penetration of wind generation. With power systems operating under stressed conditions near their loadability limits, voltage stability becomes an important issue. Many utilities are planning at the transmission level, for long-term solutions to counter this problem, such as adding transmission lines and new power plants in order to improve the reliability of the power system and meet the growing demand. An alternative solution consists in increase of generation at the distribution level. This is also a way of meeting growing economical, technical and environmental constraints. The size, the technology and the placement of wind generators play an important role in the operation of distribution systems.

Power system starts to face problems when integrating large scale wind power, which is produced in a stochastic behavior due to natural wind fluctuations. The rapid power fluctuations from the large scale wind farms introduce several challenges to reliable operation and contribute to deviations in the planned power generation which may lead to power system control problems.

Recently wind power generation has been experiencing a rapid development in a global scale. The size of wind turbines and wind farms are increasing quickly resulting in large amount of wind power integrated into the power system. As the wind power penetration into the grid increases quickly, the influence of wind turbines on the power quality and voltage stability is becoming more and more important. It is well known that a huge penetration of wind energy in a power system may cause certain issues due to the random nature of the wind and the characteristics of the wind generators. In large wind farms connected to the transmission network 132 kV and above, the main technical constraint to be taken into account is the power system transient stability that could be lost, when for example, a voltage dip causes the tripping off of a large number of wind generators.

In the case of smaller installations connected to weak electric grids such as medium voltage distribution networks, power quality problems may became a serious concern because of the proximity of the generators to the loads. The existence of voltage dips is one of the main disturbances related to power quality in distribution networks. In developed countries, it is known that from 75% up to 95% of the industrial sector claims to the electric distribution
companies are related to problems originated by this disturbance type. These problems arise from the fact that many electrical loads are not designed to maintain their normal use behavior during a voltage dip.

One of the challenges of large-scale integration of wind farms in transmission networks is the need for increased transmission capacity to transport bulk amount of wind power. Series compensation is an established means of enhancing the power transfer capability of existing transmission lines and is being increasingly considered for integrating large wind power plants. However, series compensated transmission lines may cause subsynchronous resonance (SSR) in turbine-generators, which can lead to electrical instability at subsynchronous frequencies and potential turbine-generator shaft failures. Sub-synchronous oscillations between wind turbines and a series capacitor in the transmission network results in significant damage to the wind turbines. [IEEE SSR Task force, Power system engineering committee-1977; IEEE SSR Task force Dynamic system performance working group -1985]

2.0 **Impact of Wind Generation on the Power System Stability**

With a fast increase in the DG penetration level, the power system stability can vary due to the presence of the new power generation at the distribution level. Recent studies have focused on analyzing the short-term and the long-term impact of connecting DG on the power system.

2.1 **Impact on Long-term Stability**

Large-scale wind turbine installations represent a new challenge to the power system operation. The fluctuating nature of wind power introduces several challenges to power system operation and contributes to deviations in the planned power generation which may lead to power system control and power balancing problems. Therefore, adequate models are needed to investigate the long-term stability.

Voltage and frequency stability can be regarded as long-term studies where the timeframe can be extend from a few minutes to few hours. Steady-state analysis and dynamic simulations are used to evaluate the long-term voltage stability.

2.2 **Impact on the Short-Term Stability**

All segments of stability (rotor angle, voltage and frequency) can be considered for short-term analysis. The time frame can vary from a few hundreds of milliseconds to a few seconds.

2.3 **Impact of wind farms on SSR**

Large-scale integration of wind farms in transmission networks has led to several challenges; one of which is the need for increased transmission capacity to transport a bulk amount of wind power. Series compensation is an established means of enhancing the power transfer capability of existing transmission lines and is being increasingly considered for integrating large wind power plants. However, series compensated transmission lines may cause sub-synchronous...
resonance (SSR) in turbine-generators, which can lead to electrical instability at sub-synchronous frequencies and potential turbine-generator shaft failures.

The survey primarily focuses on the potential of sub-synchronous resonance in induction generator based wind farms connected to series compensated lines. Two types of induction generators - single cage and double cage, are to be considered to develop a state space model of the overall wind farm system. Eigenvalue analyses followed by participation factor analysis and sensitivity studies are to be performed over a wide range of operating conditions. These analyses include variations in the size of wind farm, wind power output, and series compensation levels. The potential for SSR in a wind farm need to be examined through a comprehensive small signal analysis.

In the last forty years the wind energy industry has seen a rapid growth in comparison to other renewable energy industries. Enhanced technology and design improvements have played a significant role in increasing their penetration levels. The size of the wind turbines has increased, the cost has been reduced, and controllability of the wind power plants much improved, in recent years. The advancements in power electronics have placed wind energy as a serious and competitive alternative to other renewable sources.

A number of wind farms are being planned and installed in remote areas, often very far from load centers. This requires construction of new, long line transmission systems, often built with series compensation to electrically bring the resource closer to the load center. However, this increases the potential for creating SSR problems not only for the new resources, but also for existing generation and power electronic equipment. An electrical sub-synchronous resonance occurs between the induction machines at the wind farms and the series capacitors causing voltage and current distortion. Integration of wind farms into systems where the short circuit ratio (SCR) is low (<5) should be identified as potential locations for SSR.

The wind energy industry is growing rapidly. More and more utilities are connecting wind generation throughout their system. This includes some generation near series compensated lines, and in some cases, radially connected through series compensated lines as Series capacitors are one of the conventional means for compensation of the inductive reactance of the transmission line. However, if a resonant frequency of the transmission system is complementary to any of the torsional oscillating frequencies of the turbine generator mass-spring system, sub synchronous resonance (SSR) will develop where electric resonance of the transmission system and the torsional oscillations of the mass-spring system of the turbine generator set will be mutually excited causing serious shaft oscillations [1-Kundur P- 1994].

The SSR concern has lead to the approach of limiting the amount of series compensation in transmission lines to the order of 30-35% of system reactance. A system may benefit from a higher level of compensation; however this is avoided as transmission system operators are concerned about the negative impacts of SSR.

FACTS devices may be already installed for achieving other objectives and SSR damping function can be additionally included, or the FACTS devices can be exclusively connected for mitigating SSR.
instance, an SVC may be already located at the wind farm for dynamic reactive power support or for other power-quality (PQ) improvement purposes. Similarly, a TCSC may already be inserted in the transmission network to increase the power transfer capability, and the large capacity wind farm may now need to evacuate power through this series-compensated network. [Murthy A S R et.al 1991 [2], Ramamoorthy et.al 1993,[3] Kundur P 1994 [1].

3.0 Sub-Synchronous Resonance in Wind Farms

Series compensated transmission system increases the power transfer, however, the potential risk of series-compensated system is that it may cause SSR. SSR interaction is divided into three categories: Torsional Interaction TI), Induction Generator Effect (TGE), and Torsional amplification (TA). TI involves the mechanical system of T-G unit and the electrical system. When the complement of the natural frequency of the network is close or coincides with one of the torsional frequencies of the T-G shaft system. The IGE is an electrical phenomena, depends mainly on generator and electrical system. TI and IGE are related with steady state of power system.

Large-scale integration of wind farms in the transmission and distribution networks has led to several challenges. One of these challenges is the need for substantial upgrading of grid transmission infrastructures including the construction of new transmission lines to accommodate the increased power flow from the wind plants. It is well known that series compensation is an effective means of enhancing the power transfer capability of existing transmission lines. Hence, it is being increasingly considered for integrating large wind generation plants. Series capacitors have been known to cause sub-synchronous resonance (SSR) as described above. Furthermore, the presence of series capacitors in the line may also potentially cause sub-synchronous resonance (SSR) in induction generator based wind turbine generators [Anderson – 1990, 5]

Wind power penetration is rapidly increasing in today's energy generation industry. In particular, the doubly-fed induction generator (DFIG) has become a very popular option in wind farms, due to its cost advantage compared with fully rated converter-based systems. Wind farms are frequently located in remote areas, far from the bulk of electric power users, and require long transmission lines to connect to the grid. Series capacitive compensation of DFIG-based wind farm is an economical way to increase the power transfer capability of the transmission line connecting the wind farm to the grid.

For example, a study performed by ABB reveals that increasing the power transfer capability of an existing transmission line from 1300 MW to 2000 MW using series compensation is 90% less expensive than building a new transmission line.

However, a factor hindering the extensive use of series capacitive compensation is the potential risk of sub-synchronous resonance (SSR). The SSR is a condition where the wind farm exchanges energy with the electric network, to which it is connected, at one or more natural frequencies of the electric or mechanical part of the combined system, comprising the wind farm and the network, and the frequency of the exchanged energy, is below the fundamental frequency
of the system. This oscillatory phenomenon may cause severe damage in the wind farm, if not prevented. [Hossein Ali Mohammadpour and Enrico Santi, Univ of South Carolina [4].

Mokhtari M et.al [6-7] mentioned that DFIG based wind farm was utilized to damp the torsional oscillations of the conventional turbine-generator units.

Faried S O et.al [7] stated that in North America, most large wind farms employ the DFIG based wind turbines.

Slootweg J G et.al 2003, Muljadi E et.al, 2007, Gautam D et.al 2009 [8-10], Investigated the impact of the DFIG based wind farm on the small signal stability of power systems; concluded that DFIG based wind farms had both positive and negative effect on electro-mechanical oscillations.

Ostadi A et.al, 2009, Fan L L et.al 2010. Wang L et.al 2014, [11-13], ‘The SSR of the DFIG based wind farms has been studied and found that DFIG based wind farms was very vulnerable to SSR and the SSR was mainly attributed to the IGE instead of TI.

Suriyaarahahi DHR, et.al [14], [2013], presented the procedures to study the SSR in wind integrated power systems.

[15]. Wu F, Zhang X P, Godfrey K, ‘ considered the drive train which includes wind turbine, gear box, shafts and other mechanical components, and represented by a two mass model.

[16]. IEEE Sub-synchronous resonance task force of the dynamic system performance working group, power system engineering committee First Bench mark model for the computer simulation of sub-synchronous resonance.

Jing et.al [18] established mathematical model to analyze the Torsional-Interaction (TI) and the induction generator effect of the T-G units. Both eigenvalue analysis and time domain simulation demonstrate the impact of DFIG based wind farm on SSR of power system and how the control parameters of wind farms can affect the SSR. Performed SSR analysis of the T-G unit when some conventional power plants were replaced by DFIG based wind farm. The influence of the wind farm on TI and IGE of the T-G unit has been investigated. The results of the eigenvalue analysis have also been verified through the time domain solution using PSCAD/EMTDC. The replacement of conventional power plants by DFIG based wind farm has a negative effect on the TI of the TG unit.(a) The larger the wind farm capacity, the less damping of torsional oscillation (b) The higher the rotating speed of the DFIG, the less damping of the torsional oscillation.

4.0 Role of Wind Generation in growing power system
The performance of the power system in the presence of wind generation is influenced by number of factors such as: amount of wind generation, its location and wind turbine technology. Since, a variety of wind turbine technologies are commercially employed around the world, it is desirable to assess the impact of various available technologies on power system performance, so that suitable wind generator can be considered for installation. Power system performance is evaluated through simulation studies, which requires considering the appropriate models for power system components for correct representation.

In recent years, rapid increase in demand for generation of power and rising environmental concerns have led to the rapid growth of electricity generation from RE sources. Among the various RE sources, wind energy has gained importance, and it is expected that in future wind generation will have more share amongst the RE sources of energy generation. Although it offers a number of advantages, the main problem is their dependency on weather conditions, which results in intermittent and uncertain power generation. Higher penetration of wind power would lead to higher level on uncertainty in the system. The uncertain nature of wind power, together with load variations and system contingencies, may cause some undesirable impact on system security and reliability. This necessitates a need for extensive research on evaluating the impact of large amount of wind generation into the grid to ensure a secure and reliable system operation.

Power system stability becomes an important aspect in the presence of variable and uncertain wind power. The reliable and stable operation of power systems requires continuous balance between generation and demand, which becomes more difficult with variable generation sources such as wind generation and limited predictability/uncertainty. The uncertainty of wind power can be managed with better forecasting methods. Since the load cannot be controlled traditionally this power balance is achieved by controlling the output of generators in real time operation. Relatively lesser controllability of wind power output is an important aspect to achieve power balance in real time and may affect the system stability significantly.

The technical characteristics of wind generators are different than traditional synchronous generators technology. The most wind farm installations use induction generators, which interact differently with the system and introduce some additional issues such as high consumption of reactive power resulting in voltage stability limit, additional reactive power support. Since the characteristics of wind power generators are inherently different from those of traditional synchronous generators, comprehensive studies and simulations based on appropriate modeling of power system components, so that integration of these sources in to the power systems does not jeopardize its security. Traditional methods are insufficient for analysis of power systems with high penetration of wind power; therefore, new tools and techniques are required for stability assessment with large wind generation considering their intermittent and uncertain nature.

Recently, grid integration issues of RE sources has received considerable attention amongst power system planners and activated to focus on analyzing the impacts of large scale integration of these sources into the grid. The important aspect is in evaluating the impacts of these sources and developing methodologies for incorporating these sources into grid. However, the issues
associated with these sources are wide and challenging which still needs problem oriented research.

5.0 Certain aspects need attention in maintaining system stability with Wind Generation penetration

Certain aspects necessary to consider in maintaining stability of system with wind power generation penetration. Important aspect required ‘To investigate the impact of penetration of large scale wind power generation into the grid on power system stability, considering the intermittent nature of wind generation, and to explore measures to mitigate negative consequences, if any’.

The following aspects need careful attention in maintaining system stability with large penetration of wind power into the grid:

- Identify different existing models of wind power generation and investigate their suitability in stability studies.
- Develop a methodology for stability assessment of power systems with large scale integration of wind generation.
- Analyze the impact of different wind generation technologies on power system stability.
- Investigate the impact of wind power penetration level on stability limit.
- Conduct voltage stability analysis, to evaluate the impact of strategically placed wind generators on distribution systems with respect to the critical voltage variations and collapse margins.
- Study the phenomenon of SSR in wind farms with different types of wind generators
- Studies that are required to be carried out to analyze the performance: Load Flow studies, Stability studies (Rotor Angle, Frequency and voltage) and sizing and allocation of reactive power sources.

6.0 Challenges in impact of wind power generation penetration on SSR:

- The basic technical challenge comes from the variation of wind power which affects the load – generation balance, varying demand for reactive power and impact on voltage stability. Thus, there is a need for installation of dynamic compensation devices such as SVCs / STATCOMs. Allocation and size of reactive power is essential to study.
• Measures must be available to mitigate the effects of the variable reactive generation of power. As a result of this, the dynamic reactive power compensation i.e. SVC/STATCOM shall have to be provided at wind energy pooling station for dynamic voltage support and avoid any undesirable reactive power flow to or from the grid. *Dynamic voltage support required under disturbance conditions is an important aspect to study.*

• Most of the wind generators, being induction type are absorbing substantial reactive power during startup and some reactive power during normal operating condition. Due to intermittent characteristic of wind, generator start up takes place multiple times during the day, resulting in absorption of reactive power from the grid, which leads to voltage stability problems. *This requires analyzing the voltage stability problems with varying loading condition.*

• Fault analysis of wind farms connected to series compensated network and *Mitigation of SSR through application of FACTS devices such as STATCOM.*

6.1 The following aspects need careful attention to make wind penetration to system with series compensated transmission lines is viable.

   (a) Develop a comprehensive system model for the study of sub-synchronous resonance in induction generator based wind farms connected to series compensated transmission lines and to validate small signal Eigenanalysis study results through electromagnetic transient simulation studies.

   (b) Investigate the effect of various factors, such as the level of series compensation, power output and rating of wind farms, locations of faults in a wind farm radially connected to series compensated network.

   (c) Investigate the mutual interaction between induction generator based wind farms connected to series compensated lines.

   (d) Design a STATCOM controller for mitigating sub-synchronous resonance in the wind farm connected to series compensated line.

   (e) Examine the potential of sub-synchronous resonance in induction generator based wind farms connected to HVDC lines together with parallel series compensated line.

   (f) Investigate the issue of harmonic resonance and its impact on a commercially operated wind farm.
Large wind farms in the range of hundreds of MW are spread over large geographical areas. Hence, all wind turbines may not experience the same wind speed. A separate study therefore may be carried out to investigate the impact of the different wind speeds on the performance of the different wind turbine generators connected to the same series compensated lines.

A comprehensive study with other FACTS devices such as SVC and TCSC may also be performed to mitigate SSR in induction generator based wind farms.

### 7.0 Mathematical techniques to solve SSR problems

The shaft system of generator consists of six torsional masses: a high pressure turbine [Hp], an intermediate pressure turbine section [IP], two low pressure turbine section [LPA, LPB], generator [GEN] and Exciter [EXC]. Six masses are considered in the shaft system, there are six modes of oscillations: mode 0 to mode 5. The mode zero represents low frequency oscillation occurring in the range of 0.5 – 3.0 Hz. The other five modes are the torsional oscillation modes, and their mode shapes are documented [16-17]. In general, the generator of DFIG is a wound rotor induction machine. The model of the induction generator in d-q reference is documented [15]. The time simulation, type of fault to be considered and duration fault is documented [16].

There are several techniques available for the study of sub-synchronous resonance in power systems. The most common techniques are: (a) Frequency scanning (b) Eigenvalue analysis (c) Electromagnetic transient simulation. An illustrative example such as: IEEE First benchmark and Second SSR Benchmark models needs to be considered for detailed analysis, by proposing a STATCOM to alleviate SSR in such series compensated wind farms.

Eigenvalue analysis followed by participation factor analysis and sensitivity studies performed over a wide range of operating conditions is one of the methods for analyzing the risk of SSR. These analyses should include variations in the size of wind farm, windpower output, and series compensation levels. The potential for SSR in a wind farm can also be examined through a comprehensive small signal analysis.

### 8.0 Conclusions

With growing installation of wind generators rapidly across the globe besides research, there is a strong need for education also for the operational philosophy of the power system to be changed with high penetration of wind power. This necessitates the new engineering graduate and research scholars to get exposure to the challenges presented by these sources and encourage them to develop the possible solutions to overcome the problems. Furthermore the power industry is demanding an increasing number of power graduates with knowledge of theoretical and practical foundations of wind energy sources.

Large penetration of wind power can affect the stability of the system by either improving or deteriorating the stability of the system. Due to the complexity of the power system, modeling of
wind generators becomes crucial to obtain a correct response of the impact on the power system stability. Analysis will provide clear understanding of the potential impacts of wind power on power system stability.

As the level of wind penetration increases, the dynamics of the conventional T-G units would significantly be influenced by large scale wind farms. Due to high capacity low cost and flexible control, the doubly fed induction generator (DFIG) is preferred compared to other types of wind generators.

References


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