A Brief Overview of Power System Stability Parameters and the Challenges associated with High Penetration of Wind Energy on Stability

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Abstract
Due to an ever-increasing population, advancements in consumer technology and the general electrification of machines and processes, the demand for electricity is rising exponentially. Simultaneously, there is an increasing concern regarding global warming and pollution of the environment, necessitating an environmentally friendly approach towards solving challenges and developing technology. This has resulted in a turn of focus towards wind energy, among other renewables, being utilized in large amounts to provide electric power generation. However, the intermittent and relatively unpredictable nature of wind has caused a lot of problems for the stability of power systems due to large penetration levels. The different types of generators used in wind turbines than the conventional synchronous generators also increase the complexity of stability analysis due to different dynamics of the systems. This paper provides an overview of the stability parameters in conventional power systems and investigates the stability challenges associated with high penetration of wind power in the grid. Recent works on handling stability issues are also investigated in this paper.

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1. Introduction

The installed wind power generation capacity of the world stands at 650.8 GW as of the end of the year 2019 (World Wind Energy Association, 2020). However, this is expected to grow more as wind turbine technology improves and economies of scale drive the associated costs down. Many countries around the world continue to set ambitious targets for renewable system integrations into their power networks. China is pursuing a target to add 1000 GW of wind power generation capacity by the year 2050 (International Energy Agency, 2011). Moreover, projections show that by year 2030, 397 GW of wind power generation systems would be installed in the European Union (Wind Europe, 2020), whereas the U.S.A has set a target of 20% wind energy integration by 2030 (U.S. Department of Energy, 2008). Increasing wind penetrations will significantly impact grid dynamics and will become an integral part of power system planning and renewable integration studies (International Energy Agency, 2013). This is because of the differences between conventional synchronous generators and the different types of generators used in wind turbines. In addition, the intermittent nature of wind energy also contributes towards increasing power system instability and the subsequent issues associated with it.

Wind energy utilizes power converters, either partial scale as in the case of Doubly Fed Induction Generators (DFIG) or full scale as in the case of directly driven wind generators. Therefore, the converter technology and control design also determine the extent to which the wind generation system will affect the stability of the grid.

This paper provides an overview of stability parameters in conventional power systems and then discusses the challenges associated with high levels of wind power integration in the grid in terms of voltage stability, transient power stability and small signal stability. The paper also reviews the recent work that has been done to tackle these issues either by using additional compensation devices like STATCOMs and Capacitor banks or using controllers designed to utilize the intrinsic properties of wind turbine systems to alleviate system instability.

This paper is organized as follows: Section 2 provides an overview of power system stability parameters and their role in conventional power systems. Section 3 discusses the characteristics of wind and various wind turbine systems. It also discusses the various stability parameters in wind power systems and recent work done in improving the stability margins of wind integrated power systems. Section 4 concludes the paper.

2. Overview of the Stability Parameters in Conventional Power Systems

Stability parameters of conventional power systems are very well established in literature and are discussed as following.

2.1. Voltage Stability

A power system is said to be stable if at every bus, when subjected to a disturbance, the post-disturbance voltage values are within acceptable limits of the stable, pre-disturbance voltage values (CIGRE Task Force 38-02-10, 1993). The system enters a state of instability when the disturbance causes a progressive and uncontrollable drop in voltage. The main reason for this instability is the inability of the system to meet the reactive power requirements. When a short circuit fault occurs in the power system, for instance, the resulting increase in current results in a shortfall of reactive power in the system due to the immediate increase in the transmission network reactive demand as compared to the generation's ability to supply reactive power (Wang et al., 2016). Moreover, long transmission lines could also become a cause of unacceptable voltage drop when the generation cannot supply the required reactive power for the lines (Liu, 2015).

Voltage stability is a load influenced phenomenon (Venkata et al., 2013). This means that the instability is caused by the load side as opposed to the generation side. Voltage stability is usually classified into two classes: *Large-disturbance* and *small-disturbance*. Large-disturbance voltage stability is concerned with large disturbances occurring in the system, such as faults, loss of major lines or generation (Kundur et al., 1994). Usually, in such scenarios, power system protection comes into play immediately following the disturbance if system limits are exceeded to avoid cascading of the disturbance into the rest of the system. The fault is isolated and appropriate measures are taken to fix the causes. A long-term solution usually involves dealing with Under load tap changers (ULTC) or updating system infrastructure to better support the increase in load. Small-disturbance voltage stability is the ability of a system to sustain small, incremental changes in load and is usually determined instantaneously or on a short-term basis.
The most effective way to control voltage is by reactive power support (Venkata et al., 2013). Capacitor banks have been widely incorporated in power systems to provide voltage support and reduce active power loss by correcting the power factor of the system. Another device used widely is the tap changer, which could either be On-load Tap Changer (OLTC) or Under-load Tap Changer (ULTC), which works on the principle of variable turns ratio to maintain voltage stability. Recently however, FACTs (Flexible AC Transmission) devices like Static VAR Compensators and STATCOMs (Static Synchronous Compensators), etc., have become commonplace in providing voltage support by reactive power compensation.

2.2. Rotor Angle Stability

It is crucial for all the generators in a power system to be in synchronism. Rotor angle stability is the ability of a synchronous machine to remain in synchronism in a power system after being subjected to a perturbation (Venkata et al., 2013). Rotor angle refers to the angle between the Electromotive Force developed by the rotor and the voltage at the generator terminals. It is also defined by the relative angle between stator and rotor magnetic fields. In a no-load condition, the rotor angle (denoted by δ) is zero, as there is no opposing force on the rotor field from the stator field. Note that the power system is stable if $\frac{\partial P}{\partial \delta} > 0$ (where P is the power transferred into the network by the generator) and unstable otherwise.
The power fed by the generator into the system is a non-linear function of δ and will be at its maximum at an angle of $\pi/2$, beyond which it will start decreasing. Thus, it is desirable to keep the δ less than $\pi/2$. However, it is worth noting that keeping the rotor angle close to $\pi/2$ will keep it at risk of exceeding $\pi/2$, and thus resulting in instability. Whenever there is a loss of a major generator, onset of major load or fault in the power system, the rotor angle increases significantly, and may cross $\pi/2$, resulting in instability.
Rotor Angle stability can be classified into two categories: Transient and Small-signal. Transient stability is one of the most challenging phenomenon in large scale power systems and refers to the power system's ability to converge to a stable post-fault equilibrium following large disturbances such as severe faults, overloads, or loss of generating units. When a significant disturbance occurs, the electro-mechanical power imbalance is generated, which causes oscillations in speed deviations (and corresponding angle deviations) of generators in the system. If these oscillations cannot be diminished, transient instability occurs
Small signal stability is concerned with small fluctuations in power systems when subjected to small scale disturbances. If these oscillations can be suppressed such that the deviations of system parameters remain small for a considerable time, the power system remains stable (Wang et al., 2008). However, as the deviations keep on increasing, the power system can become unstable and enter a state of transient instability. Small signal instability is affected by a few factors such as initial operation conditions, strength of electrical connections among various components, controller designs, load variations, etc.

Various techniques have been employed to mitigate rotor angle instability which usually involve generator tripping, high speed fault clearing etc. Moreover, devices like power system stabilizers (PSS) have been used to provide supplemental damping to rotor oscillations via an electric torque which is in phase with the speed deviation ((Kundur et al., 1989)).

2.3. Frequency Stability

Power system stability is defined as the ability of a power system to maintain steady state frequency following a severe system upset, resulting in a significant imbalance between generation and load (Kundur et al., 2004). This usually occurs due to system upsets such as loss of generation, which could lead to imbalance between generation and load demand, or deficiency of electrical power in other words (Sabeeh & Gan (2016)). Frequency instability is usually associated with poor coordination or operating control, protection devices, weakness of equipment response and deficiency in generation (Sabeeh & Gan (2016)).
Frequency stability can be classified into short term and long-term phenomena (Kundur et al., 2004). Short term frequency instability can lead to creation of islands with inadequate generation and load balance, leading to blackouts within a few seconds (Sabeeh & Gan (2016)). Long term phenomena can be linked with factors like generation speed control and usually lasts from several seconds to a few minutes. To mitigate frequency instability, load shedding is often used around the world, where emergency procedures are outlined for various levels of load shedding depending on the intensity of instability. Moreover, Battery Energy Storage Systems (BESS) have also been employed to alleviate frequency instability.

3. Behavior of Wind energy systems and challenges associated with its high penetration into the power system

3.1. Wind forecast impact on wind energy stability

Wind is a highly variable source of energy, both in terms of geographical location and time. This makes wind power an uncontrolled or “non-dispatchable” source. Wind variability can cost a lot of money as more systems will need to be put in place to provide ancillary services. However, a study on the Italian power system concluded that even for renewable energy systems (Solar PV and Wind) with small imbalance contribution, wind forecast can effectively reduce costs for these services (Puglisi et al., 2017). Accurate wind prediction is needed for effective balancing of demand and supply as wind penetration in a power system increases. Lower prediction errors mean lower regulation balancing costs since less energy needs to go through balance settlement (Holttinen et al., 2013).

A study of ramping in the ERCOT system concluded that a wind ramp magnitude of at least 25% occurs once every other day, with ramp rates not exceeding 10% per minute of the total wind generating capacity (Wan, 2011). It was noted that the majority of up ramp events occurred in the afternoon hours and the majority of the down ramp events occurred in the morning hours. However, with the wind generation contribution to the overall generation still relatively low, the load fluctuations still dominated the overall net load fluctuations.
Considering the current wind power penetrations in most grids around the world, the current wind forecasting accuracies suffice. However, as wind power integration increases, fluctuations will more likely cause instability in the system as conventional generators are put offline and the power system inertia consequently decreases. Therefore, accurate wind prediction models and techniques will be needed as wind penetration into the systems increase. Currently, the statistical methods are employed for short term wind prediction with absolute errors within 3 degrees (Accuweather, 2016). However, this is subject to the time of the year and the geographical and weather characteristics of the measurement regions.

3.2. Impact on Power System Inertia

Having considered the problems associated with wind, the subject of wind power effects on the power system can now be approached. As has been addressed in the earlier sections, power systems have been historically based around large synchronous generators connected to a strongly meshed transmission network, with the dynamic characteristics of such systems being well understood (Flynn et al., 2016). However, wind turbine systems are interfaced with the grid through power electronic circuits and therefore, fail to provide inertia to the system due to this indirect link. At higher levels of penetration in the system, wind energy poses a threat to the power system stability because conventional generators will be put offline as a consequence, thereby reducing overall system inertia. However, it must be noted that wind generation in itself does not pose any challenges to the stability of the grid and could even enhance system capabilities in some cases by employing intelligent control (Flynn et al., 2016).

3.3. Types of Wind generators and their impact on Power system stability

Various generator technologies and wind turbine systems are being explored for use in wind power generation systems. The first type is a Fixed Speed Turbine system with a Squirrel Cage Induction Generator (SCIG). This is one of the first technologies that was used and has the main advantages of lower cost of mass production, being relatively easy to produce, and having a robust system (Li & Chen, 2008). It has also been reported to reduce power system oscillations (Widiastuti et al., 2019). Moreover, it can operate stall-controlled machines at constant speeds when connected to the grid, which provides a stable control frequency.

However, the rotor excitation for SCIG is provided by the stator terminal, which means that it absorbs reactive power from the network (Gil-Gonzalez et al., 2019) and will not be able to support grid voltage control, as well as having very low Fault Ride Through Capability (FRT). Additionally, during disturbances, it will draw in large amounts of reactive power to recover air gap flux (Hazari et al., 2019), further destabilizing the grid. Usually, capacitors connected in parallel provide it with reactive power compensation, which is sufficient during small disturbances but not the large reactive power needed during transient period. However, Superconducting Magnetic Energy Storage (SMES) have also been proposed for reactive power compensation due to their large capacity and a very fast response (Gil-Gonzalez et al., 2019). (Hazari et al., 2019) also proposed using small scale Variable Speed Doubly Fed Induction Generation system alongside large scale SCIG to provide it with reactive power support. Moreover, the fixed speed operation causes the speed fluctuations of wind to be directly translated to electromechanical torque variations, thus mechanically stressing the turbine.

The second type is a Directly Fed wind turbine, with further categorization into Electrically Excited and Permanent Magnet type generators. This comes with the advantage of a simplified drivetrain, high reliability, efficiency by eliminating the gearbox and high-power density in the case of PM generators. However, a full-scale convertor is used in these wind turbines, driving up costs of the system (Li & Chen, 2008). Moreover, since all the power has to pass through the converters, there is more power loss. On the other hand, a full converter allows more control over the generator, resulting in the best fault ride through capability of the Wind power generation systems.

One of the mostly used generator types is the Doubly Fed Induction Generator (DFIG) (Li & Chen, 2008), which is mainly preferred over other types because it is a variable speed generator. It is equipped with a multistage gearbox and the rotor is fed through a power electronic convertor while the stator is directly connected to the grid (also known as partial scale converter). DFIG are used for their flexibility, high energy transfer ability and relatively low cost (Morshed & Fekih, 2019). Other advantages include its efficiency due to its capability to operate near its optimal turbine performance, lower mechanical stress, and the fact that

torque oscillations are not transferred to the network (Widiastuti et al., 2019). Moreover, the power converter it uses has a rating of about 20%-30% of the total machine power (Li & Chen, 2008) (Xu et al., 2019), which means only this fraction of power has to pass through the converter and face converter inefficiencies. However, grid connected DFIGs are very sensitive to low frequency power oscillations (also termed as small signal instability (Liu et al., 2020) (Widiastuti et al., 2019)), typically in the ranges of 0.2-2.5 Hz, that typically occur in interconnected power systems (Morshed & Fekih, 2019). This is due to the DFIG stator being directly coupled with the grid (Liu et al., 2020) and can lead to large signal instability if the system loses the equilibrium point. These fluctuations can be challenging to damp out and can potentially lead to wide area blackouts if not dealt with properly. (Widiastuti et al., 2019) and (Xu et al., 2019) both demonstrate small signal instability caused by high penetration of DFIGs wind generation systems. Moreover, the fact that the DFIG rotor is connected to the grid through a power converter presents a case of mechanical and electrical characteristics being decoupled (Liu et al., 2020). This results in the inability to provide inertia to the grid during perturbations, as the kinetic energy of the rotating mass of the wind turbine is isolated from the grid.
Detailed comparisons of the different generation types are discussed in (Li & Chen, 2008).

3.4. Transient Stability

Random oscillations due to faults, sudden changes in large loads and lightning can possibly lead to transient instability and subsequently lead to voltage collapse of the power system, causing blackouts (Morshed, 2020). Additionally, with large scale integration of intermittent renewable resources like wind energy, the stability of the grid had become more vulnerable. Moreover, interaction of DFIGs and other types of generators used in Wind power with the preexisting conventional synchronous generators in the grid makes the study of transient stability more difficult (Yi et al., 2020) because of different dynamic characteristics.

A simulation study on the IEEE 14-bus system is conducted in (Xia et al., 2018), where it was confirmed that the system stability decreases as the wind power penetration level in the grid increases. Moreover, it is demonstrated how the wind turbine locations and wind speed affect power system stability, and the adding of capacitors at the generator bus greatly alleviates transient instability in the system.

The dynamic interactions among conventional synchronous generators and DFIG wind power generation systems, and subsequent system nonlinearities are considered in (Morshed, 2020). A control approach is proposed which resulted in a faster post fault recovery time and better transient stability compared to conventional approaches such as Power system stabilizers (PSS), Power Oscillation Damping (POD) and Interconnection-and-Damping-Assignment Passivity-Based-Control (IDA-PBC). Additionally, it has the ability to reduce the order of the feedback linearized power system, making the control design simple and cost effective.

Transient stability in wind-thermal bundled system is considered in (Liu et al., 2020). Problems of “weak grid” arises when the generators are far away from the load centers, resulting in higher equivalent reactance as compared to the equivalent reactance near the load. This results in problems of transient voltage and frequency instability. This paper proposes to improve transient voltage and frequency stability by using an adaptive terminal sliding mode control algorithm based on the rotor flux linkage of the DFIG. Using this algorithm, the transient stability can be improved within milliseconds following a fault by providing active and reactive power control from the DFIG, which is much faster than minute-level dispatch control during the current transmission system fault. The experimental results in the paper confirm this.

Improving the wind penetration capability of a power system is demonstrated in (Farrokhseresht et al., 2019) where transient stability studies are carried out with full converter wind systems using sensitivity analysis. Various converter parameters are varied and their relationship with improving the wind power stability was investigated. Results showed that the influence of wind turbine on the transient stability depended on various Fault Ride Through (FRT) parameters.

Fuzzy logic has been proposed in (Hazari et al., 2019) to be used in the Rotor Side Converter (RSC) controller of DFIG and SCIG wind farms to improve its FRT and transient stability. The proposed method was tested on the IEEE nine-bus power system and the results were compared with conventional control algorithms application. It was concluded that the proposed method is an effective solution to enhance the transient stability of multi-machine, Wind farms integrated power systems.

A transient stability study was carried out in (Sajadi et al., 2019) and (Sajadi et al., 2019) for stability related issues of short- and long-term faults, respectively, on the power system with offshore wind power generation systems connected. A practical and scalable methodology for transient stability analysis of power systems planning study is developed for integration of offshore wind power plant. Both studies used the 63k-bus test system that represents the US Eastern Interconnection, with a 1000 MW of offshore wind power integrated. Several conclusions were drawn from the short-term fault study. Firstly, this paper suggests that transient stability is not affected by the addition of the offshore wind plant. Moreover, it was revealed that the Critical Clearing Time is highly related with all major parameters like dynamics of active power, rotor angle, reactive power following faults. Finally, it was found that with integration of an offshore plant, the transient frequency stability depends on the size of the faulted system’s component and its inertial contribution (Sajadi et al., 2019). Similarly, various conclusions were drawn from the long-term fault study. It is shown that transient stability of the overall system is improved because number of oscillation modes present following a fault are reduced. Moreover, increased reactive power support at the Point of Interconnection (POI) helps damp out voltage oscillation incase following loss of offshore components. It was also shown that the maximum level of wind power generation provided the worst-case scenario in terms of rotor angle oscillations (Sajadi et al., 2019).

3.5. Small Signal Stability

The growing wind power penetration has brought a lot of challenges for small signal stability due to the stochastic nature of the wind (Morshed & Fekih, 2019). While in traditional grids, fast load variations on a small scale is what caused small signal instability, the integration of wind power into the grid now causes problems from the source side as well. Thus, it becomes even more crucial to have effective measures to damp out oscillations before they can progress to large signal instability in wind integrated power systems.

This paper verifies through theoretical analysis and experimental tests that small signal instability occurs in DFIG systems (Liu et al., 2020) (Widiastuti et al., 2019). It was shown that deeper the voltage dips are, and higher the rotor speed of the DFIG, more vulnerable the system becomes to small signal instability. Moreover, it is pointed out that small signal stability is improved with a narrower PLL bandwidth, increasing the RCCL bandwidth and properly injecting active current into the grid. Moreover, small signal stability during weak grid severe fault is also improved by implementing the two proposed Low Voltage Ride Through (LVRT) control strategies, i.e. the optimal current proportion scheme and the PLL bandwidth selection method.

An eigenvalue analysis has been carried out in this paper for a multi machine system with and without DFIG wind power system to determine impact on small signal stability of the system (Xu et al., 2019). The test systems used are the IEEE 9 and 39 bus systems. Various analyses were carried out regarding the bus placement of DFIG wind farm to test for stability. It was concluded that wind farm penetration at bus 1 and 3 in the 9-bus system, and bus 37 in the 39-bus system resulted in best stability due to improvement in the minimum eigenvalue.

A small signal stability of the type-3 wind turbine (i.e. DFIG) is studied considering the Rotor Side Converter (RSC) and the Grid Side Converter (GSC) in (Zhu et al., 2019), by establishing an impedance model. It was confirmed here too that the system stability reduces by increasing the PLL bandwidth. It was also found that with higher control delay, system stability is significantly reduced. Various other control parameters are tested on and related with small signal stability. It was finally concluded that consideration a GSC in important in accurate small signal stability analyses study.

This paper analyzes the small signal stability analysis of a type-4 wind turbine (i.e. Full converter wind turbine) in series compensated network using state-space and impedance models (Xu et al., 2020). Detailed testing is carried out considering all control stages and considering various grid dynamics and wind turbine mechanical and machine dynamics.

A study on Multi-Terminal HVDC system integrated with a diode rectifier-connected offshore wind power plant is carried out in (Bernal-Perez et al., 2020). The study covers both connected WPP operation and islanded. Variable offshore ac-grid frequency and a dynamic diode rectifier model have been considered for adequate dynamic modelling, which are then used to carry out small signal stability analysis in both modes of operation. The model is also used to assess system robustness against parametric uncertainties, communication delays and the power level to insure integration of the offshore wind plant into the grid.

Another coordinated control strategy for Multi-Terminal Direct Current (MTDC) systems with wind farm integration is proposed in (Yang et al., 2020). They use a PLL-less control utilizing DC-link voltage dynamic for a single Receiving End Controller (REC) and the autonomous power sharing and primary frequency regulation among multiple RECs utilizing DC droop characteristics. Comparative simulation studies on the Zhangbei four-terminal DC system in China is carried out, and it was concluded that low inertia and small signal stability issues are significantly reduced.

3.6. Voltage Stability

Voltage stability studies have shown that replacing synchronous generators with converter connected Renewable Energy Systems like Wind power decreases the voltage stability margin of the power system (Vittal et. al., 2010). This is due to the reduced reactive power availability in the system. Conventionally, vector control is used for DFIG converter, which does not provide voltage support during grid faults (Jiao & Nian, 2020). Various techniques have been used to improve voltage stability in wind power generation system integrated power systems.

Time domain simulation studies have been implemented to verify the stability and effectiveness of Grid Forming Control for DFIG in both grid connected and islanded mode (Jiao & Nian, 2020). Grid forming control has been shown to help renewable power generations to improve the inertia of power system and can help in voltage stability of wind power connected systems. Similarly, (Farrokhseresht et al., 2019) explores various parameters in Full converter wind turbines to mitigate voltage instability through sensitivity analysis. Moreover, voltage stability of offshore wind farms is also analyzed in (Sajadi et al., 2019).

A comparative study is carried out in (Fayek et al., 2019) between various combinations like using STATCOM, PID controller based STATCOM or using just a capacitor bank. It was concluded that using STATCOM beside PID controller provides the best performance in improving voltage stability than just using a capacitor bank.

A control strategy is proposed in (Sarkar et al., 2020) to enhance the reactive power support of wind power plants, considering grid codes. It is found that an improvement of 5% can be achieved in maximum power transfer during stressed voltage conditions using this method. This helps in reducing voltage instability better than conventional control strategies.

3.7. Fault Ride Through Capability of wind systems

The ability of a wind farm to remain connected to the grid during fault conditions referred to as it fault ride through (FRT) capability (Liu and Kong, 2014). Since wind power is an intermittent and thus non-dispatchable source of power, with higher penetration into the grid it becomes crucial to enhance FRT capabilities of wind power generation systems to ensure smooth operation of the system (Hazari et al., 2019). The concept of FRT is intertwined with the aforementioned sections on various stability parameters of wind power integrated power systems. Some other work not previously mentioned has been done to improve the FRT capabilities of Wind power systems.

An Adaptive direct power controller (ADPC) is designed using the backstepping approach for RSC and GSC in DFIG based wind farms (Roy et al., 2019). Active power, reactive power and DC link voltages are tracked in this scheme to ensure that the wind farm remains connected to the grid. Simulation studies carried out with the proposed method show that the ADPC provides sufficient reactive power support when faults occur, thus significantly improving the FRT capabilities of DFIG based wind systems.

4. Conclusion

This paper overviews the traditional power systems considering stability parameters like voltage stability, rotor angle stability and frequency stability. Moreover, wind power systems are reviewed. Firstly, the types of wind turbine systems are reviewed, and the instability problems associated with each type are also visited. Then various stability issues associated with high integration of wind power systems is reviewed and all recent work that has been done to improve stability of wind power systems is also considered.

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