Integration of Large Wind Farms into Utility Grids (Part 2 - Performance Issues)

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Abstract**-- This paper presents a discussion of the two major types of wind turbines, conventional induction generators and doubly-fed induction machines. Performance issues related to the dynamic behavior of both wind turbines are discussed. Example simulations from a major study of the integration of wind farms into a utility grid are presented to illustrate the performance issues discussed. In addition, a discussion is given on some of the potential interactions between wind turbine generators and other transmission equipment such as series compensation and HVDC; this is also illustrated with simulated examples.**

Index Terms**—Wind turbine generators, wind energy, system reliability, modeling wind farms**

I. INTRODUCTION

Renewable energy offers a promising and exciting means of generating electrical power. Wind energy is perhaps the most mature of the various renewable energy technologies and has recently gained much favor both in the USA and abroad. Proposals for wind developments in the hundreds of MWs are currently being considered. Interconnection of these developments into the existing utility grid poses a great number of challenges.

In this paper an overview of wind farms and issues concerning their integration into major electric utility grids is presented. Two major types of wind turbine generators, induction generators and doubly-fed machines, are widely used. Their respective characteristics and modeling needs are described. System reliability issues that need to be addressed particularly with respect to the installation of large wind farms are discussed. Also a discussion is given on the need and means of reactive compensation for large wind farms for the purpose of ensuring system stability.

Phenomena that are well understood for synchronous generation must be reviewed in light of the new technologies in wind generation. A discussion is presented on the potential for interactions between wind generation and series compensation and HVdc converters.

II. TYPES OF WIND TURBINE TECHNOLOGY

Wind turbine generators may be categorized into two major types (i) constant speed units, and (ii) variable speed units. Constant speed wind turbine generators essentially run at a relatively fixed mechanical speed. These units are most typically induction machines; that is, high-efficiency induction motors running at super-synchronous speed. Slight variations in the generator speed may result from changes in system conditions, however, the variations in the speed on the unit are typically less than one percent.

The most common type of variable-speed wind generation is through the use of doubly-fed induction generators (DFIG) (see Figure 1). This design employs a series voltage-source converter to feed the wound rotor of the machine. By operating the rotor circuit at a variable AC frequency one is able to control the mechanical speed of the machine. In this design the net power out of the machine is a combination of the power coming out of the machine's stator and that from the rotor and through the converter into the system.

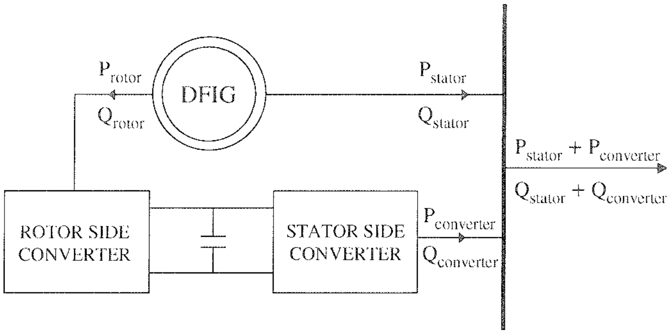

Figure 1: Doubly-fed induction generator.

The fixed speed induction generator designs, which typically employ a conventional induction machine, are simpler in design and do not incorporate power electronics and thus do not have issues relating to harmonic injection into the system. The major advantages of the variable speed designs are that they have a higher efficiency (that is, have a higher ability to capture wind energy by varying the speed of the machine with wind speed) and better power quality (that is, by storing the energy due to a gust of wind in the shaft, the power output of the unit is kept relatively constant). In addition, doubly-fed

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induction machines can produce and/or absorb reactive power and thus regulate their apparent power factor. In contrast, the standard induction generator designs consume reactive power and thus typically employ shunt compensation both at the location of the wind turbine and possibly at the substation connecting the wind farm to the system.

III. ELECTRICAL MODELING AND PERFORMANCE OF WIND GENERATORS

A. Conventional Induction Generators

The modeling and performance of conventional induction machines is well known. Because the generators have no internal excitation source, these machine absorb reactive power from the system and thus require the deployment of shunt capacitor banks at the terminals of the wind turbine generator to bring the net power factor of the unit to about 0.98 to 0.99 (from a typical 0.89 pf when uncompensated). Furthermore, additional shunt compensation may be required and deployed in the collector system and/or at the substation connecting the wind farm to the utility grid. Such compensation would be for the purpose of maintaining an acceptable power factor at the point of interconnection to the grid.

Similar to induction motors, induction generators can experience instability following a large disturbance. Should a disturbance push the machine beyond its pull-out torque (the peak torque on the machine speed-torque curve) the machine will become unstable and generator speeds keep increasing (and voltages collapses) until protection separates the unit.

Stability can be greatly enhanced (to levels comparable to those in synchronous generation) if, in addition to the “fixed” shunt compensation for power factor correction, provision is made for some level of dynamic compensation (in the form of, for example, an SVC, or a STATCOM) to “kick-in” immediately upon a disturbance. An example of this is demonstrated in the next section.

As previously indicated, conventional induction generators are essentially constant speed units, and, therefore, fluctuations in mechanical power are quickly transferred to the grid.

B. Doubly-Fed Induction Generators (DFIG)

The performance of DFIG is quite different from conventional induction generators. Although variable speed drive systems are familiar to engineers in the motor-drives industry, and although DFIG already holds a significant share of the wind market, modeling and performance aspects of this type of generation is not widely known and not readily available in commercial software tools. A companion paper [1] summarizes recent efforts in helping bridge this information gap. The paper describes both a detailed (EMTP-level) and a simplified (“transient-stability”) dynamic model suitable for the analysis of DFIG wind generation.

In addition to DFIG's ability to feed the rotor with ac power of variable frequency (thus allowing for variable speed operation) a distinct aspect of DFIG is the fact that currents are tightly controlled (with loop speeds typically ranging in the thousands of rad/sec). This means that, for example, controls have the ability to, within limits, hold electrical torque constant (as opposed to the relation between torque and angle in synchronous machines). Thus, rapid fluctuations in mechanical power can be temporarily “stored” as kinetic energy, thus improving power quality (eventually, however, outer control loops will modify current orders so as to restore speeds to their optimum setting).

As in the case of conventional induction generation, the performance of DFIG for large disturbances (such as the three-phase faults normally required by US criteria) requires thorough analysis since it might lead to the separation of the unit. Unlike the case of conventional induction generation, however, the process leading to separation might not be readily apparent from dynamic simulation results.

The concern in DFIG is usually the fact that large disturbances will, as in the case of synchronous generation, lead to large initial fault currents, both at the stator, and, due to the laws of flux conservation, at the rotor as well. These high initial currents will, of course, flow through the rotor-side converter, which could be a concern given that voltage-source converters are less tolerant to high currents than conventional converters. Furthermore, this initial surge following the fault includes a “rush” of power from the rotor terminals towards the converter. Due to low voltages at machine terminals during a disturbance, the stator-side converter is limited in its ability to pass power to the grid. Consequently, the additional energy goes into charging the dc bus capacitor and thus dc bus voltage rises rapidly, depending on the design of the converter controls. This may give rise to protection acting to short-circuit the capacitor (via a crowbar) in order to protect the converter power electronic components. This, in turn, may lead to the tripping of the unit. Reference [4] describes the issue of controlling the dc bus voltage for another type of wind turbine generator that incorporates a series-connected voltage-source converter.

C. Application Example

A recently-completed study[1] helps illustrate some of the above concepts regarding wind generation performance. The study investigated several alternatives for integrating between 500 MW and 1000 MW of conventional induction wind generation into the Dakotas transmission system, for export to the Twin Cities, Wisconsin, Iowa and Illinois. Among the

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[1] “Montana-Dakotas Regional Study, East-Side (MAPP) Studies, Phase 1”, for Western Area Power Administration. Report available at: http://www.wapa.gov/ugp/default.htm.

alternatives investigated, one comprised a combination of 500 MW coal generation at a new 345 kV station near Hettinger, and five new 100 MW wind parks, one at Hettinger (but connected at the 230 kV station), and the other four connected at the Marmarth 230 kV (midpoint between Baker and Bowman), Bowman 230 kV, Belfield 230 kV, and New England 115 kV stations.

The studies showed, however, that even though the conventional induction generators were assumed to be compensated to 0.98-0.99 power factor by mechanically switched shunt compensation, contingencies in their vicinity would lead to their “pulling away” from the interconnected system (and carrying the new 500 MW coal generation with them). Shown in Figure 2 is an example of the performance at the Hettinger wind park following a normally-cleared 3-phase fault at the Hettinger end of a proposed Hettinger-Ft. Thompson 345 kV line.

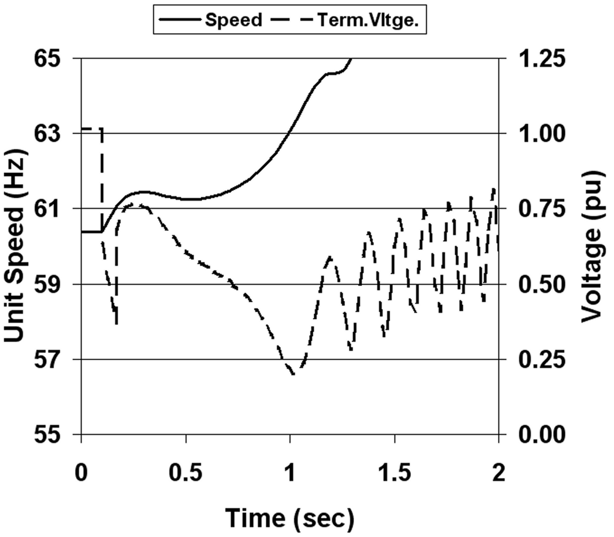

Figure 2: Conventional Induction Generation Example. 3-Phase fault in the vicinity of Wind farm. (reproduced with permission from Western UGPR)

The results show that although initially “stable”, the induction generation gradually pulls away as the voltage decays further and further, in a process very similar to that of inductor motor loads stalling.

Further analyses showed that the contingency was not resolved even if the 500 MW of coal generation were tripped within 200 ms after fault inception. In order to regain stability, a minimum of 700 MW of generation had to be tripped within 200 ms after the fault.

Among the several reinforcement alternatives investigated to resolve this situation was the furnishing of dynamic voltage support. Shown in Figure 3 (which corresponds to the same fault as in Figure 2), is the result of deployment of 70 Mvars of SVCs at each of the five wind parks. The figure illustrates the beneficial impact of such dynamic compensation in providing for fast voltage recovery, and a consequently stable performance, without resorting to generation tripping.

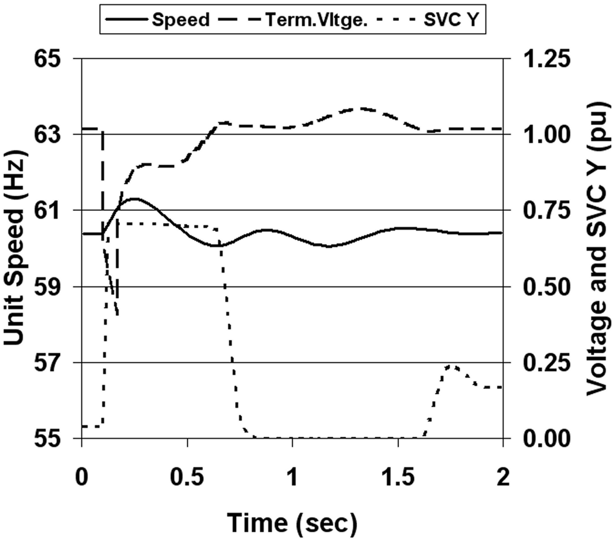

Figure 3: Conventional Induction Generation with SVCs. (reproduced with permission from Western UGPR)

For the purposes of this paper, the benefit of installing DFIG generation as opposed to conventional induction generation was studied. Models and parameters were as described in [1]. No power-factor correction was assumed in this case, with DFIGs furnishing their own reactive needs. The stability performance of DFIG for the same disturbance is shown in Figure 4.

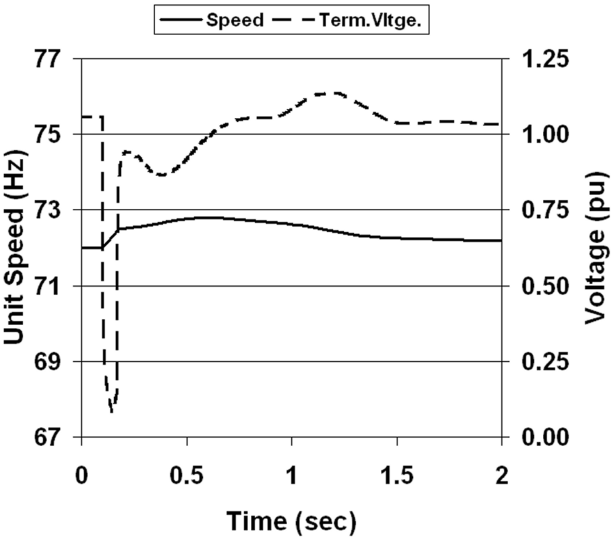

Figure 4: DFIG Generation. Same contingency as in Figures. 2 and 3.

The results suggest a stable performance; comparable to that with SVCs in Figure 3. During the fault, terminal voltage sags lower with DFIG than with conventional induction generators. This is the combined result of a lack of shunt compensation, as well as of the de-exciting effects of current controls, in their effort to restore current levels. Upon fault clearance, however, voltage is rapidly restored to pre-contingency levels. Closer analysis, however, suggests that, as discussed in [1], immediately following fault inception there might be a significant accumulation of charge (and thus overvoltage) at the capacitor linking the stator- and rotor-side converters. This is suggested by the results in Figure 5. An assessment of whether or not this might lead to the unit tripping requires simulation with more detailed 3-phase models of DFIG (EMTP-type, as described in [1]), as well as close consultation with the manufacturer. Figure 6 shows the expected response if wind generators are assumed to short-circuit (crowbar) their converters upon fault inception, and to trip three cycles later. .

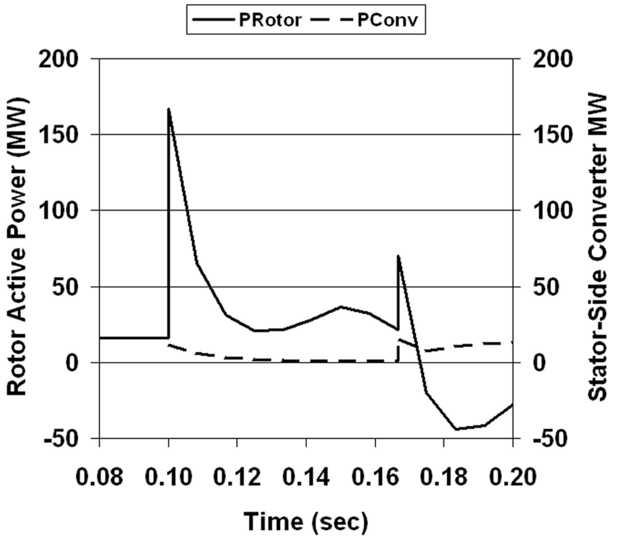

Figure 5: DFIG Generation. Active Power flowing in and out of the converter capacitor.

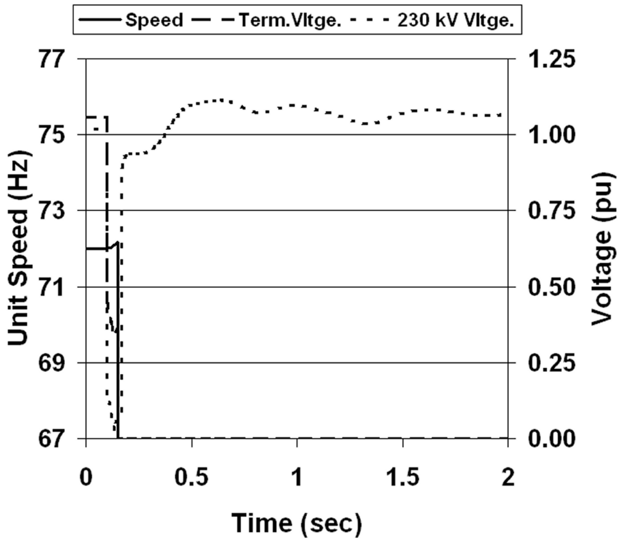

Figure 6: DFIG Generation. WTG trips due to protection.

IV. POSSIBLE INTERACTION CONCERNS

Wind turbine generators exhibit modes of mechanical oscillation for both the tower structure and the turbine. The tower, blades and turbine assembly will have both bending (deflection) modes and torsional (twisting) modes [2,3].

Subsynchronous resonance (SSR) between turbo-generators and series-compensated transmission lines is a well understood and documented subject in the literature [5]. Similarly, the subject of subsynchronous torsional interaction (SSTI) between turbo-generators and HVDC systems has been studied in detail in the past [6, 7]. Similarly, these phenomena may be of concern in relation to mechanical modes of vibration on wind turbines. In addition, in the case of wind turbine generators operating radially on the end of a series compensated transmission line, there is the potential for induction machine self-excitation [8].

These concerns can be illustrated using the simple models shown in Figure 7. Figure 8 shows the damping torque in pu on machine MVA base for a range of compensation levels for the first system in Figure 7. This is for a generic induction generator while operating at near synchronous speed. The resonance is clear and becomes more pronounced as compensation level increases.

Figure 9 shows a time simulation of the first system; that is, a wind farm on a series compensated line. One of the consequences of the type of resonance discussed above is induction machine self-excitation, as seen in Figure 9.

Similarly, in a system such as the second system shown in Figure 7 there is a potential for interaction between the HVDC controls and mechanical modes associated with machines in the wind farm.

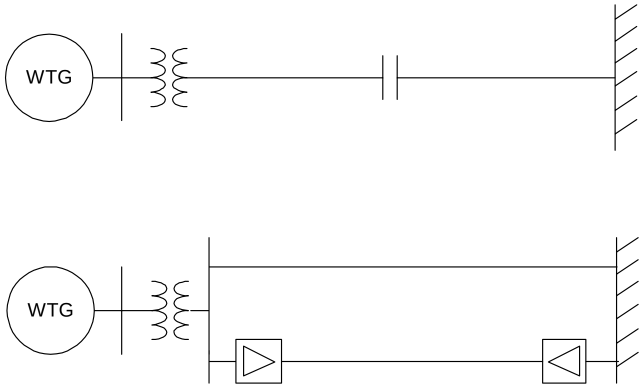

Figure 7: Simple system with wind farm and (i) series compensated line, (ii) HVDC system.

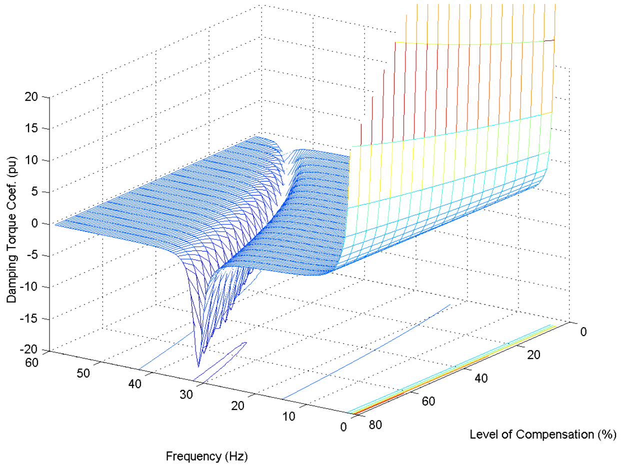

Figure 8: Damping torque versus frequency as seen on the wind turbine generator rotor for a wind farm fed by a radial line that has been series compensated.

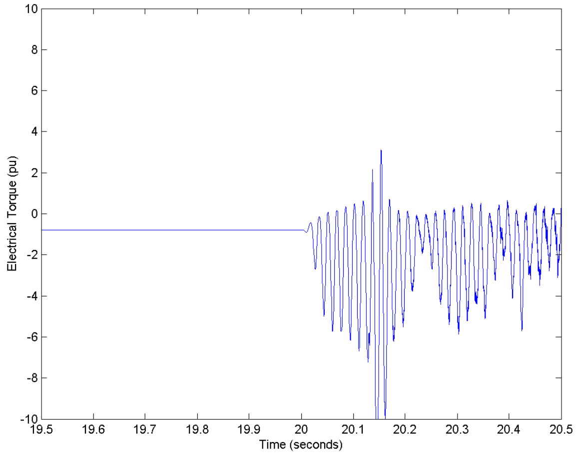

Figure 9: Time simulation showing self-excitation. Series capacitor switched in at 20 seconds.

In the case of SSTI between a wind farm and an HVDC system, the solution would be similar to that presently used to mitigate SSTI between HVDC and conventional synchronous turbine-generators. That is, the implementation of a supplementary damping controller in the HVDC system [7]. In the case of resonance between the induction machine and a series capacitor, the problem may be resolved by the application of a TCSC, filters or control modifications on the generator. In both cases, detailed studies are necessary to identify the potential for resonance and a suitable mitigation design.

V. SYSTEM RELIABILITY ISSUES

A generally accepted minimum reliability requirement is that a power plant should be stable and not trip due to a system disturbance resulting in normal clearing of a single-transmission element. In addition, systems are designed to have adequate spinning reserve to protect against the loss of the single largest unit on the system and thus prevent load-shedding for such an event. For units other than the largest unit on the system, the loss of the energy due to tripping of the unit is a commercial and contractual issue under deregulated operation. However, the loss of such a unit should not cause cascading outages.

For large wind farms there are a number of major issues that need to be addressed during the design stages of the farm. Both for the conventional induction generator type units and the DFIG wind turbine, generators might trip for low voltage conditions more quickly than conventional synchronous generator power plants. For induction generators this is driven by the potential to over-speed the machine beyond its pull-out torque at which point the machine races away. For doubly-fed induction generators, on the other hand, there exist issues related to the control and protection of the voltage on the converter dc bus that can lead to the tripping of the unit on under-voltage conditions which a synchronous generator could instead easily endure. Examples of both effects were given in Section III.

If not addressed at an early planning stage, the performance of the wind farm may be in violation of system criteria since, in the best of cases, it may require an increase in spinning reserve requirements, and, in more serious situations, it may lead to system cascading, particularly with wind generation in the vicinity of load centers, where a relatively minor contingency leading to the outage of large generation or transmission (N-1) could escalate into a severe event following the “sympathetic” tripping of a number of wind farms (N-2 or more).

Additionally, in both designs, there is the need to provide an uninterruptible power supply (UPS) for relatively prolonged under-voltage conditions to ensure that the turbine controls power supply does not fail.

Finally, as discussed in Section IV, for wind farms being proposed in the vicinity of HVDC systems or series compensated transmission lines, there is the added need to investigate possible detrimental interactions between the wind turbine generators and transmission equipment.

As large wind farms become more prevalent in bulk transmission grids the issues identified above become of increasing importance with respect to the system performance standards, raising questions such as,

- For a system with large amounts of wind generation, is a system disturbance likely to result in many wind farms tripping off-line?
- Is system protection properly coordinated with nearby wind farms to prevent tripping of wind farms due to prolonged fault clearing events?
- Thus, should a criterion be developed for “ride-through” requirements of the wind turbine generators for transient voltage sags, during and after a system disturbance?

These and other questions can be readily answered and addressed with judicious planning studies. As shown in Section III for conventional induction generator units, the proper deployment of dynamic var compensation systems can address the stability concerns with large wind farms. Furthermore, application of UPS and proper coordination between under voltage relay settings for the wind turbine generators and transmission protection relaying can alleviate concerns with tripping units on low voltage during a fault. For the doubly-fed induction machines, control modifications may be necessary in collaboration with the manufacturer to minimize the chances of units tripping during faults.

If tripping is deemed to be inevitable under certain scenarios, comprehensive studies should be conducted to ensure that such tripping does not escalate into more severe events.

VI. SUMMARY AND CONCLUSIONS

This paper has presented a discussion on the two major types of wind turbine generators, convention induction machines and doubly-fed induction generators. A presentation has been given of the performance issues relating to the integration of large wind farms using these technologies into major utility grids. As shown, the major concerns are:

1. proper coordination and design of controls and protection of the wind turbine generators to minimize sympathetic trips,
2. proper levels and types of var compensation to ensure stable operation of the wind farm during disturbances and weak system conditions following a contingency,
3. proper attention to the possibility of interaction between wind turbine generators and nearby series compensation and/or HVDC transmission equipment.

Such issues can be addressed if properly studied during the planning phase of a wind farm and in collaboration with the manufacturer and other experts.

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