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Impact of Increased DFIG Wind Penetration on Power Systems and Markets

Final Project Report

Power Systems Engineering Research Center

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Power Systems Engineering Research Center

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Executive Summary

This project examines the impact of increased penetration of doubly fed induction generator (DFIG) based wind generation on power system dynamic performance and hence reliability. DFIG wind turbines have controls that effectively isolate the inertia from the grid. In addition, large wind farms are typically connected to the grid at lower voltage levels resulting in higher fault currents. As a result, with the increase in penetration of wind generation, transient stability, the overall frequency response, regulation, voltage response, fault ride-through capability, and load following capability may be affected. This project analyzes the impact of increased wind penetration under two different scenarios: a) Increased wind penetration with concomitant displacement of aged conventional generation and b) Increased wind penetration without any decrease in existing conventional generation and determine conditions and conditions under which the increased wind penetration will result in violation of reliability criteria. The important aspects (such as low voltage ride through (LVRT), dynamic reactive compensation as per the requirements of FERC standards) are also studied. The effects of increased wind penetration on frequency stability are analyzed and solutions to mitigate the resulting problems are explored.

When the reliability criteria are violated due to the increased penetration of wind turbines, the impact of this reduced level of reliability on market operation is also examined. The analysis models the reliability impacts of wind-power and determines the impact on market mechanisms, such as day-ahead reserves on such concerns. The study focuses on markets characterized by i) energy, reserves and capacity bidding, and ii) market settlement. In addition, technical solutions to maintain the requisite reliability standards are examined and the impact of these solutions on market mechanisms are analyzed.

In this report, each aspect of impact of increased DFIG penetration on 1) small-signal and transient stability, 2) frequency stability, 3) voltage response, and 4) market operation is studied in detail and presented as a separate part. An overview of the work accomplished in each part is presented below:

Part I. Impact of Increased DFIG Penetration on Small-Signal and Transient Stability (work done at Arizona State University)

Growing environmental concerns and attempts to reduce dependency on fossil fuel resources are bringing renewable energy resources to the mainstream of the electric power sector. Among the various renewable resources, wind power is assumed to have the most favorable technical and economical prospects. When deployed in small scale, as was done traditionally, the impact of wind turbine generators (WTGs) on power system stability is minimal. In contrast, when the penetration level increases, the dynamic performance of the power system can be affected.

Among the several wind generation technologies, variable speed wind turbines utilizing doubly fed induction generators (DFIGs) are gaining prominence in the power industry. As the performance is largely determined by the converter and the associated

controls, a DFIG is an asynchronous generator. Since DFIGs are asynchronous machines, they primarily have four mechanisms by which they can affect the damping of electromechanical modes (since they themselves do not participate in the modes):

1. Displacing synchronous machines thereby affecting the modes
2. Impacting major path flows thereby affecting the synchronizing forces
3. Displacing synchronous machines that have power system stabilizers
4. DFIG controls interacting with the damping torque on nearby large synchronous generators.

This part of the report addresses the first two mechanisms listed above. Following a large disturbance, the restoring mechanisms that bring the affected generators back to synchronism are related to the interaction between the synchronizing forces and the inertia of the generators in the system. In the case of a DFIG, however, the inertia of the turbine is effectively decoupled from the system. The power electronic converter at the heart of the DFIG controls the performance and acts as an interface between the machine and the grid. With conventional control, rotor currents are always controlled to extract maximum energy from the wind. Hence, with the increased penetration of DFIG based wind farms, the effective inertia of the system will be reduced and system reliability following large disturbances could be significantly affected.

In order to examine the impact on small signal stability a systematic approach to pin point the impact of increased penetration of DFIGs on electromechanical modes of oscillation using eigenvalue sensitivity to inertia is developed. In evaluating the sensitivity of specific modes of oscillation with respect to inertia, the DFIGs are replaced by conventional round rotor synchronous machines with the same MVA rating. The sensitivity analysis is performed only for the system where all the generators are synchronous machines. The sensitivity analysis identifies electromechanical modes of oscillations that are detrimentally and beneficially impacted by increased DFIG penetration. The method inherently accounts for the insertion point of the DFIGs in the network. The results of the sensitivity analysis are then confirmed using exact eigenvalue analysis performed by including the DFIGs in the base case and in the increased wind penetration case. Three specific cases of transient stability are also examined. In this analysis the modes observed in small signal analysis are excited by placing specific faults at buses close to the generators having the largest participation factors in the oscillatory modes identified. Transient stability behavior in terms of sufficient system damping and rotor angle stability is analyzed.

For the system operating conditions considered, the analysis conducted indicates that it is possible to identify a certain inter-area mode which is detrimentally affected by the increased DFIG penetration. Moreover, using the concept of participation factors, the specific mode can be excited in time domain.

The system is found to have both beneficial and detrimental impact with the increased penetration of DFIG. Both of these situations observed by sensitivity analysis for small signal stability are also observed in nonlinear time domain analysis by considering corresponding fault scenarios in time domain.

The sensitivity of the real part of the eigenvalue with respect to inertia evaluated for a system where the DFIGs at their planned insertion points in the network are replaced by equivalent round rotor synchronous machines provides a good metric to evaluate the impact due to increased DFIG penetration on system dynamic performance. Both detrimental and beneficial impacts of increased DFIG penetration can be identified. The eigenvalue sensitivity analysis together with the detailed eigenvalue analysis carried out for each of the cases considered is also substantiated by the results obtained from time domain simulation.

Part II. Impact of Increased DFIG Penetration on Frequency Response and Stability (work done at Iowa State University)

Wind energy, being non-dispatchable, has different operational characteristics than conventional energy sources. Additionally high levels of wind penetration create issues of power system control and interconnection issues. In this work we focus on MW-frequency control issues, system attributes, the grid problems introduced due to those attributes, and possible solutions to address them. The ultimate objective is to provide an approach for identifying the right combination of solutions for a given power system with a given projection regarding wind penetration levels. To do so, we need to establish the performance impact of each solution on each problem and we need to estimate cost per unit for each solution. The overall problem is an optimization problem of a combinatorial nature. The challenge is to ensure, at a particular wind penetration level, minimum cost and, at the same time, maximum impact sets of solution. Although this is the ultimate goal of our work, the objective in this project was to understand the impact of high wind penetration on transient frequency dip and on regulation/reserve requirements.

A 2008 case for the U.S. Eastern Interconnection was analyzed to assess transient frequency behavior under different wind penetration levels. The installed capacity for the system was 541 GW. Two very severe (and highly unlikely) contingencies of 2.9 GW and 10.16 GW outages were studied. Assuming conventional generation is displaced, and assuming DFIGs are not provided with inertial emulation, DFIG wind generation will cause deterioration in transient frequency performance. The frequency dips in both cases were found to be small and of little concern in terms of tripping underfrequency load shedding or of tripping generator protection, even when wind penetration was increased to 8% of total Eastern Interconnection capacity. This would also be the case for wind penetration levels significantly higher than 8% due to the fact that even a 10 GW outage does not create significant transient frequency dips, owing to the very large size of the Eastern Interconnection. This would not be the case for the Western or Texas Interconnections. It should be recognized, however, that islanded conditions would necessarily magnify the detrimental effect of DFIG penetration on transient frequency performance. In addition, it is expected that high DFIG penetration will cause degraded performance in terms of control performance standards CPS1 and CPS2, but this issue was not studied in this project.

We also examined wind effects on and ability to provide regulation. A statistical study was performed to determine the impact of wind addition on the generation portfolio and ramping requirements in a control area with a given load distribution and in different time frames (i.e., ten-minute and one-hour). Different solutions to reduce the impact of wind on MW variability were considered.

Our investigations conclude that generator controls can alleviate the problems of transient frequency dip and regulation. Inertial emulation is a good and necessary idea, although attention should be paid to the overall cost of replicating this control on so many turbines, assuming wind penetration increases to the 300 GW level in the nation. The cost of distributed control must be considered for using wind to provide regulation; however, the very real cost of spilling wind should also be considered.

Part III. Impact of increased DFIG penetration on voltage response and stability (work done at Iowa State University)

Assessing the reactive power capability of a DFIG machine is essential to analyze the effect of high penetration of DFIG wind parks on voltage response and stability. DFIG machines have sensitive power electronic devices which are sensitive to high voltages and currents. Control enhancements have been developed to fully utilize the reactive power capability of the machine and the power electronic converters. These control enhancements include grid-side reactive power boost which allows the grid-side power converter to inject reactive power into the grid when the rotor is short circuited with a crowbar to protect the rotor-side converter. The enhancements also include retrip prevention and DC overvoltage prevention which protect the power electronics and allow maximum utilization of reactive power.

The reactive capability curve is developed for a 1.5 MW machine and scaled up to represent the reactive capability of a wind park. The reactive capability of a wind park at low wind levels can become a significant reactive power source. Since there is no control on the real power output of a wind farm, the additional reactive capability at low wind output can significantly enhance the voltage performance of the system. The operation of a DFIG wind park with a new voltage controller is compared with two reactive power strategies. In one strategy the capability curve is utilized and in the second strategy with +/- 0.95 power factor restriction is used. With the restricted power factor operation, the available reactive power decreases with decreasing wind output whereas while employing the capability curve, the available reactive power increases with reducing wind levels. The two strategies are compared for both static and dynamic performance, and an improved performance over the entire range of wind speed from cut in to full potential is observed. From static analysis, a greater power transfer margin and lower system losses are obtained using the capability curve. The additional benefits are more significant at lower wind speeds. In the dynamic analysis, the capability curve provides a better post fault voltage profile, and, at lower wind speeds, the additional reactive capability can prevent transient instability.

At the plant level, the Irish grid code maintains a requirement that, during a fault, the wind park must provide the maximum possible amount of reactive current without violating generator limits. By modifying this rationale to include the capability curve, a revised U.S. grid code could implicitly define the exact injection to be commanded at the point of interconnection for a given operational point. A policy revision mandating wind park owners to submit plant capability curves to system operators may lend itself to not only economic dispatch improvements, but also to increased stability during voltage emergencies. The additional enhancement in voltage performance is obtained at no additional cost. The presence of the additional reactive capacity in high penetration scenarios is crucial to enhancing system performance.

The final section of Part 3 deals with the impact of wind variability on voltage security assessment. Electricity generated from wind power can be highly variable with several different time scales: hourly, daily, and seasonal periods. This variability can lead to increased regulation costs and operating reserves. Wind variations in the small time frame (~seconds) is very small (~0.1%) for a large wind park. Thus, static tools can be used to assess impact of wind variation.

Traditional P-V curves assume that generation is dispatchable and voltage stability of the test power system with respect to load variation. Wind energy is an intermittent resource, hence, it cannot be assumed to be dispatchable. Thus, the traditional PV curves are unable to capture the stability margin for an integrated system which has high wind penetration. Thus, a new tool that would incorporate wind variability is required for assessing long term voltage stability of power systems with high levels of wind generation.

The developed tool calculates sets of PV curves plotted along parallel planes, thus giving a three dimensional voltage secure region of operation. The tool calculates the most restrictive contingency at each wind level and obtains the PV curve for that contingency. Different redispatch strategies are also utilized to compensate for wind gusts and loss of wind. The developed tool was used to study the impact of wind variability on two test systems. One system was the 23-bus PSS/E test system and the second system considered in the Eastern Interconnection.

The results indicate that the redispatch strategy has an important impact on the transfer margin of a system. The most severe contingencies in a system depend on the level of wind generation. Also, the maximum power transfer need not be at either minimum or maximum wind but could be at an intermediary wind level.

Part IV: Impact of increased DFIG penetration on market mechanisms (work done at the University of Illinois at Urbana-Champaign)

Increased penetration of wind-based resources into the generation mix is expected to have a distinct impact on the functioning of power markets. As electricity markets gravitate towards a regime where renewables, such as windpower, are an integral part of a firm's generation mix, multiple questions persist in terms of how market mechanisms should evolve to contend with the challenges arising from uncertainty and intermittency. As part of the work done at the University of Illinois at Urbana-Champaign, we develop a flexible methodology for modeling strategic behavior in markets where firms may have wind-based generation. Importantly, we introduce a risk-based mechanism that charges firms when their bids have a large exposure to risk. Unlike the more standard deviation cost metric, this is an ex-ante measure and possesses the benefit that it can be computed prior to the clearing of the real-time market. Introducing this risk measure results in a rather challenging game-theoretic problem that is well beyond the reach of existing analytical and computational tools. Yet, it is this class of models that can provide us with insights on both existing and improved market designs. Accordingly, our research effort concentrated on the developing a modeling framework that can accommodate a host of complexities, ranging from capturing uncertainty and risk preferences in the setting of a two-settlement forward-spot market.

We consider the strategic behavior of firms in an imperfectly competitive networked electricity market under uncertainty. Firms in such a setting are assumed to have access to first and second period (recourse) decisions while minimizing a mean-risk objective. Motivated by the risk exposure arising from market participants with uncertain generation assets, agents are exposed to the risk of capacity shortfall in the real-time market through a conditional value-at-risk (CVaR) measure. Unfortunately, there is little available by way of existence theory or convergent schemes for this class of problems. In other words it remains unclear if equilibria can be expected to exist and if they do, whether they can be computed efficiently. Our main contribution in this part of the research is showing that in a broad class of games arising in these settings, Nash equilibria are expected to exist. Furthermore, a perturbed game is seen to admit a unique equilibrium. Note that these results do not directly follow directly from known results on games and represent an important step in understanding strategic behavior in large networked engineering-economic systems.

Clearly, any effort to draw policy insights requires computing these equilibria in networks of a practical size. The challenge in such a computation lies in the sheer size of the problems and the coupling through the shared constraints. In particular, every firm in the game is faced by the challenge of optimizing over what is possibly a massive network. Furthermore, the firm's problem has to be cognizant of uncertainty in available capacity (such as arising from wind power), amongst others leading to a growth in complexity arising from scenario-based modeling. Finally, any computation requires one to aggregate all the firm problems, suggesting that a large number of firms would make solvability difficult at best. As part of our research, we constructed an algorithm that scales slowly in effort with respect to growth in problem size. This scalability is crucial being able to solve problems of meaningful sizes and represents an important building block as we make efforts to integrate renewables into our portfolio. Our scheme is naturally distributed across agents while the firm problems are solved via a scalable cutting-plane method. A key contribution of our work is the provision of theoretical convergence guarantees and error bounds. Preliminary numerical tests suggest that the algorithm scales slowly in all three sources of complexity (network size, number of scenarios and number of firms). We see this work as extremely important in terms of efficiently solving a broad class of game-theoretic problems that are complicated by risk and uncertainty.

Finally, we derive some insights using a 53-node model of the Belgian network. Here, we allow a set of generators, some with a significant proportion of wind assets, to compete in the forward and spot-market in the face of uncertainty. Every firm intends to maximize expected profit over both periods while reducing his risk of capacity shortfall. For generators with highly predictable availability, this risk is largely zero; for wind-based generators that bid aggressively, this risk can be significant. Our models provide several insights for market design. For instance, we observe that higher levels of risk-aversion lead to lower participation in the forward markets while higher level of wind penetration.