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Transient Stability Impacts from Distribution Connected Wind Farms

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Abstract—Wind generation penetration levels are increasing in power systems across the world. Along with transmission connected wind farms, distribution connected wind farms are becoming more prevalent in power systems. How these distribution connected farms control reactive power is of concern to the transmission system operator. This paper examines a hybrid system, where the transmission system is modeled with a significant penetration level of radial distribution feeders connected to a collection of small wind farms. By varying control strategies at the distribution farms the impacts of the reactive power control strategy implemented by the wind farms are observed. It aims to show that the additional impedance of the distribution system will have unintended consequences on the transmission system and the application of voltage control is less critical.

Index Terms—reactive power, reactive power control, synchronous generators, transient analysis, wind power generation

I. INTRODUCTION

WIND generation is becoming an important renewable resource in power systems. The nature of wind generation presents challenges from both an operational and stability perspective. The scheduling and dispatch of conventional generation will be impacted by the variable nature of wind, while the stability of the system will be impacted by the asynchronous nature of wind, as well as how reactive power is controlled by the wind farms. Work in [1]–[5] has demonstrated that the manner in which reactive power control is will significantly influence both the voltage stability and rotor angle stability of the conventional generation in the system. As the penetration levels of wind generation increase, these impacts will become more pronounced. In smaller systems, in order to accommodate high penetrations of wind generation, wind farms may be embedded within the distribution network. At the transmission level the type of reactive power control implemented by wind farms will influence the field voltage of synchronous generation in the system, impacting both the voltage stability and rotor angle stability of the system. This paper will explore the impact of reactive power control of wind farms embedded at the distribution level. Reactive power control is available on most modern variable speed wind

turbines (VSWT). They can provide targeted terminal voltage control [6]–[8] or control reactive power to achieve a fixed power factor [9].

This paper will demonstrate that the active control of reactive power from wind farms in the distribution network has little impact on the behavior of the transmission system. However, transmission system stability is still impacted by the control of wind farms that are connected at the transmission level as demonstrated in [1], [2]. The impacts of control of reactive power at the distribution level are damped by the configuration of the network. Lower X/R ratios in the distribution network increase the impedance of the system and dampen the voltage impacts seen by the farms embedded within the distribution network. This arrests the voltage drop seen by the wind farms and allows for improved voltage stability. This is a distinct benefit of wind farms embedded at the distribution level, and as a result the type of reactive power control implemented by the wind farms in the distribution network have minimal impact on the transient stability of the synchronous generators in the system. When wind generation is connected directly to the transmission level, the effects of a fault are more pronounced and the type of control strategy implemented by wind generation will play a significant role in maintaining the rotor angle stability of the system [2].

Further, this paper will aim to demonstrate that although the configuration of the distribution network helps minimize the voltage drop of the wind farm, the rate of change of the voltage seen by the wind farm controllers is still fast enough to active the fault ride-through (FRT) controls of the farm. FRT controls are based on grid code and provide fast injections of reactive power that allow the wind farm to remain connected to the system during a low voltage event [10]–[12]. The FRT capability of VSWTs is well established in the literature and is a requirement of wind farms that connect into the power system. The fast injection of MVAr into the system by FRT controls seems to further aids in the recovery of the transmission level voltages and helps maintain the stability of the system regardless of the control strategy that was in use pre-contingency. The results in improved transient stability conditions when a system has a significant penetration of distribution connected wind in comparison to a system that has a majority of wind connected directly to the transmission level.

This paper will be divided as follows. Section II will discuss the methodology used to complete this study. Section III will describe the test system. Section IV will present and discuss the results. Finally, Section V will conclude this paper.

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II. METHODOLOGY

To assess the stability of a system with a significant penetration of distribution level wind generation, a methodical approach is required. First, a distribution network must be accurately modeled within the transmission system and include the requisite tap changers and radial feeders. Next, wind generation in the combined distribution/transmission model is operated with varying reactive power control strategies. Doubly-fed induction generator (DFIG) wind turbines have the ability to control reactive power in different manners and the impacts of the various control strategies will be observed. Finally, the cases that will be studied needs to be clearly defined. Here, three cases will be studied in which wind farms at both the transmission and distribution level vary their reactive power control strategy.

Initially all farms (distribution and transmission level) will be modeled with terminal voltage control implemented. These farms will control their reactive power to achieve a target voltage at a designated remote bus. For the remaining two cases, the transmission level farms will vary their control strategy, implementing fixed power factor control at two settings, unity power factor and 0.95 capacitive power factor. The farms in the distribution network will operate at a 0.95 inductive power factor. This is done since distribution networks have significantly lower X/R ratios and as a result they are more sensitive to both active and reactive power changes. To maintain robust voltages on the distribution level as well as support local loads, distribution system operators (DSO) generally operate wind farms with inductive power factors. As such, for the unity transmission case and capacitive transmission case, all of the wind farms in the distribution network will be operated with a 0.95 inductive power factor. The cases studied in this paper are identified in Table I. This paper will examine how the type of control implemented by wind generation will impact the stability of the distribution network, and the resulting impacts on the transmission network. To assess the stability of the system a fault is applied to the system and the resulting impacts on the voltage stability and rotor angle stability of the system are observed for the three cases described in Table I.

TABLE I
STUDIED WIND CONTROL CASES

Case	Description
Terminal Voltage Case	All wind farms modeled with terminal voltage control
Unity Transmission Case	Transmission connected wind farms modeled with unity power factor control, distribution farms at 0.95 inductive
Capacitive Transmission Case	Transmission connected wind farms modeled with capacitive power factor control, distribution farms at 0.95 inductive

Fig. 1. The New England 39 bus test system used in this study

III. TEST SYSTEM

The test system used for this study is a modified version of the New England 39 bus test system, Fig. 1. Rather than 10 conventional synchronous units, only five are included in this study. The information of each conventional synchronous unit modeled in the system is provided in Table II. The load of the system is reduced to 2400 MW and 554 MVar, and modeled as a 33% constant impedance, 33% constant current, and 33% constant power. Wind farms are connected at the transmission level at six buses in the system, Table III. Energy harvesting networks (EHN) are connected at six more buses in the system, also listed in Table III. The EHN is representative of a collection of small farms at the distribution level. An example of an EHN connected at bus 6 is given in Fig. 2. Each wind farm in the EHN is connected to a 41 kV distribution bus by a line and another step up transformer. Overall, there are 1182 MW of wind generation installed in the system, giving a penetration level of 47%. Of the 1182 MW of wind generation, 582 MW are embedded in the distribution network through the EHNs. As a result, the penetration of distribution connected wind is 47%.

The line and transformer data are based on data provided by the Irish distribution system operator (DSO), ESB Networks. In comparison to the transmission network where the lines have very high X/R ratios (between 40 and 50), lines in the distribution network have very low X/R (between 1 and 2). For each of the cases described in Table I, a fault is applied at bus 19 for five cycles. The response of the synchronous units, along with the bus and line data of the system is monitored pre- and post-contingency.

IV. RESULTS AND DISCUSSION

This section presents the results of contingency analysis completed on the modified New England test system described in the previous section. All analysis was completed using the DSATools software package [13].

TABLE II
SYNCHRONOUS GENERATION DATA

Generator Bus	Max MW	Min MW	Max MVar	Min MVar
30	250	100	250	-50
31	580	220	500	-250
34	650	260	300	-300
36	560	220	250	-250
38	632	250	300	-300

TABLE III
WIND FARM LOCATIONS

Transmission Connected Farms	
Bus	24, 26, 32, 33, 35 and 37
Distribution Connected Farms	
Bus	2, 6, 8, 12, 16, and 18

Fig. 2. The EHN at bus 12 in the test system. Here four farms are modeled through radial feeders and tap changers and connect to the 110 kV transmission bus.

A. Distribution Connected Wind versus Transmission Connected Wind

In Fig. 3, the rotor angle response of the synchronous generator at bus 34 is given for each of the wind turbine reactive power control cases. As seen in the figure, there is very little difference in the behavior of the synchronous generator regardless of wind turbine control strategy. This is confirmed when a Prony analysis is applied to each trace, Table IV. The magnitude and damping of the dominant mode for each of the cases is very similar and demonstrate the impact of reactive power control from the distribution connected wind farms on transient stability of the system is minimal. To see if this behavior was exclusive to a system with high penetration of distribution connected wind generation, a new scenario where each of the wind farms are connected through a single transformer directly to the transmission system was created and simulated. The transmission farms were sized at the same level as total output of the EHN that was connected to the distribution network.

When all of the wind was connected to the transmission

Fig. 3. The rotor angle traces of generator 34 for the three wind control cases.

TABLE IV
PRONY ANALYSIS FOR GENERATOR 34 FOR TRANSMISSION AND DISTRIBUTION CONNECTED WIND

Case	Mag.	Freq. (Hz)	Damping
Terminal Voltage Case	7.440	0.736	8.12%
	1.040	1.224	8.34%
Unity Transmission Case	8.088	0.729	8.58%
	0.833	1.221	8.25%
Capacitive Transmission Case	8.350	0.722	9.58%
	1.251	1.198	8.94%

level, the type of control implemented by the wind farms had a significant impact on the rotor angle stability of the conventional synchronous units Fig. 4 and from the Prony analysis Table V. In examining the rotor angle behavior for the wind generation connected exclusively to the transmission system, it is clear that the control implemented by wind generation plays a significant role. The impacts of the fault are amplified, i.e. higher magnitudes in the modes of the Prony analysis, and the rotor angle behavior of the convention synchronous units in the system is significantly impacted by the type of reactive power control implemented by the transmission connected wind farms. By actively controlling the reactive power output of the wind farms (terminal voltage case), the rotor angle stability of the conventional generator is significantly improved in comparison to the other two strategies. However, when a significant percentage of the wind is embedded at the distribution level as done previously, the impact of the reactive power control strategy is less pronounced. This is a result of the distribution network configuration and how it interacts with the transmission network.

In Fig. 5, the field voltage for the synchronous generator at bus 34 is given for two cases, the terminal voltage case (with 47% distribution level wind generation) and the case where all of the wind generation is connected exclusively to the transmission system. From the figure it is observed that when wind generation is embedded within the distribution network, the maximum deviation in field voltage is considerably less than when all wind farms are at the transmission level, 0.62 pu (distribution case) to 1.13 pu (transmission case). This result implies that when there is a significant penetration of

Fig. 4. The rotor angle traces of generator 34 for only transmission connected wind with the three reactive power control cases.

TABLE V
PRONY ANALYSIS FOR GENERATOR 34 WITH *only* TRANSMISSION
CONNECTED WIND

Case	Mag.	Freq. (Hz)	Damping
Terminal Voltage Case	8.91	0.830	10.24%
	9.62	0.951	6.58%
Unity Transmission Case	9.46	0.846	10.82%
	10.33	0.960	6.88%
Capacitive Transmission Case	12.09	0.840	10.23%
	9.24	1.026	13.09%

Fig. 5. The field voltage of the generator at bus 34 for a terminal voltage case (with distribution connected wind) and the case where all wind is connected at the transmission level.

distribution connected wind generation, the voltage impacts on the conventional synchronous unit is eased and allows for more robust field voltages at the generator, preventing under or over excitation of the unit and improving the rotor angle stability of the system. As described in [2], by minimizing the deviation in field voltage, the rotor angle stability of the synchronous units in the system are improved. Hence, the rotor angle stability of the system is improved when wind generation is connected to the distribution network when compared to wind that is connected directly at the transmission level. The next section will examine why the wind generation connected in the distribution network has this impact on the rotor angle stability of the synchronous units in the system.

Fig. 6. The voltage plot for the four buses connecting the EHN wind farm to the transmission level bus.

B. Voltage Response of Distribution Connected Wind Generation

To gain further insight into behavior of distribution connected wind generation the bus voltages at each voltage level in the EHN was also monitored. In the EHN, the impact of a fault at the transmission level is damped by several layers of impedance. For the EHN given in Fig. 2, the voltage drop at bus 12 (110 kV) and bus 1201 (41 kV) is significantly greater than the drop at bus 12001 (41 kV) and bus 120001 (10 kV), Fig. 6 for the terminal voltage control case. As seen in the figure, the voltage at the two distribution buses that connect the wind farm to the transmission level, 12001 (41 kV) and 120001 (10 kV), the drop in voltage is significantly decreased compared to the buses near or at the transmission voltage level, 1201 (41 kV) and 12 (10 kV) respectively. The same also seem to hold true for the unity transmission case and the capacitive transmission case.

The two buses in the distribution level at connected through a transformer and line that significantly increase the apparent impedance seen by the voltage, Fig. 7. Here, the apparent impedance (Ω) is seen for the three elements connecting the farm to the distribution bus. As seen in the figure, the impedance between the 110 kV transmission level bus (bus 12) and the first distribution level bus (bus 1201 at 41 kV) is significantly lower during the fault when compared with the two elements that are entirely in the distribution network. This increase in apparent impedance is due to the lower X/R ratios in the lines and transformers at the distribution level and helps damp the voltage drop seen by the wind farm at bus 120001 (10 kV).

However, although the voltage drop seen by the wind farm is decreased, the rate of change of the voltage is still very fast. It is this change in voltage that activates the FRT controls. This control strategy over-rides the pre-contingency setting and provides for a fast injection of reactive power into the system, Fig. 8. As seen in the figure, pre-fault, the unity transmission and capacitive transmission case the EHN is consuming reactive power as per 0.95 inductive power factor operation and in the terminal voltage case, the EHN is producing a low level of reactive power. When the fault occurs, all three cases seem to revert into FRT mode, and produce a very fast injection of reactive power into the system. This

Fig. 7. The apparent impedance (Ω) of the EHN at bus 12 during and after the fault.

Fig. 8. The total reactive power output of the farms connected at bus 12 through the EHN for the three control cases.

supports the local voltages of the wind farms as well as the voltage of the EHN. This results in a reduction of the reactive power requirements of the transmission system and improves the overall stability of the system.

V. CONCLUSION

The FRT response and improved voltage stability are unique to a system where there are significant penetrations of wind generation embedded within the distribution network. The additional impedance of the distribution network helps damp the impact of a fault in the transmission network, and supports the voltage locally in the EHN. Although the level of the voltage drop is arrested at the EHN, the rate of change of voltage following a fault is still fast enough to activate the FRT controls of the wind farm. This provides a fast injection of reactive power into the system and improves the voltage stability, and in turn the rotor angle stability of the conventional synchronous generation. Although, distribution connected wind generation can be of benefit to the stability of the transmission network, the presence of local loads can disrupt voltages and create significant stability issues locally. This is something that will be explored in the future as the network model develops and more detailed load models are used. Overall, this paper has demonstrated that when a significant penetration of the system's wind generation is connected through the distribution network, the impacts of a

fault at the transmission level are damped and system stability is improved.

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