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Transient Stability Enhancement of Wind Farms using Flexible AC Transmission Technology (Comparison of SVC and STATCOM)

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***Abstract:** Uncontrollable nature of wind power causes using wind turbine induction generators. From the viewpoint of stability, induction generators consume reactive power similar to the induction motor, and it has a negative impact on short-term voltage stability and system voltage profile. This main issue of wind turbines that equipped with doubly fed induction generators (DFIGs) becomes bold in the grid faults. In this thesis, a new solution for uninterrupted operation of wind turbine driving a DFIG has been proposed during fault condition in the grid. A fault current limiter (FCL) is placed in series with the rotor circuit. During fault condition FCL enters a huge solenoid in the rotor circuit to inhabit increasing of current in the rotor circuit. When the fault is cleared the FCL bypasses the solenoid. A static synchronous compensator (STATCOM) and a static VAR compensator (SVC) have been applied for supplying required reactive power in faults and steady states. Capability and modeling accuracy of the proposed method confirmed with simulating a sample power system in MATLAB/Simulink software.*

***Keywords:** FACTS, Wind power, Transient stability, Doubly fed induction generators, Power system.*

I. INTRODUCTION

There has been a growing interest in distributed generation by renewable green energy resources. Among these renewable resources, wind energy has grown rapidly as an important electricity source. Wind turbines used with fixed speed induction generators provide a cost effective solution for wind power generation and are still the most commonly used type of wind turbine. However, a notable characteristic of the fixed speed induction generators is that this type of generator always consumes reactive power. While shunt capacitors are typically used to fully compensate for this reactive power consumption during steady state operation, these devices exhibit rather poor performance during transient events. Therefore, controllable reactive power (VAR) supporters, such as STATic synchronous compensators (STATCOM) are in some cases necessary to provide dynamic voltage support with their actively controllable VAR injection, especially under voltage depression.

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Previous research and practical experience in this field has shown that disturbances in a power system, such as the loss of one of a pair of transmission lines, voltage sags due to faults, etc, can lead to over speeding of fixed speed induction generators and can cause voltage instability or even voltage collapse [1]-[9]. STATCOM technology has been shown to have the capability to increase stability limits and improve system dynamic response following disturbances [1]-[7]. Applications of STATCOMs to increase power quality [1], [2] and to reduce transmission line losses [1] have also been studied for wind power systems. The influence of induction machine parameters on induction generator transient stability has been analyzed as well [8]. The stability improvement, realized in the form of longer Critical Clearing Times (CCT), by capacitor banks [9] or STATCOMs [3], on induction generators have been discussed. Further, the performance of STATCOMs to improve system dynamic response has been compared fully with the performance of capacitor and Static VAR Compensators (SVC) [4]. Using STATCOMs for compensation has been studied with particular emphasis for the integration of wind farms into weak grids [2], [5], which have low short circuit current [5]. This paper presents results from the investigation into the impact of installing a STATCOM at an existing wind farm. This wind farm consists of 83 fixed speed induction generators and is integrated through a weakly connected 69 kV portion of the Bonneville Power Administration (BPA) utility system. A STATCOM is to be installed at the Point of Common Coupling (PCC), where the wind farm is integrated with the utility system [10]. It utilizes a new power electronic device, the Emitter Turn-Off thyristor (ETO), developed by North Carolina State University, for enhanced high-power switching performance, simplified triggering technology, and overall reduced device and system costs [11]. Figure 1 illustrates the system situation. Additional information about the system and its model is given below in section II. A.

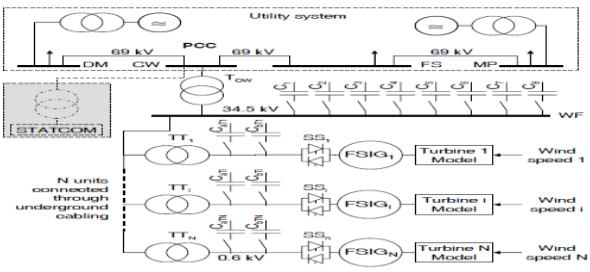

Figure. 1 Basic system layout used for RTDS model (adopted from [10])

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In order to help mitigate risk associated with deployment of the STATCOM and help to minimize the time required for on-site testing and tuning of the controls, the controller is to first be dynamically tested in a hardware-in-the-loop (HIL) environment emulating the BPA system and wind farm. The model of this wind farm together with the utility system has been implemented on the Real-Time Digital Simulator (RTDS and has been validated in many aspects against SCADA data acquired from the actual system [10]. In this paper, the results from the study of the stability improvement provided by a generic 10 MVAr STATCOM connected at the PCC are presented. The paper specifically compares results from a simplified analytical model approach, often applied to gain basic insight into voltage stability phenomena, with the highfidelity model implemented on the RTDS. The analysis and RTDS simulation results show that the STATCOM can improve the voltage profile of this wind farm system and prevent the system from voltage collapse after it has been subjected to serious disturbances. The work summarized herein is intended to provide the groundwork for subsequent HIL testing of the controller to be employed by the actual STATCOM. A test system model, including a generic STATCOM, has been implemented for the RTDS and is described in section II. The simulation results presented in section III verify the enhancement of transient voltage recovery by the STATCOM after serious system disturbances, including the opening of one of a pair of lines and a three-phase fault. Finally, conclusions and suggested future works are given in section IV.

II. SYSTEM DESCRIPTION

Modeling for the wind farm and the integrated BPA system has been described in detail in work on previous model validation efforts [10], but the modeling is briefly summarized herein. The simulation is executed on a 14-rack RTDS installation [12], allowing full transient simulations in real time with typical time-step sizes of approximately 50 μs for the majority of the system, with typical time-step sizes of 1.5 μs for power electronic converter subsystems. This installation allows simulation of systems of up to 756 electrical nodes, with associated power components and controls.

A. Wind Farm and BPA System

Due to the constraints of the simulator, the 83 turbines of the wind farm were represented by 40 appropriately scaled individual wind turbine units. The turbine generator models use two dq-frame induction machine models, native to the RTDS, per turbine to account for both high- and low-speed modes of operation, and include local transformers and power factor correction capacitors, as well as switching soft-starter models as illustrated in Figure 1. The wind turbine rotor model is based on a general model described in [15]. Each of the 40 turbines is supplied an individual wind speed and is equipped with associated controls for adjusting the rotor pitch and switching between high- and low-speed modes of operation. A local 10 MVAr capacitor bank within the wind farm (i.e. coupled to the PCC through the substation transformer), along with associated controls, is also modeled. The BPA system is represented by a number of transmission line and transformer models which compose two separate transmission paths back to the backbone grid. Because this is a relatively weak system, the wind farm, which is rated for 50 MW, is not allowed to operate at full power if either of these two lines supplying it are opened. While normally both lines are energized, faults and regular maintenance may cause or require this contingency situation, respectively. The addition of the STATCOM is expected to increase the allowable power output of the wind farm under these situations.

B. Generic STATCOM

As shown in Figure 1, a generic STATCOM is connected at the PCC through a 69/4.16 kV transformer. The configuration of this STATCOM and its controllers is shown in Figure 2. For the purposes of the work described herein, the STATCOM is modeled as three controllable voltage sources. Although for the purposes of the HIL testing, the STATCOM will be represented as a full switching model, the fundamental frequency voltage source model was chosen for this work in order to avoid issues associated with control interaction and resonant frequency excitation which must be studied more thoroughly in order to draw meaningful conclusions from the simulation. The controllers of the STATCOM are designed according to commonly known control principles [13], [14]. The control parameters are shown in Table 1. The outputs of the STATCOM controller are amplified and used as the controllable inputs of the three-phase voltage source. If the STATCOM source voltage is larger than the voltage at the PCC (VPCC), the STATCOM generates reactive power. Otherwise, the STATCOM withdraws reactive power. The real power is controlled by the voltage angle difference between the STATCOM and the PCC. In this study, the real power request from the DC link capacitor voltage control is always zero (VDC = VDCref) since no DC link capacitors where modeled within the presently implemented model. Furthermore, VPCCref is the reference voltage for the PCC while Id, Iq, Vd, and Vq are the STATCOM dq-axis feedback currents and voltages at the PCC.

Table 1 Parameters of a generic STATCOM

kP	kI	kP_1	kP_2	kI_2	X_L (p.u.)	K
0.352	40.46	3	10	20	0.15	2.4018

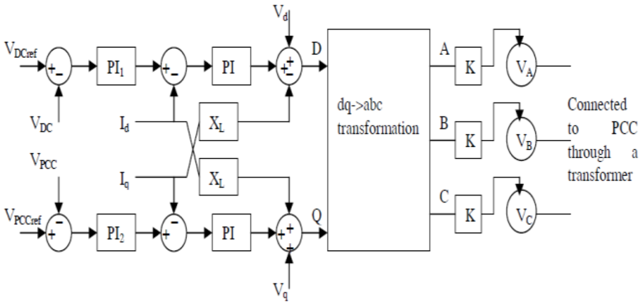

Figure. 2 A generic STATCOM and its Controller

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III. SIMULATION STUDIES

Simulation studies were carried out with the RTDS simulation for the test system described in the previous section. The dynamic behavior of this test system was obtained for two network disturbances. For one of the scenarios, one of the lines serving the wind farm is abruptly opened. For the other scenario, a three-phase fault is applied at a nearby substation. The dynamic voltages at the PCC with and without the STATCOM are compared. The improvement of the dynamic response provided by the STATCOM shown in the simulation is compared with analytical results.

A. Opening of Line

In this case, a severe condition for voltage recovery analysis is considered in which the line between the buses labeled DM and CW in Figure 1 is opened. Due to the increase of the equivalent line reactance, extra reactive power is needed in order to maintain the voltage at PCC. While switched capacitor banks can supply this reactive power, the additional reactive power is supplied in discrete steps which may cause undue voltage fluctuations. Furthermore, the reaction time of the capacitor bank controls may be too slow to provide adequate support for such a dynamic event. Therefore, the STATCOM is expected to provide this extra reactive power support dynamically with continuous change of output quickly enough for voltage recovery when the line opens. Figure 3 illustrates the ability of the STATCOM to mitigate a voltage collapse scenario. In this scenario, the wind farm produces around 37 MW (0.74 pu of its 50 MW raing), when the line is opened. In the present situation, with only power factor correction capacitors available, this would eventually lead to a voltage collapse if no other corrective action were taken (e.g. tripping out the wind generators). With less than 5 MVAr dynamic reactive power injection from the 10 MVAr STATCOM (i.e. 0.5 pu of its rating), the voltage collapse is avoided, and the power for the wind farm might be more gradually reduced to a safer operating point until the line is put back in service. The figure also shows the reactive power contribution from the STATCOM in per unit values of a 10 MVAr rated STATCOM.

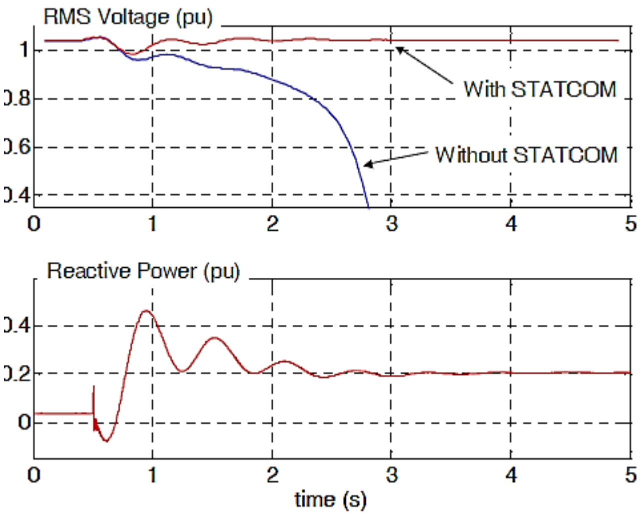

Figure. 3 Mitigation of voltage collapse and associated reactive power injected by a 10 MVAr STATCOM.

Using the equations listed in the Appendix for a simplified equivalent circuit approach, the PV curves of the simplified system without and with the line open, with and without contribution from the capacitor bank, and at different levels of STATCOM compensation currents, are shown in Figure 4. From this analysis we see that if the wind farm output is at or exceeds approximately 0.62 pu the system will experience voltage collapse after the line is opened, even with the capacitors providing adequate reactive power support prior to the event. With the STATCOM providing additional reactive power support, the system can maintain voltage stability until the maximum allowable power reaches approximately 0.82 pu. These estimated power limits are close but noticeable smaller than the power limits of 34 MW (0.68pu, with only one line connected) and 44 MW (0.88pu, with both lines connected) derived from RTDS simulations under quasi steady-state operations. Simplifications in the analytical model, such as the use of only one equivalent induction generator model and a constant current injection for the STATCOM may contribute to the smaller power limits obtained from this approach. In comparison, the more detailed RTDS model uses 40 induction generators and a better representation of the utility system.

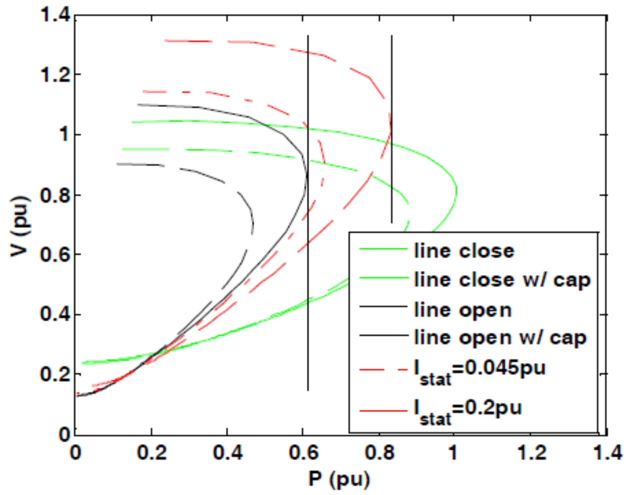

Figure. 4 PV curves from analytical analysis

B. Three Phase Fault

For this scenario, a severe condition of fault recovery is considered in which a three-phase short circuit is applied at a bus close to the wind farm PCC. During a fault, the stator of the induction generator is demagnetized due to subsequent drop in voltage at the PCC while the rotor speed increases. Since the rotor flux cannot change immediately, the machine experiences a transient and delivers a large amount of reactive power into the system. At the same time, the real power delivered to the utility system becomes small and the rotation speed increase significantly because of excess energy from the constant wind turbine power. After the fault is cleared, the machine consumes a large amount of reactive power due to the re-magnetization and the increased speed during the fault.

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If the increased speed is above the maximum allowable speed corresponding to the CCT, the large amount of required reactive power may induce voltage collapse. Wind generators are required to remain connected and supply real power to the electrical system immediately after network faults. This capability of wind generators is called Fault Ride Through (FRT) capability. According to the Low Voltage Ride Through (LVRT) standard by FERC [16], which is shown in Figure 5, the induction generators should stay connected when the voltage at the PCC is as low as 15% of its nominal value for 0.625 s. Furthermore, the wind farm must remain online as long as the voltage at the PCC reaches 90% of its nominal value within 2.375 s after the fault has been cleared.

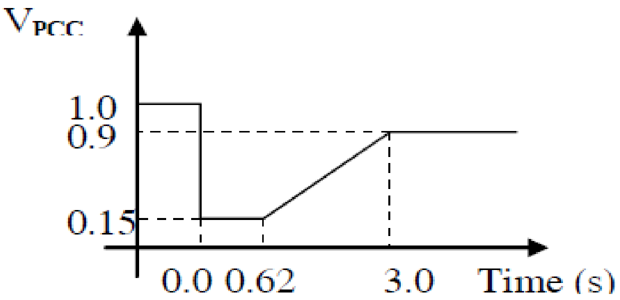

Figure. 5 FRT Requirement by FERC

One way to increase the FRT capability is to install a STATCOM at the wind farm terminals. While during a fault, a relatively small STATCOM contributes little to support voltage it may provide sufficient reactive power after the fault clears to extend the FRT capability. Figure 6 illustrates the support by the STATCOM in recovery from a fault. For this scenario, the wind farm was supplying about 37 MW (.74 pu) when a three-phase fault is applied to the 69 kV bus at a nearby substation. The fault is cleared after 9 cycles. Without the STATCOM, the wind farm would be unable to recover and requires to trip off line in order to prevent voltage collapse. With the STATCOM, however, the wind farm is able to recover successfully. As illustrated in Figure 6 the STATCOM control was commanded zero reactive power during the fault in order to avoid additional fault current contribution into the utility system.

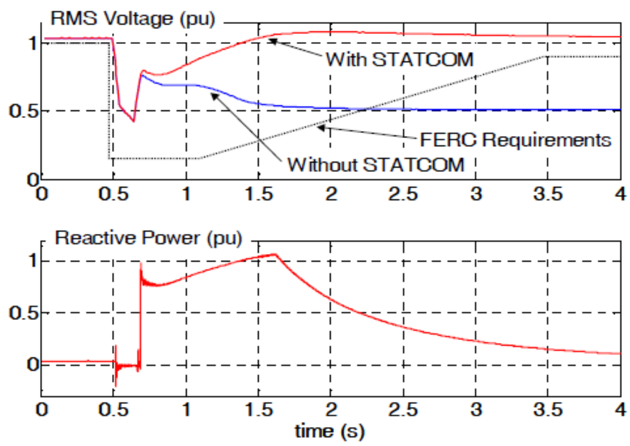

Figure. 6 Support of FRT capability of the wind farm by the 10 MVAr STATCOM

IV. CONCLUSION AND FUTURE WORK

Herein, the stability improvement of an existing wind farm through the addition of a STATCOM have been illustrated and discussed. Using a generic STATCOM model, improvements to system stability have been demonstrated for selected disturbance scenarios. The results from a large-scale, high-fidelity real-time transient simulation model of the wind farm and utility system, which has been developed in preparation for hardware-in-the-loop (HIL) testing of the STATCOM's new controller before field deployment, have been compared to results from theoretical analysis. The comparison indicates that the simplified analytical solution provide reasonable good but rather conservative values for the stability margins. This work provides important insight into potential improvements to the existing system and lays the groundwork for meaningful dynamic HIL testing of the STATCOM controller. In the future, thorough parametric analysis with both the steady state and the transient models will reveal the total gain in stability margin throughout the operating range provided by the application of the STATCOM at this site.

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