Behavior of Doubly-Fed Induction Generator Under Nearby Wind Plant Fault

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***Abstract*—Wind energy is the fastest growing source of renewable energy in the power industry and it will continue to grow worldwide as many countries are developing plans for its future development. For power system operators, this increasing contribution of wind energy to the grid poses new challenges that need to be addressed in order to ensure the reliability and security of the electric power grid. One of the main concerns by system operators is the ability of wind turbines to ride through faults without disconnecting from the grid according to FERC-661. This paper analyzes a three phase fault event on a wind plant modeled in EMTP and investigates the behavior of the doubly fed induction generator (DFIG) during grid fault conditions.**

***Index Terms*—induction generators, wind power generation, fault tolerance.**

I. Introduction

THE last few years has seen a huge investment in renewable energy resources as alternative sources of energy. Wind energy is the fastest growing source of renewable energy in the power industry and it will continue to grow worldwide as many countries are formulating plans for its future development. Many countries have developed plans to meet the growing energy demands in the future by taking advantage of the abundant energy in wind so as to protect the environment from CO_2 released through some of the more conventional ways of generating power. Worldwide wind power generating capacity grew by 30% in 2008, with capacity increasing by 28 GW to reach 122 GW by the end of 2008. Wind power accounted for 2% of the world electricity production in 2008 [1].

The U.S. is targeting about 20% of the electricity produced in 2030 to be from wind energy. For power system operators, increasing contribution of wind energy to the grid poses new challenges that need to be addressed in order to ensure the reliability and the security of the electric power grid. One of the main concerns by system operators is the ability of wind turbines to ride through a fault without disconnecting from the grid. The ability of wind turbines to remain connected during disturbances is very important especially for large wind plants, since it could influence the stability and security of the overall power system. Previously, wind turbines were designed to disconnect from the grid when the voltage falls below 0.7-0.8 pu so as to protect the wind turbine from fault current damaging it. The low voltage ride through (LVRT) capability of a wind turbine has gained more interest recently because of the increasing contribution of wind energy to the grid power and the rules per FERC-661 issued in 2005.

Many technologies have competed over the years for the concept of designing the generators and the power electronics used for the control of wind turbines. Wind turbines have evolved from using fixed speed turbines to using variable speed turbines that improves the controllability of the energy tapped from the wind. Modern wind turbines allow a variable-speed operation of the generator through a power converter interface with the grid.

Today in the U.S., the main type of variable-speed wind turbine generator technology uses an induction machine that is connected to the grid through a partial-scale power converter; this type of wind turbine generator is referred to as doubly fed induction generator (DFIG). The other type of wind turbine generator in the market is a variable-speed turbine with a full-scale power converter and a synchronous generator.

The main advantage of the DFIG technology with the partial-scale power converter is that only 20-30% of the power generated by the generator has to pass through the power electronic converter as compared with the full-power converter technology where 100% of the power generated has to pass through the converter. From an economic standpoint, DFIG has a substantial cost advantage when compared with the full power concept [2].

This paper discusses the fault analysis performed on an 80 MW wind plant modeled using the ElectroMagnetic Transients Program Restructured Version (EMTP-RV). This model uses a DFIG wind turbine model available in EMTP-RV for an assessment of the transient stability of the system after a three phase fault event. The low voltage ride-through (LVRT) requirements for wind turbines and the behavior of DFIGs during fault is also discussed.

II. Principles of DFIG

A DFIG is essentially a wound rotor induction generator with slip rings. The stator of the machine is directly connected through a back-to-back partial-scale power converter as shown in Fig. 1. The rotor is fed from this three phase back-to-back converter with a variable frequency source, which provides a variable speed capability for the DFIG unit unlike the fixed speed wind turbine generators.

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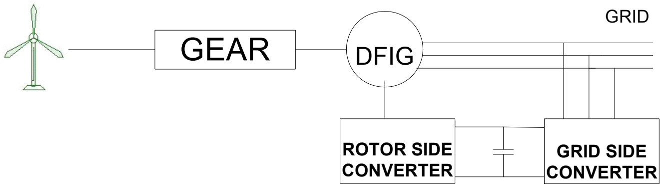

Fig. 1 Simplified schematic of a DFIG wind turbine depicting partial-scale power converter.

The ability of a wind turbine to operate with variable speed allows for optimization of the power generated from the wind [3]. The converter consists of two back-to-back voltage-source converters connected via a dc link. The rotor side converter allows for variable speed operation of the wind turbine and other necessary controls by controlling the active and reactive power fed to the rotor. The grid side converter is controlled to keep the dc-link capacitor voltage constant and to provide a unity power factor operation of the plant.

The rotor-side converter also has the ability to control the terminal voltages and power factor by exchanging reactive power with the grid; this type of control is usually needed when a disturbance occurs on the power system. The rotor side converter provides a variable speed operation for the rotor while the utility grid imposes the frequency of the DFIG. The rotor side and the grid side converters are controlled using the vector-control schemes as described in [4], which allows the active and reactive power to be decoupled and controlled independently.

The power converter with its control and protection are the key for the DFIG performance both during normal and fault operations. The control performance of DFIG is excellent in normal grid conditions allowing active and reactive power changes to be accomplished in a few milliseconds due to the presence of power electronics. In contrast to this very good performance in normal operation, the DFIG wind turbine concept is more sensitive to grid disturbances compared to the full power converter concept and requires special-power converter protection [3].

The EMTP-RV model used in this project is advantageous because it provides a detailed modeling of the DFIG, including its controls. One disadvantage of the EMTP-RV model observed for large power systems is the long simulation time. For screening purposes, simplified models of DFIGs have been presented by other authors as described in [3], which are also suitable for transient stability studies. However, the detailed EMTP-RV model can be used for the analysis of fault events in the wind plant.

III. WIND PLANT CASE STUDY

Fig. 2 represents a wind plant with 40-2MW DFIG wind turbine generators, rated at nominal 690V output. The voltage is stepped up by Y-Y grounded 2750kVA, 34.5 kV/690 V three-phase padmount transformers. At the wind plant interconnection substation, a Y-Y-D 345/34.5/13.8 kV three winding transformer steps up the medium voltage collection system voltage of 34.5 kV to 345 kV line connected to the utility for transmission. Each wind generator point of interconnection shown on the collector circuits of Fig. 2 represents a 690V, 2 MW wind turbine connected to an associated 690 V / 34.5 kV step up transformer as shown in Fig. 3.

The information of the different components for the major equipment represented in Figs. 2 and 3 is summarized below:

345 kV Substation:
R_1 = 1.377 ohms
X_1 = 40.12 mH
R_0 = 3.87 ohms
X_0 = 82.67 mH

Substation transformer in Fig. 2:
Y-Y-D
69/92/115 MVA
345/34.5/13.8 kV
7.8% impedance

Padmount transformer in Fig. 3:
2750 kVA
Yg-Yg
34.5 kV/690 V
5.75% impedance

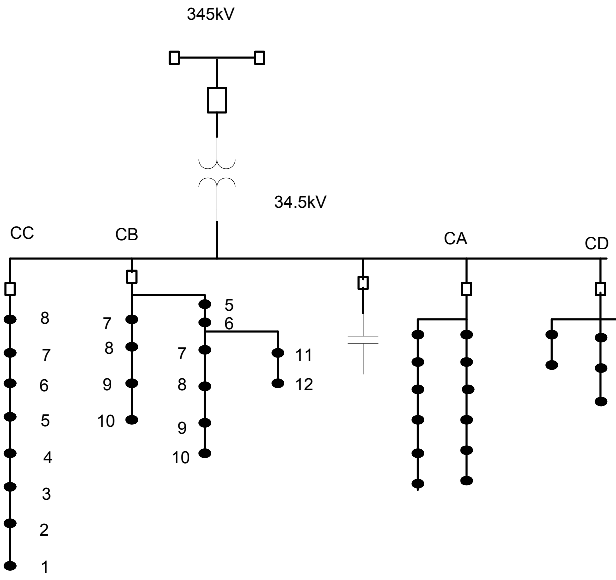

Fig. 2. One line diagram representation of the wind plant model. Each interconnection dot represents a wind turbine connected through a step up transformer as shown in Fig. 3.

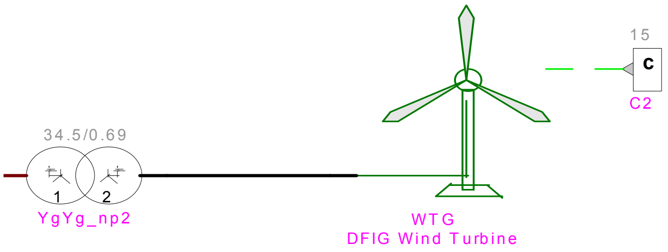

Fig. 3. Wind turbine point of interconnection equivalence showing step up transformer from 690 V to 34.5 kV.

The assumptions made in modeling the wind plant are next detailed. The EMTP-RV model in DFIG was only used to model the wind turbine whose behavior is under study during the fault. The rest of the wind turbine generators were modeled using a voltage source with impedance as a representation of an equivalent generator model. This assumption was made to improve the simulation run time and also to accommodate the modeling of the wind plant since a student version with limited number of devices is used.

A number of test cases were performed to verify the accuracy of this representation under fault. It should be noted that when performing the transient stability of a system, the dynamics of the system should be considered to give a better representation of the results.

IV. FAULT ANALYSIS

Line faults in a power system are a major concern for engineers working in power generation, transmission and distribution. The short circuit current at the point of interconnection plays an important role in the behavior of the wind power plant. During a fault the current flowing through the line can be as much as ten times the nominal current flowing prior to the fault. Therefore, a quick action must be taken to determine the exact nature and location of these faults so that the proper action can be taken to restore the system [5].

A fault can be single phase to ground or multi phase to ground where a single line or multiple lines are shorted to ground or are in contact with each other. Three phase faults are more severe and are therefore used during analysis to determine the maximum current to be interrupted. These faults can be temporary which are cleared after a few cycles of fault or can be permanent. An electrical engineer is required to provide a fault and coordination study of complete electrical system to be installed or connected to the grid. The intent of the analysis is to determine all locations in the entire system where the symmetrical short circuits ampere exceeds a certain current level. The short circuit analysis is done to compare interrupting ratings of all electrical protective devices connected to each bus with that available fault current flowing.

V. LVRT REQUIREMENTS OF WIND TURBINE GENERATORS

A fault on a transmission line near a wind plant could cause the voltage at that point to drop to zero momentarily before the fault is cleared. Previously, wind turbines were designed to disconnect from the grid when the voltage falls below 0.7-0.8 pu to protect itself. However, with the increasing penetration of wind power in the grid, the standards for connecting a wind plant to the grid have been revised by most countries to ensure the reliability of the whole system. The low voltage ride-through requirement of wind turbines is important so as to ensure the stability of the system and to avoid a situation where many wind turbines disconnect from the grid at the same time.

The Federal Energy Regulatory Commission (FERC) issued Order No. 661-A that specified the standard procedures and revised the agreements for the interconnection of large wind plants. Order No. 661-A imposes that wind plants shall be able to remain connected during voltage disturbances if these are not severe and the transmission providers system impact study shows that low voltage ride-through capability is required from the wind plant to ensure a good operation of the grid. During fault, if the voltage remains at a level greater than 15 % of the rated voltage for a period that does not exceed 0.625 s, the wind plant shall stay connected. If required by the transmission providers that the wind plant stays connected during a disturbance, the wind plant must be able to operate within 0.95 lagging and 0.95 leading power factor.

The low voltage ride-through control of the EMTP-RV model used in this project is designed to meet the Hydro Quebec requirements related to voltage dips. The wind turbine is to stay connected through a normally cleared three phase fault and a delayed single line to ground fault. The wind plant should remain online for 150 milliseconds or 9 cycles of three-phase fault, even if the voltage at the high side of the wind plant step-up transformer is reduced to zero.

VI. WIND PLANT IMPLEMENTATION

A fault study was performed on the wind plant modeled in EMTP to determine the fault current at different locations on the first collector of the wind plant. The behavior of the detailed DFIG wind turbine (G_A) is also observed during and after the fault.

Fig. 4 represents the one line diagram for the first collector of the wind plant. A detailed cable sizing and layout was included in the system model. Several locations (A, B, H, E, and F) were selected on the transmission line, and a three-phase fault with fault impedance of 0.01 ohms is applied on the high voltage side (34.5 kV) of the collector system.

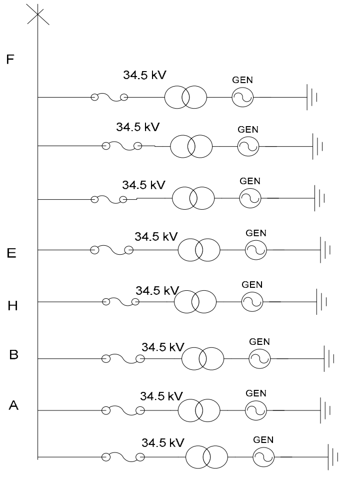

Fig. 4. Single line diagram of feeder 1 showing where fault locations were simulated.

VII. SIMULATION TEST CASE RESULTS

Three-phase faults were induced at different locations throughout the wind plant to check the ability of the DFIG to ride through the fault.

A. Test Case 1

Initially the wind turbine operates normally, then suddenly, a three-phase fault occurs near the main substation on line A at t = 1 s. The fault lasts for six cycles as shown in Fig. 5. The following figures illustrate the behavior of the doubly fed inductor generator before and after the fault.

At the fault instant, the voltage at the DFIG generator terminal drops, and it leads to a corresponding decrease of the stator and rotor flux in the generator. This results in a reduction in the active power—see Fig. 6. As the stator flux decreases, the magnetization that has been stored in the magnetic fields is released. Immediately after the fault, the generator starts to absorb reactive power for its magnetization from the power system as shown in Fig. 7. As the grid voltage drops during the fault, the grid side converter is not able to transfer the power from the rotor side converter to the grid; therefore, the additional power received goes to charging the capacitor, and thus the dc voltage across the converters increases rapidly – see Fig. 8. The protection system monitors different signals, such as the rotor current or converter dc-link voltage, and when at least one of the monitored signals exceeds its relay settings, the protection is activated.

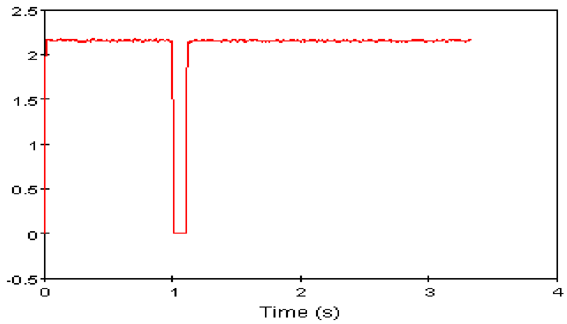

Fig. 5. RMS line-ground voltage (×10^4 V) at location A.

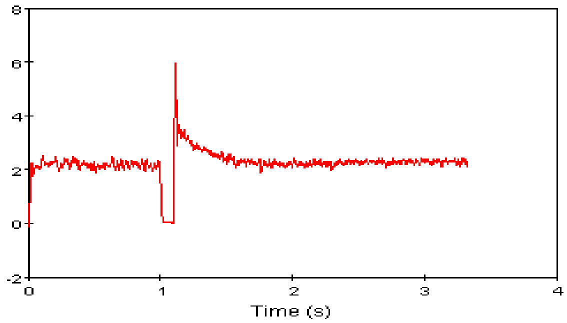

Fig. 6. Active power (MW) from Generator A.

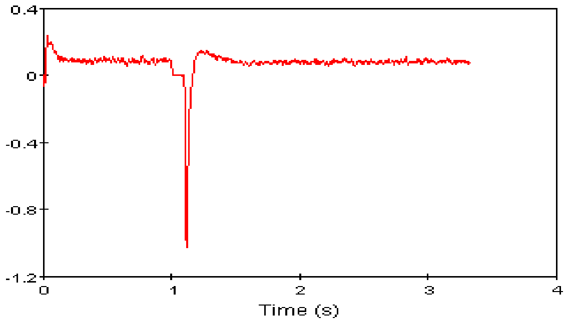

Fig. 7. Reactive power (MVAR) from Generator A.

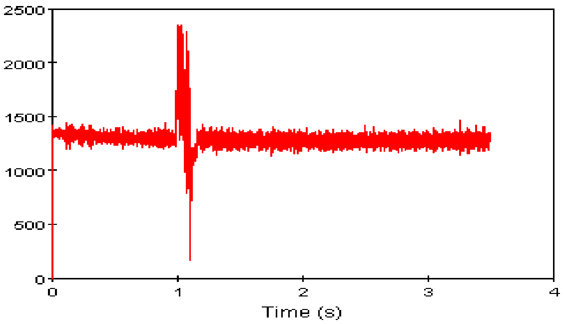

Fig. 8. Voltage across dc-link in power converter.

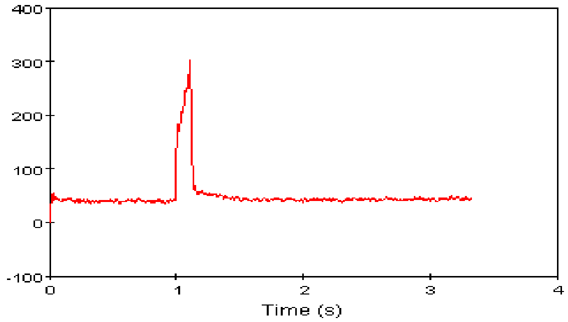

Fig. 9. RMS current in high voltage side of transformer at location A.

After the fault is cleared, the stator voltage is restored and the active power of the generator starts to increase. As the grid voltage and flux increases, the demagnetized stator and rotor oppose this change, thus leading to an increase in rotor and stator currents as seen in Fig. 9. The pitch control system is also activated during the fault to counteract the over-speeding of the generator.

B. Test Case 2

A situation where the fault does not get cleared on time is simulated for the wind plant model. An eighteen cycle three-phase fault is applied at location A on the transmission line, and the behavior of the DFIG was observed.

The generator is tripped off because the voltage is zero for eighteen cycles of fault as shown in Figs. 10-12; this behavior is expected since this condition is not inside the fault ride-through region of the wind turbine. The LVRT relay trips the generator during a prolonged fault of 18 cycles with the voltage at the point of fault approximately zero. The protection system monitors different signals, such as the rotor current, the dc-link voltage, and when at least one of the monitored signals exceeds its respective relay settings, the protection is activated.

Disturbances such as momentary voltage dips can disconnect many wind turbines and cause instability on the transmission grid. In wind plants, the low voltage ride-through capability of a wind turbine can be improved by installing a dynamic var (D-Var). It enhances the ability of wind turbine generators to avoid tripping off-line due to voltage disturbances that occur on the transmission network. Usually, in addition to the voltage ride-through capability of wind turbines through the rotor side converter, most transmission providers still require wind plants to have a dynamic Var compensator installed to improve performance during disturbances and to help supply reactive power if the wind turbine need to stay connected during fault [6, 7].

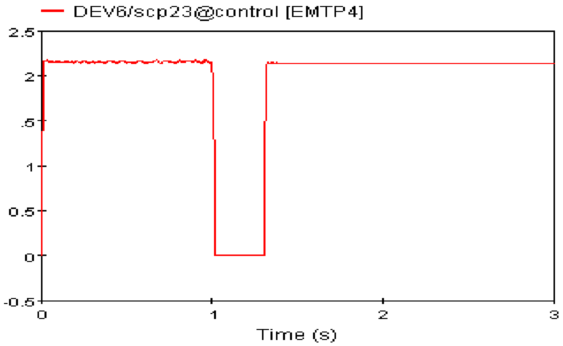

Fig. 10 RMS line-ground voltage (×10^4 V) at location A.

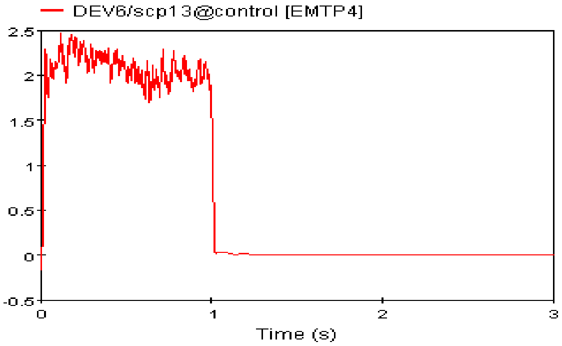

Fig. 11. Active power (MW) from Generator A.

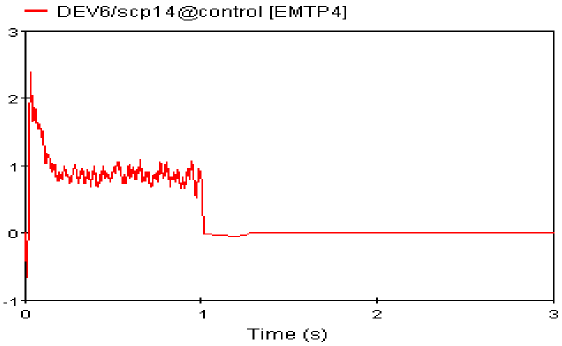

Fig.12. Reactive power (MVAR) from Generator A.

VIII. CONCLUSIONS

This paper discusses the fault analysis of a wind plant and investigates the behavior of the DFIG under fault conditions. The survival of a wind turbine under fault depends on the location of the of the fault with respect to the wind plant, the duration of fault, the type of fault, the method of reactive power compensation and also on the control algorithm of the wind turbine. More improvement will also be seen in developing a better control algorithm for wind turbines. Dynamic simulation performed on this variable speed wind turbine indicates that the wind turbine can survive a nine-cycle fault event, which satisfies the low voltage ride through requirement for which it was designed. New grid codes with even more restrictions during grid faults are expected in the future and more advanced control strategies have to be developed.

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X. BIOGRAPHIES

Olumide Aluko (S'07) was born in Nigeria. He received the B.S. and M.S. in electrical engineering from The University of Tennessee, Knoxville, in 2008 and 2009, respectively. His research interests include power electronic conversion for wind energy and distributed energy resources.

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Leon M. Tolbert (S'89–M'91–SM'98) received the B.E.E., M.S., and Ph.D. degrees in electrical engineering from the Georgia Institute of Technology, Atlanta, in 1989, 1991, and 1999, respectively. He joined Oak Ridge National Laboratory (ORNL) in 1991 and worked on several electrical distribution projects at the three U.S. Department of Energy plants in Oak Ridge, TN. In 1997, he became a Research Engineer in the Power Electronics and Electric Machinery Research Center at ORNL. In 1999, he was appointed as an Assistant Professor in the Department of Electrical and Computer Engineering, University of Tennessee, Knoxville, where he is currently an Associate Professor. He is a registered professional engineer in the state of Tennessee. He is an associate editor of the *IEEE Transactions on Power Electronics*. He does research in the areas of electric power conversion for distributed energy sources, multilevel converters, hybrid electric vehicles, and SiC power electronics.