Representation of Variable Speed Wind Turbine Generators for Short Circuit Analysis

E. Gursoy, *Member, IEEE,* R. A. Walling, *Fellow, IEEE*

***Abstract*—Type 3 (doubly-fed asynchronous) and Type 4 (full conversion) wind turbine generators provide much more flexible operation and increased efficiency due to power electronic converters employed in their circuit. The short-circuit characteristics of these wind turbines are complex because of these power electronic circuit and the controls of the power conversion system. This paper presents the short-circuit current characteristics of these machines under different operating conditions and provides an approach to represent these characteristics in short-circuit analysis.**

***Index Terms*— Power system faults, wind power generation.**

I. Introduction

SHORT circuit analysis is crucial for identifying the short-circuit withstand ratings of the power system equipment, determining relay settings, and maintaining a proper coordination of the system protection. Short circuit currents and voltages are calculated at fault location, as well as other locations in the system, with emphasis on the maximum and minimum values, in addition to the variations in these magnitudes over time.

The common practice of short circuit analysis is well established and defined in standards for common power system applications [1]. These standards are based on the assumption that the synchronous generators and motors can be represented as a voltage source in series with an equivalent impedance.

The change in energy policies, environmental concerns, scarcity of fossil fuels and the advancement in power electronic technology have increased wind turbine installations in the world in the last decade. Most developed countries are focused on utilization of wind energy and establishing near future targets such as 20% installed wind power capacity in their electric power systems.

For a reliable and secure operation of the electric grid, wind turbines have to provide performance compatible with the grid. Due to increasing wind power generation, electric utilities and system operators define the performance and connection requirements of the generation plants, including wind plants, in so-called grid codes. The grid code requirements define operating conditions such as fault ride through, frequency deviation, voltage limits. However one performance characteristic that is not as well defined is the short circuit contribution from wind turbines. Short circuit analysis practices and tools, adequately representing the currents provided by these wind turbines machines during faults, are quite important.

There are several types of wind turbines, with definition of these types based on the mechanical to electrical energy conversion systems. Most modern wind turbine installations are based on one of two variable-speed types of wind turbines: doubly-fed induction asynchronous generators (Type 3) and full ac-dc-ac conversion of power output using power electronic converters (Type 4), [2]. Due to power electronic converters employed in the energy conversion systems of these Type 3 and 4 machines, the short circuit behavior is much more complex than the Thevenin equivalent representation of synchronous generators.

There are a handful studies published in the literature which define the short circuit contribution from wind turbines. In [3], the short-circuit performance of the various wind turbine generator types are described from a theoretical standpoint. Approximate analytical equations are derived for doubly-fed induction generator in [4] and in [5] with crowbar protection.

The short circuit behavior of the machine is dependent on the machine parameters, pre-fault operating conditions, electric network, fault impedance as well as the control logic of the converter circuit. Previous studies have focused on generally a single operating point and 3-phase time domain simulations which may not be practical for use in short-circuit programs. In this paper, the short circuit contributions from variable speed Type 3 and Type 4 wind turbine generators (WTG) are studied. Recommendations for representation of these generators in short-circuit programs are provided.

II. Variable Speed Wind Turbine Generators

Wind velocity is not constant and has significant variation from hour to hour or even minute to minute. The energy capture from the wind is maximized when the circumferential tip speed of the wind turbine blades, relative to the velocity of the wind, is maintained at an optimal ratio. Variable speed operation of the wind turbines is important to maximize the output power of the turbines over a wide range of wind

Reigh. A. Walling and Ekrem Gursoy are with GE Energy, Schenectady, NY.

speeds.

Early wind generation technologies were capable of only minimal speed variation, and had relatively stiff coupling between the electric generator and the wind turbine. Wind turbulence and grid disturbances put a great mechanical stress on the drive-train of these wind turbines. Modern large power variable speed wind turbines employ either doubly-fed or full-conversion generator technologies, which provide a less stiff coupling and greatly reduces stress on the drive train and the tower structure.

Doubly-fed asynchronous generators (DFAG) are designated as Type 3 and generators decoupled from the grid with a power electronic converter is designated as Type 4. In this paper, the short-circuit characteristics of Type 3 and Type 4 wind turbine generators are studied.

A. *Doubly-Fed Asynchronous Generators (Type 3)*

Doubly-fed asynchronous generators (DFAG), also commonly called doubly-fed "induction" generators (DFIG) have three-phase alternative current (AC) windings in the stator and rotor with slip-rings. The stator of the DFAG is directly connected to the electric grid. The three phase rotor windings of the DFAG are connected to a power electronic converter through slip-rings which provides the variable magnitude and the frequency of the rotor voltage. The other converter is connected to grid. In terms of excitation, DFAG is similar to a synchronous machine, however the excitation applied to the rotor is AC with variable frequency and reversible phase rotation.

The stator field angular rotation, ω_s is the sum of the mechanical angular speed rotation of rotor, ω_m and the rotor field voltage frequency ω_r. as shown in (1). The p_s and p_r are the stator and rotor pole numbers in (1). Therefore the application of an AC excitation causes an apparent rotation of the rotor's magnetic field, relative to the rotor.

$$\frac{\omega_s}{p_s} = \frac{\omega_r}{p_r} \pm \omega_m \qquad (1)$$

When the wind turbine is operating below the synchronous speed (sub-synchronous speed), the excitation applied is in the same mechanical rotation of the rotor, therefore magnetic field seen from the stator is the sum of the rotor's mechanical rotation speed plus the apparent rotation speed caused by the applied ac excitation. In sub-synchronous operation, the stator output power provides the power supplied to grid and the power fed from converter to the rotor.

In contrast to the sub-synchronous operation, when the wind turbine is operating above the synchronous speed (super-synchronous speed), the apparent rotor magnetic field rotates backward with respect to the mechanical rotation of rotor. The power supplied to the grid is the sum of the power from the stator and the power from the rotor through converter.

The DFAG is connected to the grid through a step-up transformer as shown in Figure 1. Variable frequency excitation of DFAG's rotor circuit provides operation over a wide range of speeds. The power rating of the converter circuit is based on the range of the speed of the wind turbine. The power rating of the converter is typically around 25-30% of the nominal rated power output of the wind turbine where the operating speed range would be around ±33%. The flow of real power through the converter is bi-directional depending on whether the generator is operating above or below synchronous speed.

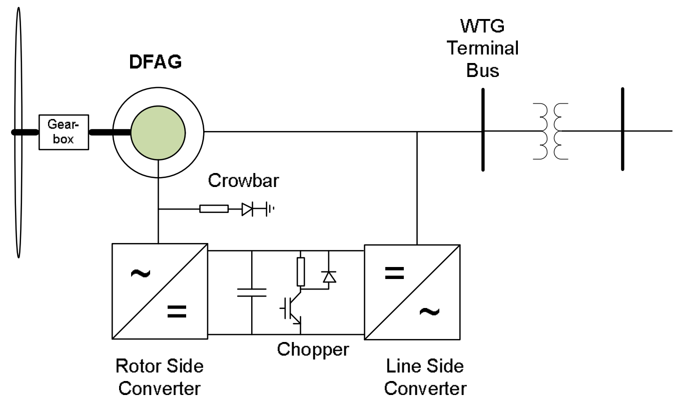

Figure 1 Topology of a doubly fed asynchronous generator (Type 3)

There are two main control blocks of the DFAG. The first block is the control of the rotational speed of the wind turbine in conjunction with the blade pitch control for the control of the real power output of the wind turbine generator. The second one is the converter control for the real and reactive power control by adjusting the rotor voltage magnitude and the phase angle. Reactive power output can be directly regulated or it can be managed to regulate the terminal voltage of the wind generator. When combined with a plant-level control system, the reactive output of all the wind turbine generators in a wind plant can be managed to regulate the grid voltage at the point of interconnection or other location [6].

DFAG can be seen as similar to a synchronous machine, due to rotor flux rotating at synchronous speed. However the operational behavior is quite different. The fast control of the real and reactive power output of the wind turbine results in an approximately constant source of real power and voltage regulation response that is much faster than the response of a synchronous generator; more akin to a STATCOM.

B. *Full-Conversion Generator (Type 4)*

A Type 4, full conversion, wind turbine generator is also a variable speed wind turbine generator which is connected to the grid through back-to-back ac-to-dc and dc-to-ac voltage source inverters.

Type 4 wind turbine generators have two converters: a generator-side converter and a line-side converter, which decouples the generator from the grid. The generator-side converter rectifies the alternating current generated by the machine. The frequency of this current varies with the speed of the wind turbine. The line-side inverter inverts the direct current (DC) of the DC link to AC at the grid frequency, 50 Hz or 60 Hz. The topology of a Type 4 wind turbine generator is shown in Figure 2.

Because of the decoupling provided by the converter, grid performance characteristics are virtually independent of the type of physical generator used, and are primarily determined by the characteristics and controls of the line-side converter. Therefore actual generator can be a synchronous machine with a wound rotor, a permanent magnet machine, or an induction machine. Unlike the DFAG, the converter of the Type 4 wind turbine generator is rated at the nominal power rating of the wind turbine.

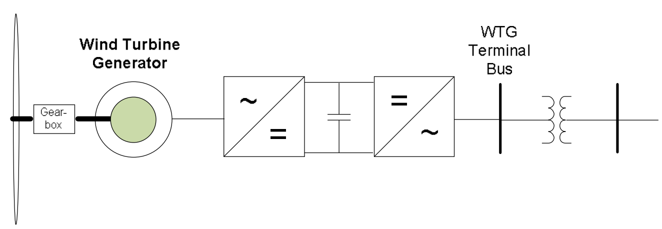

Figure 2. Topology of a full conversion generator (Type 4)

The line-side converter is a "voltage-source converter"; however the converter is controlled at high bandwidth to yield a controlled current source behavior. The real power is controlled to manage wind turbine speed and mechanical loads, and the reactive power is used to achieve STATCOM-like control of voltage similar to Type 3 WTG.

III. Fault Behavior Characterization

The variable speed operation of Type 3 and Type 4 generators using power electronic converters increases the efficiency and provides flexible operation. However due to the converter circuits, the machine dynamics is primarily defined by the control characteristics rather than the physical machine parameters. These control characteristics can be modified to provide a voltage control like a STATCOM or a frequency response like a synchronous generator. Therefore the response of the wind turbine generators during fault conditions is quite different than the physical response of a stand-alone permanent magnet or an induction generator.

A. *Fault Current of DFAG and Full-Conversion Wind Turbines*

The short-circuit current behavior of Type 3 and Type 4 wind generators can be significantly different, depending on the control algorithm and settings. The discrete switching actions, limiting functions, and parameter changes will alter the waveform of the current in a manner which cannot be adequately modeled by a Thevenin equivalent representation of the generator. The response of typical Type 3 and Type 4 wind turbine generators to a three-phase short circuit with a residual voltage of 20% at the MV side of the step-up transformer is shown in Figure 3 and Figure 4. In most grid short-circuit studies today, WTGs are modeled as an ideal voltage source behind a generator reactance for the positive sequence and as a passive reactance in the negative sequence in the same way that conventional synchronous generators and induction machines are represented. Such models do not represent the controlled current behavior nor the non-linear behavior, which characterizes modern wind turbines.

A Type 4 wind turbine generator is not connected to the grid directly. Due to the converter-inverter interface between wind turbine and the grid, the output current of the WTG will also be regulated during the fault periods. The short circuit current is determined by the converter and generally limited to the nominal rating of the converter. Depending on the control logic of the ac-dc-ac converter, the upper limit of the short-circuit contribution from the wind turbine generator is in the range of 2 to 3 p.u. for the first one to two cycles and to the value ordered by higher level controls afterwards. The lower limit of the short circuit current is the pre-fault current output of the wind turbine. Type 4 wind turbines can be represented by a current source with these upper and lower limits for short circuit analysis.

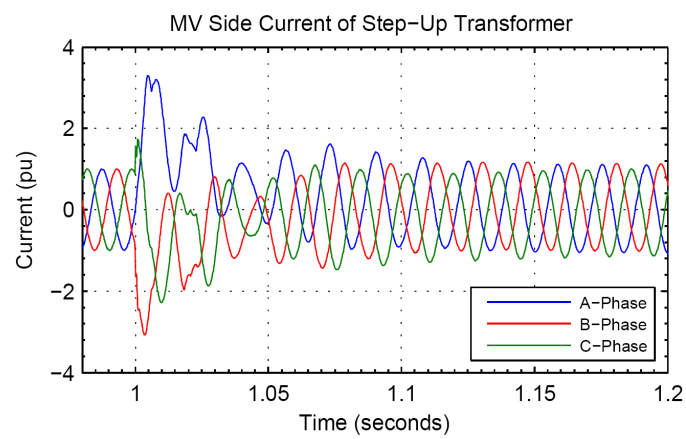

Figure 3. Fault behavior of a typical Type 3 WTG

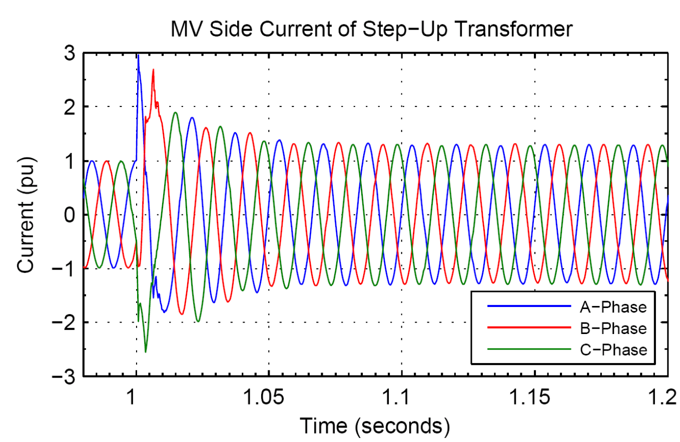

Figure 4. Fault behavior of a typical Type 4 WTG

Type 3 generators are directly connected to the grid with a converter circuit between the rotor and the grid. Because the stator windings are connected to grid directly, a voltage drop at the terminals of the wind turbine will result in high currents in the stator, and consequently the rotor, due to the magnetic coupling. These high rotor currents may increase the DC link voltage to an unacceptable level or the thermal limits of the semiconductor devices can be exceeded. All Type 3 wind turbine generators have some form of protection for the converter circuit, "crowbar" or "chopper" as shown in Figure 1. The crowbar scheme short-circuits the rotor, either directly or through an impedance. The high rotor currents will flow through the bypass instead of the converter circuit. The effect of the crowbar scheme is to transition the generator from a controlled source to an induction generator. The wind turbine generator performance is characterized by the physics of the induction machine during the crowbarred period. There are various schemes for controlling the crowbar. In some schemes, depending on the magnitude and the duration of the fault current, the crowbar action can take place several times resulting in a highly discontinuous short-circuit current.

B. Representation of Wind Turbine Generators for Short Circuit Studies

1) Approximate Representation

The total short circuit current at the fault location is the sum of the currents from the sources connected to the fault location. The total short circuit current is typically dominated by the synchronous generators in the electric grid due to the size of the grid equivalent system compared to the wind plant rating. The ratio of system short circuit capacity to wind plant MVA rating can be as low as 2.5. Even at this low short-circuit capacity, the short circuit current is primarily from the synchronous generators in the grid. Therefore, for approximate short circuit calculations, Type 3 wind turbines can be considered as synchronous generators with transient and sub-transient reactances. This assumes DFAG rotor circuit shorted or crowbarred with an upper-limit current. This kind of approximation will provide conservative result for determining the short-circuit withstand rating of equipment. However this may not provide adequate short circuit current information for the protection coordination and relay settings because the minimum short circuit current may not be obtained accurately with this approximate representation. The minimum short-circuit current will depend on the pre-fault output current of the wind turbine. The short-circuit analysis software need to have capability of incorporating this information into the simulation.

2) Detailed Time Domain Representation

Electromagnetic transients program (EMTP) type of software allow a very detailed and in depth modeling of electric equipment with a three-phase representation of the system where short time intervals from micro seconds to several seconds can be studied. Wind turbine generators and control systems can be modeled in detail to represent the actual operation of the wind turbine. Detailed models for the other system equipment such as cables, transformers, motors etc can also be included in the analysis. However short circuit analysis often requires a large system model where the size of the system that can be modeled in EMTP-type programs is generally limited and implementation of a large system is cumbersome. Also it is generally difficult to obtain detailed models of the wind turbine, such as control algorithms, from the manufacturers as this is generally considered to be proprietary information. Limited representation of the wind turbine based on the assumptions without the knowledge of actual details may lead to misleading results.

IV. Modified Phasor Approach for Short Circuit Analysis

There are several operating conditions, which may result in different fault currents from WTG. The power output range of the WTG can range from 0% to 100% of the nominal power rating. The minimum power output can be higher than 0% for some WTG types. The lagging, leading and unity power factor operation of the WTG need to be considered.

The pre-fault operating conditions are also important to identify the range of short-circuit current contributions of the WTG. Operating conditions that are necessary to be studied for the short circuit analysis of WTG are based on the maximum and minimum operating conditions of the WTG and system conditions. These requirements can be application specific and may be different for different wind plant installations.

Control logic is another important factor that changes the short circuit behavior of the wind turbines. Control systems may use different control parameters during fault conditions than are used during normal operation. The crowbar action of Type 3 wind turbine generators takes place at a certain level of current and duration, which depends on the control logic settings. A fully-detailed control algorithm is not generally made available by wind turbine manufacturers. Most importantly, implementation of detailed control logic is cumbersome even for EMTP type programs.

The search space of the operating conditions and parameters of the wind turbines is quite large for the short circuit analysis. Defining the short circuit current of the WTG with a single equation or a waveform is generally not possible. Therefore, a suitable approach is to provide a maximum and minimum range of currents based on the voltage at the point of interconnection of the WTG to the grid. Therefore maximum short circuit currents for the equipment sizing or the minimum short circuit currents for the protection coordination can be obtained from these graphs to be used in the short circuit analysis programs.

In this study, the fault current contributions from Type 3 and Type 4 wind turbine generators are obtained for several operating conditions of the wind turbine. Simulations are performed using the Electromagnetic Transients Program (EMTP). EMTP type of programs provides a point on wave time domain analysis for a more accurate modeling of the electric network. The wind turbine generator controls, converter, parameters as well as the rest of the network are modeled in detail. Short-circuit programs do not include the flexibility to model control details. Therefore wind turbine generator currents during faults can be obtained by EMTP programs using detailed models and can be incorporated as predefined current sources into short-circuit programs.

The single line diagram of the simulated system is shown in Figure 5. The disturbance is created by step-changing the voltage at the medium voltage (MV) terminals of the step-up transformer. This is equivalent to having a WTG connected to a network with different system impedance or strength. The pre-fault operating conditions of the simulated system include a pre-fault voltage level of 0.9 pu to 1.1 pu at the WTG terminals. Power factor operation range of WTG is 0.90 lagging, unity and 0.90 leading for 100% power output of WTG. In addition to 100% nominal power, 0% power output of the WTG is studied. In general, short-circuit analysis is not performed with knowledge of the specific operating conditions. Therefore, the analysis must generally be inclusive of the full range of pre-fault operating condition possibilities.

The superimposed plots of the short circuit currents from all the simulated cases shows an envelope of maximum and minimum short circuit currents. The maximum and minimum currents as a function of MV bus voltage are shown for Type 3 machines in Figure 6 and Figure 7. Figure 6 shows the current magnitude immediately after the fault and Figure 7 shows the current three cycles after the fault. Similarly Figure 8 and Figure 9 show the short circuit currents for Type 4 wind turbine generator.

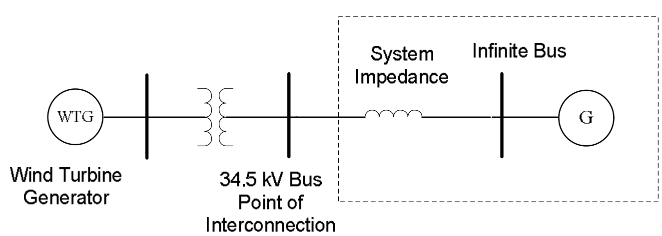

Figure 5. One line diagram of the case system

Because of the complexity of the fault current behavior and the search space of all the operating points of the wind turbine, defining short circuit currents by an envelope such as in Figures 6 to 9, will provide a more comprehensive representation of wind turbine short circuit characteristics. The short-circuit analysis software needs to be modified to accommodate voltage-dependent current source models, defined by lookup tables. While this requires a substantial modification of the industry's short-circuit analysis software tools, it is the most feasible way for this software to accommodate non-conventional generation sources including Type 3 and 4 wind turbines, PV inverters, battery energy storage inverters, voltage-source HVDC, and even FACTS device such as STATCOMs.

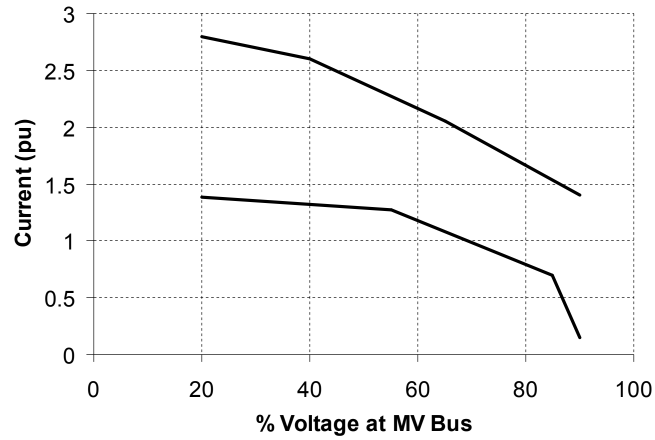

Figure 6. Maximum and minimum symmetrical short-circuit current magnitudes immediately after fault application for a typical Type 3 wind turbine generator

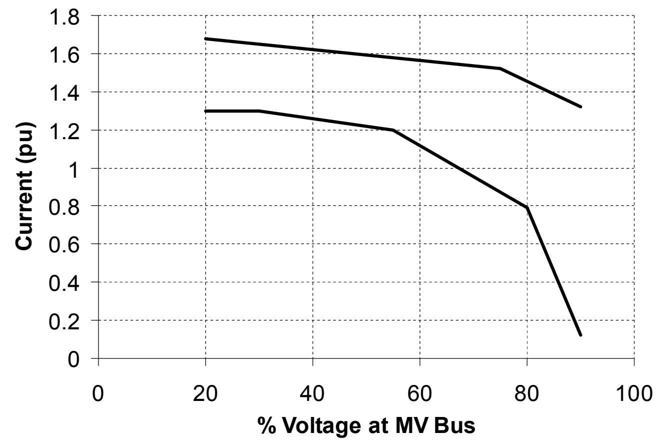

Figure 7. Maximum and minimum symmetrical short-circuit current magnitudes three cycles after fault application for a typical Type 3 wind turbine generator

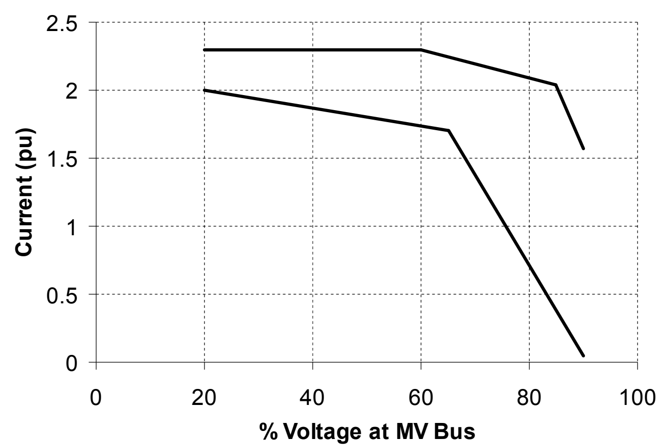

Figure 8. Maximum and minimum symmetrical short-circuit current magnitudes immediately after fault application for a typical Type 4 wind turbine generator

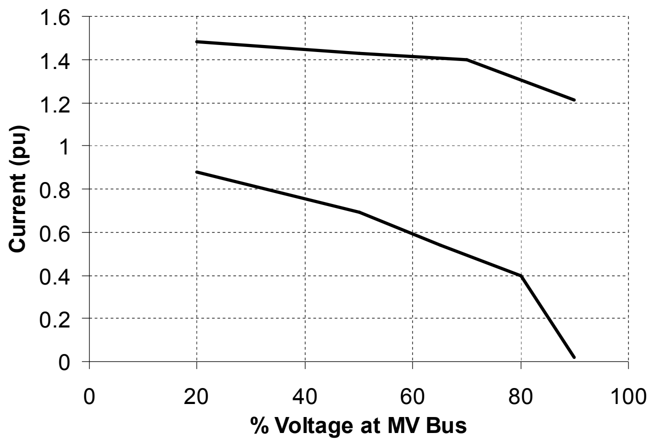

Figure 9. Maximum and minimum symmetrical short-circuit current magnitudes three cycles after fault application for a typical Type 4 wind turbine generator

V. Conclusion

The fault behaviors of Type 3 and Type 4 wind turbine generators are quite complex due to power electronic converters and the wind turbine controls. The representation of wind turbines in short circuit programs by a Thevenin equivalent circuit is generally not adequate. Derivation of an analytical representation, or a detailed time domain analysis, may not be possible due to the proprietary nature of control circuits and algorithms. Because of these shortcomings and the number of pre-fault conditions to be studied, a more efficient way is to define the envelopes for the maximum and minimum short-circuit currents as a function of point of interconnection bus voltage (i.e. medium bus voltage). This approach requires modifications in the existing short circuit programs to accommodate voltage-dependent current source models.

References

[1] "IEEE Recommended Practice for Calculating Short-Circuit Currents in Industrial and Commercial Power Systems, 551-2006 (Violet Book)", *IEEE Standards*, 2006.

[2] IEEE PES Wind Plant Collector System Design Working Group, "Characteristics of Wind Turbine Generators for Wind Power Plants", *Proceedings of the 2009 IEEE Power & Energy Society General Meeting*.

[3] V. Gevorgian and E. Muljadi, "Wind Power Plant Short Circuit Current Contribution for Different Fault and Wind Turbine Topologies" in *The 9th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*, Québec, Canada, October 18-19, 2010.

[4] Vicatos, M.S., Tegopoulos, J.A.,"Transient state analysis of a doubly-fed induction generator under three phase short circuit", *IEEE Transactions on Energy Conversion*, March 1991, Vol. 6, Issue 1, Page 62.

[5] Morren, J. de Haan, S.W.H.,"Short-Circuit Current of Wind Turbines With Doubly Fed Induction Generator", *IEEE Transactions on Energy Conversion*, March 2007, Vol. 22, Issue 1, Pages 174.

[6] R. A. Walling, N. W. Miller, and M.E. Cardinal, "Advanced Wind Plant Controls to Enhance Grid Integration", *Sixth International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms,* 26-28 October, Delft, Netherlands.

Biographies

Reigh Walling (M'1978, F'2005) Reigh Walling received his Bachelor's and Master's Degrees in Electric Power Engineering from Rensselaer Polytechnic Institute in 1974 and 1979, respectively, and is a registered Professional Engineer. He is a Director of Energy Consulting for GE Energy and is involved in a wide range of power system issues including distributed and renewable generation systems, as well as transmission and distribution technologies.
In 2009, Mr. Walling was awarded the IEEE PES Excellence in Distribution Engineering Award. He has authored over sixty papers and articles, and has nine awarded patents

Ekrem Gursoy (M'00) received the B.S. and M.S. degrees in electrical engineering from Istanbul Technical University, Istanbul, Turkey, in 1998 and 2000, respectively, and the Ph.D. degree in electrical engineering from Drexel University, Philadelphia, PA in2007.
He is currently working at General Electric Inc., Schenectady, NY. He is involved with power flow, short-circuit and stability analysis. He has also worked on wind and solar integration studies. Prior to joining GE, he was employed by AREVA T&D where he worked on Static VAR Compensator (SVC) systems.