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Wind Power Plant Short Circuit Current Contribution for Different Fault and Wind Turbine Topologies

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Wind Power Plant Short-Circuit Current Contribution for Different Fault and Wind Turbine Topologies

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Abstract--**An important aspect of wind power plant (WPP) impact studies is to evaluate the short-circuit (SC) current contribution of the plant into the transmission network under various fault conditions such as single, two, and three-phase faults in different network locations. This task can be challenging to protection engineers due to the topology differences between different types of wind turbine generators (WTGs) and conventional generating units. This paper presents simulation results for SC current contribution for WTGs obtained through transient simulation. The obtained waveforms are analyzed to explain the behavior, such as peak values and rate of decay, of the WTG.**

The effect of turbine and substation transformer winding and grounding configuration on positive, negative, and zero-sequence current and voltage magnitudes is demonstrated. The behavior of fault currents is illustrated by the output of simulations in positive, negative and zero sequence components.

We show that the response of the WPP to faults will vary based on the type of the installed WTGs. The SC current will be determined by the generator's physical characteristics and system transformers configurations. For some wind turbine types, the SC current will also depend on power converter's control algorithms, which are usually considered proprietary information by the wind turbine manufacturers.

Index Terms—**Wind Power Plant, Short Circuit Current, Voltage Fault.**

I. NOMENCLATURE

WPP – wind power plant
WTG – wind turbine generator
SC – short circuit
SCC – short circuit current

II. INTRODUCTION

Recently, the energy and environmental crises have become one of the biggest issues around the world. In response to energy needs and environmental concerns, renewable technologies are considered the future energy technologies of choice [1], [2]. Renewable energy is harvested from nature, and it is clean and free. However, it is widely accepted that renewable energy is not the panacea that comes without challenges. With the federal government's aggressive goal of achieving 20% wind energy penetration by 2030, it is necessary to understand the challenges that must be overcome when using renewable energy.

In the years to come, there will be more and more WPPs connected to the grid. In high penetration scenarios, the WPP's operation should be very well planned. The power system switchgear and power system protection for WPPs should be carefully designed to be compatible with the operation of conventional synchronous generators connected to the same grid. This paper attempts to illustrate the behavior of SC current contributions for different types of WTGs.

A. Operation of Wind Turbine Generator

The generator at each turbine should be protected individually and independently because of the WPP diversity. In practice, this is an advantage of a WPP compared to a conventional power plant. During a disturbance, the electrical characteristic at each terminal of the turbine is different from the other WTGs, and only the most affected WTGs will be disconnected from the grid. For general faults (distance faults at the transmission), only 5%-15% of the turbines are disconnected from the grid [3]. This is partially because WPPs are required to have zero voltage ride-through capability. Thus, the loss of generation is not as severe as in a power plant with large generators.

At the turbine level, the WTG generates at low voltage levels (480 V-690 V). Type 1 and Type 2 WTG are typically compensated by switched capacitor banks to generate at a unity power factor. Type 3 and Type 4 generators are operated to generate a constant voltage at a designated bus, or they may be operated at a constant power factor or constant reactive power. The generator is connected to a pad-mounted transformer to step up the voltage to 34.5 kV.

B. Wind Power Plant Equivalent

The collector system consists of miles of line feeders connecting the high side of the pad-mounted transformer to the substation. Usually, the wind turbines are divided into groups of turbines connected in a daisy chain fashion using underground cables. They are then connected to the substation by either underground cables or overhead lines at 34.5 kV. Since it is not practical to model hundreds of turbines in a power flow calculation or in a dynamic simulation, it is common to find the equivalent of the turbines as either a single equivalent turbine representation or as a multiple turbine representation [4],[5].

C. Organization of the Paper

The organization of this paper is as follows: in section III, the SCC characteristics of different WTG types will be summarized and discussed. In section IV, the aggregated SCC contribution of a WPP and the impact of the wind plant configuration will be presented. Finally, in section V, the conclusion will summarize the paper findings.

III. OVERVIEW OF SHORT CIRCUIT CURRENT FAULT CURRENT FOR DIFFERENT WIND TURBINE TOPOLOGIES

A utility-sized wind turbine is larger than non-grid wind turbine applications. In the early days, the turbines were sized from 10 kW – 100 kW. Nowadays, wind turbines are sized above 1000 kW (1 MW).

A. Three-Phase Symmetrical Fault on R-L Circuits

SC faults can occur in various locations of the power system in a number of different ways including line-to-ground and line-to-line faults. For simplicity purposes, we'll consider a symmetrical three-phase fault since it is the easiest to analyze. A simple equivalent diagram of a power system under such fault conditions is shown in Fig. 1.

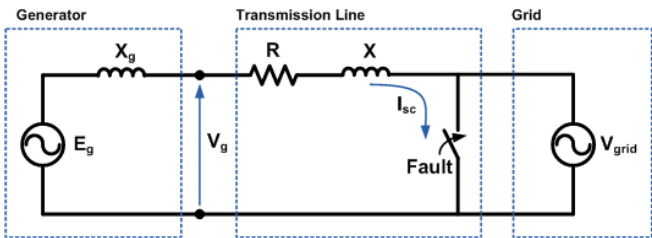


Fig. 1: Equivalent diagram of symmetrical fault

The fault in Fig. 1 is represented by a shorting switch. Immediately after the fault, the SCC contribution from the generator can be found using the following equation.

$$u_g = L\frac{di}{dt} + iR \quad (1)$$

Where u_g is the instantaneous voltage on the generator terminals, and R and L are line resistance and inductance. Solving equation (1) for current

$$i = \frac{V_g}{Z}\sin\left(\omega t + \alpha - \operatorname{atan}\left(\frac{X}{R}\right)\right) - e^{-\frac{R}{L}t}\left[\frac{V_g}{Z}\sin\left(\alpha - \operatorname{atan}\left(\frac{X}{R}\right)\right)\right] \quad (2)$$

Where V_g is peak generator voltage, $Z = \sqrt{R^2 + X^2}$ - line impedance, and α is the voltage phase. The solution (2) has two components; the first component is stationary and varies sinusoidally with time. It represents the steady SCC. The second component decays exponentially with a time constant equal to $\frac{R}{L}$. It represents the DC component of the current. The steady state simmetrical fault current I_{sc} from the generator can be calulcated from the first component of equation (2).

$$I_{sc} = \frac{V_g/\sqrt{2}}{\sqrt{R^2 + X^2}} \quad (3)$$

Obviously, the steady state fault current depends on impedance of the line. The closer the fault occurrence location to generator terminals, the larger the SCC contributed to the fault. The peak magnitude of the transient component in equation (2) depends on line impedance as well, but it also depends on impedance angle $\varphi = \operatorname{atan}\left(\frac{X}{R}\right)$ at the point of the fault. The DC term does not exist if $= \varphi$, and will have its maximum initial value of $\frac{V_g}{Z}$ where $\alpha - \varphi = \pm\frac{\pi}{2}$. So, depending on the time when the fault occurs and the circuit characteristics, the transient current waveform will be different. This means that in three-phase systems the phase transient currents will have different peaks due to a 120^0 shift in voltages.

In large power systems with many generators and transmission lines, the actual fault current at any location in the grid will be the sum of collective contributions from all generators, making the above described analysis extremely complicated. So, some sort of simplification is needed for the fault current calculation in such a case.

B. Short Circuit Current from a Type 1 WTG

The first generation of utility-sized WTGs were a fixed speed turbine with a squirrel-cage induction generator (SCIG) and is called a Type I generator in wind-related applications. The SCIG generates electricity when it is driven above synchronous speed. The difference between the synchronous speed and the operating speed of the induction generator is measured by its slip (in per unit or in percent). A negative slip indicates that the wind turbine operates in generating mode. Normal operating slips for an induction generator are between 0% and -1%. The simplified single-phase equivalent circuit of a squirrel-cage induction machine is shown in Fig. 2 [6].

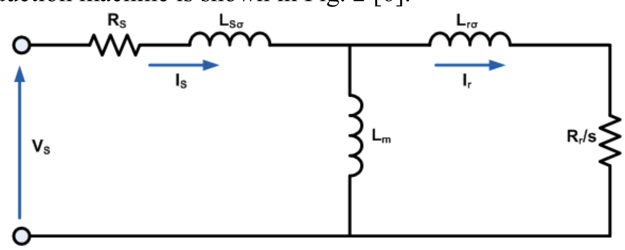


Fig. 2: Equivalent circuit of a Type 1 generator

The circuit in Fig. 2 is referred to the stator where R_S and R_r are stator and rotor resistances, $L_{S\sigma}$ and $L_{r\sigma}$ are stator and rotor leakage inductances, L_m is magnetizing reactance, and S is rotor slip. The example single-line connection diagram of a Type I generator is shown in Fig. 3. In the case of voltage fault, the inertia of the wind rotor drives the generator after the voltage drops at the generator terminals. The rotor flux may not change instantaneously right after the voltage drop due to fault. Therefore, voltage is produced at the generator terminals causing fault current flow into the fault until the rotor flux decays to zero. This process takes a few electrical cycles. The fault current produced by an induction generator must be considered when selecting the rating for circuit breakers and fuses. The fault current is limited by generator impedance (and can be calculated from parameters in Fig. 2) and impedance of the system from the SC to the generator terminals.

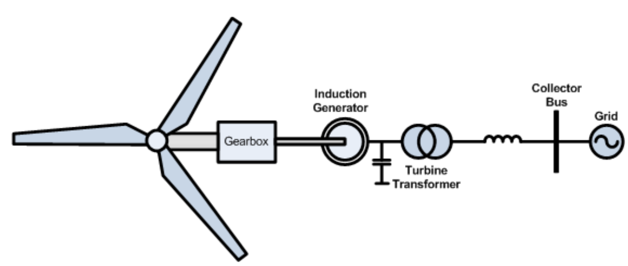


Fig. 3: Type 1 WTG

The initial value of fault current fed in by the induction generator is close to the locked rotor inrush current. Assuming a three-phase symmetrical fault, an analytical solution can be found to estimate the current contribution of the generator. According to [7], the SCC of an induction generator can be calculated as

$$i(t) = \frac{\sqrt{2}V_S}{X_S'}[e^{-\frac{t}{T_S'}}\sin(\alpha) - (1-\sigma)e^{-\frac{t}{T_r'}}\sin(\omega t + \alpha)] \quad (4)$$

Where δ is the voltage phase angle for a given phase, σ is the leackage fator, $X_S' = \omega L_S'$ is stator transient reactance, and T_S' and T_r' are stator and rotor time constants for damping of the DC component in stator and rotor windings. The transient stator and rotor inductances L_S' and L_S' can be determined as

$$L_S' = L_{S\sigma} + \frac{L_{r\sigma}L_m}{L_{r\sigma}+L_m};\; L_r' = L_{r\sigma} + \frac{L_{S\sigma}L_m}{L_{S\sigma}+L_m} \quad (5)$$

$$T_S' = \frac{L_S'}{R_S};\; T_r' = \frac{L_r'}{R_r} \quad (6)$$

$$\sigma = 1 - \frac{L_m^2}{L_S L_r} \quad (7)$$

$$L_S = L_{S\sigma} + L_m\,;\; L_r = L_{r\sigma} + L_m \quad (8)$$

The current calculated from equation (4) is shown in Fig. 4 using parameters for a typical 2-MW induction generator when $\alpha = 30^0 + \pi/2$ and pre fault voltage $V_S = 0.7\,pu$. As can be seen from Fig. 4, the current reaches the maximum value at $t = T/2$ (first half a period). Therefore, it may be a good approximation to calculate the maximum (peak) current by substituting $t = T/2$ into (4). The resulting equation for peak current will be

$$i_{max} = \frac{\sqrt{2}V_S}{X_S'}[e^{-\frac{T}{2T_S'}} + (1-\sigma)e^{-\frac{T}{2T_r'}}] \quad (9)$$

It was demonstrated experimentally in [8] that equation (9) gives satisfactory accuracy for peak current assessment. The resulting current is shown in Fig. 4.

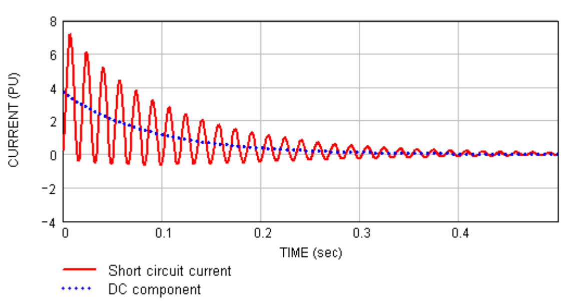


Fig. 4: Short circuit current from a Type I WTG

C. *Short Circuit Current from Type 2 WTG*

The variable slip generator is essentially a wound-rotor induction generator with a variable resistor connected in series to the rotor winding (Type 2 generator). This external resistor is controlled by a high-frequency switch. Below rated power, the resistor control is inactive, so the system operates as a conventional induction generator. Above rated power, the resistor control allows the slip to vary, so variable speed operation is possible for a speed range of about 10% [9]. If the blade pitch angle is kept constant at zero degrees, the rotor speed, and thus the slip, will vary with wind speed. However, operation at higher slips generates a lot of loss because of the rotor resistance. Thus, the heat loss can be excessive. On the other hand, if the blade pitch angle is controlled to keep the rotor speeds within a small deviation from the rated slip, the losses in rotor resistance can be minimized. An equivalent electrical diagram of a variable slip induction generator is shown in Fig. 5, with a variable external resistor R_{ext}.

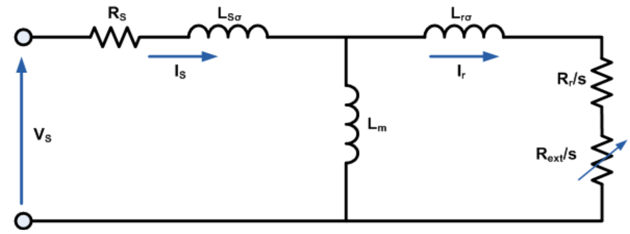


Fig. 5: Equivalent circuit for a Type 2 generator

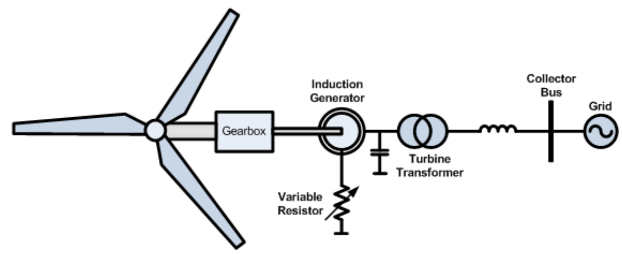


Fig. 6: Connection diagram for a Type 2 WTG

The connection diagram example for this type of generator is shown in Fig. 6. In case of three-phase symmetrical fault, the same equations as for a Type I generator are applied. The only difference will be for rotor time constant T_r' that needs to account for additional external resistance R_{ext}. The modified rotor time constant can be calculated as

$$T_{r.ext}' = \frac{L_r'}{R_r + R_{ext}} \quad (10)$$

Where R_{ext} is the value of external resistance that happens to be in the circuit at the time of a fault. The effect of such additional resistance on SCC is shown in Fig. 7 for the case where $R_{ext} = R_r = 0.005pu$. So, adding the external resistors doubles the overall rotor resistance. The modified equation for maximum current can then be written as [7]

$$i_{max} = \frac{\sqrt{2}V_S}{\sqrt{X_S'^2 + R_{ext}^2}}[e^{-\frac{\Delta T}{T_S'}} + (1-\sigma)e^{-\frac{\Delta T}{T_{r.ext}'}}] \quad (11)$$

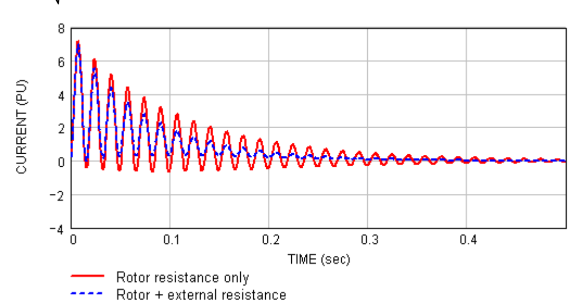


Fig. 7: Effect of external resistance for a Type 2 WTG

Where ΔT is the time after a fault when current reaches its first peak. In this case, this additional resistance decreases the overall AC component in current, but does not much affect the first peak value of the current since the increase in resistance is relatively small. The same conclusion can be made by analyzing equations (4) and

(9), where the additional external resistance has an effect on a second term that represents the AC component of the current.

D. Short Circuit Current from a Type 3 WTG

A Type 3 WTG is implemented by a doubly fed induction generator (DGIF). It is a variable speed WTG where the rotor speed is allowed to vary within a slip range of ± 0.3. Thus, the power converter can be sized to about 30% of rated power. The equivalent electrical diagram of a DFIG generator is shown in Fig. 8. It is similar to one for a regular induction generator except for additional rotor voltage V_r, representing voltage produced by a power converter. The typical connection diagram for a DFIG (Type 3) WTG is shown in Fig. 9. A crowbar system is usually used for protecting the power electronics converter from overvoltage and thermal breakdown during SC faults. Additional dynamic braking on the dc bus is also used to limit the dc bus voltage.

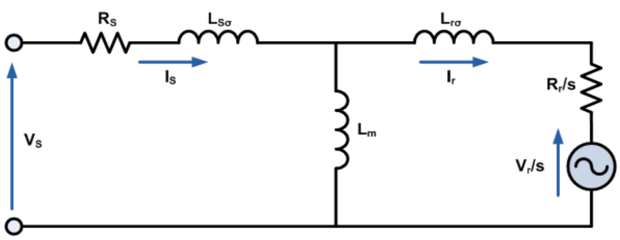


Fig. 8: Equivalent diagram of a DFIG

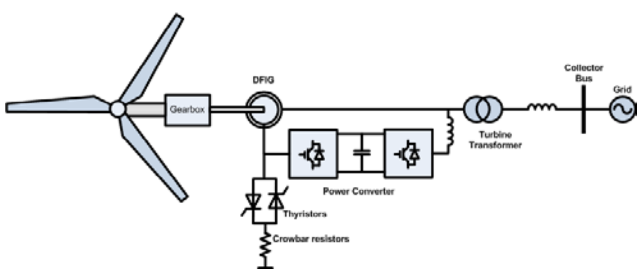


Fig. 9: Connection diagram for a Type 3 WTG

During faults, the rotor windings are essentially short circuited by an equivalent crowbar resistance R_{CB}. According to [7], the transient time constant for a DFIG generator will be

$$T'_{r.CB} = \frac{L'_r}{R_r + R_{CB}} \quad (12)$$

And, the maximum SCC of a DFIG will be

$$i_{max} = \frac{\sqrt{2}V_S}{\sqrt{X_S'^2 + R_{CB}^2}}\left[e^{-\frac{\Delta T}{T'_S}} + (1-\sigma)e^{-\frac{\Delta T}{T'_{r.CB}}}\right]$$

(13)

If $R_{CB} \gg R_r$, then $T'_{r.CB}$ is small and the time of the first peak $\Delta T \rightarrow 0$. In such a case, [7] proposes a simplified equation for DFIG maximum SCC

$$i_{max} \approx \frac{1.8V_S}{\sqrt{X_S'^2 + R_{CB}^2}} \quad (14)$$

Calculated SCCs for a DFIG for two different crowbar resistance values are shown in Fig. 10. In this case $R_{CB2} > R_{CB1} \gg R_r$. The red plot represents zero crowbar resistance when $R_r = 0.005pu$. The blue and green plots represent cases when $R_{CB} = 0.05pu$ and $R_{CB} = 0.1pu$ respectively. As can be seen in Fig. 10, larger crowbar resistance will lead to a lower peak current and smaller AC component. The maximum value of crowbar resistance $R_{CB.max}$ can be found from equation (14) if maximum allowable rotor voltage is specified.

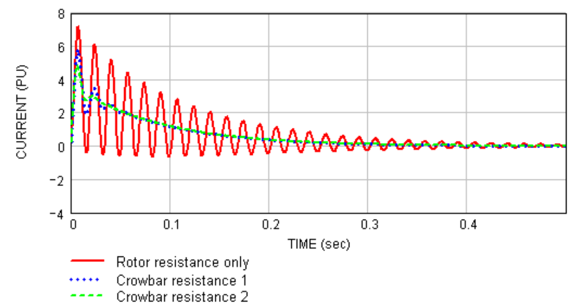


Fig. 10: Effect of crowbar on max DFIG current

E. Short Circuit Currents from a Type 4 WTG

An example of a Type 4 direct drive WTG with permanent magnet synchronous generator (PMSG) is shown in Fig. 11. This is a variable-speed wind turbine generator implemented with full power conversion. Recent advances and lower cost of power electronics make it feasible to build variable-speed wind turbines with power converters with the same rating as the turbines. The full power conversion allows separation between the WTG and the grid, thus, the mechanical dynamic can be buffered from entering the grid and the transient dynamic on the grid can be buffered from entering the wind turbine dynamic. Thus, while the grid is at 60 Hz, the stator winding of the generator may operate at variable frequencies. The temporary imbalance between aerodynamic power and generated power during a transient is handled by the pitch control, dynamic brake, and power converter control.

The SCC contribution for a three-phase fault is limited to its rated current or a little above its rated current. It is common to design a power converter for a Type 4 wind turbine with an overload capability of 10% above rated. Note that in any fault condition, the generator stays connected to the power converter and is isolated from the faulted lines on the grid. Thus, although there is a fault on the grid, the generator output current is controlled to stay within the current limit (e.g., 1.1 p.u.). However, keep in mind that with a fault on the grid, the output power delivered to the grid is less than rated power. Although the currents can be made to balance, due to reduced voltage and/or unbalanced voltage, only a reduced output power can be delivered. Therefore, the wind turbine must be controlled to reduce the aerodynamic input accordingly (pitch control and converter control). Any difference in the power converter (i.e., between output power to the grid and input power from the generator) will rise or drop the DC bus voltage.

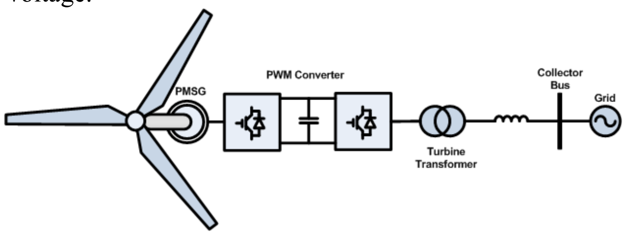


Fig. 11: PMSG direct drive WTG diagram

F. *Short Circuit Current from WTG with Synchronous Generator Directly Connected to Grid*

The latest advances in hydro-dynamic torque converter technology allowed development of variable-speed wind turbines with synchronous generators (SG) directly connected to grid. The torque converter allows decoupling of the variable speed mechanical output of a turbine gearbox from the generator shaft. As a result, the synchronous generator rotates at constant speed, so no power electronics converter is needed. The SC analysis for such WTGs then becomes an SC analysis of a regular synchronous generator that has been studied extensively in the literature. A simplified equivalent electrical diagram of a synchronous generator is shown in Fig. 12, where $L_{a\sigma}$ is the armature leakage reactance, L_{ar} is the armature reaction, and E_f is the generator EMF at no load. A more detailed diagram for a two-axis representation is available from multiple sources and is not considered in this report. A configuration diagram example of a WTG with a directly connected SG is shown in Fig. 13.

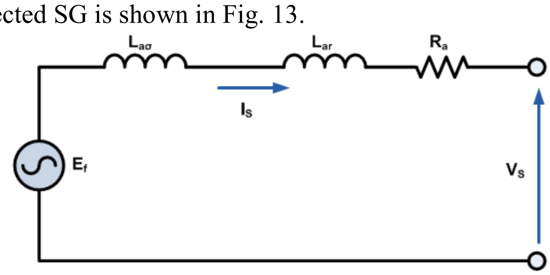


Fig. 12: Equivalent diagram of a SG

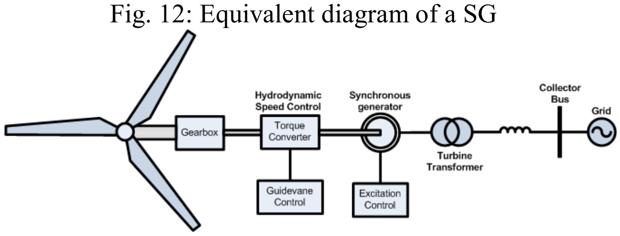


Fig. 13: WTG with a directly connected SG.

In the case of a three-phase symmetric short-circuit, the analytical solution for current contribution of the synchronous generator according to [10] can be written as

$$i(t) = V_S\left[\frac{1}{x_d} + \left(\frac{1}{x'_d} - \frac{1}{x_d}\right)e^{-\frac{t}{T'_d}} + \left(\frac{1}{x''_d} - \frac{1}{x'_d}\right)e^{-\frac{t}{T''_d}}\right]\cos(\omega t - \alpha) - \frac{V_S}{2}\left[\left(\frac{1}{x''_d} + \frac{1}{x''_q}\right)\cos(\alpha) + \left(\frac{1}{x''_d} - \frac{1}{x''_q}\right)\cos(\omega t - \alpha)\right]e^{-\frac{t}{T_a}} \quad (15)$$

Where X_d, X'_d, X''_d is the d-axis synchronous, transient, and sub-transient reactance; X''_q is the q-axis sub-transient reactance; T'_d, T''_d are the transient and sub-transient time constants; T_a is the armature time constant; α is the angle between phase A, and d-axis at the beginning of the SC. The current in equation (15) has both AC and DC components. The maximum current will vary depending on phase angle α as shown in Fig. 14 for a typical megawatt size SG. Although machine reactances are not true constants and depend on saturation of the magnetic circuit, their values are usually within certain predictable limits.

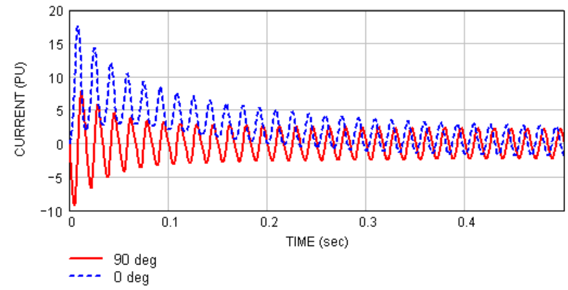


Fig. 14: SG short circuit current for two different angles

G. *Standard Practices for Short Circuit Level Calculation*

A procedure for fault current calculation based on an equivalent voltage source at the fault point is used in the IEC 60909 standards [11]. The Thevenin theorem is applied to the unloaded networks with a corrected source voltage. The voltage correction factor for voltages is used to account for the variations of the actual voltage from nominal value. In the case of a symmetrical fault, the IEC 60909 method suggests calculating initial symmetrical SCC as

$$I''_k = \frac{cV_n}{\sqrt{3}\,Z_k} \quad (17)$$

Where c is a voltage scaling factor, V_n is the nominal line-to-line voltage at the point of fault, and Z_k is the Thevenin impedance of the grid. The standard suggests using values $c=1.05$ for MV/HV networks and $c=1.10$ for LV networks. The peak SCC is then calculated as

$$I_P = k\sqrt{2}I''_k \quad (18)$$

Where the factor k is given as a function of R/X and can be calculated as

$$k = 1.02 + 0.98e^{-3\frac{R}{X}} \quad (19)$$

The factor k takes into account the transient component of SCC and allows estimating the highest possible instantaneous value of the SCC. The equation (19) is valid for a case of a single-fed far-from-generator fault. The standard proposes different equations for k factor calculations for different types of circuits. The IEC method for SCC calculations is applied to both 50-Hz and 60-Hz systems.

H. *Asymmetrical Faults*

Balanced three-phase faults can be analyzed using an equivalent single-phase electrical circuit similar to the one shown in Fig. 1. For example, a comparison for SCC from a Type I wind turbine is calculated using Equation 4 and a three-phase PSCAD model is shown in Fig. 15. For a symmetrical fault, Equation 4 gives good approximation for peak current and decay time.

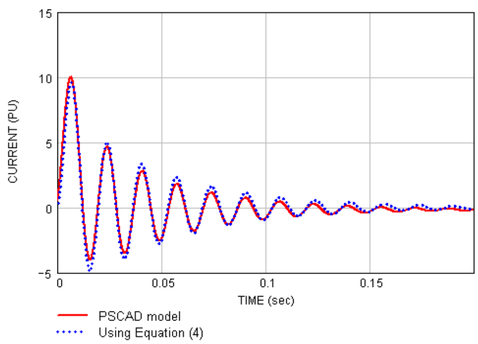


Fig. 15: Comparison of SCC for Type 1 WTG

Single or two-phase faults can be analyzed using symmetrical components to reduce the complexity of the calculations. The symmetrical components method splits the unbalanced three-phase system into three balanced components: positive, negative, and zero sequence. The symmetrical components method and its applications to power system fault analysis have been described in detail in the technical literature. It is important to note that this method is based on steady-state analysis and does not consider transient effects in power systems. In a case with power systems with high wind penetrations, such approach may be used with Type I wind turbines. It may become inaccurate for Type II, III, and IV wind turbines since it does not account for damping and transient effects in such non-linear elements of wind turbines as slip control systems or power converters.

Based on the above consideration, it was decided to conduct detailed time domain modeling of various types of wind farms operating with a power system under different fault conditions. Such time domain transient analysis allows capturing peak values of fault currents and accompanied voltage surges at different locations throughout the network. Results from such a simulation will be more realistic than results obtained from steady-state circuit analysis. The programming environment used for power system time-domain simulation is PSCAD (also known as PSCAD/EMTDC), developed by the Manitoba HVDC research Centre. PSCAD has been adopted worldwide by utilities, manufacturers, and research institutions, so it became an industry standard for electromagnetic transient simulations in power systems.

IV. Modeling Results

A. Power System Model

The power system model used for wind farm SC behavior simulation was adopted from a modeling guide developed by the Western Electricity Coordinating Council (WECC) Wind Generator Modeling and Validation Work Group (WGMG) [12]. The WGMG recommends the use of a single-machine equivalent representation of multiple wind turbines operating in a single wind farm. Based on industry experience, this representation is also considered adequate for positive-sequence transient stability simulations. The WECC single machine equivalent power flow representation is shown in Fig. 16. The interconnection transmission lines, transformers, and reactive power compensation are present in this representation.

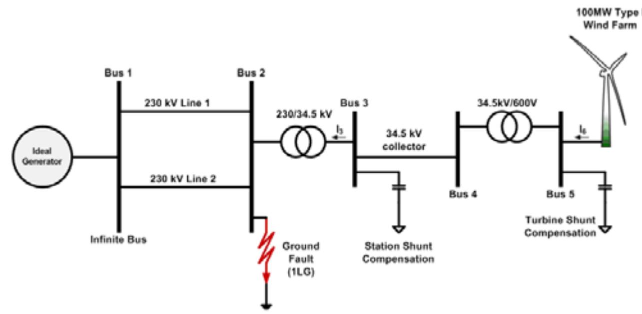


Fig. 16: A single-machine equivalent power flow representation

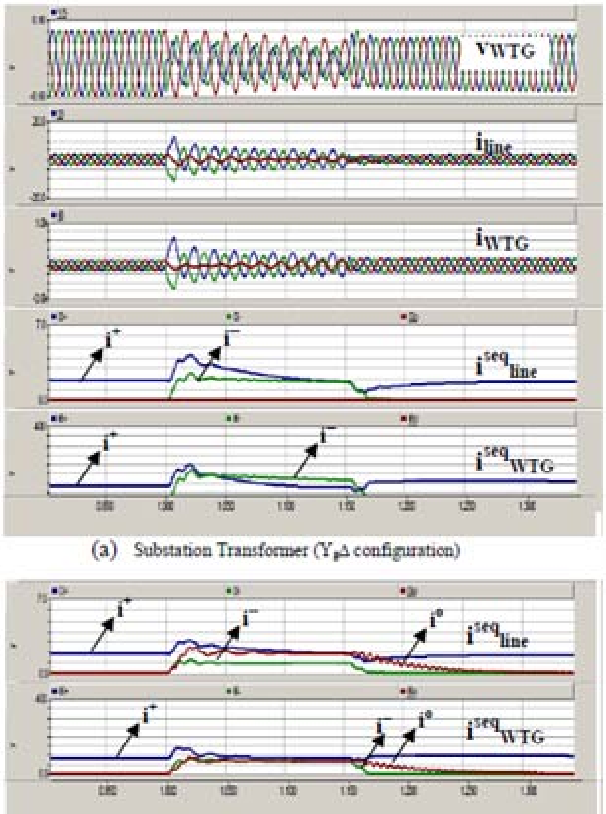
By considering a single turbine representation, all the WTGs in the WPP are assumed to be operating at the same operating condition, thus, a study of the worst case scenario is obtained. Power factor correction capacitors are necessary for Type 1 and Type 2 WTGs. And in some cases (e.g., weak grid condition or variation of the power factor or voltage control at the POI), it may be necessary to install additional plant-level reactive compensation implemented by a Static VAR Compensator (SVC), STATCOM (Static Compensation), Mechanically Switched Capacitor (MSC), or a combination of them. Under normal conditions, the Type 3 and Type 4 WTGs have the capability to vary the reactive and real power instantaneously and independently. Plant-level reactive compensation may be omitted for these WTG types.

B. Transformer Configuration within a WPP

The WPP will have two different types of transformer. The first one is the substation transformer. The substation transformer interfaces between the WPP and utility. It steps up the voltage of the collector system (e.g., 34.5 kV) to a transmission level voltage (e.g., 230 kV). The size of the substation transformer is the same size as the wind plant output in MVA. However, it is common to use several transformers (for redundancy, reliability, and economic consideration). Many WPPs use a three winding transformer as the substation transformer $Y_g/\Delta/Y_g$. Note that the subscript g is used to indicate solid ground connection at the star point of the transformer. The second one is the pad-mounted transformer. It is installed at each turbine to step up the voltage from generation voltage (e.g., 690 V) to the medium voltage used in the collector system (e.g., 34.5 kV). In many wind plants, the Y_g/Δ connection is used for the pad-mounted transformer. With this connection, the zero sequence contribution from the power plant is blocked. Only positive and negative sequence components can flow to the fault along the transmission line. As shown in Fig. 16, a WPP can be represented by the wind turbine, the pad-mounted transformer, the collector system, the substation transformer, and the interconnecting transmission line [13] [14] .

Most WPPs consist of uniform turbines from a single turbine manufacturer. Thus, a single turbine representation should be sufficient to represent the WPP. In some cases, a WPP may need to be represented by multiple turbines to capture the unique characteristics of the turbine generators within the WPP.

The SC behavior of a WPP is affected by the type of generator, type of faults, configuration of the transformer, and other components such as reactive power compensation and cable capacitance. Other factors that may impact the SC behavior include unbalanced impedance within the WPP, unbalanced switching (stuck breaker), non-linear behavior of the transformer magnetic saturation, harmonics within the plant, and many other factors.



(a) Substation Transformer ($Y_g\Delta$ configuration)

(b) Substation Transformer (Y_gY_g configuration)

Fig. 17: SCC for a single line-to-ground in a Type 1 WPP

The symmetrical component is often used in calculating the unbalanced condition in a power system network. In a normal balanced condition, only the positive sequence component of voltage and current are found within the network. In an unbalanced condition, the negative and the zero sequence components of voltage and current can be found in the power system network. Using the symmetrical component, we can perform fault analysis and predict the SCCs and the bus voltages from a steady-state power system network. However, the steady state calculation considers only the fundamental component of voltage and current. Thus, the DC offset, the non-fundamental component occurring during the transient, are not accessible.

The simulation performed in this paper uses a three-phase network [13][14]. The WPP is subject to different SC conditions at the transmission lines. The power system configuration within the WPP will have an impact on operation. Depending on the system configuration, the simulation will capture the positive, negative, and zero sequence components during transients, as well as the DC and non-fundamental components of voltage and current.

As an illustration, a different transformer configuration and grounding will be studied in this section to illustrate the path of ground current. As an example, Fig. 17a shows SCC for a wind plant with a Type 1 turbine. The substation transformer is connected as Y-Δ (230 kV-Y_g / 34.5 kV-Δ). The pad-mounted transformer is connected as Y-Y (34.5 kV-Y_g / 0.690 kV-Y_g). A single-line–to-ground-fault occurs at the high side of the substation transformer. The line currents and the sequence currents are shown at the transmission line (i.e., the contribution from the wind plant only) and at the turbine side. As might be expected from the transformer configuration ($Y_{g\Delta}$), there is no zero sequence current contribution from the WTG side.

In Fig. 17b, the substation transformer is reconfigured to Y-Y (230 kV Y-grounded / 34.5 kV Y-grounded). Shown in Fig. 18 is the simplified equivalent circuit of the power system derived from Fig. 16 to illustrate the SC paths. The positive, negative, and zero sequence diagrams are connected in series for a single-line-to-ground-fault. The switch indicates the difference between Y_gY_g versus $Y_g\Delta$ configurations at the substation transformer.

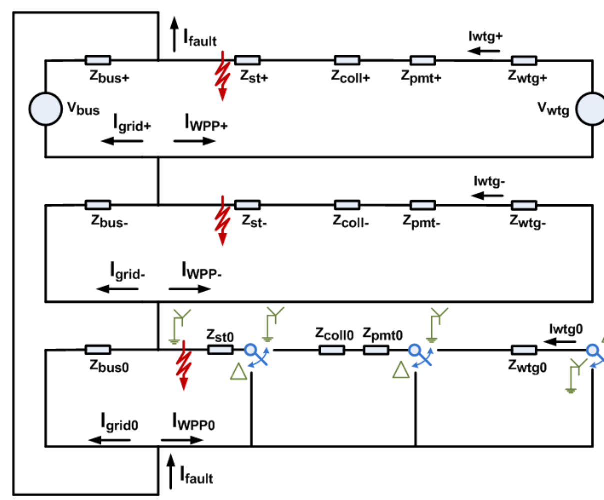


Figure 18: The equivalent circuit for a single line-to-ground fault

The collector system and the transmission line are actually represented by the pi circuit to represent the inductance and capacitance of the lines. It is not shown in Fig. 18 to simplify the drawing. Note that the flow of sequence currents (positive, negative, and zero sequence) are affected by two sources (i.e., the network bus and the wind turbine equivalent within the wind plant).

The modeling results for a Type 1 wind power plant are consolidated in Fig. 19 and Fig. 20. These figures show peak transient and sequence component values for current I_3 (as shown in Fig. 16) for different sub-station and pad-mounted transformer configurations after a single line-to-ground fault (phase A is faulted). As can be seen in Fig. 19, the highest transient current in phase A corresponds to the case when the substation transformer is configured as Y-Y (230 kV Y-grounded / 34.5 kV Y-grounded) and the pad-mounted transformer is configured as Y-Δ (34.5 kV-Y_g / 0.690 kV- Δ). Both negative I_{3-} and zero I_{30} sequence components are also highest in this case (Fig. 20). The zero sequence components are completely eliminated when the substation transformer's 34.5-kV winding is configured as Δ or ungrounded Y. However, the positive and negative sequence current contribution always exists for all configurations, as seen in Fig. 20.

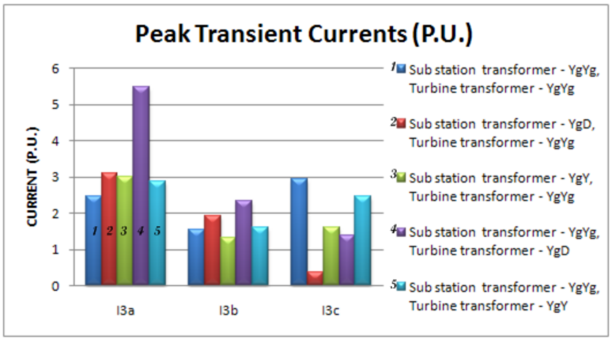


Fig. 19: Peak transient currents for different transformer configurations

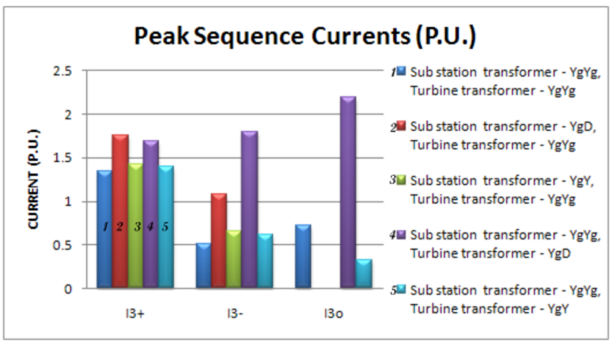


Fig. 20: Peak sequence currents for different transformer configurations.

V. CONCLUSIONS AND FUTURE PLANS

This paper describes a simple approach to compute and understand the behavior of the SCC for different types of WTGs. Five different types of WTGs were investigated. The method describes and approximates the peak and the settling time of the SCCs. From the comparisons made between the detailed high level model and the simple SC representation, the simple method can predict and approximate the SCCs with good accuracy.

Another part of the paper describes the short circuit behavior of Type 1 wind plant for different transformer configurations. The effect of the transformer configuration impedes or passes the zero sequence current from the wind plant, while the positive and negative sequence portions are not impeded.

Future plans include conducting similar type of SCC modeling for other types of WPP.

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VI. BIOGRAPHIES

Vahan Gevorgian (M'97) graduated from the Yerevan Polytechnic Institute (Armenia) in 1986. During his studies he concentrated on electrical machines. His thesis research dealt with doubly-fed induction generators for stand-alone power Systems. He obtained his Ph.D. degree in Electrical Engineering Dept. from the State Engineering University of Armenia in 1993. His dissertation was devoted to a modeling of electrical transients in large wind turbine generators. Dr. Gevorgian is currently working at the National Wind Technology Center (NWTC) of National Renewable Energy Laboratory (NREL) in Golden, Colorado, USA, as a research engineer. His current interests include modeling and testing of various applications of wind turbine based power systems. He is a member of IEC61400-21 wind turbine power quality standard development group.

Eduard Muljadi (M'82-SM'94-F'10) received his Ph. D. (in Electrical Engineering) from the University of Wisconsin, Madison. From 1988 to 1992, he taught at California State University, Fresno, CA. In June 1992, he joined the National Renewable Energy Laboratory in Golden, Colorado. His current 9 research interests are in the fields of electric machines, power electronics, and power systems in general with emphasis on renewable energy applications. He is member of Eta Kappa Nu, Sigma Xi and a Fellow of the IEEE. He is involved in the activities of the IEEE Industry Application Society (IAS), Power Electronics Society, and Power and Energy Society (PES).

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