Introduction

Wind generation has experienced tremendous levels of growth, exceeding 8000 MW installed in the US in 2008 alone [1], and is the second-leading form of generation additions installed on the US grid in that year. Utility relay engineers are in need of guidance with respect to wind generation modeling for short circuit calculations in order to perform protective relay applications and settings.

With very few exceptions, wind turbine generators (WTGs) do not use conventional line-connected synchronous generators, for which the short-circuit characteristics are very well understood in the relay community. For various reasons discussed in this paper, WTGs use induction generators, doubly-fed generators, and generators interfaced to the grid via ac-dc-ac converters. The short-circuit characteristics of these forms of generation differ from the familiar synchronous generator behavior. There are also significant differences between various types of WTGs, and between different designs of WTGs in the same type.

Wind Turbine Generator Types

The variable nature of wind drives WTG designs away from conventional synchronous generator application. To limit mechanical loads on the WTG system, including the blades and towers, there is a need to provide some form of “soft” coupling to allow deviation from fixed speed when the turbine blades are exposed to turbulence and gusting. In addition, the energy capture of a WTG can be maximized if the speed of a WTG can be varied to maintain a constant relationship between the circumferential speed of the blade tips, and the wind velocity. To meet these needs, nearly all WTGs are designed with one of four basic types of generators. The industry appears to be converging on the following type number designations for these generators:

- **Type 1** – Squirrel-cage induction generators
- **Type 2** – Wound rotor with controlled rotor resistance
- **Type 3** – Doubly fed generator (sometimes called a doubly-fed induction generator)
- **Type 4** – Generator interfaced to the grid totally through a variable speed power electronic drive system.

Squirrel-Cage Induction Generators (Type 1)

An induction generator is physically identical to an induction motor. Power generation results when an induction machine is turned by a source of mechanical torque, such as a wind turbine, at a speed greater than synchronous speed. Figure 1 illustrates a speed-torque curve for an induction machine. The portion of the curve below synchronous speed is the familiar speed-
torque characteristic of a motor. Above synchronous speed, the torque characteristic is a mirror image of the motor characteristics, except that torque is applied to the generator, and the generator delivers real power to the grid. However, induction generators always consume substantial reactive power. Therefore, compensating capacitors are typically installed with each WTG, and are switched in stages according to the power output of the generator as shown in Figure 2.

A Type 1 WTG is operated at nearly constant speed, a few percent slip above synchronous speed. A small amount of speed variation allows some reduction in the mechanical loads imposed by wind turbulence.

Recent interconnection requirements have mandated that wind power plants (WPPs) have low-voltage ride-through capability, such as the requirement in FERC Order 661A that wind plants
ride through a three-phase fault, up to nine cycles duration, at the wind plant’s transmission point of interconnection. Just like an induction motor, re-magnetization of an induction generator following a fault consumes a large amount of reactive power. If the grid to which the WPP is connected is not strong, reactive demands of induction WTGs can suppress voltage recovery and potentially cause voltage collapse. Therefore, it is often necessary to provide some means of dynamic reactive compensation, such as STATCOMs or SVCs to meet low-voltage ride-through requirements with Type 1 induction generators. When considering short-circuit contribution of WPPs, potential contributions of auxiliary equipment such as STATCOMs should be included.

Wound Rotor Induction Generators (Type 2)

A wound rotor induction machine design allows an external variable rotor resistor to be applied. Variation of rotor resistance modifies the machine’s speed-torque characteristic, such that a wider range of speed variation is possible, relative to a Type 1 machine. In modern Type 2 WTGs, the external resistance is controlled via power electronics to allow fast variation. Speed variation range is on the order of 10%, allowing a degree of energy capture optimization, as well as some smoothing of power output and machine mechanical loading during wind turbulence and gusting.

Similar to a Type 1 WTG, a Type 2 WTG always requires reactive power, which is typically supplied by switched capacitor units. Type 2 WTGs are also subject to the same low-voltage ride-through performance issues as a Type 1 WTG, and may need supplemental dynamic reactive compensation equipment to meet interconnection standards.

Doubly-Fed Generators (Type 3)

Doubly-fed generators, also known as doubly-fed induction generators or doubly-fed asynchronous generators, use an ac-de-ac power converter to “excite” the rotor of the machine with a variable frequency three-phase ac “excitation” as illustrated in Figure 3. The ac excitation causes the flux field of the rotor to have an apparent rotation with respect to the rotor. The frequency and phase sequence of the rotor current is controlled by the converter such that the sum of the physical rotation of the rotor, and the apparent rotation of the magnetic field with respect to the rotor, is synchronous speed. Thus, the doubly-fed generator produces line-frequency output while having the capability of rotating over a wide range of speed, typically ±33% of synchronous speed. When the rotor turns at less than synchronous speed, real power flows through the converter into the generator rotor. Above synchronous speed, power flows out of both the rotor and stator.
Synchronous speed for a six-pole 60 Hz electrical machine is 1200 rpm. If, for example, a Type 3 WTG with a six-pole generator is desired to rotate at 800 rpm, the excitation applied to the rotor by the converter is 20 Hz with a positive phase sequence as illustrated in Figure 4(a). This causes the magnetic field to rotate at 400 rpm with respect to the rotor, yielding the 1200 rpm synchronous speed when summed to the rotor’s physical speed. If the WTG is to turn at synchronous speed (1200 rpm) then the excitation applied to the rotor is dc as in Figure 4(b). At this speed, there is no difference between the doubly-fed generator and a synchronous generator. To operate the machine at 1600 rpm, a 20 Hz negative phase sequence excitation is applied as shown in Figure 4(c). This causes the magnetic field to counter-rotate with a speed of –400 rpm, with respect to the rotor, again yielding a flux wave rotation at synchronous speed with respect to the stator.

A doubly-fed generator can both source or sink reactive power. By adjusting the magnitude and angular position of the flux wave via converter control, the real and reactive power output of the generator can be precisely regulated. Because the rotor is laminated, flux time constants are very short, allowing the regulation bandwidth of the generator to be greater than 60 Hz. This means that output can be controlled within a time span of a few milliseconds.

Doubly-fed generators can be designed to provide low-voltage, even zero-voltage, ride-through capability without the need for any supplementary reactive compensation devices.
Unlike an induction generator in which rotor currents are induced, a doubly-fed generator is an externally excited machine. Characteristics of this machine, particularly reactive power capabilities, differ greatly from induction generators. Therefore, the traditional term for this type of generator, “doubly-fed induction generator”, is quite misleading. While physically similar to a wound-rotor induction machine, a doubly-fed generator is conceptually similar to a synchronous generator with variable speed, and in practice is controlled to be a constant current source like a power converter.

**Full Conversion (Type 4)**

A Type 4 WTG achieves variable speed operation by interconnecting the generator to the grid via an ac-dc-ac converter. The generator type can be synchronous, permanent magnet, or induction; the type of generator has little consequence to grid issues like short circuit current contributions due to the isolation provided by the converter. The power converter can be designed to source or sink reactive power identically to the function of a STATCOM.

Type 4 WTGs use IGBT (insulated-gate bipolar transistor) or IGCT (insulated gate-commutated thyristor) devices in a voltage-source converter (VSC) to synthesize the ac output voltage using pulse-width modulation. Figure 5 illustrate converter output voltage and the resulting converter current flowing through the inductance of the output transformer into the sinusoidal grid voltage. Converter output current is controlled by the modulation index and phase of the pulse-width modulation pattern. Very fast control speed can be readily obtained, with bandwidth well in excess of 60 Hz.

![Figure 5 Illustration of pulse-width modulated Type 4 WTG output.](image)

IGBTs and IGCTs are very sensitive to excess currents. In typical applications, current more than two or three per unit is sufficient to destroy IGBTs in a very short time. Therefore, the high-speed controllability of the voltage-source converter is used to limit output current, especially during faults. The current limitation is achieved by both a high-bandwidth current regulator, and a “hard limit” where an IGBT or IGCT device is turned off just before the maximum device current level is reached.
Fault Current Characteristics

Induction Generators

Type 1 and Type 2 WTG short-circuit current characteristics are similar, and these two types will be discussed jointly. The short circuit current behavior of induction generators is the same as for induction motors. The initial current contribution to a three-phase fault is defined by the sum of the generator’s subtransient reactance and the system impedance from the machine terminals to the fault. This initial fault current decreases as the flux in the machine collapses, and will eventually reach zero unless there is sufficient reactive compensation to maintain generator excitation during the fault. Results of detailed simulation of a Type 1 WTG plotted in Reference [2] show fault current dropping to one per unit of the machine rating in about five cycles for a three-phase fault on the high side of a WTG unit transformer.

For coordination of instantaneous relays, the WTG short circuit contribution in the initial cycle is relevant. This contribution can be modeled in a standard short-circuit analysis program by representing the induction generator as a voltage behind subtransient reactance, the same representation as a synchronous generator. For unbalanced faults, both the negative and positive sequence impedances are assumed to be equal to the subtransient reactance. However, the dynamic behavior of the generator flux during the fault complicates the short-circuit behavior as shown in Figure 6.

WTGs are normally ungrounded sources, so there is no ground current contribution. However, wind power plants typically have grounding transformers and power transformers that act as ground sources which should be included in WPP representation in short-circuit studies.
For fault studies on the transmission system, it is inconvenient to represent all of the WTGs of a WPP individually. It is sufficient to represent the entire WPP with one equivalent WTG, having a rating equal to the sum of the operating WTGs in the plant, in series with a reactance representing the composite impedance of the individual WTG unit transformers, collector cables, and substation power transformers. Reference [2] describes an approach to deriving this equivalent impedance.

Full Conversion (Type 4) Generators

Conceptually, the voltage-source converter used as the output device of a Type 4 generator has similarity to a synchronous generator because it produces a voltage behind the output inductance, and the magnitude and phase of this voltage governs the real and reactive power output. However, the voltage is synthesized by the pulse-width modulation, and is thus highly controllable. This allows the current output of the generator to be highly controlled, without flux time constants. Because the power electronics are highly susceptible to overcurrent, this fast control action is used to limit Type 4 generator short-circuit currents to a small magnitude. Unlike a synchronous generator, for which the fault behavior is governed by physics and differences from one design to another are small, the fault currents of a Type 4 generator are functions of the specific proprietary control design. There can be significant differences in fault current behavior from one design to another.

Figure 7 shows current contribution from a Type 4 generator into a three-phase grid fault, at the WPP point of transmission interconnection, based on a detailed simulation. There is a momentary peak of 2.4 p.u. in the initial half cycle, followed by a current output slightly above the pre-fault level. For the same fault case, but with the pre-fault loading at 10% rather than 100% of generator rating,

![Figure 7](image)

Figure 7 Type 4 WTG terminal current for a three-phase fault at the wind plant point of transmission interconnection.

Figure 8 shows results for a three-phase fault at the MV bus of the WPP, a location electrically closer to the WTG by the impedance of the substation transformer. Despite the significantly different impedance between the WTG and the fault location, the fault current is nearly the same as in Figure 7. A conclusion drawn from this is that conventional short-circuit modeling, where a fixed voltage is behind a fixed generator impedance, is not a highly accurate assumption for Type 4 WTGs.
For unbalanced faults, the objective of the control is to limit currents on the individual power electronic devices. Delta-wye configuration of unit step-up transformers and the phase-to-phase nature of the voltage-source converter bridge removes the one-to-one correspondence of inverter legs to transmission phases. Various control techniques can be employed to limit device currents. As a result, unbalanced fault current behavior of Type 4 WTGs can be complex, and differ substantially between designs.

**Doubly-Fed (Type 3) Generators**

Type 3 generators are discussed last because they combine the characteristics of a full conversion generator with an induction generator. Fault transients can place extreme voltage and current duty on the converter of a doubly-fed generator. To limit this duty, a “crowbar” is used to short the rotor. When the crowbar is closed, the doubly-fed generator becomes a simple induction generator. When it is not closed, the generator fault current contribution is controlled similar to a Type 4 generator. The fault severity resulting in crowbar application, and the duration that it is applied, is a function of the specific generator design.

To illustrate the performance of a Type 3 generator for a grid fault, the model configuration shown in Figure 9a is used. The star configuration of grid impedances can be reduced to the Thevenin equivalent system model shown in Figure 9b. The impedances were chosen to give a 0.5 p.u. grid source voltage, and 0.2 p.u. Thevenin impedance (on WTG rating base) seen from the WTG terminals. This represents a 50% voltage dip fault in a strong grid. The resulting WTG current is shown in Figure 10a. Modification of the impedances representing the grid, yielding a 0.5 p.u. Thevenin voltage and a 0.4 p.u. Thevenin impedance, resulting in the WTG current shown in Figure 10b. Despite a 2:1 difference in effective impedance between the WTG and the fault, there is little difference in the fault current.
The conclusion that can be drawn here is that the short-circuit current contribution of Type 3 wind plants, to grid faults, is small in magnitude but also relatively invariant to system impedance conditions.

**Short Circuit Analysis Considerations**

The short-circuit behavior of induction WTGs can be modeled reasonably well in conventional short-circuit analysis programs. Different programs, however, provide different capabilities to address the rather significant decrease in short-circuit contribution over time. For single-phase faults, the flux dynamics are not precisely represented by typical short-circuit analysis tools, but reasonable accuracy can be obtained for the initial fault cycles using the generator subtransient reactance for both the positive and negative sequence impedance.

New induction wind plants typically have dynamic reactive compensation to meet current low-voltage ride-through requirements. When STATCOM devices are used, the dynamic devices have a potential short-circuit contribution similar to a Type 4 WTG. Complete representation of the WPP dictates that the contributions of dynamic reactive devices be included.

For wind plants with full-conversion (Type 4) WTGs, present short-circuit modeling tools may not directly represent the near constant current behavior. The program user could use synchronous generator modeling and iteratively adjust the WTG impedance to achieve the desired current value. A useful addition to this software would be some form of source model that represents inverter characteristics. Because the fault current contribution tends to be very small, particularly in comparison with grid fault current contribution, great precision is usually not justified.

Doubly-fed (Type 3) WPPs can usually be modeled in the same manner as Type 4 plants for faults outside of the plant. Faults inside the plant are more complex. If maximum short-circuit...
current is the limiting condition, as for breaker ratings, representation as an induction generator for in-plant faults is conservative.

If great accuracy in modeling Type 3 and Type 4 plant short circuit current contributions is required, an atypical situation, detailed transient simulation using tools such as PSCAD or EMTP must be performed. Such simulations, however, are of no merit if the power converters and controls are not modeled in great detail according to the manufacturer’s design and control algorithms. Generic or idealized models are likely to produce misleading results.

Protection Considerations

In regards to transmission line protection, WPPs should typically be treated as weak sources in comparison to the utility grid. Type 1 and Type 2 WTGs will provide classical induction machine fault contributions that quickly decay, but which generally have a greater magnitude than that of Type 3 and Type 4 WTGs. In windfarms connect radially to a utility transmission substation, existing digital impedance measuring relays should operate correctly given any of the four WTG Types. Windfarms connected to three-terminal lines may create issues with respect to apparent impedance when faults occur. The windfarm impedance measuring relay will have accurate impedance measurement to the three-terminal line tap. However, the impedance from the tap to the fault will be amplified by the factor of total current/ windfarm current, thus the apparent impedance to the fault is larger than the sum of actual line impedances. This phenomenon could result in a large impedance reach that encompasses normal load impedance.

\[
I = \frac{V}{I}
\]

\[
V = IZ_a + (I+I)Z_b
\]

\[
V = IZ_a + IZ_b + IZ_b
\]

\[
Z_r = \frac{IZ_a + IZ_b + IZ_b}{I}
\]

\[
Z_r = Z_a + Z_b + Z_b(I/I)
\]

**Figure 11** Wind plant infeed and apparent impedance reach with three-terminal lines

Protection applications where windfarms connect to the bulk transmission system will have redundant pilot schemes. Inherent in these schemes is the ability to perform transferred tripping of remote terminals. The protection applications should incorporate transferred tripping of the windfarm from the utility substation(s) for any protection or breaker opening condition.

Conclusions

The growth of wind power has brought a new form of generation equipment into the power grid that has short-circuit characteristics different than synchronous generators. Although these
characteristics are unconventional, the magnitude of short-circuit current produced by the various types of wind turbine generators is typically small relative to conventional synchronous generators in the grid. This is particularly true for doubly-fed (Type 3) and full-conversion (Type 4) generators. Representation of these latter types in short-circuit analysis requires some modification to existing practices, and modification of the industry’s tools will facilitate these changes. The power grid is moving from the age of copper and iron to one where solid-state power electronics plays an ever-increasing role. The introduction of new forms of generation is one manifestation of this paradigm shift.

References

2. N. Samaan, “Modeling of Wind Power Plants for Short Circuit Analysis in the Transmission Network”, presentation at the January, 13, 2009 meeting of the IEEE PES Joint Working Group on Fault Current Contributions from Wind Plants, Atlanta, GA.