Considerations for Fault Protection of Wind Power Plant Collector Systems

Presented at
Western Protective Relay Conference 2011
October 18-20, 2011
Spokane, Washington

George S. Tsai Li
S&C Electric Company

Abstract - Protection requirements of Wind Power Plants (WPPs) collector systems depend largely on cable system design and system grounding. Collector systems are often underground. In some cases, they are overhead. Systems are effectively grounded or high-resistance grounded (HRG).

Multifunction relays located at the medium voltage substation typically provide the primary protection to collector feeder circuits. Microprocessor-based relays are typically used because of their versatility.

Wind turbine generator (WTG) fault current performance under fault condition, which depends on the type, make and model of the particular turbine, is considered for overcurrent protective device coordination. Present grid requirements impose that generator terminal voltage protection allow the turbines to ride through a 150 millisecond-fault at the Point of Interconnection (POI). Faults on the collector system could take longer to clear and would result in a number of wind turbine generators going offline. Adequate sensitivity of the feeder protection is crucial. Available fault current contribution (minimum and maximum) from the grid should be considered for relay sensitivity and overcurrent protective device coordination.

This paper also discusses the options available when detection of faults at the end of long circuits is difficult.

Challenges in locating faults in the collector system and application of faulted circuit indicators (FCI) are discussed as well.

Keywords - collector system, directional, fault current, point of interconnect, relay, ride-through, wind turbine generator, wind power plant, faulted circuit indicator, WPP, FCI, WTG

I. Introduction

Construction of wind power plants (WPPs) has surged in recent years and these plants have become an important part of the renewable energy portfolio of the United States. These generating plants have their own particular design requirements and protection issues. This paper discusses the protection considerations of wind power plants and in particular collector system protection.

Wind power plants consist of one or more wind turbine generators that connect to a collector substation through a network of medium voltage underground and/or overhead cables, most commonly at 34.5 kV. This “reverse distribution system” is known as the collector system. The collector system originates at the substation and reaches out to each wind turbine generator. Depending on the number of wind turbine generators, the collector system may be divided into several feeder circuits. At the collector substation, each feeder circuit is connected to a common bus and the medium voltage is stepped up to the interconnection transmission voltage level through a step-up transformer. The wind farm connects to the grid at the Point of Interconnection (POI), which is usually at the high side of the step up transformer(s) or at a nearby switching. When the POI is at a nearby switching station, there could be a transmission line between the collector substation and the switching station or the interconnect substation and that collector substation may be built next to each other and there may simply be a short length of bus over the fence to connect the two substations to each other. Smaller wind power plants sometimes also interconnect to the grid directly at subtransmission voltage levels of 34.5 kV.

Wind power plants are required to meet specific voltage, power factor and fault ride through requirements detailed in a small (< 20 MW) and large (≥ 20 MW) generator interconnection agreement [1][2]. For instance, the interconnection agreement document would require a wind power plant to have the capability to operate continuously at the POI with power factor range from 0.95 leading to 0.95 lagging for voltages ranging from 0.95 to 1.05 p.u. Power factor requirements of the wind power plant and those of the wind turbine generators should be considered when setting directional overcurrent relays in relays.

Disconnection of large generating plants due to external fault disturbances can have significant impact on system stability. Large generator interconnection agreements (LGIA) require that wind power plants should remain connected for a 0.15-second, zero-volt fault at the POI [3]. The LVRT requirement should be taken into consideration in setting overcurrent and voltage relays as ideally none of the protection in the wind farm should interfere with the ability of wind turbine generators to ride through faults.

II. Wind Farm Collector System Design

Collector systems consist of underground, overhead, or both underground and overhead cable sections. Underground cables are often used due to reliability, safety, and aesthetic considerations where soil conditions are adequate and first cost is not the primary consideration. Overhead lines are used where soil conditions are not favorable (e.g., high thermal resistance or difficulty trenching due to rock), access to land is limited, or the collector system consists of long sections. Overhead conductors are typically Aluminum Conductor Steel Reinforced (ACSR) or Aluminum Conductor Composite Reinforced (ACCR), although other types, including messenger wire spacer cable systems are sometimes also used. Underground cables are usually three single aluminum conductor type URD cables with concentric neutrals in trefoil arrangement, which are directly buried in the soil with a separate ground cable. Typical sizes for underground cable sections are 1500 MCM, 1250 MCM, 1000 MCM, 500 MCM, 4/0, 2/0 and 1/0. Each segment of cable is sized to carry a maximum number of wind turbine generators based on ampacity. Collector systems could be hybrid, consisting of both underground and overhead segments. Some installations use underground padmounted switchgear with overcurrent protection to limit the extent of an outage in the collector system, which would otherwise be cleared by the feeder relay.

Wind power plant collector systems in North America are typically effectively grounded. Grounding practices vary in other countries. The type of grounding has significant impact on fault sensitivity and selectivity.

In North America, the main substation transformer is typically a wye grounded - wye-grounded transformer with buried delta tertiary or wye grounded - delta with grounding transformer connected. The grounding transformer provides a reference ground and a path for zero-sequence current. Grounding transformers are usually also found downstream of each feeder circuit breaker in the collector substation. Each grounding transformer will contribute zero-sequence current for ground faults in the collector cable system and will maintain the ground reference for the feeder once the feeder circuit breaker has tripped.

The main purpose of the grounding transformer for each feeder is to provide a ground reference after the feeder breaker has opened to clear a ground fault in the collector system. In ungrounded systems, the voltage of the unfaulted phases for a single phase to ground fault could reach 1.73 per unit and could cause insulation breakdown and equipment damage if the equipment were not rated properly. Grounding transformers are sized to lower the voltage of unfaulted phases effectively under 1.4 per unit for a duration of time (typically 10 seconds). Not all wind power plants have feeder grounding transformers. Some plants use special feeder circuit breakers that automatically short the three phases to ground with minimum delay after the circuit breaker has opened.

The separate ground conductor that is carried through each cable segment is in continuous contact with the earth and is bonded to the concentric neutrals and grounded to earth at regular intervals. Because of this practice, the ground relay setting should be set above the total fault current contribution seen by the relay through the ground conductor plus return current paths through earth.

Ungrounded systems provide an advantage over effectively grounded systems in that the magnitude of fault current level is limited and the wind power plant could continue to operate normally until an outage of the feeder is scheduled. The disadvantages of ungrounded systems being the difficulty of detecting and locating faults and the increased insulation levels required due to sustained overvoltage that occurs during a ground fault.

III. Wind Turbine Generator Short-Circuit Performance

Wind turbine generators are induction or synchronous generator based. Currently, turbine generators are usually less than 3.6 MW in rated capacity. In general, wind turbine generators fall within one of five types of designs. Type 1 consists of an induction generator with squirrel-cage rotor. Type 2 consists of an induction generator with wound rotor and variable and controllable resistance. Type 3 consists of a doubly-fed induction generator (DFIG) with back-to-back inverters in the rotor circuit. (The Type 3 replaces the resistor of the Type 2 design with a variable frequency ac excitation to the rotor circuit to push rotor power out to the power system instead of just turning it into waste heat.) Type 4 consists of an induction or synchronous generator with full scale ac to dc to ac conversion. Type 5 consists of a synchronous generator. In the Type 5, the variable-speed and variable torque output from the mechanical drive train is connected to a fluid coupling torque/speed converter to provide the constant-speed output to the drive the synchronous generator.

Type 1 thru 4 wind turbine generators are low-voltage (575 to 1000 V). Each wind turbine generator has a dedicated dry-type or liquid filled generator step-up transformer (GSU) to raise the voltage to collector system voltage. The windings of these transformers are typically connected wye grounded on the generator side and delta on the collector system side. Pad mounted transformers are protected by fuse links in series with current limiting fuses. For some types of wind turbine generators, the GSU is located in the nacelle and the protection of the transformer and medium voltage cable in the tower is provided by an SF6 insulated vacuum fault interrupter switchgear, which is located at the foot of the tower. The switchgear features phase and ground overcurrent relays. Type 5 wind turbine generators can operate 12.47 kV; therefore, they can interconnect directly to a utility distribution system.

The implementation of controls and methods of operation vary with the make and model of the turbine. The response of a specific wind turbine generator to system faults is dependent on the electrical parameters of the generator and electronic control implementation. Knowledge of the response of the specific wind turbine generator under fault condition is important for fault and coordination studies as well as relaying and protection. Electrical parameters of the generator and control details should if possible be provided by the wind turbine manufacturer, although detailed information is often considered proprietary. The initial fault contribution from a Type 1 and Type 2 generators can be determined using the subtransient reactance of the induction machine. Given that these are induction generator, the fault current contribution decreases to a magnitude dictated by the transient reactance faster than it would if it were a synchronous generator. For some generators, this is approximately 5 per unit. Fault contribution from Type 3 and Type 4 turbines are largely dependent on the electronic control implementation and the short-time rating of the inverters. Power electronic components can tolerate a short-time overload of 2 to 3 per unit current for few seconds before ramping down to rated current. Type 5 generators would largely be dependent on the synchronous machine electrical parameters. Subtransient, transient and synchronous reactance should be considered depending on the time frame of operation of protective relays.

Wind turbine generators feature overvoltage (59) and undervoltage (27) relays and overfrequency (81O) and underfrequency (81U) relays. High voltages can cause insulation breakdowns while low voltages can cause misoperations of power electronic components and motor stall conditions. Underspeed and overspeed conditions that result from underfrequency and overfrequency can subject rotating machines to excessive mechanical stress and damage. Furthermore, many of these rotating machines also use V/Hz overexcitation relays (24) to protect the machines from magnetic core saturation that may overheat the generator.

IV. Protective Relaying Practices and Considerations

Microprocessor-based relays are widely used in wind power plants. Each relay provides multiple protection functions and sophisticated protection algorithms not available in electromechanical relays. The current inputs of these relays are low burden (except high impedance relays) and can often tolerate CT saturation. Custom control and protection logic can be programmed in these relays, which would otherwise have to be implemented with external control wiring. They also act as metering devices and fault data recorders. They are reliable and reduce maintenance cycles.

The primary function of the feeder relays is to provide overcurrent protection to the collector system. Protection to the feeder grounding transformers is also usually provided by the feeder relay. The feeder relay is involved indirectly in the protection of the substation collector bus if a fast bus application is used. Frequency and voltage relays, if available in the feeder relay, can be programmed to offer backup protection to the wind turbine generators or overexcitation protection to the main transformer. In the event that a fault in the collector system has not cleared, the feeder relay can also be programmed to act as a breaker failure relay.

A. Collector System Bus Protection

Fast bus schemes can add unnecessary complexity and thus are not very popular with wind power plants. Low impedance bus relays (87B) can be used to protect collector substation bussing, but high impedance bus differential relays (87Z) are more popular. With the high impedance relay, each bus section is protected with a separate relay. The zone of protection covers the main transformer secondary breaker or disconnect switch, feeder breakers and tie breaker. Current transformers for station service transformers or potential transformers are not generally required by the relay because the pickup level can be set high enough to avoid false trip due to these miscellaneous loads. The voltage differential trip setting should not exceed the ANSI class rating of the smallest CT; otherwise, the CT ratio or the ANSI class should increase to gain appropriate operating margin. If possible, the minimum current required to operate the relay (corresponding to the voltage differential trip setting) should be set higher than the station service transformer and potential transformer primary winding phase thru fault current to allow the main secondary breaker or primary fuses to clear the secondary-side faults.

Percentage restrained current differential relays (87T) are typically used for main transformer protection, but they can also be used to provide bus protection. If the percentage restrained current differential relay is used primarily for transformer protection, then the zone of protection should not be extended to include the collector bus. Such an application is not recommended because relay operation for faults not involving the transformer would result in unnecessary and costly testing of transformers to confirm that there is no internal problem following a differential trip. Also, each set of current transformers should be connected to a dedicated current restrained input on the relay. This is not always possible, especially for large wind power plants with numerous feeder circuits.

B. Collector System Cable and Feeder Grounding Transformer Protection

The feeder relay should be capable of detecting any type of collector circuit faults including faults at the far end of the collector circuit and high impedance faults (HIFs) from downed overhead conductors. During energization of a wind farm, each circuit from the collector system is first energized up to the GSU and each wind turbine generator is placed online one at a time. To evaluate the sensitivity of overcurrent pick up settings, the highest source impedance should be considered with no infeed from wind turbine generators. Directional overcurrent control (67) sensitive to currents flowing into the collector circuit, in the direction from the collector substation towards the wind turbine generators, can be used to obtain higher sensitivity for phase-overcurrent relays. The directional phase-overcurrent relay could be set below the full load current of the circuit, but above the GSU primary phase protective device (i.e., SF6 switchgear phase overcurrent relay).

Non-directional phase-overcurrent relays (51, 50) should be set above the full load current of the circuit. Directionally controlled negative-sequence overcurrent relays (46) may be used to detect unbalanced faults (i.e., phase-to-phase) in the collector system. The negative-sequence overcurrent setting does not need to be higher than the full load current of the circuit. However, it should be set higher than the trip setting of the GSU primary phase protective device (i.e., SF6 switchgear phase overcurrent relay). For effectively grounded and high resistance grounded collector circuits, the feeder relay ground overcurrent relays operate on calculated residual current (3I0). If each of the GSUs are protected with fuse links, then the ground overcurrent relay setting should be higher than the total clearing current for the current at which the fuse begins to melt. If fault interrupters in SF6 switchgear are used instead, then the feeder ground overcurrent relay should be set higher than the fault interrupter ground overcurrent setting. Directional overcurrent control from ground overcurrent elements may be used to distinguish between currents flowing into the collector system from those leaving the collector system.

The feeder relay also provides protection to the feeder grounding transformer. The feeder relay should detect high impedance arcing faults at 600 V, which it can accomplish by using directional overcurrent control for the phase and negative-sequence overcurrent relays. If the grounding transformer is internally fused, then the feeder phase and ground overcurrent relays must coordinate with the grounding transformer fuses so that the fuses do not melt before the feeder protection clears the fault. The grounding bank must be able to supply ground fault current to external faults in order for the system to operate as intended. There would be a race between the time needed to clear a ground fault in the collector system and the melting time of the grounding transformer fuses. As a result, it is recommended for grounding transformers not to be fused. Rather, the feeder protection should be set sensitively enough to provide required protection of the feeder grounding transformers. Directional relaying can help to provide this required sensitivity for faults on the protected collector circuit while still restraining properly for faults in the opposite direction.

Collector system bus PTs are connected to the feeder relays. The feeder relay uses the positive, negative and zero-sequence voltages to polarize the directional overcurrent relays. For close-in three-phase faults, the relay uses memory polarization. That is, it retains the previous voltage information in memory and uses it to determine the direction of the fault current.

In setting the directional overcurrent control, the maximum torque angle (MTA) of the positive, negative and zero-sequence polarizing quantities should be selected carefully to provide the maximum sensitivity to faults in the collector cable system and feeder grounding transformer, yet not operate under normal operating conditions. The angle of the collector system impedance varies with the location of the fault because different types of cables are used. The feeder relay also measures an apparent impedance instead of an actual cable impedance. The apparent impedance is the result of fault current contribution from multiple wind turbine generators in front of the feeder relay to the fault location. Suitable MTAs for positive, negative, and zero-sequence can only be determined after simulating faults in short-circuit analysis software for collector system and wind turbine generator locations and with varying infeed from wind turbine generators. The MTA for the positive-sequence polarizing impedance should be set considering the power factor operating range of the wind turbine generators based on interconnection requirements at the POI. This is to prevent the feeder relays from making an incorrect declaration of current direction during normal operating conditions.

HIFs due to downed overhead conductors on soil, gravel, or concrete can be detected using micro-processor based relays that have patent-pending/patented algorithms (based on statistics, rate-of-change of current, etc.). HIF current has traditionally been estimated using 40 Ohms as the worst case fault resistance between overhead line conductors and earth. The assumed 40 Ohm fault resistance may not be sufficiently conservative.

Coordinated response of relays for faults in the collector system is necessary to prevent unnecessary outages of unfaulted feeder circuits or the plant. Relays typically used for feeder protection feature ANSI and IEC standard inverse-time overcurrent curves. Some relays allow custom curves to be developed by specifying a formula or by entering current versus time points. The directional phase, ground and negative-sequence overcurrent curves must take into account the combined magnetizing inrush current for the GSUs in the circuit. A conservative estimate for the inrush current is 8 to 10 times of rated GSU current at 0.1 seconds and 25 times of rated GSU current at 0.01 seconds. There are no cold or hot load pickup currents.

In setting the non-directional overcurrent relays, it is important to take into consideration the low-voltage ride through requirements of the wind plant. Wind turbine generators should ride through low voltage conditions for at least 0.15 seconds. Coordination of wind plant protective devices for faults outside of the wind plant is not achievable in many cases. However, coordination of protective devices including the feeder relay for faults in a wind turbine generator, a GSU or collector cable section should be maintained. The lowest source impedance and appropriate fault current contribution for wind turbine generators should be considered for the coordination study. Coordination between the GSU primary winding protection and the feeder relay would normally recognize the fault current seen by the feeder relay and the current seen by the GSU primary protective device are different. The GSU primary protective device detects the total fault current while the feeder relay detects a portion of the total fault current. This is an important consideration when protecting collector system #1/0 cables connected to a GSU.

C. Fault Locating

Because of the non-homogeneous topology of the collector system, the feeder relay as a single ended device cannot accurately determine the location of a fault. To automatically and accurately pinpoint the location of a fault, the phase-to-ground voltages and currents for each phase from each wind turbine generator and feeder relay location would be needed for fault locating algorithms. This is impractical at the scale level of a wind farm collector circuit. Faulted Circuit Indicators (FCIs) are utilized and installed at each GSU location and at the feeder circuit breaker location. There are two types of FCIs currently in use for wind farm fault locating applications. Both types can be mounted on the dead end terminals of a pad mounted GSU transformer. One variety provides directional overcurrent control. The presence of a fault is signaled by flashing LED indication. The direction of the fault is signaled by the color of the flashing LEDs. One color indicates that fault is to the left of the FCI and a different color that the fault is to the right.

The other variety is a non-directional FCI. The overcurrent pickup setting and response time of each FCI is set in the factory based on a short-circuit study performed for the system. Each FCI is configured to pickup only for fault current contributions from the grid and not for fault current contributions from wind turbine generators.

V. Conclusion

Given the interconnection requirements, topology of wind power plants, and characteristics of wind turbine generators, the considerations in the protection of wind power plants and in particular, the collector system that are unique from other generating plants. The present practices balance relay performance and system cost to achieve practical fault detection and discrimination in a cost efficient manner.

VI. References

[1] Federal Energy Regulatory Commission (FERC) Order No. 2003-C “Standard Interconnection Agreements & Procedures for Large Generators,” *June 16, 2005*

[2] Federal Energy Regulatory Commission (FERC) Order No. 2006-A “Standard Interconnection Agreements & Procedures for Small Generators,” *November 22, 2005*

[3] Federal Energy Regulatory Commission (FERC) Order No. 661-A “Standard Interconnection Agreements for Wind Energy and Other Alternative Technologies,” *December 12, 2005*

[4] IEEE PES Wind Plant Collector System Design WG “Wind Plant Collector System Design Considerations,” *2009 IEEE PES General* Meeting, Calgary, Alberta, Canada, July 2009.

[5] IEEE PES Wind Plant Collector System Design WG "Characteristics of Wind Turbine Generators for Wind Power Plants," *2009 IEEE PES General Meeting*, Calgary, Alberta, Canada, July 2009.

[6] D. Miller, J. K. Niemira, "Fault Contribution Considerations for Wind Plant System Design and Power System Protection Issues," *2011 IEEE PES General Meeting*, Detroit, Michigan, July 2011.

VII. Biographies

George S. Tsai Li graduated with B.S. and M.S. in Electrical Engineering from The Ohio State University. He is a Senior Engineer in the Power System Services Division of S&C Electric Company in Chicago, Illinois, where he has worked in various engineering and consulting capacities for 11 years. Presently he works primarily on relaying, protection and SCADA projects and provides technical sales and application/integration support for S&C Remote Supervisory Switchgear products.