Protection of Wind Electric Plants

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***Abstract*—A wind electric plant (WEP) is made of many wind turbine generators spread over a large area and includes many subsystems that need to be protected. It is important to ensure that all the subsystems are well protected and coordinated to maximize the reliability (security and dependability) of the overall protection and control system. Working Group C25 of the Power System Relaying and Control (PSRC) Committee wrote a report to document up-to-date relay protection and coordination practices for WEPs. The report provides engineering details covering possible wind farm electrical layouts, equipment ratings, system grounding, transformer connections and characteristics, harmonics and sub-harmonics analysis, voltage and frequency ride-through requirements, and protective relay schemes. This paper summarizes the report prepared by Working Group C25.**

***Index Terms*—Collector Feeder, Fault, Grounding, Harmonic, Protection, Substation, Wind Electric Plant, Wind Turbine Generator**

I. Introduction

WITH the proliferation of renewable energy resources, large wind electric plants (WEPs) are becoming more prevalent as generation sources on the electric power system. Construction of these plants is significantly different from traditional large generating stations. This paper summarizes the report documenting relay protection and coordination practices that have been commonly used at terrestrial WEPs [1]. The goal for the report and this paper is to serve as references for practitioners working in the design of WEPs.

II. Differences Between Wind Electric Plant Substations And Conventional Substations

Wind electric plants consist of many wind turbine generators (WTGs) that are connected to a collector substation through a collector system. The collector substation is connected to a point of interconnection (POI) through a step-up interconnection transformer. While utility substation designs mainly focus on maintaining continuous reliability, economics and unit availability play more important roles in the design of medium-voltage (MV) collector systems, collector substations, switchyards, and high-voltage transmission lines/cables of a WEP. The following subsections present some of the main design characteristics of WEP substations and their collector systems.

A. Collector System Design and Characteristics

A collector system consists of a series of underground cables and/or overhead lines that deliver power from WTGs to the collector substation. The design and layout of the WEP collector system depends on several factors, among which the location of wind turbines and the POI are more critical factors of the design. The collector substation may be connected directly to the POI or through a transmission line/cable. The collector feeders are connected to one or more substation transformers at the collector substation, where the collector system voltage is stepped up to the transmission system voltage.

Collector systems of large WEPs normally have a radial configuration where turbines are interconnected in a daisy-chain style, moving from the collector substation to the farthest turbine. WTGs are often interfaced with the collector feeder through a generator step-up transformer that increases the generator voltage (typically 690 V or lower for WTGs smaller than 3 MW, and 3.3 kV or 6 kV for larger generators) to the collector system voltage (as high as 34.5 kV). Several studies are normally performed on the collector system to identify the effects of the WTGs on the power system.

B. WEP Substation Arrangements

Different WEP substation and switchyard arrangements may be selected depending on required reliability, operability, and maintainability. WEP substation designs typically consist of collector (medium-voltage bus) and interconnection (high-voltage bus) configurations. These two systems are connected through wye-wye (with buried delta), delta-wye, or even wye-delta transformers. Collector substations for WEPs typically use an open-air bus design, with either a single-bus arrangement or sectionalized-bus arrangement; the latter arrangement improves system reliability and availability. Figure 1 shows two common collector substation configurations. The high-voltage buses could be of five common configurations: single, sectionalized, ring, breaker-and-a-half, and double-breaker double-bus, as detailed in IEEE Standard 666 [2]. The double-breaker double-bus configuration and breaker-and-a-half configuration provide higher reliability but at higher cost.

C. Wind Turbine Generator Characteristics

Wind turbines are classified by their mechanical power control as stall or pitch regulated. According to speed control, WTGs can be divided into fixed speed (Type 1), limited variable speed (Type 2), variable speed with partial power electronic conversion (Type 3), variable speed with full power electronic conversion (Type 4), and variable speed with mechanical speed/torque converter (Type 5). A summary of the characteristics of the five WTG types is provided in the following subsections.

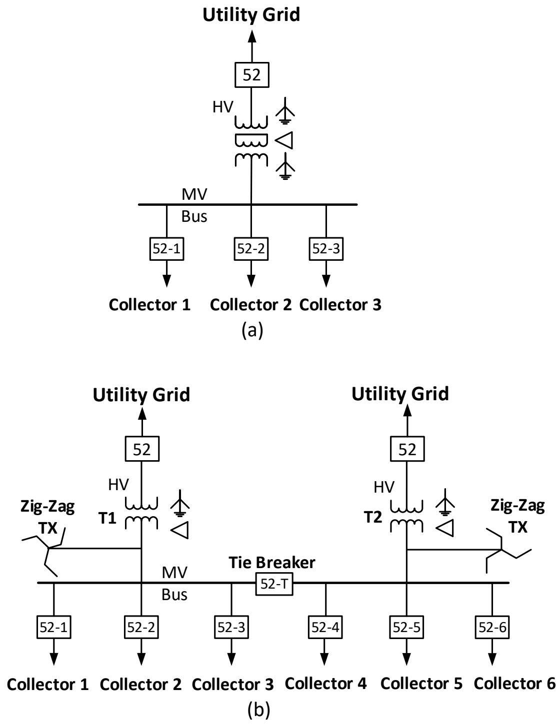

Figure 1. Common collector substation MV bus configurations

1) Type 1

A typical Type 1 WTG is a squirrel-cage induction machine. This induction machine is typically connected to the collector system through a step-up transformer and soft starter. Power factor correction capacitors are typically included and can be flexibly switched in or out during differing operating speeds. The speed of the turbine shaft is controlled to a near constant value (typically 2–3 percent faster than the grid's synchronous frequency).

2) Type 2

A typical Type 2 WTG is an induction machine having an external resistance inserted into the rotor circuit to provide operation over a wider range of slips when compared to a Type 1 WTG. The induction machine is typically connected to the collector system through a step-up transformer and soft starter. Power factor correction capacitors are also typically included. Like a Type 1 WTG, the speed of the turbine shaft of the Type 2 WTG is controlled to a near constant value (typically as much as 10 percent faster than the grid's synchronous frequency).

3) Type 3

A typical Type 3 WTG is also called the doubly fed induction generator or doubly fed asynchronous generator. An AC-DC-AC converter provides variable frequency ac excitation to the rotor circuit to enable the WTG to operate at variable speeds (typically ±30 percent of the synchronous speed), and to provide reactive power control and ac voltage regulation capabilities. The power factor of a Type 3 WTG at rated active power generation typically ranges from 0.9 (lagging capacitive) to 1.0 (unity) to 0.9 (leading inductive).

4) Type 4

A typical Type 4 WTG is composed of an electrical machine interconnected to the collector system through a full-scale back-to-back (AC-DC-AC) frequency converter. In contrast to Types 1 to 3, the generator of a Type 4 WTG is completely decoupled from the grid, hence a gearbox may not be required. If an asynchronous generator is used, a gearbox is often included in the design. The electrical output of a Type 4 WTG is completely defined by the full-scale converter. This design allows Type 4 WTGs to provide extreme flexibility in generation and reactive power capabilities with a wide voltage and frequency operating range.

5) Type 5

A typical Type 5 WTG consists of a WTG variable-speed drivetrain connected to a speed/torque converter coupled with a synchronous generator. A Type 5 WTG exhibits typical synchronous generator characteristics and behavior during faults. Therefore, generator contributions to faults can be calculated from the generator machine constants provided from the respective generator manufacturers.

D. Fault Currents and Equipment Ratings

To choose the ratings of equipment in the substation of a generating plant, maximum fault currents need to be calculated. For selection and settings of protective devices, both maximum and minimum fault currents need to be calculated.

The fault currents for WEPs for a given fault on the collector circuit or at the POI depends on the type of WTGs employed in the plant. While Type 1 and 2 WTGs can usually be represented by a Thevenin model, Type 3 and 4 exhibit unconventional behavior. The fault contribution from these machines depends on the proprietary controls implemented in their converters. A Type 3 machine can switch back and forth between crowbarred mode and controlled mode, whereas a Type 4 is fully controlled, limiting fault currents to values comparable to load currents (e.g., 110–130 percent of load current) within one or two cycles. Phasor domain short-circuit programs can model these machines as a voltage-dependent current source with an iterative method of solution to account for the nonlinear fault response caused by the converter controls [3].

The fault current for Type 1, Type 2, and Type 3 (crowbarred) WTGs may contain a dc offset. However, in practice, because of the resistance of cables, pad-mounted transformers, and the resistance of the arc between circuit breaker contacts, the dc offset decays quickly and does not pose a serious challenge to the operation of circuit breakers [4].

E. System Grounding

Wind electric plant system grounding is an important consideration in the plant design because it directly leads to the selection of protection schemes that can be applied to maximize the safe and reliable operation of this generating asset. The primary (low-voltage or generator) side of the WTG step-up transformer is typically connected in grounded wye to provide a stable reference point for the system phase-to-neutral voltages and to enhance equipment and personnel safety. The grounded wye connection also causes the majority (or all) of the current for a ground fault on the WTG and low-voltage (LV) bus to come from the step-up transformer where the ground fault current magnitude is usually large enough to operate simple phase/ground overcurrent or fuse protection. According to the IEEE Standard 142-2007 [5], solid grounding is generally recommended for the following:

a) LV systems (600 V and below) where automatic isolation of a faulted circuit can be tolerated or where capability is lacking to isolate a ground fault in a high-resistance grounded system.
b) Medium- or high-voltage systems (above 15 kV) to permit the use of equipment with insulation levels to ground rated for less than line-to-line voltages.
c) Medium- or high-voltage applications where higher ground fault current magnitudes are required to provide selective ground fault detection on lengthy distribution feeders.

F. Transformer Connections and Characteristics

There are typically three ac voltages used in a WEP: (1) the voltage at the WTG outputs, (2) the voltage of the collector system, and (3) the voltage at the intertie to the utility system. Transformers are needed between these systems. The transformers between the WTG and the collector system typically use wye–delta configuration with the wye on the WTG side and its neutral grounded; however, wye–wye transformers have also been used between the WTG and the collector system. There is typically a transformer for each of the WTGs and depending on the size and location of these transformers, they are protected with MV breakers and/or fuses.

The configuration of the transformer between the collector system and the utility system is driven by the need for the transformer to provide an effectively grounded source for the collector system, the utility system, or both. The WTG transformers typically do not provide a ground reference to the collector system; hence, to minimize the cost of the insulation for the collector system, the collector substation transformer(s) needs to provide an effectively grounded source to that system [6]. The transmission system operator may require the same for the utility system. If the ground reference is required for both sides, a three-winding transformer with wye configuration for both the collector and utility sides and a tertiary delta configuration can be utilized (see Figure 1a). The neutrals of both wye windings are typically connected to the earth, although the neutral on the collector system side can sometimes be connected through an impedance to limit the fault duty. Other alternatives require two transformers, such as a main power transformer with delta–wye configuration and a grounding transformer connected to the delta side (see Figure 1b). The grounding transformer is sized to provide adequate grounding to the collector system with the delta main power transformer winding.

G. Harmonics and Subharmonics

The harmonics generated by WEPs depends on converter topology, applied harmonic filters, and short-circuit current at the collector substation. Even harmonics in wind generation can arise because of asymmetrical half waves and may appear during fast load changes. Sub-harmonics are spectral components whose frequencies are lower than the fundamental power frequency and can arise from phenomena such as induction generator effects, control interactions, torsional interactions, and the interaction between wind generation and series-compensated transmission lines.

Capacitors in series with transmission lines may cause sub-synchronous resonance (SSR) with generators near a series capacitor. SSR occurs when the mechanical mass of the generator shaft has a natural frequency that resonates with the effective impedance of the system. This can lead to turbine-generator shaft failure and electrical instability at oscillation frequencies lower than the normal system frequency.

Sub-synchronous control interaction (SSCI) is a relatively new problem which has been observed between power-electronic devices, such as a static VAR compensator or a wind turbine and a series-compensated system [7], [8], [9]. A typical SSCI event is a condition where the wind turbines/controls interact with nearby series capacitors, resulting in undamped/fast growing oscillations. This is a widespread and serious problem, affecting turbines from most major manufacturers. Furthermore, typical dynamic stability studies performed per the interconnection standards do not expose this problem because they use fundamental frequency phasor solutions. In all cases of potential SSCI, it is important to obtain detailed electromagnetic transient models of the turbine directly from the manufacturer.

H. Voltage and Frequency Ride-Through Requirements

The voltage ride-through (VRT) requirements of WTGs may be regulated by various governing authorities. Some Type 1 WTGs have limited VRT capability and may require a central reactive power compensation system to meet the required VRT for the WEP. Other types of WTGs, especially Types 3 and 4 WTGs, have improved VRT capabilities. Similarly, WTGs may be required by various governing authorities to provide frequency ride-through. A Type 5 WTG is similar to a conventional synchronous generator and has both voltage and frequency ride-through capability. It is important to verify that the system protection complies with ride-through requirements established by the applicable governing authorities.

III. Typical Protective Relaying Schemes at Wind Electric Plant Substations

A. Collector Feeder Protection

Collector feeder circuit operation exhibits both radial and network characteristics. When the WTGs are offline, they operate radially and draw only a relatively low load current required by their station auxiliary equipment (lights, heaters, turbine gear motors, etc.) from the main collector substation. When the WTGs are online, the collector feeder operates as a network with their collective output current flowing from the WTGs to the collector substation. Most of the fault current for a collector feeder fault comes from the collector substation, but a small fault current contribution does come from those WTGs that are online at the time of the fault. Both nondirectional and directional overcurrent protection schemes have traditionally been used for collector feeder protection.

1) Nondirectional Overcurrent Protection

Nondirectional overcurrent protection of collector feeder circuits typically includes the application of both instantaneous and time-delayed phase and ground overcurrent elements.

Negative-sequence overcurrent elements can also be applied for additional protection or to satisfy specialized device coordination requirements.

The current pickup level of the phase inverse time overcurrent (51P) element or relay at the substation collector feeder breaker can be set at some factor times the combined output current capability of the WTGs on the protected feeder. The selection of the 51P current pickup level may be governed by requirements established by various regulating authorities. The curve type and time dial are then selected to coordinate with the expulsion fuse on the medium-voltage side of the WTG step-up transformer.

Wind turbine generator step-up transformers may be equipped with an expulsion fuse in series with a current limiting fuse on each phase of the high-voltage side of the transformer. A low-voltage breaker equipped with an overcurrent trip device may also be applied to protect the LV cables and auxiliary equipment. Since the WTG vendors usually size the transformer high-side fuses and coordinate them with the breaker trip device settings, the inverse time overcurrent relays at the main collector feeder breaker can simply be coordinated with high-side fuses of the WTG step-up transformer. A typical phase overcurrent coordination between the phase relay at the main feeder breaker and the WTG transformer high-side fuses is shown in Figure 2 for a three-phase fault at the first WTG on the circuit.

The main disadvantage of the nondirectional phase overcurrent element is that its current pickup setting can be 8 to 12 times the full load capability of any individual WTG, resulting in loss of sensitivity for low-current faults. For example, the 51P relay curve in Figure 2 (11F4-50/51P) provides good collector feeder protection for the smallest conductor size on the feeder, but marginal protection for the WTG step-up transformer. However, the high trip current setting of the 51P relay enables it to operate securely, regardless of the direction of current flow on the collector feeder.

Ideally, the current pickup setting of the nondirectional instantaneous phase overcurrent element (50P) is set above the combined inrush current of the WTG step-up transformers, but low enough to see a phase-to-phase feeder fault at the farthest WTG on the collector circuit. In cases where the transformer inrush current exceeds the instantaneous trip current setting required to detect a fault at the end of the collector feeder, harmonic current blocking can be used to inhibit the phase instantaneous overcurrent element from tripping for transformer inrush [1]. Alternatively, the trip delay of the 50P element can be increased from instantaneous to a delay of 10–12 cycles to improve coordination with the initial transformer inrush.

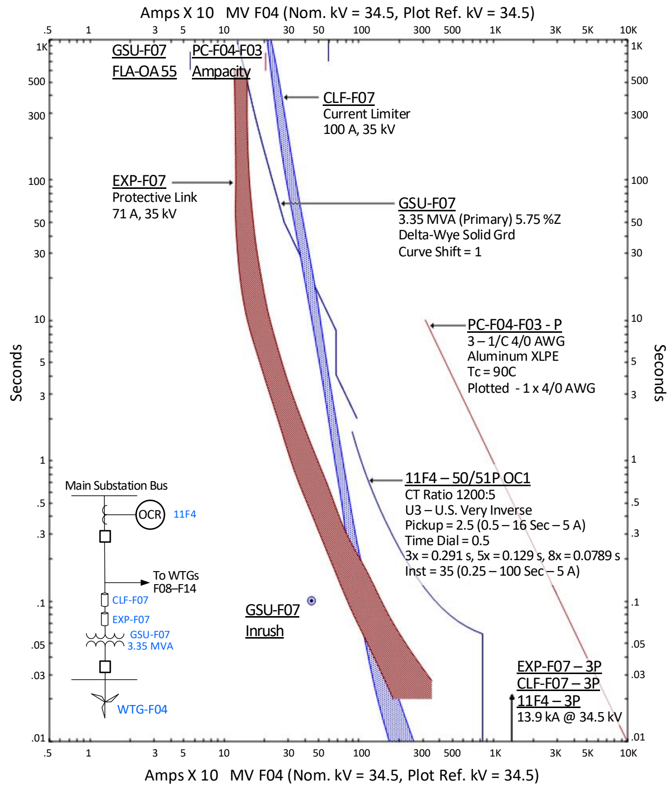

Figure 2. Nondirectional phase overcurrent coordination

The relatively poor sensitivity of the 51P protection scheme can be mitigated by applying a nondirectional negative-sequence overcurrent element (51Q) for unbalanced faults. Because a 51Q relay operates on I_2 (or $3I_2$), it can be set below balanced three-phase load current. This enables the user to set the minimum operating current level of the 51Q element more sensitively than that of the 51P, thus providing a better match with the minimum current at which the WTG transformer high-side fuse begins to melt. For coordination purposes, the 51Q element may be considered as an "equivalent" phase overcurrent element. Pickup, curve type, and time-dial settings can then be derived for the "equivalent" phase overcurrent element to coordinate with downstream phase overcurrent devices. Once the coordination is complete, the "equivalent" phase overcurrent pickup setting can be multiplied by the appropriate factor to convert it to a negative-sequence pickup setting for 51Q [10]. With the lower trip current setting, a curve type can be selected whose slope better matches the slope of the fuse characteristic curve, and a time dial can be selected to provide a closer coordination margin of time between the 51Q and the high-side transformer fuse curves over a broader range of unbalanced fault current.

The coordination plot of Figure 2 with a 51Q time-current characteristic (11F4-50/51Q) set based on the proposed trip current pickup is shown in Figure 3. The 11F4-51Q curve provides better coordination with the expulsion fuse curve for unbalanced fault currents that are too low for the 51P element (11F4-50/51P) to detect. However, a 51Q element will not operate for balanced three-phase faults. As with the 50P element, the current pickup setting of a 50Q element can also be set at the user's discretion above the combined inrush current of the WTG step-up transformers, but low enough to see a phase-to-phase feeder fault at the farthest WTG on the circuit.

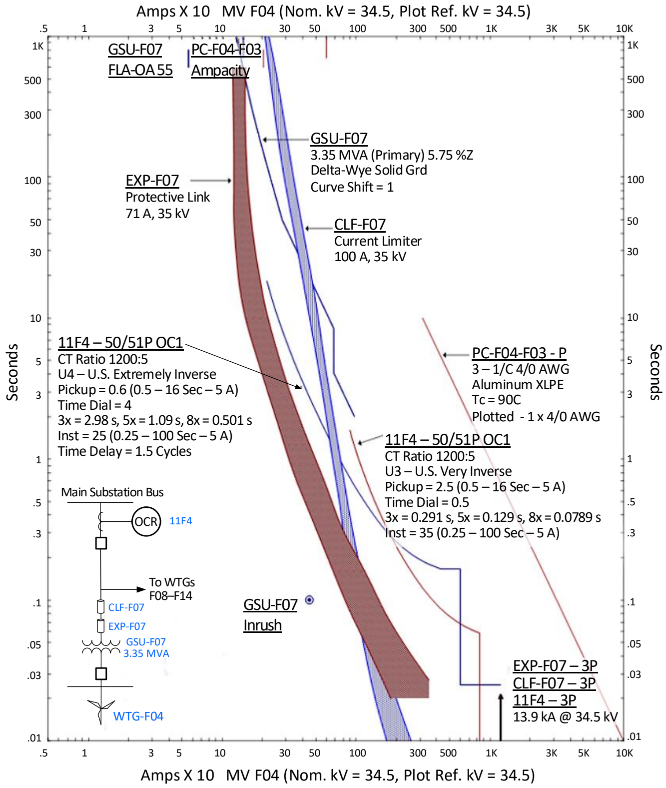

Figure 3. Nondirectional phase and negative-sequence overcurrent coordination

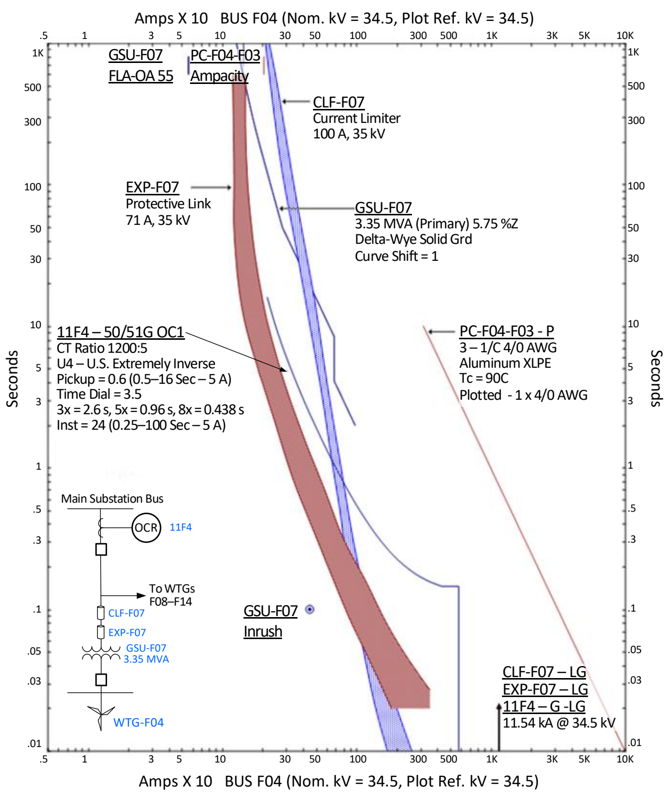

Figure 4. Nondirectional ground overcurrent coordination

Because the WTG output to the substation feeder breaker is essentially balanced, the current pickup of the neutral or residual ground time overcurrent element (51N or 51G) can be set relatively low, typically 10–30% of the phase time overcurrent setting. The curve type and time dial are then selected to coordinate with the expulsion fuse on the medium voltage side of the WTG step-up transformer. An example of the coordination between a 51G element (11F4-50/51G) and the high-side fuses of a WTG transformer appears in Figure 4. In this figure, the trip current setting of the 51G element is greater than approximately 140 A current level at which the 71 A expulsion fuse begins to blow.

Non-directional instantaneous neutral or residual ground overcurrent elements (50N or 50G) can be set low enough to operate for a phase-to-ground feeder fault at the farthest WTG on the circuit, but high enough to avoid potential misoperation from any CT secondary or system unbalanced currents that may occur during initial energization of the collector circuit.

2) Directional Overcurrent Protection

When the WTGs are online, the direction of power flow is from the WTGs to the substation main bus. Directional phase-time overcurrent elements (67P) at the substation feeder breaker can be set such that the forward direction is towards the WTGs on the collector circuit. The minimum trip current setting of the 67P element can therefore be set below the combined WTG output capacity of the collector feeder and above the minimum melting current of the high-side fuse of an individual WTG transformer. The curve type and time dial can be selected to coordinate with the high-side fuse of the WTG transformer.

In the directional phase overcurrent coordination, the 67P element (11F4-67P in Figure 5) provides both collector feeder protection and backup phase overcurrent protection for WTG

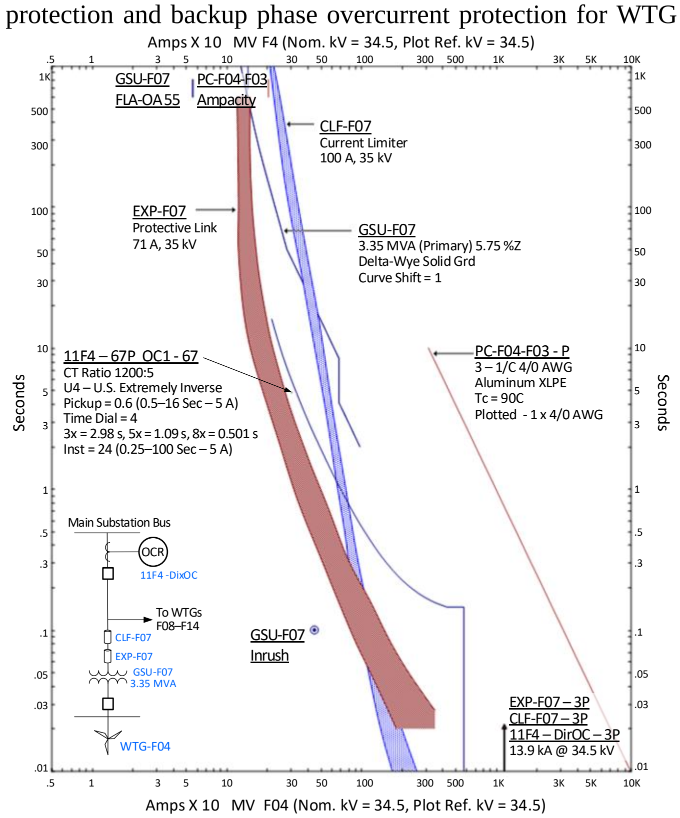

Figure 5. Directional phase overcurrent coordination

step-up transformers (both three-phase and unbalanced faults).

It is important to manage the response of the 67P element to an inadvertent loss of voltage on one or more phases, such as the loss of a voltage transformer secondary fuse. Most microprocessor-based relays have loss-of-potential logic which either blocks the 67P element or allows it to operate nondirectionally. Blocking the 67P element for loss of voltage and relying on a backup nondirectional 51P element with a higher trip current setting has been applied as a secure solution to the loss of voltage problem.

In general, when Type 3 and Type 4 WTGs are operated in a voltage control mode, they absorb reactive power when they are lightly loaded to counter-act the effects of the capacitance of the collector system. Conversely, the WTGs may be required to supply reactive power to the system to raise the voltage. Therefore, it is important to select the directional settings of the 67P element so that it does not inadvertently declare a fault if the WTGs are supplying/absorbing large amounts of reactive power.

If the directional characteristic angle of the 67P is adjustable, the directional characteristic angle may only need to be adjusted slightly to remove any overlap between the 67P trip zone and the WTGs operating region at high reactive power. If the 67P element has a load-blinding feature, it may be possible to adjust the load-blinding angles to confine the trip zone of the 67P element to the first quadrant as illustrated in Figure 6.

The directional phase instantaneous overcurrent element can be given the same pickup setting as the nondirectional 50P element because it will detect the same collective inrush of the WTG transformers upon energization.

Directional neutral or residual ground time overcurrent relays (67N or 67G) can also be used for collector feeder protection. However, because they are normally set to coordinate with the high-side fuse of the WTG step-up transformer, the minimum trip current setting of a 67N/67G element will be the same as that of a 51N/51G; the coordination would also be the same, as shown in Figure 4. Similarly, the setting criteria and coordination considerations for directional neutral/residual ground instantaneous overcurrent elements are essentially the same as those for nondirectional 50G/50N elements.

B. Grounding Transformer Protection

Grounding transformers provide a system ground reference and aid in the control of temporary overvoltage conditions. There are basically two types of grounding transformer configurations that might be selected: (i) grounded wye with a secondary delta or (ii) zig zag [12].

Though either transformer configuration may be protected by overcurrent elements or differential elements, the use of overcurrent elements is typical. The application of overcurrent elements generally includes a 51 element on each phase and a 51N element connected in the neutral-ground path. A ground overcurrent element can be used to provide backup ground fault protection coordinated with bus and/or collector circuit ground protection. Differential elements can provide selective high-speed protection to the grounding banks, when available.

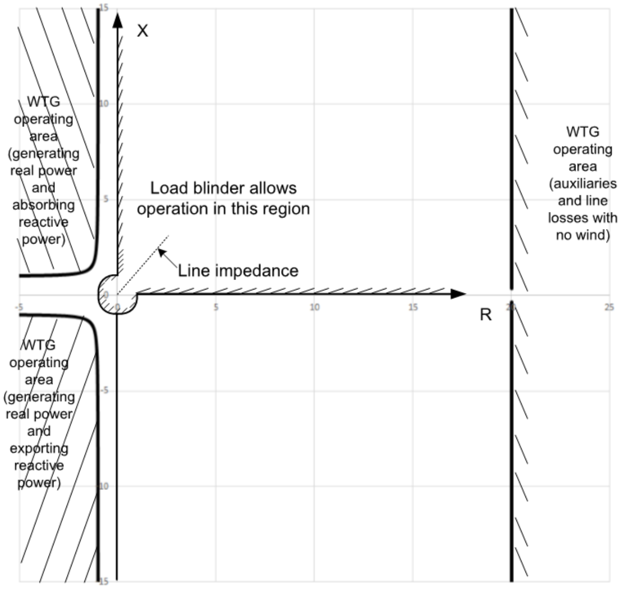

Figure 6. Normal WTG operating regions with example load blinding characteristic

C. Bus Protection

The operating voltage selected for the MV-side bus in a WEP collector substation can vary over a range of voltage levels, with 34.5 kV being the most common. WEP collector substations are characterized by multiple sources of power connecting to the circuits out of the collector substation, and power transformers that are significantly large can push the bus fault duties higher. This can drive the need to clear the bus faults faster than what time-delayed overcurrent relaying permits, hence justifying applying dedicated bus protection in collector substations.

The following is a brief description of three different types of bus protection [11] that are suitable for a collector substation.

1) Zone-Interlocked Scheme

The zone-interlocked scheme is the least expensive of the dedicated bus protection schemes. Figure 7 shows a simplified one-line diagram of a typical collector substation with a zone-interlocked scheme applied for the bus protection. In this scheme, nondirectional instantaneous overcurrent elements monitor the current through the collector feeder breakers and send a blocking signal to the instantaneous overcurrent element of the step-up transformer. The pickup of the overcurrent relay associated with the step-up transformer is set securely so the relay does not pick up under load or for the fault current contributed from the WTGs.

This scheme may be implemented using hard wires or high-speed communications over a local area network. The advantage of this type of bus protection is that no additional relays and current transformers (CTs) are needed. The disadvantages are that the bus protection is not as fast as other schemes, sensitivity to high-impedance bus faults is limited, complex networking between devices may be required, and coordination for both sensitivity and speed is required between the multiple elements of the scheme.

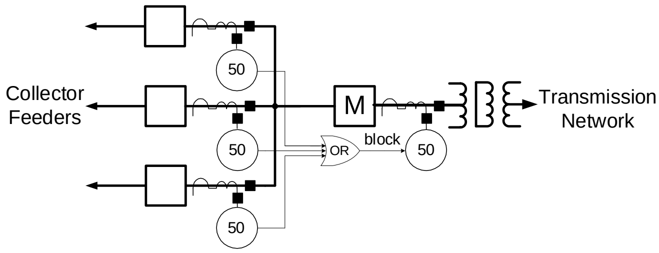

Figure 7. Zone-interlocked bus protection scheme

2) Percentage-Restrained Differential Protection

The basic circuit design for the percentage-restrained differential protection is shown in Figure 8. This protection uses current measurements from the individual branches to develop a restraint current that is indicative of the current flowing through the zone of protection (typical methods are to sum the branch currents magnitudes or use the maximum of the branch currents). The operate current is the phasor sum of all the currents flowing into and out of the bus. The operate current is compared to the restraint current to detect and trip for a bus fault.

The advantage of this type of bus protection is that the relays are sensitive, fast, and secure. Unlike the high-impedance bus differential protection discussed later, the CTs used by this protection can also be used for other functions. The disadvantage is that it can be susceptible to a mis-operation due to CT saturation because the CTs for each circuit are typically connected directly to the relay. Therefore, secure application and settings of this protection benefits from consideration of CT sizing [13].

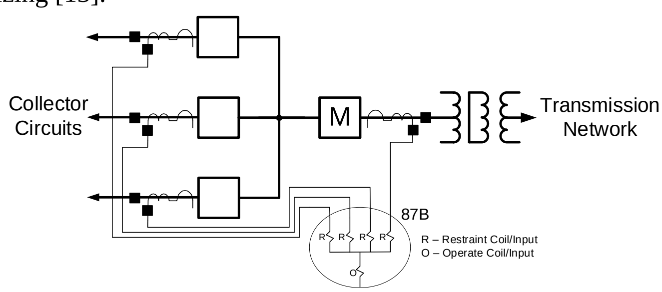

Figure 8. Percentage-restrained bus differential protection

3) High-Impedance Bus Differential Protection

The high-impedance bus differential protection avoids the problem of poor CT performance for high-current through faults by making the impedance of the operating circuit very high. Figure 9 shows the application of a high-impedance bus differential protection. For an internal bus fault, the voltage produced by the CTs in saturation is impressed across the operate circuit of the bus differential relay causing it to operate. The relay in this scheme is set to operate based on a voltage level, not a current level.

The CTs used by a bus differential circuit can only be used for this application because of the high impedance and high voltage of the circuit. All the CTs applied to this circuit normally have the same accuracy class and are connected on the same ratio. Advantages of high-impedance bus protection include:

- The relays are sensitive, fast, simple, and secure.
- The CT secondary circuits are not wired all the way to the relay.
- The CT wiring at the relay is very simple.

The following are disadvantages of high-impedance bus differential protection:

- A termination box in the substation yard is needed.
- The CTs used are dedicated to the scheme.
- All CTs are connected for the same ratio, preferably using the full turns ratio of the CTs.
- If some CTs have different accuracy class ratings, the differential setting may be dependent on the CTs with the lower accuracy class rating.

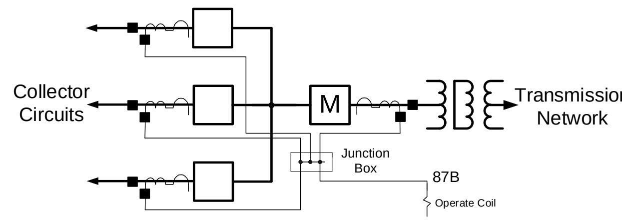

Figure 9. High-impedance bus differential protection

D. Main Transformer Protection

The main power transformer is likely the most expensive piece of equipment in the collector substation. The high cost of repair or replacement and the possibility of violent failure or fire involving adjacent equipment makes the protection of the main power transformer a priority. The following is a brief description of different types of transformer protections [12] that are suitable for a collector substation.

1) Transformer Differential Protection

Transformer protection schemes at WEPs typically utilize a percentage-restrained differential element with harmonic restraint and/or harmonic blocking. The basis of the percentage-restrained differential relay is that the difference current (measured at the ends of the protected zones) is more than a predetermined percentage of the restraint current. The percentage-restrained characteristic can be fixed, variable, or adaptive, based on the relay design. There is also a minimum differential current threshold before tripping without regard to the restraint current. Details of restraint current and characteristic slope vary among manufacturers. Therefore, secure application and settings of the percentage-restrained differential element, as with the bus protection, benefits from consideration of CT sizing [13].

2) Restricted Earth Fault Protection

The percentage-restrained differential element can sensitively detect ground faults in solidly grounded transformers. However, for transformers grounded through a low impedance [6], it may be ineffective because of the low faulted phase currents, even for ground faults at the transformer terminals [14]. For ground faults in a low-impedance-grounded transformer, the zero-sequence current measured at the transformer neutral can be much higher than the zero-sequence current measured at the terminals. A restricted earth fault protection element can utilize the neutral current measurement to provide a more dependable and sensitive ground fault protection.

3) Transformer Overcurrent Protection

Instantaneous overcurrent elements may be used for fast clearing of high-magnitude internal faults. These elements are normally set above the maximum through-fault current for a fault outside the transformer zone of protection. The pickup range is generally 125–200 percent of a three-phase fault on the low side of the transformer. The pickup settings should be checked to verify it is set below the maximum available fault current at the station. The elements are also set to be secure during transformer inrush. In these cases, harmonic-restrained instantaneous elements may be considered for enhanced protection security.

Time overcurrent elements are used to protect transformers because of a failure of the protection system to clear an external fault. High through-fault current can cause thermal or mechanical damage to the main transformer. The time overcurrent curve, pickup, and time dial are selected to coordinate with the transformer damage curve. The pickup setting is also selected to carry the transformer load plus a margin for overload. A coordination check is then performed with the collector circuit overcurrent protection. Sufficient margin is typically included to provide adequate coordination between the collector circuit and the main power transformer.

It should be noted that there are several methods of detecting transformer faults other than by electric measurements including sudden pressure and gas accumulator relays. Those protection schemes are the same as those utilized at conventional substations. For more information, the interested readers can refer to the IEEE Guide for Protecting Power Transformers [12].

E. Capacitor and Harmonic Filter Protection

Protection schemes applied to capacitors and harmonic filters at the main collector substation are essentially the same as those applied at conventional substations. The primary purpose of the protection scheme is to take the protected equipment out of service for faults [15].

1) Overvoltage Protection

For shunt capacitors at collector feeder substations, two levels of overvoltage settings are typically applied. For example, a Level 1 overvoltage setting of approximately 110 percent of nominal voltage and a Level 2 overvoltage setting of approximately 120 percent of nominal may be applied. Selection of appropriate delay settings are based on the "ride-through" time for a system overvoltage condition and the maximum overvoltage withstand capability of the capacitor units and other equipment connected to the bus. In addition, the overvoltage ride-through settings are coordinated with the overvoltage protection settings that are applied to the WTGs. Ideally, the capacitor overvoltage protection settings are delayed long enough to allow the WTG overvoltage protection equipment to take the WTG offline before the capacitor breaker or circuit switcher at the collector feeder substation trips.

2) Overcurrent Protection

Overcurrent protection schemes are typically applied to trip shunt capacitors or harmonic filters for both phase and ground faults in the equipment. Instantaneous overcurrent elements are set based on the maximum expected inrush current, and time overcurrent elements are set based on the maximum current rating of the capacitor or reactor. The instantaneous element may require a short delay to provide proper coordination with the expulsion fuses on the capacitor bank. Inverse time curves are normally used for time overcurrent applications, and the time dial is selected to coordinate with both the capacitor bank fuses and any upstream time overcurrent relays, such as the backup time overcurrent relays associated with the main power transformer. When overcurrent relays are used for capacitor or harmonic filter protection, the presence of harmonics may require the use of relays equipped with rms-based current detectors capable of measuring both fundamental and harmonic currents.

F. Transmission Tie Line Protection

Tie line protection has several application considerations compared to a typical transmission line because of the presence of the WEP [16], [17], [18], [19].

Primary protection may consist of a distance zone and a communication-assisted tripping scheme such as line current differential (87L), permissive overreaching transfer trip (POTT), etc. The negative-sequence current injected by a WEP may exhibit incoherent behavior with respect to the voltages [16], [17]. Additionally, memory-polarized distance elements may exhibit reduced reliability (i.e., the underreaching zone may overreach whereas the overreaching zone may underreach) [17]. Modifying the protection settings is required so that the behavior of directional elements, fault-type identification, and distance elements improves tie-line protection reliability [18]. For applications where there is only one tie-line connecting the grid to the WEP with no other interconnection paths, a distance zone that reaches to a percentage of the WEP step-up transformer may be applied without time delay at the grid terminal, hence protecting the entire tie-line. The use of the POTT scheme with weak-infeed echo logic and direct transfer trip at the WEP terminal improves tie-line protection dependability [18]. The 87L element can also face certain security and dependability challenges near WEPs, but they may be addressed by modifying the settings to allow them to achieve a higher degree of reliability [19].

Backup protection may include application of time-delayed protection such as step-distance zones, ground time overcurrent, and phase-to-phase undervoltage backup. Backup protection settings require coordination with primary protection [20] and any ride-through requirements [16], where applicable.

IV. Conclusion

The protection and system requirements for wind power plants can be unique and challenging for the following reasons:

- Wind power plants typically consist of numerous relatively small wind turbine generators distributed geographically over a wide area as opposed to a small number of large generating units at one location.
- WTGs typically have some degree of power-electronic-based interface. This affects the fault current levels and characteristics which protection engineers expect from sequence analysis.
- The interconnection between WTGs and transmission systems employing series compensation can result in sub-synchronous interactions.
- Wind power plants can require specialized electrical layouts and grounding options, depending on the grid to which the wind power plants are connected.
- Wind power plants are typically subject to applicable regulatory requirements, such as voltage/frequency ride-through, loadability, and power quality requirements.

Various protection elements and practices presented in this paper are intended as an aid for the protection engineer to satisfy the general protection requirements for wind power plants. As the number of wind electric plants in power systems increases, the challenges and protective considerations continue to evolve.

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