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GREEN POWER – WIND GENERATED PROTECTION AND CONTROL CONSIDERATIONS

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I. OVERVIEW

The recent demands for Green Power and the Federal Government Tax incentives for electrical energy generation are rising. Some of the recent system additions of Green Power have been from medium to large wind farms. These wind farms have been completed over the last 2 to 3 years in several locations in North America. There are more in the system-planning queue scheduled for the next 3 to 5 year horizon. Regulatory pressure will cause a certain percentage of available electrical energy production to come from renewable resources.

Wind-generated energy systems have some unique challenges for protection and control engineers. The typical wind farm is not a new form of generation being interconnected to the bulk power system. Several were constructed in the 1978 to 1980 era after the PURPA national energy act was implemented.

Figure 1 shows a typical overall single-line diagram for a Green Power Wind Turbine Farm. This paper will address the following topics for a typical wind farm:

- Wind Turbine-Generator Protection and Control
- 34.5kV Distribution Wind Farm Substation and Feeders protection
- Wind Farm Transmission Interconnection
- Monitoring, Command and Control of the Wind Turbines and the Interconnection System
- Start up and commissioning of the wind farm and associated substations
- Unusual Operating and Maintenance experience

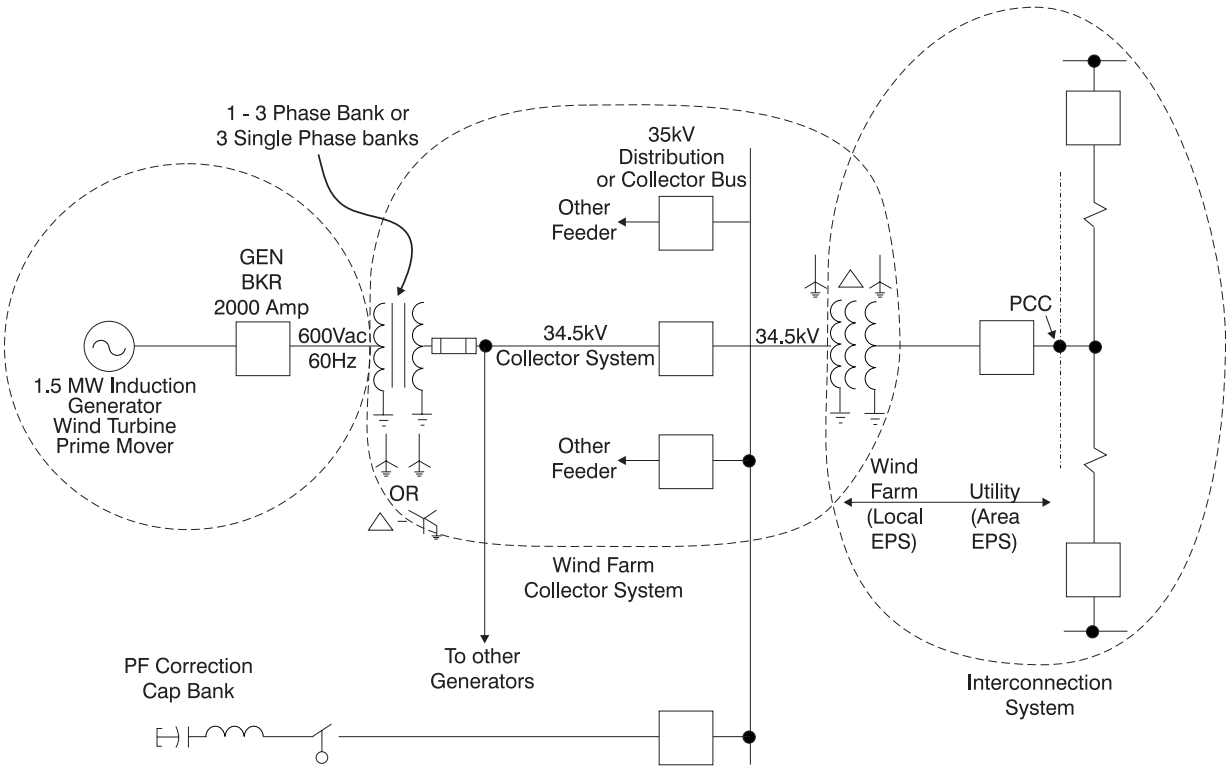


Figure 1: Typical Overall Single Line Diagram –
Green Power from Wind Turbine Generator Wind Farm

II. Wind Turbine Generator

The typical large wind farm turbine is a large wind-driven turbine generator mounted at the top of a steel tower in a nacelle. The wind turbines are speed controlled by measuring the wind speed and direction with on board instrumentation. The speed (rpm) of the turbine is controlled by the pitch of the turbine blades or by a gear box. The turbine and its auxiliary load and mechanical drive are controlled from a controller and isolation system located in the base of the turbine tower. The smart controller regulates power to be generated into a grid under various wind conditions that allow variable power outputs versus wind speed and direction. The wind turbine generator starts to generate and can be connected to an electrical power system when the wind speed is about 4-5 meters per second minimum and shuts down at maximum wind speed of about 25 meters per second.

The modern medium to large sized wind farm consists of 20-150 of these turbine generators, ranging in size from .5MW to 1.8MW each. Larger wind turbine generators of 3MW to 5MW in size are available and are installed and connected in the European power grid. Some U. S. sites are being considered.

Figure 2 shows some details of a typical wind turbine generator system.

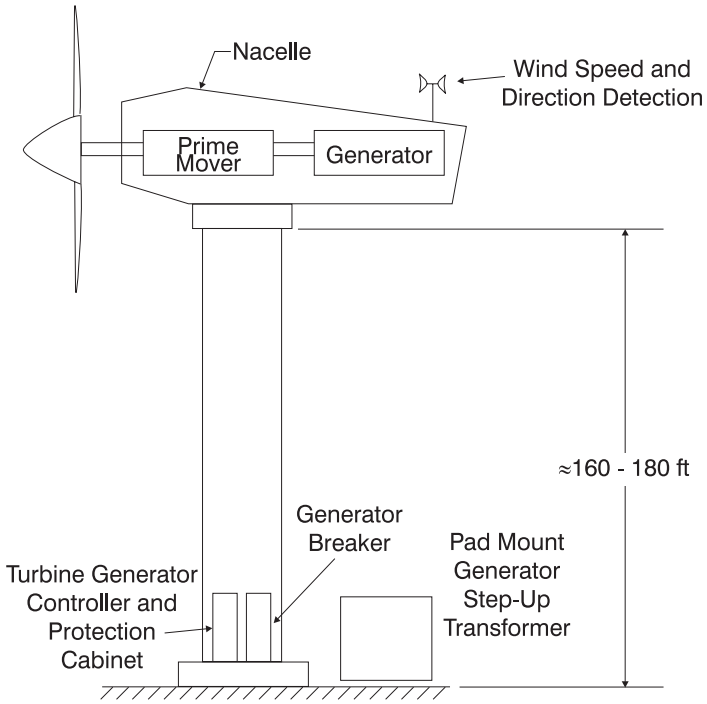


Figure 2: Typical Wind Turbine Generator

Typical modern wind turbine generators are induction machines that can be synchronously connected to the power grid. The wind turbine generator is directly connected to the utility ac system (Area EPS) via generator step up transformers. The typical generator's terminal voltage may range from 575 volts to 690 volts, 3 phases, 60Hz nominal.

The generator terminal voltage is typically stepped up to a 34.5kV Distribution Collector System. The generator step-up transformer is a three-phase, oil cooled, pad mounted unit located at the base of the wind turbine tower. Some designs would have the generator step-up transformer mounted in the turbine nacelle. This transformer bank is made from three single-phase, dry type units. It is considered that line loss is minimized when the transformer is placed in the nacelle next to the generator and connected to the generator with minimum lead length. The generator step-up transformer primary phase voltage is 34.5 kV, its windings connected Delta or grounded Wye, and its secondary voltage is either 575 V or 690 volt with windings connected grounded Wye. The design of the winding connection is per the generator manufacturer's requirement. Due to the design of the induction generator winding and rotor, it generates the 5^{th} and the 7^{th} harmonic current. Harmonic current magnitudes are normally low. Harmonic currents also appeared from the generator and turbine control solid state devices. However, the harmonics components generated by the wind turbine generators are very low and measured well below the limits according to the ANSI Standard IEEE 519. The transformer self-impedance is designed to limit the short circuit current to the generator control system. However, the impedance of the generator step-up transformer must be carefully designed to avoid possible resonance to the harmonic current generated in the induction generator. Typically, the impedance of the generator step-up transformer is 5%, based on 750 kVA in one turbine design and 6% on 1,500 kVA on that of the other and depends on the manufacturer's recommendation.

The generator is a special asynchronous induction generator that operates with a variable slip between 1% and 10%. The generator controller is a multifunction numerical integrated controller providing the following functions:

- Speed of rotation is synchronized with the grid frequency to limit the inrush current (cut-in current)
- Thyristor circuit is applied to limit the inrush current at the time of connection to the grid.
- Cut-in current is less than full load current.
- Power factor correction control based on unit output kW.
- Turbine trip protection for fault/disturbance.
- Turbine/Generator provided with over/under voltage protective relays (27/59).
- Turbine/Generator provided with over/under frequency protective relays (81O/U).
- Other turbine control and generator protective relays are integrated into the turbine/generator control systems. The parameters monitored by the turbine and generator control systems include: Electrical, Yaw, Hydraulic, Environment, Transmission, Generator, Phase Compensation, Thyristors, Pitch, Emergencies, Energy Inputs and Outputs, Rotor Current Control RCC, Communication, Self test and miscellaneous events records. Some typical parameters are:
    - Electrical: Extreme High/Low Voltage and time out limits, Extreme High/Low Current and time out limits, High/Low Frequencies and time out limits, Negative Power limits, Main Breaker trip current and time limits, High/Low Voltage and Current Hysterisis limits, Voltage and Current average, leak current (ground fault), asymmetric in grid voltage and current, etc.
    - Yaw: Wind speed 0-25m/s, max. and min. Yaw time, Generator RPM limit auto yaw, etc.
    - Environment: Nacelle control temperature, wind speed attenuation, Delat Gear temperatures, Oil temperature, etc.
    - Generator: Phase sequence, generator high temperature (RTDs), RPMs, rotor RPMs, gear ratio matching, etc.
    - Phase compensation: Capacitors step size and controls, power factor compensation feed back circuit, etc.
    - Thyristors: Maximum temperature.
    - Pitch: Low and high limits sets, power errors.

These relays and control functions provide protection for the turbine/generator system, not the interconnection system to the bulk power grid (Area EPS).

The generator step-up transformer, whether it is connected Delta-Grounded Wye or Grounded Wye-Grounded Wye, will be provided with short circuit protection with primary fuses. The transformer fuses are designed based on the transformer rated full load current and inrush. The fuse provides transformer secondary fault protection. The transformer fuses are normally submersed in the transformer tank oil. Dead front no-load break elbow connectors may be used to provide disconnect and isolation of the step-up transformer. When a circuit breaker is used in the case where the transformer is located on the nacelle, the circuit breaker must be designed for the maximum available short circuit current including currents contribution from generators connected on the adjacent feeders and the area grid EPS. A phase and ground time overcurrent relay is used for the protection of the generator step-up transformer. Typically, the generator maximum fault current contribution to a transformer primary three phase fault is about 4-5 times the transformer (generator) full load current. The transformer secondary is connected to a circuit breaker and an interconnecting contactor. The generator interconnecting contactor is not

designed and not rated to interrupt the generator fault current contribution to transformer primary fault.

Due to the characteristic of the induction generator design, its voltage and frequency limits are different from a synchronous generator. The wind turbine generator limits for voltage control are ±10% of the terminal voltage of the machine (690 V or 575 V). This may not be compatible with the normal 27/59 settings imposed by the Interconnected Electric System (Area EPS). This also may not be in line with existing or new NERC Standards for Interconnected Operation. The over/under voltage protection functions furnished with the turbine generator control system are the primary protection of the unit and the back-up interconnection protection of the unit to the area grid. Depending on the manufacturer's design, the generator operating voltage band or trip points varied. Below are possible voltage protection settings of turbine generator.

- At or above the 20% nominal voltage, delay trip in 0.1 seconds
- At or above the 10% nominal voltage, delay trip in .6 seconds
- At or above the 11% nominal voltage, delay trip of internal PF capacitors in 0.08 seconds
- At or below the 11% nominal voltage, delay trip in 1 second
- At or below the 15% nominal voltage, delay trip in 0.6 seconds
- At or below the 25% nominal voltage, delay trip in 0.01 seconds

A representation of the voltage trip time is shown in Figure 3. Note that the envelope of the ISO system voltage is outside the generator voltage protective relay settings. It must be noted that the turbine generator terminal voltage and the point of common coupling, or interconnection with the area EPS (grid), are not the same location. The terminal voltage of a turbine located at the end of a long collector feeder can have higher voltage than the unit located at the substation and near the point of interconnection with the area EPS system. It is possible that some turbines in a wind farm may trip for under/over voltage condition while the remaining group of turbines may continue to operate.

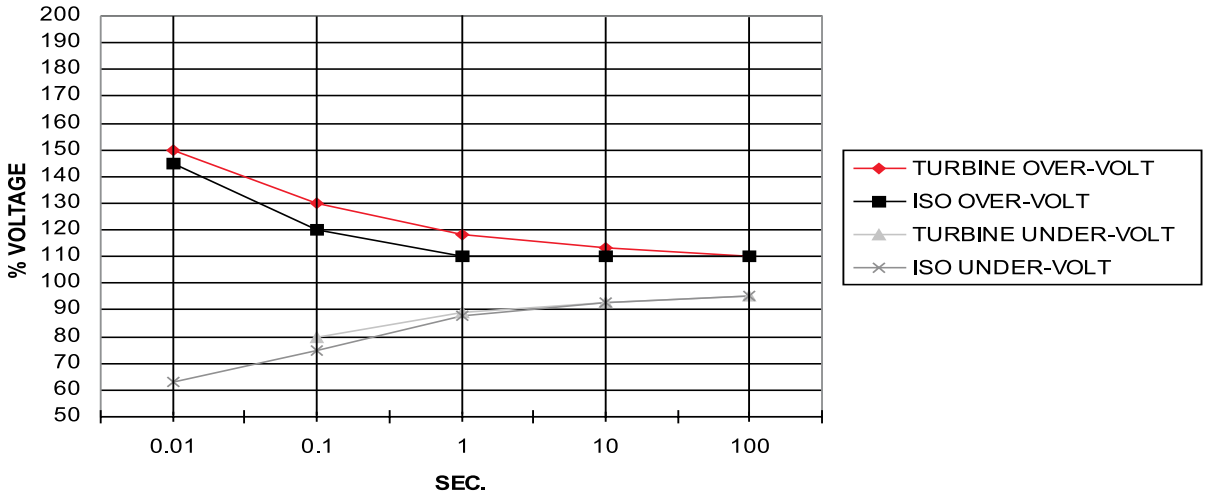


Figure 3: Turbine operating voltage and EPS power system operating voltage

The wind turbine generator's frequency trip settings are also different from that of steam and combustion turbine machines and are an area of concern. This is because the present NERC or ISO Control Area frequency settings are also more applicable to Synchronous Turbine Generators. Again, these settings may not be in agreement with the existing or new NERC Standards for Interconnected Operation. The over/under frequency protection functions furnished with the turbine generator control system are the primary protection of the unit and the back-up interconnection protection of the unit to the area grid. The frequency protection of the generators may or may not meet the load shedding frequency scheme of the Area EPS, depending on the local ISO requirement.

Below are the typical wind turbine generator frequency protection settings:

- At or above 62 Hz delay trip in 0.2 seconds, and disconnect PF capacitors in 0.1 seconds
- At or below 57 Hz delay trip in 0.2 seconds

These settings are different than those of the typical synchronous unit. Figure 4 shows the wind turbine generator frequency trip and a possible load shedding frequency requirement.

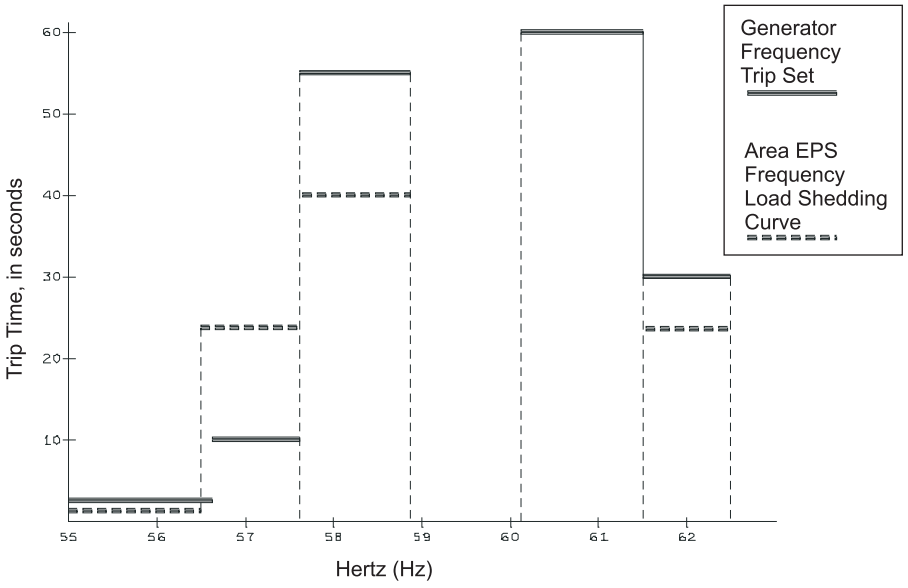


Figure 4: Turbine generator frequency protection setting vs. Control Area Load Shedding frequency setting requirement

Depending on the area of EPS or ISO, the frequency protection of the wind turbine generator may be coordinated with the area transmission system load shedding frequency. The frequency protection varies among different manufacturer designs, just as in the case of synchronous, fossil turbine generators.

Manufacturers are developing the wind turbine generator control system which may include the low voltage override capability for short and sudden drop in system voltage, such as during a

remote fault. These generator controllers will be provided with a “voltage regulator” system that maintains generator terminal voltage for several cycles.

The Interconnection System also has over voltage/under voltage (27/59) and Over Frequency and Under Frequency (81O/U) relays that will be set to remove transmission line faults, isolation (Islanding), and substation faults as well as other protective schemes necessary to protect the bulk power grid integrity (Area EPS). The wind turbine generator protective characteristics are, in fact, back-up protection to the Interconnection System Devices. Therefore, the Inter-connection System devices are set more sensitive than those of the wind turbine generator. Table 1 shows typical grid connection requirements.

Parameter	**Value**	**Unit**
• Nominal grid voltage	575	V
• Nominal frequency	60	Hz
• Frequency tolerance		Frequency tolerance ±1Hz
•Grid voltage tolerances	+15 to +30% 0.1 sec* +10 to +16% 1.0 sec* ±10% continuous operation -10% to -15% 10 min* -15% to -15% 10 sec* -25% to -30% 1 sec.	
• Self Impedance of grid Interface transformer	5-6 % on self cool KVA	
•Transformer connection	Y on turbine side, Δ on grid side (or Y)	
•Ground connection of the mid voltage transformer	Starpoint Grounded	

Table 1: Grid Connection Requirements – Type 2 Wind Turbine Generator

III. Voltage Control Characteristics

This topic describes how the generator units or the collector system controls system voltage. Typically, that depends on the turbine manufacturer’s methods.

Type 1 units use the method of switched capacitor banks in steps that typically use 25 Kvar units. Stage size ranges from 50 Kvars, 75 Kvars, 100 Kvars, etc. are used. Inductor circuits are used to minimize delta voltage and to de-tune harmonics-power quality considerations. The capacitors and control protection system are provided in a turbine control cabinet located at the base of the turbine tower. Typically, the induction generator (motor) has a nominal power factor of 0.92. The capacitors are used to maintain generator terminal power factor between 0.98 and .99 lagging. The cap banks are switched in and out with controlled contactors and with some form of damping resistors. The required Kvar compensation is a function of the generated output kW. The turbine generator integrated control and protective relaying systems are as shown in Figure 5, illustrating the single control diagram for the Type 1 wind turbine generator design.

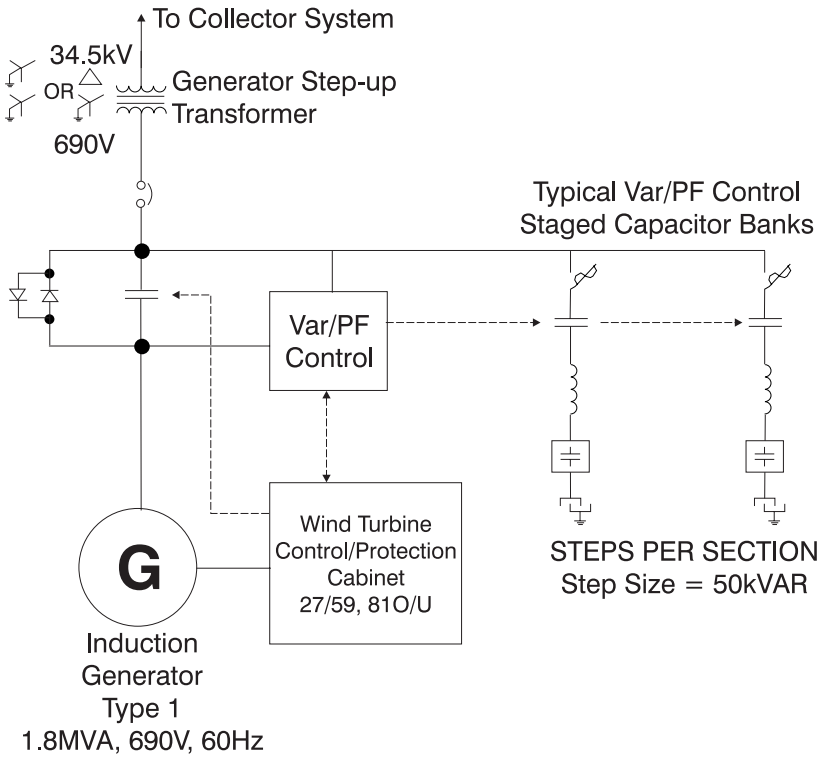


Figure 5: Typical One-line Diagram for Type 1 Wind Turbine

Type 1 wind turbine generators can be manually or automatically started when wind speed exceeds a minimum of 4-5 meters per second. The gated thyristor control provides a soft start to connect the generator to the power grid. The turbine blades will pitch to regulate the speed of the turbine and generator. This soft starting method minimizes the inrush current normally seen in older induction generator starting designs. When the generator terminal voltage and frequency are matched with that of the interconnecting power grid, the generator interconnecting contactor closes and the thyristor control system is removed from the generator circuit. The soft start design limits the voltage flicker and distortion to the voltage and current waveform to within the ANSI Standard C84.1-1989.

Note that the generator PF capacitances are available as soon as the generator is connected to the power grid. The switching of the generator PF capacitance does not cause switching transient to the grid voltage.

Type 2 units may use a method of control for the induction generator terminal voltage that uses a voltage regulator system. As mentioned above, this system may provide voltage ride-through during external power system faults. Normally, the regulator control system would regulate the generated reactive output between the range of .95 pf either leading or lagging. This is comparable to the pf control of a synchronous generator. Figure 6 illustrates the single line control diagram for the Type 2 wind turbine generator design.

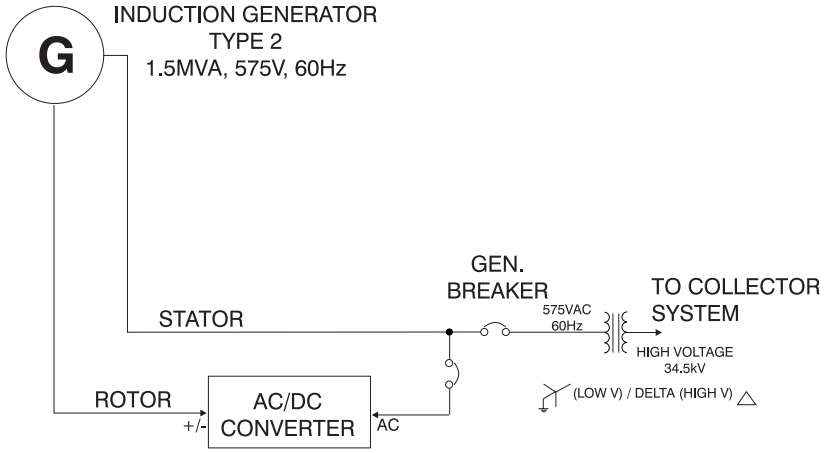


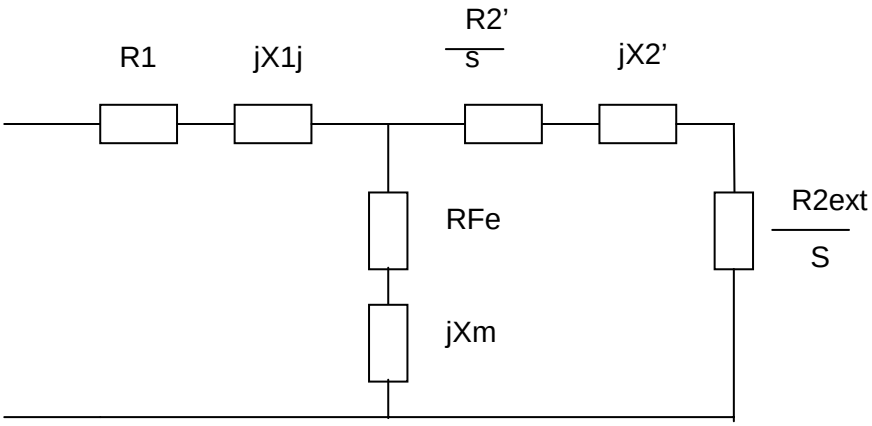
Figure 6: Typical One-Line Diagram for the Type 2 Wind Turbine

Static VAR systems in the form of power factor and voltage control capacitor bank also may be used in the wind farm distribution system. For economic reasons, the static capacitor banks are connected to the 34.5kV collecting system via circuit breaker, with capacitor bank switching devices. These capacitor banks can be used to offset the inductive losses in the generators, the generator step-up transformers, and the interconnection step up transformer. It should be noted that, due to the length of the underground cable used in the collecting system, there is a considerable amount of reactive power (capacitance) in the feeder system. The area EPS normally requires the power factor to be about .99 lead and .99 lag. The cap bank switching transient over voltage limit is set by the area EPS and normally Delta V = 3% maximum. The power factor control is normally overridden by the system voltage limit.

Most Interconnection Systems and the Transmission System Owner (Area EPS) will require the measured power factor at the point of common coupling (PCC) to be about unity power factor. Tolerance limits are narrow and usually are 0.99 pf lead or lag. This will require careful design of the switched capacitor banks. The reasons are related to the delta voltage when switching is done to prevent overshoot of voltage at the point of common coupling (PCC). The challenge is related to the Area EPS stiffness and the fact that the wind generators are constantly changing due to changing wind speeds. The Area EPS can use these capacitor banks for system voltage support even though there is no wind generation available.

Some wind farms use the dynamic VAR control systems to regulate the PF and PCC terminal voltage. System requirements and economics should be considered in the design of the PF control system.

The response of a wind turbine generator to the interconnected system disturbances is a challenge to the power system studies area. A fair amount of research has gone into developing the models used for the studies. Steady state model results that are used for load flow and short circuit analysis are good, but constructing a turbine model used for transient conditions and dynamic response studies requires more work. For short circuit analysis and load flow studies, the wind turbine generator can be modeled as a synchronous generator with a sub-transient reactance behind a constant voltage source. The sub-transient reactance is the same as that of the induction motor of the same size. The generator kW output and its corresponding PF correction capacitance can be modeled as a synchronous generator operated at that PF. The wind turbine generator slip (S) can be determined as indicated in Figure 7.



S = generator slip in %

GENERATOR EQUIVALENT MODEL

Table: Generator Parameters

Stator resistance:	R1	= .0048 ohm
Stator reactance:	X1	= .0816 ohm
Rotor resistance, internal	R'2	= .0040 ohm
Rotor resistance, exter. (2% slip)	R'2 ext2	= .0086 ohm
Rotor resistance, exter. (10% slip)	R'2 ext10	= .0596 ohm
Rotor reactance:	X'2	= .108 ohm
Iron loss:	Rfe	= .111 ohm
Magnetizing reactance	Xm	= 3.72 ohm
Voltage	U	= 400 V

Figure 7: Typical parameters of a 750 KVA induction wind generator

IV. Distribution Wind Farm Collector System

The typical wind farm collector system consists of a 34.5kV substation and the associated radial distribution feeders collecting the kW output of multiple wind turbine generators. A typical distribution collector system is shown in Figure 8. In this example, the collection feeders are rated for a maximum load current of 500 amps at 34.5kV equivalent to 30 MVA. Multiple collection feeders are connected to the wind farm substation collector bus where the voltage is stepped up to the interconnection grid voltage of the transmission system of the utility (Area EPS). In most wind farm designs, the collector distribution feeders are 34.5kV underground cable systems, and each may be up to 8 miles in length. The distributed capacitance of the underground feeders is usually insufficient to compensate for the reactive losses in the feeder system and induction machines. However, it should be noted that the reactive power of a 6-mile collector feeder cable is 1-2 MVARS. Figure 8 is a typical one-line diagram of the Wind Farm Collector System.

There is usually some reactive compensation connected to the 34.5kV bus in the form of switched capacitor banks or Dynamic Var control system mentioned above. The station service

for the wind farm substation will be a reliable dual fed configuration with transfer switches between the normal feed and the alternate standby gen set or from a local area distribution network.

The design of the collector feeder must take into consideration the earth (soil) thermal resistivity (RHO). Thermal or heat dissipation due to current flowing in the cable will depend on the soil thermal resistivity. The design of the feeder cable installation should consider the induced current on the cable shield which adds heat to the cable insulation. Long feeders should be “cross bonding” the neutral to limit the effect of induced current on the outer shield of the cable. In Figure 8, the typical home run feeder cable size is 1000 KCM, A1, branch circuits are made of cable size 500 KCM, No. 4/0 AWG or No. 2/0 AWG. Junction boxes are used along the feeder for branch circuit collection and isolation. The collector feeder is looped fed the turbine generator step-up transformer via dead front elbow-connectors.

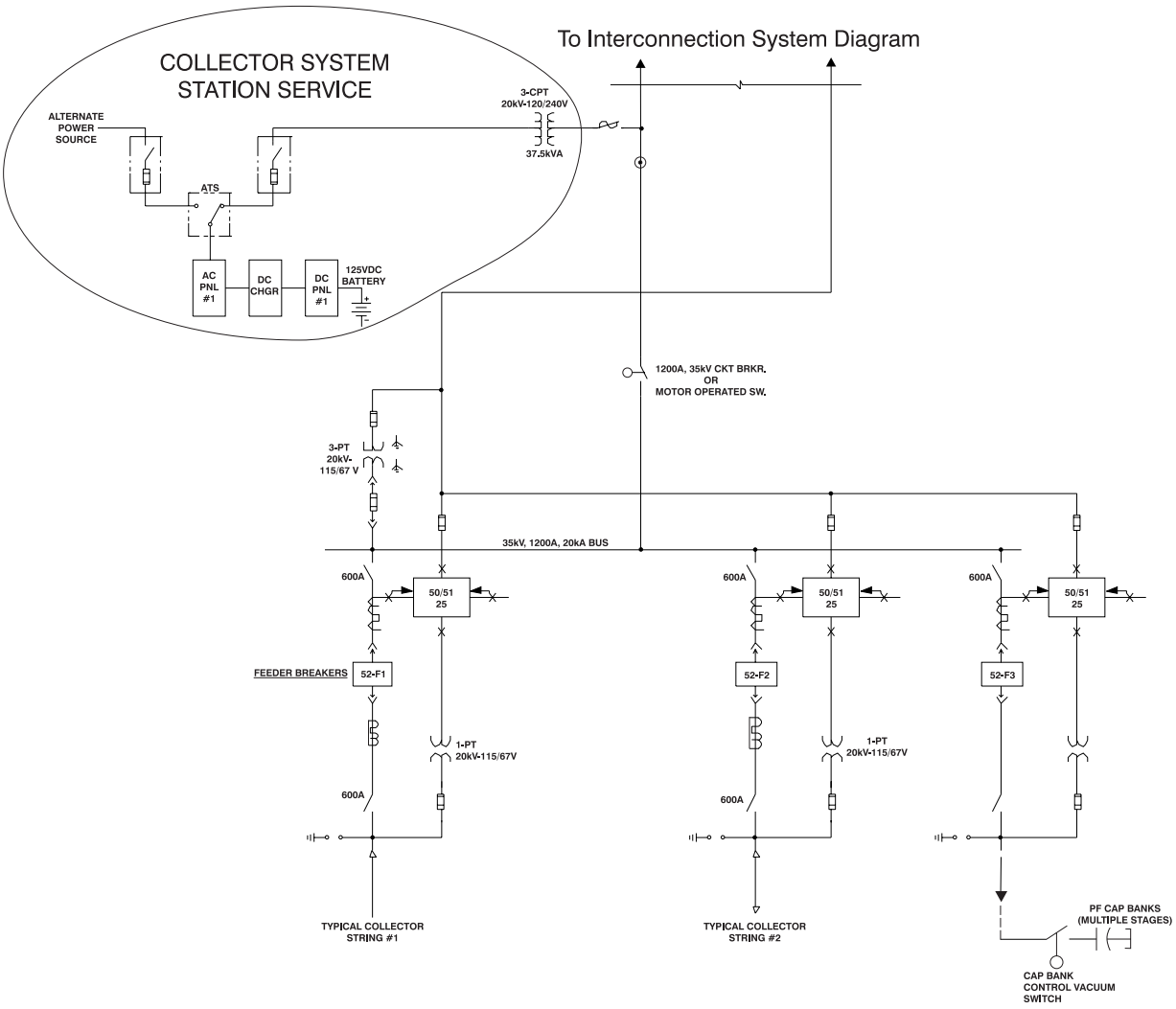


Figure 8: Typical One-Line Diagram, Wind Farm Collector System

The collector feeder is dedicated to the connection of the wind turbine generators, and no other independent load is connected to the feeder. Furthermore, the fault contribution from the

interconnecting area EPS to a fault on the collector feeder is normally much higher than that of the wind generator on that feeder. Therefore, the collector feeder can be treated as a radial feeder, and its protection has typically consisted of the 50/51 with 25 devices. This protection comes from multifunction numerical systems. The protection challenge for the distribution feeder protection and control are the distributed generators connected to the radial distribution system. Special consideration should be taken for the in-feed contribution from the generators on the adjacent feeder and on each feeder when setting the collector bus feeder protective relay. The wind generator is induction type. However, it is recommended that voltage check and sync-check supervision should be provided for the closing of the feeder breaker. The breaker should be closed for Live Collector Bus and Dead collector feeder. A single phase PT is connected to the feeder pull off, and three phase PT's are provided on the collector main bus for relay and metering purposes.

Regardless of the generator step-up transformer winding and grounding designs described above, the five legged core three phase transformer and the single phase transformer banks do not pass zero sequence current between the windings. Therefore, when the collector feeder is disconnected from the main station transformer, it is considered an ungrounded system. Operating experiences show that when a ground fault occurs on the collector feeder, the induction generators could be self-excited and run on, but eventually the protective relays 27 or 59 and 81O or 81U will trip the generator interconnecting contactor or circuit breaker. However, if a 34.5kV collector feeder breaker trips for any type of feeder fault, the protective relay of the wind turbine generators connected to that feeder are designed to trip to a loss of main source voltage. However, if a generator protective relay and control system fails to isolate the generator, it may continue to run on for several cycles. When the fault is a "phase-to-ground" fault, a few generators remain connected to the collector feeder after the feeder breaker has tripped and will continue to energize the ground fault. This weak source connected to an ungrounded system can create a 60 Hz resonance condition during the ground fault if the circuit ratios X_0/X_1 are between –1 and – 40. The feeder capacitance to ground can have a negative X_0/X_1 value that can cause resonance and voltage amplification at the grounded fault on the feeder. Figure 9 illustrates the sequence diagram for a Delta-Wye padmount and low resistance grounding.

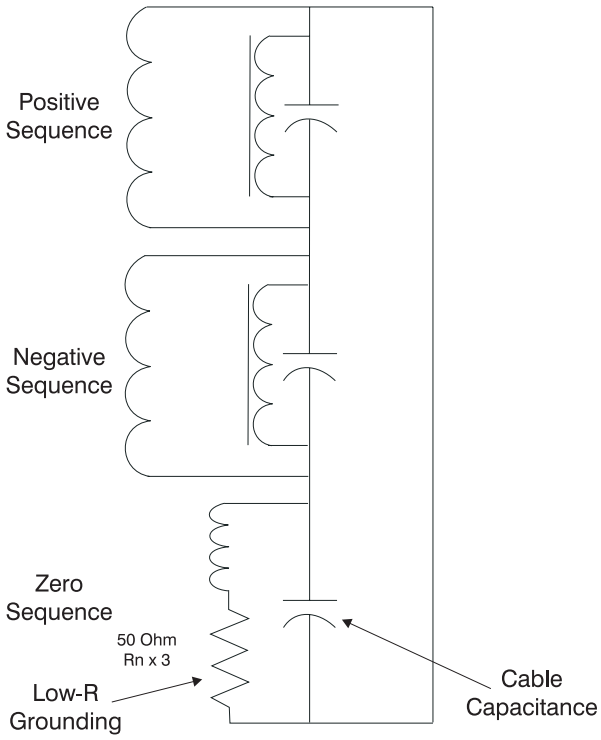


Figure 9: Sequence diagram with D-Y padmounts and Low-R grounding

Figure 10 shows a feeder voltage profile during a ground fault with the number of generators connected isolated to the ungrounded feeder. Note, the smaller the number of generators connected to the feeder (weak source), the higher the resonance overvoltage condition.

Transient overvoltage occurs and causes flashover of insulators and line arrestors. A grounding transformer can be installed on each feeder to control this transient overvoltage condition. The transformer can be a Zig-Zag or a Wye grounded-Delta type and is designed with a grounding resistor to limit the ground current contribution to the feeder fault.

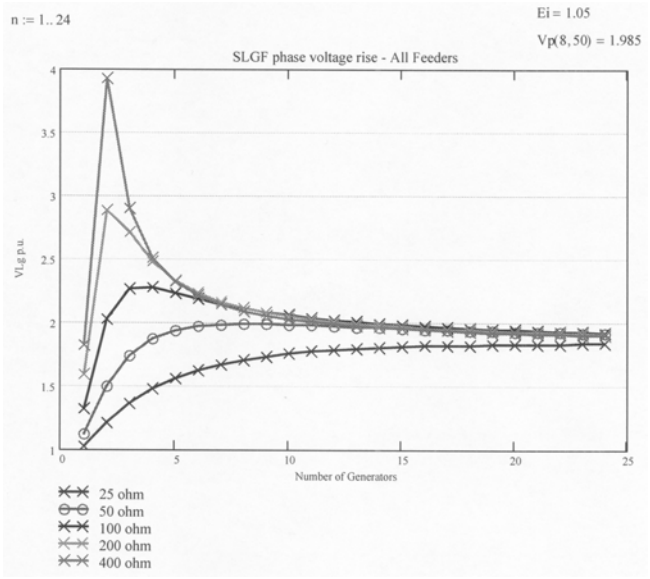


Figure 10: SLGF Voltage Rise on F7 vs. Generators Connected

Figure 11 shows the effect of the ungrounded collecting system when the main transformer and its grounded neutral are disconnected from the collector bus for a ground fault on the main collector bus.

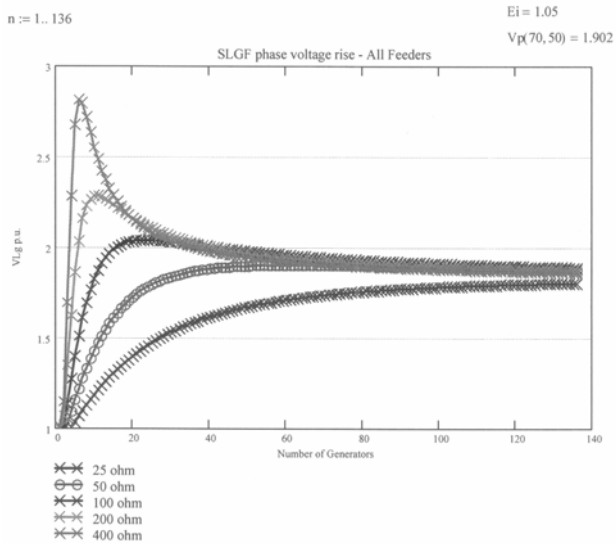


Figure 11: SLGF Voltage Rise on All Feeders vs. Generators Connected

IV. i. Wind Farm Interconnection Substation

Figure 12 shows a typical protection and control one-line diagram of a large Wind Farm Interconnection System.

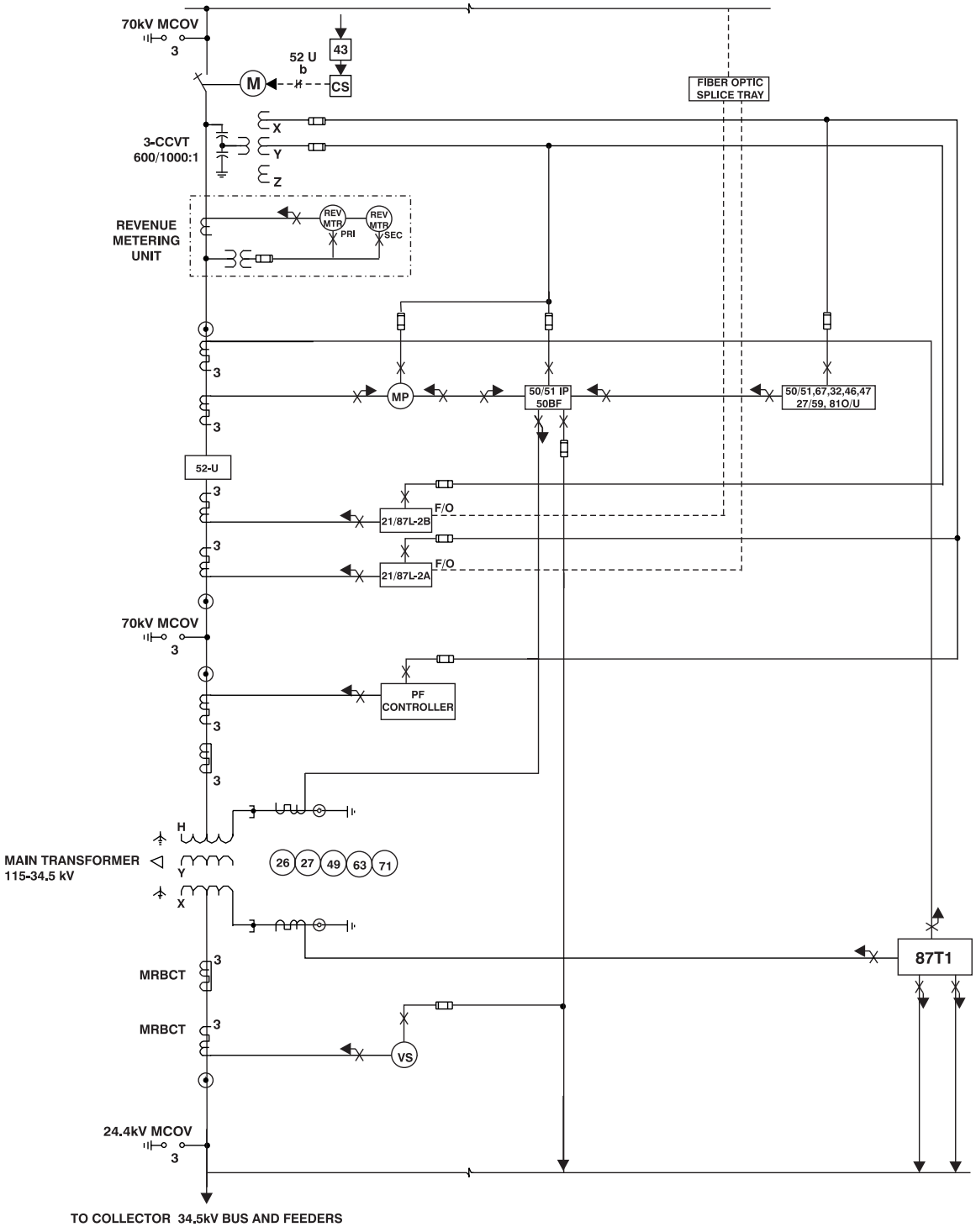


Figure 12: Typical P & C One-Line Diagram Interconnection System – Local EPS Substation

IV. ii. Interconnection Step-up Transformer

The interconnection transformer that steps up the 34.5 kV collector system voltage to the Utility transmission delivery system is a 3-winding configuration. The low voltage winding is a grounded Wye, and the high voltage winding is also grounded Wye. The tertiary winding is connected Delta.

The same argument that applies to the collector feeder grounding transformer also applies to the main transformer winding design, which has grounded Wye primary and grounded Wye secondary, and a Delta Tertiary winding. The Delta Tertiary is used to stabilize the neutrals of the transformer and provide zero sequence current to ground fault on both sides of the main transformer bank. The impedance of the transformer, including its Tertiary, must be designed to provide sufficient ground fault current for the transmission interconnection relays to operate as well as those on the collector feeders. The Tertiary winding MVA rating is normally designed to 35% of that of the main transformer. See reference 1.

If a Delta-Wye transformer is used for the main interconnecting transformer, a grounding transformer may be installed on the Delta side of the transformer to provide stabilization of the transformer primary neutral. Other possible zero sequence voltage relay circuits may be installed to detect the system neutral shift during a ground fault condition. However, this system operates sequentially after the transmission ground protection has operated. Coordination with back-up ground protection and recloser should be considered. The ungrounded neutral of the Delta-Wye interconnecting transformer is usually installed in the same size wind farm plants.

IV. iii. The wind farm substation and collector feeder protection

The protection for the wind farm distribution substation consists of multifunction numerical systems including a main transformer differential relay, transformer Time-Overcurrent relay for the main transformer back-up protection, collector bus differential relay, distribution Time-Overcurrent relay, and breaker failure protection. Other possible zone distance back-up relays for the distribution feeder's protection provide coordination of feeder TOC's, sync-check relay.

These substation protective relays can be applied as in a radial distribution substation that is serving load. The feeder protective relays must be set to include the contribution fault current from the generators. The transformer primary ground Time-Overcurrent relays' protection must be set to coordinate with the interconnection protection TOC provided by the interconnecting utility (area EPS).

There are differences between the wind farm distribution system protective relay and that of the typical utility distribution radial feeder serving the public load, which may have DG's connected in parallel with the area EPS.

The wind farm distribution system is dedicated to the connection of wind turbine generators only, with no other load serving on the feeder. The wind farm distribution feeder is solely owned and operated by the owner of the wind farm. Thus, controlling and operating the wind farm is done through one identity, while the DG's owner individually controls and operates his DG's. The control and protection of the system is uniformly and identically in the wind farm while the DG's are not. There is one Point of Common Coupling for the interconnection of the multiple generators in the wind farm. Thus, the interconnection protection is simplified.

IV. iv. Area EPS Transmission Delivery System Substation

For the interconnection of a wind farm to an area EPS system, these induction generators should be treated the same as if they are synchronous generators, due to the fact that they can contribute large fault current for several cycles. The interconnecting transmission line protection may include all or some of the following schemes: a direct transfer trip scheme, an interconnecting line differential or a pilot line relay scheme, zones distance and back-up Time-Overcurrent, over/under voltage, over/under frequency, breaker failure and sync-check. These protective schemes are a part of the interconnection technical requirements imposed by the Area EPS (Utility). They will vary somewhat depending on the Area EPS system.

The typical transmission delivery system is as shown in Figure 13. The wind farm interconnects to the area EPS via a tap to an existing transmission line. This wind farm substation is typically relatively simple and contains the point of common coupling (PCC) between the Area EPS (utility) and the Local EPS (wind farm). The protection schemes are normally multifunction numerical systems that include a direct transfer trip scheme, a zone distance or pilot scheme, breaker failure transfer trip scheme and a local back-up. The remote ends of the transmission delivery system require some revision of the protection system settings to accommodate multiple terminals effect such as infeed.

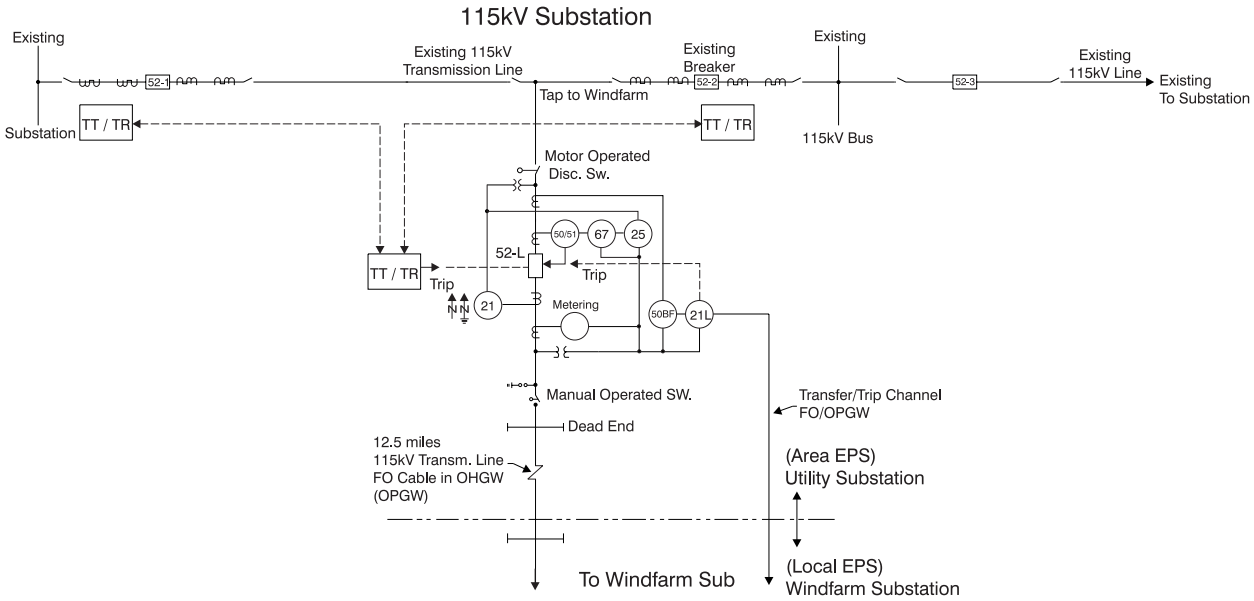


Figure 13: Typical One-Line Diagram Area EPS Transmission Delivery System – Tapped T-Line

Another large wind farm interconnection is a radial two terminal line configuration where the wind farm substation is connected to the area EPS transmission system via a radial connected transmission line. In Figure 14, the interconnection of the wind farm to the area EPS consists of the transmission line protective relaying system that includes a pilot scheme, back-up zone distance relay, breaker failure transfer trip and, possibly, a local voltage and frequency limit protection.

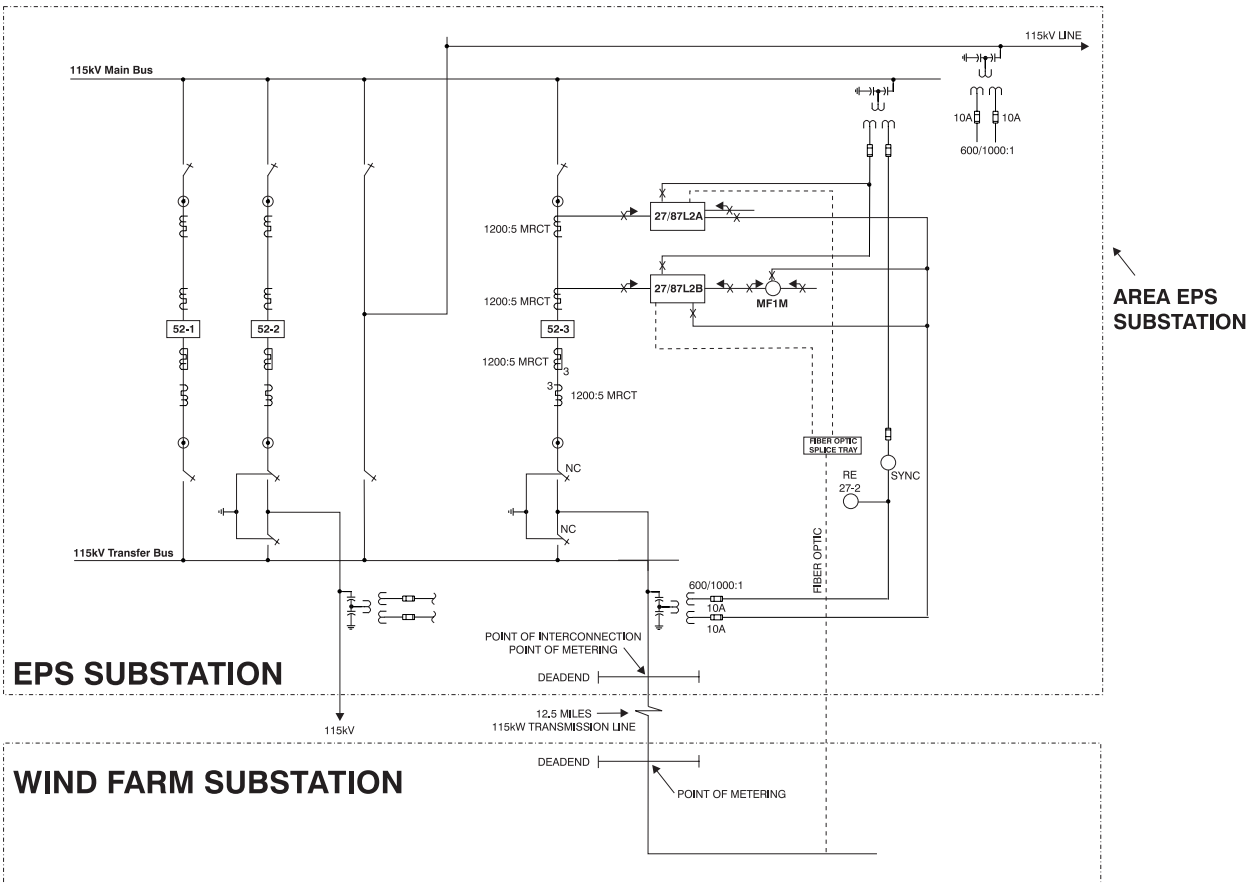


Figure 14: Typical One-Line Diagram of Area EPS Radial Transmission Delivery System – Main-Transfer Bus Design Substation

V. Monitoring, Command, and Control Systems

The communications system, along with the SCADA interfaces for a green power project, is complex, and the design is dependent on the multifunction numerical protection and control devices. The wind farm operations center, the substations, and the interconnection system need to monitor the operations in real time.

Figures 15 and 16 illustrate one method used for exchanging pertinent information among the wind farm operations, wind farm collector system, wind farm substation, interconnection system, var/power factor control at the PCC, and the wind farm owner. Data from each of the wind turbine control systems are collected over a fiber optic cable installed in the same duct bank of the 34.5kV collector feeder. The data is transmitted over a spread spectrum/microwave transmitter/receiver system to a corresponding transmitter/receiver at the substation and/or the site operating maintenance facility.

In other wind farm facilities, a complete fiber optic system may be used to provide communication between the wind turbine units and the operator control center.

Data points, including alarms and on/off control of the turbine generators, are provided. The list of turbine and generator parameters monitored by the control system is as mentioned in the above section.

Due to the underground collector feeder design and transformer trip lockout, automatic reclose of the feeder and/or the substation interconnecting breaker (transformer primary isolation device) are not implemented. SCADA close control of the station breakers may be applied for certain operating conditions, such as the interconnecting EPS area transmission system restoration after an outage may allow the operator to restore the wind farm substation via SCADA. This SCADA control may be part of the substation communication design.

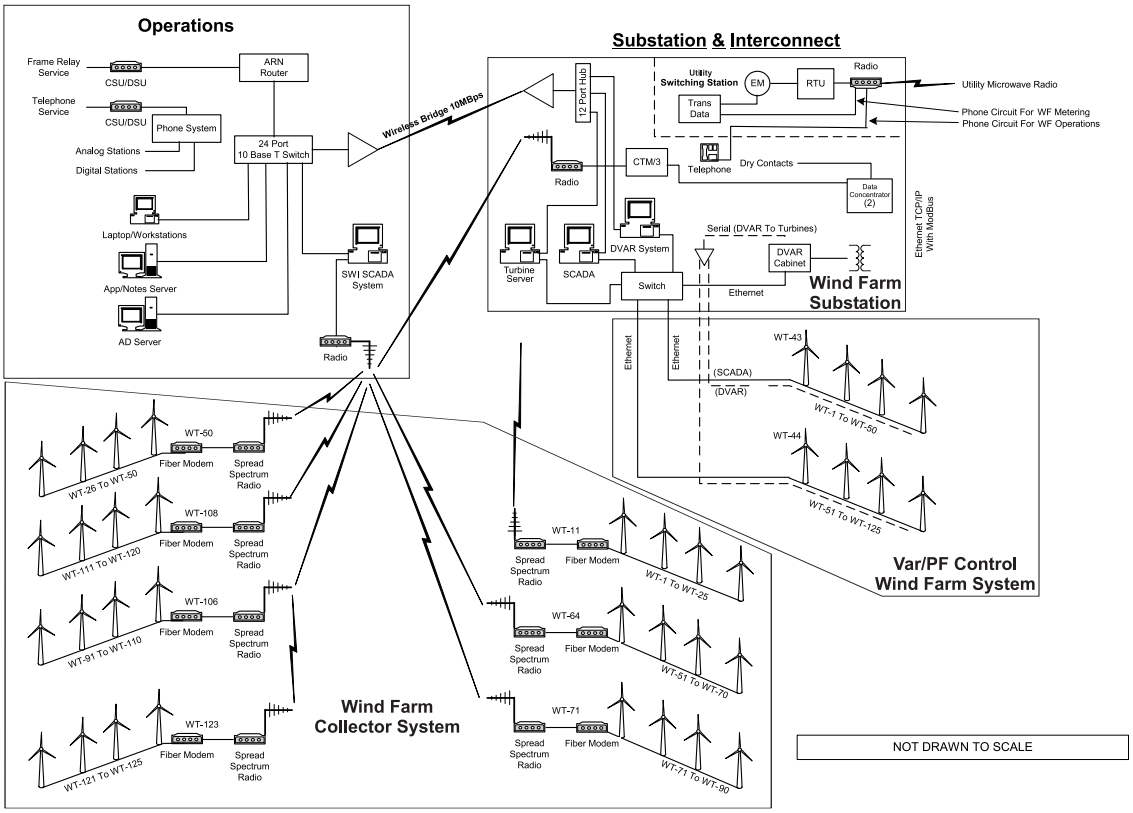


Figure 15: Typical Command and Control System

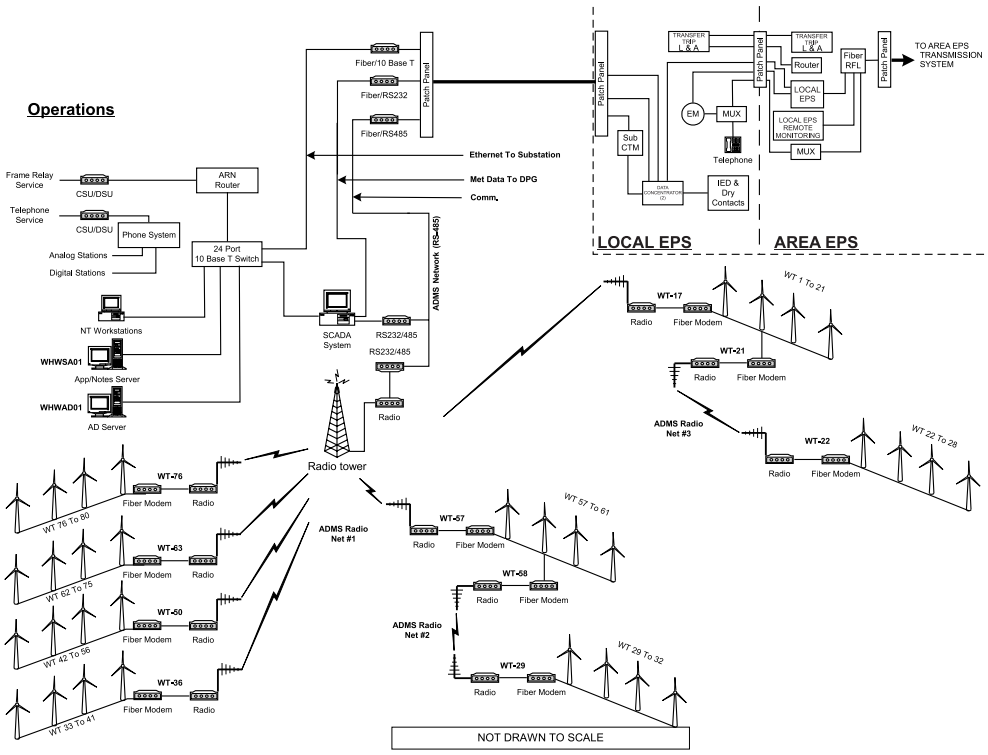


Figure 16: Another Typical Command and Control system of a Large Wind Farm Facility

The communication SCADA, metering, and RTU designed for the interconnection must also satisfy the region ISO. Wind data may be included in the information strings that provide the operator a prediction of wind farm generating MW output for system scheduling purposes.

Another consideration is the wind farm capability to provide voltage support to the area EPS transmission system. The PF correction capacitor bank may be controlled by the system operator to maintain EPS system voltage. From past experience, the PF correction capacitor bank is normally used to control the interconnection system voltage, and the PF correction required by the interconnecting contract has become a secondary function for the device.

Start-up and Commissioning

The start-up and commissioning is a joint effort between the Wind Farm (Local EPS) and the Interconnecting Utility (Area EPS). Careful coordination and planning is necessary for a successful commissioning that includes records that will support future operations and maintenance needs. The multifunction numerical protection and control devices are dependent on proper sensing connections, logic schemes, metering, recording and communications among them for prudent electrical system design.

Verification of the protection and control schemes is mandatory if the future operations can be resolved quickly, so that adjustments can be made in a timely fashion. Close coordination is required between the Local EPS and the Area EPS assigned technical groups.

Summary and Conclusions

The success of the evolving Green Power Interconnected Projects is very dependent on the following of a logical method used by electrical systems, leading to a long life for the assets and investments made for the project. This method involves timely participation of all parties with ownership in the project, and those processes involved are as follows:

- Planning the project
- Designing the project in accordance with the planning effort
- Construction of the project in accordance with the planning and design effort
- Commissioning the project to verify that the construction was in compliance with the planning effort
- Operation and maintenance of the Green Power Asset for the benefits set forth in the project planning effort.

The protection and control aspects of the multifunction numerical devices enhance the ability to operate reliably and to maintain the project electrical systems for the life of the asset. Power system faults will happen, and analysis tools imbedded in the numerical systems assist the engineer to ensure that the protection operates as designed. This allows adjustments to be made, if necessary.

Green Power projects like wind farms allow protection and control engineers to use modern technology to provide cost effective systems that were not available until the implementation of multifunction numerical devices. This allows the Green Power project owners to work smarter, not harder, so that the economic benefits are achieved.

Command and Control Information Exchange systems, along with a stable communications system, make real time observation very cost effective and necessary.

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