Wind Farm Collector Protection using Directional Overcurrent Elements

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Abstract - The protection of wind farm collector circuits is complicated by high generator output, long runs of cable, a variety of cable sizes, wind turbine step-up transformer inrush, and a variety of wind turbine technologies. Non-directional overcurrent protection often does not provide the necessary sensitivity for detecting faults on remote points of the circuit or backup protection for wind turbine step-up transformers. This issue is further complicated when attempting to mitigate arc flash incident energies. Directional elements are necessary to set overcurrent pickups below maximum generation levels. Setting the directional element by traditional means may result in a reliability risk at varying generation VAR outputs. Using event reports collected by relays, this paper demonstrates the limitation of non-directional overcurrent protection on wind farm collector circuits, and the pitfalls of an improperly configured directional element. A unique solution using directional overcurrent elements further secured by a load encroachment function can be used to solve these problems. Field data verifies the security of the application over a wide range of operating conditions.

I. INTRODUCTION

Wind farm substation and collection system topologies are very similar to traditional distribution substations, but there are key differences. Wind farm substations are generally larger in size. Modern wind farm substations are typically 50 MVA or more. Power is generated by the wind farm, therefore power flow is typically into the main bus where it is out of the main bus for a distribution substation. The larger size of the wind farm substations dictates a more robust protection system due to the replacement cost of equipment and the increased potential for damage due to higher fault currents. Substation transformers and metal clad switchgear are particularly expensive and vulnerable to damage during faults. A generating power flow can mean large swings in voltage and power factor during normal operation posing challenges for directional phase overcurrent elements.

Perhaps the key difference is the protection of conductors located on the feeder circuits. The traditional distribution circuit uses a combination of fuses and reclosers to protect smaller lateral circuits. The distribution substation feeder relay generally provides conductor protection of the main trunks only and coordinated backup of the lateral protection devices. In a wind farm collection system, there is an increased burden on the collector relay to protect main trunk conductors as well as the smallest lateral conductors. When fault detection on the low voltage side of wind turbine step up transformers is necessary, the collector relay sensitivity requirement increases. Directional overcurrent elements provide a balance between security for generator output and sensitivity for all collector faults.

II. TYPICAL WIND FARM COLLECTOR PROTECTION

A typical wind farm collector circuit contains a series of either overhead or underground cables. Similar to traditional distribution, conductors near the substation are frequently larger than those further away (Fig. 1).

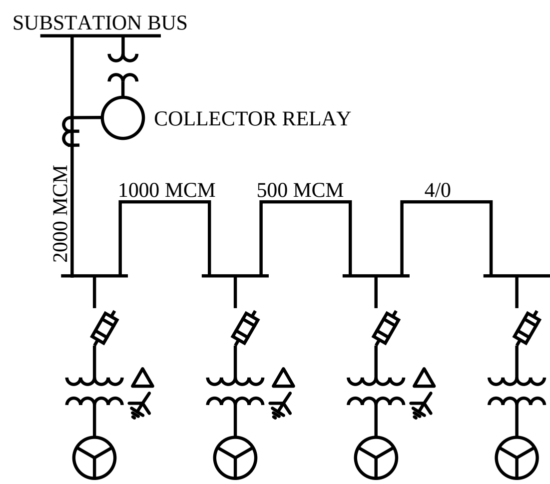


Fig. 1. Typical Wind Farm Collection Circuit

Individual wind turbine generators (WTG) are connected to the collector through a generator step-up transformer (WTGSU). To make a generalization, wind turbines less than 2.5 MW (Fig. 2) often are coupled with a padmount WTGSU located next to the wind turbine base. These padmount transformers are protected by internally mounted fuses and occasionally have low voltage breakers. The connection to the turbine is via cables connected to the line side of a low voltage main breaker housed in the wind turbine base.

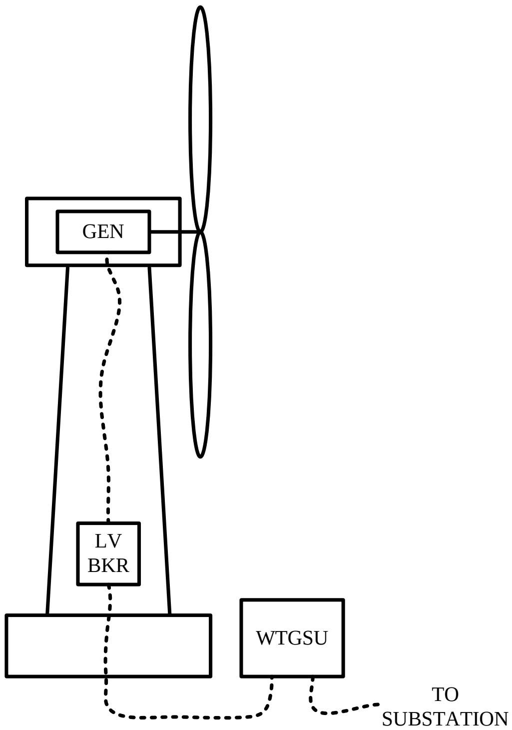


Fig. 2. Wind Turbine with LV Main Breaker

Wind turbines greater than 2.5 MW (Fig. 3) often have an overcurrent relayed medium voltage main breaker contained in the turbine base. The medium voltage cables connect to the WTGSU located in the nacelle of the wind turbine.

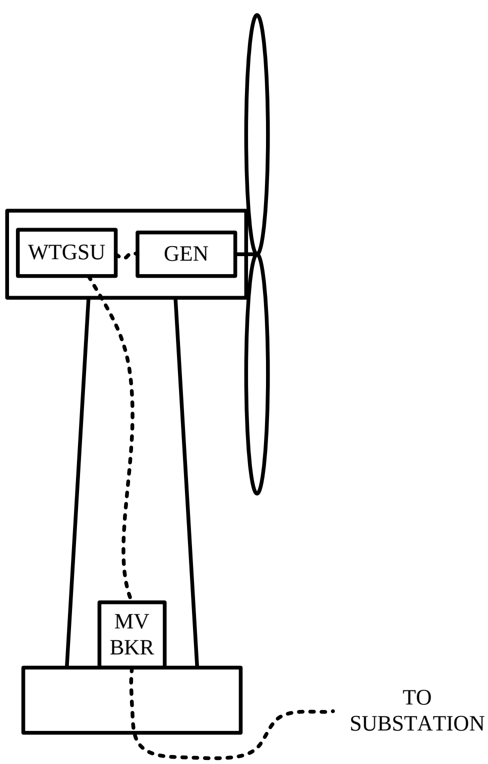


Fig. 3. Wind Turbine with MV Main Breaker

Non-directional overcurrent relaying at the collector substation is used to protect the circuit conductors, splices, junction boxes, transformer connections, and elbows, as well as provide backup protection for wind turbine generator step up transformers. This overcurrent relay must protect these assets while maintaining coordination with the wind turbine generator transformer protection, avoiding inadvertent trips during collector circuit energization inrush, and allowing full wind farm generation output.

The collector relay phase and ground instantaneous overcurrent elements can be set to detect faults between the collector breaker and the first WTGSU. The pickup is commonly set with some margin over the maximum fault current seen at the closest WTGSU. This setting must also account for and coordinate properly with the inrush currents that occur when the WTGSU transformers are energized within the collector circuit. A conservative estimate for inrush current on the collector is twelve (12) times the total MVA ratings of all connected transformers on the collector. The inrush current is considered to be present for 0.1 seconds, per IEEE Standard 242-2001 (Buff Book).

Non-directional inverse time overcurrent (51P & 51G) elements are used to protect the balance of the collector circuit beyond the first WTGSU. To avoid tripping on generating current from the collector, the phase overcurrent pickup setting must be set above the full load of the entire collector circuit. The ground overcurrent pickup must be set above the residual current generated by normal unbalance current, which is typically low. The time-overcurrent curve and time dial must coordinate with WTGSU protection while maintaining a sufficient margin of protection for the smallest lateral cable. This is often a challenge. Depending on the maximum fault magnitude and the size of the cable, a definite-time overcurrent element may be necessary.

Fig. 4 below shows an example where the 51P element could not be set fast enough to protect a 1/0 cable. Rather than lower the time dial of the 51P element, a definite time element can be added with a very small time delay to allow the current limiting fuse to clear WTGSU faults. This situation leaves very little security margin for the relay element to reset and demonstrates a compromised situation that is difficult to avoid with small laterals, particularly when they are close to the collector substation.

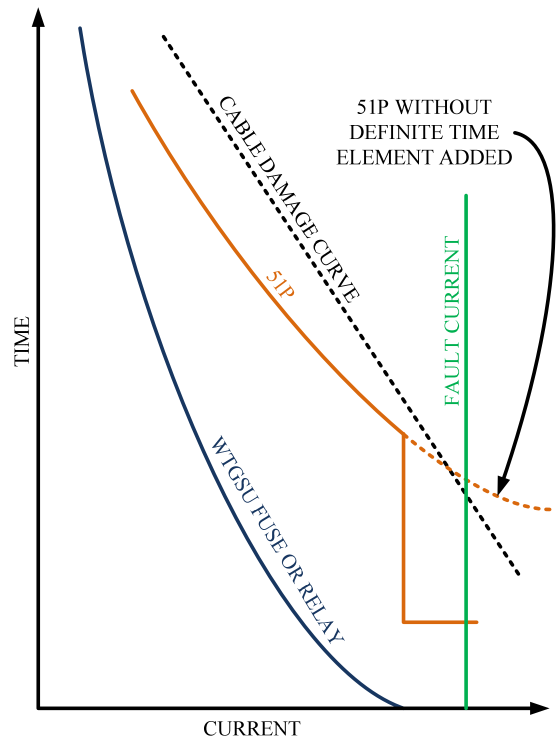


Fig. 4. Time Overcurrent Coordination with WTGSU Fuse and 1/0 Lateral Cable

Non-directional phase overcurrent protection lacks sensitivity because it must be set above maximum generating levels. Increased sensitivity may be required to detect faults near the end of the circuit, and may be desired to detect faults on the low side of the WTGSU's. Using directional phase inverse time overcurrent elements (67P) allows set points below the circuit generation levels by only responding to forward current flowing into the circuit. Forward current is limited to either faults or very small turbine loads (lights, heaters, etc) when the wind turbines are not producing power. Set the pickup considering the desired sensitivity for faults at the most electrically remote (highest impedance) wind turbine. Don't forget to consider sensitivity for arcing faults (i.e. – reduction of arc flash incident energies). Select the curve and time dial using the same coordination approach as the non-directional element.

III. WIND FARM VAR RESOURCE CONTROL

Wind farm outputs are often controlled to maintain near unity power factor at the point of interconnect (POI). A variety of capacitive VAR resources, such as staged capacitor banks and dynamic VAR power electronics connected to the substation bus, are used to compensate for the collection system inductance. Some wind turbines have dynamic VAR controls that allow them to maintain the power factor at the substation or POI without additional VAR resources at the substation.

As wind farms gain deeper penetration in the transmission grid, wind farm VAR resources are needed to maintain voltage within acceptable levels on some networks. Both regional organizations and interconnecting utilities may require wind farms to maintain either a voltage at the POI or a variable PF or VAR output. When connected to strong systems the VAR import/export needed to control voltage can vary significantly more than that needed to maintain unity power factor. POWER Engineers is helping clients combine and control the substation and wind turbine VAR capabilities to meet these new requirements to help them avoid the need for additional dynamic VAR resources.

IV. WIND TURBINE VAR CAPABILITIES

The VAR capabilities for each type of wind turbine technology vary. Type I, II, III, and IV wind turbine generators use different VAR support systems to provide or consume different amounts of reactive power.

Type I wind turbine generators are standard squirrel cage induction generators, therefore they require external VARs to excite the rotor windings of the machine. Typically Type I wind turbines contain staged capacitors to provide the VARs needed at a variety of output levels. These staged capacitors can often be control by a wind farm management system (WFMS).

Type II wind turbine generators are similar to Type I but a variable rotor resistance allows operation over a greater range of speeds. Type II wind turbines also require capacitor banks in the same manner as Type I wind turbines.

Type III wind turbines are known as doubly fed induction generators (DFIG). The stator is built similar to a squirrel cage induction machine, but the rotor is connected to the power system through an AC-DC-AC converter. This converter allows the turbine to operate over a greater speed range and produce or consume VARs.

Type IV wind turbines can be a variety of generator types connected to the power system through a full power AC-DC-AC conversion system. This provides a full range of speed and VAR control capabilities.

When wind farms operated in a voltage control mode are subjected to voltage swings at the POI, the wind turbines can output large variations of VARs in an effort to maintain the prescribed voltage. This large VAR flow can result in current angles that may confuse relay directional overcurrent elements.

V. LESSONS LEARNED FROM DIRECTION OVERCURRENT MISOPERATIONS

For this example a common distribution feeder relay is used for collector protection. The directional over-current elements on the collectors are designed to only respond to faults on the collector (forward), and not current flowing out of the collector (reverse). The element is set well below maximum generating levels; therefore it begins timing to trip as soon as the directional element indicates forward.

The relay monitors positive-sequence impedance (Z1) and makes a comparison to the line impedance angle (Z1<). When the measured Z1 angle differs from Z1< by more than 90° the current is determined to be reverse. For most applications the line impedance angle makes a nice benchmark for forward/reverse fault current.

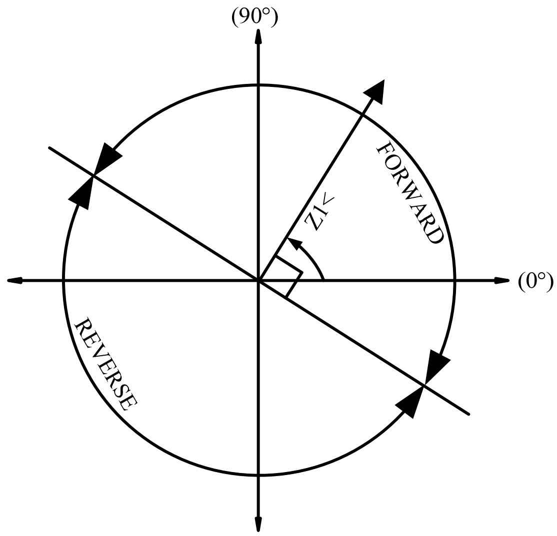


Fig. 5. Phase Directional Element Impedance Diagram

For direct comparison to event report phasor diagrams, Fig. 6 shows the relay's directional element referenced to the positive-sequence voltage (V1). In the relay event reports V1 is set to 0° and all phasor are rotated accordingly. When the positive-sequence current (I1) differs from Z1< by more than 90° the current is determined to be reverse.

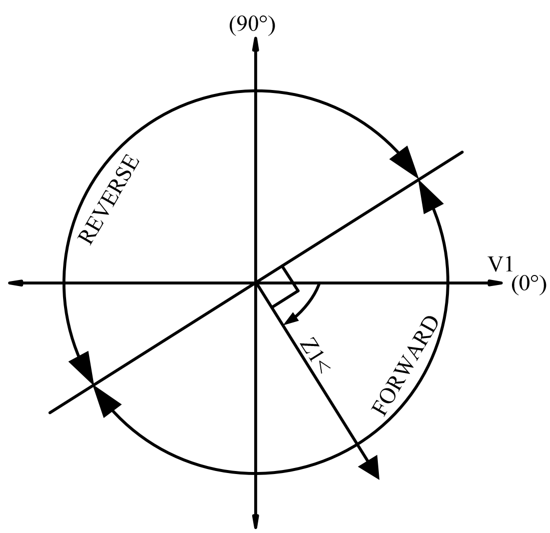


Fig. 6 –Phase Directional Element I1 vs. V1

Normal generation output at unity power factor on a wind farm collector plots on Fig. 7 at 180°.

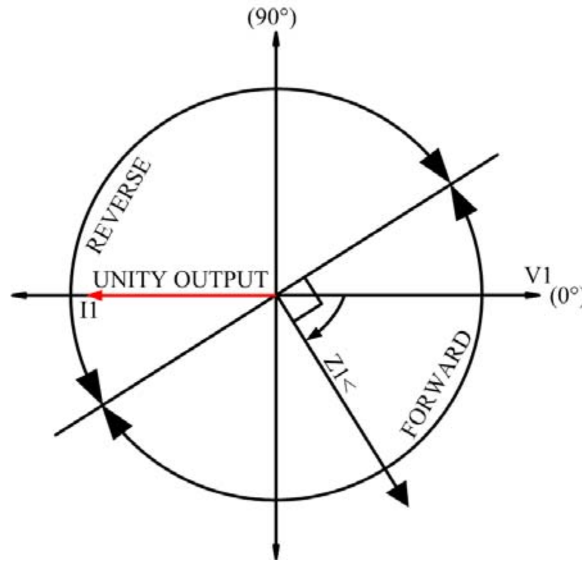


Fig. 7. Unity PF Output on a Collector

As the VAR output of the collector increases and the PF decreases, the relay can eventually trip. Fig. 8 is zoomed in on the lower left quadrant where the directional element is most vulnerable.

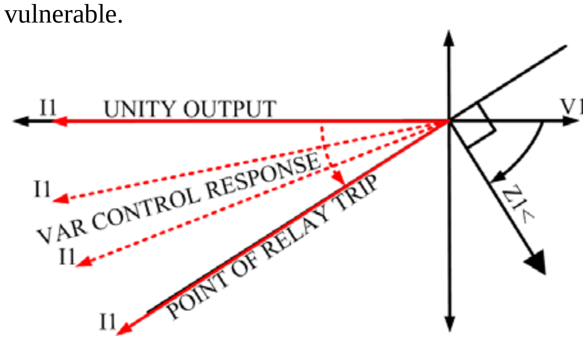
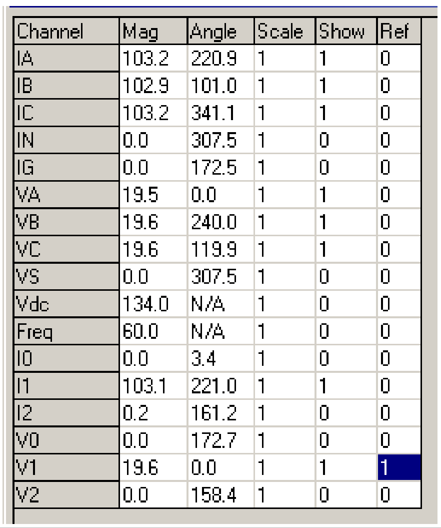


Fig. 8. Collector Relay Trip on Low PF

In the winter of 2010, responding to a request by ERCOT to increase VAR output to help raise the voltage on a 345 kV line, a wind farm in Texas used a WFMS to increase VAR output. This particular wind farm uses Type III machines with a WFMS capable of controlling PF.

As the VARs increased, the current angle relative to the voltage angle increased. One of the collector relays tripped on over-current when the current angle became large enough for the directional element to indicate forward direction.

All collectors had a Z1< setting of 50.09º. The over-current pickup was set to 72 Amps. As the current became more capacitive, the angle became larger. When it exceeded (90º - Z1<) + 180º = 219.91º (+180º because generating angle is measured as angle from 180º), the relay interpreted the current as forward, began timing, and eventually tripped. See Fig. 9 below with phasors from the trip event:



Channel	Mag	Angle	Scale	Show	Ref
IA	103.2	220.9	1	1	0
IB	102.9	101.0	1	1	0
IC	103.2	341.1	1	1	0
IN	0.0	307.5	1	0	0
IG	0.0	172.5	1	0	0
VA	19.5	0.0	1	1	0
VB	19.6	240.0	1	1	0
VC	19.6	119.9	1	1	0
VS	0.0	307.5	1	0	0
Vdc	134.0	N/A	1	0	0
Freq	60.0	N/A	1	0	0
I0	0.0	3.4	1	0	0
I1	103.1	221.0	1	1	0
I2	0.2	161.2	1	0	0
V0	0.0	172.7	1	0	0
V1	19.6	0.0	1	1	1
V2	0.0	158.4	1	0	0

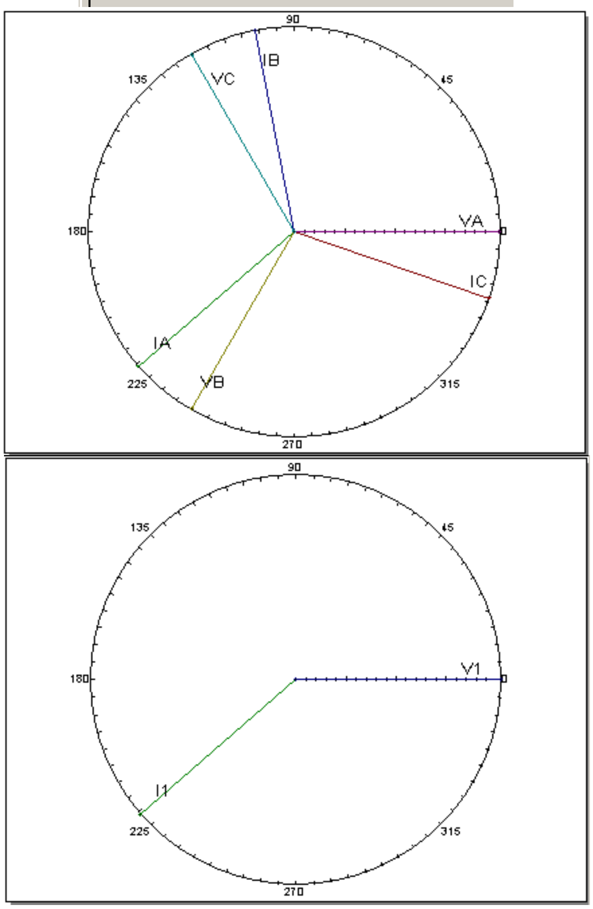


Fig. 9. Collector Trip Event

Note the positive-sequence current equals 220.9°, which plots just inside the forward region of the directional element as shown in Fig. 10.

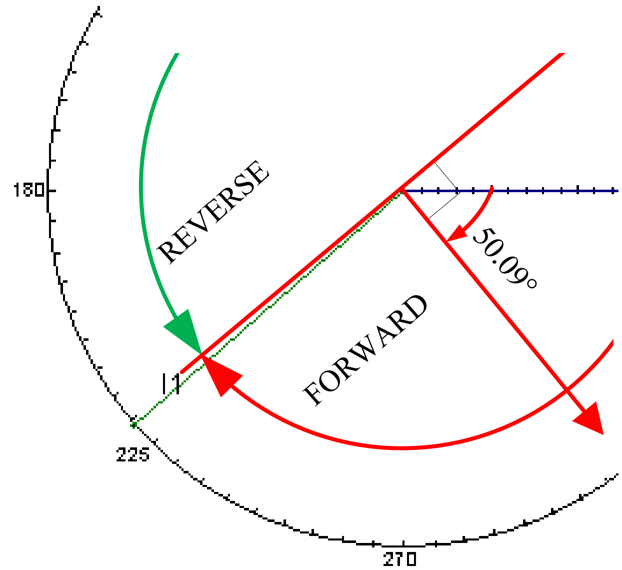


Fig. 10. Positive-Sequence Current vs. Relay Directional Characteristic

From Fig. 10, real power (MW) is flowing out of the collector, yet the angle of the current causes the relay to misinterpret the signals as forward current.

Our first recommendation was to lower the Z1< setting to 35° to avoid tripping for this condition. 90-35+180 = 235° or a power factor of 0.57. At the time we did not believe the wind turbines were capable of providing a capacitive power factor less than 0.57 based on the manufacturer's advertised power factor range of +/- 0.95.

A couple of months later POWER commissioned a VAR control scheme for this wind farm following an ERCOT requirement to use wind farm VAR resources automatically to maintain voltage on this 345 kV line, known to have frequent voltage fluctuations. The WFMS was capable of receiving a PF set point to be maintained at the POI. For the previous event, this PF set point was modified manually to increase the VAR output. The new VAR control scheme calculates and provides the appropriate PF set point to the WFMS, plus controls multiple capacitor banks. The capacitor banks provide step changes in MVAR output, while the wind turbines provide the "fine tuning" in between those changes.

Not long after the VAR control scheme was implemented several collectors tripped on the directional overcurrent element again. The event reports quickly revealed our assumption about the wind turbine VAR capabilities was wrong when the positive-sequence current angle was reported at 236.7°.

Channel	Mag	Angle	Scale	Show	Ref
IA	103.8	236.7	1	1	0
IB	103.7	117.4	1	1	0
IC	103.9	-3.1	1	1	0
IN	0.0	200.7	1	0	0
IG	1.0	200.7	1	0	0
VA	19.6	0.1	1	1	0
VB	19.7	240.1	1	1	0
VC	19.6	119.8	1	1	0
VS	0.0	200.7	1	0	0
Vdc	134.0	N/A	1	0	0
Freq	60.0	N/A	1	0	0
I0	0.3	200.9	1	1	0
I1	103.8	237.0	1	1	0
I2	0.4	107.4	1	1	0
V0	0.0	65.5	1	1	0
V1	19.6	0.0	1	1	1
V2	0.1	164.4	1	1	0

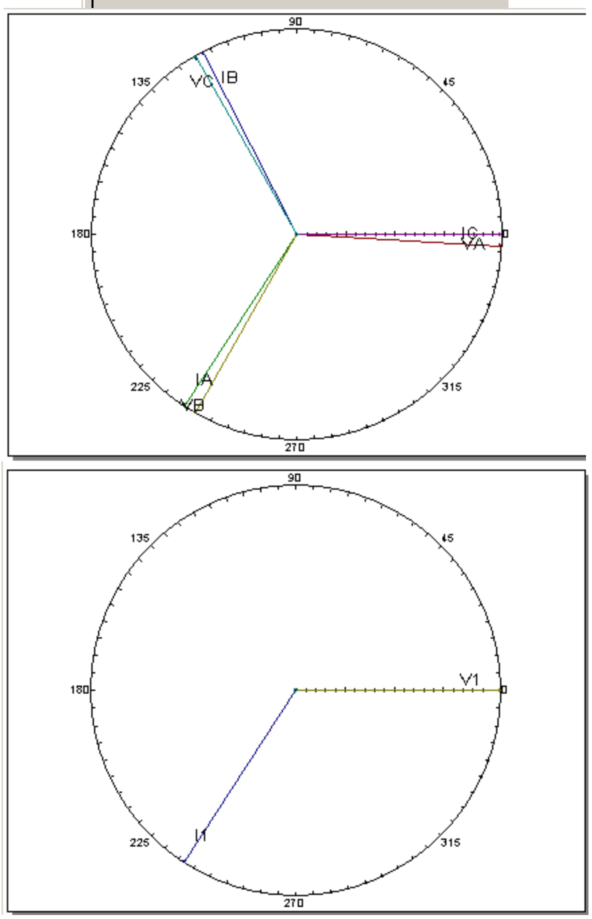


Fig. 11. Trip with Collector Z1< set to 35°

This points out three things: First, the traditional directional overcurrent is not suited well for this situation. Second, we should not rely on wind turbine specifications as this information is often closely held by the manufacturers, and does not always represent the full range of the turbines capabilities. Finally, we needed to secure the directional element for all possible generating load angles.

VI. SECUREING COLLECTOR PROTECTION

POWER devised a method using the relay's load encroachment function to secure the entire range of possible generating currents.

The load encroachment function in the relay is designed to block overcurrent elements from operating for load. The relay monitors the positive-sequence impedance. When the impedance is in the load region the overcurrent elements can be blocked. The element is designed to provide flexible regions in the forward and reverse direction independently.

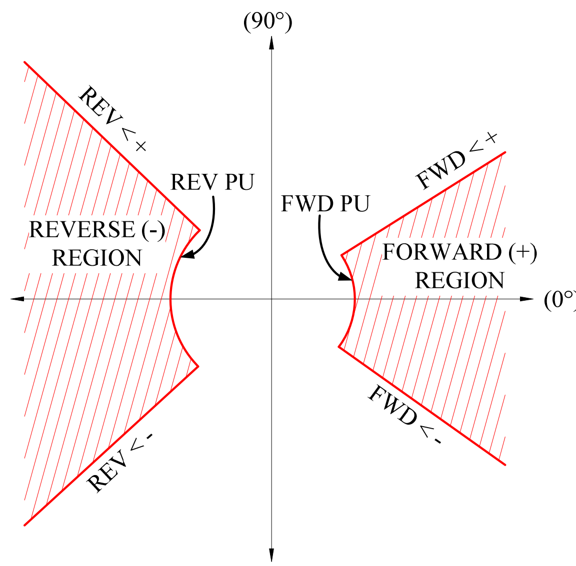


Fig. 12. Typical Load Encroachment Diagram

The setting range allows us to set positive and negative angles for the reverse region to 90° and 270° respectively to fully block the entire generating output region (REV<+ = 90° AND REV<- = 270°). We are only concerned about blocking the generating region (i.e. – reverse or negative region), but the forward region cannot be disabled. We set positive angle for the forward region to 90° (FWD<+ = 90°) and negative angle for the forward region to 85° (FWD<- = 85°). The forward load pickup (FWD PU) is set to the maximum setting to effectively prevent the blocking of any forward fault. The reverse load setting (REV PU) is set to 120% of the maximum generation capability of the collector circuit to ensure it blocks for all normal generating conditions.

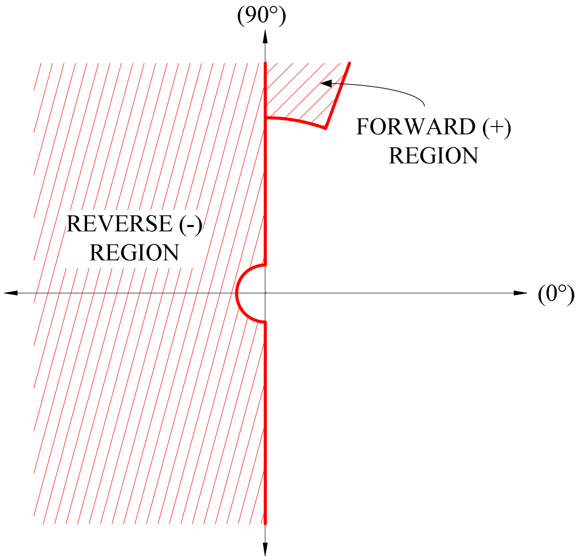


Fig. 13. Load Encroachment Diagram for Secure Collector Directional Control

Combining Fig. 13 with the directional element we get the combined directional control of the overcurrent element. We expect all fault impedances to lie between 0° and 85°.

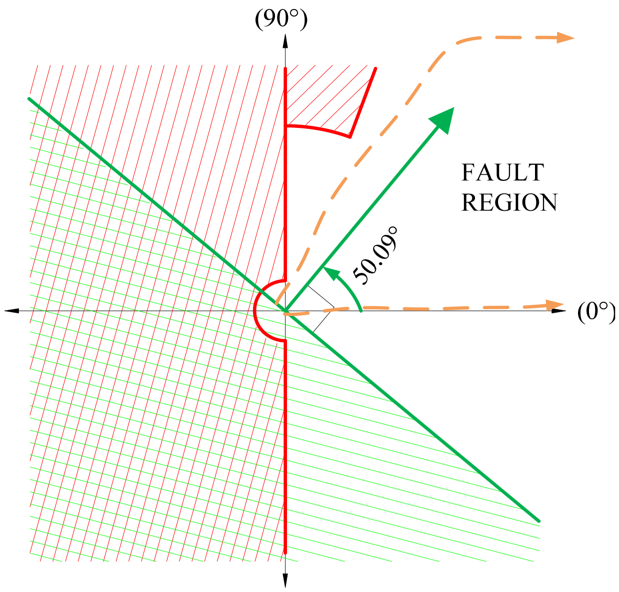


Fig. 14. Aggregate Directional Control for Directional Overcurrent Element Impedance Diagram

For comparison to event report phasor diagrams Fig. 15 shows the directional overcurrent element supervision referenced to the positive-sequence voltage (V1).

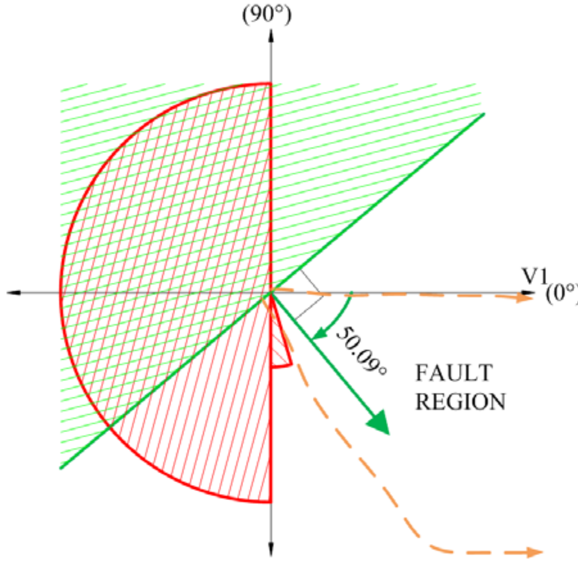


Fig. 15. Aggregate Directional Control for Directional Overcurrent Element – V1 Reference

VII. CONCLUSION

A traditional directional overcurrent element application on a wind farm collector is susceptible to incorrect tripping for desirable generator output. Adding load encroachment supervision provides security over the entire range of generating current angles without compromising detection of faults on the collection collector.

VIII. BIOGRAPHIES

Doug Jones received a BSEE from Colorado State University in 1997. He spent six years designing and commissioning substations for Electrical Systems Consultants before joining System Protection Services in 2005 to specialize in the protective relaying. System Protection Services was acquired by POWER Engineers, Inc. in 2007 where he continues to specialize in automated protection systems for a large variety of clients. Currently he is a Sr. Project Engineer in the SCADA and Analytical Services (SAS) business unit serving as the area lead in POWER's Denver, Colorado and Billings, Montana offices. Doug is a member of IEEE and a professional engineer in the states of Colorado, California, Illinois, Michigan, South Dakota, Utah, and Wyoming.

Kyle Bennett graduated with his BSEE from Washington State University in 2004. He worked at Micron Technologies from 2004 to 2007 as an R&D DRAM engineer before earning his MSEE from the University of Idaho in 2010 to enter the power field. He is currently an Engineer II with POWER Engineers, Inc. focusing on arc flash analysis and protective relaying in the SCADA and Analytical Services (SAS) business unit.