Future Distribution Feeder Protection Using Directional Overcurrent Elements

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***Abstract*—Distribution feeder protection could soon be complicated by nonradial flows of real and reactive power available from high penetration distributed generation and potentially from microgrids. Nondirectional overcurrent protection may not provide necessary security and sensitivity for faults on remote points of the circuit. Directional supervision is necessary to set overcurrent pickups with adequate sensitivity for remote faults. Setting the directional element by traditional means provides a reliability risk at varying VAR flows within reach of specific types of distributed generation. This paper will demonstrate the limitations of nondirectional overcurrent protection and the pitfalls of an improperly configured directional element. A unique solution using directional overcurrent elements further secured by a load encroachment function can solve these problems. This approach has been validated in renewable plant collector circuit protection applications over a wide range of operating conditions.**

***Index Terms*—Directional overcurrent, distributed generation, distribution protection, feeder protection, future distribution feeder, load encroachment, renewable feeder protection, smart grid, VAR control.**

I. Introduction

DISTRIBUTION feeders with a high penetration of distributed generation will require different protection approaches than traditional nondirectional overcurrent elements. When interconnected generating sources provide fault current to the protected feeder, the substation relays' sensitivity is reduced. This will require the substation relay to be set as sensitively as possible to detect remote faults on the circuit. With this high degree of sensitivity, directional overcurrent elements will be necessary to prevent incorrect substation feeder relay tripping for faults on parallel feeders served by the distribution substation. Bi-directional power flow at the substation feeder connection can mean large swings in voltage and power factor during normal operation posing challenges for directional phase overcurrent elements, necessitating yet another level of supervision for greatest security. Experience with similar challenges on wind plant collector circuits suggests a solution for these potential problems. Make distribution protection upgrades with a view to these future protection challenges.

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II. Present and Future Distribution Feeder Characteristics

A typical distribution feeder circuit consists of a main, three-phase trunk circuit having single-phase and/or three-phase lateral taps to serve loads away from the feeder route. For higher ampacity, conductors near the substation are frequently larger than lateral and remote conductors. Laterals and remote feeder sections are often protected by fuses or automatic reclosers. Nondirectional overcurrent elements at the substation and within the reclosers have been adequate for traditional feeder protection. Development of multi-function overcurrent relays having negative-sequence nondirectional overcurrent elements relieved some compromises caused by heavy line loading [1]. Loads are served radially, with normal and fault current flowing from the substation out to the load/fault.

Interest in and practicality of distributed generation has increased steadily. More recently, microgrid development has been discussed to locally aggregate loads, storage, and generation with utility service to meet a variety of objectives. The possibility of wheeling real and reactive power across the distribution substation bus cannot be far off.

Adding sources to distribution feeders creates substantial protection challenges that often cannot be adequately addressed by nondirectional overcurrent protection alone. Consideration of another medium-voltage protection application having similar characteristics to the future distribution feeder is instructive.

III. Wind Plant Collector Protection

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

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.

Nondirectional overcurrent relaying at the collector substation protects the circuit conductors, splices, junction boxes, transformer connections, and elbows, while providing backup protection for wind turbine generator step up transformers.

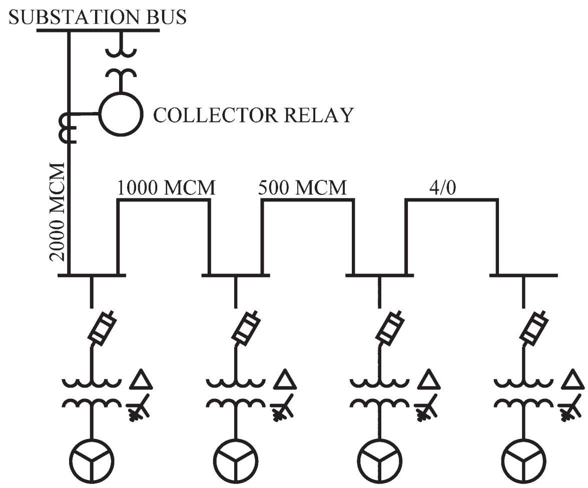

Fig. 1. Typical wind farm collection circuit.

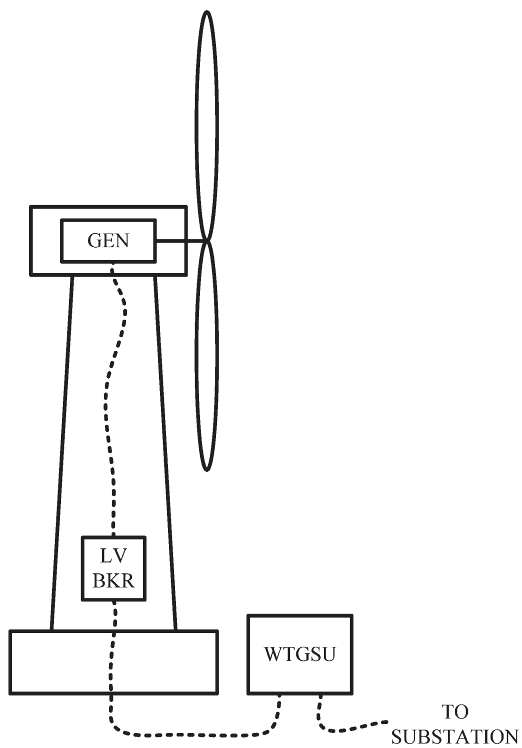

Fig. 2. Wind turbine with LV main breaker.

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 [2], [3].

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 [4], [5].

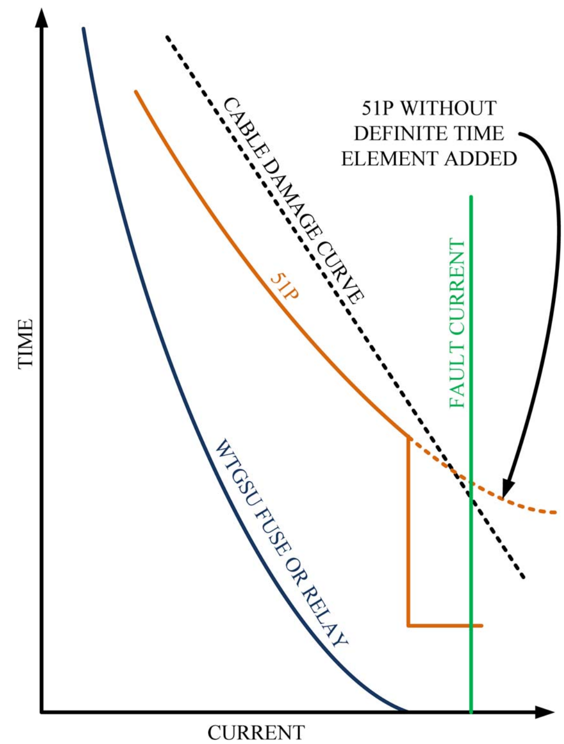

Fig. 3. Time overcurrent coordination with WTGSU fuse and 1/0 lateral cable.

Nondirectional inverse time overcurrent (51P & 51G) elements 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 greater than the full load of the entire collector circuit. The ground overcurrent pickup must be greater than 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 [6].

Fig. 3 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 where fault duties are high.

In the wind collector application, nondirectional 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 WTGSUs. 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. In the wind collector circuit, forward current is limited to either faults or very small turbine loads (lights, heaters, etc.) when the wind turbines are not producing power. This is a substantial and important difference from distribution feeders whose forward current is limited by the system capability (transformer/breaker/feeder load limits) and the magnitude of the loads served. In the wind collector application, we set the directional overcurrent pickup considering the desired sensitivity for faults at the most electrically remote wind turbine, accounting for the possibility of arcing faults, and using the same time-coordination approach as the nondirectional element.

IV. Renewable VAR Resource Control

A distribution feeder with a high penetration of distributed generation will need VAR controls implemented for several reasons: 1) maintain VAR "neutrality", i.e.,—maintain a power factor of unity to avoid being an additional VAR load on the circuit; 2) provide or consume VARs to help manage voltage along the circuit; 3) manage the circuit power factor at the substation; and/or 4) avoid overloading sections of the circuit with excessive VAR flow. The VAR control needs of a particular circuit will require load flow and voltage drop studies to determine how this will be accomplished.

When connected to strong systems, the VAR import/export at the renewable resource needed to control voltage can vary significantly more than that needed to maintain unity power factor. Either static or dynamic resources can be used to meet these needs. Often the same renewable generator resource being used to produce real power can also be a VAR resource. Substation and wind turbine VAR capabilities can be combined to meet these new requirements to avoid the need for additional static or dynamic VAR resources.

V. Renewable Var Capabilities

Several common source types are found in distributed generation resources:

- synchronous generators;
- induction generators;
- wind turbines;
- solar inverters.

Synchronous generators are presently the most common generating resource used in most fossil fuel and nuclear facilities. As distributed generation, they are frequently found in medium hydro, biomass, some geothermal, and smaller fossil fuel installations. They can supply and consume reactive power. As a traditional resource they are not discussed at length here.

Induction generators, while not uncommon, are often not preferred as they only consume VARs, and thus have no inherent VAR control ability. They are typically compensated for by a static capacitor bank.

Presently wind turbine technologies come in several types. The VAR capabilities for each type of wind turbine technology vary. Types I, II, III, and IV wind turbine generators use different VAR support systems to provide or consume different amounts of reactive power and offering varying degrees of control.

Type I wind turbine generators are standard squirrel cage induction generators, so they require external VARs to compensate their inductive characteristics. Typically Type I wind turbines contain staged capacitors to provide the VARs needed at a variety of output levels. These staged capacitors are usually controlled by the wind farm management system.

Type II wind turbine generators are similar to Type I but a wound rotor connected to an external variable resistance allows operation over a greater range of speeds. Type II turbines require capacitor banks similar to Type I.

Type III wind turbines are also known as doubly fed induction generators (DFIG). In a Type III machine, the wound 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 converter. This provides a wide range of speed and VAR control capabilities [7].

Solar PV inverter based installations are typically a dc–ac inverter system. Similar to Type IV wind turbines, they often provide a wide range of VAR control capabilities, even when not producing real power.

When the controllable VAR resources are operated in a voltage control mode, they 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.

VI. Lessons Learned From Directional Overcurrent Misoperations

For this example, a common distribution feeder relay is used for collector protection. The directional overcurrent 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 (Fig. 4).

The relay directional element 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.

For direct comparison to event report phasor diagrams, Fig. 5 shows the relay's directional element referenced to the positive-sequence voltage (V1) at 0°. When the positive-sequence current (I1) differs from $Z1 <$ by more than 90° the current is determined to be reverse.

Normal generation output at unity power factor on a wind farm collector plots on Fig. 6 at 180°.

As the VAR output of the collector increases and the PF decreases, the traditionally supervised directional overcurrent relay can eventually trip. Fig. 7 highlights the lower left quadrant where the directional element is most vulnerable.

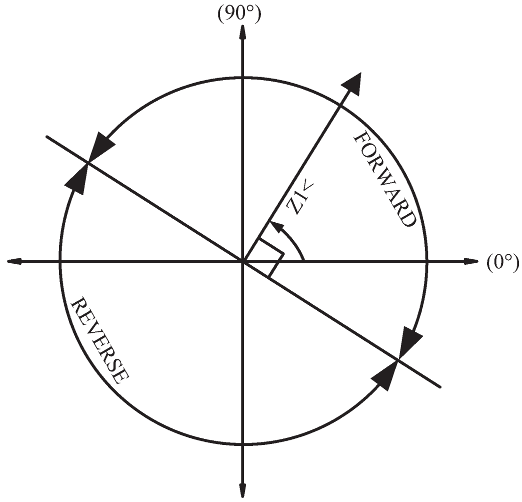

Fig. 4. Phase directional element impedance diagram.

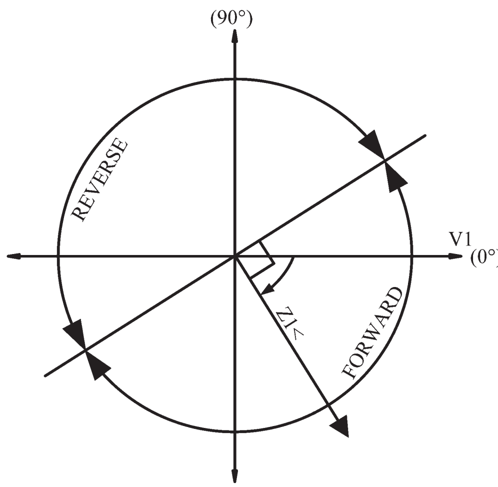

Fig. 5. Phase directional element I1 versus V1.

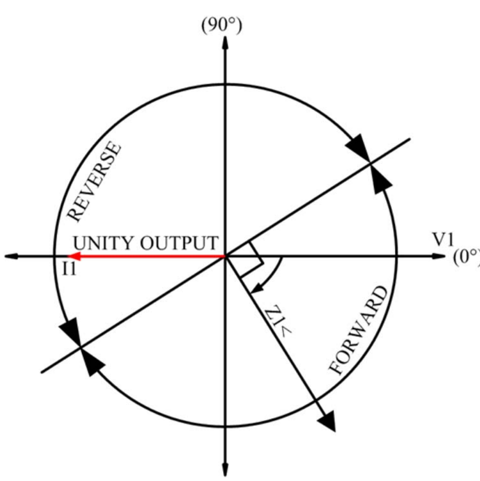

Fig. 6. Unity PF output on a collector.

Reducing the $Z1 <$ setting permits additional VAR flow from the collector. However, sources having broad VAR output capabilities are able, under certain conditions, to produce sufficient VARs that this directional supervision alone is not secure.

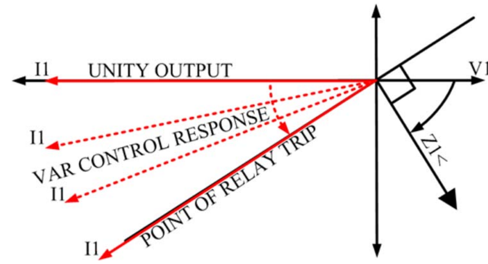

Fig. 7. Collector relay trip on low PF.

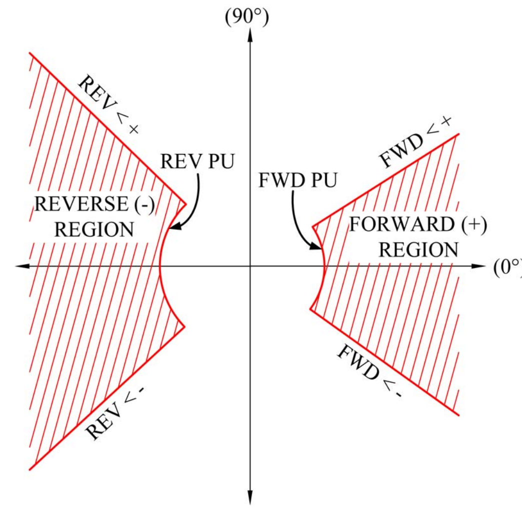

Fig. 8. Typical load encroachment impedance diagram.

This points out several things: The traditional directional overcurrent element is not well-suited for this situation. We need to secure the overcurrent element for all possible generating load angles. And finally, distribution feeders having a high penetration of distributed generation having broad VAR output capabilities (such as Type IV turbines or solar PV inverters) may be subject to similar protection challenges.

VII. Securing Collector Protection

As a result of the experience above, 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 user-defined load region, the overcurrent elements can be blocked. The element is designed to provide flexible regions in the forward and reverse direction independently (Fig. 8).

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 ($\text{REV} < + = 90^\circ$ AND $\text{REV} < - = 270^\circ$). 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 $90^\circ (\text{FWD} < + = 90^\circ)$ and negative angle for the forward region to $85^\circ (\text{FWD} < - = 85^\circ)$. The

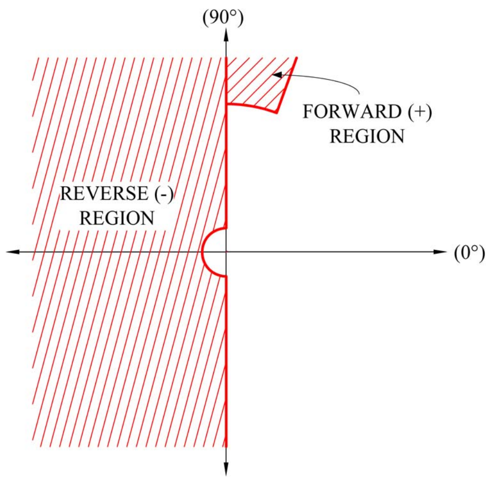

Fig. 9. Load encroachment diagram for secure collector directional control.

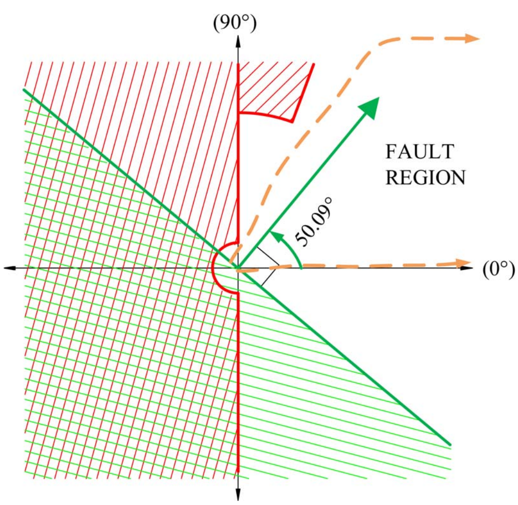

Fig. 10. Aggregate directional control for directional overcurrent element impedance diagram.

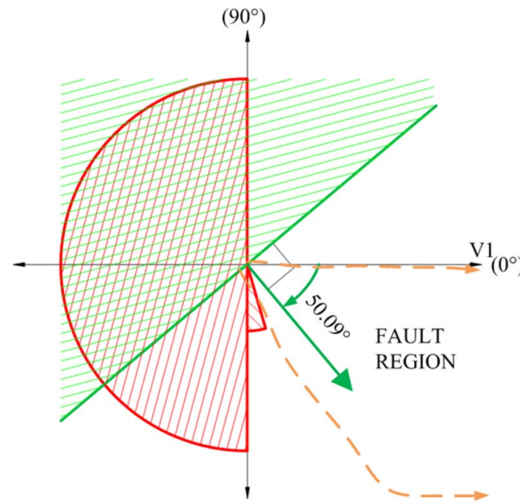

Fig. 11. Aggregate directional control for directional overcurrent element—V1 reference.

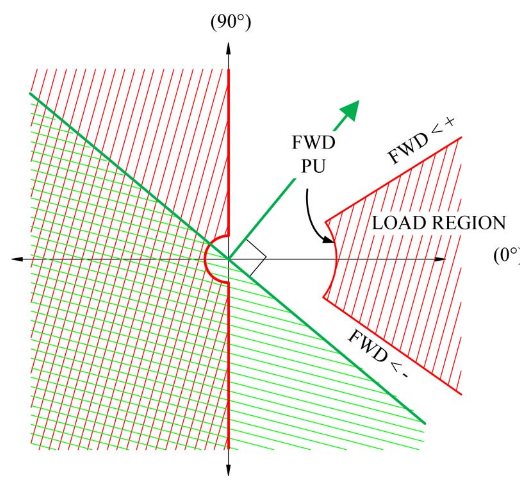

Fig. 12. Feeder aggregate directional control for directional overcurrent element impedance diagram.

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.

Combining Fig. 9 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. 10).

For comparison to event report phasor diagrams, Fig. 11 shows the directional overcurrent element supervision referenced to the positive-sequence voltage (V1).

VIII. Securing High-Penetration Feeder Protection

The method developed above may be applied to high-penetration distribution feeders with a minor adjustment. In the distribution feeder, when distributed generation is unavailable or not producing, the distribution substation and feeder are expected to carry the full distribution load. The apparent Z1 impedance seen by the feeder relay is illustrated by the Load Region in Fig 12. Setting the relay load encroachment Forward segment to reject this area retains overcurrent relay security under heavy load flow with some loss of sensitivity to heavily resistive faults. Since this supervision is only applied to balanced, three-phase faults which are typically not highly resistive, the practical impact on fault sensitivity is negligible while the improvement in security is valuable. Performance of ground overcurrent protection elements for all faults is unaffected.

Care should be taken when setting the FWD angle set points. The angles must take into account possible power factor as a result of heavy forward load at the substation feeder breaker, and maximum VAR exchange as a result of volt/VAR control action by the distributed resources. When studying maximum power flows, consider that the distributed resource may have greater VAR capabilities than published specifications, but cannot exceed the maximum MVA rating of the unit. Note the "FWD $<+$" setting is critical as it will have the greatest effect on fault detecting performance. The "FWD $<-$" can likely be set to 270° with no adverse effect on protection.

IX. 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 collector.

Future distribution feeders seeing high penetration of Type IV wind turbines and/or solar PV inverters with broad, two-quadrant operation may face similar challenges.

To prepare for the future, distribution utilities upgrading protective relays today should consider using devices that have the overcurrent supervisory capabilities to address these security concerns.

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