When Load Encroachment Fails to Prevent Tripping Service to an Undersea Cable, a Wind Farm and an Island Municipality

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Abstract

A radial service to both an island municipal load and an offshore wind farm nuisance tripped for non-fault and non-overload conditions. The scheme under investigation was a backup directional overcurrent relay that was torque controlled by a load encroachment function. The line that tripped was an overhead line, which was in series with an undersea cable. Just before the line trip occurred, wind farm turbines tripped successively on overvoltage, which became a contributing factor to the upstream line trip. Fault data analysis revealed that the loss of exported real power resulted in an operating power factor trajectory that moved outside the relay's load encroachment restraint region. Analysis confirmed the event was a non-fault condition. It also confirmed non-assertion of load encroachment restraint. Further analysis revealed that a backup non-directional overcurrent element torque controlled by a distance element could similarly be vulnerable to nuisance tripping. This nuisance trip event illustrates the need for fully understanding expected and maybe unexpected line operating conditions before assuming the appropriateness of any conventional line protection scheme for any particular line instance.

Introduction

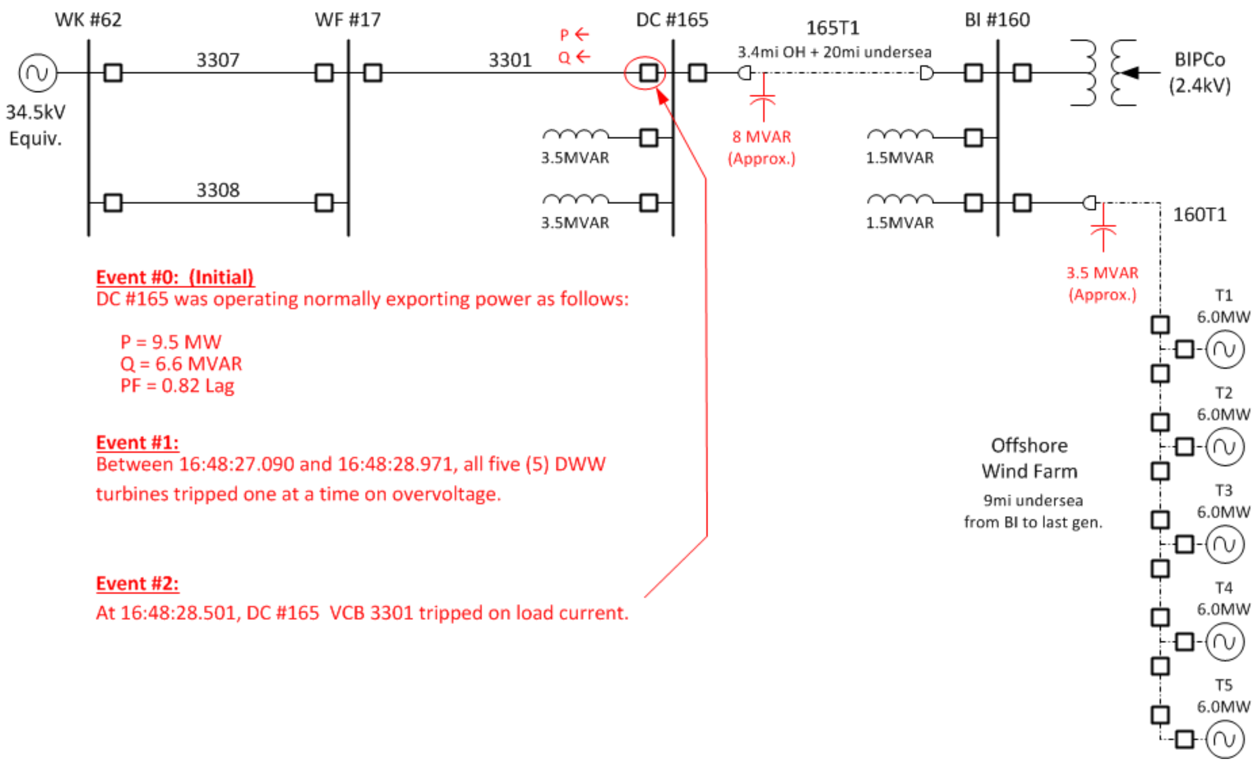
Protection engineers are familiar with two defining attributes of any protection scheme. Textbook language refers to them as *Dependability* and *Security*, with the former being the tendency for a protection to trip when tripping is needed and the latter being the tendency to restrain when tripping is not needed. Informally expressed, protections must: (a) detect faults and trip, and (b) carry load (not trip).

This brings into focus a common conflict with overcurrent and distance relay applications when the maximum load current magnitude is close to, equal to, or even greater than the available fault current magnitude. The resolution often is the application of some form of load encroachment restraint or blocking. For distance relays, load encroachment can take the form of collapsing a mho characteristic into a lens shape, a straight-line blinder or the application of a defined load region (butterfly characteristic) in the R-X plane. For overcurrent relays, load encroachment can also take the form of a defined load region in the R-X plane or the application of a distance (mho characteristic) relay torque control. Any of these methods essentially leverages the angle of current with respect to a voltage reference to differentiate between fault current and load current.

System Overview

The system under study is essentially a radial 34.5kV distribution system from the WK #62 station to the BI #160 station which then interconnects with an offshore wind farm (Refer to *Figure 1* for details). BI #160 is a 34.5kV distribution station on an island about 20 miles off the coast of Rhode Island providing load service to the island's municipal utility and interconnecting with the offshore Wind Farm located an additional 9 miles out at sea. Wind Farm interconnection is via the undersea cable designated as 160T1. The Wind Farm consists of five 6.0MW turbines for a total connected capacity of 30MW. Obviously, Actual generator output being driven by available wind is variable and not necessarily easily predicted.

Figure 1: Area 1-Line Diagram



The mainland station, DC #165, serves BI #160 via the undersea cable designated as 165T1. WF #17 serves DC#165 via the overhead line designated as 3301 and, finally, WK #62 serves WF #17 via parallel overhead lines designated as 3307 and 3308. At BI #160 there are two 1.5MVAR shunt inductors that provide 2-stage reactive compensation for 160T1 cable charging VARs; which amount to roughly 3.5MVAR. At DC #165 there are two 3.5MVAR shunt inductors that provide 2-stage reactive compensation for 165T1 cable charging VARs; which amount to roughly 8MVAR.

DC #165 3301 line protections consist of a multifunction line differential relay (Primary) and a multifunction directional overcurrent (backup) relay. The differential relay also provides a backup directional overcurrent function.

Incident Summary

On August 18, at about 16:48, the 34.5kV 3301 line between DC #165 and WF #62 tripped for a non-fault (i.e. load) condition at the DC #165 end only. This event resulted in loss of electrical service to BIPCo load as well as the interconnection with the Wind Farm. It was determined that the 3301 line's backup directional overcurrent relay tripped when the export power factor (exported VARs) moved outside of limits allowed by the relay's load encroachment function.

About 1 second before the DC #165 3301 line breaker opened, the Wind Farm's T2, T3, T4 and T5 turbine breakers opened. The T1 turbine and BI #160 160T1 line breakers opened just after the DC #165 3301 line breaker opened. All five (5) turbine breakers tripped on overvoltage. Turbine overvoltage protections that tripped the wind turbines also transfer tripped the BI #160 160T1 line breaker, isolating and deenergizing the 160T1 line.

Investigation and Analysis

A review of the backup overcurrent relay fault record (refer to *Figure 2*) shows that prefault currents were balanced with magnitudes on all three phases being just above the relay's directional overcurrent (ANSI Device 67) function pickup setting. There was no evidence of voltage depression or deviation before or after tripping. So far this does not appear to have been a fault. Since the relay's 67 function pickup setting (185A) is well below the 3301 line's 679A rating, this was also not an overload condition. With the Wind Farm being a weak source, the low pickup setting is necessary to provide sufficient fault sensitivity. Consequently, some form of torque control is necessary to provide restraint for non-fault (i.e. load) conditions. The backup overcurrent relay's load encroachment (LE) function is a common solution applied to overhead transmission and subtransmission lines so the function was applied and power factor blinders set to accommodate typical load power factor ranges (between 0.85 leading and lagging).

Figure 3 illustrates what a load encroachment application looks like for a typical overhead line. Diagram annotations represent in-service relays settings and fault record measurements related to the 3301 line. Consider the load angle in Quadrant 1 (PLAF = +32deg or approximately 0.85 lagging PF). Quadrant 1 represents the condition where the DC #165 bus is exporting real (P) and reactive (Q) power towards WF #17 along the 3301 line. While the power factor limits represented by this example are typical for overhead line applications, further analysis will show them to be problematic in this instance.

The oscillograph record (*Figure 2*) shows the prefault power factor on each phase to be below the 0.85 lagging power factor limit imposed by the backup overcurrent relay's load encroachment blinder. This explains why the relay tripped. Earlier DFR and relay event records recorded throughout the day showed the apparent impedance power hovered just above the relay's 0.85 lagging power factor limit for most of the day while the line current exceeded the relay's directional overcurrent element pickup setting. Tripping was just a matter of time.

Figure 2: DC #165 3301 Line Backup Overcurrent Relay Record (Actual Event Time is 16:48:28)

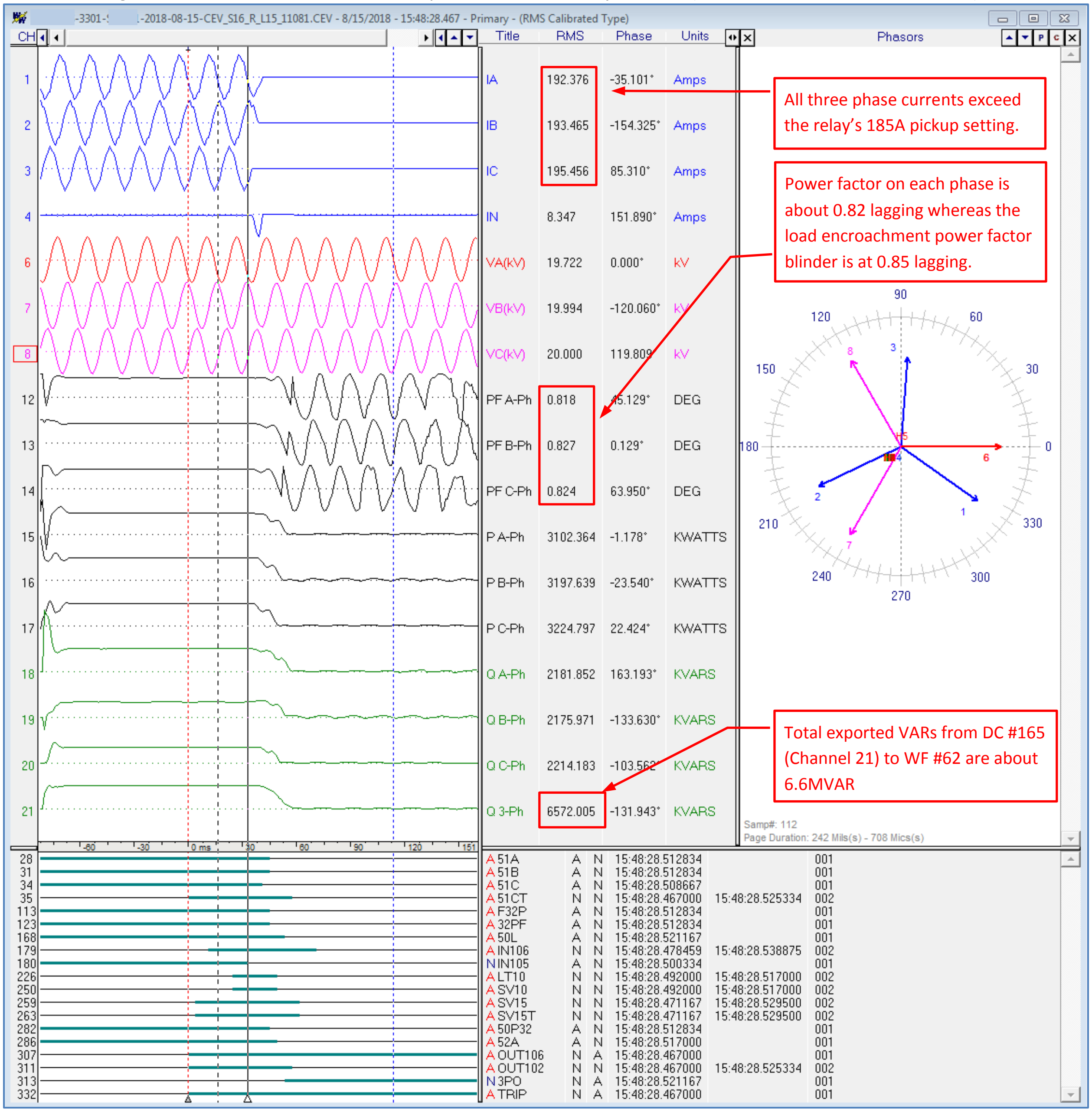


Diagram Comments

- *Excess VARs exported from DC #165 (Channel 21) to WF #17 suggest that the 165T1 [DC #165 to BI #160] and 160T1 [BI #160 to Wind Farm] cables were not sufficiently compensated by shunt reactors at both stations.*
- *The DC #165 bus voltage is right at about 1.0pu suggesting that BI #160 and the wind farm bus voltages would be higher than still. That the Wind Farm turbines tripped on overvoltage just before the 3301 line tripped, suggests the need for more aggressive shunt reactive compensation.*

The *Figure 3* base load encroachment diagram illustrates normal relay tripping for a 3-phase fault. It shows how the positive sequence apparent impedance angle follows a trajectory from within the load region towards the line's impedance angle (about 60 degrees for the 3301 line), illustrating how the load encroachment function normally discriminates between fault current and load current. The red annotations show how the observed operating apparent impedance was just inside the load region before the tripping event. It is easy to see how excess VAR exports became problematic as exported Watts were lost.

Figure 3: Overcurrent Relay with Load Encroachment Restraint Characteristic

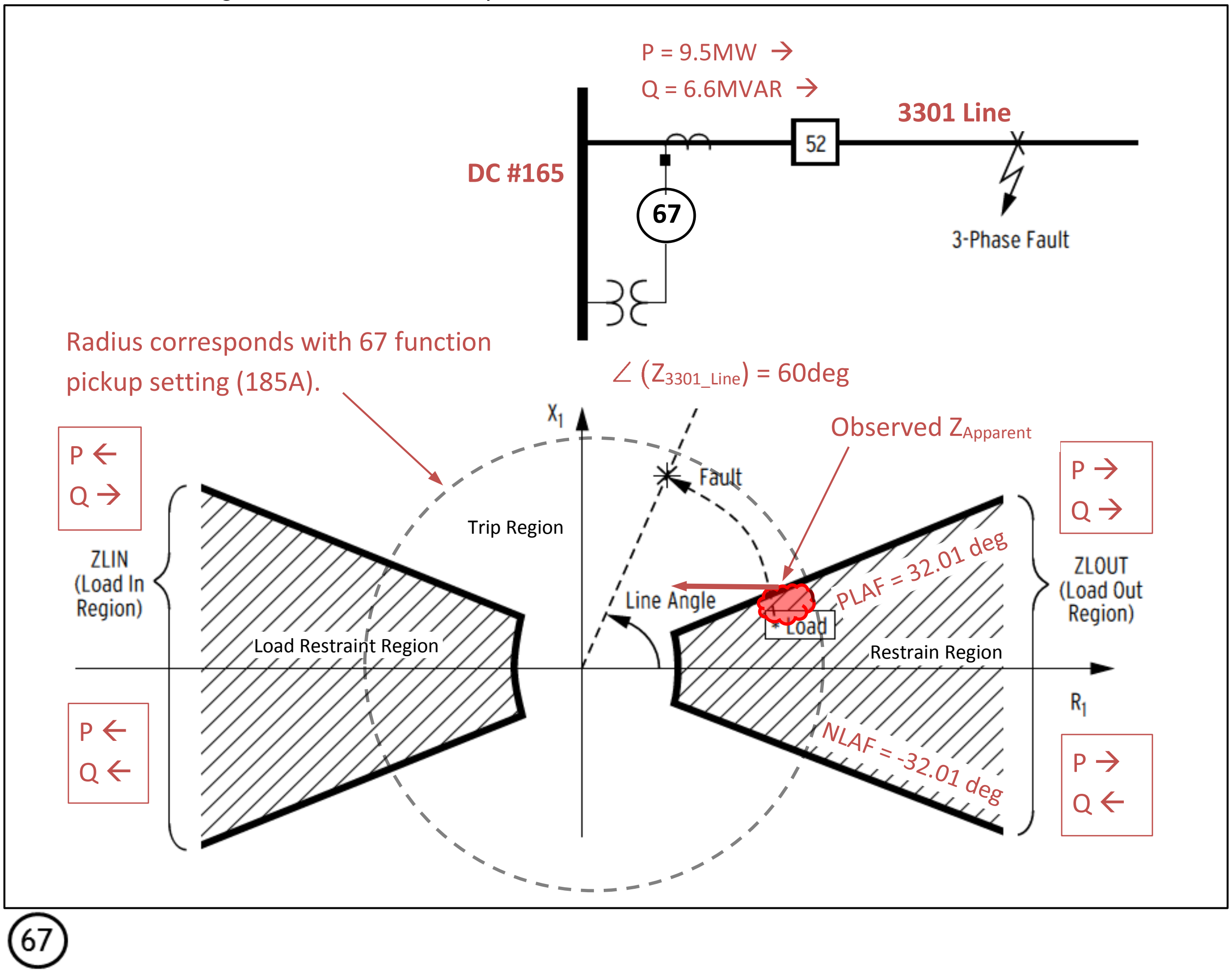


Diagram Comments

- *Assuming that the Wind Farm turbines were operating at unity power factor, successive unit trips reduced exported real power P while exported reactive power Q (sourced by the undersea 165T and 160T cable capacitance) remained constant. Consequently, as each unit tripped the export power factor became more lagging.*

So, if the power factor limits illustrated in *Figure 3* are common for overhead lines, why are they problematic for this line? The inherent capacitance (charging VARs) of the 165T and 160T undersea cables, downstream from the 3301 line, is what complicates matters. With overhead lines, charging VARs are practically negligible. Not only are undersea cable charging VARs not negligible, they represent fixed 8MVAR and 3.5MVAR shunt capacitor banks attached to the DC #165 and BI #160 buses respectively, regardless of whether wanted or not. Among other problems, the extra VARs can produce high voltages so the 165T1 and 160T1 cables both require reactive compensation in the form of shunt inductors. These are installed at both DC #165 and BI #160.

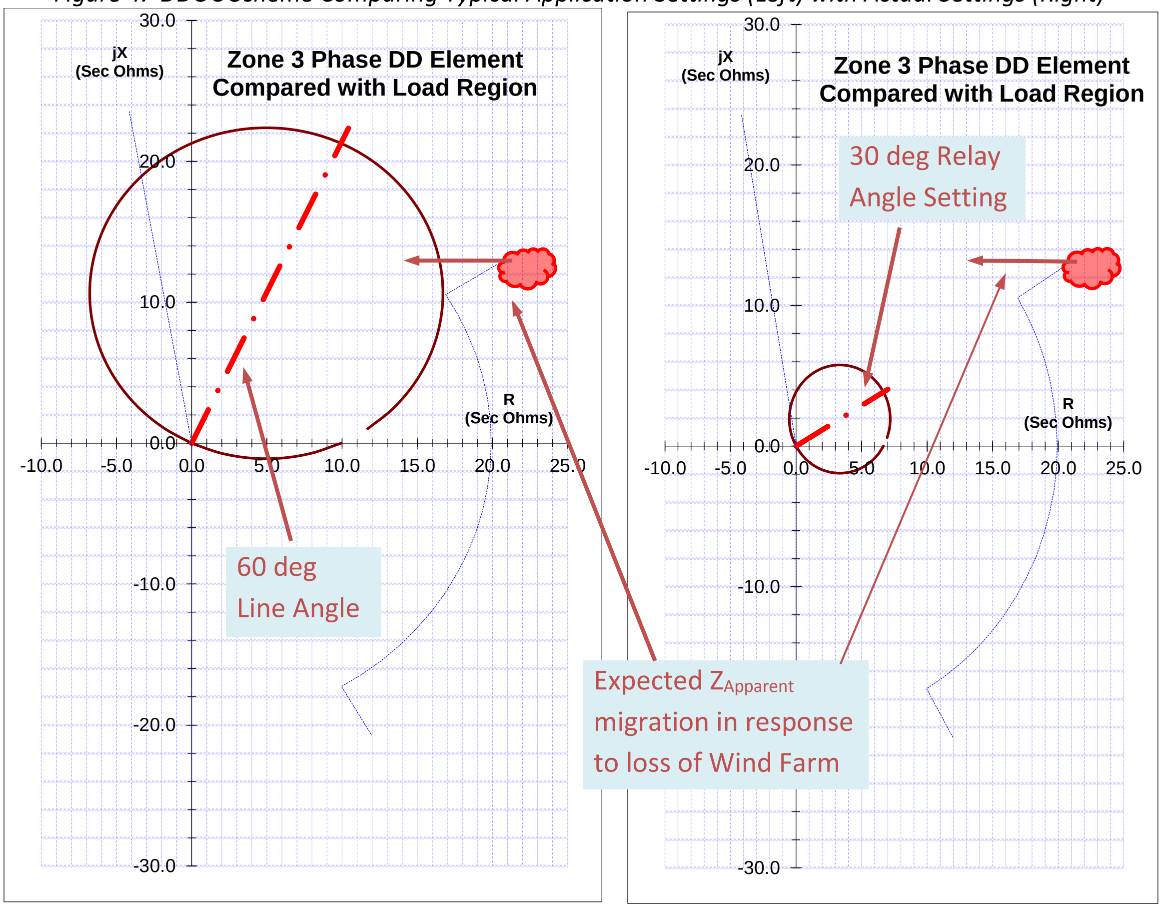
Because the Wind Farm's power output is variable and usually less than the nameplate rating, the export of reactive power (VARs) over the 3301 line from DC #165 is largely unaffected by Wind Farm generation. When the Wind Farm turbines tripped, exported real power (MWs) literally disappeared while exported reactive power (VARs) remained unchanged –pushing the export power factor outside of allowable bounds. In *Figure 3*, this is seen as the apparent impedance following a horizontal trajectory towards the jX axis. It was discovered that Wind Farm turbines frequently trip on overvoltage conditions in response to various system events. Before this August 18 event, the next most recent occurrence of Wind Farm high voltage tripping occurred on April 5, 2018 in response to a fault on a neighboring utility's 345kV line in the greater Boston area of Massachusetts. It would appear from this analysis that the relay's load encroachment function is simply not suitable for application on this particular line.

While the load encroachment function in this particular relay is not a suitable application choice, this relay does not provide any other form of load encroachment restraint. Fortunately, another option can be leveraged. Generator interconnection protections commonly include an undervoltage restrained or undervoltage controlled overcurrent (ANSI Device 51V) function. This function leverages the expected voltage collapse that accompanies a fault. That collapse is lower than allowable normal undervoltage conditions. Coupled with directional supervision, undervoltage torque-control appears to be a better solution for the portions of the radial supply between the utility electrical power system (EPS) and the Wind Farm. Therefore, it was explored and ultimately adopted as a replacement for the relay's load encroachment torque control on the BI #160 165T line breaker. DC #165 3301 line break, and WF #17 3307 and 3308 line breakers, all looking back towards WF #62.

This analysis raised concerns for the security of the 3301 line's multifunction line differential relay's backup overcurrent function. Since this particular multifunction differential relay does not provide a load encroachment function, a Zone 3 distance (mho) characteristic was applied as a torque control for a nondirectional overcurrent (51) function instead. This arrangement is sometimes referred to as a directional distance overcurrent (DDOC) scheme.

The R-X diagrams in *Figure 4* illustrates how this DDOC scheme works with respect to the migration of apparent impedance in response to loss of Wind Farm and/or BIPCo backup generation. The left diagram illustrates this migration for a typical DDOC application where the diameter of the Zone 3 characteristic is maximized to carry the highest permitted load current. It demonstrates that such migration could certainly be a source of concern. The right diagram illustrates this same impedance migration but, this time, with respect to the actual 3301 line relay settings. With the actual relay settings, the Zone 3 characteristic diameter is only large enough to accommodate required fault sensitivity. Now, the Zone 3 mho trip region is sufficiently removed from the load region so there is little risk of nuisance tripping.

Figure 4: DDOC Scheme Comparing Typical Application Settings (Left) with Actual Settings (Right)



Conclusions and Lessons Learned

- Wind Farm turbine overvoltage trips were a contributing factor to the 3301 line trip but not the root cause. The removal of each turbine reduced the real power (MWs) exported from DC #165 and, consequently, the export power factor. However, the turbine trips were also a symptom of an unwanted operating condition – namely insufficient use of shunt inductive compensation and its resulting high voltage on the undersea cables and at the Wind Farm. Therefore, insufficient use of shunt inductive compensation at either or both of DC #165 and BI #160 substations was the root cause of the unwanted 3301 line trip. Continuous operation too close to allowable power factor limits is what ultimately lead to the unwanted 3301 line trip as well as repeated tripping of Wind Farm turbines.

- Wind Farm overvoltage tripping was correct in response to measured high voltages. However, it was determined that the frequency of these occurrences could be reduced with better voltage and VAR control.

- System operators need to apply shunt inductor compensation to these undersea cables to more aggressively control VAR exports and resulting high voltages. The original operating strategy was to switch in inductors only response to high voltage alarms. The preferred strategy is to start with inductors switched in with their respective undersea cables. Then the Operators should switch them out in response to low voltage alarms. This operating strategy has no adverse impact on BIPCo loads since the 2.4kV bus voltage is load tap changer (LTC) controlled. This operating strategy is also be more respectful of undersea cable overvoltage ratings.

- The 3301 line tripping operation was correct but not desired. The application of a directional overcurrent scheme with a low pickup setting and load encroachment restraint is common for subtransmission lines with a weak source at one end. The 0.85 lagging power factor limit inherent for the applied load encroachment restraint function is typical for transmission and subtransmission lines. Therefore, the operation was determined correct because protections operated exactly as designed and the design was consistent with good utility practice. The operation was determined undesired because it occurred during non-fault and non-overload conditions.

- With respect to scheme modifications to the multifunction directional overcurrent relay, it was determined that undervoltage torque control was a better form of restraint than load encroachment for the 165T1, 3301, 3307 and 3308 line terminals looking back towards the EPS (WK #62). While it was determined that these modifications would yield more latitude with respect to VAR control, under exposes the undersea cables to a greater risk of overvoltage. Therefore, more persistent use of inductive compensation is now the preferred strategy.

- With respect to potential DDOC scheme modifications for the multifunction line differential relay, it was determined that none were necessary. However, the event raised a renewed awareness of security concerns related to any form of load encroachment control applied near undersea or long underground cables.

Author:

<u>Dean Sorensen</u> received a B.S. degree with distinction in Electrical Engineering in 1984 and an M.S. degree in Power Systems Management in 2002 both from Worcester Polytechnic Institute (WPI). He is a member of IEEE and is a registered professional engineer in the state of Massachusetts. Dean has over 30 years of experience in the power industry serving in various engineering capacities in transmission, distribution and generation primarily in the areas of protection and controls and power quality. Dean is a principal engineer in the Department of Protection Policy and Support at National Grid. Dean has also been on the faculty of WPI since 2011 as an adjunct instructor teaching graduate courses related to power system protection.