Directional Element Design for Protecting Circuits with Capacitive Fault and Load Currents

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***Abstract*— This paper, based on real world event data, introduces a state of the art directional element that has been proven to prevent many of the commonly reported mis-operations caused by traditional directional elements. Such examples include wind farm collector circuits where there have been a significant number of documented occurrences of false trips due to leading power factor loads caused by dynamic VAR controllers. To mitigate, several 'work around' solutions have been devised and published. These include creative yet cumbersome approaches that use load encroachment and reverse power functions, both of which have limitations since they were never intended for that purpose. There are also challenges using traditional directional elements for situations where the fault current is capacitive. Such examples include ground fault current in networks that can be operated as either isolated or compensated. All of these challenges can be overcome using an 'easy to set' flexible directional element design that allows for the phase angle operating characteristics to be extended or retracted through its minimum/maximum forward and reverse angle settings. For quick and efficient evaluation of study cases, specific directional element settings have been modeled in protection design software as they appear in the relay to ensure the relay will respond securely and reliably for all operating conditions (grounding methods), system variables and fault scenarios encountered. The paper provides test data and oscillography reports from event (COMTRADE) files to validate the directional element's performance.**

Key Terms*— Capacitive load , capacitive fault (ground), capacitive and conductive discharge, wind farm collector unit, dynamic VAR controller, isolated network, compensated network, Peterson coil, parallel resistance, characteristic angle, operate area

I. INTRODUCTION

Traditional directional elements have many applications, and for the most part they are well understood. There are however a few unique, but not uncommon, situations involving capacitive load and fault currents where this is not the case. For these situations, a new, more flexible directional element design is introduced that allows the phase angle operating area to be extended or retracted through *its Minimum/Maximum forward* and *reverse angle* settings to prevent mis-operations [1]. This paper looks at two real world examples where retracting/extending the operating area has proven effective in mitigating false trips. The first example addresses recorded events from directional relays that mis-operated due to capacitive load generated from wind turbine generators using dynamic VAR controllers. The second, deals with potential mis-operations due to connecting a normally isolated network, where the ground fault current is capacitive (both directions), to a compensated network where ground fault current is resistive-inductive in the forward direction and capacitive in the reverse direction. The directional element settings have been modeled in protection design software to validate the relay's performance for all operating conditions and fault scenarios.

II. DIRECTIONAL ELEMENT DESIGN FEATURES

Designing a flexible directional element requires a thorough knowledge of the power system. Many things must be taken into account such as the selection of polarization quantity (i.e., V_1 or V_A for phase directional and $-V_0$ or $-V_2$ for ground faults), method of neutral point grounding and fault impedance to name a few. However, for the scope of this paper only the key design features necessary to understand the main concepts for the project examples will be discussed. For a full explanation on how the directional over-current function operates refer to the relay technical manual [1] and other references cited in this paper.

A. Modes of Operation

The relay makes its directional decision by determining if the angle between the operating current and polarizing voltage has entered the elements operating sector. Table 1 shows three commonly used operation mode settings in the relay.

TABLE 1
OPERATION MODES

Operate Mode	Description
'Phase angle'	Operating sector defined by *Min/Max forward* and *reverse angle* settings relative to *Relay Characteristic Angle* (RCA)
'I_0Sin'	Operating sector defined as forward when 'I_0Sin' value is positive and reverse when negative. Uses reactive component of operate current in isolated networks
'I_0Cos'	Operating sector defined as forward when 'I_0Cos' value is positive and reverse when negative. Uses active component of operate current in compensated networks

B. Relay Characteristic Angle

The *Relay Characteristic Angle* (RCA) setting is used in 'Phase angle' *Operation mode*. A 360 degree setting range is used to adjust the directional element operation according to the method of neutral point grounding. It is the impedance angle commonly referred to as the maximum torque angle (MTA). By convention it is the complex conjugate of the operate current phasor (at maximum torque) with respect to the polarizing voltage (reference). In solidly grounded networks, the RCA (φ) is set typically between + 60° to +75° (lagging or inductive) depending on the voltage level. For isolated networks φ is set to -90° (leading or capacitive) and for compensated networks it is set to 0° (unity or resistive).

C. Extended or Retracted Operating Area

When the *Operation mode* setting is selected to 'Phase angle' the operating area can be extended or retracted using its *Minimum/Maximum forward* and *reverse angle* settings to provide greater or less directional coverage for the capacitive fault and load currents described in the this paper.

III. PHASE ANGLE CHARACTERISTICS

The phase angle criterion method is used to determine direction when the O*peration mode* is set to ‘Phase angle’. This mode allows full flexibility for defining the forward and reverse directional operating sectors. The sector limits for the forward operating area are controlled using the *Min forward angle* and *Max forward angle* settings. The *Min forward angle* setting adjusts the sector clockwise relative to the RCA, and the *Max forward angle*, counter-clockwise. Likewise, the reverse operating area is controlled using the *Min reverse angle* and *Max reverse angle* settings. The *Min reverse angle* setting adjusts the sector clockwise relative to the RCA, and the *Max reverse angle*, counter-clockwise.

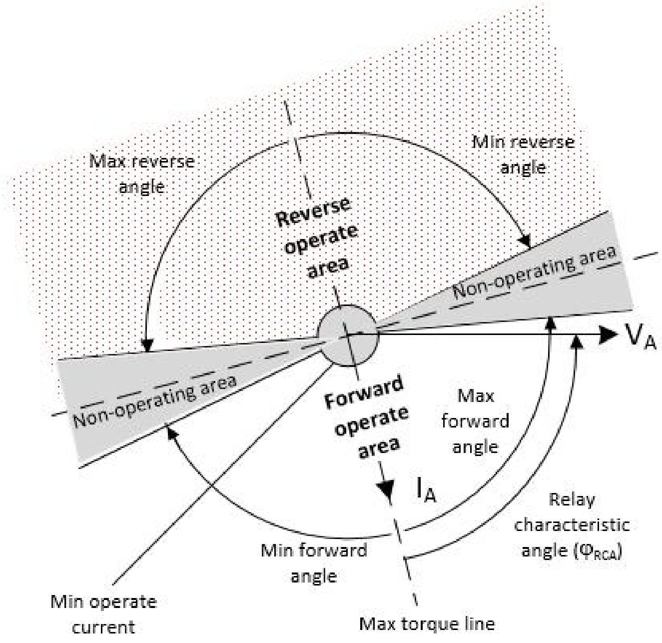


Fig 1. Phase angle characteristics for solidly grounded system (67P).

Figure 1 shows phase angle characteristics for a traditional phase over-current directional element (67P). The operating sectors and RCA are typical for a solidly grounded network.

IV. ISOLATED NETWORKS

Historically isolated neutral (ungrounded) networks have been used in mission critical environments where continuity of power is very important. Although fault levels are generally low, there is a risk of insulation damage due to evolving and re-striking ground faults. This has led to a trend using high resistance grounding which accomplishes the same purpose only with less chance of escalating voltages during arcing faults [2].

In isolated neutral networks, there is no intentional connection between the power system neutral and ground. The only path for zero sequence (ground) current to flow is through the line-to-ground capacitance (C_0) and leakage resistance (R_0) for each phase. For this reason, the ground fault current is mainly capacitive. Figure 4 illustrates “The healthy feeds the faulty” principle that results in the -90° angular phase shift with respect to the – V_0 polarizing voltage [3]. Therefore the RCA should be set to -90°. Figure 2 shows phase angle characteristics for a typical 67N function used in an isolated neutral network.

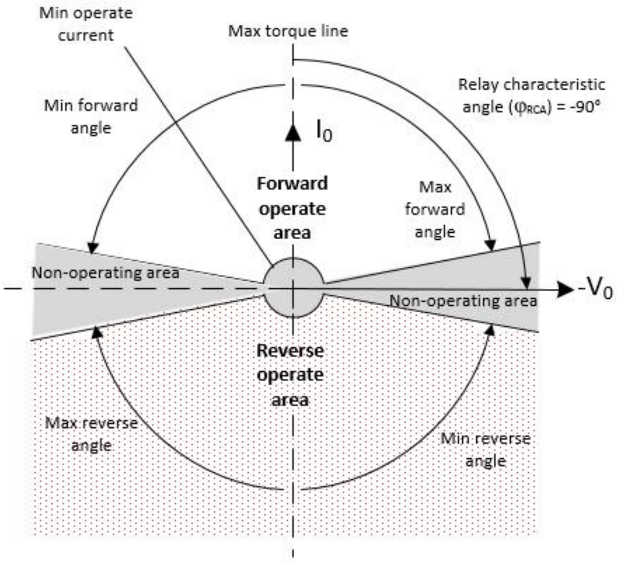


Fig 2. Phase angle characteristics for an isolated neutral network (67N).

Directional decision making in isolated neutral networks can also be made by setting the *Operation mode* to ‘I_0Sin’. This method uses the reactive component of the operate current. The operate criteria for ‘I_0Sin’ is the same as the ‘Phase angle’ *Operation mode* since both rely on a -90° RCA. Figure 3 shows ‘I_0Sin’ criteria for a typical 67N function used in an isolated neutral network.

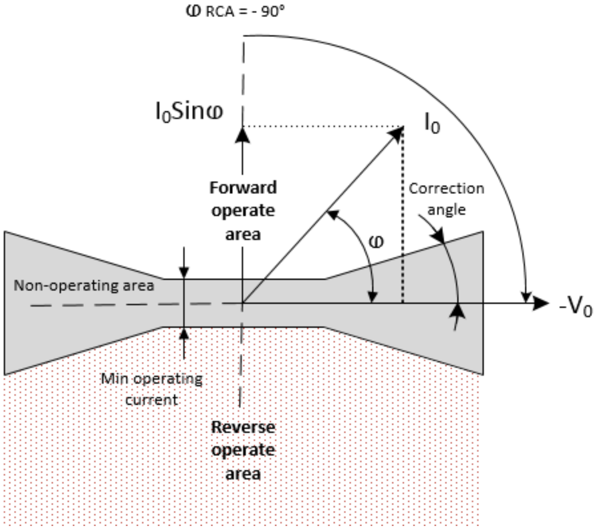


Fig 3. ‘I_0Sin’ characteristics for an isolated neutral network (67N).

V. COMPENSATED NETWORKS

Also known as ‘resonance’ grounding (somewhat of a misnomer), compensated networks use an adjustable arc suppression (ASC) or ‘Peterson coil’ in ungrounded systems to quench arcing faults on overhead lines [4]. This is accomplished by selecting a reactor inductance such that the magnitude of current flowing through the reactor is nearly equal to (in order to avoid resonance), or ‘compensates’ for, the capacitive single line to ground fault current. The compensating effect of the coil and the resulting resistive current seen by the relay are illustrated in Figure 7. The resistive current remaining (≈ 5% of capacitive current) due to network losses facilitates extinguishing of arc [4].

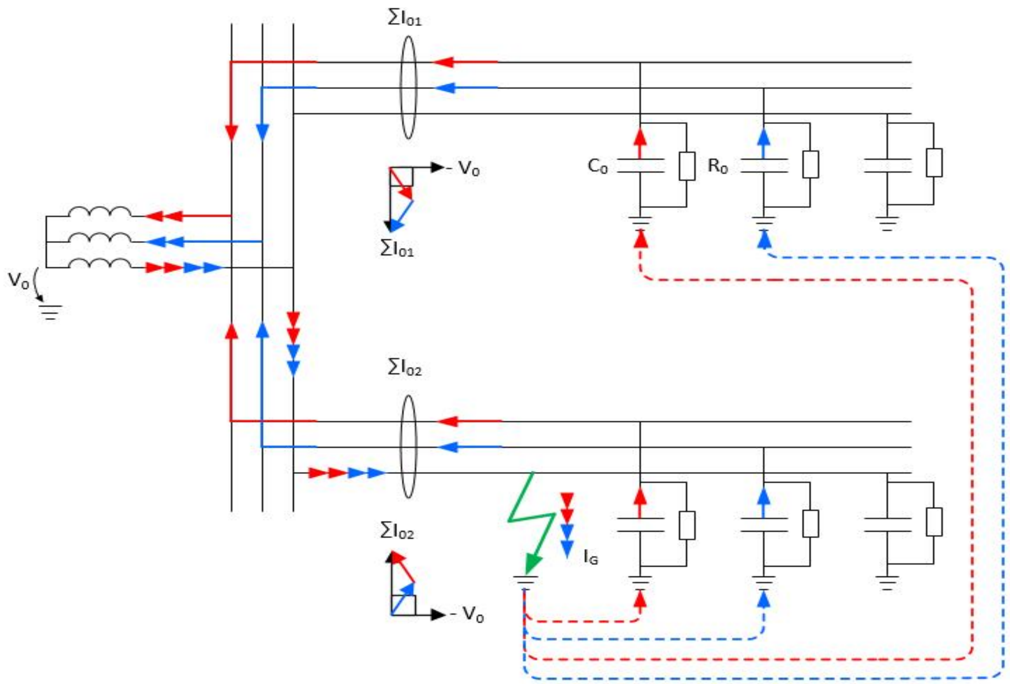


Fig 4. Ground fault in an isolated neutral network.

A system in which the inductive fault current is greater than capacitive fault current is referred to as over-compensated, and when less than, under-compensated. In practice the network is typically operated 5% overcompensated for most European systems (where this type of grounding is most prevalent). This is based on the assumption that it is more likely for sections of the network to become disconnected, which if operated under-compensated, could result in a resonant condition. This condition is undesirable since it can lead to over-voltages causing insulation breakdown. Harmonics can also be amplified which can lead to voltage distortion and thermal over-loading of equipment [5].

Because capacitive and inductive fault currents nearly cancel each other out, it is mainly the remaining resistive operate current that is used to make the directional decision. Therefore the RCA should be set to 0°. Figure 5 shows phase angle characteristics for a typical 67N function used in a compensated network. Since the resistive current is often small, a parallel resistor in the compensation circuit is often needed to boost its magnitude to detectable levels. The added resistance also improves directional security by countering the angle of the reactive component which can vary depending on the degree of coil compensation.

Directional decision making in compensated networks can also be made by setting the *Operation mode* to 'I_0Cos'. This method uses the active component of the operate current. The operate criteria for 'I_0Cos' is the same as the 'Phase angle' since both rely on a 0° RCA. Figure 6 shows 'I_0Cos' criteria for a typical 67N function used in a compensated neutral network. This method is similar in principle to the wattmetric relay [6].

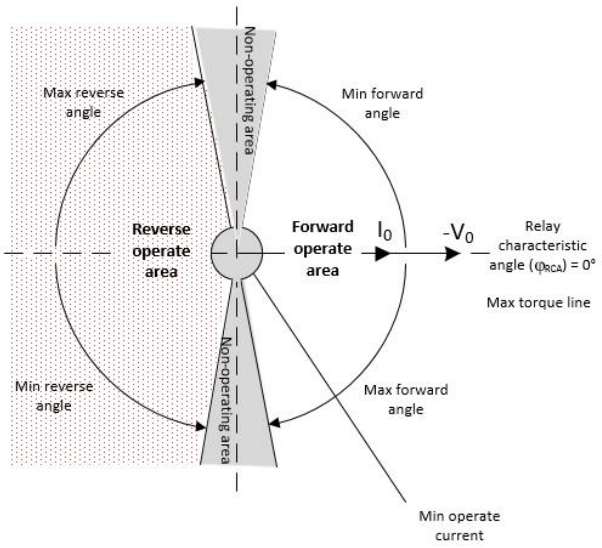


Fig 5. Phase angle characteristics for a compensated network (67N).

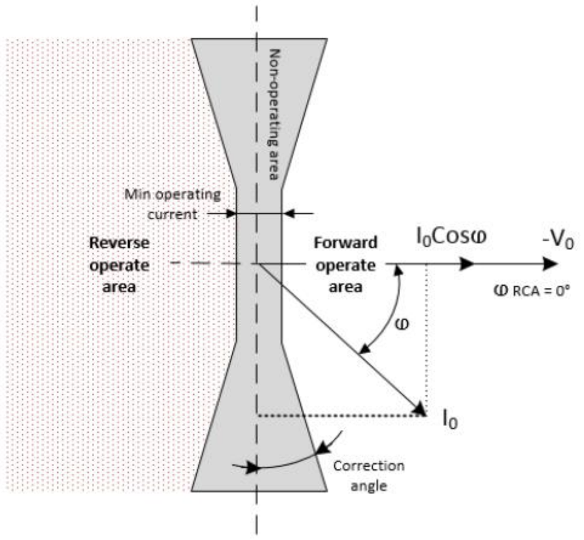


Fig 6. 'I_0Cos' characteristics for a compensated network (67N)

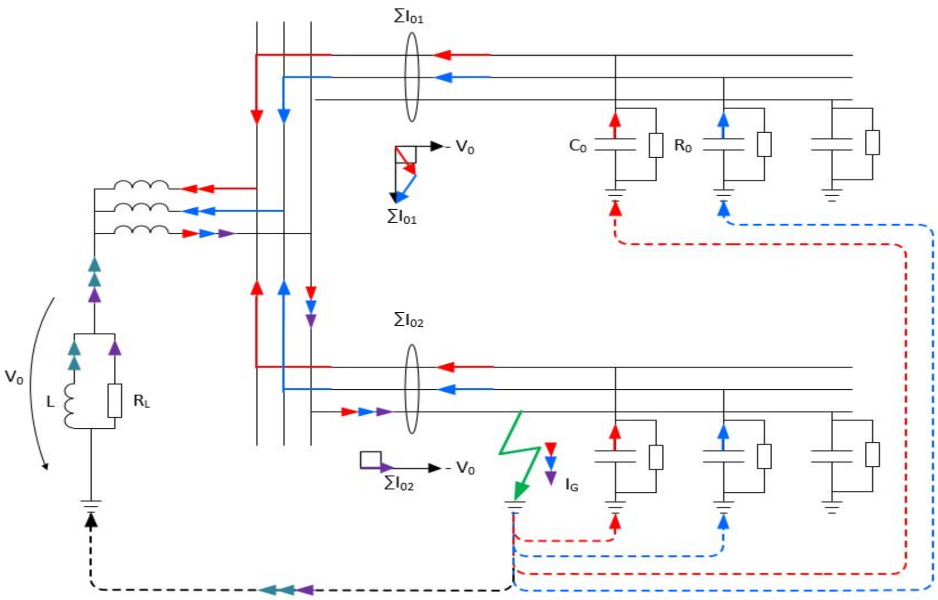


Fig 7. Ground fault in a compensated network

VI. EXAMPLE – COLORADO HIGHLANDS WIND FARM

False tripping of directional elements in relays protecting wind farm collector circuits is a phenomenon that until recently, has not been well understood. Several papers have been published recommending methods to make directional decisions at wind farms more secure. Such methods include lowering the MTA (to skew the operating area) and incorporating various load encroachment solutions [7], [8], [9]. All of these methods are aimed at blocking a portion of the relay's tripping area, which by convention is defined as forward looking into the Wind Turbine Generator (WTG) referenced from the collector bus (Figure 9).

This is the region where the WTG is absorbing VARS (reactive power flowing out of collector bus or into WTG) while delivering Watts (real power flowing into collector bus or out of WTG) to the utility. For this condition the load is capacitive since the WTG is absorbing VARS. From the utility the WTG looks like an inductive load that is used to bring down the terminal voltage. Because the over-current pickup is set sensitively (about 120% of maximum auxiliary load), the relay will trip unintendedly for leading (capacitive) power factor loads. Figure 8 shows that traditional directional element settings will cause a relay trip if there is enough capacitive load (on the system side).

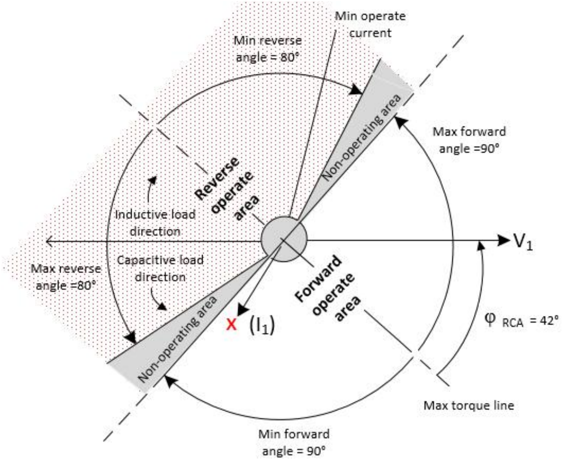


Fig 8. Mis-operation of traditional directional element

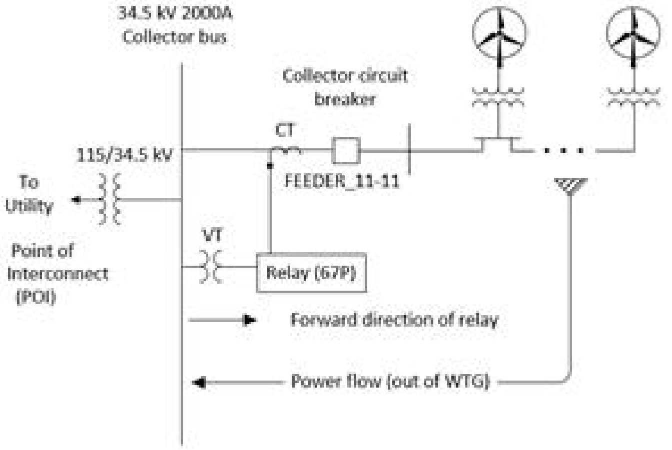
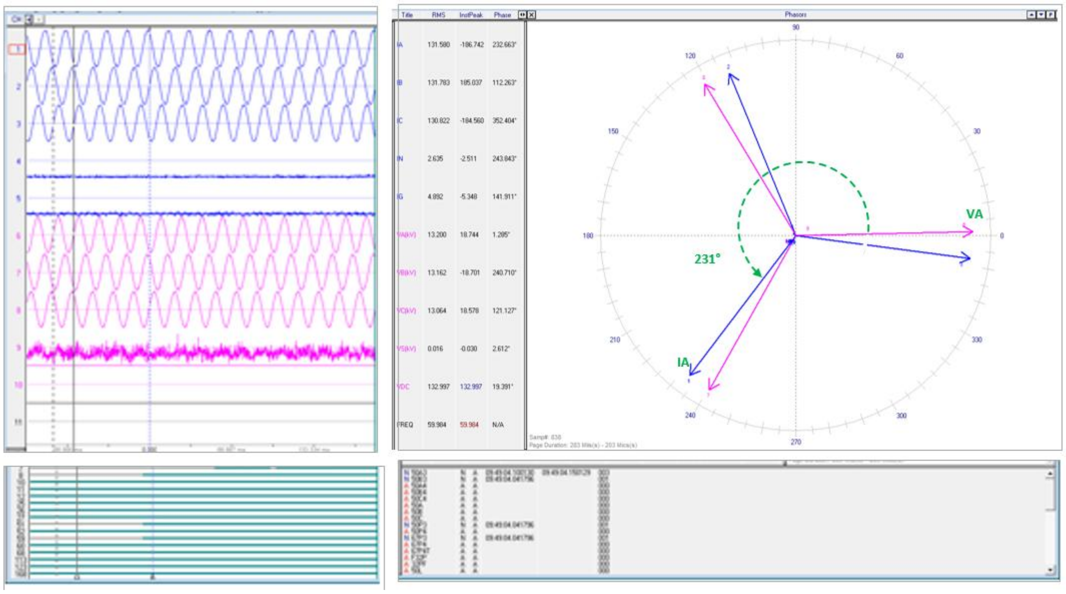


Fig 9. Simplified one line diagram of wind farm collector circuit

The same phenomenon occurred several times at Colorado Highlands Wind Farm. Figure 9 shows a simplified one line diagram of the wind farm collector circuit. To investigate the problem, an electrical power systems testing company downloaded the relay event files that were triggered by these mis-operations. From those, the greatest WTG capacitive load angle was 231° leading (with respect to V_1 reference of relay). The wave form capture for this event is shown in Figure 10. To mitigate the false trips, a load encroachment solution was suggested.

Load encroachment is an impedance based application for blocking distance elements. To implement this solution numerous settings and logic would have to be manipulated in order to adapt it to wind farm directional applications. There are also setting limitations that require pickup current, which needs to be set sensitively, to be greater than 10% of CT secondary (positive sequence only) [10]. This could also be problematic.

Skewing the MTA moderately to rotate the forward operating area away from capacitive region has also been considered as an option, but was ruled out in favor of load encroachment due to high capacitive angles shown in event reports [7]. Even if lowered to the minimum setting in the relay (5° lagging) it may not be enough to block for highly capacitive loads especially if some measurement error is introduced. It also prevents blocking in the first quadrant (upper right) of phasor plot, and therefore does not cover the entire range of possible load generating angles. Determining the likelihood of this condition occurring however, requires further study than what the event reports are showing. This will be addressed later in the paper.

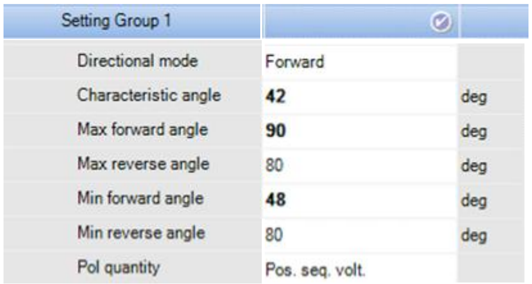


Title	RMS	InstPeak	Phase
IA	131.580	-186.742	232.663°
IB	131.783	185.037	112.263°
IC	130.822	-184.560	352.404°
IN	2.635	-2.511	243.843°
IG	4.892	-5.348	141.911°
VA(kV)	13.200	18.744	1.285°
VB(kV)	13.162	-18.701	240.710°
VC(kV)	13.064	18.578	121.127°
VS(kV)	0.016	-0.030	2.612°
VDC	132.997	132.997	19.391°
FREQ	59.984	59.984	N/A

Fig10. Phasors from wave form capture program for capacitive load generating event at Colorado Highlands Wind Farm.

Therefore due to the number of mis-operations, the complexity of the suggested solution, and the setting limitations of the solution, the testing company sought out to find a relay manufacturer that could offer a more convenient and practical method, one already built into the directional element.

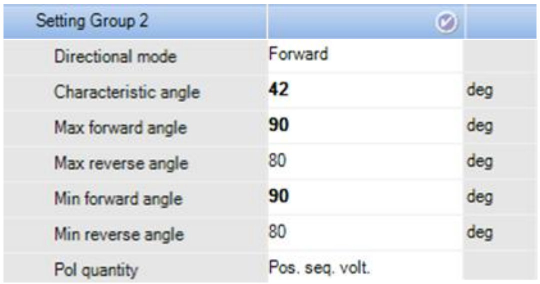
The recommended solution was to use the relay which had the *Min/Max forward* and *reverse angle* settings described in section III. Setting group 1 in the relay (Figure 11) was then used to retract the forward operating area by setting the *Minimum forward angle* setting to 48°. Phase angle characteristics are shown in Figure 13. This allows all capacitive load points to be blocked for active power flowing out of WTG. This was adequate for all the capacitive generation angles recorded in the Colorado Highlands events reports and other event reports cited in this paper using the load encroachment solution. To confirm the relay was secure, the Comtrade file for the event was played back to the relay, and as expected the relay did not trip.



Setting Group 1		
Directional mode	Forward	
Characteristic angle	**42**	deg
Max forward angle	**90**	deg
Max reverse angle	80	deg
Min forward angle	**48**	deg
Min reverse angle	80	deg
Pol quantity	Pos. seq. volt.	

Fig 11. Relay settings for retracted forward operating area.

Setting Group 2 in the relay (Figure 12) was used as a baseline to mimic the traditional directional element settings in the relay that caused the mis-operation. To confirm the mis-operation, the Comtrade file for the event was played back to the relay, and as expected the relay tripped. The event report from the relay verified that the phasors matched the event report from the relay that mis-operated. The reverse angle settings for both tests were left at default since they did not impact the test.



Setting Group 2		
Directional mode	Forward	
Characteristic angle	**42**	deg
Max forward angle	**90**	deg
Max reverse angle	80	deg
Min forward angle	**90**	deg
Min reverse angle	80	deg
Pol quantity	Pos. seq. volt.	

Fig 12. Relay settings to mimic tradition directional element.

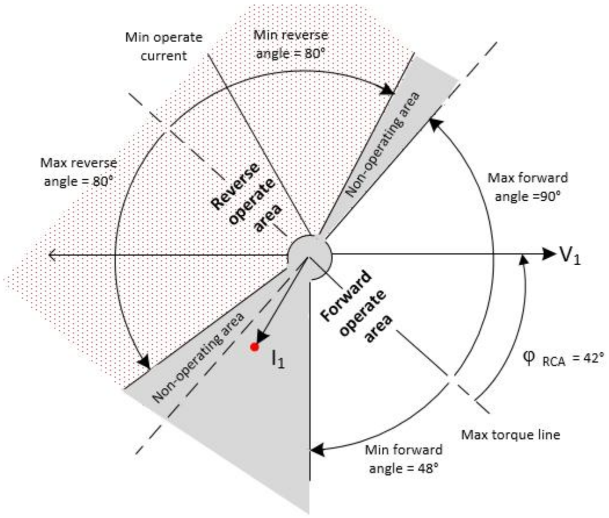


Fig 13. Correct operation using retracted operating area.

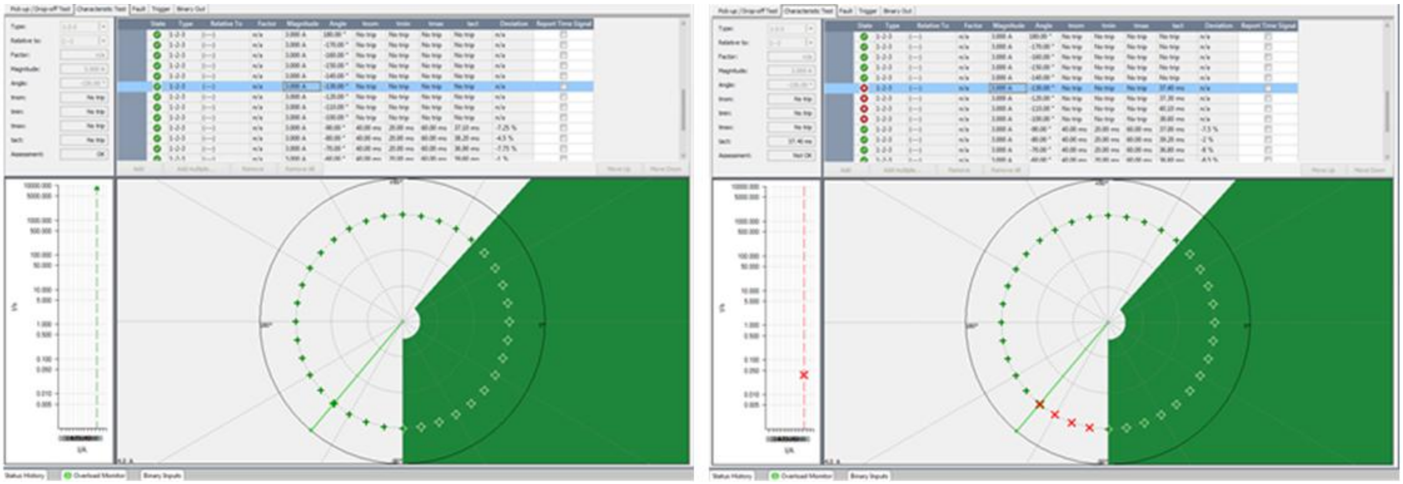


Fig 14. Test results for retracted operating area (left) and traditional directional element settings (right) showing potential area of mis-operation.

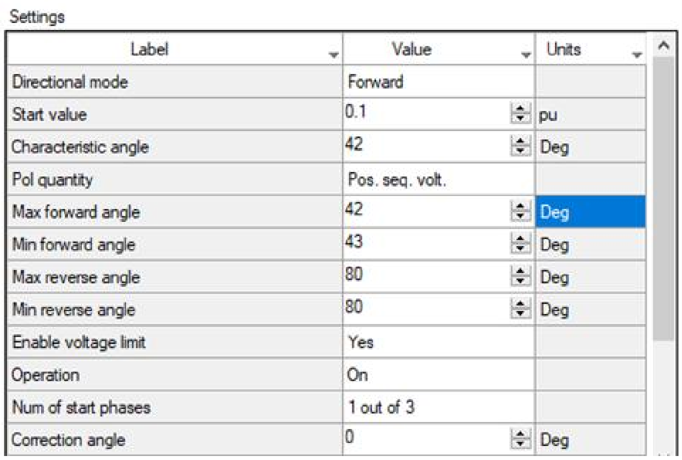
The relay was also tested using a directional element module to verify correct operation over the entire range of operating angles. Figure 14 shows the retracted forward operating area (+48 to -90° on plot) for the test which is shaded in green. Test results for the recommended relay settings to retract the operating area (Setting Group 1) are shown on left side of Figure 14. The test was successful since points inside the forward area resulted in a relay trip while points outside of it did not. The test results for the relay settings mimicking a traditional directional element (Setting Group 2) are shown on the right side of Figure 14. The test points recorded in red denote the potential area of mis-operation caused by the relay unintendedly tripping in the forward zone under capacitive load.

Event reports alone however will not address all potential mis-operations. There are some other important factors to consider. A majority of WTGs today have either partial or full converter based power electronics (Type 3 & 4) that are able to provide reactive power and voltage support capabilities. Although beyond the scope of this paper, it is essential to understand that these types of WTGs have behaviors that can be unpredictable for fault conditions [11]. Consequently numerous directional mis-operations have resulted. For this reason, line differential protection has been suggested as an option to make protection more secure [11]. Unlike conventional generation, WTGs cannot be modeled with a voltage source behind an impedance. Instead a transient time domain model based on the control system characteristics is required. The algorithm of the control system significantly limits the fault current to protect switching devices in the converter electronics. It is also important to note these characteristics vary widely with manufacturer and version of the control system [11].

To determine the full range of possible generating angles, a wind farm collector circuit was modeled in protection design load flow and short circuit analysis software (Figure 16). Six collector circuits totaling 22.5 MW each were used for the study. The wind turbines were Type 3 Doubly-fed induction generators. Several factors were taken into consideration:

- WTG ratings
- Capability curves
- Rated maximum auxiliary power
- Utility voltage (at POI)

The *Min* and *Max forward angle* settings were chosen to block all generating points with exception of the expected fault region (0 to 85°) for a relay characteristic angle of 42°. The settings for the directional element were entered using an interface that was developed specifically to emulate the relay setting and logic structure in the relay (Figure 15).



Settings

Label	Value	Units
Directional mode	Forward	
Start value	0.1	pu
Characteristic angle	42	Deg
Pol quantity	Pos. seq. volt.	
Max forward angle	42	Deg
Min forward angle	43	Deg
Max reverse angle	80	Deg
Min reverse angle	80	Deg
Enable voltage limit	Yes	
Operation	On	
Num of start phases	1 out of 3	
Correction angle	0	Deg

Fig 15. Relay settings (67P) page in protection design software to mimic traditional directional element.

The main object of the study was to find out what conditions caused load generating points to enter the forward operating area, particularly in the expected fault region (0° to 85°) where directional element angle settings and load encroachment logic could not be used to block trip since the load appears as a fault. The study showed that when active power is zero (lack of wind) or significantly lower than auxiliary load, then mis-operations will occur. Auxiliary power was assumed to be 10% of MVA wind turbine generator rating at 0.85 lagging power factor.

The effects of active power for 0, 20 and 80 percent of WTG rating are shown on the impedance plot Figure 17. When terminal voltage is uniformly increased from 0.95 pu to 1.05 pu, it can be seen what sections of positive sequence impedance trajectories (Z seen) are entering the forward operating area and causing a trip (within the blue pick-up impedance circle). The forward operating area is shown for a 60° MTA (instead of 45°) for the purpose of clarity on the plot.

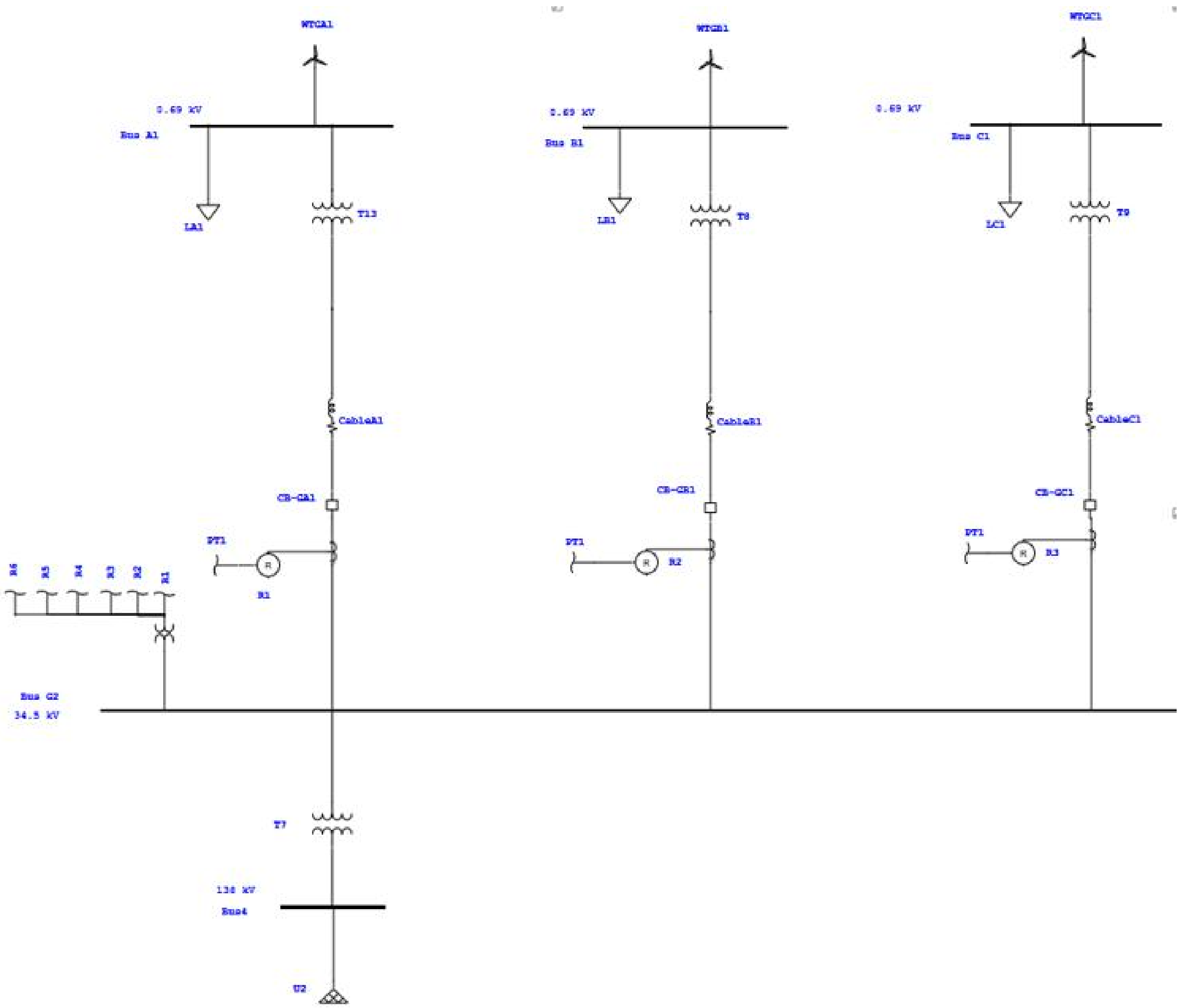


Fig 16. One line diagram of wind farm collector unit modeled in protection design software.

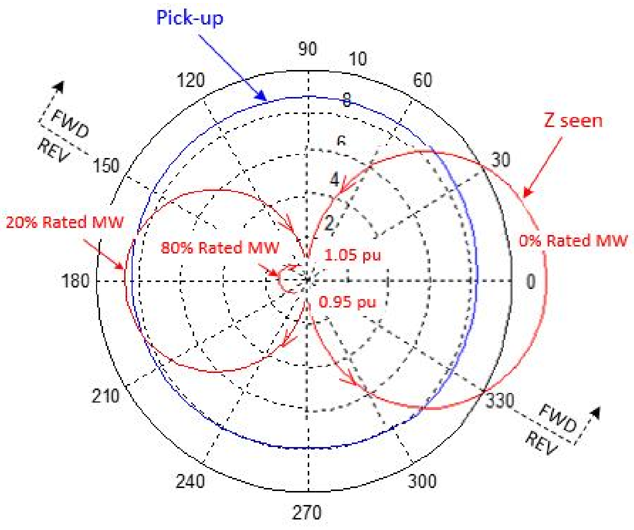


Fig 17. Impedance trajectory plot showing effect of changing utility voltage (0.95 – 1.05 pu) for active power levels of 0, 20 and 80%.

From Figure 17, it can be clearly seen that at 20 and 80 percent of WTG rating, the trajectories will enter the forward operating area in the second quadrant (upper left) of the plot. (active power is greater than auxiliary power). If traditional directional elements are used then a mis-operation (trip) will result. However because these points are not in the expected fault region, load encroachment or angle settings can be used to block trip. Note as the terminal voltage increases, the load becomes more capacitive (WTG is absorbing more VARS). In this situation, the WTG acts as an inductive load to bring the voltage down at the utility.

At 20 percent of WTG rating, the load angle is approaching 90° which is what the angle settings to block trip should be based on. At 80 percent of WTG rating, the load angle reaches to about 120°. Settings to block trip based at this angle are only adequate based on what the event reports indicate, not the entire range of generating angles outside the fault region.

For 0 percent of WTG rating, the trajectory will enter the forward operate area in the first (upper right) and fourth quadrants (lower right) of the plot (active power is less than auxiliary power). However, the first quadrant is the only area of concern since load points are within the pick-up range of the relay and in the expected fault region. Unfortunately in this situation, neither load encroachment nor directional element angle settings can be used to block relay trip. In this case, these methods can only be used to minimize the chance of mis-operation. If picked up in the forward area of quadrant 4 then this is not a problem since load encroachment or angle settings can be used to block trip. Results from load flow study are shown in Figure 18. Trip points are denoted by a red ‘x’. Red dots indicate relay did not operate.

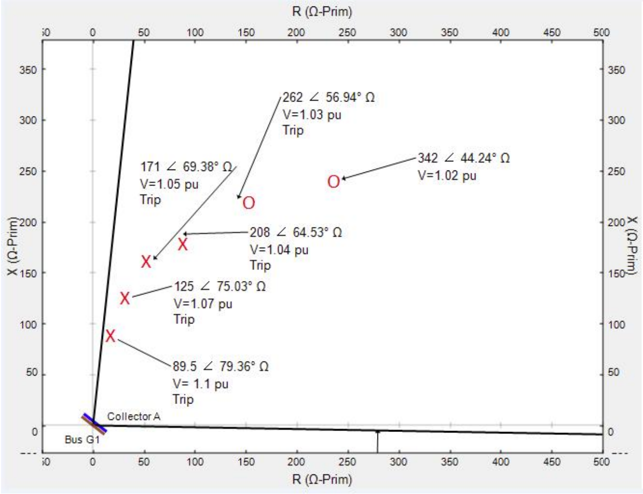


Fig 18. Impedance plot for most secure retracted operating area.

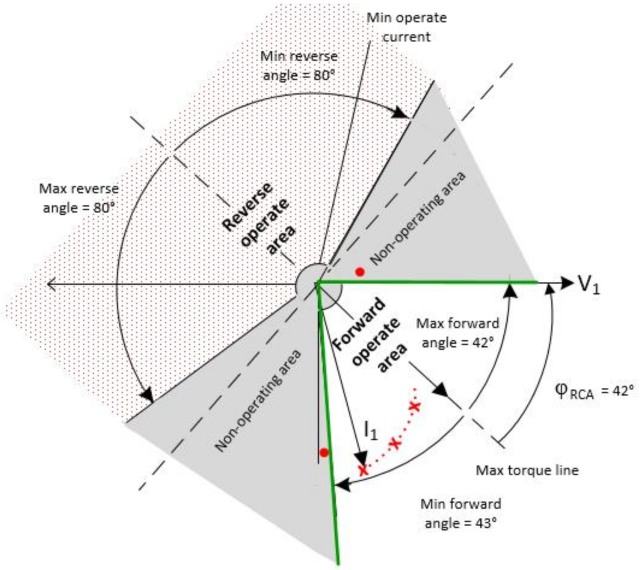


Fig 19. Phase angle characteristics for most secure retracted operating area.

Because the results of the study can differ, it is not always known which generation points will enter the forward operating area. Therefore a conservative approach was taken to block all possible forward generating angles outside the expected fault region of 0 to 85°. This provides the most secure relay operation possible. Phase angle characteristics are shown in Figure 19.

This does not imply however that false trips will occur. It all comes down to the following two questions:

1. What is the minimum active power of the wind generation unit while producing maximum capacitive current?
2. What is the maximum auxiliary load consumed by the wind generation unit?

If active power generation is greater than auxiliary load then the seen impedance in the forward operating area will be in the second quadrant of the z plot shown in Figure 17. Therefore directional element angle settings can be used to retract the forward operating angle in accordance with Figure 13. This condition occurs if wind generation requires some active power to produce reactive (capacitive) power (VARS flowing into WTG). This is characterized by the 'Triangular' shaped capability curve shown in Figure 20.

If reactive power can be produced with no active power or active power less than auxiliary load (characterized by the 'Rectangular' or 'D' shaped red and black capability curves in Figure 20) then the seen impedance in the forward operating area will be in the first and fourth quadrant of the z plot shown in Figure 18 [13]. In this case, the conservative directional element angle settings in Figure 19 can be used to at least minimize the chance of mis-operations by allowing trip in the fault region (quadrant 1) and blocking trip in inductive load region (quadrant 4, VARS flowing out of WTG).

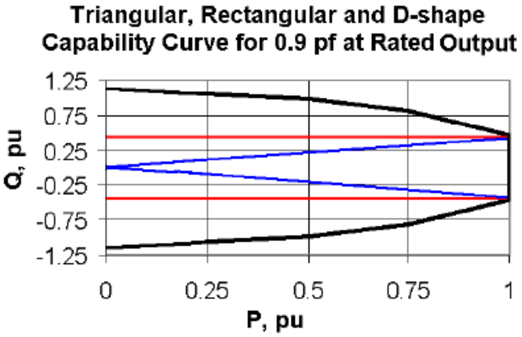


Fig 20. Wind turbine generator capability curves at nominal voltage.

Based on question 2 above, the over-current pick-up can be set above maximum auxiliary (about 120%) to provide the highest sensitivity with a safe margin. If active power is less than auxiliary load then another solution would be to increase the over-current pick-up until simulation results show no operation for load in expected fault region. Then check if relay can see faults at most remote lateral or low side of WTG step-up transformer [7]. If pick-up is above 120% of total rated WTG load then over-current protection can be non-directional. Otherwise it may be necessary to re-evaluate minimum power operational limits. This condition is based on theoretical results from the load flow study. The likelihood of operating at zero or low active power is unknown and requires further investigation.

VII. EXAMPLE – REFSDAL POWER SYSTEM

Directional element security using traditional methods is also a concern for capacitive ground faults in some situations. For instance when a normally isolated power system is connected to a compensated system. In this case using only one mode of operation for directionality is not possible since the method of neutral point grounding changes. One approach to this problem is to use two setting groups, one for the isolated system (I_0Sin) and one for the compensated one (I_0Cos). However in some situations this solution may not be practical since the grounding facility may be located several kilometers from the substation. An alternative solution would be to use the *Min* and *Max* forward *angle* settings to extend the operating area of the directional element so that the same settings could be used to detect faults for both isolated and compensated power systems.

This idea was proposed in a master's thesis by Anniken Liland Fredriksen from the Norwegian University of Science and Technology (NTNU) to apply the same settings for both isolated and compensated systems [3]. The solution was to extend the forward operating set for a compensated system (RCA = 0°) to allow fault detection in an isolated system using a relay with the directional element design discussed in this paper [12]. The simulations showed that extending the operate area offered a valid solution for detecting forward and reverse faults up to

3000Ω (standard for the Norwegian state). Furthermore that accurate modeling was needed to set the directional element angle settings correctly. In particular for reverse faults which could possibly enter the forward operating area, now extended for the dual application.

The thesis was written in cooperation with Statkraft who provided simulations and modeling for the 22 kV power system using ATPDraw, a program with an EMTP and graphical user interface developed by professor Hans Kristian Hoidalen of NTNU [3]. The relay under study was to set to protect the Fosse line in the Refsdal distribution system (owned by the Norwegian energy producer Statkraft) shown in Figure 21. The Refsdal distribution system, operates with an isolated transformer neutral by default. In case of an emergency the system is connected in parallel to a compensated system known as 'Hove' (owned by local distributor Sognekraft) shown in Figure 25. The coil at Hove, operating at 5% overcompensated, has two parallel resistors. R_{P1} and R_{P2}: having respective ohmic values of 2581Ω and 1291 Ω. R_{p1} is connected during normal operation. When V_o exceeds 10% of phase voltage R_{p1} is disconnected (after a 1.5s delay), and then 2 seconds later R_{p2} is connected.

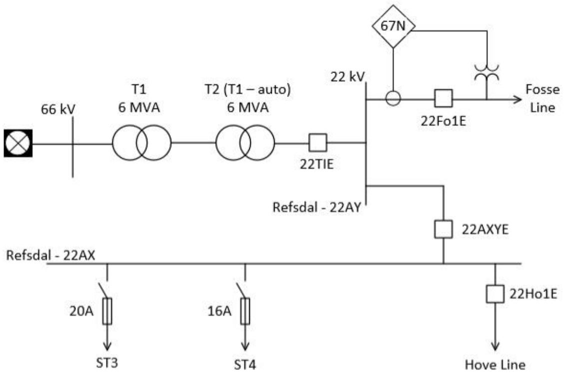
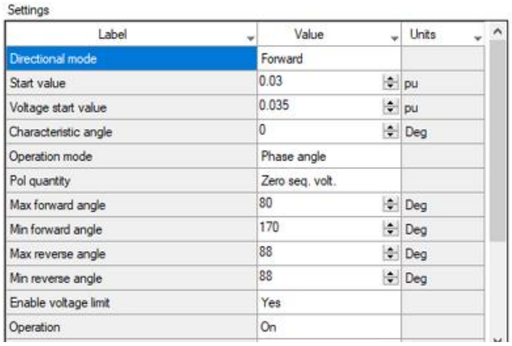


Fig 21. One line diagram of Refsdal distribution system.

The 22 kV system and relay settings were also modeled in protection design software, similar to ATPDraw, from the information provided in the thesis. The recommended relay settings to extend the forward operating area are shown in Figure 22, and the one line diagram (relay located at 22Fo1E) is shown in Figure 25. The shunt capacitance of the lines and cables was taken into account. However, it was assumed that the lines were transposed. In reality, lines or cables may not be transposed or fully transposed leading to unbalanced shunt capacitance. Therefore an adequate margin for the angle settings needs to be considered since the seen impedance will shift slightly. For conductive discharge, which always exists, regardless of whether lines are transposed, the recommended value of 15% of capacitive discharge from the thesis was used.


Settings

Label	Value	Units
Directional mode	Forward	
Start value	0.03	pu
Voltage start value	0.035	pu
Characteristic angle	0	Deg
Operation mode	Phase angle	
Pol quantity	Zero seq. volt.	
Max forward angle	80	Deg
Min forward angle	170	Deg
Max reverse angle	88	Deg
Min reverse angle	88	Deg
Enable voltage limit	Yes	
Operation	On	

Fig 22. Relay setting page in protection design software for Refsdal relay.

After the modeling was completed, a fault study was run to evaluate the impact of connecting to the compensated system as well as the effect of the two parallel resistors. For forward faults the Fosse bus was selected, and for reverse faults the ST3 bus was selected. Fault resistance was assumed to be 0 Ω. Fault values remained approximately the same regardless of which busses were selected. When the system is operated isolated, faults in both directions are capacitive. If connected to the compensated system, then faults in the forward direction are resistive (with inductive component due to over-compensation), and faults in the reverse direction are capacitive. Switching from R_{P1} and R_{P2} increases the resistive component of the operating current providing improved directional security. The impedance plot shown in Figure 23 displays the results of the simulation. The plot characteristics and fault points are shifted 180° to align with the $-V_0$ reference of the relay when converted to the phasor domain plot shown in Figure 24. It can be seen that the directional element will detect faults correctly in both directions using the same settings.

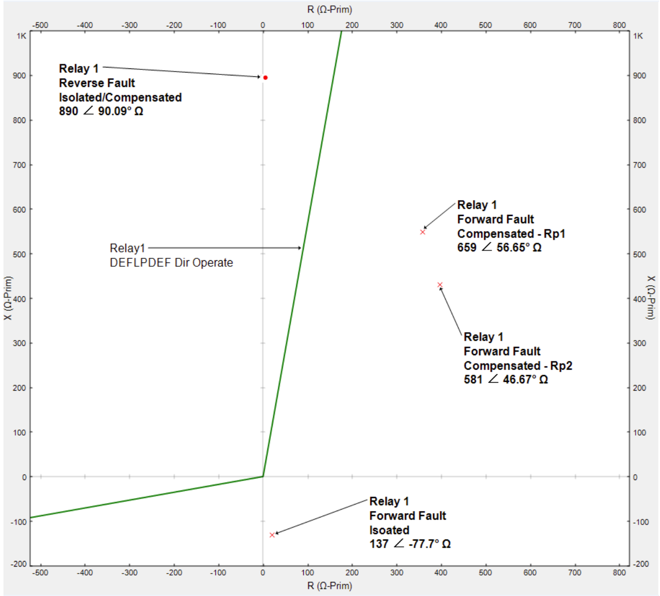


Fig 23. Impedance plot for extended operating area (correct operation).

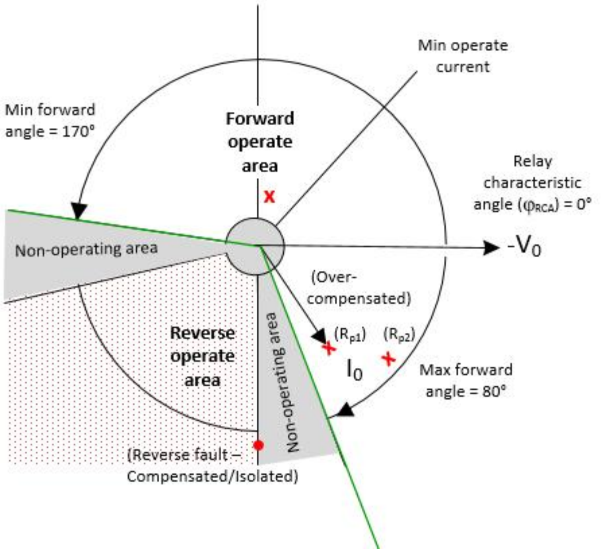


Fig 24. Phase angle characteristic for extended operating area (correct operation).

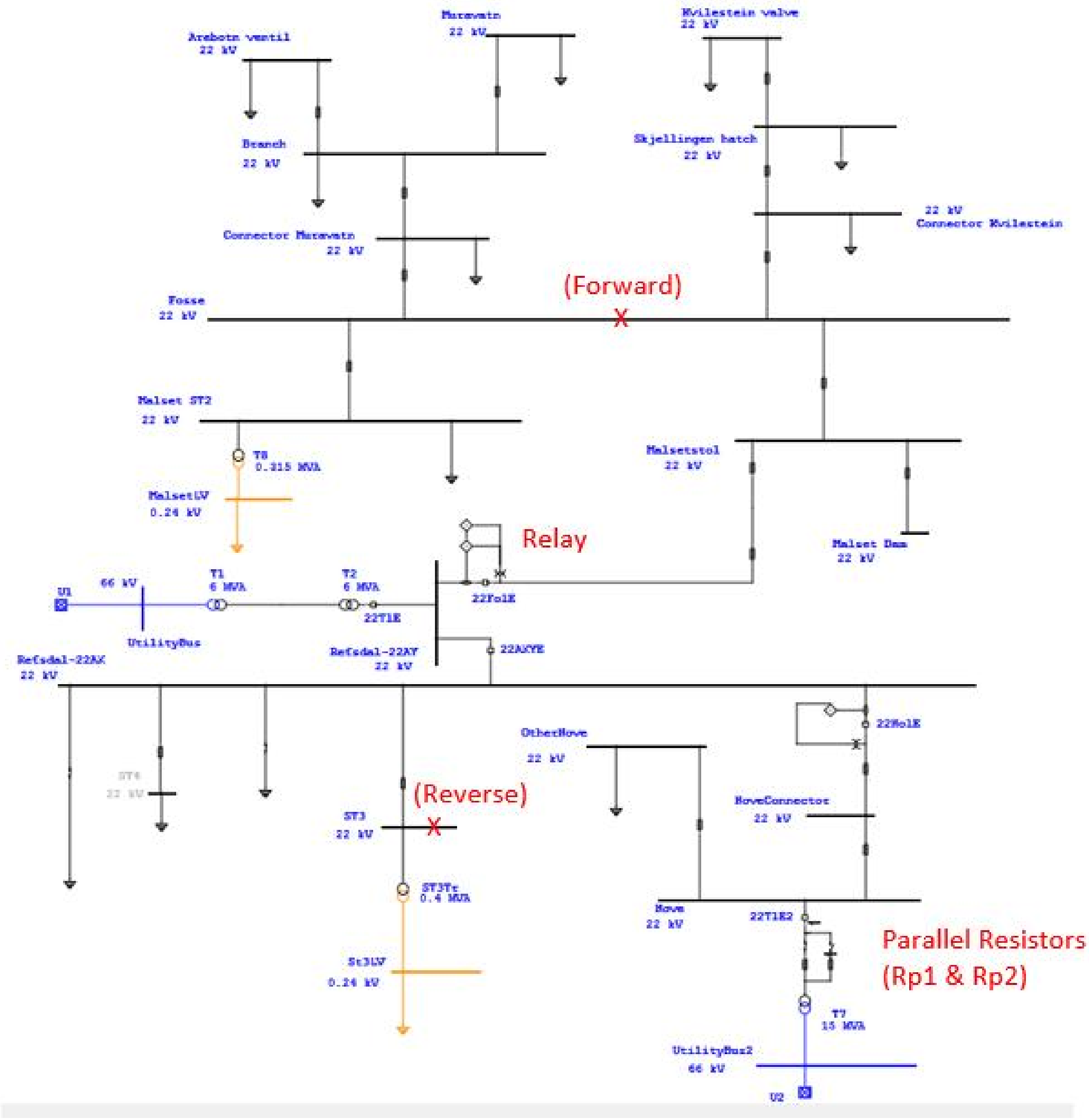


Fig 25. 22 kV system owned by Statkraft modeled in protection design software.

VIII. CONCLUSION

This paper addressed two applications where capacitive loads and faults are problematic for traditional directional elements. Overcoming these challenges required a new way of thinking with respect to how directional elements are designed and the systems they are protecting are modeled. From a design standpoint, extending and retracting the operating area using the flexible *Minimum/Maximum forward and reverse angle* settings, and adjusting the RCA to accommodate the method of neutral point grounding are the key factors. Also because these features are built in to the directional element, the relay is easier to set. With respect to modeling, it is essential to understand fault behavior for different types of systems and operating scenarios. For example, simulations for wind farm collector units determine if the conservative approach in this paper is adequate, or if the relay needs to be desensitized and possibly be made non-directional since neither angle settings nor load encroachments methods can be used to block in the expected fault region. If desired protection cannot be achieved then operational limits may need to be re-evaluated. For the Refsdal distribution system, many factors can influence directional element security, such as degree of coil compensation, value of parallel resistors, and unbalances due to capacitive/conductive discharge. Advancements in protection design software now allow for seamless integration of relays, using custom relay setting interfaces, and components, such as wind turbine models, to run the necessary simulations.

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On behalf of those authoring this paper it is a privilege to express our gratitude for the hard work, long hours and dedication Mohammad Zadeh, Ph.D., SMIEEE, PE, and Sajal Jain, PE of ETAP have spent creating the power system and relay models necessary for the completion of this paper. It is certainly worth mentioning again that the seamless integration of relay settings into ETAP's new distance protection StarZ module as they appear in the relay is a highly effective tool for validating relay performance. From personal experience ETAP's leadership, professionalism and commitment to high quality training is unmatched in the protection design software market. Their highly talented staff and resulting innovations are clearly setting the benchmark for the future.

It is also a privilege to express our gratitude to Anniken Liland Fredriksen and Professor Hans Kristian Hoidalen from the Norwegian University of Science and Technology (NTNU) – Department of Electrical Power Engineering for their dedication and pioneering efforts which contributed significantly to this paper. The ideas and modeling data published in Anniken's thesis titled '*Earth fault protection in isolated and compensated power distribution systems*' are what the Refsdal example is based on.

IX. REFERENCES

[1] ABB *1MAC050144-MB 615 series Technical Manual* Issued: 06/06/2015 Revision E Product version 4.2.1

[2] Robert Beltz, Ian Peacock, William Vilcheck, P.E., "*Application Considerations for High Resistance Ground Retrofits in Pulp and Paper Mills*". Pulp and Paper Industry Technical Conference, 2000. IEEE 2000

[3] Anniken Liland Fredriksen. "*Earth fault protection in isolated and compensated power distribution systems*". Master's thesis, NTNU, 2016.

[4] HV Power Measurements & Protection Ltd. HV Power File: *Peterson Coils Basic Principle and Application.doc*. Version 1.0 16/4/2012

[5] Ari Wahlroos, Janne Altonen. ABB Oy Distribution Automation – Finland. "*Compensated Networks and Admittance Based Earth-Fault Protection*".

[6] ABB Online Support for Power and Automation Products. "*Brief comparison between IoCos(phi) and WattMetric earth-fault protection principles*". Published 2007-01-23

[7] Doug Jones and Kyle Bennett, POWER Engineers, Inc., "Wind Farm Collector Protection using Directional Overcurrent Elements".

[8] Ryan McDaniel. Application Guide Volume III AG2013-04. "*Phase Directional Overcurrent Settings Recommendations for Wind Farm Applications Using the SEL-351S*".

[9] John Horak. "*Directional Overcurrent Relaying (67) Concepts*".

[10] SEL- 351-5, -6, -7 Protection System Instruction Manual 20170215.

[11] Bing Chen, Arun Shrestha, Fred A. Ituzaro, and Norman Fischer. "Addressing Protection Challenges Associated With Type 3 and Type 4 Wind Turbine Generators". 68th Annual Conference for Protective Relay Engineers. IEEE 2015

[12] ABB *1MRS756508 630 series Technical Manual* Issued: 2014-11-28 Revision E Product version 1.3

[13] Abraham Ellis, Robert Nelson, Edi Von Engeln, Reigh Walling, Jason McDowell, Leo Casey, Eric Seymour, William Peter, Chris Barker, and Brendan Kirby. "*Reactive Power Interconnection Requirements for PV and Wind Plants – Recommendations to NERC*". SANDIA REPORT, SAND2102-1098. Printed February 2012

X. BIOGRAPHIES

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