Protection Challenges for Transmission Lines with Long Taps

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Abstract

Tapped transmission lines are quite common as they provide a low cost solution to connect remote loads without incurring the prohibitive cost of building a substation and the associated protective equipment. However, adding a tap in the line complicates the protection scheme and introduces unique challenges for the protection engineer. Protecting transmission lines with long taps is even more challenging. The effects of infeed can result in a fault on the tap having a larger apparent impedance than a fault at the remote end of the line. Setting relay elements to provide adequate coverage of long taps can cause coordination issues with remote lines.

This paper will illustrate, through some real world examples, the issue of protecting transmission lines with long taps and discuss some options for protecting long taps. Three examples will be used to explore different scenarios with tapped transmission lines:

- The first example will look at how a redundant POTT scheme is used to protect a line with a 15 mile tap in the middle of a 20 mile 69 kV sub-transmission line.
- The second example will highlight the effect of the location of the tap on the line by examining a line with a tap located at 95% of the line length from one end.
- The third example will explore how the relative strength of the system will impact the protection of lines with a long tap. In this example, one terminal is much stronger source than the other. The system strength on the line under study will be determined by calculation of the source impedance ratio.

A short circuit program with automated scripts will be used to illustrate these examples and run different contingency scenarios. Sensitivity and coordination scripts will be run to check the validity of the proposed settings.

The last part of the paper will discuss the issues related to fault location on transmission lines with long taps.

I. Introduction

It is common utility practice to tap transmission lines to serve distribution load. Tapping transmission lines to serve distribution load is a cost-effective alternative to building a substation. Adding a tap to the transmission line introduces protection complications, especially when the tap is long. This paper will review how infeed impacts the apparent impedance a relay sees for faults on a tap. Real world examples from the American Transmission Company (ATC) system will be used to demonstrate how the length of the tap, the location of the tap on the line and the relative strength of the two terminals impact the apparent impedance for faults on the tap. Before discussing the examples, a brief overview of ATC's protection philosophy will be provided as well as a discussion for how automated scripts can be used in the setting development process. The last part of the paper will provide a brief discussion of issues related to calculating fault location on transmission lines with long taps.

II. Protection Challenges for tapped Lines

Transmission lines may have tapped distribution transformers to serve distribution load as shown in Figure 1.

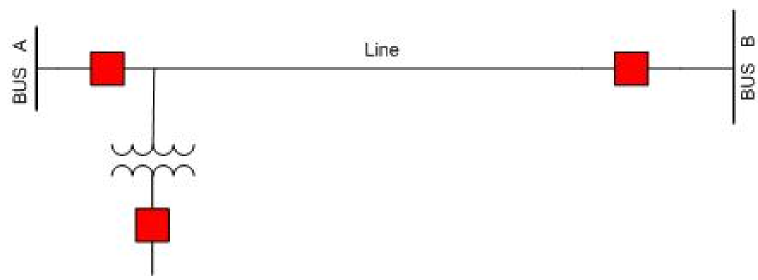

Figure 1: Tapped transmission line

Transformers can be tapped off at any location on a transmission line, and there can be more than one tap.

All tapped transformers should be provided with their own dedicated protection systems that operate for faults in the transformer to isolate the faulted transformer or, if high voltage fault-clearing facilities are not available at the tapped station, will initiate tripping of the breakers at the remote terminals of the line followed by automatic isolation of the transformer by a motor-operated disconnect switch.

If the transformer has a delta winding, and the high-voltage winding is connected grounded wye, the transformer will be a ground source for zero-sequence currents, causing under-reach of the line ground relays. The resulting zero-sequence current infeed should be considered when setting the remote ground distance relays or ground overcurrent relays. The zero-sequence current infeed will desensitize both ground distance and ground overcurrent relays at the main terminals.

The overreaching distance Zone 2 used in communication assisted schemes must overreach the farthest line terminal to achieve dependability. To achieve security, Zone 2 should not see faults on the low – voltage side of the tapped transformers. This conflicting reach coordination might be impossible to achieve on cases where the tap is located close to a main terminal of an electrically long line. In this case, the protection engineer might adopt solutions like sending a blocking signal from the tapped transformer to block Zone 2 operation at the line main terminals [1].

The same concern might apply to the underreacting zone 1 of long line. Zone 1 reach should be shortened in this case to avoid overreaching for low-voltage faults of the transformer. Zone 1 might compete with the instantaneous protection of the tapped transformer (Transformer 87 or instantaneous Overcurrent). In This case, Zone 1 should be even shortened not to see faults on the high side of the transformers.

III. Effects of Infeed on Apparent Impedance

At its most basic level a distance relay operates by calculating the apparent impedance Z = V/I and checking to determine if that impedance falls within the relay's operating characteristic (i.e. mho or quad characteristic). To ensure protection of the entire line, a zone 2 distance element is set to the total line impedance plus a margin to allow for errors in CT and PT measurements; typically 120-130% of the line impedance. However, the apparent impedance seen by the relay does not always match the line impedance from the relay terminal to the fault location. When the fault is located on a tap on the transmission line, the impedance seen by the relay depends on the current contribution from the remote line terminal.

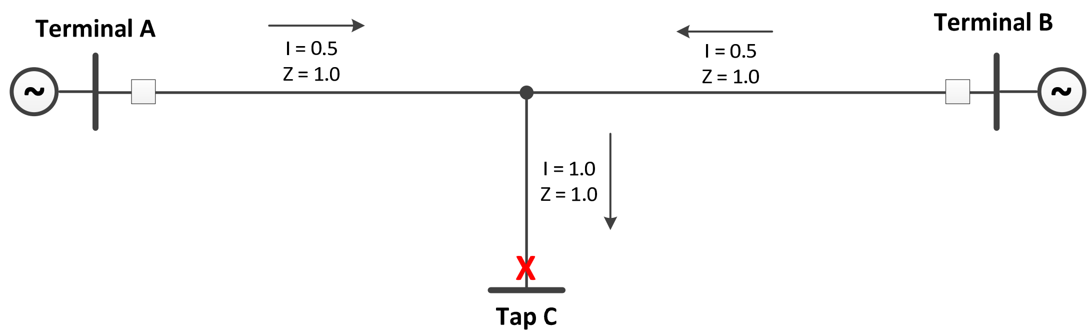

Figure 2: Current infeed

As shown in Figure 2, the impedance from terminal A to the fault is 2 ohms. The apparent impedance seen at terminal A can be calculated as follows:

$$Apparent\ Impedance = \frac{V}{I} = \frac{(0.5*1)+(1*1)}{0.5} = 3\ ohms \quad (1)$$

Due to the infeed current from terminal B, the relay at terminal A will see an apparent impedance of 3 ohms, which is greater than the line impedance to the fault location.

As the length of the tap on the transmission line increases, this infeed effect can result in a protection challenge because the apparent impedance for faults along the tap become greater than the line impedance between the two breakered terminals.

IV. Setting Philosophy

In general, for 69kV lines, ATC applies redundant relays with step distance and ground inverse time overcurrent protection. The setting philosophy for ATC includes the following guidelines for distance elements:

1. In order to prevent over reach of the remote bus, the zone 1 reach should be set no more than 85% of the line impedance. For lines with mutual coupling, the zone 1 ground element should be set no more than 85% of the minimum apparent impedance for a fault at the remote bus.
2. Zone 2 must see faults on the entire line. The zone 2 setting is typically 130-150% of the maximum apparent impedance for faults on the line with an absolute minimum setting of 120%. Preferably, the zone 2 reach is not more than 50% of the remote bus shortest line. In all

cases, Zone 2 should not see faults on the low side of the transformers. If Zone 2 sees faults at low side of the transformer and is already at the minimum of 120 %, the protection engineer should evaluate the protection at the tapped transformer. If a fuse protects the tapped transformer, the total clearing time of the fuse should be checked and zone 2 time delay adjusted to allow the fuse to blow before the relay trips.

3. The typical zone 2 time delay is 18-24 cycles. If the zone 2 setting over reaches the zone 1 of a remote line(s) the zone 2 time delay is increased to coordinate with the remote zone 2 time delay. A minimum margin of 12 cycles is required.
4. In locations where the zone 2 time delay must be increased to coordinate a zone 4 element may be implemented. Zone 4 is implemented with a standard zone 2 time delay and set to reach no more than 50% of the remote shortest line.

V. Automation

As an aid in developing the settings for the lines considered in this paper and ensuring coordination with surrounding relays Automated Wide Area Protection Coordination (WAPC) study tools were used. Automated Wide Area Protection Coordination study is a tool that allows utilities to analyze protection coordination of all adjacent protection systems in detail and in a relatively short period of time compared to traditional methods of coordination analysis. The different parts of the WAPC study are described below in detail [2].

Standards and Guidelines: These include the utility's own standards and practices, combined with requirements and standards mandated by regulatory bodies and independent system operators. The purpose of the standards and guidelines is to guide the WAPC process.

Protection Software Platform: The protection software platform is the computer-based model of the utility's power system, including the protection system.

Macros: Macros are automated batch processes that run within the framework of the protection software platform. There were two main types of macros used in the study: sensitivity and coordination macros. The sensitivity macro performs automated relay setting checks against the criteria set in the setting philosophy. The coordination macro simulates the defined scenarios of fault types, fault locations, and system contingencies and assesses the behavior of protection devices one-to-two substations away from the fault. The greatest advantage of the batch process approach is its ability to perform large-scale studies that are impossible to undertake in a manual fashion.

Study Output and Protection System Analyser: The macros, running on the protection software platform, generate a large amount of raw data. These take the form of Rich Text Format (RTF) files, color-coded with detailed sequence-of-events output that demonstrate how every fault that was applied on the system was cleared. While this output is useful, it is difficult for an engineer to analyse and provide setting change recommendations. Therefore, the study output is processed by the Protection System Analyser to create condensed spreadsheets that help focus the relay engineer's attention on the most severe problems identified that need to be addressed.

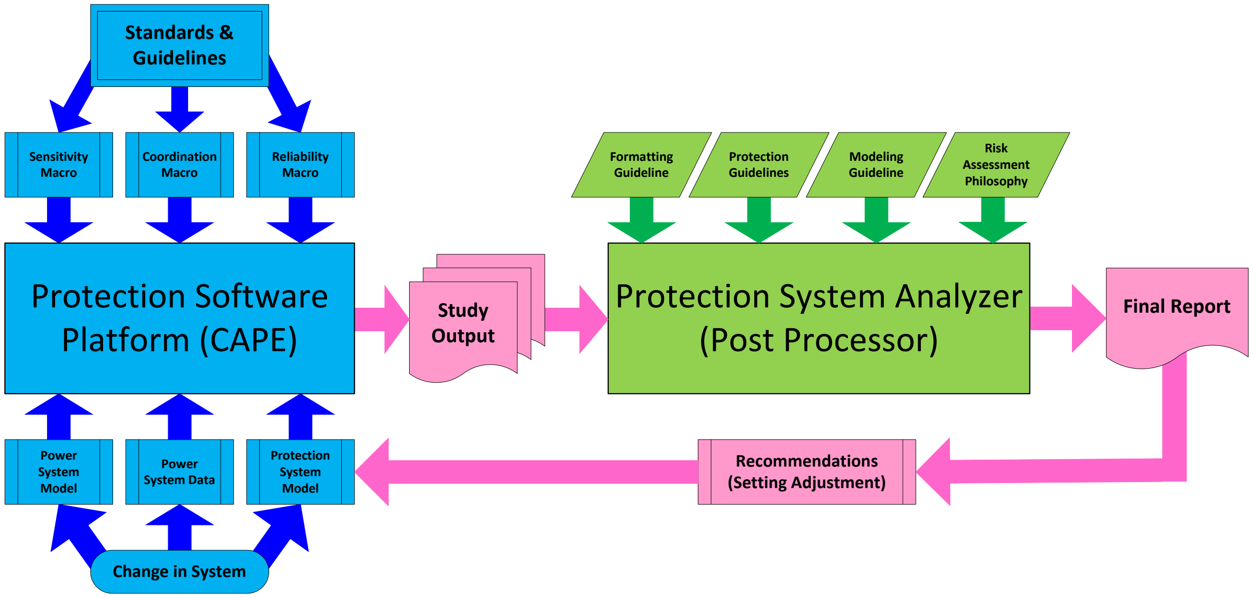

Figure 3: Wide Area Protection Coordination (WAPC) Process

1. Example 1

The first example will demonstrate how communication schemes can be used to improve clearing times and coordination for lines with long taps. Figure 4 shows the system configuration of the example we are considering.

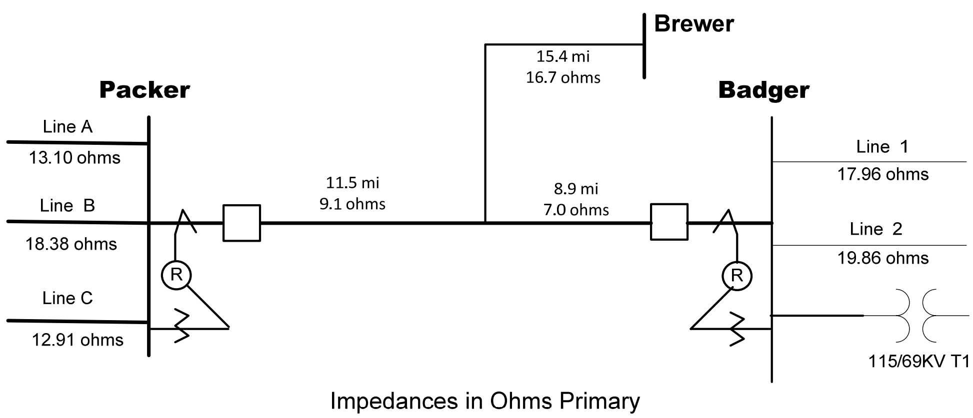

Figure 4: Example 1 system one line

This example looks at a 15-mile tap located near the center of a 20-mile line. As can be seen, even without infeed, the impedance from Packer to Brewer is greater than the impedance from Packer to Badger. Once infeed is taken into account, the situation is exacerbated. Table 1 details the apparent impedance (Zapp) for faults at Brewer for various situations.

Fault scenario	Zapp seen by relay at Packer	Zapp seen by relay at Badger
3PH fault at Brewer, system normal	55.4 Ω	35.2 Ω
3PH fault at Brewer, strong source behind Packer out of service	62.5 Ω	30.9 Ω
3PH fault at Brewer, strong source behind Badger out of service	40.2 Ω	42.5 Ω
3PH fault at Brewer, Badger end open	25.6 Ω	NA
3PH fault at Brewer, Packer end open	NA	23.5 Ω
SLG fault at Brewer, system normal	54.2 Ω	33.5 Ω
SLG fault at Brewer, strong source behind Packer out of service	71.2 Ω	29.9 Ω
SLG fault at Brewer, strong source behind Badger out of service	42.1 Ω	40.4 Ω
SLG fault at Brewer, Badger end open	25.8 Ω	NA
SLG fault at Brewer, Packer end open	NA	23.7 Ω

Table 1: Apparent impedance for faults at Brewer

As can be seen from the fault scenarios shown in Table 1 above, the apparent impedance with infeed for faults on the tap is significantly larger than the line impedance. The effects of infeed are further illustrated by examining the results of the zone 1 phase reach tests from the sensitivity macro. Figure 5 shows how far the zone 1 phase element at Badger reaches to Packer and Brewer under different system conditions. The results show that the set reach and actual reach are the same for faults along the main line between Badger and Packer. However, for faults along the tap to Brewer, the actual reach is less than the set reach for all scenarios except when the Packer end of the line is out of service. This demonstrates how infeed can reduce the reach of relay elements when protecting a long tap on a transmission line.

```
-----------------------------------------------------------------------------------------------------
Phase Distance Elements Zone: 1;  please wait ...
-----------------------------------------------------------------------------------------------------
Badger    1551 DIST "M1P" (SEL-321-R100); Contact Logic Code: 21P1.P
Testing zone 1 reach on path 837500 Badger-837600 Brewer Tap-  1 to remote bus 837800 Packer
                                                    Line   Line    Set    Set    Act.   Des.
                                                    Imp.   Angle   Reach  Reach  Reach  Reach  PASS
No. Fault    Outages Considered (Contingencies)    Ohms   Degrees Ohms    %      %      %     FAIL
--- ----- ---------------------------------------- ------ -------- ------ ------ ------ ------ ----
  1 TPH   None                                      16.10    69.67  13.65  84.79  84.89  85.00 PASS
  2 TPH   Term.  : 994600 Brewer                    16.10    69.67  13.65  84.79  84.89  85.00 PASS
  3 TPH   LTXFMR: 837700-1026-1  ( )                16.10    69.67  13.65  84.79  84.89  85.00 PASS
  4 TPH   XFMR   : 837500-1499-1  ( )               16.10    69.67  13.65  84.79  84.89  85.00 PASS
  5 TPH   Line   : 837500-837400-1(LINE_1)          16.10    69.67  13.65  84.79  84.89  85.00 PASS
  6 TPH   Line   : 837500-838700-1(LINE_2)          16.10    69.67  13.65  84.79  84.89  85.00 PASS
  7 LTL   None                                      16.10    69.67  13.65  84.79  84.89  85.00 PASS
  8 LTL   Term.  : 994600 Brewer                    16.10    69.67  13.65  84.79  84.89  85.00 PASS
  9 LTL   LTXFMR: 837700-1026-1  ( )                16.10    69.67  13.65  84.79  84.89  85.00 PASS
 10 LTL   XFMR   : 837500-1499-1  ( )               16.10    69.67  13.65  84.79  84.89  85.00 PASS
 11 LTL   Line   : 837500-837400-1(LINE_1)          16.10    69.67  13.65  84.79  84.89  85.00 PASS
 12 LTL   Line   : 837500-838700-1(LINE_2)          16.10    69.67  13.65  84.79  84.89  85.00 PASS
-----------------------------------------------------------------------------------------------------
Number of faults applied       :  12
Number of zone 1 reach failures:   0
Largest reach                  :  84.89%
-----------------------------------------------------------------------------------------------------
Badger    1551 DIST "M1P" (SEL-321-R100); Contact Logic Code: 21P1.P
Testing zone 1 reach on path 837500 Badger-837600 Brewer Tap-  1 to remote bus 994600 Brewer
                                                    Line   Line    Set    Set    Act.   Des.
                                                    Imp.   Angle   Reach  Reach  Reach  Reach  PASS
No. Fault    Outages Considered (Contingencies)    Ohms   Degrees Ohms    %      %      %     FAIL
--- ----- ---------------------------------------- ------ -------- ------ ------ ------ ------ ----
  1 TPH   None                                      23.51    58.35  13.37  56.87  46.59  85.00 PASS
  2 TPH   Term.  : 837800 Packer                    23.51    58.35  13.37  56.87  58.48  85.00 PASS
  3 TPH   LTXFMR: 837700-1026-1  ( )                23.51    58.35  13.37  56.87  46.59  85.00 PASS
  4 TPH   XFMR   : 837500-1499-1  ( )               23.51    58.35  13.37  56.87  43.08  85.00 PASS
  5 TPH   Line   : 837500-837400-1(LINE_1)          23.51    58.35  13.37  56.87  45.71  85.00 PASS
  6 TPH   Line   : 837500-838700-1(LINE_2)          23.51    58.35  13.37  56.87  45.81  85.00 PASS
  7 LTL   None                                      23.51    58.35  13.37  56.87  46.49  85.00 PASS
  8 LTL   Term.  : 837800 Packer                    23.51    58.35  13.37  56.87  58.48  85.00 PASS
  9 LTL   LTXFMR: 837700-1026-1  ( )                23.51    58.35  13.37  56.87  46.49  85.00 PASS
 10 LTL   XFMR   : 837500-1499-1  ( )               23.51    58.35  13.37  56.87  43.08  85.00 PASS
 11 LTL   Line   : 837500-837400-1(LINE_1)          23.51    58.35  13.37  56.87  45.71  85.00 PASS
 12 LTL   Line   : 837500-838700-1(LINE_2)          23.51    58.35  13.37  56.87  45.81  85.00 PASS
-----------------------------------------------------------------------------------------------------
Number of faults applied       :  12
Number of zone 1 reach failures:   0
Largest reach                  :  58.48%
```

Figure 5: Zone 1 phase reach along line

In order to ensure coverage for all faults on the line the Zone 2 Phase pickup at Packer was set at 130% of the maximum apparent impedance for a three-phase fault at Brewer, which is 62.5 ohms. So the Z2P setting = 1.3*62.5 = 81.25 ohms pri. This large zone 2 setting presents challenges for coordination with remote lines. Figure 6 shows results from the sensitivity macro testing how far the zone 2 element will operate on adjacent lines. The results show that this setting will operate for faults on the entire length of both Line 1 and Line 2 out of Badger. Line 1 and Line 2 at Badger both have a zone 2 time delay of 24 cycles, so the zone 2 time delay at Badger is set to 36 cycles in order to provide a 12 cycle coordination margin.

```
Phase Distance Elements Zone: 2; please wait ...

Performing reach test on lines connected at all remote buses ...

Local Zone 2 Elements:
FWD ELEMENT: 1: Packer   3750 DIST "M2P" Zone "2" (SEL-321-3_5A); Contact Logic Code: "21P2_PILOT.P"
FWD ELEMENT: 2: Packer   3776 DIST "M2P" Zone "2" (SEL-311C_5A); Contact Logic Code: "21P2_PILOT.S"

The "Actual Reach" column shows the reach of each element on the line in the "Fault Location" column.
This reach is displayed as a percentage of the positive-sequence line impedance.
For the FWD elements, the actual reach must be less than 50% (of the line impedance).
"IND." in the PASS/FAIL column indicates that the reach of the element extends beyond the next remote bus.
We do not search for the reach in the network beyond that bus.
```

No.	Fault	Outages Considered (Contingencies)	Fault Location	Line Imp. Ohms	Line Angle Degrees	ELEM	Actual Reach %	Des. Reach % or Marg.	PASS FAIL
1	TPH	None	Fault on LINE_1 to 836900 Lion	17.96	66.50	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
2	TPH	Term. : 994600 Brewer	Fault on LINE_1 to 836900 Lion	17.96	66.50	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
3	TPH	LTXFMR: 837700-1026-1 ( )	Fault on LINE_1 to 836900 Lion	17.96	66.50	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
4	TPH	XFMR : 837500-1499-1 ( )	Fault on LINE_1 to 836900 Lion	17.96	66.50	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
5	TPH	Line : 837500-838700-1(LINE_2)	Fault on LINE_1 to 836900 Lion	17.96	66.50	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
6	LTL	None	Fault on LINE_1 to 836900 Lion	17.96	66.50	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
7	LTL	Term. : 994600 Brewer	Fault on LINE_1 to 836900 Lion	17.96	66.50	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
8	LTL	LTXFMR: 837700-1026-1 ( )	Fault on LINE_1 to 836900 Lion	17.96	66.50	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
9	LTL	XFMR : 837500-1499-1 ( )	Fault on LINE_1 to 836900 Lion	17.96	66.50	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
10	LTL	Line : 837500-838700-1(LINE_2)	Fault on LINE_1 to 836900 Lion	17.96	66.50	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
11	TPH	None	Fault on LINE_2 to 840600 Tiger	19.86	70.04	FWD1	94.83	50.0	FAIL
						FWD2	94.83	50.0	FAIL
12	TPH	Term. : 994600 Brewer	Fault on LINE_2 to 840600 Tiger	19.86	70.04	FWD1	94.83	50.0	FAIL
						FWD2	94.83	50.0	FAIL
13	TPH	LTXFMR: 837700-1026-1 ( )	Fault on LINE_2 to 840600 Tiger	19.86	70.04	FWD1	94.83	50.0	FAIL
						FWD2	94.83	50.0	FAIL
14	TPH	XFMR : 837500-1499-1 ( )	Fault on LINE_2 to 840600 Tiger	19.86	70.04	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
15	TPH	Line : 837500-837400-1(LINE_1)	Fault on LINE_2 to 840600 Tiger	19.86	70.04	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
16	LTL	None	Fault on LINE_2 to 840600 Tiger	19.86	70.04	FWD1	94.83	50.0	FAIL
						FWD2	94.83	50.0	FAIL
17	LTL	Term. : 994600 Brewer	Fault on LINE_2 to 840600 Tiger	19.86	70.04	FWD1	94.83	50.0	FAIL
						FWD2	94.83	50.0	FAIL
18	LTL	LTXFMR: 837700-1026-1 ( )	Fault on LINE_2 to 840600 Tiger	19.86	70.04	FWD1	94.83	50.0	FAIL
						FWD2	94.83	50.0	FAIL
19	LTL	XFMR : 837500-1499-1 ( )	Fault on LINE_2 to 840600 Tiger	19.86	70.04	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.
20	LTL	Line : 837500-837400-1(LINE_1)	Fault on LINE_2 to 840600 Tiger	19.86	70.04	FWD1	99.90	50.0	IND.
						FWD2	99.90	50.0	IND.

Figure 6: Zone 2 Phase element reach on remote lines

Similar calculations must be made for the Badger end. The largest apparent impedance seen by the relays at Badger for a fault at Brewer is 42.5 ohms. The Z2P setting is set to 130% of the maximum apparent impedance; 1.3*42.5 = 55.25 ohms pri. This setting will also overreach the zone 1 setting of lines A, B and C out of Packer. The lines out of Packer have a 24 cycle zone 2 time delay, so Badger is set with a 36 cycle zone 2 time delay to coordinate.

After the initial settings were calculated based on the results of the sensitivity macro, the coordination macro was used to simulate faults on the Packer-Badger line and all adjacent lines. The coordination macro simulates thousands of faults and flags any mis-coordinations to focus the engineer's attention on problem areas. The results of the coordination macro in Figure 7 show that the Badger zone 2 phase element will operate for a three phase fault on the low side of a distribution transformer on line A that is located near the Packer end of the line when line B is out of service. In order to coordinate with the distribution transformer protection, the zone 2 time delay at Badger must be increased to 90 cycles.

However, extending the zone 2 time delay at Badger also results in slower clearing times for faults outside of the Badger zone 1 reach, including faults on the tap to Brewer. This delayed clearing increases the risk of equipment damage and in some locations could present stability concerns.

No packages have been outaged; Pilots Enabled

No.	Network Situation/Outages in Effect	Fault	Fault Location	Time(sec)	Operation
160	Line : 837800-838000-1(LINE_B)	TPH	Remote close-in : on 5148-5149-2 (T8 <none>)	0.700	MISCOORDINATION

Figure 7: Coordination macro results showing mis-coordination

A recent line rebuild between Packer and Badger installed fiber optic shield wire which allowed a communication-aided trip scheme to be implemented. To improve clearing times for faults on the tap to Brewer a Permissive Overreaching Transfer Trip (POTT) scheme over fiber was implemented. The POTT scheme enables fast clearing of the entire line, including the tap. The zone 2 reach is set to cover all faults on the tap and the zone 2 time delay is set to coordinate with the relaying for the other lines out of Badger substation.

2. Example 2

The second example demonstrates how the location of the tap along the line can impact the apparent impedance seen from the two line terminals. Figure 8 shows the system under consideration.

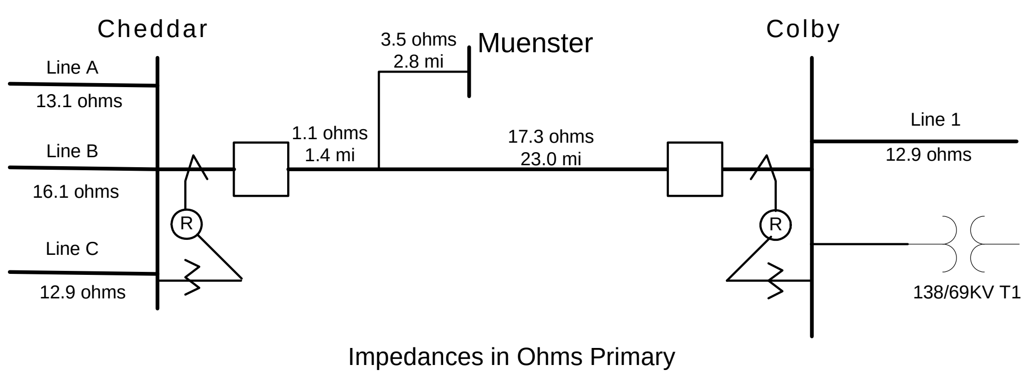

Figure 8: Example 2 system one line

This example looks at the case of a 2.8 mile (3.5 ohm) tap on a 24.4 mile (18.4 ohm) line. The tap is located about 5% of the line from Cheddar substation and 95% from the Colby end of the line. As seen from the Colby end, the impedance to Muenster is greater than the impedance to Cheddar. From Cheddar the impedance to Muenster is much smaller than the impedance to Colby. Table 2 details the apparent impedance (Zapp) for faults at Muenster for various situations.

Fault scenario	Zapp seen by relay at Cheddar	Zapp seen by relay at Colby
3PH fault at Muenster, system normal	6.4 Ω	26.2 Ω
3PH fault at Muenster, strong source behind Cheddar out of service	8.5 Ω	23.2 Ω
3PH fault at Muenster, strong source behind Colby out of service	5.5 Ω	31.5 Ω
3PH fault at Muenster, Colby end open	4.5 Ω	NA
3PH fault at Muenster, Cheddar end open	NA	20.5 Ω
SLG fault at Muenster, system normal	5.4 Ω	25.8 Ω
SLG fault at Muenster, strong source behind Cheddar out of service	6.9 Ω	23.9 Ω
SLG fault at Muenster, strong source behind Colby out of service	4.7 Ω	31.6 Ω
SLG fault at Muenster, Colby end open	3.9 Ω	NA
SLG fault at Muenster, Cheddar end open	NA	20.2 Ω

Table 2: Apparent impedance for faults at Muenster

As can be seen in Table 2 above, since the tap is located close to the Cheddar end of the line, even with infeed the apparent impedance seen by the relay at Cheddar for faults on the tap is still significantly less than the line impedance. For a zone 1 reach set at 85% of the line impedance (0.85*18.4 = 15.6 ohms), the relay at Cheddar will see all faults on the tap within the zone 1 reach.

From the Colby end, however, the apparent impedance for faults at Muenster is greater than the 18.4 ohm line impedance for all scenarios. It was not considered cost-effective to install a communication scheme on this line, so a step distance scheme was implemented for protection. At Colby the zone 2 reach was set at 130% of the maximum apparent impedance seen for faults at Muenster. The results from the sensitivity macro in Figure 9 show that with this setting the zone 2 setting will over reach the zone 1 setting of the lines out of Cheddar.

```
-------------------------------------------------------------------------------------------------------------------------------
Phase Distance Elements Zone: 2; please wait ...
-------------------------------------------------------------------------------------------------------------------------------
Performing reach test on lines connected at all remote buses ...

Local Zone 2 Elements:
FWD ELEMENT: 1: COLBY   5012 DIST "M2P" Zone "2" (SEL-321-R100); Contact Logic Code: "21P2.P"
FWD ELEMENT: 2: COLBY   5013 DIST "M2P" Zone "2" (SEL-311C_5A); Contact Logic Code: "21P2.S"
-------------------------------------------------------------------------------------------------------------------------------
The "Actual Reach" column shows the reach of each element on the line in the "Fault Location" column.
This reach is displayed as a percentage of the positive-sequence line impedance.
For the FWD elements, the actual reach must be less than 50% (of the line impedance).
"IND." in the PASS/FAIL column indicates that the reach of the element extends beyond the next remote bus.
We do not search for the reach in the network beyond that bus.
                                                                                                                 Des.
                                                                                 Line   Line             Actual  Reach
                                                                                 Imp.   Angle            Reach   % or  PASS
No. Fault    Outages Considered (Contingencies)        Fault Location            Ohms   Degrees ELEM       %     Marg. FAIL
--- -----  ----------------------------------------  ---------------------------------- ------ ------- ----  ------ ----- ----
  1 TPH    None                                       Fault on LINE_B to 837500 Parmesan  16.10  69.67 FWD1  73.59  50.0 FAIL
                                                                                                       FWD2  73.59  50.0 FAIL
  2 TPH    Term. : 838100 Muenster                    Fault on LINE_B to 837500 Parmesan  16.10  69.67 FWD1  73.59  50.0 FAIL
                                                                                                       FWD2  73.59  50.0 FAIL
  3 TPH    XFMR  : 837800-917-1 ( )                   Fault on LINE_B to 837500 Parmesan  16.10  69.67 FWD1  73.59  50.0 FAIL
                                                                                                       FWD2  73.59  50.0 FAIL
  4 TPH    Line  : 837800-838600-1(LINE_A)            Fault on LINE_B to 837500 Parmesan  16.10  69.67 FWD1  99.90  50.0 IND.
                                                                                                       FWD2  99.90  50.0 IND.
  5 TPH    Line  : 837800-913500-1(LINE_C)            Fault on LINE_B to 837500 Parmesan  16.10  69.67 FWD1  73.49  50.0 FAIL
                                                                                                       FWD2  73.49  50.0 FAIL
  6 LTL    None                                       Fault on LINE_B to 837500 Parmesan  16.10  69.67 FWD1  73.59  50.0 FAIL
                                                                                                       FWD2  73.59  50.0 FAIL
  7 LTL    Term. : 838100 Muenster                    Fault on LINE_B to 837500 Parmesan  16.10  69.67 FWD1  73.59  50.0 FAIL
                                                                                                       FWD2  73.59  50.0 FAIL
  8 LTL    XFMR  : 837800-917-1 ( )                   Fault on LINE_B to 837500 Parmesan  16.10  69.67 FWD1  73.59  50.0 FAIL
                                                                                                       FWD2  73.59  50.0 FAIL
  9 LTL    Line  : 837800-838600-1(LINE_A)            Fault on LINE_B to 837500 Parmesan  16.10  69.67 FWD1  99.90  50.0 IND.
                                                                                                       FWD2  99.90  50.0 IND.
 10 LTL    Line  : 837800-913500-1(LINE_C)            Fault on LINE_B to 837500 Parmesan  16.10  69.67 FWD1  73.49  50.0 FAIL
                                                                                                       FWD2  73.49  50.0 FAIL
 11 TPH    None                                       Fault on LINE_B to 837700 ROT 69    16.11  64.31 FWD1  63.55  50.0 FAIL
                                                                                                       FWD2  63.55  50.0 FAIL
 12 TPH    Term. : 838100 Muenster                    Fault on LINE_B to 837700 ROT 69    16.11  64.31 FWD1  63.55  50.0 FAIL
                                                                                                       FWD2  63.55  50.0 FAIL
 13 TPH    XFMR  : 837800-917-1 ( )                   Fault on LINE_B to 837700 ROT 69    16.11  64.31 FWD1  63.55  50.0 FAIL
                                                                                                       FWD2  63.55  50.0 FAIL
 14 TPH    Line  : 837800-838600-1(LINE_A)            Fault on LINE_B to 837700 ROT 69    16.11  64.31 FWD1  83.82  50.0 FAIL
                                                                                                       FWD2  83.92  50.0 FAIL
```

Figure 9: Zone 2 Phase element reach on remote lines

As a result, the zone 2 time delay is set long to coordinate with the zone 2 timers on the other lines out of Cheddar. In order to reduce the clearing time for faults on as much of the line as possible, an additional zone (zone 4) was implemented at Colby that was set to see no farther than 50% of the shortest line out of Cheddar. This zone was set with a typical zone 2 time delay since there was no concern of over reaching the zone 1 reach on the lines out of Cheddar. Using this additional zone will result in faster clearing for faults along the main line and may also speed clearing for faults on the tap since the apparent impedance seen by the Colby relay will move into zone 4 after the Cheddar end of the line trips in zone 1 time. When the sensitivity macro was re-run after implementing the zone 4 settings, it can be seen in Figure 10 that they do not reach more than 50% of any of the remote lines out of Cheddar.

```
-----------------------------------------------------------------------------------------------------------------------------
Phase Distance Elements Zone: 2; please wait ...
-----------------------------------------------------------------------------------------------------------------------------
Performing reach test on lines connected at all remote buses ...

Local Zone 2 Elements:
FWD ELEMENT: 1: COLBY   5012 DIST "M2P" Zone "2" (SEL-321-R100); Contact Logic Code: "21P2.P"
FWD ELEMENT: 2: COLBY   5012 DIST "M4P" Zone "4" (SEL-321-R100); Contact Logic Code: "21P4.P"
FWD ELEMENT: 3: COLBY   5013 DIST "M2P" Zone "2" (SEL-311C_5A); Contact Logic Code: "21P2.S"
FWD ELEMENT: 4: COLBY   5013 DIST "M4P" Zone "4" (SEL-311C_5A); Contact Logic Code: "21P4.S"
-----------------------------------------------------------------------------------------------------------------------------
The "Actual Reach" column shows the reach of each element on the line in the "Fault Location" column.
This reach is displayed as a percentage of the positive-sequence line impedance.
For the FWD elements, the actual reach must be less than 50% (of the line impedance).
"IND." in the PASS/FAIL column indicates that the reach of the element extends beyond the next remote bus.
We do not search for the reach in the network beyond that bus.

                                                                                                                     Des.
                                                                                     Line    Line          Actual  Reach
                                                                                     Imp.    Angle         Reach  % or  PASS
No. Fault    Outages Considered (Contingencies)            Fault Location            Ohms   Degrees ELEM    %     Marg. FAIL
--- -----  ----------------------------------------  ----------------------------------- ------ ------- ----  ------ ----- ----
  1 TPH    None                                       Fault on LINE_B to 837500 Parmesan  16.10   69.67 FWD1  73.59  50.0 FAIL
                                                                                                        FWD2  21.15  50.0 PASS
                                                                                                        FWD3  73.59  50.0 FAIL
                                                                                                        FWD4  21.15  50.0 PASS
  2 TPH    Term. : 838100 Muenster                    Fault on LINE_B to 837500 Parmesan  16.10   69.67 FWD1  73.59  50.0 FAIL
                                                                                                        FWD2  21.15  50.0 PASS
                                                                                                        FWD3  73.59  50.0 FAIL
                                                                                                        FWD4  21.15  50.0 PASS
  3 TPH    XFMR  : 837800-917-1 ( )                   Fault on LINE_B to 837500 Parmesan  16.10   69.67 FWD1  73.59  50.0 FAIL
                                                                                                        FWD2  21.15  50.0 PASS
                                                                                                        FWD3  73.59  50.0 FAIL
                                                                                                        FWD4  21.15  50.0 PASS
  4 TPH    Line  : 837800-838600-1(LINE_A)            Fault on LINE_B to 837500 Parmesan  16.10   69.67 FWD1  99.90  50.0 IND.
                                                                                                        FWD2  41.13  50.0 PASS
                                                                                                        FWD3  99.90  50.0 IND.
                                                                                                        FWD4  41.03  50.0 PASS
  5 TPH    Line  : 837800-913500-1(LINE_C)            Fault on LINE_B to 837500 Parmesan  16.10   69.67 FWD1  73.49  50.0 FAIL
                                                                                                        FWD2  21.15  50.0 PASS
                                                                                                        FWD3  73.49  50.0 FAIL
                                                                                                        FWD4  21.15  50.0 PASS
  6 LTL    None                                       Fault on LINE_B to 837500 Parmesan  16.10   69.67 FWD1  73.59  50.0 FAIL
                                                                                                        FWD2  21.15  50.0 PASS
                                                                                                        FWD3  73.59  50.0 FAIL
                                                                                                        FWD4  21.15  50.0 PASS
  7 LTL    Term. : 838100 Muenster                    Fault on LINE_B to 837500 Parmesan  16.10   69.67 FWD1  73.59  50.0 FAIL
                                                                                                        FWD2  21.15  50.0 PASS
                                                                                                        FWD3  73.59  50.0 FAIL
                                                                                                        FWD4  21.15  50.0 PASS
  8 LTL    XFMR  : 837800-917-1 ( )                   Fault on LINE_B to 837500 Parmesan  16.10   69.67 FWD1  73.59  50.0 FAIL
                                                                                                        FWD2  21.15  50.0 PASS
                                                                                                        FWD3  73.59  50.0 FAIL
                                                                                                        FWD4  21.15  50.0 PASS
  9 LTL    Line  : 837800-838600-1(LINE_A)            Fault on LINE_B to 837500 Parmesan  16.10   69.67 FWD1  99.90  50.0 IND.
                                                                                                        FWD2  41.13  50.0 PASS
                                                                                                        FWD3  99.90  50.0 IND.
                                                                                                        FWD4  41.03  50.0 PASS
 10 LTL    Line  : 837800-913500-1(LINE_C)            Fault on LINE_B to 837500 Parmesan  16.10   69.67 FWD1  73.49  50.0 FAIL
                                                                                                        FWD2  21.15  50.0 PASS
                                                                                                        FWD3  73.49  50.0 FAIL
                                                                                                        FWD4  21.15  50.0 PASS
```

Figure 10: Zone 2 and Zone 4 Phase element reach on remote lines

The sensitivity macro results in Figure 11 show that Zone 4 does not provide complete coverage for faults on the tap to Muenster, but it will provide greater coverage than zone 1 and faster clearing than zone 2.

COLBY 5012 DIST "M4P" Zone "4" (SEL-321-R100); Contact Logic Code: "21P4.P"
Testing Sensitivity for remote-bus faults
The "Calc. Reach" column shows the set reach of the relay at the angle of the apparent impedance.

No.	Fault	Outages Considered (Contingencies)	Fault Location	Magn. Appz.	Angle Appz.	Calc. Reach	Act. Ratio	Des. Ratio	PASS FAIL
1	TPH	None	837800 Cheddar	18.36	70.89	24.95	1.36	1.20	PASS
2	TPH	XFMR : 866002-610-1 ( )	837800 Cheddar	18.34	70.93	24.95	1.36	1.20	PASS
3	TPH	Line : 866001-866050-1(LINE_1)	837800 Cheddar	18.36	70.89	24.95	1.36	1.20	PASS
4	LTL	None	837800 Cheddar	18.36	70.89	24.95	1.36	1.20	PASS
5	LTL	XFMR : 866002-610-1 ( )	837800 Cheddar	18.34	70.93	24.95	1.36	1.20	PASS
6	LTL	Line : 866001-866050-1(LINE_1)	837800 Cheddar	18.36	70.89	24.95	1.36	1.20	PASS
7	TPH	None	838100 Muenster	26.24	61.68	24.63	0.94	1.20	FAIL
8	TPH	XFMR : 866002-610-1 ( )	838100 Muenster	31.45	56.90	24.21	0.77	1.20	FAIL
9	TPH	Line : 866001-866050-1(LINE_1)	838100 Muenster	26.91	61.84	24.64	0.92	1.20	FAIL
10	LTL	None	838100 Muenster	26.24	61.68	24.63	0.94	1.20	FAIL
11	LTL	XFMR : 866002-610-1 ( )	838100 Muenster	31.45	56.90	24.21	0.77	1.20	FAIL
12	LTL	Line : 866001-866050-1(LINE_1)	838100 Muenster	26.91	61.84	24.64	0.92	1.20	FAIL

Figure 11: Colby Zone 2 phase margin for faults at Cheddar and Muenster

Using the initial settings calculated based on the results of the sensitivity macro, the coordination macro was used to simulate faults on the Cheddar-Colby line and all adjacent lines. The results of the coordination macro showed no mis-coordinations.

3. Example 3

The third example explores how the relative strength of system impacts the apparent impedance seen by the two ends of a line with a long tap. Figure 12 shows the system under consideration.

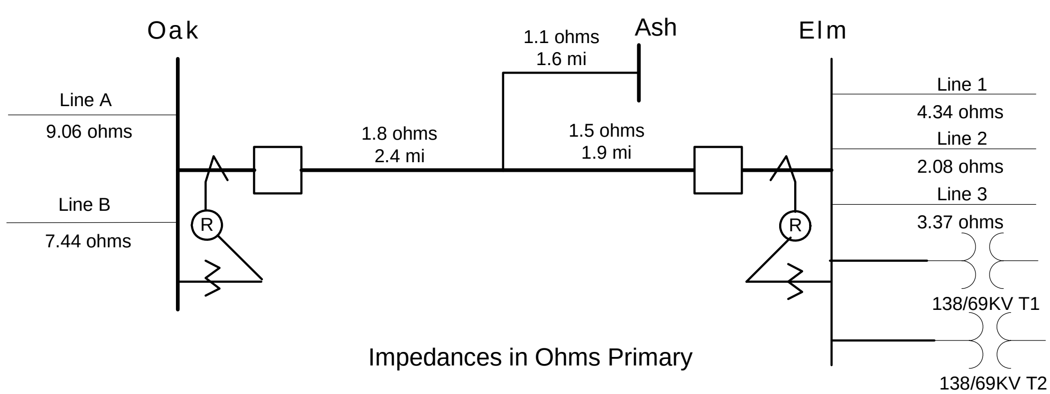

Figure 12: Example 3 system one line

This example examines a 1.6 mile tap on a 4.3 mile 69kV line. The Elm end is a much stronger source than the Oak end of the line. SIR for the Elm end is 0.43 for a fault at Ash under system normal conditions, while for Oak the SIR is 3.84. Table 3 details the apparent impedance (Zapp) for faults at Ash for various situations.

Fault scenario	Zapp seen by relay at Oak	Zapp seen by relay at Elm
3PH fault at Ash, system normal	8.4 Ω	2.75 Ω
3PH fault at Ash, strong source behind Oak out of service	14.76 Ω	2.64 Ω
3PH fault at Ash, strong source behind Elm out of service	6.95 Ω	2.83 Ω
3PH fault at Ash, Elm end open	2.91 Ω	NA
3PH fault at Ash, Oak end open	NA	2.54 Ω
SLG fault at Ash, system normal	8.54 Ω	2.88 Ω
SLG fault at Ash, strong source behind Oak out of service	14.5 Ω	2.75 Ω
SLG fault at Ash, strong source behind Elm out of service	7.67 Ω	2.92 Ω
SLG fault at Ash, Elm end open	2.98 Ω	NA
SLG fault at Ash, Oak end open	NA	2.63 Ω

Table 3: Apparent impedance for faults at Ash

As can be seen from Table 3, the effects of infeed are much larger for Oak, the weak source, than they are for the strong source, Elm. For Elm, the apparent impedance seen for faults at Ash is smaller than the Elm-Oak line impedance. Consequently, no special settings are needed at Elm to adequately protect the tap to Ash; a zone 2 reach set to protect Oak will also protect the tap to Ash. This is demonstrated in the sensitivity results shown in Figure 13; which shows that a Zone 2 element that is set to 150% of the Elm-Oak impedance has greater than 150% margin for faults at Ash for all scenarios.

ELM 6523 DIST "M2P" Zone "2" (SEL-321-3_5A); Contact Logic Code: "21P2.P"
Testing Sensitivity for remote-bus faults
The "Calc. Reach" column shows the set reach of the relay at the angle of the apparent impedance.

No.	Fault	Outages Considered (Contingencies)	Fault Location	Magn. Appz.	Angle Appz.	Calc. Reach	Act. Ratio	Des. Ratio	PASS FAIL
1	TPH	None	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
2	TPH	XFMR : 866800-982600-1 (T7)	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
3	TPH	XFMR : 866800-985600-1 ( )	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
4	TPH	XFMR : 866801-982700-1 (T8)	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
5	TPH	XFMR : 866801-985900-2 ( )	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
6	TPH	Tie : 866801-866800	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
7	TPH	Line : 866800-867300-1(LINE_1)	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
8	TPH	Line : 866800-868450-1(LINE_2)	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
9	TPH	Line : 866801-866851-1(LINE_3)	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
10	LTL	None	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
11	LTL	XFMR : 866800-982600-1 (T7)	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
12	LTL	XFMR : 866800-985600-1 ( )	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
13	LTL	XFMR : 866801-982700-1 (T8)	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
14	LTL	XFMR : 866801-985900-2 ( )	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
15	LTL	Tie : 866801-866800	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
16	LTL	Line : 866800-867300-1(LINE_1)	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
17	LTL	Line : 866800-868450-1(LINE_2)	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
18	LTL	Line : 866801-866851-1(LINE_3)	813100 OAK	3.30	69.40	4.95	1.50	1.20	PASS
19	TPH	None	813200 ASH	2.75	66.59	4.95	1.80	1.20	PASS
20	TPH	XFMR : 866800-982600-1 (T7)	813200 ASH	2.75	66.59	4.95	1.80	1.20	PASS
21	TPH	XFMR : 866800-985600-1 ( )	813200 ASH	2.77	66.61	4.95	1.78	1.20	PASS
22	TPH	XFMR : 866801-982700-1 (T8)	813200 ASH	2.75	66.59	4.95	1.80	1.20	PASS
23	TPH	XFMR : 866801-985900-2 ( )	813200 ASH	2.78	66.61	4.95	1.78	1.20	PASS
24	TPH	Tie : 866801-866800	813200 ASH	2.83	66.87	4.95	1.75	1.20	PASS
25	TPH	Line : 866800-867300-1(LINE_1)	813200 ASH	2.76	66.61	4.95	1.79	1.20	PASS
26	TPH	Line : 866800-868450-1(LINE_2)	813200 ASH	2.78	66.69	4.95	1.78	1.20	PASS
27	TPH	Line : 866801-866851-1(LINE_3)	813200 ASH	2.77	66.63	4.95	1.79	1.20	PASS
28	LTL	None	813200 ASH	2.75	66.58	4.95	1.80	1.20	PASS
29	LTL	XFMR : 866800-982600-1 (T7)	813200 ASH	2.75	66.58	4.95	1.80	1.20	PASS
30	LTL	XFMR : 866800-985600-1 ( )	813200 ASH	2.77	66.60	4.95	1.78	1.20	PASS
31	LTL	XFMR : 866801-982700-1 (T8)	813200 ASH	2.75	66.58	4.95	1.80	1.20	PASS
32	LTL	XFMR : 866801-985900-2 ( )	813200 ASH	2.78	66.60	4.95	1.78	1.20	PASS
33	LTL	Tie : 866801-866800	813200 ASH	2.83	66.87	4.95	1.75	1.20	PASS
34	LTL	Line : 866800-867300-1(LINE_1)	813200 ASH	2.76	66.61	4.95	1.79	1.20	PASS
35	LTL	Line : 866800-868450-1(LINE_2)	813200 ASH	2.78	66.69	4.95	1.78	1.20	PASS
36	LTL	Line : 866801-866851-1(LINE_3)	813200 ASH	2.77	66.62	4.95	1.79	1.20	PASS

Number of faults applied : 36
Number of zone 2 AppZ Failures : 0
Smallest ratio of AppZ to LineZ: 1.50
Operate for all faults: Yes

Figure 13: Elm Zone 2 phase margin for faults at Oak and Ash

Conversely, for Oak, the apparent impedance for faults at Ash are more than double the Elm-Oak line impedance when infeed is considered. At Oak, in order to ensure that all faults on the line will be cleared, the zone 2 reach is set to cover faults at Ash. As the sensitivity macro results show in Figure 14, this zone 2 setting will overreach the zone 1 setting on Line 2 out of Elm. To prevent mis-operations, the zone 2 time delay is increased to coordinate with the Line 2 settings. In a similar fashion to Example 2, a zone 4 element is implemented at Oak that will not over reach any of the lines out of Elm with a typical zone 2 time delay.

```
-------------------------------------------------------------------------------------------------------------------------
Phase Distance Elements Zone: 2; please wait ...
-------------------------------------------------------------------------------------------------------------------------
Performing reach test on lines connected at all remote buses ...

Local Zone 2 Elements:
FWD ELEMENT: 1: OAK    6519 DIST "M2P" Zone "2" (SEL-421-5_5A); Contact Logic Code: "21P2.P"
FWD ELEMENT: 2: OAK    6520 DIST "M2P" Zone "2" (SEL-311C-1_Z100_5A); Contact Logic Code: "21P2.S"
-------------------------------------------------------------------------------------------------------------------------

The "Actual Reach" column shows the reach of each element on the line in the "Fault Location" column.
This reach is displayed as a percentage of the positive-sequence line impedance.
For the FWD elements, the actual reach must be less than 50% (of the line impedance).
"IND." in the PASS/FAIL column indicates that the reach of the element extends beyond the next remote bus.
We do not search for the reach in the network beyond that bus.

                                                                                                              Des.
                                                                                 Line    Line          Actual Reach
                                                                                 Imp.    Angle          Reach % or  PASS
No. Fault   Outages Considered (Contingencies)        Fault Location             Ohms   Degrees ELEM      %   Marg. FAIL
--- -----  ----------------------------------------  --------------------------------- ------ ------- ----  ------ ----- ----
  1 TPH    None                                       Fault on LINE_1 to 867300 SPRUCE   3.37   74.03 FWD1  33.24  50.0 PASS
                                                                                                      FWD2  33.24  50.0 PASS
  2 TPH    Term. : 813200 ASH                         Fault on LINE_1 to 867300 SPRUCE   3.37   74.03 FWD1  33.24  50.0 PASS
                                                                                                      FWD2  33.24  50.0 PASS
  3 TPH    XFMR  : 866800-982600-1 (T7)               Fault on LINE_1 to 867300 SPRUCE   3.37   74.03 FWD1  33.24  50.0 PASS
                                                                                                      FWD2  33.24  50.0 PASS
  4 TPH    XFMR  : 866800-985600-1 ( )                Fault on LINE_1 to 867300 SPRUCE   3.37   74.03 FWD1  40.45  50.0 PASS
                                                                                                      FWD2  40.45  50.0 PASS
  5 TPH    XFMR  : 866801-982700-1 (T8)               Fault on LINE_1 to 867300 SPRUCE   3.37   74.03 FWD1  33.24  50.0 PASS
                                                                                                      FWD2  33.24  50.0 PASS
  6 TPH    XFMR  : 866801-985900-2 ( )                Fault on LINE_1 to 867300 SPRUCE   3.37   74.03 FWD1  40.84  50.0 PASS
                                                                                                      FWD2  40.84  50.0 PASS
  7 TPH    Tie   : 866801-866800                      Fault on LINE_1 to 867300 SPRUCE   3.37   74.03 FWD1   0.00  50.0 PASS
                                                                                                      FWD2   0.00  50.0 PASS
  8 TPH    Line  : 866800-868450-1(LINE_2)            Fault on LINE_1 to 867300 SPRUCE   3.37   74.03 FWD1  42.30  50.0 PASS
                                                                                                      FWD2  42.30  50.0 PASS
  9 TPH    Line  : 866801-866851-1(LINE_3)            Fault on LINE_1 to 867300 SPRUCE   3.37   74.03 FWD1  37.14  50.0 PASS
                                                                                                      FWD2  37.14  50.0 PASS
 10 TPH    None                                       Fault on LINE_2 to 868400 POPLAR   2.08   78.35 FWD1  71.25  50.0 FAIL
                                                                                                      FWD2  71.25  50.0 FAIL
 11 TPH    Term. : 813200 ASH                         Fault on LINE_2 to 868400 POPLAR   2.08   78.35 FWD1  71.15  50.0 FAIL
                                                                                                      FWD2  71.15  50.0 FAIL
 12 TPH    XFMR  : 866800-982600-1 (T7)               Fault on LINE_2 to 868400 POPLAR   2.08   78.35 FWD1  71.25  50.0 FAIL
                                                                                                      FWD2  71.25  50.0 FAIL
 13 TPH    XFMR  : 866800-985600-1 ( )                Fault on LINE_2 to 868400 POPLAR   2.08   78.35 FWD1  97.66  50.0 FAIL
                                                                                                      FWD2  97.66  50.0 FAIL
 14 TPH    XFMR  : 866801-982700-1 (T8)               Fault on LINE_2 to 868400 POPLAR   2.08   78.35 FWD1  71.25  50.0 FAIL
                                                                                                      FWD2  71.25  50.0 FAIL
 15 TPH    XFMR  : 866801-985900-2 ( )                Fault on LINE_2 to 868400 POPLAR   2.08   78.35 FWD1  99.61  50.0 IND.
                                                                                                      FWD2  99.61  50.0 IND.
 16 TPH    Tie   : 866801-866800                      Fault on LINE_2 to 868400 POPLAR   2.08   78.35 FWD1   0.00  50.0 PASS
                                                                                                      FWD2   0.00  50.0 PASS
 17 TPH    Line  : 866800-867300-1(LINE_1)            Fault on LINE_2 to 868400 POPLAR   2.08   78.35 FWD1  76.61  50.0 FAIL
                                                                                                      FWD2  76.61  50.0 FAIL
 18 TPH    Line  : 866801-866851-1(LINE_3)            Fault on LINE_2 to 868400 POPLAR   2.08   78.35 FWD1  81.28  50.0 FAIL
                                                                                                      FWD2  81.28  50.0 FAIL
```

Figure 14: Oak Zone 2 Phase element reach on remote lines

Using the initial settings calculated based on the results of the sensitivity macro, the coordination macro was used to simulate faults on the Oak-Elm line and all adjacent lines. The results of the coordination macro showed no mis-coordinations.

VI. Fault Location challenges on tapped lines

The effects of infeed for faults on a tapped transmission line also presents a challenge with fault locating. Many numerical relays use an impedance-based single-ended method to calculate the fault location. Single-ended fault locators use the apparent impedance seen by one end of the line to calculate the fault location [3]. But as has been demonstrated in the examples previously discussed, the apparent impedance seen by the relays may not accurately reflect the actual line impedance from the terminal to the fault, especially when the fault is located on a tap. It is important to be aware that single-ended fault locations will not be accurate when a fault is located on a tap. If the fault locations provided by the relays at each end of the line add up to greater than the line length on the path between the two terminals, this can be a good indication that the fault is located on the tap. Two-ended fault locating tools, including off-line analytical tools can improve the fault location estimate [3].

Fault Indicators can be applied on the tap to help locate faults. Since the tap is radial, fault indicators can be applied at the start of the tap. If a fault occurs on the tap, the flashing light or LED on the fault indicator will direct line crews that the fault is located on the tap. For faster restoration small, lightweight current sensing devices can be installed at tap locations. These devices can provide fault direction to SCADA/EMS to allow operators to open disconnect switches to isolate the fault and restore unaffected customers more quickly [4].

VII. Conclusion

Long taps on transmission lines can create protection challenges when the apparent impedance seen by the relays for a fault on the tap is greater than the impedance of the main line section. When developing relay settings, fault studies should be performed to determine the apparent impedance for faults on the tap under different system scenarios. Some factors that will impact the apparent impedance include:

- The length of the tap
- The location of the tap along the main line.
- The relative strength of the line ends.

Sensitivity and coordination macros are useful tools to help the system protection engineer ensure that protection requirements are met and coordination with the surrounding system is maintained.

When the apparent impedance for faults on the tap is larger than the impedance of the line, care must be taken to coordinate with settings on remote lines. For cases with very long taps, very slow zone 2 timers may be required to coordinate with surrounding relays. In these instances, it may be helpful to implement communication-aided tripping to speed clearing for faults on the tap to avoid stability issues. For locations where communication-aided schemes are not considered cost effective, the implementation of an additional “Short Zone 2” element that does not overreach any of the remote lines’ Zone 1 settings can provide faster clearing for portions of the line.

Finally, it is also important to remember that single-ended fault locations provided by numerical relays will not be accurate for faults located on the tap. Fault locating tools that use fault information from both ends of the line will be more accurate. Installing Fault Indicators at the start of a tap can provide indication to line crews that the fault is located on the tap.

VIII. References

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IX. Biographies

Jenny Patten, PE, *Senior Advisor, Protection & Control*, *Quanta Technology,* is a professional engineer with over 12 years of utility experience. She has extensive experience designing protection and control schemes for transmission relays, developing relay settings, and performing coordination studies using software tools like CAPE and ASPEN. She is also experienced in the review of AC/DC schematics.

Majida Malki, PE, PMP, *Senior Advisor, Regional Manager, Protection & Control, Quanta Technology,* is a professional engineer and certified project manager with over 20 years of utility and consulting experience working directly with power utilities and consulting companies. She has extensive experience in designing protection and control schemes in digital and electromechanical technologies for transmission and distribution systems, developing relay settings and coordination studies using software tools like ASPEN and CAPE, and performing power quality engineering analysis and distributed generation impact studies. Majida has knowledge of IEC 61850 and experience in performing T&D loss assessment studies and improvements.

Matt Jones, PE, *Senior System Protection Engineer, American Transmission Company,* is a professional engineer with over 30 years of experience. He has significant experience designing protection and control schemes for transmission relays, developing relay settings, and performing coordination studies using software tools like CAPE. He also has significant experience in the design of utility substations.