APPLICATION OF DISTANCE AND CURRENT DIFFERENTIAL RELAYS FOR A THREE TERMINAL LINE IN THE ENTERGY SYSTEM

Authors:

Tu Nguyen: Entergy Transmission Systems, Jackson, Mississippi

Jarrett Fuselier, P.E.: PCS2000, Baton Rouge, Louisiana

Joe Perez, P.E.: SynchroGrid Labs, College Station, Texas

Presented before the
66th Annual
Texas A&M Protective Relay Conference
College Station, Texas
April 9th – 11th, 2013

APPLICATION OF DISTANCE AND CURRENT DIFFERENTIAL RELAYS FOR A THREE TERMINAL LINE IN THE ENTERGY SYSTEM

Jarrett Fuselier P.E., PCS2000, Baton Rouge, Louisiana 70816
Tu Nguyen, Entergy Transmission Services, Jackson Mississippi, 39215
Joe Perez P.E., SynchroGrid Labs, College Station, Texas 77845

Introduction:

Many of us in system protection have the opportunity to develop line settings for two terminals lines with series capacitors, series reactors, taps, series transformers, taps, etc. These types of applications are common and require typical settings. However, not many have the opportunity to create settings for three terminal lines. This could be because the utility system might be small and no three terminal lines exist or maybe three terminal lines are not part of the utility practices. Entergy Transmission Services successfully applied a three terminal line application using line differential and distance relays. The application of line differential is straight forward since each current is being summed at each terminal but is solely dependent on communication. However, the application of distance relaying for three terminal lines application can be quite complex because of the infinite number of tap locations, lines and system impedances, and system loading and operating conditions. Therefore, careful considerations must be taken into account in order to ensure proper coordination of the protective zones.

Apparent Impedance:

A very important concept to understand when setting distance relays is the apparent impedance that the relay measures for different types of faults at different locations. During a fault, the impedance seen by the relay does not necessarily equal the actual impedance where the fault is located. This is because the relay measures the apparent impedance based on the voltage drop experienced at the relay location and the fault and the measured current at the relay location [1]. As a result, the apparent impedance depends on the infeed of current from the other terminals.

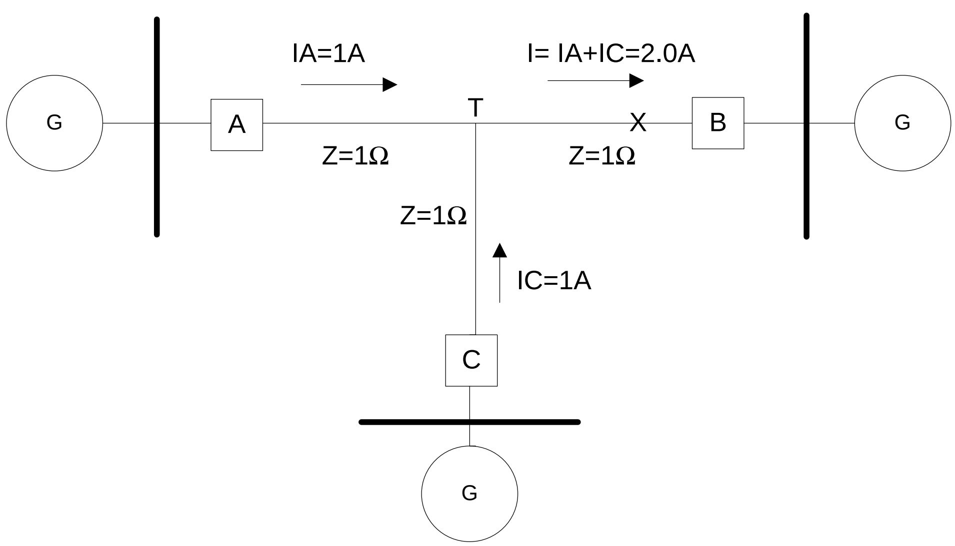


Figure 1: Apparent Impedance and Infeed Effect

Assuming no infeed from terminal C in Figure 1, the impedance as seen by the relay at terminal A is calculated as follows:

$$VA = VAT + VTF$$

$$= IA * ZAT + IA * ZTF$$

$$= IA(ZAT + ZTF)$$

$$= IA * ZAF$$

The true impedance is:

$$ZAF = \frac{VA}{IA}$$

The impedance measure at terminal A when terminal C is close is calculated as follows:

$$VA = VAT + VTF$$

$$= IA * ZAT + (IA + IC) * ZTF$$

$$= IA * ZAT + IA * ZTF \ + IC * ZTF$$

$$= IA * (ZAT + ZTF) + IC * ZTF$$

$$Zapp = \frac{VA}{IA} = \ ZAF + \frac{IC}{IA} * ZTF$$

Zapp is the apparent impedance that the relay at terminal A sees when terminal C is closed.

$\frac{IC}{IA}$ is the infeed factor for the relay at terminal A.

$\frac{\text{IC}}{\text{IA}}*\text{ZTF}$ is the error factor that is observe as a result of the infeed.

For our example in Figure 1, the actual impedance ZAF as seen by the relay at terminal A when terminal A is open is:

$$Zactual = \ 2\Omega$$

However, when terminal C is closed, the Zapp for a fault at F as seen by the relay at terminal A is:

$$Zapp = \ 2\Omega + \frac{1A}{1A} * 1\Omega = 3\Omega$$

If the zone relay was set using the actual impedance, the infeed effect will cause the relay to under-reach and not be able to see the fault. As a result of closing terminal C, the infeed factor has increased the apparent impedance that the relay sees at terminal A and in effect reduces the reach of a zone relay. This means that the zone impedance coverage needs to be increased. This infeed effect on the zone mho characteristic for the same fault location can be seen in Figure 2.

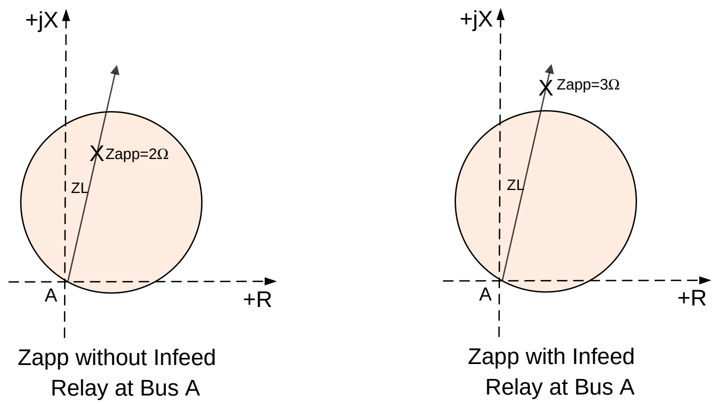


Figure 2: Effect of Infeed on Apparent Impedance

Now consider the system in Figure 3, where we experience an outfeed effect instead of a infeed effect.

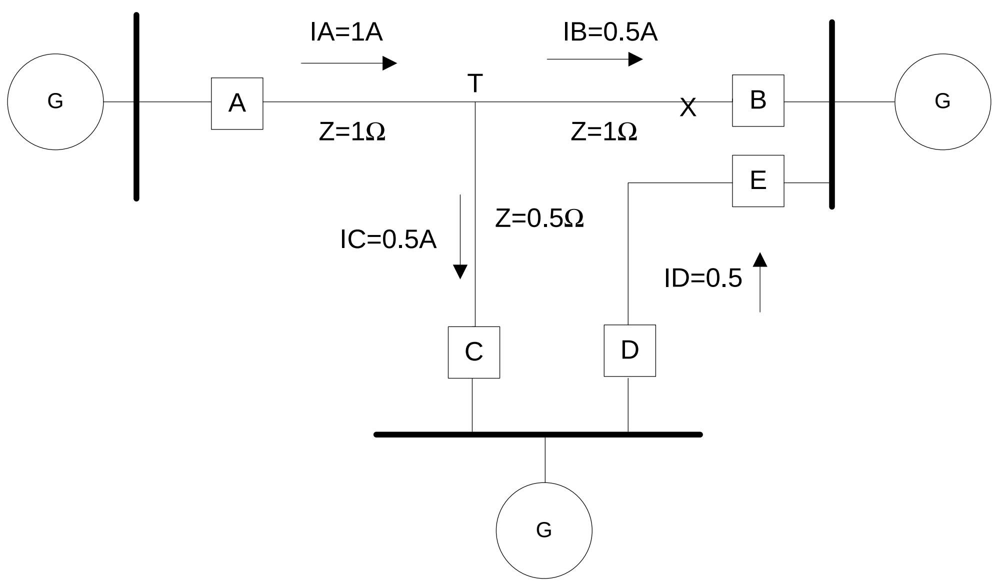


Figure 3: Apparent Impedance and Outfeed Effect

$$Zapp = 2\Omega - \frac{0.5A}{1A} * 1\Omega = 1.5\Omega$$

In this case, the outfeed of current from terminal C causes the relay at terminal A to see an apparent impedance of 1.5 ohms. However, the actual impedance from terminal A to the fault is 2 ohms. Therefore, the outfeed effect will cause the relay to overreach. Additionally, since the current is flowing out of terminal B, the relay might declare this as an external fault and if there is a blocking scheme being implemented, the relays may never trip for an internal fault.

As expressed in the above examples, the apparent impedance measured by the distance relay is mostly affected by the current contributions at the various line terminals. As a result, the Zone 1 and Zone 2 reach impedances must be determined based on the system conditions of the application by looking at the apparent impedance seen by the relay.

Entergy Application:

A three terminal line application was created in the Entergy system in order to provide transfer capability for a new generation facility at Rain Carbon. The previous 69kV system was composed of a two terminal 69kV line that extended from Catalyst to Choupique with Lone Star as tap. See Figure 4. A 69kV breaker was installed at Lone Star, which created the three-terminal line system as shown in Figure 5.

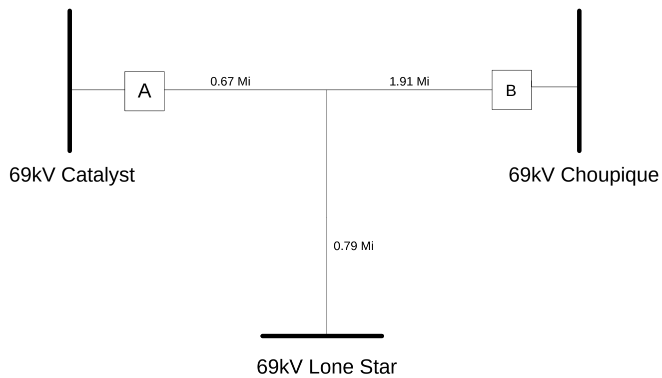


Figure 4: Lone Star Substation as Tap

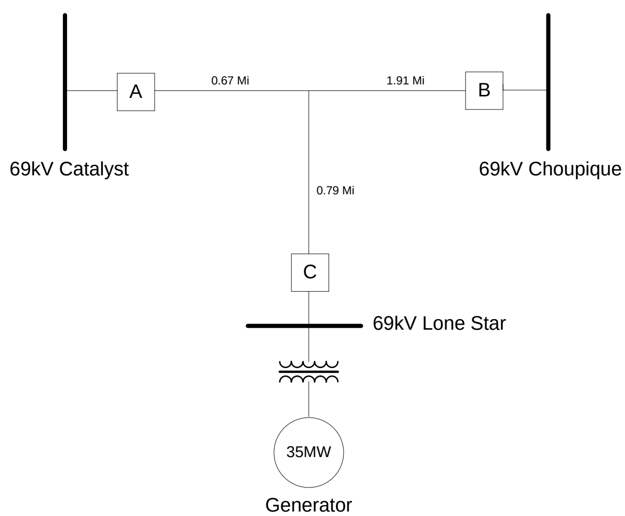


Figure 5: Lone Star as Part of a Three Terminal Line System

The main problem presented by the addition of the three-terminal line configuration was the effect of the mid-line infeed on the distance elements. For this application, the distance relay located at Catalyst will measure the current and voltage only at its terminals. A fault on the section between the tap point and Choupique will "appear" to be farther away from the perspective of the distance relay at Catalyst. The effect of the infeed from Lone Start is to reduce the reach of the bus at Catalyst relay since the Choupique current is not accounted for at the Catalyst relay. To overcome this, we have to use what is known as the apparent impedance. This takes into account the extra infeed current in determining the necessary reach to cover the line. The apparent impedance at Catalyst for the fault near Choupique can be determined as follows:

$$Zapp\ @\ Catalyst = \frac{V@\ Catalyst}{I\ @\ Catalyst} + \frac{I\ @\ Catalyst}{I\ @\ Choupique} * Z(tap - Choupique)$$

$$\frac{I\ @\ Catalyst}{I\ @\ Choupique}\ is\ known\ as\ the\ infeed\ ratio$$

$$Z(tap - Choupique)\ is\ the\ impedance\ from\ the\ tap\ point\ to\ Choupique.$$

This apparent impedance concept along with the calculated infeed ratio is what is used to determine Z2 reach as well as the pilot reach that will be used in conjunction with the communication scheme. It does not apply to Z1 since the absence of infeed, such as an open terminal, will cause the relay to overreach. This overreaching applies to Z2 and Zpilot as well, which is the reason that the reverse looking reaches will need to be extended to cover this scenario. The reverse reach is used with the communication scheme as well; it provides the identifying signal for an out of zone fault for which the scheme should not operate. The Z3 reach would significantly be increased as well due to the infeed not only at the mid-line tap point but also at the remote bus since Z3 is required to provide backup coverage for lines beyond this remote bus. This brings up the importance of load encroachment features of the relays to ensure that optimum loadability of the line can be accomplished. Entergy decided to use a SEL 311L and SEL 421 for primary and backup protection as shown in Figure 6. The settings are explained in the following section.

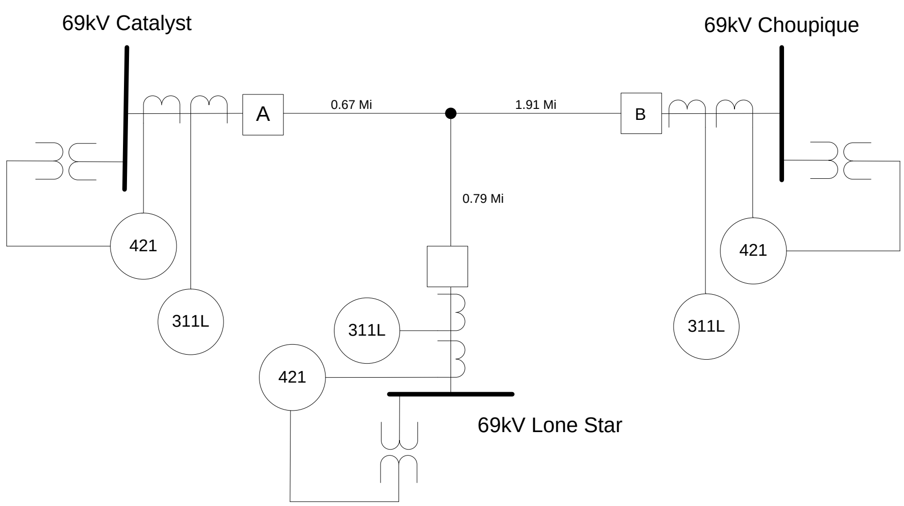


Figure 6: System Oneline

Application Relay Settings:

Like any other utility, Entergy has implemented a relay philosophy for its zones of protection. Entergy uses Zone 1, Zone 2, Zone 2 Pilot, Zone 3 Reverse, Zone 3 Forward, and Zone 5 Extended Pilot. The system information for the three-terminal line application is shown in Table 1.

System Voltage = 69kV	Choupique-Tap	Catalyst-Tap	Lone Star-Tap
PT	600	600	600
CT	240	400	400
Z1Mag	0.57	0.35	0.41

Z1Ang	72.3	66.8	66.9
Z0Mag	1.82	1.09	1.28
Z0Ang	76	74.2	74.2
Line Length	1.91	0.67	0.79

Table1: Line Information

Directional Elements:

The negative and zero sequence directional elements of the distance relays are based on the impedance settings of the Z1 MAG and Z0Mag and are automatically calculated for two terminal line applications. However, for three terminal line applications, the manufacture recommends to calculate these values manually according to reference [1].

The directional elements for this application are calculated follows:

For Terminal R:

$$Z2F = 0.5 * (ZRTap + \frac{ZSTap * ZTTap}{ZSTap + ZTTap}$$

ZRTap is the positive sequence impedance from station R to the Tap point

ZSTap is the positive sequence impedance from station S to the Tap point

ZTTap is the positive sequence impedance from station T to the Tap point

Where:

Station R = Catalyst Station S = Choupique Station T = Lone Star

ZRTap = 0.13792+j032256 ZSTap = 0.28896+j0.90272 ZTTap = 0.1632+j0.3808

Inserting values into the Z2F formula above,

$$Z2F = 0.31$$

For Z2R,

$$Z2R = Z2F + 0.1$$

$$Z2R = 0.32 + 1 = 0.42\ ohms$$

In a similar manner, the zero sequence directional elements were calculated as follows:

$$Z0F = 0.5 * (ZRTap0 + \frac{ZSTap0 * ZTTap0}{ZSTap0 + ZTTap0}$$

ZRTap0 is the zero sequence impedance from station R to the Tap point

ZSTap is the zero sequence impedance from station S to the Tap point

ZTTap is the zero sequence impedance from station T to the Tap point

Where:

ZRTap0 = 0.296+j1.04416 ZSTap0 = 0.7376+j2.9491 ZTTap0 = 0.3488+j1.232

Applying Z0F,

$$Z0F = 0.99\ ohms$$

For Z0R,

$$Z0R = Z0F + 0.1 \qquad Equation\ (4)$$

$$Z0R = 0.99 + 0.1 = 1.09\ ohms$$

The directional settings for all three terminals are show in Table 1.

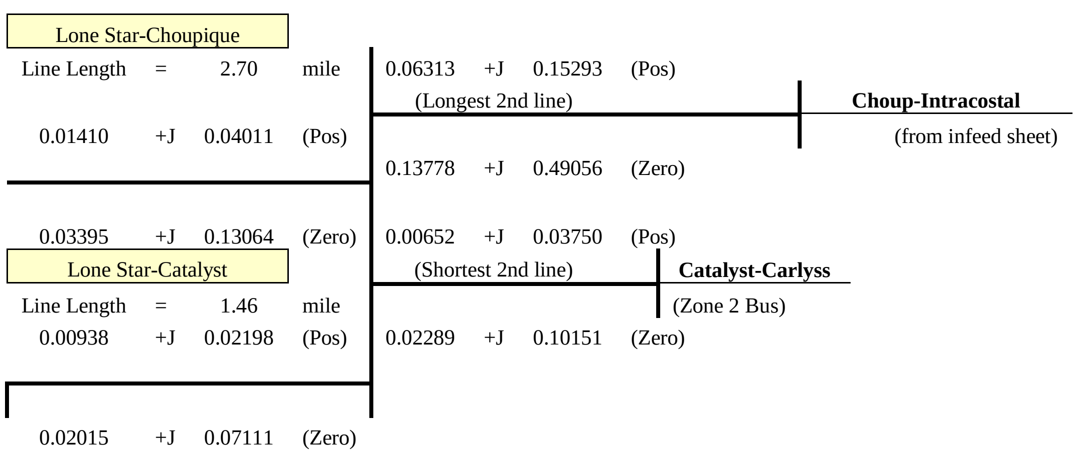
Directional Element	Choupique	Catalyst	Lone Start
Z2F	0.34	0.32	0.34
Z2R	0.44	0.42	0.44
Z0F	1.09	0.99	1.04
Z0R	1.19	1.09	1.14

Table 2: Directional Elements

Zone 1 Settings:

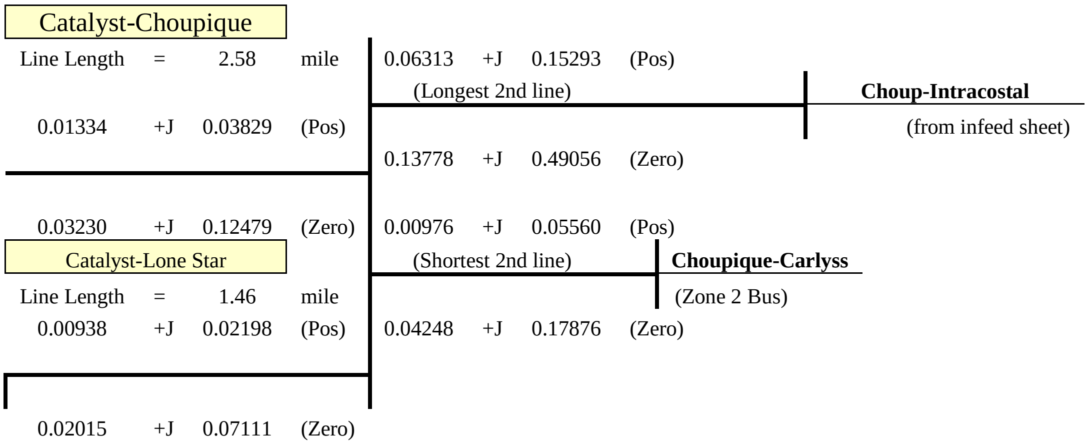
The Zone 1 settings need to be set so that they do not overreach any of the remote terminals. These settings are also based on the actual line impedance rather than the apparent impedance due to the current infeed. If the Zone 1 settings were based on the apparent impedance due to the current infeed, those settings could overreach the remote terminal.

Lone Star- Zone 1 Settings:



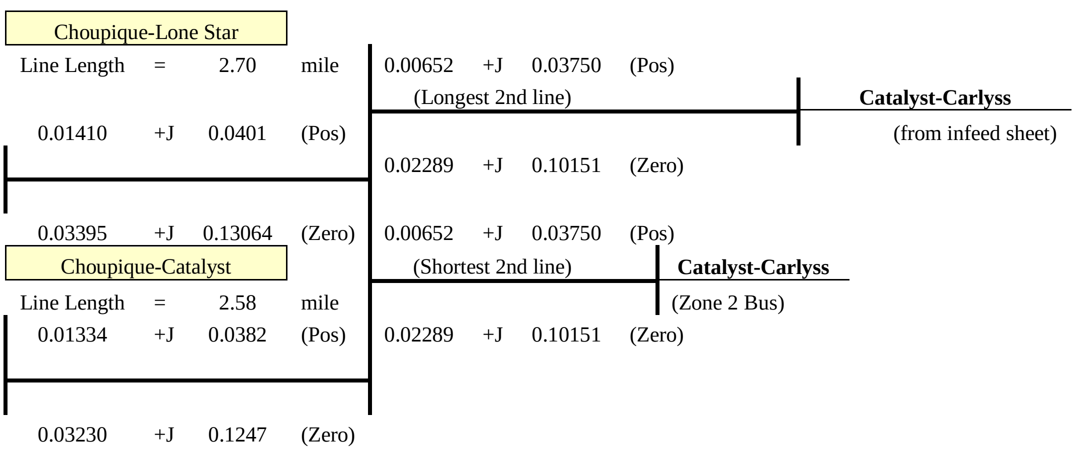
The Zone 1 settings should be selected based on the shortest line to the next terminal. In this case, Lone Star-Catalyst has the shortest impedance, and the settings are set to 80% of the line. If we were to select the Lone Star to Choupique, than our Zone 1 would overreach at the Lone Star to Catalyst terminal causing a mis-operation.

Catalyst-Zone 1 Settings:



In this case, the Zone 1 setting for this terminal is selected from the Catalyst – Lone Star-Catalyst Impedance since it is the shortest line.

Choupique- Zone 1 Settings:



The Zone 1 Impedance is selected based on the shorting impedance of the three terminals. In this case, the Choupique-Catalyst is set to 80% of the line impedance.

Zone 2 Settings:

The Zone 2 settings for a two-terminal line are usually set to 120% of the line impedance, but for a three-terminal line application the reach might have to be extended beyond 125%. In addition, the Zone 2 elements are used for the permissive trip elements or POTT schemes, and it is desirable that the Zone 2 elements detect all internal faults. Furthermore, the echo functions of microprocessor relays can be used for high speed pilot tripping at all remote terminals provided that no reverse element has issued a blocking signal.

For this three-terminal line application, the reach of the Zone 2 elements are affected by the infeed currents, and the impedance reach cannot be set as a percentage of the line impedance. It is Entergy’s philosophy to set the Zone 2 as follows:

Zone 2 is set at 100% of the secondary line impedance plus 50% of the secondary line impedance of the remote shortest line. This provides coverage beyond the 120% margin, adds sufficient arc resistance protection, and coordinates well with remote Zone 1 settings. Since the effect of the infeed needs to be considered, all calculations must be done on the calculated apparent impedance seen by the relay. The Zone 2 settings were calculated as follows:

<u>Choupique Substation:</u>

There are two parts to setting the Zone 2 element for this terminal:

- Zone 2 should be between 100% of the line impedance plus 50% of the second shortest line and 120% of the line impedance. In this case, we use 100% of the Choupique to Catalyst impedance and 50% of the second shortest line from Choupique to Carlyss.
    - 100% (Choupique- Catalyst)+ 50% (Catalyst-Carlyss) Impedances
        - Zone 2 = 1.15 @ 73.85
    - 120% Choupique-Lone Start Impedance
        - Zone 2= 1.2@70.63

Since the Zone 2 impedance for the Choupique-Lone Star section is greater than the impedance of the second shortest line, Catalyst-Carlyss, the greater of the two impedances of 1.2 ohms is taken because this would cover faults up to the Lone Star terminal.

The calculated values were inserted into the Aspen program to validate the performance of the settings.

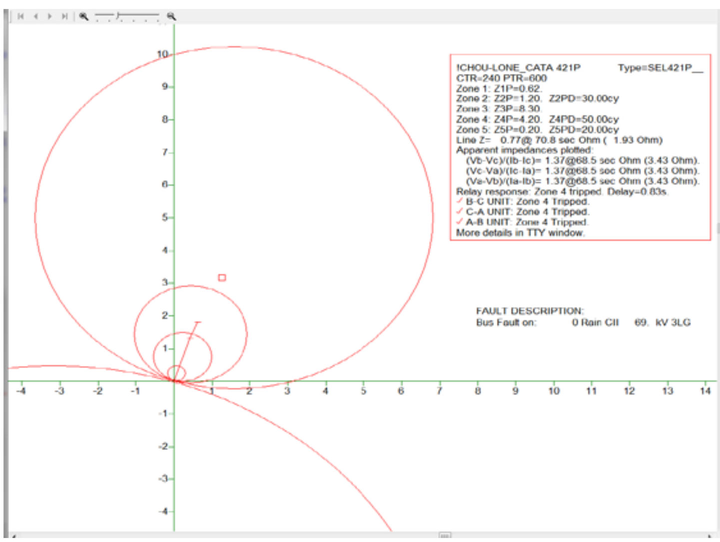


Figure 7: Zone 2 based on Calculated Values

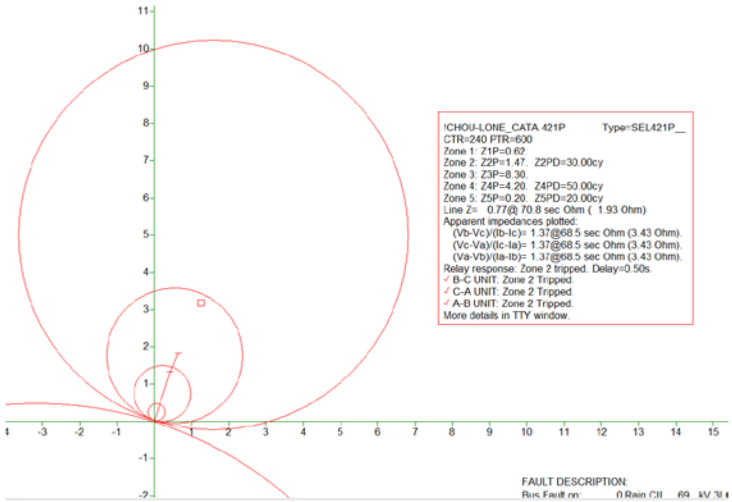


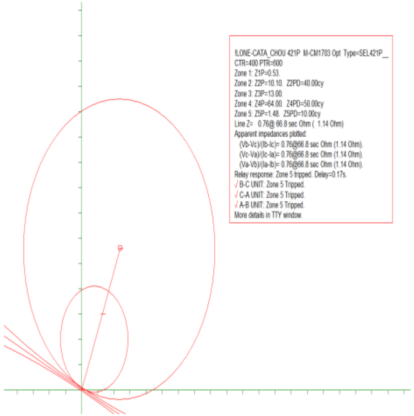
Figure 8: Zone 2 based on Apparent Impedance

Figure 7 shows that the calculated values will not see the fault for a line end fault at Lone Star. As a result, the apparent impedance for a line end fault at Lone Star was used. Therefore, the Zone 2 settings are set to 1.47 ohms. This is shown in Figure 8. Since this overreaches the shortest second line, Catalyst-Carlyss, with no infeed, the timer was increased to 30 cycles to provide coordination with the remote ends.

Catalyst Substation: The Zone 2 element for the other terminals is set as in the previous terminals. Catalyst Z2 is set to the impedance of Catalyst-Choupique plus 50% of the impedance of Choupique-Carlyss and will trip in 20 cycles. This covers all line faults with infeed. A short circuit study confirmed this.

Lone Star Substation: Lone Star Zone 2 settings proved to be more challenging due to the weak source of the small generator. A system of two Zone 2 impedances was used. Z2-1 is set to the impedance of Lone Star-Catalyst plus 50% of the impedance of Catalyst-Carlyss and will trip in 20 cycles. This Z2-1 provides fast tripping for line faults without infeed but will not cover much with infeed. Z2-2/Zp is set to 125% of the apparent impedance of a line-end fault at Tap L293-Choupique. This Zone trips in 30 cycles and provides the minimum required line coverage with consideration to infeed. It also functions as the pilot zone to ensure that the permissive overreaching scheme can function properly.

The implementation of these two impedances can be seen in Figure 9a and 9b. We can see that for bus fault on Choupique for the relay at lone Star and when the breaker at Catalyst is open, the relay sees the fault since there is no presence of infeed. This is shown in figure 9a. However, when the breaker is closed at Catalyst, the relay no longer sees the fault since it is out of reach. This is shown in Figure 9b.



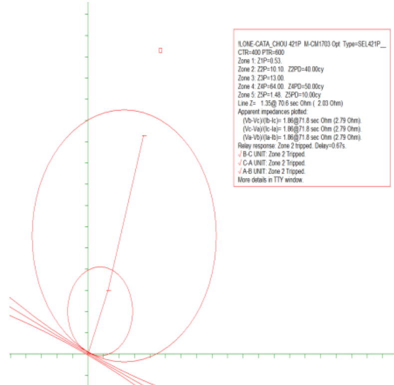


Figure 9a: Lone Star Z2app without Infeed

Figure 9b: Lone Start Z2app with Infeed

Zone 3 Forward Settings:

It is Entergy's philosophy to set Zone 3 Forward to see a fault to the end of the second longest line with line end open. Each Zone 3 Forward for each terminal was set as follows:

<u>Choupique Terminal:</u> Zone 3 Forward is set to reach to the end of the longest second line with infeed. Since we take the infeed on the second line in order to perform the infeed ratio calculation, the mid-line infeed on the three-terminal line is automatically included. On the second longest line (Catalyst-Carlyss), there are a couple of tapped lines. Expline tap proved to be the longest second line with infeed. Zone 3 Forward was increased to ensure coverage for faults on this tapped line. See Figure 10. Zone 3 Forward was set to 120% of the apparent impedance for a fault at the end of the Expline tapped line.

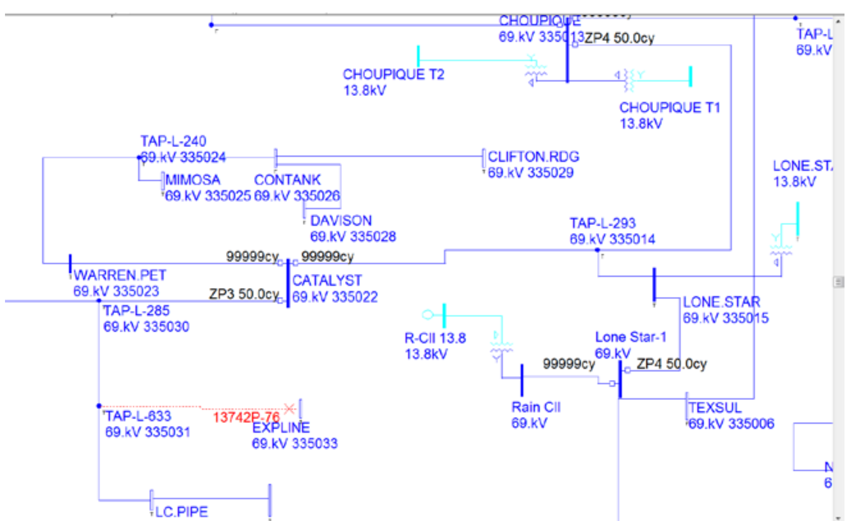


Figure 10: Choupique Zone 3 Forward Reach

Catalyst Terminal: Zone 3 Forward is set to reach to the end of the longest second line, Choupique-Intracoastal, with infeed.

Lone Star Terminal: Lone Star: Zone 3 Forward is set to a maximum reach of relay of 64 ohms secondary. Since this terminal has a very weak source, the apparent impedance of a fault on the longest second line, from Choupique to Intracoastal, is too large for this relay to see. As a result, this relay will use sequential tripping if it is required to clear a fault at the end of the Choupique-Intracoastal line.

Zone 3 Reverse Settings:

Zone 3 Reverse must be set to see any fault in the reverse direction that the other terminals' pilot zones can detect; this includes the extended pilot zones that Entergy utilizes such as Zone 2 Pilot and Zone 5 Extended Pilot.

Choupique Terminal: Zone 3 Reverse is set to 150% of Zone 2 Lone Star pilot zone-line impedance.

Catalyst Terminal: Zone 3 Reverse is set to 150% of Zone 2 Lone Star pilot zone-line impedance.

Lone Star Terminal: Zone 3 Reverse is set to loadability limits based on NERC requirements.

Table 2 below shows the summary of the Phase and Ground distance settings employed on this system.

Zone Reach	**Choupique**	**Catalyst**	**Lone Star**
Z1P Zone 1 Reach	0.62	0.61	0.53
Z2P Zone 2 Reach	1.47	2.19	10.1
Z3P Zone 3 Reach	8.3	13.8	13
Z4P Zone 4 Reach	4.2	18.8	64
Z5P Zone 5 Reach	1.15	2.6	1.48

Table 2: Impedance Setting Summary

Pilot Scheme Choices for Three Terminal Lines:

For short lines, the preferred primary method of protection is to employ a phase and residual using differential algorithms. The differential calculation is done at each terminal with the help of the communication mediums such as fiber optics. The advantage of using a current differential as opposed to step distance is that the use of CCVts or PTs is not required. This eliminates transient effects caused by the coupling capacitor, which in turn affect the distance protection algorithm. However, the current differential is solely dependent on the communication medium. Therefore, distance and blocking schemes are recommended as backup protection.

For step distance protection, the most popular communication schemes used in the industry are Permissive Overreach Transfer Trip (POTT), Directional Comparison Blocking (DCB), and Direct Underreach Transfer Trip (DUTT). Microprocessor relays now also offer special features such as echo-back functions for extra reliability and security. All of the communication schemes mentioned above work on the same principle in that they require a signal to be sent from one terminal and to be received at the remote terminal for the breaker to trip. Therefore, a receiver and transmitter must be employed via Power Line Carrier, Fiber Optic, Microwave, etc.

Fiber optic communications is available in each line of the three terminal line application. For this application, Entergy decided to use two types of communications transfer trip schemes by employing Directional Underreaching Trasfer Trip and Permissive Overreach Transfer Trip. Each distance relay at each terminal uses two communication channels using Mirrored Bit A and Mirrored Bit B to send its respective transfer trip signal to its remote terminal. Figure 11 shows the communication oneline that depicts how each port is communicating to its respective remote relay.

The DUTT scheme employs a Zone 1 distance element that will send a trip signal to the all terminals in case of any relay sees an internal fautl. In other words, when Zone 1 from any of the terminals sees a fault, a transfer trip signal is sent to the other two terminals to clear the fault. For this type of scheme, Zone 1 must not overreach beyond any of the two terminals. Because the apparent impedance can change due to the infeed during faults, Zone 1 can overreach beyond the remote terminals. As a result, careful coordination must be taken into account before this scheme can be employed in a three terminal line application. [2]

For a POTT system to work, an overreaching element such as zone 2 must be picked up and receive a signal from all terminals for any breaker to trip. As a result, this scheme must receive a permissive signal to trip from the other two terminals to trip the local breaker. This makes POTT schemes more secure, but less reliable.

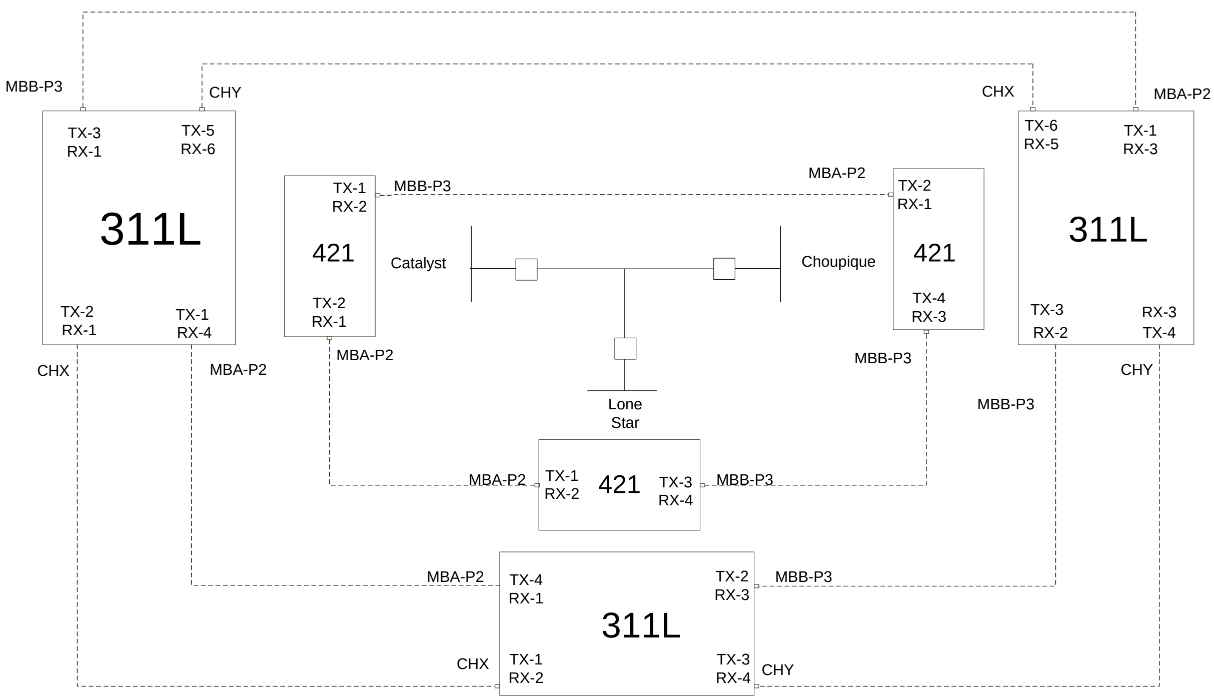


Figure 9: Three Terminal Line Communication Oneline

Differential Relay and Communications

The use of line differential relays is the preferred method for primary protection of three terminal lines. This type of scheme does not suffer from voltage variations, loading and swings [3]. I addition, the line differential are immune to the infeed error. Nevertheless, this type of scheme is solely dependent on a reliable communication system.

A current differential scheme is always dependent on the quality of the CTs that are being used to measure terminal currents. This is even more critical in a three-terminal application. If an external fault were to saturate a CT severely enough, the current it reports could be reduced to a value that is lower than the currents reported from either of the other two terminals. This would cause the 311L relay to incorrectly identify its “local” current, since the magnitude of one of the other terminal currents would be larger. This could result in the scheme improperly operating for an external fault. CTs should be matched as closely as possible in terms of the class, i.e. the maximum operating voltage, at all terminals. This would help to ensure that they would saturate nearly equally for external faults and the scheme would still be able to properly determine a trip/restrain judgment. CT ratios may differ among the different terminals. Schweitzer relays as well as other manufacturers can easily account for this internally to the relay. However, having grossly different ratios around the three terminals of the line can result in reduced sensitivity.

Communications channels are imperative for this scheme to function. As stated before, two channels are needed on each relay so that any one terminal can communicate with both of the other two relays. SEL311L relays can still correctly operate the scheme even if there is a loss of one of these channels; in fact, the scheme is set up with one channel contingency. In this scenario, there is only one relay that has all of the currents available to process the 87 elements. This relay will make the trip/restrain decision and if tripping is required, the other two terminals will be cleared via the high-speed direct transfer tripping DTT function in the relay. This is shown in Figure 11.

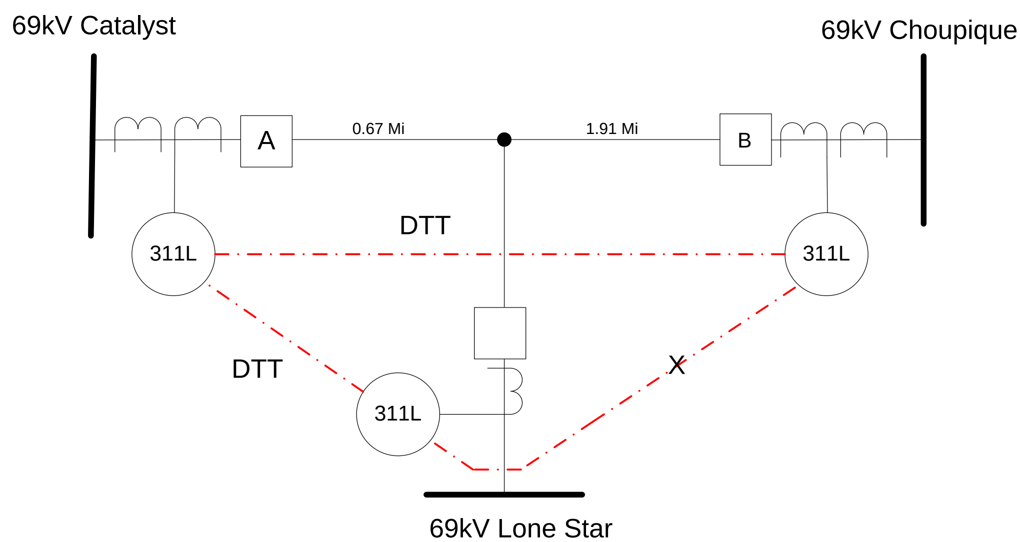


Figure 11: 311L Communications

Conclusions:

The application of three terminal lines are more challenging than two terminal applications. As explain in this paper, the apparent impedance plays an important role in this application since it can affect the zone distance elements. The effect of the infeed current from different terminals can make distance relays to underreach or overreach depending on the magnitude of the infeed. As a result, a careful short circuit study must be done before distance relays are applied. In addition to the apparent impedance, it is imperative that the proper communication systems must be in place in order to ensure that the differential relays and permissive schemes works reliably.

References:

[1] G.E. Alexander, Applying the SEL 311C Relay on Three Terminal Lines, Schweitzer Engineering Laboratories, Inc., Application Guide AG2000-12.
[2] Koehler John, Marble David, Mack Jim, Three Terminal Lines: Which is Better, Permissive Transfer Trpping Schemes, Blocking Shemes or Something Else?, Schweitzer Engineering Laboratories, Inc.
[3] NERC, The Complexity of Protecting Three Terminal Transmission Lines, Technical Report, Sep 13, 2006.

Biography:

Tu Nguyen has a Bachelor's degree in Electrical Engineering and has over 25 years of experience in relay settings and systems protection applications. Tu's relay experience has focused on relay settings for Entergy's transmission systems which has giving him the opportunity to grasp vast amount of experience from the electromechanical philosophies to the new microprocessor age.

Jarrett Fuselier graduated from Louisiana State University in 2004 with a bachelor degree in Electrical Engineering. After college, he joined PCS2000 as a system protection engineer. He has extensive experience in system protection design, analysis and relay settings. His expertise includes working on relay settings for generation and transmission systems for two-three terminal line applications. Jarrett resides in Baton Rouge, LA and is a registered professional engineer in the state of Louisiana, Arkansas and Alabama.

Joe Perez is the owner of SynchroGrid Labs. He received his B.S. degree in Electrical Engineering from Texas A&M University in 2003. After college, he worked as a field engineer installing and commissioning medium voltage switchgears, AC and DC drives, and control houses. In 2004, Joe joined the utility world as a transmission engineer for TMPA. He gained close experience with system protection design, fault analysis and how to face blackouts of a transmission system. He also was in charge of transmission system planning studies such as power flow and contingency analysis. In 2007, Joe decided to move to the relay manufacturing side and joined ERLPhase Power Technologies, previously known as NXTPhase. At ERL, he gained extensive experience in relay protection algorithms for line distance, transformer and bus differential relays.

In 2012, Joe Perez established SynchroGrid Labs to provide electric utilities with simplified power system protection design, analysis, applications, and research. Joe is the author and many relay application notes and has presented technical papers at WPRC, Texas A&M and Georgia Tech Relay Conferences. Joe is a registered professional engineer in the state of Texas and a member of PSRC, IEEE, and PES. Joe resides in the Bryan/College Station area. He can be contacted at jperez@synchrogrid.com.