ANALYTICAL TECHNIQUE TO EVALUATE IMPACT OF MUTUAL COUPLING ON TRANSMISSION LINE PROTECTION SCHEMES

By

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Abstract

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While there are numerous literatures that have addressed the impact of mutual coupling on the reliability and security of protection schemes and have provided possible mitigation solutions, there has not been adequate research and documentation presenting a comprehensive analytical approach to 1) estimate the magnitude of mutual coupling and 2) quantify the adverse impact of mutual coupling in real-life scenarios under several system faults across various types of protective elements. This should be considered as the first stage of any mutual coupling related study preceding the second stage in which the mitigation against mutual coupling is to be developed. The proposed methodology can be used to study the impact of mutual coupling on ground overcurrent relays, ground and phase distance as well as pilot protection schemes. As part of the proposed approach, EMT simulation is utilized to quantify the extent of sub-transient

overshoot and current reversal that may have adverse impact on the performance of studied relays. A real-life case study within the ERCOT network has been used to demonstrate the proposed study approach.

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Chapter 1

Introduction

In power transmission networks, there could be locations in which two or more transmission circuits are sharing right of way or common tower structures along the transmission path. This “parallel” configuration can be seen in various structural scenarios including, but not limited to, double-circuit lines on the same tower structure or single-circuit lines running in parallel in narrow corridors or even on common tower due to financial or spatial constraints. [1], [2].

In energized parallel configurations, each parallel circuit, in addition to the self-generated magnetic flux, experiences the alternating magnetic flux generated by the other parallel circuit. This is called “mutual coupling” and leads to induction of zero-sequence currents and voltages on both parallel circuits. The strength of mutual coupling has an inverse relation with the spacing between the parallel circuits and direct relation with the length of the parallel sections. The induced zero-sequence current, if not accounted for, may cause challenges for protection, control and operation personnel [1], [3], [4].

Since mutual coupling effect results in induction of zero-sequence current and voltages, it is expected that it may affect the protection schemes against ground faults, by either altering the measured fault current magnitude or direction [1].

Thus, compensation methods are required in setting the ground directional overcurrent, distance and directional comparison elements of a protection system, associated with parallel transmission lines [1]-[4].

While number of solutions have been proposed to avoid mis-operation of protective elements in presence of mutual coupling not all of these solutions are robust enough to mitigate the adverse impact of mutual coupling under all the practical scenarios [1]-[4].

A tutorial on protection schemes and recommendations on relay setting and compensation methods in presence of mutual coupling effect is provided in [1], [3]. References [2] and [5] study the application of negative-sequence component as the polarizing quantity in ground directional elements in the presence of mutual coupling. This is warranted primarily due to the negligible magnitude of negative-sequence mutual coupling impedance.

While authors in [6] have mainly focused on double-circuit lines and how associated protective elements can be improved to mitigate against mutual coupling effect, [4] addresses other possible configurations that result in mutual coupling and its impact on ground distance, ground overcurrent and directional protection schemes. Furthermore, the calculation of current flowing through the transmission line under various operating and topological conditions considering the effects of mutual coupling event has been provided in [7].

In addition to improvements and recommendations around ground directional overcurrent and distance relays, there are literatures that have considered using of other form of protection schemes to address the adverse impacts of mutual coupling. A current differential protection scheme is developed in [8] using transmission line π-equivalent model and phase coordination approach. Adaptive digital distance relaying scheme has been proposed by [9], [10] to mitigate against the drawbacks associated with conventional ground distance elements in the presence of mutual coupling. It has been argued that the proposed digital distance relaying schemes can measure the correct magnitude of apparent impedance in presence of mutual impedance and fault resistance during an inter-circuit LL and LLG faults.

While there are numerous literatures that have addressed the impact of mutual coupling on the reliability and security of protection schemes and have provided possible mitigation solutions, there has not been adequate research and documentation presenting a comprehensive analytical approach to 1) estimate the magnitude of mutual coupling and 2) quantify the adverse impact of mutual coupling in real-life scenarios under several system faults across various types of protective elements. This should be considered as the first stage of any mutual coupling related study preceding the second stage in which the mitigation against mutual coupling is to be developed.

This effort presents an analytical approach to study the impact of mutual coupling induced zero-sequence components on the operation of protection systems. A case study has been developed within the ERCOT network to evaluate the performance of directional Ground Overcurrent (GOC), Ground and Phase Distance elements as well as pilot protection schemes for neighbouring transmission lines running in close proximity of one another.

Chapter 2

Theory of mutually coupled transmission lines

2.1 An overview on transmission line impedances

Transmission Line impedances can be represented with an impedance matrix comprising of self and mutual impedances. These impedance matrices are used for any line protection system. Unlike positive-sequence line impedance, zero-sequence impedance of a transmission line depends on many factors such as earth return and tower impedances, tower footing, fault impedances as well as some extra terms caused by the coupling effect of the lines which are parallel, either the phases of the same transmission line or different transmission lines sharing right of way for a portion of their length. This cause less accuracy in zero-sequence impedances estimation than positive-sequence components of line impedance.

Zero-sequence coupling effect can cause of a mutual impedance up to 50-70% of the self-impedance, while the effect of positive and negative-sequence component on the adjacent line is negligible. This is derived considering the flux linkage related to the positive and negative-sequence components of the phase current, linking the adjacent line which depends to the relative distance and position of the conductors and results in a small value in practice [1], [2], [3].

2.1.1 Calculation of Self and Mutual Impedances

Self and Mutual impedances in transmission line is discussed in details in [12]. Carson's equation, explained in details in [11], is going to be used to derive the mathematical equivalent for self and mutual impedances.

The self-impedance of a conductor with returning ground path and the mutual impedance of any two or more parallel conductors running in close vicinity which share the returning earth path are given as follow [13]:

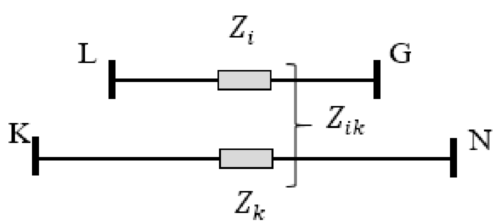


Figure 2-1 Two parallel lines with Self and Mutual impedances

$$Z_i = R + 0.000988 f + j0.0029 f \log_{10} \frac{D_e}{D_s} \tag{2.1}$$

$$Z_m = Z_{ik} = 0.000988 f + j0.0029 f \log_{10} \frac{D_e}{D_{ij}} \tag{2.2}$$

Z_i is the self-impedance of conductor *i* and Z_m is the mutual impedance between conductor *i* and *j* in (Ω/km). In these equation sets, R represents the ac resistance of the conductor in (Ω/km), D_s is the conductor Geometrical Mean Radius (GMR), D_{ij} is the distance between the parallel conductors *i* and *j* and *f* is the system frequency. $D_e = 216\sqrt{\rho/f}$ is the equivalent spacing of the earth return path, with ρ as the earth resistivity in (Ω/cm^3).

2.1.2 Calculation of Sequence Impedances

For a symmetrical three phase system, the sequence impedances can be expressed as follow:

$$\begin{aligned} Z_1 &= Z_2 = Z_i - Z_m \\ Z_0 &= Z_i + 2Z_m \end{aligned} \qquad (2.3)$$

Replacing equations 2.1 and 2.2 in 2.3 we will have the sequence impedances of symmetrical three phase system.

$$Z_1 = Z_2 = R + j0.0029 f \log_{10} \frac{D}{D_s} \qquad (2.4)$$

$$Z_0 = R + 0.000296 f + j0.00869 f \log_{10} \frac{D_e}{\sqrt[3]{D_s D^2}} \qquad (2.5)$$

In these series of equations, D is the spacing between the conductors, D_s is the conductor GMR and D_e is the earth return path as described above. $\sqrt[3]{D_s D^2}$ is the GMR of the conductor group. 2.4 and 2.5 provides the impedances in (Ω/km).

Equidistant conductors lead to small off-diagonal components in impedance matrix. However, phase arrangements in unsymmetrical three phase transmission systems can cause different magnitudes of impedances.

In unsymmetrical three phase transmission systems with transposed conductors, D in 2.4 and 2.5 can be replaced with Geometric Mean Distance (GMD) between conductors equal to $GMD = \sqrt[3]{d_{ab} d_{ac} d_{bc}}$ in which d_{ab}, d_{ac} and d_{bc} are the distances between conductors.

Using transposition is an attempt to decrease these off-diagonal components. For n numbers of the line, there should be 3^n numbers of transposition. Yet, even with transposition, the zero-sequence mutual impedance would not be zero since the zero-sequence current flows in one circuit creates quite considerable magnetic flux linkage on the other conductors [2], [3]. Equation 2.6 represents the impedance matrix of two parallel single circuit transmission lines which are completely transposed.

$$\begin{bmatrix} Z_{0aa} & 0 & 0 & Z_{0ab} & 0 & 0 \\ 0 & Z_{1aa} & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_{2aa} & 0 & 0 & 0 \\ Z_{0ab} & 0 & 0 & Z_{0bb} & 0 & 0 \\ 0 & 0 & 0 & 0 & Z_{1bb} & 0 \\ 0 & 0 & 0 & 0 & 0 & Z_{2bb} \end{bmatrix} \tag{2.6}$$

More details in deriving these equations are given in [3],[11], [13].

2.2 Different Arrangement of Mutually Coupled Lines

Many configurations can be considered for the parallel lines with mutual coupling effect on one another. In this section, some of the typical network configurations coupled lines which may cause protection challenges are provided. More detail on how mutual coupling may affect the protection system operation on these lines, will be discussed in chapter 3.

2.2.1 Isolated Mutually Coupled Lines

Two or more parallel lines can run in close proximity to each other and still induce zero-sequence currents in the other circuits even though they are electrically isolated. As an illustrative example to this effect, Figure 2-2 depicts a general case of two electrically isolated parallel lines with the equivalent network for the effect of mutually coupled impedances. These parallel lines can also have different voltage levels [2].

In the equivalent network, the effect of mutual coupling is expressed with an ideal transformer to reflect the zero-sequence mutual impedance in both circuits. The voltage drops across these circuits are given in equation 2.7 with the Z_{0M} representing the mutual coupling zero-sequence impedance between two coupled circuit derived from Carson's equations [2]. The per-unit value of this Z_{0M}can be obtained using equation 2.8.

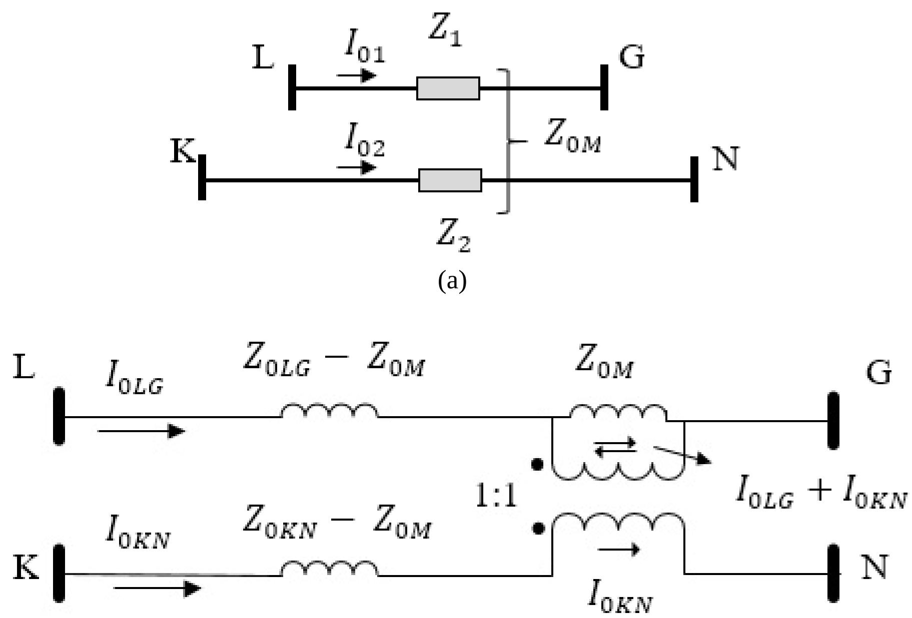


Figure 2-2 (a) Two isolated mutually coupled lines with Self and Mutual impedances
(b) Equivalent network

$$V_{LG} = Z_{0LG} I_{0LG} + Z_{0M} I_{0KN}$$
$$V_{KN} = Z_{0KN} I_{0KN} + Z_{0M} I_{0LG} \tag{2.7}$$

$$Z_{0M} = \frac{MVA_{base} * Z_{0M}\,(\Omega)}{kV_{LG} * kV_{KN}}\,(p.u.) \tag{2.8}$$

2.2.2 Mutually Coupled Lines Bused at One Ends

Parallel lines bused at one end are quite common. This configuration can happen either between two lines being bused together with a bus tie breaker open at one of the ends or between two lines bused at one side and ending in two different stations. Figure 2-3 and 2-4 illustrate two mutually coupled lines with such configurations. The equivalent network associated with these two configurations would be the same.

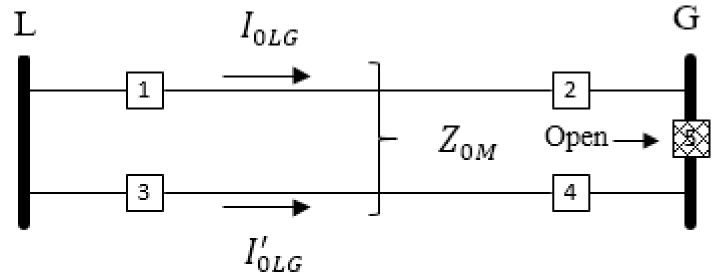


Figure 2-3 Mutually coupled lines bused at both ends with the bus tie breaker open

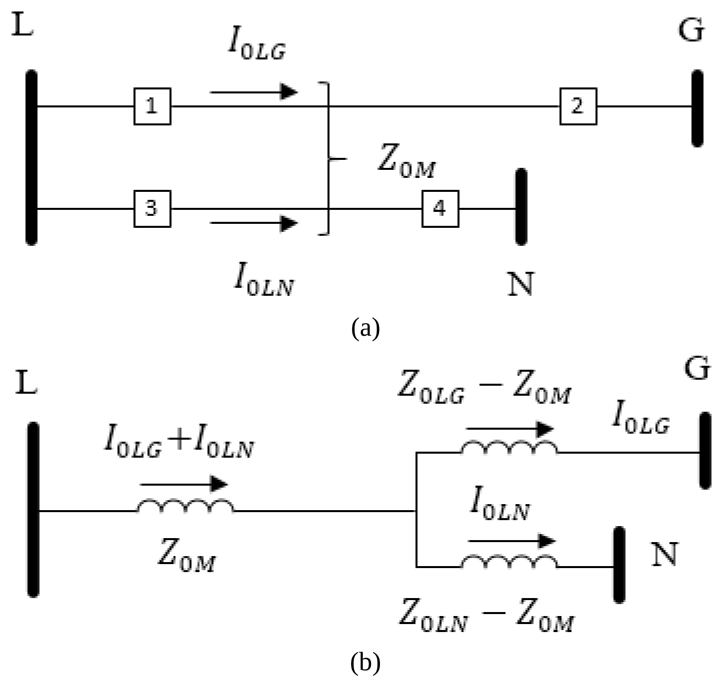
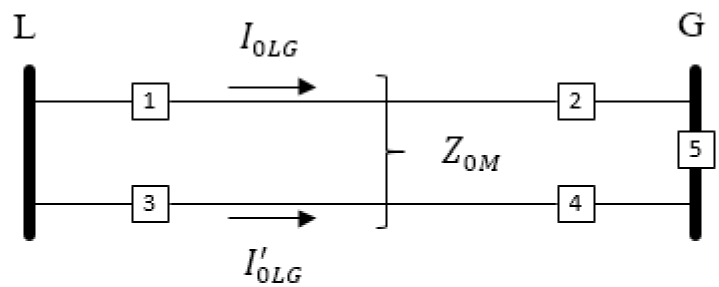


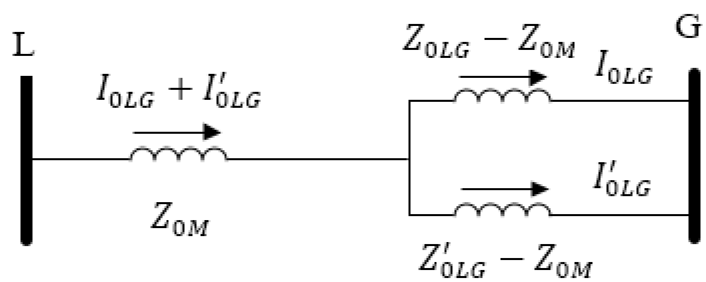
Figure 2-4 (a) Mutually coupled lines bused at one side and ending in two different stations
(b) Equivalent network

2.2.3 Mutually Coupled Lines Bused at Both Ends

Another common configuration is where the parallel lines are bused at both ends. Figure 2-5 depicts this configuration as well as the equivalent network. In this configuration, the electrical connection between two mutually coupled lines is strong enough to avoid current reversal in polarizing quantity in the virtue of mutual coupling[1].



(a)



(b)

Figure 2-5 (a) Mutually coupled lines bused at both ends (b) Equivalent network

2.2.4 Looped Mutually Coupled Lines

Comparing to the network configuration given in Figure 2-4, this network configuration is more prone to current reversal due to the presence of mutual coupling between the parallel lines as it presents a weaker electrical connection [1]. Figure 2-6 is and illustrative example for this configuration of coupled lines.

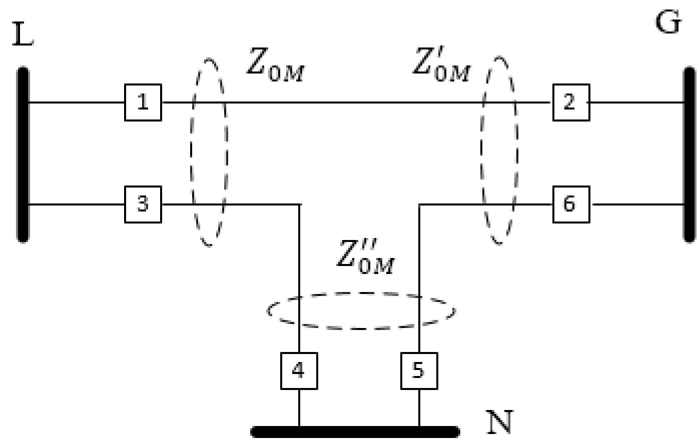


Figure 2-6 Mutually coupled lines in a loop configuration

2.2.5 Several Mutually Coupled Lines

Another possible configuration for coupled line can consist of more than two lines running in close proximity as shown in Figure 2-7 with three lines being coupled. The effect of mutual coupling is less pronounced when more than two lines are coupled together as coupling strength is shared between greater numbers of lines than only two lines. In other word, mutual coupling can have greater impact on the zero-sequence current of a third line if the other two lines are coupled with it but not coupled together [4].

There can be so many other configurations considered for parallel lines with mutual coupling effect on each other. Here a few but most common were illustrated.

In the next chapter, the effect of mutual coupling on the operation of protection system on some of these configurations will be discussed.

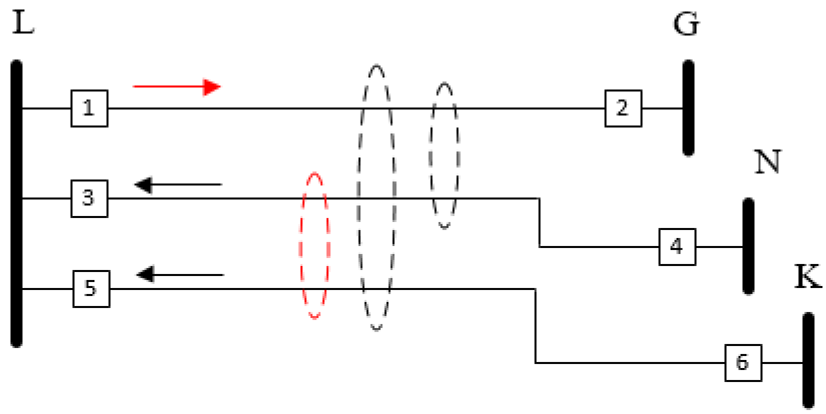


Figure 2-7 Three mutually coupled lines

Chapter 3

Mutual Coupling Effect on Transmission Lines protection system

3.1 Introduction to Mutually Coupled Transmission Line Protection

According to [2], lines are categorized as Radial/Feeders or Loop/Network when it comes to the protection purposes. Radial or Feeder lines have source at one ends supplying power to a load at the other end. During the fault this source is the only supply of positive-sequence current to the fault location and contributes to the fault current. For the large induction motor loads the short circuit contribution from those motors can be substantial and we must consider these type of the circuit as the loop one. Protection systems can de-energize the fault by disconnecting this source from the network by relay trip command, however, mutually coupled zero-sequence effect of nearby transmission line can cause the ground fault current to exist even though the positive-sequence source has been disconnected.

On the other hand, Loop or Network lines have positive-sequence sources at more than one end which contribute to the line fault and all these terminal sources must be interrupted to de-energize the fault. Again, for the parallel lines that run adjacent to each other, induced zero-sequence mutual coupling current can flow a considerable amount of fault current into the line and need to be considered at the protection design stage.

As the power network grew and expanded, the need for a reliable and secure protection system become essential specially for transmission section of the power system that runs through an open area, and therefore have a higher chance to be exposed to the faults and disturbances affecting the overall system operation.

Line protection scheme should have some specific features, which some of the most important ones are enumerated as follow [2], [13]:

- In order to maintain the stability of power system, minimize damages to the equipment, and avoid unnecessary operation of circuit breakers in un-faulted part of the transmission system, the fault clearing time of protection system should be as minimum as possible
- As the fault occurs, only the closest circuit breaker to the fault location should be tripped, causing the outage of as few transmission line or customer as possible
- In the case of failure in clearing the fault through the closest circuit breaker, the next closest breaker to the fault location should operate as a back-up protection
- Transmission line protection should have the ability to re-energize the system automatically after the fault clearance to keep the line in service for the temporary faults

Considering the above-mentioned requirements in protection system design, makes transmission line protection scheme much different from protection system being used for the other power systems' equipment such as transformers, generators etc. Meanwhile, the nature of the associated system need to be protected has a great influence on the characteristic, features and applications of the protection elements. The main three methods of transmission line protection are:

1. Time graded over current protection
2. Distance protection
3. Differential protection

In the ensuing sections, the characteristic and operation principles of some of the above line protection elements that can be affected by mutual coupling is discussed.

3.2 Over Current Protection

Time graded overcurrent protection can simply be referred as overcurrent protection, which can be considered as one of the simplest and most inexpensive protection elements and following the system changes needs readjustment or even sometimes replacement [2], [4],[13].

To apply the protection against excess current correctly, having a good knowledge of the network during the fault occurrence through system analysis is essential. Talking about the fault calculations and network analysis during the fault is out of scope of this effort. Some of the crucial data required toward correct setting and appropriate implementation of overcurrent protection are as follow [13]:

- Impedance of power Transformers, Loads, Alternators, Transmission Lines, etc.
- Power system information such as Single Line Diagram (SLD) and equipment data such as rating, transformers' inrush characteristics, etc.
- Maximum and minimum short circuit current and maximum load current values experienced by each protective device
- Starting current and locked rotor/stalling time of motors
- CT operation curve
- Decaying curve associated with the Fault current

3.1.1 Definite Time Overcurrent

In this protection scheme, a definite time setting is applied to each relay to protect specific section of the line by sending trip commands to the breaker associated to that line section. All the sections of the line have such a definite time setting which are coordinated in a way that during the fault only the faulted section is isolated after the operation of protective relays. In this coordination method, the more the relay is located toward the end of the line the less the time setting would be and as the relay gets closer to the source the time setting increases accordingly. Figure 3-1, illustrate a radial system with a source at point E and load at point A.

In this system, the relays trip time increases from Point A to Point E. Here, the definite time relay has a sensitive element which initiate time delay if the current observed by the relay gets higher than current setting [13].

There are some advantages and disadvantages associated with this method. The most important advantage could be its simplicity and the fact that in this scheme only the closest circuit breaker to the fault location will isolate the faulted section, leaving the healthy part of the line in operation. And one of the core disadvantages attributable to this scheme is that any fault close to the source will be cleared with the longest time delay while the fault current near the source is highest in value, and consequently it can have severe destructive impact on power system equipment experiencing that huge amount of fault current for such a long-time delay [13].

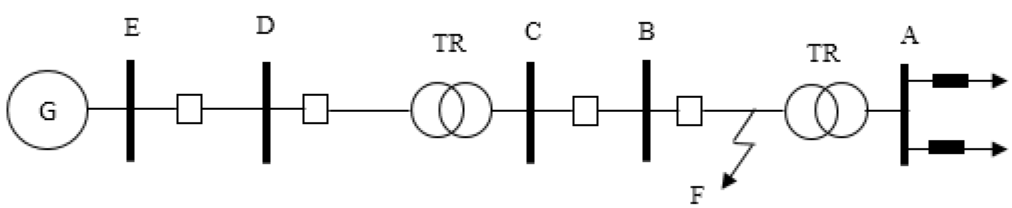


Figure 3-1 Time Discrimination on radial Systems

3.1.2 Inverse Time Overcurrent

Unlike the previous method, the discrimination can rely on the current rather than time. Therefore, the time of relay operation would change inversely with fault current. In fact, this way helps to overcome the main drawbacks of definite time scheme as the relay closest to the source will still trip in quite short time if any fault occurs near the source since it's operation time varies inversely with fault current, although it's time setting might be maximum per the other protective elements on the same line.

Figure 3-2 illustrates a part of radial system being protected by current discriminated relays. The fault current at F1 is much higher than the fault current at F4 since it is closer to the source, therefore the breaker at point C will operate faster than relay at point A. As it is obvious this scheme is working based on the fault current magnitude which varies with the fault position due to the change in impedances can be seen at the fault location. However, if there are two circuit breakers with small distance from each other, since the change in impedance is not considerable the change in the fault current would be small and this method may not operate properly [13].

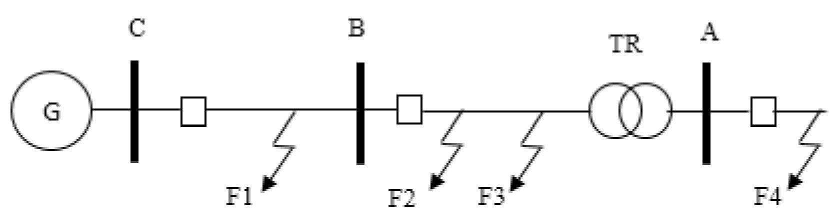


Figure 3-2 Current Discrimination on radial Systems

The idea of inverse time relays has been suggested to cover the drawbacks of time and current discriminated relays, in which the operation of relays rely on both time and current settings. The goal is to have the relay operate faster for the faults located closer to the source with higher fault current magnitude [13].

Inverse time relays are also referred to Inverse Definite Minimum Time (IDMT) relays in some of the references. The relay initiated when the current flowing the line exceeds the pick-up value, and depending on the current magnitude the operation time varies inversely. At lower magnitude of fault current, the relay operates in its inverse time current characteristic and at higher values of fault current, it acts more in its definite time mode. According to [13] and [14], there are several characteristics defined for the inverse definite minimum time relays with their mathematical descriptions, shown in the Table 1 and Figure 3-3.

Table 1 IEC 60255 IDMT characteristics' equations

Relay Characteristic	**Equation (IEC 60255)**
Standard Inverse (SI)	$t = TMS \times \frac{0.14}{I_r^{0.02} - 1}$
Very Inverse (VI)	$t = TMS \times \frac{13.5}{I_r - 1}$
Extremely Inverse (VI)	$t = TMS \times \frac{80}{I_r^2 - 1}$
Long Time Standby Earth Fault	$t = TMS \times \frac{120}{I_r - 1}$

3.1.3 Instantaneous Overcurrent

In the instantaneous overcurrent relays, when the network current seen by relay exceeds a certain amount, which called pick up setting current, the trip contact in the relay operates without any deliberate time delay. Practically the operating time of an instantaneous overcurrent relay is around a few milliseconds (0.015 to 0.05 sec) associated with the time required to energize and close the relay trip circuit's coil and trip contact [2].

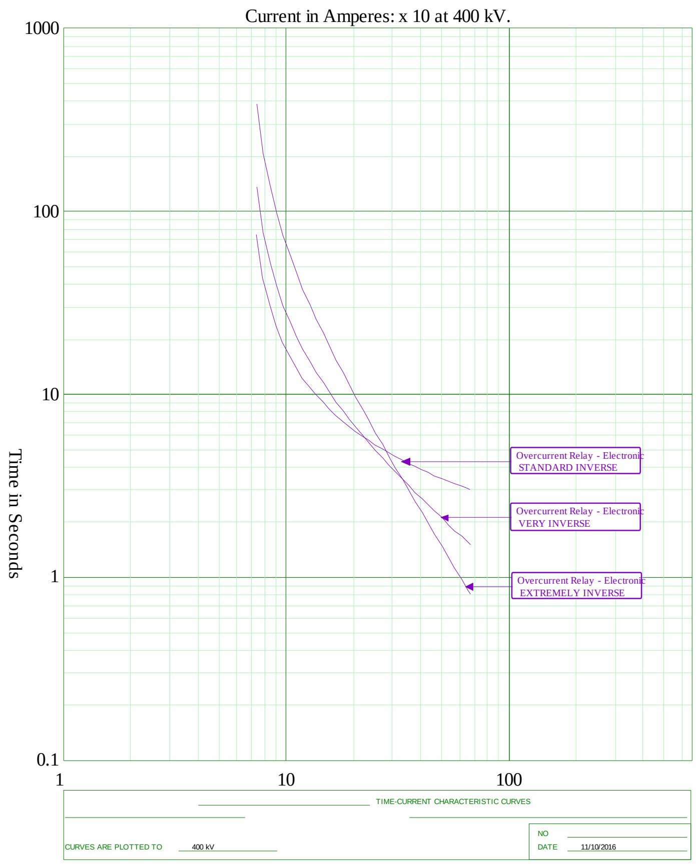


Figure 3-3 Different Inverse time relay characteristic

As a setting for pick up current, there are some conditions must be considered, such as, this value must be different with the maximum current flow for a fault at the remote end of the line. This setting needs to make the relay as sensitive as not tripping for unfaulty conditions or for the faults not located in its zone of protection [2]. "*The value must be high enough to avoid the protection tripping (whatever the circumstances) in the event of a line overload or current increase – e.g. as a result of a brief interruption on a parallel line*" [15].

As a brief comparison between the three different types of overcurrent protection mentioned above, the followings can be enumerated, and depicted as in Figure 3-4:

Inverse time overcurrent, can be considered as the slowest relay in operation but the most sensitive one (as it has the lowest pick up current value). It is usually used in coordination for load protection with high starting currents. On the other hand, definite time relay element is less sensitive comparing to inverse overcurrent as it has higher pick up value with less operating time, making it useful to avoid tripping for load inrush current. This element is use in coordination with other instantaneous and definite time elements. Instantaneous elements, are not as much sensitive as the other two, and it is desired not to operate before the downstream relays and/or for the inrush current. These are normally used without any coordination with other relays. Figure 3-4 Can help to understand the differences of these three elements from operation time perspective [2], [13], [15].

Instantaneous Overcurrent relay is very simple as its operation criterion is only the magnitude of the current without any intentional time delay, which makes it highly valuable protective element.

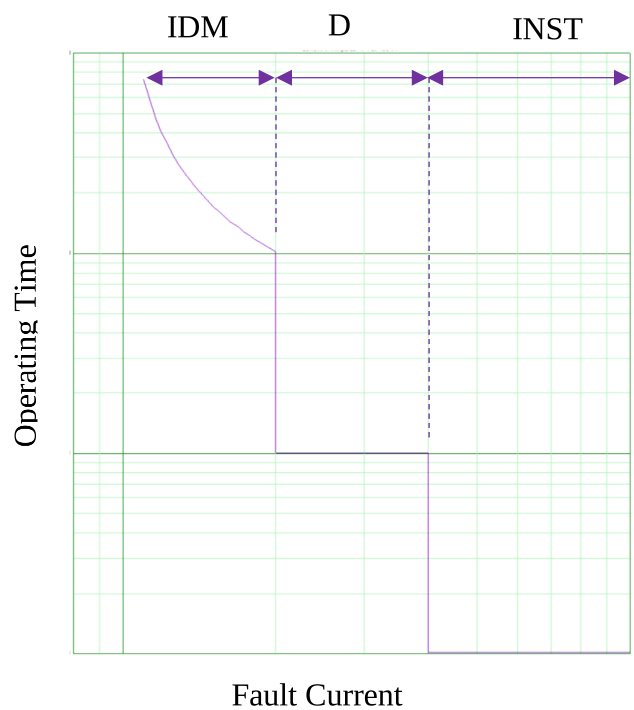


Figure 3-4 Inverse Time, Definite Time and Instantaneous Overcurrent elements

3.1.4 Directional Overcurrent

In some configuration of the network, using a non-directional overcurrent may cause unnecessary tripping of part of a network due to a fault occurrence in other part of the network. Directional elements are useful in non-radial systems, such as when parallel feeders are connecting to a generating unit.

For operation of these relays, current magnitude, time delay and directionality must be satisfied. The directionality of current flow can be identified using a reference quantity which is known as the polarizing quantity as well. Depends on the application of the relay, zero-sequence or negative-sequence current or voltage can be used for the polarizing and directional sensing element. Based on the polarizing quantity being chosen, the connection of the CT or VT through which the relay reads the value of the current or voltage may vary [2], [13], [15]. The more detail on the directional sensing methods is out of the scope of work of this effort.

3.3 Ground Distance Protection

The detail discussion on the distance element operation principles is out of the scope of this effort, however a simple explanation is given in this section. Ground distance protection is using an operating quantity and a polarizing quantity to determine the reach point and directionality respectively. For the operating quantity of negative value, the relay in fact is experiencing the fault within its operating zone and therefore trip to open the breaker. On the other hand, for a positive operating quantity Relay is not command to trip as the fault is locating out of its operating zone [2], [3], [13].

If the distance element is not able to detect the fault which is located inside its operating zone, it calls under-reach and if it operates for those faults located outside the operating zone the relay is over-reached.

3.4 Impact of Mutual coupling on Transmission Line Protection Systems

As explained in the previous chapter, since mutual coupling effect results in induction of zero-sequence current and voltages, it is expected that it only affects the protection schemes for the faults involving ground, by either altering the magnitude of measured zero-sequence component of fault current or the direction [1][1]. The induction effect of positive- and negative-sequence current is small enough to be ignored. Therefore, ground directional overcurrent elements and ground distance elements are more prone to be affected by mutual coupling and compensation methods are required in setting the ground directional overcurrent, distance and directional comparison elements of a protection system, associated with parallel transmission lines [1]-[4].

Directional overcurrent elements may use, zero-sequence current and/or voltage as polarizing quantity and zero-sequence current as operating quantity. The problem arose from the fact that in presence of mutual coupling, zero-sequence operating current measured by the relays comprised of two components, fault-based zero-sequence and induced zero-sequence current. Depending on the network configuration and fault location this induced zero-sequence component of the fault current may be additive or subtractive to the fault-based zero-sequence current. Existence of mutual coupling, can cause zero-sequence voltage reversal by inducing a voltage rise. This leads to reversal in current and consequently mis-operation of the zero-sequence polarized directional overcurrent element.

In the case that zero-sequence polarizing quantities are not high enough or do not have proper phase angles with respect to the operating quantities, the voltage rise induced by mutual coupling between parallel lines affect the directional comparison system. This kind of mis-operation in directional overcurrent element is most likely when there is either no electrical connection between the two parallel lines or the zero-sequence mutual coupling is stronger than the electrical connection between the two parallel lines. Mutually coupled lines with different kV levels form a strong mutual coupling zero-sequence. These lines can be totally isolated or being electrically connected through transformer, which forms a weak electrical connection. When the two parallel lines are electrically isolated the worst scenario is happening since the only connection among them would be the mutual coupling zero-sequence network and current reversal is more probable. Also in networks that are not zero-sequence electrically isolated, having multiple mutual coupling can lead to the current reversals [1]-[3].

Figure 3-5 serves to depict how zero-sequence mutual coupling can affect the directional comparison system. In this case, the relays at the terminal of an un-faulted line, which is experiencing the fault in its reverse direction, falsely determine the direction of the current flowing the line in forward and therefore mis-operate due to the current reversal [1]-[3].

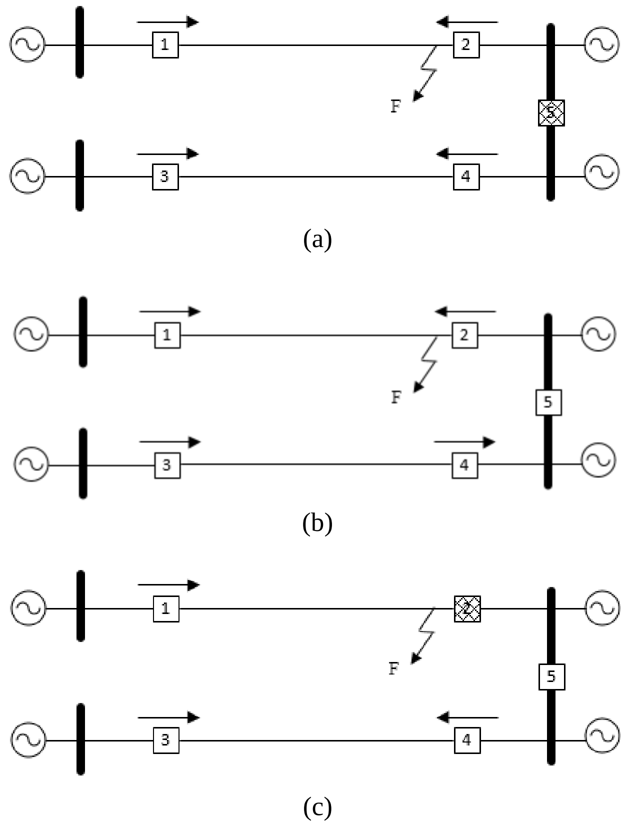


Figure 3-5 Directional Comparison system mis-operation

In this Figure 3-5 a, assume that Breaker 5 is open and cause the two parallel lines not being electrically connected. For a fault, close to breaker 2, there circulate a zero-sequence mutual coupling induced current in line 2. The relays at breaker 3 and 4 use their polarizing quantity and operating quantity to determine the direction of the fault. Calculating a negative V0/I0, relay at breaker 3 and 4 consider a forward fault, and hence trip the un-faulted line. Now considering the case in which the breaker 5 is closed and two lines are not isolated, Figure 3-5 b and c. The same mis-operation may still happen, if breaker 2 opens faster than the remote end breaker 1 due to the trip command from its protective relay. In this case, we will have two separate zero-sequence network which the only link among them is mutual coupling zero-sequence. Before breaker 2 operates, relays at 3 and 4 correctly determine the fault direction as forward and reverse respectively. However, by the operation of breaker 2, the phase relationship between the voltage and current that relays at station 3 and 4 are measuring may alter in a way that both relays see the fault in their forward direction and trip the un-faulted line due to the voltage and current reversal [3].

Mutual coupling, do not affect the current differential protection, as these protective elements compare the measured current in and out the terminal [3] and therefore, this protection element is not covered in this effort.

Mutual coupling can affect the operating and polarizing quantity of ground distance elements. The over-reach may happen when the zero-sequence current in the parallel lines are not in the same direction and under-reach may occur when parallel lines are carrying current in the same direction [1].

To eliminate the adverse impact of mutual coupling on protective elements, there are some solution suggested in various references. Some of the most important ones are enumerated as follow [1], [4]:

- Negative-sequence components can be utilized as the directional elements. Based on [4] for more than 10% mutual coupling this coupled be a good solution to avoid loss of system security in presence of mutual coupling

- Using current differential element
- Negative-sequence overcurrent as a supervision to ground directional comparison system
- Adaptive ground directional element, which take the advantage of different directional elements depending on each ground fault
- For the distance elements, reach settings need to be applied while the effect of mutual coupling is considered in the operating quantity equation
- Distance relays must be provided by the zero-sequence induced current
- There are some mutual coupling compensation methods suggested in [1] for distance elements
- Replace ground distance element in heavily mutually coupled lines with other protection elements

However, like other aspects of protection any solution is a combination of art and science therefore none of the above-mentioned solutions are the sole answers to eliminate the adverse impacts of mutual coupling. In the case of parallel lines with the effect of Mutual coupling, the new impedances of the line and mutual coupling zero-sequence current must be incorporated in the protection systems. Short circuit studies need to be performed to evaluate the polarizing quantities and directional elements. Configurations that may lead to worst case scenario and/or isolated zero-sequence networks must be taken into account.

Chapter 4

Model Development

Case study within the ERCOT network was developed to assess the impact of mutual coupling between various existing transmission lines and a future planned double circuit transmission line. This new proposed double circuit line parallels multiple existing transmission lines for nearly 56 miles in several sections along its length. The new proposed facility and all the existing facilities that are in close geographical proximity are expected to be mutually coupled. The main goal of this study was to evaluate the impact of mutual coupling on protective relays, particularly ground overcurrent (OC) and distance relays, on the existing facilities, due to the interconnection of the proposed 345 kV double circuit line. Appendix A provides an illustration of the facilities nearby this new proposed line.

The model development effort requires two key steps. The first step involves transmission line model development using a frequency dependent model in PSCAD/EMTDC software to quantify the mutual coupling impedances. The second step is to develop a short-circuit model in ASPEN OneLiner to conduct the mutual coupling in the study area.

4.1 Transmission Line Model Development

The theory behind the self and mutual impedance calculation explained in chapter 2. The transient model development was done in PSCAD/EMTDC software. EMTDC stands for the Electromagnetic Transients including DC and represents time domain differential equations and solve them using fixed time steps. This time domain solutions can be transformed to phasors and angles for further practices via built-in tools within the software [16]. As part of this effort, the frequency dependent model in PSCAD/EMTDC is developed for the proposed new line and all the neighbouring transmission lines using the following information associated with each transmission line:

- Distance between phase conductors
- Distance between phase and ground conductors
- Distance between the earth surface and phase/ground conductors
- Radius and DC resistance of phase and ground conductors
- Phase conductor bundle specifications
- Earth resistivity

Another critical parameter in estimation of mutual coupling impedances is the horizontal separation distance between each of the two parallel transmission lines included for analysis. After the separation distances being incorporated into the PSCAD/EMTDC models, estimation on the mutual coupling impedances between the proposed double circuit line and any of the existing line of interest is performed through the line constant computation module in PSCAD/EMTDC.

4.1.1 Transmission Tower and Conductors Modeling using PSCAD/EMTDC

One of the parallel sections in this analysis is selected as a representative example. As shown in Figure 4-1, the 138kV single circuit transmission line connecting Bus 3 to Bus 4 and then BUS 5, denoted as “line 2” and “Line 3”, are in parallel with the 345kV proposed double circuit line connecting Bus 1 to Bus 2, “Line 1”.

As an illustrative example, the mutual impedances estimation of the lines shown in Figure 4-1 is performed. The PSCAD/EMTDC model for the Line 1 and Line 2 is depicted in Figure 4-2, indicating that Line 1 consists of two circuits with double bundle conductors and Line 2 is a single circuit transmission lines. Type of phase and ground conductors, the value of the sag for each of the conductor, earth resistivity as well as all the separation distances between the conductors and conductors to earth are incorporated in this model.

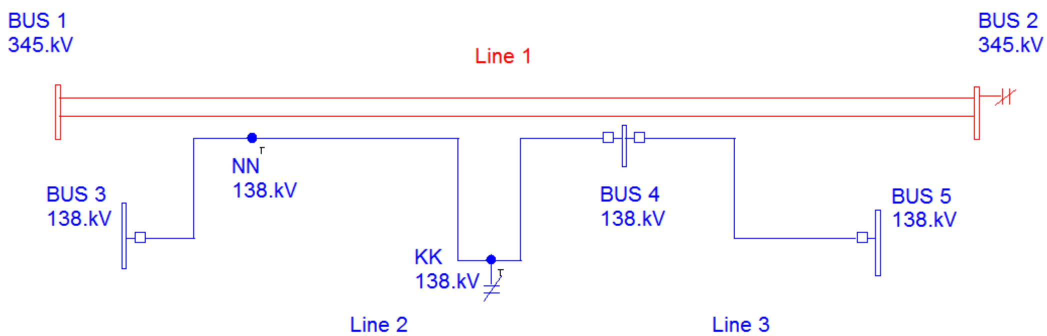


Figure 4-1 An illustrative example of mutually coupled lines - Line 1 with Line 2 and Line 3

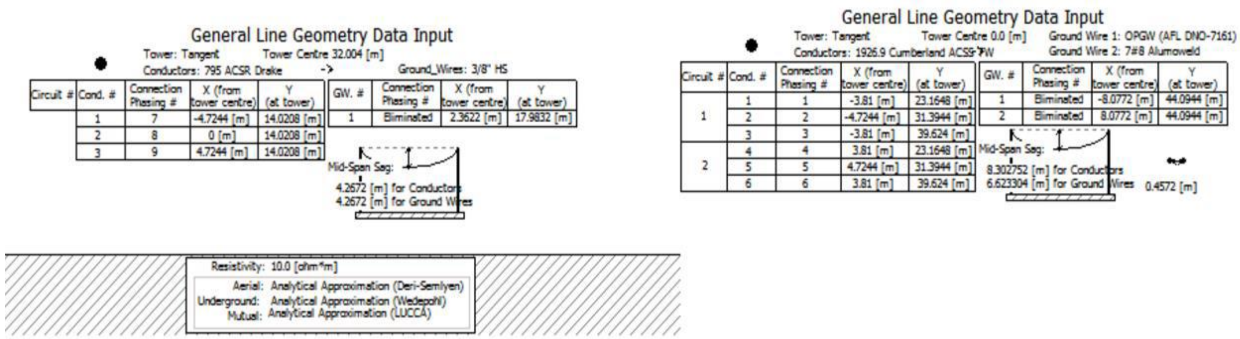


Figure 4-2 Mutual Coupling Computation using PSCAD/EMTDC – Illustrative Example

4.1.2 Self and Mutual Impedances Calculation

The constant computation module in PSCAD/EMTDC is utilized to estimate:

- Positive and Zero-sequence impedances of each circuits of the lines of interest
- Mutual coupling impedances between the circuits of Line 1
- Mutual coupling impedances between coupled lines (Line 2 & Line 3 with each circuits of Line 1)

Components of impedance matrix obtained in this method are in [ohm/m] which must be converted to per-unit values using the following formula [2]:

$$Z_{oM} = MVA_{base} * \frac{Z_{oM-OHM}}{kV_{Line1} * kV_{Line2}} \tag{4.1}$$

As a sample for the result of PSCAD estimation, calculated impedance matrix for transmission lines 1 and 2 of Figure 4-2 is provided in Appendix B (imp. Matrix of the lines 1 & 2)

4.2 Short Circuit Model Development

The 2nd step is to develop a comprehensive short-circuit model in ASPEN OneLiner to conduct the mutual coupling study for the facilities of interest utilizing the mutual coupling impedances calculated in the 1st step. An ERCOT short circuit model in ASPEN OneLiner is utilized as the starting point for model development. The mutual coupling impedances calculated as part of the first step were incrementally modeled in the study case. Finally, protective relay elements as well as pilot protection scheme for neighbouring facility must be included to develop this comprehensive model.

4.2.1 Modeling the mutual coupling impedances

In the first phase of creating the comprehensive model, we need to model transmission over-headlines based on the calculated detail impedance discussed in section 4.1. In this regard, the following important points should be taken into account:

- Percentage of mutually coupled section on each line
- Line orientation as implied by the ordering of end bus

To get the best outcome for this study, the model must be developed based on the parameters close to the values in the real case. Therefore, for the mutually coupled transmission lines, one of the most significant factors is to precisely define the length and location for each coupled segment. Furthermore, the physical layout of coupled line should be considered to determine the line orientation [17].

The coupled section demonstrated in Figure 4-1 is used to explain the implementation of the above-mentioned considerations. Line 2 and Line 3 are coupled with Line 1 for a part of their length. To implement the exact location of coupled sections on each line, the starting and ending points of the same are calculated as a percentage of the lines' length.

Figure 4-3 and Figure 4-4 depict the dialog box for entering the mutual coupling pair for the line 2 coupled with line 1 in ASPEN Oneliner. Line 2 is coupled with both circuits of 345 kV double circuit line 1. The beginning and ending percentage of mutual coupling sections on each line's length in the pair is entered in "From %" and "To %". On each line, up to 5 mutually coupled segment can be added. This coupled section is located at 48% of Line 2 (from Tapping Station NN) to 100% (ending in Tapping Station KK).

One of the other important item that must be considered in modeling these mutual impedances is lines orientation as implied by the ordering of the end buses which is shown in the top side of the dialog box in Figure 4-4. This orientation is based on the physical layout of the coupled lines. To match the orientation one may use the "swap end" button, or use the negative value of impedances rather than positive ones when using ASPEN OneLiner so that the orientation corresponds with the physical and geographical layout of the coupled lines[17]. Otherwise the short circuit analysis will not accommodate correct results.

Finally, the mutual impedances calculated through PSCAD/EMTDC, as the first step, needs to be modeled in the case study. These impedances need to be converted to per-unit values using the following Zbase [17]:

$$Z_{base} = \frac{kV_1 * kV_2}{MVA_{base}} \tag{4.2}$$

Where kV1 and kV2 are nominal kV of the two lines and MVA base is the system MVA base.

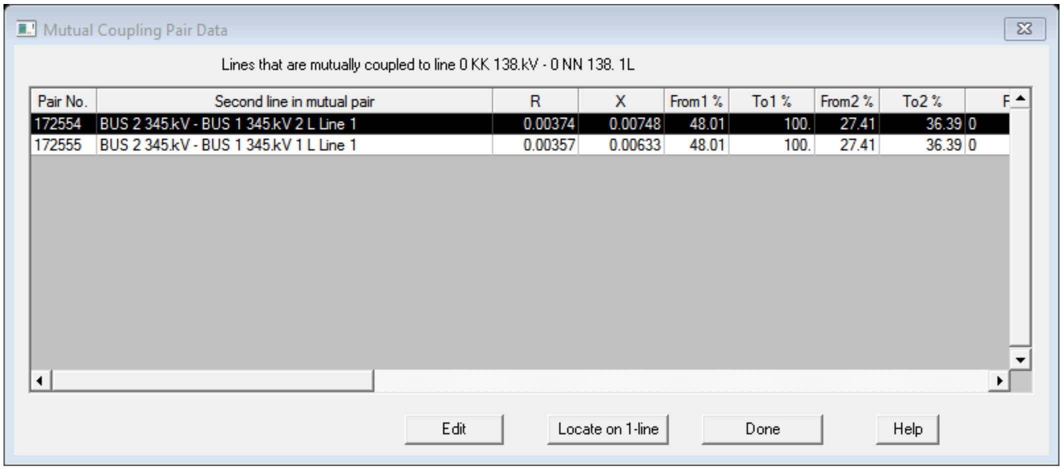


Figure 4-3 Mutual Coupling Impedance - Line 1 and Line 2

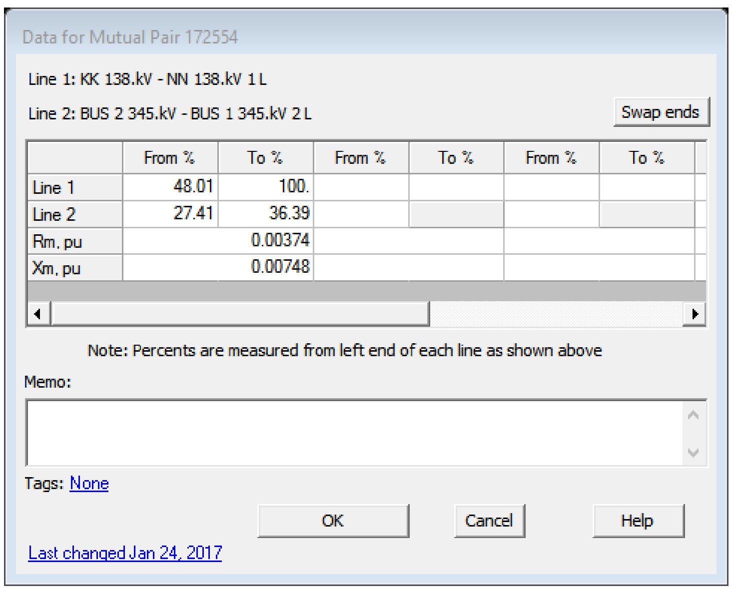


Figure 4-4 Modeling of Mutual Coupling pair - Line 1 and Line 2

4.2.2 Protection System Modeling- Ground Overcurrent and Distance Elements

In order to evaluate the impact of mutual coupling on protection system, in addition to detail impedance modeling of transmission system, discussed in previous sections, protective relay elements as well as pilot protection schemes for neighbouring facility must be included in the study model.

"Each protective element has advantages and disadvantages. Overcurrent, ground instantaneous, and ground time-overcurrent elements operate on the magnitude of the measured ground current and are typically supervised by a directional element. Distance elements are inherently directional and operate based on V/I principles. Distance elements are normally much more secure when mutual coupling is not present because they are not susceptible to source changes. Ground overcurrent elements are influenced by the change in sources over time, especially the instantaneous element. However, the ground time-overcurrent element is much more dependable because of its sensitive pickup setting, and it provides greater resistive fault coverage. For these reasons, overcurrent elements are typically applied in conjunction with distance elements, capitalizing on the benefits of both" [4].

As explained in detail, (directional) ground overcurrent and distance elements are more prone to be affected by the changes in current/voltage profile and apparent impedance measured by relay due to presence of mutual coupling. Depending on the system configuration or the operation of the circuit breakers or switches isolating some part of network from another, coupled lines may experience additive or subtractive induced mutual voltage, causing to have increased or decreased fault current seen by overcurrent elements [4]. The apparent impedance measured by distance elements can be smaller or greater than the actual system impedance due to the flow of I_{0M} in the line. This may cause the distance element over-reach or under-reach [3]. This over-reach/under-reach happens in distance elements when the mutual coupling induced current I_{0M} appears to be subtractive/additive to the zero-sequence fault current I_0. Further, the detail modeling of ground overcurrent (GOC) and distance element is discussed:

To model ground (directional) overcurrent elements (instantaneous and time-overcurrent), the following parameters are required:

- Time Element:
    - CT/PT information (ratio and location)
    - Time dial
    - Pick-Up current
    - Type of curve
    - Directionality
- Instantaneous Element:
    - CT/PT Ratio
    - Primary current (A)
    - Time Delay
    - Directionality
- Polarization method (V_0/I_0, V_2/I_2, or any other directional logic depending on the Relay manufacturer)
- Operating quantity ($3I_0$, $3I_2$, I_0, I_2)

- Characteristic angle

Figure 4-5 to 4-7, is demonstrating a model development (Settings and curve) associated with SEL421 ground overcurrent relay in ASPEN OneLiner. As it is obvious in this illustration, for polarizing quantity "V_2/I_2" is used. In some cases protection engineers, may make use of "SEL V_2 directional logic" for the SEL overcurrent relays. In this method, extra parameters are required for the directional element setting as it is shown in Figure 4-6.

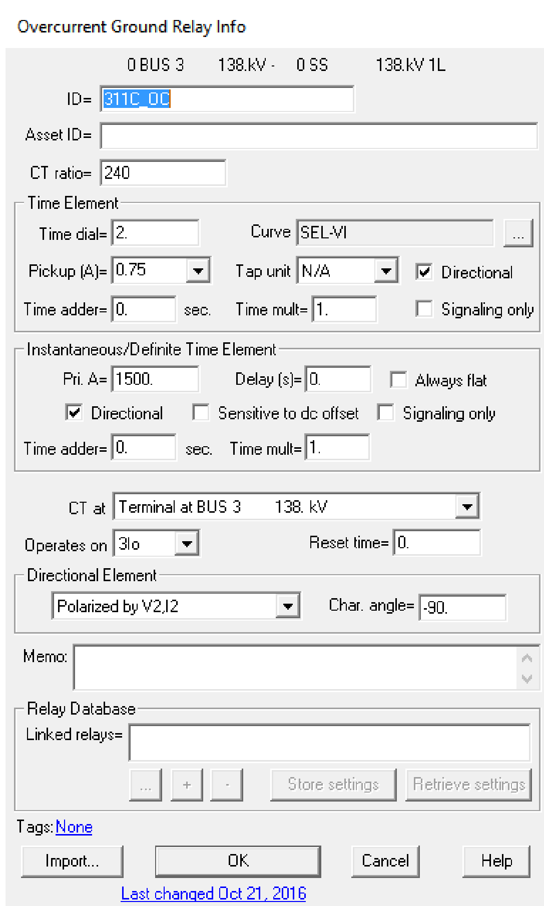


Figure 4-5 SEL421 Ground Overcurrent element – Time and Instantaneous Elements Setting

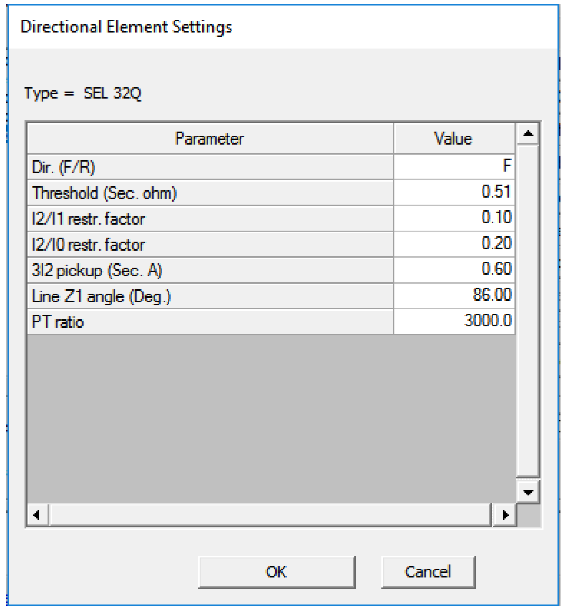


Figure 4-6 SEL421 Ground Overcurrent element - Polarization setting

To model the phase and ground distance elements following parameters are the main characteristic of the relay needs to be modeled [17]:

- CT/PT information (ratio and location)
- Basic relay technology (balanced-beam, mho, quadrilateral etc.)
- Z1, Z2, Z3 and Z4 reach in secondary ohms
- Z1, Z2, Z3 and Z4 characteristic angle in degree
- Offset impedances/angles in secondary ohms/degrees (Z2, Z3 and Z4)
- Z3 and Z4 direction (forward or reversed)
- Time delay in seconds (mostly Z2, Z3 and Z4, as Z1 time delay may not be applicable to some manufacturers' distance relays)

- Directional control (in the case that distance element is supervising the ground directional element)

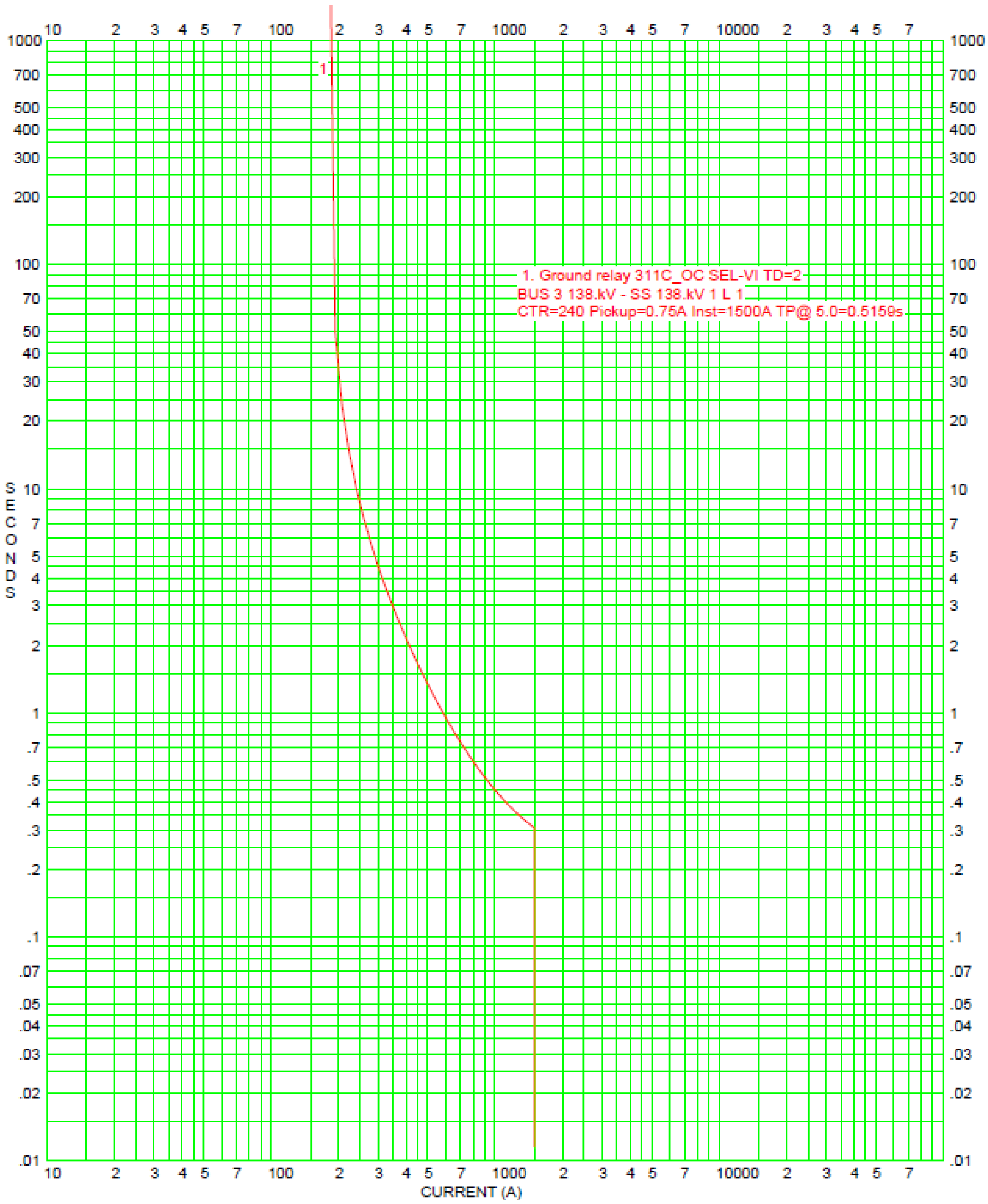


Figure 4-7 SEL421 Ground Overcurrent element Time Current Curve (TCC)

- Order of priority for ground directional element supervision
- Load-encroachment logic to set the phase distance and phase overcurrent element independent/dependent to load
- Current compensation factors (if there is any)

Figure 4-8 demonstrates a protection setting modeling associated with an SEL421 ground distance protection modeled in ASPEN OneLiner. The Mho curve of an SEL421 ground distance relay as the primary protection is given in Figure 4-9.

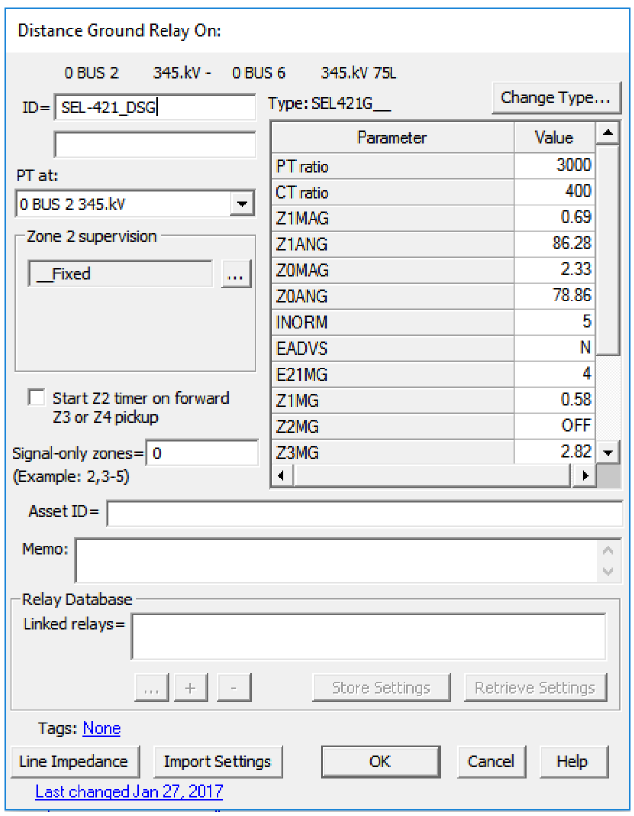


Figure 4-8 SEL421 Ground Distance element settings

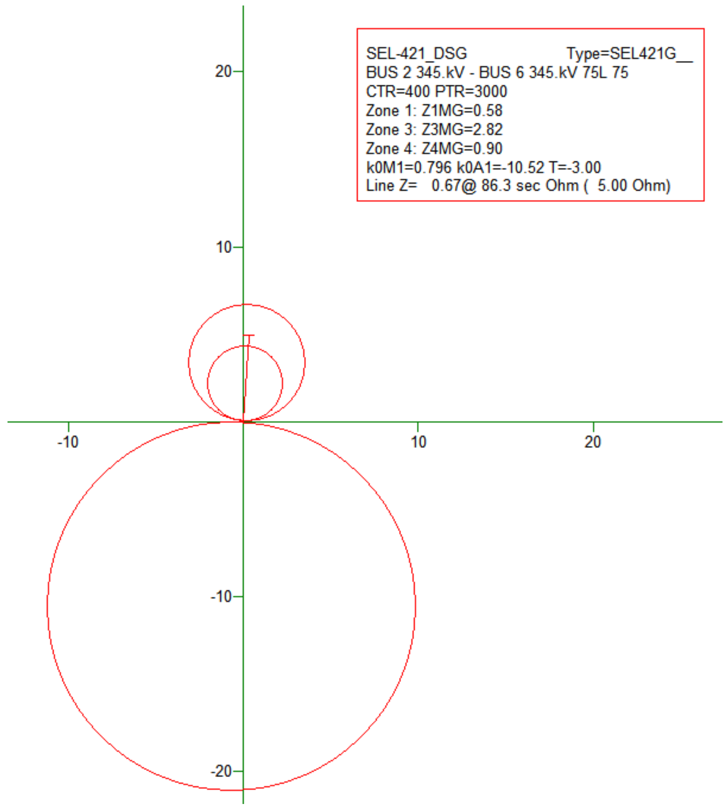


Figure 4-9 SEL421 Ground Distance element – MHO Curve

4.2.3 Protection System Modeling-Pilot schemes

Pilot protection used for lines provides the possibilities of high-speed simultaneous detection of phase- and ground-fault protection for 100% of protected section from all terminals [2]. As a part of differential protection, the Pilot protection element can be used in all voltage levels within the network and uses a communication channel to compare the terminal quantity and send an appropriate signal to maintain stability by clearing the fault in the shortest possible time. In practice, pilot schemes are used to ensure that under internal fault conditions the protective relay elements operate simultaneously to clear the fault, however mis-operation of the same would be destructive to the system operation.

As the induced zero-sequence component in presence of mutual coupling may cause alternation in the current and impedance magnitude measured by relays, pilot protection schemes may mis-operate due to the failure in fault location recognition. The study area of interest includes certain types of pilot scheme (DCB and POTT) as part of the protection system, enhancing the coordination between adjacent relays and stability concerns. Being prone to mis-operation, DCB and POTT schemes included as part of protection system of the study area, were modeled to monitor the possible impact of mutual coupling on the operation of these elements under various fault locations.

To model the pilot schemes, the protection logic of the scheme needs to be virtually modeled in the ASPEN One-liner. Following is an example for one of the DCB trip logic of the protection scheme modeled in the study case, which is also illustrated in Figure 4-10:

Z2PGS*M2P+67QG2S*Z2G*! ZLOAD+67G2T*67G2+67G4T*67G4 (101)

The description of inputs to this logic are given as follow:

- Z2PGS: Delayed zone 2 mho phase and ground distance element
- M2P: Zone 2 mho phase distance element
- 67QG2S: Negative-sequence and residual directional overcurrent short delay

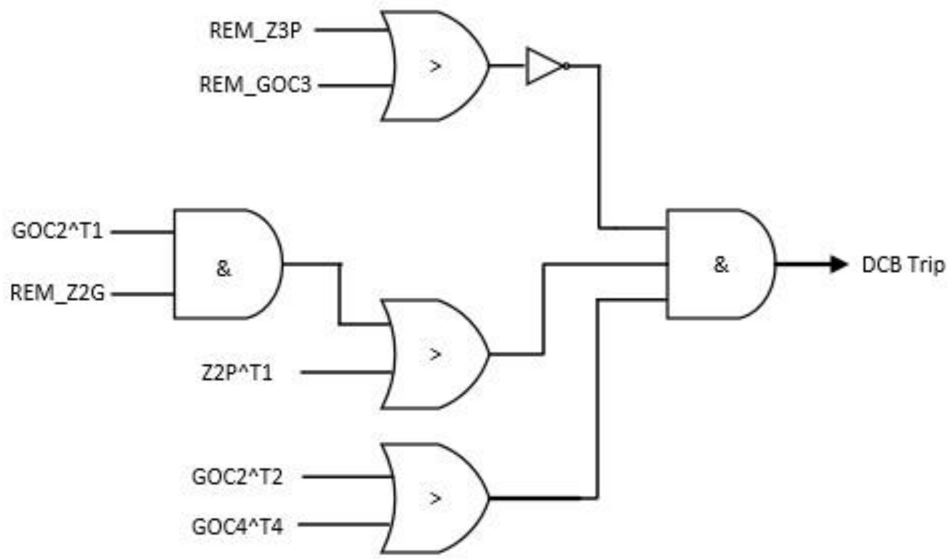


Figure 4-10 Logic scheme of (101) – DCB Trip Logic

- Z2G: Zone 2 mho ground distance element
- 67G2T: Level 2 residual delayed directional overcurrent element
- 67G2: Level 2 residual directional overcurrent element
- 67G4T: Level 4 residual delayed directional overcurrent element
- 67G4: Level 4 residual directional overcurrent element

As for the DCB scheme it is desired not to operate for the external faults, the first step for the protection logic being modeled is to ignore any faults outside the protecting area by:

! (REM_Z3P+REM_GOC3) (102)

REM_Z3P and REM_GOC3 are the zone 3 or level 3 of the phase distance and ground overcurrent elements of the far end terminal which will get the value of one for any fault in its reverse direction. These two need to be defined within the relay protection group of the far end terminal as well. The next step is to model the trip logic in the Case study logic scheme as it is shown in Figure 4-11.

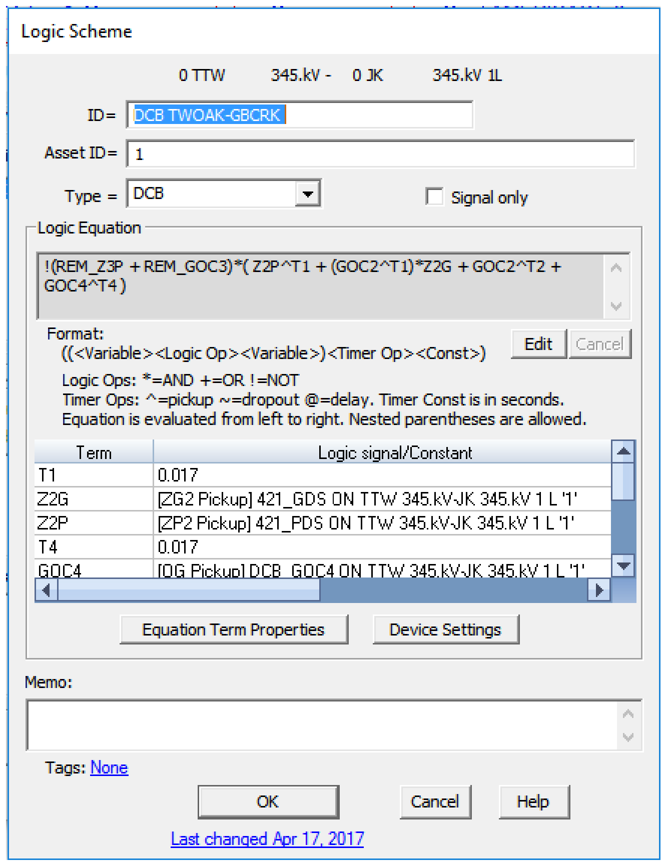


Figure 4-11 Logic scheme of (101) virtually modeled in the case study-ASPEN OneLiner

Beside calculation and modeling all mutual impedances and protection system into the case study, another important aspect in short-circuit model development is inclusion of fault contribution from generation resources in vicinity of the study area. Higher fault current levels on the transmission system are expected to result in a worst-case scenario from a mutual coupling and relay mis-operation standpoint.

Using the latest ERCOT Generation Interconnection Status (GIS) report available at the time of study, and modeling the generation resources in the study area creates the most conservative case.

The final short-circuit case is utilized to assess the impact of mutual coupling on the operation of protective relay elements and pilot protection scheme.

Chapter 5

Study Approaches and Observations

The objective of this study is to identify the impacts of induced zero-sequence current on the performance of the protection system installed on the nearby existing facilities due to the mutual coupling effect between these facilities and the new proposed transmission line. In the case that the operation of protective elements was affected, appropriate mitigation plans need to be addressed.

The adverse impact on the protection system may include:

- Incorrect pick-up of ground over-current (OC) relays
- Over/under-reach in distance relays
- Mis-operation in the pilot protection schemes

In this chapter, different approaches employed towards conducting the mutual coupling study is presented. To prepare the study case, mutual coupling between the new double circuit line and all other existing transmission lines modeled based on the values estimated using the PSCAD/EMTDC model. Then, protective relays on each line modeled to develop the Short Circuit model in ASPEN One-liner for further analysis. The result associated with this analysis is divided into four (4) sections. Using this ASPEN case study, the operation of ground overcurrent, ground and phase distance as well as the pilot protection schemes were evaluated under various fault scenarios. Finally, time domain simulation using PSCAD/EMTDC software was used to validate the results and confirm proper polarization of the relays under study.

5.1 Assessment of Ground Directional Overcurrent Element

The operating quantity for all the ground overcurrent elements modeled in this study is $3I_0$ and presence of AC connection between the new proposed double circuit line and the existing transmission lines introduces certain complication. This complication arose from the fact that in presence of mutual coupling, operating $3I_0$ measured by the relays comprised of two components, fault-based $3I_0$ and Induced $3I_0$.

- Fault based $3I_0$: When an unbalanced fault involving connection to ground occurs on our new line, current of $3I_0$ will circulate through the neighbouring transmission lines given the presence of electrical connection between these transmission facilities. Magnitude of this current is solely a function of electrical connection between this new proposed line and its neighbouring facilities. This current would exist even if there were no mutual coupling.

- Induced $3I_0$: Presence of mutual coupling will induce an additional $3I_0$ component on the neighbouring transmission lines during a fault on the new proposed line.

The induced $3I_0$ component that occurs due to mutual coupling may be additive or subtractive in polarity to fault based $3I_0$. Consequently, the total operating current $3I_0$ that is measured by ground OC relays may increase or decrease due to presence of mutual coupling.

Figure 5-1 serves to illustrate the difference between the fault-based and induced components of the operating current $3I_0$. The section shown in Figure 5-1, can be called as one of the longest sections being coupled with the new proposed line (Line 1 in Figure 4-1) running in narrow right of way for more than 25 miles. It is evident that for any fault on the new proposed line, the operating current $3I_0$ at the 138kV BUS 3 is significantly increased due to presence of mutual coupling. In this scenario, there is a possibility that the pick-up time of the ground OC relays will be significantly reduced.

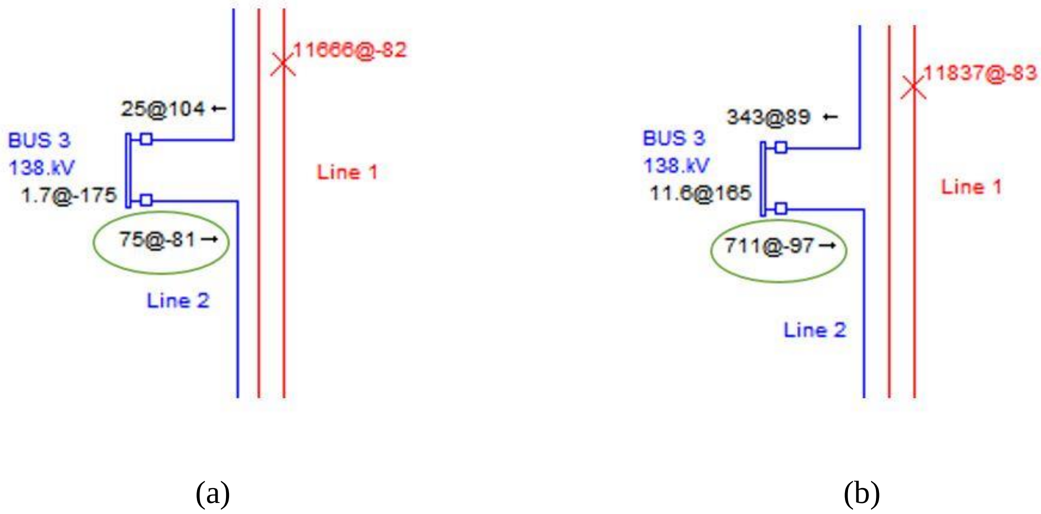


Figure 5-1 Operating Current $3I_0$ Measured at BUS 3 Relay (a) Without considering the Mutual Coupling (b) Considering the Mutual Coupling – for faults at Line 1

Given the nature of impact of mutual coupling discussed above, the objectives of this analysis can be enumerated as follow:

The first objective is to determine whether the pick-up time of ground OC relays on transmission facilities of interest, during a fault on Line 1 is significantly reduced due to mutual coupling – such a situation may cause an un-faulted neighbouring transmission lines to trip before the fault on the new line is cleared.

Second, in case of adverse impact on the operation of the existing relays, corrective actions and recommendations associated with the same would be provided.

To conduct analysis for operation of ground overcurrent relays, four steps has been taken.

- First, Single line to ground fault (SLG) is being simulated on Line 1 along 0% to 100% of its length in 5% increments. Noting that any fault on Line 1 will be fed from both end terminals (BUS 1 & BUS 2).
- Second, the pick-up time for all the relays on neighbouring facilities is being recorded for each fault location on the 345kV Line 1.
- Third, repeating the first two part, using an alternate short-circuit model in which none of the mutual coupling between the new proposed Line 1 and existing facilities is modeled.
- Finally, to track the operation of the relays in presence of mutual coupling, relay pick-up times with and without mutual coupling modelled is compared to see whether the pick-up value of each protective relay is reduced to the extent that it affects the performance of those relays and impacts the security of the protection system.

Table 1 presents the result of this analysis for the relays shown on Line 2 and 3 of Figure 4-1. For the SLG faults along the 345kV transmission Line 1 within 5% increments, the relay pick-up time as well as zero-sequence current seen by relays on Line 2 and 3 is depicted for two different scenarios, with and without mutual coupling. Relays used at BUS 3 and BUS 5 are SEL 311C as primary and

LPRO as back-up ground overcurrent protection and relays utilized at BUS 4 are SEL 421 and 311C as Primary and back-up ground overcurrent protection respectively.

As mentioned before, this section of the study is selected as an example since it represents the longest section mutually coupled with the new proposed Line 1.

Trip time of 9999 in these Tables indicate that relays do not operate because the measured currents are lower than the set points.

Table 2-a Relays measured current (A) and trip time (Sec) at BUS 3

Fault Location from BUS 1	SEL 311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time
0%	48	9999	286	9999	48	9999	286	9999
5%	6	9999	436	9999	6	9999	436	9999
10%	24	9999	511	4.1	24	9999	511	5.3
15%	36	9999	570	3.2	36	9999	570	4.2
20%	45	9999	624	2.6	45	9999	624	3.4
25%	53	9999	676	2.2	53	9999	676	2.9
30%	60	9999	732	1.9	60	9999	732	2.5
35%	68	9999	741	1.9	68	9999	741	2.5
40%	75	9999	711	2.0	75	9999	711	2.7
45%	83	9999	655	2.4	83	9999	655	3.1
50%	92	9999	546	3.5	92	9999	546	4.6
55%	102	9999	447	5.7	102	9999	447	7.4
60%	114	9999	353	11.7	114	9999	353	15.3
65%	129	9999	258	86.8	129	9999	258	113.5
70%	146	9999	151	9999	146	9999	151	9999
75%	169	9999	151	9999	169	9999	151	9999
80%	199	9999	278	38.9	199	9999	278	50.9
85%	240	3896.2	155	9999	240	5097	155	9999
90%	303	22.7	52	9999	303	29.7	52	9999
95%	406	7.4	100	9999	406	9.7	100	9999
100%	613	2.7	174	9999	613	3.6	174	9999

Table 2-b Relays measured current (A) and trip time (Sec) at BUS 4 towards BUS 3

Fault Location from BUS 1	SEL 421 (Primary)				SEL 311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time
0%	48	9999	286	5.8	48	9999	286	7.9
5%	6	9999	436	2.1	6	9999	436	2.9
10%	24	9999	511	1.5	24	9999	511	2.1
15%	36	9999	570	9999	36	9999	570	9999
20%	45	9999	624	9999	45	9999	624	9999
25%	53	9999	676	9999	53	9999	676	9999
30%	60	9999	732	9999	60	9999	732	9999
35%	68	9999	741	9999	68	9999	741	9999
40%	75	9999	711	9999	75	9999	711	9999
45%	83	9999	654	9999	83	9999	654	9999
50%	92	9999	545	9999	92	9999	545	9999
55%	102	9999	446	9999	102	9999	446	9999
60%	114	9999	353	9999	114	9999	353	9999
65%	129	9999	257	9999	129	9999	257	9999
70%	146	9999	151	9999	146	9999	151	9999
75%	169	9999	151	9999	169	9999	151	9999
80%	199	9999	278	9999	199	9999	278	9999
85%	240	9999	154	9999	240	9999	154	9999
90%	302	9999	52	9999	302	9999	52	9999
95%	406	9999	101	9999	406	9999	101	9999
100%	613	9999	174	9999	613	9999	174	9999

Table 2-c Relays measured current (A) and trip time (Sec) at BUS 4 toward BUS 5

Fault Location from BUS 1	SEL 421 (Primary)				SEL 311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time
0%	42	9999	311	9999	42	9999	311	9999
5%	6	9999	454	9999	6	9999	454	9999
10%	12	9999	527	9999	12	9999	527	9999
15%	20	9999	586	0.95	20	9999	586	1.40
20%	27	9999	639	0.84	27	9999	639	1.23
25%	32	9999	692	0.75	32	9999	692	1.10
30%	37	9999	747	0.68	37	9999	747	0.99
35%	42	9999	769	0.66	42	9999	769	0.96
40%	47	9999	761	0.66	47	9999	761	0.97
45%	52	9999	735	0.69	52	9999	735	1.02
50%	58	9999	671	0.78	58	9999	671	1.15
55%	65	9999	618	0.88	65	9999	618	1.29
60%	73	9999	574	0.98	73	9999	574	1.44
65%	82	9999	536	1.10	82	9999	536	1.61
70%	94	9999	497	1.25	94	9999	497	1.83
75%	108	9999	551	1.05	108	9999	551	1.54
80%	128	9999	722	0.71	128	9999	722	1.04
85%	155	70.45	731	0.70	155	103.12	731	1.02
90%	195	13.15	473	1.36	195	19.25	473	1.99
95%	262	4.91	121	9999	262	7.19	121	9999
100%	395	1.90	130	9999	395	2.79	130	9999

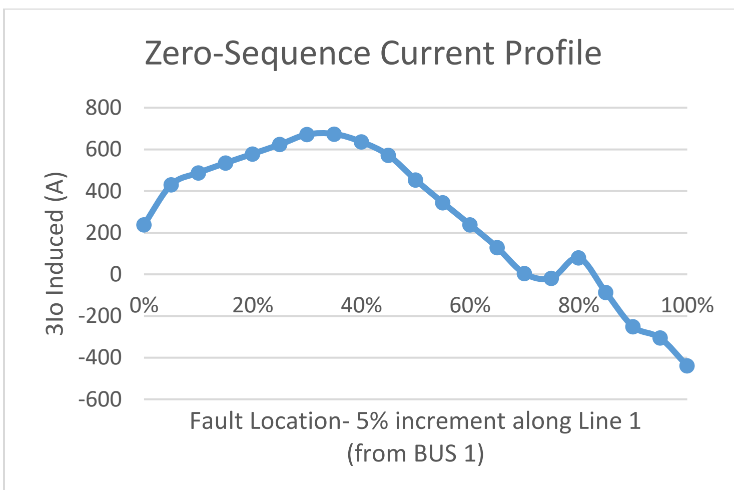
Table 2-d Relays measured current (A) and trip time (Sec) at BUS 5

Fault Location from BUS 1	SEL 311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time
0%	42	9999	311	9999	42	9999	311	9999
5%	6	9999	454	9999	6	9999	454	9999
10%	12	9999	527	75.3	12	9999	527	104.7
15%	20	9999	586	9999	20	9999	586	9999
20%	27	9999	639	9999	27	9999	639	9999
25%	32	9999	692	9999	32	9999	692	9999
30%	37	9999	747	9999	37	9999	747	9999
35%	42	9999	769	9999	42	9999	769	9999
40%	47	9999	761	9999	47	9999	761	9999
45%	52	9999	735	9999	52	9999	735	9999
50%	58	9999	671	9999	58	9999	671	9999
55%	65	9999	618	9999	65	9999	618	9999
60%	73	9999	574	9999	73	9999	574	9999
65%	82	9999	535	9999	82	9999	535	9999
70%	94	9999	497	9999	94	9999	497	9999
75%	108	9999	551	9999	108	9999	551	9999
80%	128	9999	722	9999	128	9999	722	9999
85%	155	9999	731	9999	155	9999	731	9999
90%	195	9999	473	9999	195	9999	473	9999
95%	262	9999	121	9999	262	9999	121	9999
100%	395	9999	130	9999	395	9999	130	9999

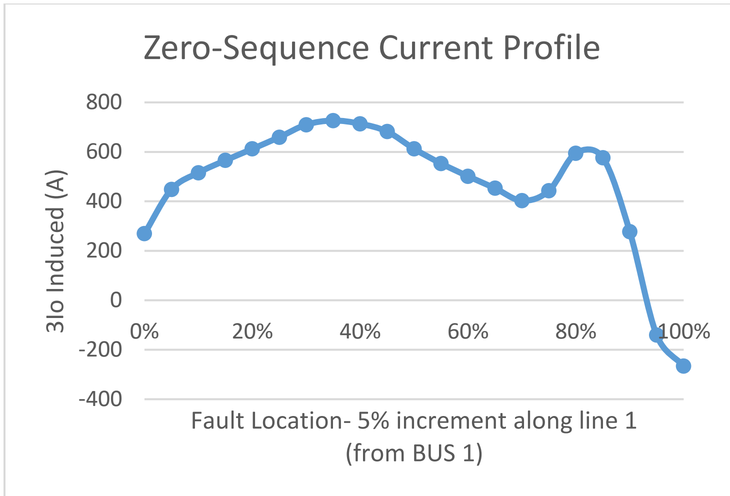
There are many instances in which the pick-up time associated with ground overcurrent relays at BUS 3, 4 and/or 5 were changed due to the presence of mutual coupling. In case of the relays on BUS 3, there are numerous instances in which the relay does not operate in absence of mutual coupling but is observed to pick-up once mutual coupling is considered. The fastest pick-up time for ground OC relays at BUS 3 in presence of mutual coupling is 1.9s when the SLG fault on the Line 1 is located 30 - 35% away from BUS 1. On similar line, the relay at BUS 4 is observed to pick-up in 1.5s when the SLG fault is 10% away from BUS 1 on the Line 1. In case of all aforementioned events, presence of mutual coupling induces relatively higher $3I_0$ current as measured by relays on line 2 causing the relays to pick-up.

Further, there are specific instances as well in which the relay pick-up time in presence of mutual coupling is higher in comparison to the case with no mutual coupling. In such situations, the mutually induced $3I_0$ was observed to be in opposite polarity to the fault based $3I_0$.

The current profile for the induced zero-sequence on each of Line 2 and Line 3 is illustrated in Figure 5-2 for the faults along the Line 1. The observation is indicative of the fact that the induced $3I_0$ component of fault current may have additive or subtractive behaviour to the fault-based zero-sequence current depending on the fault location and interaction of other coupled sections in vicinity.



(a)



(b)

Figure 5-2 a) Induced $3I_0$ current profile-138kV Line 2-Faults on Line 1 in 5% increment
b) Induced $3I_0$ current profile-138kV Line 3--Faults on Line 1 in 5% increment

As discussed, for the results presented in Table 1, the simulated SLG faults on Line 1 are being fed from BUS 1 as well as BUS 2. Though, it deemed essential to conduct a sensitivity analysis in which an SLG fault on Line 1 is cleared from one end but continues to be fed from the other end. This situation can occur when line-end faults may be instantaneously cleared from the near end while being subjected to delayed-clearing from the remote end. When the fault on Line 1 is cleared from one end but continues to be fed from the remote end, there is a possibility that the polarity of induced $3I_0$ current in neighbouring lines will be reversed. Ground OC relays, which had previously restrained from operation due to their polarization settings, may pick-up due to change in direction of $3I_0$. To that extent, analysis for all the existing line being coupled with Line 1is extended to include scenarios involving delayed fault clearing at the remote end.

Again, coupled section of Line 2 and 3 is used as a representative example of this part of analysis. To that extent, SLG faults that are located within 0-20% of Line 1 from BUS 1 are cleared instantaneously from this station. However, these may be subjected to delayed-clearing from the remote end BUS 2. Conversely, faults that are located within 80-100% from BUS 1 may be subjected to delayed-clearing from BUS 1 terminal with BUS 2 protection system opening instantaneously. It should be noted that faults located at 20-80% from the BUS 1 are expected to be cleared instantaneously from both terminals and hence, not included in the sensitivity assessment.

Table 2 depicts the pick-up times for ground OC relays at BUS 3, BUS 4 and BUS 5, respectively, in case of delayed fault clearing events. It is instructive to compare the trip times in Table 2-b to those listed in Table 1-b. It is observed that when the fault on Line 1 is being fed from both ends, the ground OC relays at BUS 4 do not pick-up for faults that are located 80% to 100% from BUS 1. However, if the fault on Line 1 is only being fed from BUS 1, the relays at BUS 4 are observed to pick-up for all locations that are 80-100% away from BUS 1. This observation highlights the need for including delayed fault clearing events for the mutual coupling study.

A similar approach to evaluate the impact of the mutual coupling on pick up time of other neighbouring facilities' ground OC relays has been utilized. The results associated with the GOC protection in the study area have been provided in Appendix C.

Table 3 Ground OC relays measured current (A) and trip time (Sec), with and without Mutual Coupling; Line 1 open at one end

a) Relays at BUS 3, b) Relays at BUS 4 looking towards BUS 3

c) Relays at BUS 4 looking towards BUS 5, d) Relays at BUS 5

Fault Location from BUS 1	SEL 311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time
BUS 1 End Opened								
0.5%	25	9999	333	14.7	25	9999	333	19.2
5%	28	9999	359	11.0	28	9999	359	14.3
10%	31	9999	391	8.3	31	9999	391	10.8
15%	35	9999	427	6.4	35	9999	427	8.4
20%	39	9999	467	5.1	39	9999	467	6.6
BUS 2 End Opened								
80%	36	9999	209	9999	36	9999	209	9999
85%	37	9999	257	9999	37	9999	257	9999
90%	38	9999	294	9999	38	9999	294	9999
95%	39	9999	313	9999	39	9999	313	9999
99.5%	39	9999	290	9999	39	9999	290	9999

(a)

Fault Location from BUS 1	421 (Primary)				311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	25	9999	333	9999	25	9999	333	9999
5%	28	9999	359	9999	28	9999	359	9999
10%	31	9999	391	9999	31	9999	391	9999
15%	35	9999	427	9999	35	9999	427	9999
20%	39	9999	467	9999	39	9999	467	9999
BUS 2 End Opened								
80%	36	9999	209	19.3	36	9999	209	26.4
85%	37	9999	258	8.0	37	9999	258	11.0
90%	38	9999	294	5.3	38	9999	294	7.3
95%	38	9999	314	4.5	38	9999	314	6.1
99.5%	39	9999	290	5.6	39	9999	290	7.6

(b)

Fault Location from BUS 1	421 (Primary)				311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	16	9999	339	2.6	16	9999	339	3.9
5%	18	9999	366	2.2	18	9999	366	3.3
10%	20	9999	398	1.9	20	9999	398	2.7
15%	22	9999	435	1.6	22	9999	435	2.3
20%	25	9999	475	1.4	25	9999	475	2.0
BUS 2 End Opened								
80%	23	9999	87	9999	23	9999	87	9999
85%	24	9999	120	9999	24	9999	120	9999
90%	24	9999	209	9999	24	9999	209	9999
95%	25	9999	326	9999	25	9999	326	9999
99.5%	25	9999	317	9999	25	9999	317	9999

(c)

Fault Location from BUS 1	311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	16	9999	339	9999	16	9999	339	9999
5%	18	9999	366	9999	18	9999	366	9999
10%	20	9999	398	9999	20	9999	398	9999
15%	22	9999	435	9999	22	9999	435	9999
20%	25	9999	475	9999	25	9999	475	9999
BUS 2 End Opened								
80%	23	9999	87	9999	23	9999	87	9999
85%	24	9999	120	9999	24	9999	120	9999
90%	24	9999	209	9999	24	9999	209	9999
95%	25	9999	326	9999	25	9999	326	9999
99.5%	25	9999	317	9999	25	9999	317	9999

(d)

Results associated with the mutual coupling analysis for ground OC relay elements is indicative of the following:

- Ground OC relay elements on neighbouring lines may pick-up for faults on Line 1 in presence of mutual coupling
- Pick-up time for the ground OC relays may be significantly reduced due to presence of mutual coupling
- If the pick-up time is significantly low, there is a potential risk of un-faulted neighbouring lines tripping due to faults on Line 1

- In certain instances, presence of mutual coupling prevents ground OC relay elements from picking up during SLG faults
    - In such cases, induced zero-sequence current is in the opposite direction to the zero-sequence current circulating due to the fault

To find a mitigation action to prevent tripping of un-faulted neighbouring lines, it is important to note that the main cause of incorrect operation of ground OC relays is for SLG faults on Line 1. If the SLG fault on Line 1 is cleared, ground OC relays on neighbouring lines which have picked-up will drop out. Consequently, there will be no risk of tripping un-faulted neighbouring lines once the relays have dropped out. In view of the same, a filtered approach for relay settings changes may be derived. This approach can be summarized as follows:

- Identify the fastest ground OC relay trip time in presence of mutual coupling (in the existing facilities)
- Compare the fastest trip time for each existing relay with the most delayed fault clearing time possible on Line 1
- If the fastest ground OC relay trip time of neighbouring facility is greater than the delayed clearing time on Line 1 there is no risk of un-faulted neighbouring lines tripping before the fault on Line 1 is cleared and no action is needed
- If fastest ground OC relay trip time of neighbouring facility is less than the delayed clearing time on Line 1, un-faulted neighbouring lines may trip

before fault on Line 1 is cleared. Setting changes may be needed in such cases

The maximum delayed clearing time for faults on the proposed 345kV double circuit Line1 has been reported to be 31 cycles or 0.5167 sec. Considering all the pick-up times associated with existing relays in presence of mutual coupling, except for one fault scenario for one of the relays, mutual coupling is not observed to reduce the neighbouring relay's pick-up time below 31 cycles for the fault scenarios studied. Therefore, for such fault scenarios the relays on Line 1 are expected to trip faster than the existing facilities' relays for faults on Line 1 even in the presence of the mutual coupling, limiting the risk of any adverse impacts on the performance of studied relays.

For the only scenario that was observed to result in the trip time of marginally faster than 31 cycles in the presence of mutual coupling, protection system security can be increased by adjusting the settings of the affected ground OC relay to account for the change in the pick-up time caused by the mutual coupling-induced zero-sequence current. These setting changes will further ensure the prevention of potential mis-operation of such relays. As mentioned earlier, the ground OC relays of this analysis operate on $3I_0$, therefore alongside with other possible setting changes, $3I_2$ can also be used as an operating current as it remains unaffected by zero-sequence mutual coupling. In the case that polarizing quantity is other than negative-sequence components, V_2/I_2 can be also used as polarizing quantity to avoid being affected by zero-sequenced induced currents in presence of mutual coupling.

5.2 Assessment of Phase and Ground Distance Relays

In addition to ground over current relays, ground distance relays, due to dependency on zero-sequence current, are typically expected to be impacted by mutual coupling. Under mutual coupling condition, these relays may trip for faults that are beyond their zone reach point (over-reach). They may also restrain from tripping for faults that are within the zone reach point (under-reach). Additionally, assessment of phase distance relays is included in the scope of this effort. Although phase distance relays are generally not impacted by zero-sequence mutual coupling, an investigation to determine potential mis-operations associated with the same is performed.

Double line to ground (LLG) and Single Line to Ground (SLG) faults were placed on each relay-protected neighbouring transmission lines to evaluate the operation of phase and ground distance relay respectively. Line-line or 3-phase faults do not lead to zero-sequence current flow on the network and are excluded from analysis. Zone 1 reach points for phase and ground distance relays were identified in absence of mutual coupling. LLG and SLG faults were placed on either side of the reach point with mutual coupling included. To investigate the operation of distance elements, two different scenarios associated with the in-service status of Line 1 were included:

- Line 1 in-service
- Line 1 out of service and grounded on both ends

As the result of this analysis zone 1 reach-point with and without mutual coupling for each phase and ground distance relay is observed to be identical for all conditions. To that effect, no potential for over/under-reach due to inclusion of mutual coupling was observed based on the results of this investigation.

5.3 Assessment of PILOT Protection schemes

As discussed previously, failure to recognize the location of the fault may cause the pilot scheme to mis-operate. This is prevalent among mutually coupled lines as the induced zero-sequence components may alter the current and impedance magnitude of the line. In presence of mutual coupling, pilot protection schemes such as DCB and POTT may falsely interpret the direction of the fault and cause instantaneous tripping of nearby relays.

Therefore, an analysis to evaluate the impact of mutual coupling on operation and security of PILOT protection systems (such as POTT, DCB communication schemes etc.) was performed. As part of this analysis, a detailed model of PILOT protection schemes was developed and incrementally added to the study cases keeping in mind that each communication assisted scheme does not falsely pick up and cause instantaneous tripping of nearby relays.

Figure 5-3 illustrates a simplified section of the study network that includes POTT and DCB schemes along with its protective elements. To ensure that DCB and/or POTT schemes are not mis-operating even before the mutual coupling coming into picture, several faults inside and outside the protecting area have been simulated. As an illustrative example for operation of DCB scheme modeled at BUS 2, an SLG fault at 10% of Line 4 from BUS 6 to BUS 2 had been simulated. From Figure 5-3, it is observed that for the internal fault of Line 4, DCB scheme at BUS 2 Provides remote fault clearing much faster (within 2 cycles) than remote pick-up times and improves the stability of the system.

Communication schemes were tested to assess the communication-assisted relay operation in the study region. The DCB/POTT communication scheme was not observed to mis-operate across various testing procedures. It is important to note that all relays included for study are negative-sequence polarized, hence PILOT protection schemes remained unaffected by the zero-sequence current induced by mutual coupling.

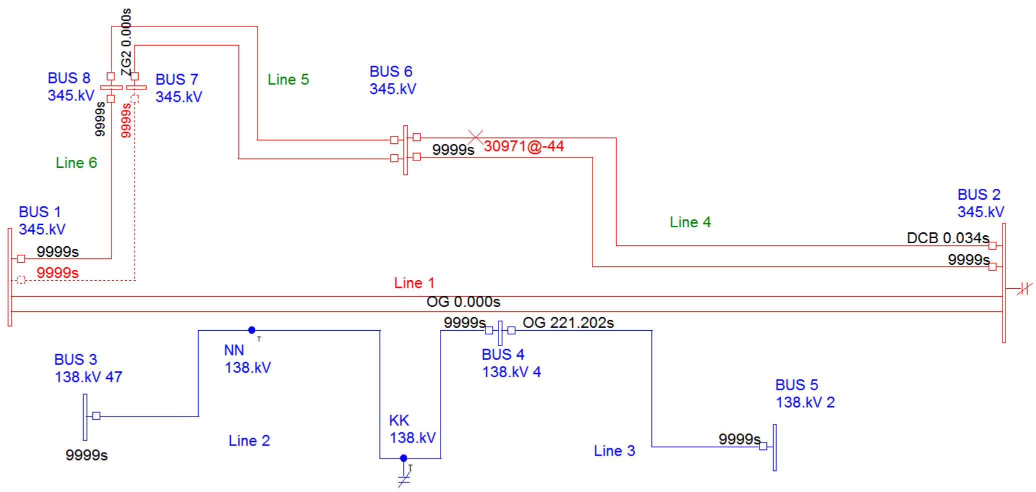


Figure 5-3 DCB Pilot scheme operation at BUS 2 in the absence of mutual coupling - Fault on Line 4 (10% from BUS 6)

5.4 Time Domain Result Validation

While the performance of protection systems with respect to the impact from mutual coupling were extensively evaluated using ASPEN Oneliner software, the ASPEN Oneliner platform only provides a steady state (i.e. post transient) solution and does not capture any subtransient response that may occur during faulted conditions. A steady state solution, as provided by ASPEN Oneliner, is not capable of capturing any DC offset or current reversal which may occur during the subtransient interval after the fault. A significant level of DC offset may cause the relay trip time to reduce as the relay will observe a higher fault current. Similarly, a reversal in current during the fault can result in a subtransient change in polarity and may cause the mis-operation of protection systems. PILOT protection schemes such as POTT and DCB schemes may falsely interpret the fault to be in the forward direction which could potentially cause instantaneous tripping. Based on this, an EMT simulation in PSCAD/EMTDC software was performed to capture the subtransient response during faulted conditions. The subtransient response observed as part of this effort is then used to validate the previous study results obtained via ASPEN OneLiner.

The ASPEN model is used to create an equivalent simplified model for further simulation in PSCAD/EMTDC software. For the purpose of this analysis, the part of coupled network shown in Figure 4-1 has been chosen to assess the subtransient response under faulted conditions. Figure 5-4 illustrates this model in PSCAD. This line segment is chosen as it represents the longest mutually coupled section along the new proposed transmission line (approximately 30 miles). This is expected to provide a better understanding of the effects of mutual coupling using a time domain simulation.

To ensure all corresponding relays are properly polarized and correctly identify the direction of the fault, several fault locations were studied. To that extent, EMT simulations were performed for Single-Line-Ground (SLG) fault based conditions at various locations in vicinity of Line 1, such as the stations shown in Figure 4-1 as well as SLG fault on 50% of Line 1.

For illustrative purposes, Figure 5-5 depicts the current response as measured by the relay at 138kV BUS 5 protecting the 138kV Line 3 for SLG fault located at 345kV station BUS 1. As seen in Figure 5-5, the overshoot observed immediately after occurrence of the fault is not significantly larger that the post-transient component. The amount of overshoot is limited given the system strength of the study region. The study region is strongly interconnected and yields high fault current levels promoting the strength of the system.

In addition, the PSCAD model was utilized to determine any relay mis-operation caused by current reversal leading to an incorrect relay polarization. Each of the ground OC relays included as part of this analysis are polarized using negative sequence components. Based on [1] and [18], each relay uses the following polarization method to determine the direction of the fault:

- Forward Fault Detection: Current Leads the Voltage (I leads V or I lags -V)
- Reverse Fault Detection: Current Lags the Voltage (I lags V or I leads -V)

Figure 5-5b depicts that the negative sequence current leads the negative sequence voltage. Therefore, the relay located at 138kV BUS 5 protecting the 138kV transmission Line 3 correctly identifies the fault located at 345kV BUS 1 in the reverse direction. Therefore, in this illustrative example, the mutual coupling was not observed to cause any current reversal and mis-operation with respect to the polarization of the relay.

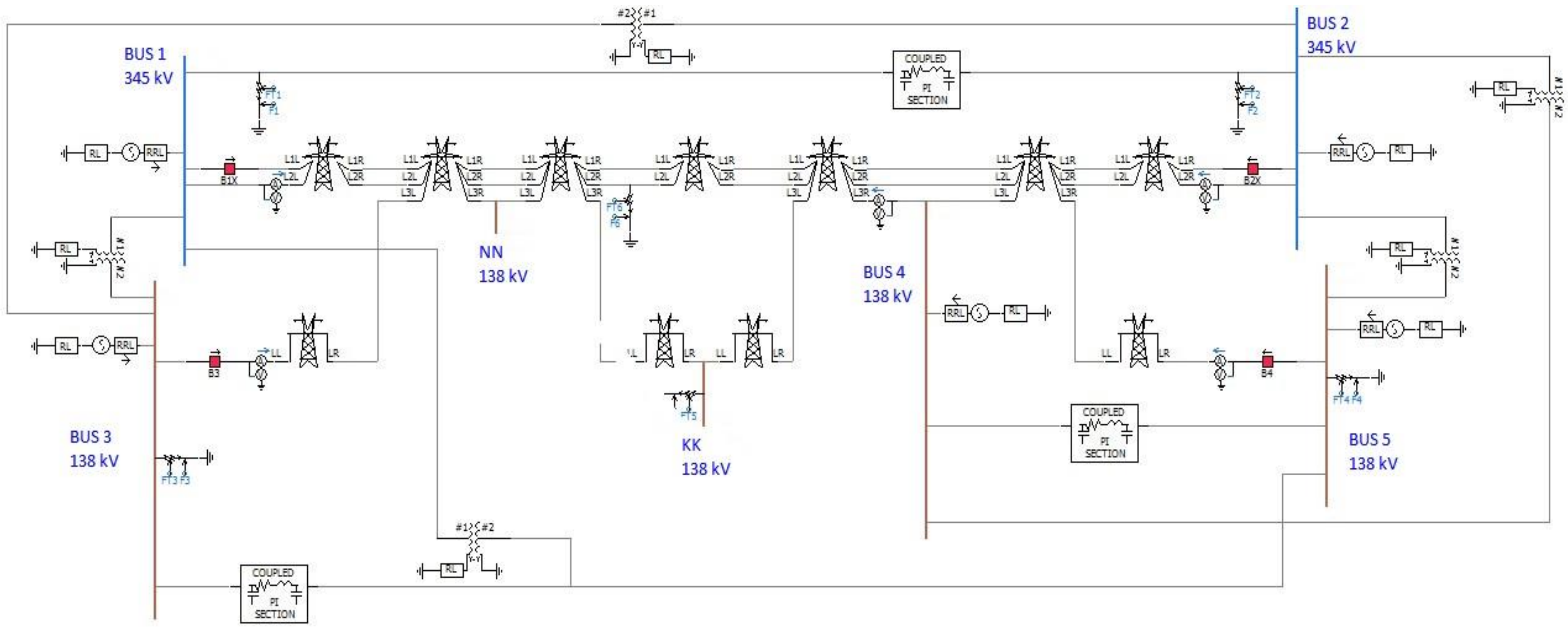


Figure 5-4 PSCAD Equivalent Model

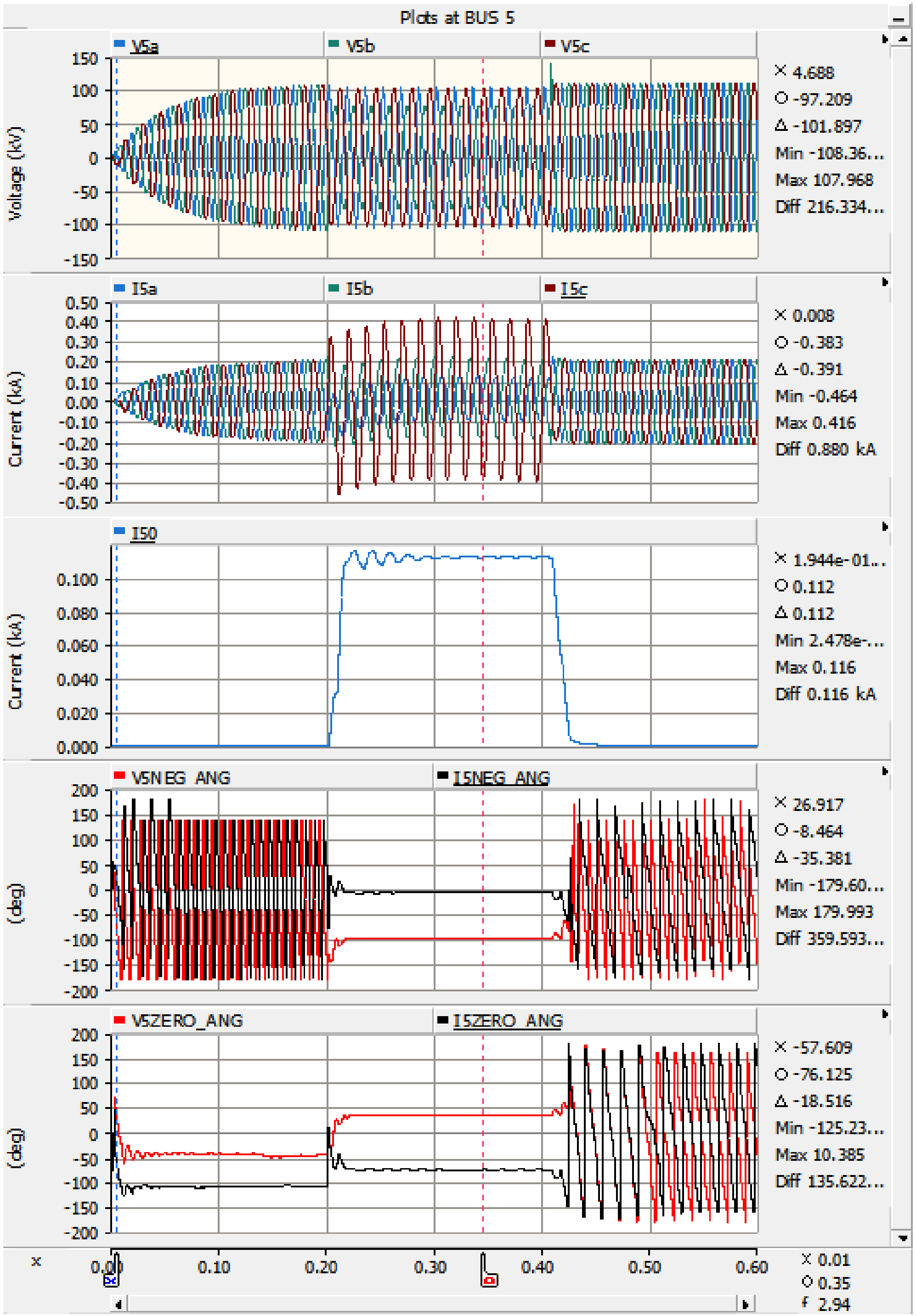


Figure 5-5 Current and voltage values for Relay at 138kV BUS 5 Station Protecting Line 3 (SLG Fault at BUS 1)

Moreover, EMT simulations have been repeated for several other SLG faults to ensure proper operation of relays with respect to the polarization quantity. The sequence current and voltages measured by relays at the following four (4) locations have been evaluated:

- 345kV BUS 1 relay along the Line 1
- 345kV BUS 2 relay along the Line 1
- 138kV BUS 3 relay along the 138kV Line 2
- 138kV BUS 5 relay along the 138kV Line 3

None of the EMT simulation results were indicative of any current reversal (polarity change) or significant sub-transient overshoot to the extent that it impacts the performance of the above-mentioned relays. The current and voltage curves for these evaluations are presented in Appendix D.

Chapter 6

Conclusions

In power Transmission network, it is prevalent to have limited right of way in some locations where two or more transmission circuit are sharing common tower structure or running parallel in close proximity. This configuration can happen among the circuits of individual transmission lines sharing right of way in narrow corridors or being structured on the same tower as well as other structural scenarios [1],[2].

In such parallel transmission lines, each circuit is experiencing an additional magnetic flux generated by the other circuit in addition to its self-generated magnetic flux. This is called "mutual coupling" which can have more pronounced effect when the length of the shared right of way, in other word coupled section, increases or the spacing between parallel circuits decreases.

Since mutual coupling effect results in induction of zero-sequence current and voltages, it is expected that it only affects the ground-fault-related protection schemes, by either altering the measured fault current magnitude or direction [1]-[3]. To avoid this induced zero-sequence current causing challenges for protection and control systems, compensation methods are required in setting the ground directional overcurrent, distance and directional comparison elements of a protection system, associated with parallel transmission lines [1]-[4].

Therefore, the main purpose of this study is to present a comprehensive analytical approach that can be used by system planner to evaluate and quantify the magnitude and adverse impact of mutual coupling on the operation of various types of protective elements in real-life scenarios under several system fault conditions. This is the first part of this study proceeding the second part in which the mitigation against mutual coupling is to be developed. This methodology consists of detailed modelling of mutual coupling and is used to study the impact of mutual coupling on ground overcurrent relays (GOC), ground and phase distance as well as directional comparison pilot protection.

As the last part of this effort, EMT simulation is utilized to quantify the extent of sub-transient overshoot and current reversal that may have adverse impact on the performance of studied relays as well as to validate the study results obtained in previous stage.

To demonstrate the proposed study approach, a real-life case study within ERCOT network has been utilized, where a new 345 kV double circuit transmission line runs in close proximity to many other existing transmission facilities. As mentioned earlier, this study aims to investigate the impacts of zero-sequence mutual coupling introduced by this proposed transmission line on the protective relays of the nearby facilities. Following, the key conclusions derived from this study are enumerated.

Ground over-current (GOC) relays on neighbouring transmission lines are affected due to zero-sequence mutual coupling that is introduced by the new proposed line. When a single-line-to-ground (SLG) fault occurs on the proposed line, pick-up times associated with these relays are observed to be significantly reduced due to presence of mutual coupling. Before suggesting any mitigation plan, the relays' trip time were compared to the most delayed fault clearing time on the new proposed line (to be called tripping time threshold). Once the fault on the new proposed line is cleared, GOC relays on neighbouring facilities are expected to drop-off. Therefore, for such fault scenarios the relays on proposed 345 kV line are expected to trip faster than the protective elements on existing transmission facilities in the presence of the mutual coupling, limiting the risk of any adverse impacts on the performance of studied relays.

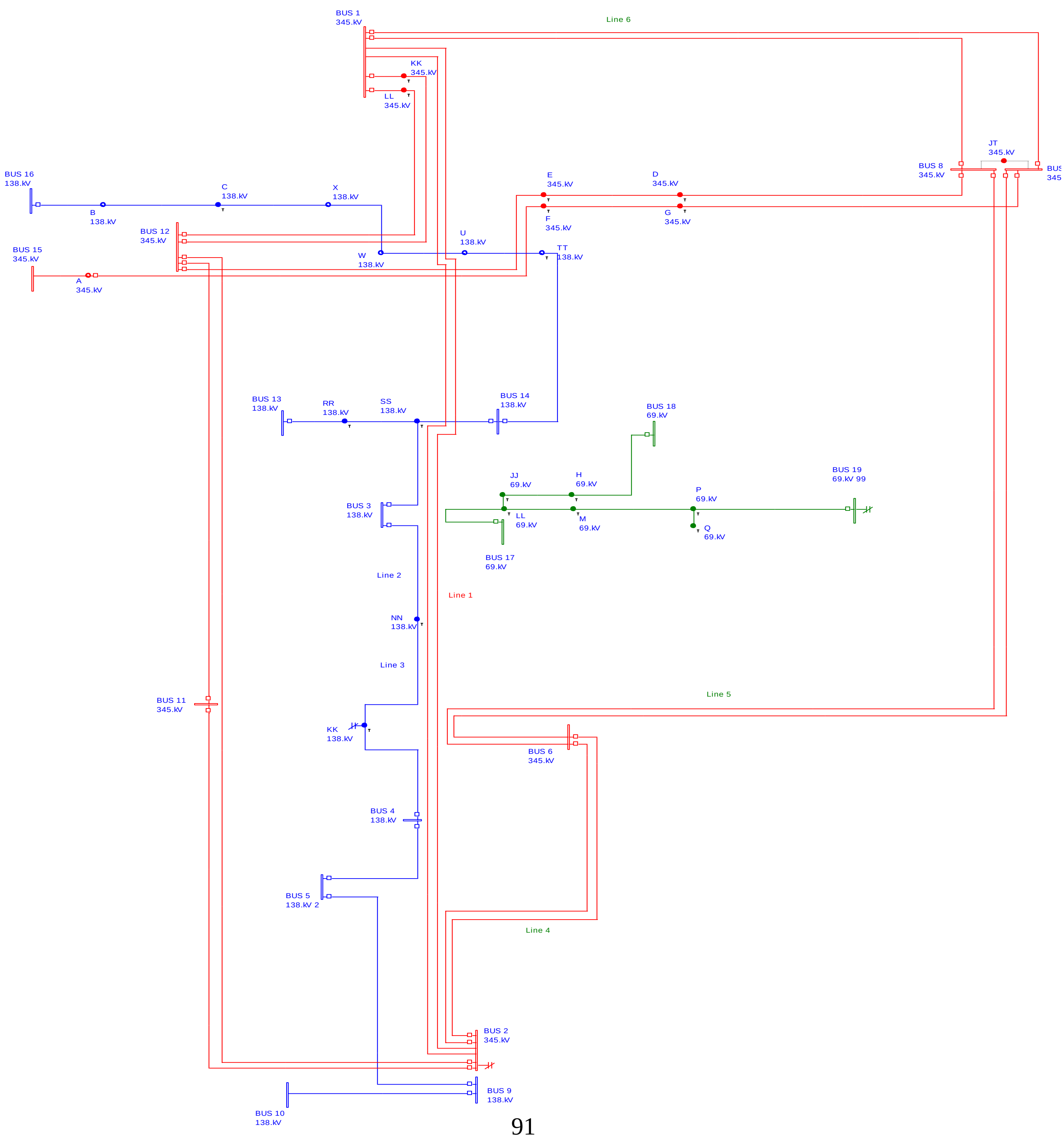
For the scenarios in which the trip time of existing relays were observed to be marginally faster or close to above mentioned threshold, protection system security can be increased by adjusting the neighbouring facilities' ground OC relay settings to account for the change in the pick-up time caused by the mutual coupling-induced zero-sequence current. These setting changes will further ensure the prevention of potential mis-operation of existing relays. Choosing the negative-sequence current and voltage as polarizing quantity or changing the operating quantity from 3I0 to 3I2 are among possible setting options [2] as 3I2 is unaffected by zero-sequence mutual coupling.

Ground OC relays on the existing facilities were not observed to be impacted by mutual coupling to the extent that it will alter the performance of the relays for a fault on the corresponding protected elements.

Ground and phase distance relays as well as PILOT protection schemes on the neighbouring transmission lines of interest are observed to remain unaffected by zero-sequence induced current by mutual coupling as well. Performing time domain simulations using PSCAD/EMTDC software validates the study results and confirms proper polarization of relays under study.

Appendix A

One-Line Diagram for the Study Area and Facilities Nearby



Appendix B

Impedance Matrix calculated for coupled section between Line 1 and Line 2

	CKT 1						CKT 2						CKT 3					
	Zero Sequence		Positive Seuence		Negative Seuence		Zero Sequence		Positive Seuence		Negative Seuence		Zero Sequence		Positive Seuence		Negative Seuence	
CKT 1	0.000132	0.000587	0	0	0	0	0.000123	0.000340	0	0	0	0	0.000114	0.000191	0	0	0	0
	0	0	0.000012	0.000239	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	-6.73E-20	0	0.000012	0.000239	0	0	0	0	0	0	0	0	0	0	0	0
CKT 2	0.000123	0.000340	0	0	0	0	0.000138	0.000603	0	0	0	0	0.000119	0.000224	0	0	0	0
	0	0	0	0	0	0	0	0	0.000012	0.000240	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0.000012	0.000240	0	0	0	0	0	0
CKT 3	0.000114	0.000191	0	0	0	0	0.000119	0.000224	0	0	0	0	0.000182	0.000819	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000048	0.000314	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-8.98E-20	-6.73E-20	0.000048	0.000314

Appendix C

Ground Overcurrent Relay Results-Measured Current and Trip Time

Fault Location from BUS 1	311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
0%	189	77	78	9999	189	116	78	9999
5%	85	9999	252	8.2	85	9999	252	12.5
10%	45	9999	329	3.5	45	9999	329	5.3
15%	24	9999	388	2.3	24	9999	388	3.5
20%	9	9999	437	9999	9	9999	437	9999
25%	1	9999	482	9999	1	9999	482	9999
30%	10	9999	528	9999	10	9999	528	9999
35%	18	9999	479	9999	18	9999	479	9999
40%	25	9999	343	9999	25	9999	343	9999
45%	32	9999	337	9999	32	9999	337	9999
50%	39	9999	271	9999	39	9999	271	9999
55%	46	9999	209	9999	46	9999	209	9999
60%	55	9999	151	9999	55	9999	151	9999
65%	65	9999	90	9999	65	9999	90	9999
70%	76	9999	29	9999	76	9999	29	9999
75%	91	9999	32	9999	91	9999	32	9999
80%	109	9999	115	9999	109	9999	115	9999
85%	135	9999	37	9999	135	9999	37	9999
90%	173	9999	75	9999	173	9999	75	9999
95%	236	9999	149	9999	236	9999	149	9999
100%	362	9999	81	9999	362	9999	81	9999

Line from BUS 3 to BUS 13/BUS 14: Operation of Relays at BUS 3 – Current (A) and Trip Time (Sec)

Fault Location from BUS 1	311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	9	9999	246	9999	9	9999	246	9999
5%	11	9999	267	9999	11	9999	267	9999
10%	13	9999	290	9999	13	9999	290	9999
15%	15	9999	317	9999	15	9999	317	9999
20%	17	9999	347	9999	17	9999	347	9999
BUS 2 End Opened								
80%	15	9999	192	58.9	15	9999	192	89.3
85%	16	9999	222	15.2	16	9999	222	23.0
90%	17	9999	244	9.5	17	9999	244	14.4
95%	18	9999	255	7.9	18	9999	255	12.0
99.5%	19	9999	236	11.0	19	9999	236	16.7

Line from BUS 3 to BUS 13/BUS 14: Operation of Relays at BUS 3 – Current (A) and Trip Time (Sec) – Line 1 Opened

Fault Location from BUS 1	421 (Primary)				311C (Backup)				Io Induced
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling		
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time	
0%	174	54.7	264	5.8	174	80.1	264	8.4	91
5%	100	9999	219	11.2	100	9999	219	16.4	119
10%	73	9999	213	12.6	73	9999	213	18.5	140
15%	60	9999	212	13.0	60	9999	212	19.0	152
20%	52	9999	216	11.9	52	9999	216	17.5	164
25%	47	9999	223	10.4	47	9999	223	15.2	176
30%	44	9999	233	8.7	44	9999	233	12.8	190
35%	41	9999	235	8.5	41	9999	235	12.4	194
40%	40	9999	176	46.9	40	9999	176	68.6	135
45%	40	9999	172	59.5	40	9999	172	87.1	133
50%	40	9999	144	9999	40	9999	144	9999	104
55%	41	9999	118	9999	41	9999	118	9999	78
60%	42	9999	94	9999	42	9999	94	9999	52
65%	44	9999	69	9999	44	9999	69	9999	26
70%	47	9999	42	9999	47	9999	42	9999	-5
75%	51	9999	40	9999	51	9999	40	9999	-11
80%	57	9999	67	9999	57	9999	67	9999	10
85%	65	9999	34	9999	65	9999	34	9999	-31
90%	79	9999	13	9999	79	9999	13	9999	-65
95%	101	9999	35	9999	101	9999	35	9999	-66
100%	146	9999	26	9999	146	9999	26	9999	-120

Line from BUS 13 to BUS 3/BUS 14: Operation of Relays at BUS 13 – Current (A) and Trip Time (Sec)

Fault Location from BUS 1	421 (Primary)				311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	13	9999	99	9999	13	9999	99	9999
5%	14	9999	106	9999	14	9999	106	9999
10%	14	9999	116	9999	14	9999	116	9999
15%	15	9999	126	9999	15	9999	126	9999
20%	16	9999	137	9999	16	9999	137	9999
BUS 2 End Opened								
80%	16	9999	56	9999	16	9999	56	9999
85%	15	9999	69	9999	15	9999	69	9999
90%	15	9999	79	9999	15	9999	79	9999
95%	14	9999	84	9999	14	9999	84	9999
99.5%	14	9999	78	9999	14	9999	78	9999

Line from BUS 13 to BUS 3/BUS 14: Operation of Relays at BUS 13 – Current (A) and Trip Time (Sec) – Line 1 Opened

Fault Location from BUS 1	311C (Primary)				LPRO (Backup)				Io Induced
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling		
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time	
0%	49	9999	90	9999	49	9999	90	9999	41
5%	30	9999	83	9999	30	9999	83	9999	53
10%	23	9999	85	9999	23	9999	85	9999	62
15%	20	9999	87	9999	20	9999	87	9999	68
20%	18	9999	91	9999	18	9999	91	9999	73
25%	16	9999	95	9999	16	9999	95	9999	79
30%	16	9999	101	9999	16	9999	101	9999	85
35%	16	9999	131	9999	16	9999	131	9999	115
40%	16	9999	187	9999	16	9999	187	9999	172
45%	16	9999	101	9999	16	9999	101	9999	85
50%	16	9999	85	9999	16	9999	85	9999	69
55%	17	9999	71	9999	17	9999	71	9999	54
60%	18	9999	57	9999	18	9999	57	9999	40
65%	19	9999	44	9999	19	9999	44	9999	25
70%	21	9999	29	9999	21	9999	29	9999	8
75%	23	9999	27	9999	23	9999	27	9999	4
80%	26	9999	42	9999	26	9999	42	9999	15
85%	31	9999	24	9999	31	9999	24	9999	-7
90%	38	9999	8	9999	38	9999	8	9999	-30
95%	49	9999	12	9999	49	9999	12	9999	-37
100%	73	9999	17	9999	73	9999	17	9999	-56

Line from BUS 17 to BUS 18/BUS 19: Operation of Relays at BUS 17 – Current (A) and Trip Time (Sec)

Fault Location from BUS 1	311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	5	9999	44	9999	5	9999	44	9999
5%	5	9999	47	9999	5	9999	47	9999
10%	6	9999	52	9999	6	9999	52	9999
15%	6	9999	56	9999	6	9999	56	9999
20%	7	9999	61	9999	7	9999	61	9999
BUS 2 End Opened								
80%	6	9999	23	9999	6	9999	23	9999
85%	6	9999	30	9999	6	9999	30	9999
90%	6	9999	35	9999	6	9999	35	9999
95%	6	9999	38	9999	6	9999	38	9999
99.5%	6	9999	36	9999	6	9999	36	9999

Line from BUS 17 to BUS 18/BUS 19: Operation of Relays at BUS 17 – Current (A) and Trip Time (Sec) – Line 1 Opened

Fault Location from BUS 1	421 (Primary)				311C (Backup)				Io Induced
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling		
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time	
0%	24	9999	40	9999	24	9999	40	9999	16
5%	16	9999	36	9999	16	9999	36	9999	21
10%	13	9999	37	9999	13	9999	37	9999	25
15%	11	9999	38	9999	11	9999	38	9999	27
20%	11	9999	39	9999	11	9999	39	9999	29
25%	10	9999	41	9999	10	9999	41	9999	31
30%	10	9999	43	9999	10	9999	43	9999	33
35%	11	9999	52	9999	11	9999	52	9999	42
40%	11	9999	65	9999	11	9999	65	9999	54
45%	11	9999	41	9999	11	9999	41	9999	30
50%	12	9999	36	9999	12	9999	36	9999	24
55%	12	9999	31	9999	12	9999	31	9999	19
60%	13	9999	27	9999	13	9999	27	9999	13
65%	15	9999	22	9999	15	9999	22	9999	8
70%	16	9999	18	9999	16	9999	18	9999	2
75%	18	9999	19	9999	18	9999	19	9999	1
80%	21	9999	25	9999	21	9999	25	9999	5
85%	25	9999	21	9999	25	9999	21	9999	-3
90%	30	9999	19	9999	30	9999	19	9999	-12
95%	40	9999	20	9999	40	9999	20	9999	-20
100%	59	9999	38	9999	59	9999	38	9999	-22

Line from BUS 19 to BUS 17/BUS 18: Operation of Relays at BUS 19 – Current (A) and Trip Time (Sec)

Fault Location from BUS 1	421 (Primary)				311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	4	9999	19	9999	4	9999	19	9999
5%	4	9999	20	9999	4	9999	20	9999
10%	4	9999	22	9999	4	9999	22	9999
15%	4	9999	24	9999	4	9999	24	9999
20%	5	9999	26	9999	5	9999	26	9999
BUS 2 End Opened								
80%	5	9999	7	9999	5	9999	7	9999
85%	5	9999	10	9999	5	9999	10	9999
90%	5	9999	12	9999	5	9999	12	9999
95%	5	9999	13	9999	5	9999	13	9999
99.5%	5	9999	12	9999	5	9999	12	9999

Line from BUS 19 to BUS 17/BUS 18: Operation of Relays at BUS 19 – Current (A) and Trip Time (Sec) – Line 1 Opened

Fault Location from BUS 1	421 (Primary)				311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
0%	25	9999	51	9999	25	9999	51	9999
5%	14	9999	47	9999	14	9999	47	9999
10%	10	9999	48	9999	10	9999	48	9999
15%	8	9999	50	9999	8	9999	50	9999
20%	7	9999	52	9999	7	9999	52	9999
25%	6	9999	55	9999	6	9999	55	9999
30%	6	9999	58	9999	6	9999	58	9999
35%	5	9999	79	9999	5	9999	79	9999
40%	5	9999	122	9999	5	9999	122	9999
45%	5	9999	60	9999	5	9999	60	9999
50%	5	9999	50	9999	5	9999	50	9999
55%	5	9999	40	9999	5	9999	40	9999
60%	5	9999	31	9999	5	9999	31	9999
65%	5	9999	22	9999	5	9999	22	9999
70%	5	9999	12	9999	5	9999	12	9999
75%	6	9999	10	9999	6	9999	10	9999
80%	6	9999	17	9999	6	9999	17	9999
85%	7	9999	5	9999	7	9999	5	9999
90%	9	9999	12	9999	9	9999	12	9999
95%	11	9999	27	9999	11	9999	27	9999
100%	16	9999	22	9999	16	9999	22	9999

Line from BUS 18 to BUS 17/BUS 19: Operation of Relays at BUS 18 – Current (A) and Trip Time (Sec)

Fault Location from BUS 1	421 (Primary)				311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	2	9999	26	9999	2	9999	26	9999
5%	2	9999	27	9999	2	9999	27	9999
10%	2	9999	30	9999	2	9999	30	9999
15%	2	9999	32	9999	2	9999	32	9999
20%	2	9999	35	9999	2	9999	35	9999
BUS 2 End Opened								
80%	2	9999	16	9999	2	9999	16	9999
85%	2	9999	20	9999	2	9999	20	9999
90%	2	9999	24	9999	2	9999	24	9999
95%	2	9999	26	9999	2	9999	26	9999
99.5%	2	9999	24	9999	2	9999	24	9999

Line from BUS 18 to BUS 17/BUS 19: Operation of Relays at BUS 18– Current (A) and Trip Time (Sec) – Line 1 Opened

Fault Location from BUS 1	SEL 311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time
0%	48	9999	286	9999	48	9999	286	9999
5%	6	9999	436	9999	6	9999	436	9999
10%	24	9999	511	4.1	24	9999	511	5.3
15%	36	9999	570	3.2	36	9999	570	4.2
20%	45	9999	624	2.6	45	9999	624	3.4
25%	53	9999	676	2.2	53	9999	676	2.9
30%	60	9999	732	1.9	60	9999	732	2.5
35%	68	9999	741	1.9	68	9999	741	2.5
40%	75	9999	711	2.0	75	9999	711	2.7
45%	83	9999	655	2.4	83	9999	655	3.1
50%	92	9999	546	3.5	92	9999	546	4.6
55%	102	9999	447	5.7	102	9999	447	7.4
60%	114	9999	353	11.7	114	9999	353	15.3
65%	129	9999	258	86.8	129	9999	258	113.5
70%	146	9999	151	9999	146	9999	151	9999
75%	169	9999	151	9999	169	9999	151	9999
80%	199	9999	278	38.9	199	9999	278	50.9
85%	240	3896.2	155	9999	240	5097	155	9999
90%	303	22.7	52	9999	303	29.7	52	9999
95%	406	7.4	100	9999	406	9.7	100	9999
100%	613	2.7	174	9999	613	3.6	174	9999

Line 2 from BUS 3 to BUS 4: Operation of Relays at BUS 3 – Current (A) and Trip Time (Sec)

Fault Location from BUS 1	SEL 311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time
BUS 1 End Opened								
0.5%	25	9999	333	14.7	25	9999	333	19.2
5%	28	9999	359	11.0	28	9999	359	14.3
10%	31	9999	391	8.3	31	9999	391	10.8
15%	35	9999	427	6.4	35	9999	427	8.4
20%	39	9999	467	5.1	39	9999	467	6.6
BUS 2 End Opened								
80%	36	9999	209	9999	36	9999	209	9999
85%	37	9999	257	9999	37	9999	257	9999
90%	38	9999	294	9999	38	9999	294	9999
95%	39	9999	313	9999	39	9999	313	9999
99.5%	39	9999	290	9999	39	9999	290	9999

Line 2 from BUS 3 to BUS 4: Operation of Relays at BUS 3 – Current (A) and Trip Time (Sec) – Line 1 Opened

Fault Location from BUS 1	SEL 421 (Primary)				SEL 311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time
0%	48	9999	286	5.8	48	9999	286	7.9
5%	6	9999	436	2.1	6	9999	436	2.9
10%	24	9999	511	1.5	24	9999	511	2.1
15%	36	9999	570	9999	36	9999	570	9999
20%	45	9999	624	9999	45	9999	624	9999
25%	53	9999	676	9999	53	9999	676	9999
30%	60	9999	732	9999	60	9999	732	9999
35%	68	9999	741	9999	68	9999	741	9999
40%	75	9999	711	9999	75	9999	711	9999
45%	83	9999	654	9999	83	9999	654	9999
50%	92	9999	545	9999	92	9999	545	9999
55%	102	9999	446	9999	102	9999	446	9999
60%	114	9999	353	9999	114	9999	353	9999
65%	129	9999	257	9999	129	9999	257	9999
70%	146	9999	151	9999	146	9999	151	9999
75%	169	9999	151	9999	169	9999	151	9999
80%	199	9999	278	9999	199	9999	278	9999
85%	240	9999	154	9999	240	9999	154	9999
90%	302	9999	52	9999	302	9999	52	9999
95%	406	9999	101	9999	406	9999	101	9999
100%	613	9999	174	9999	613	9999	174	9999

Line 2 from BUS 4 to BUS 3: Operation of Relays at BUS 4 – Current (A) and Trip Time (Sec)

Fault Location from BUS 1	421 (Primary)				311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	25	9999	333	9999	25	9999	333	9999
5%	28	9999	359	9999	28	9999	359	9999
10%	31	9999	391	9999	31	9999	391	9999
15%	35	9999	427	9999	35	9999	427	9999
20%	39	9999	467	9999	39	9999	467	9999
BUS 2 End Opened								
80%	36	9999	209	19.3	36	9999	209	26.4
85%	37	9999	258	8.0	37	9999	258	11.0
90%	38	9999	294	5.3	38	9999	294	7.3
95%	38	9999	314	4.5	38	9999	314	6.1
99.5%	39	9999	290	5.6	39	9999	290	7.6

Line 2 from BUS 4 to BUS 3: Operation of Relays at BUS 4 – Current (A) and Trip Time (Sec) – Line 1 Opened

Fault Location from BUS 1	SEL 421 (Primary)				SEL 311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time
0%	42	9999	311	9999	42	9999	311	9999
5%	6	9999	454	9999	6	9999	454	9999
10%	12	9999	527	9999	12	9999	527	9999
15%	20	9999	586	0.95	20	9999	586	1.40
20%	27	9999	639	0.84	27	9999	639	1.23
25%	32	9999	692	0.75	32	9999	692	1.10
30%	37	9999	747	0.68	37	9999	747	0.99
35%	42	9999	769	0.66	42	9999	769	0.96
40%	47	9999	761	0.66	47	9999	761	0.97
45%	52	9999	735	0.69	52	9999	735	1.02
50%	58	9999	671	0.78	58	9999	671	1.15
55%	65	9999	618	0.88	65	9999	618	1.29
60%	73	9999	574	0.98	73	9999	574	1.44
65%	82	9999	536	1.10	82	9999	536	1.61
70%	94	9999	497	1.25	94	9999	497	1.83
75%	108	9999	551	1.05	108	9999	551	1.54
80%	128	9999	722	0.71	128	9999	722	1.04
85%	155	70.45	731	0.70	155	103.12	731	1.02
90%	195	13.15	473	1.36	195	19.25	473	1.99
95%	262	4.91	121	9999	262	7.19	121	9999
100%	395	1.90	130	9999	395	2.79	130	9999

Line 3 from BUS 4 to BUS 5: Operation of Relays at BUS 4 – Current (A) and Trip Time (Sec)

Fault Location from BUS 1	421 (Primary)				311C (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	16	9999	339	2.6	16	9999	339	3.9
5%	18	9999	366	2.2	18	9999	366	3.3
10%	20	9999	398	1.9	20	9999	398	2.7
15%	22	9999	435	1.6	22	9999	435	2.3
20%	25	9999	475	1.4	25	9999	475	2.0
BUS 2 End Opened								
80%	23	9999	87	9999	23	9999	87	9999
85%	24	9999	120	9999	24	9999	120	9999
90%	24	9999	209	9999	24	9999	209	9999
95%	25	9999	326	9999	25	9999	326	9999
99.5%	25	9999	317	9999	25	9999	317	9999

Line 3 from BUS 4 to BUS 5: Operation of Relays at BUS 4 – Current (A) and Trip Time (Sec) – Line 1 Opened

Fault Location from BUS 1	SEL 311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time	3Io	Trip Time
0%	42	9999	311	9999	42	9999	311	9999
5%	6	9999	454	9999	6	9999	454	9999
10%	12	9999	527	75.3	12	9999	527	104.7
15%	20	9999	586	9999	20	9999	586	9999
20%	27	9999	639	9999	27	9999	639	9999
25%	32	9999	692	9999	32	9999	692	9999
30%	37	9999	747	9999	37	9999	747	9999
35%	42	9999	769	9999	42	9999	769	9999
40%	47	9999	761	9999	47	9999	761	9999
45%	52	9999	735	9999	52	9999	735	9999
50%	58	9999	671	9999	58	9999	671	9999
55%	65	9999	618	9999	65	9999	618	9999
60%	73	9999	574	9999	73	9999	574	9999
65%	82	9999	535	9999	82	9999	535	9999
70%	94	9999	497	9999	94	9999	497	9999
75%	108	9999	551	9999	108	9999	551	9999
80%	128	9999	722	9999	128	9999	722	9999
85%	155	9999	731	9999	155	9999	731	9999
90%	195	9999	473	9999	195	9999	473	9999
95%	262	9999	121	9999	262	9999	121	9999
100%	395	9999	130	9999	395	9999	130	9999

Line 3 from BUS 5 to BUS 4: Operation of Relays at BUS 5 – Current (A) and Trip Time (Sec)

Fault Location from BUS 1	311C (Primary)				LPRO (Backup)			
	Without Mutual Coupling		With Mutual Coupling		Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time	Io	Trip Time	Io	Trip Time
BUS 1 End Opened								
0.5%	16	9999	339	9999	16	9999	339	9999
5%	18	9999	366	9999	18	9999	366	9999
10%	20	9999	398	9999	20	9999	398	9999
15%	22	9999	435	9999	22	9999	435	9999
20%	25	9999	475	9999	25	9999	475	9999
BUS 2 End Opened								
80%	23	9999	87	9999	23	9999	87	9999
85%	24	9999	120	9999	24	9999	120	9999
90%	24	9999	209	9999	24	9999	209	9999
95%	25	9999	326	9999	25	9999	326	9999
99.5%	25	9999	317	9999	25	9999	317	9999

Line 3 from BUS 5 to BUS 4: Operation of Relays at BUS 5 – Current (A) and Trip Time (Sec) – Line 1 Opened

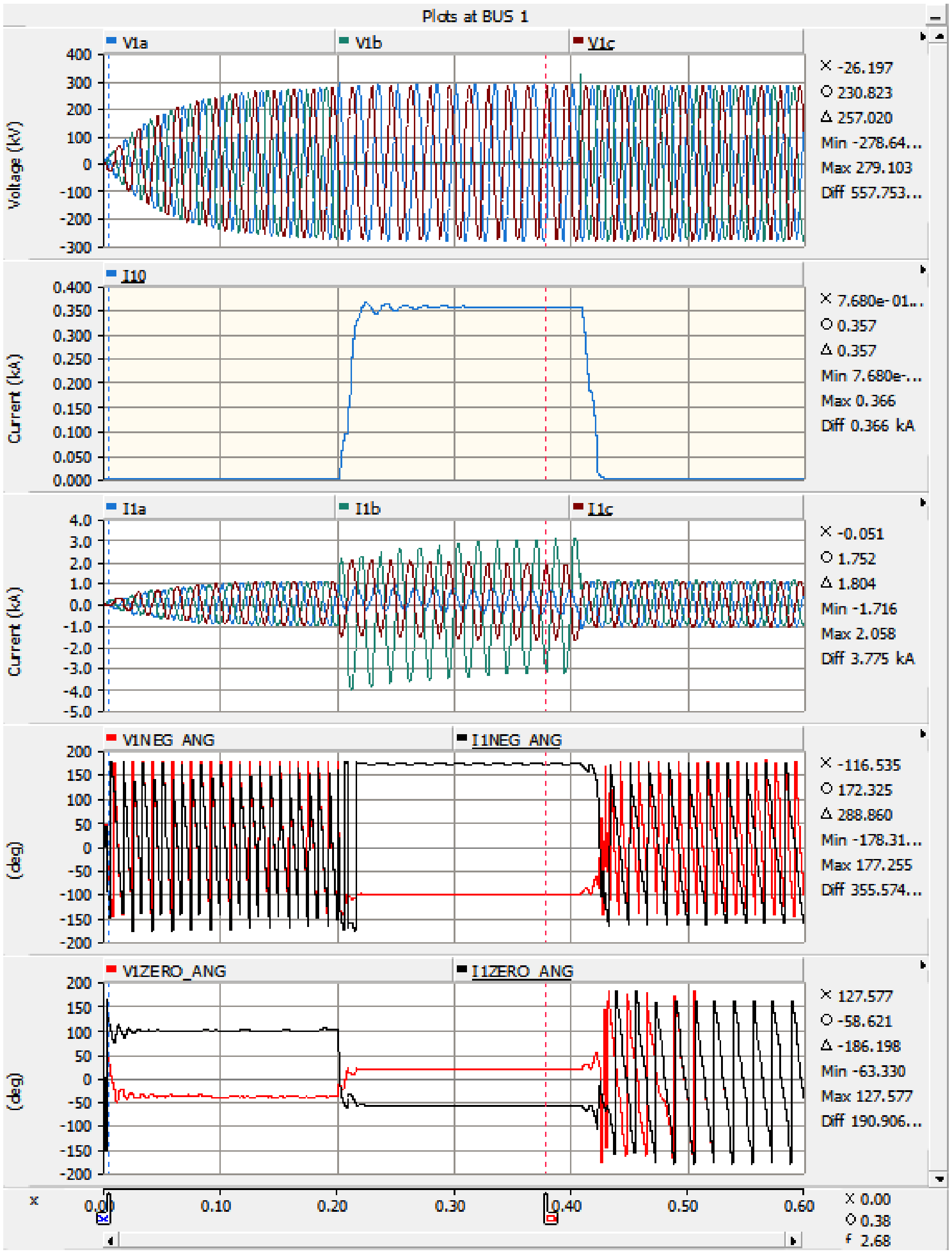
Fault Location from BUS 1	311C (Primary)			
	Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time
0%	97	9999	409	18.02
5%	141	9999	547	4.12
10%	163	9999	626	2.72
15%	180	9999	689	2.10
20%	196	9999	747	1.72
25%	211	9999	806	1.44
30%	227	9999	868	1.22
35%	245	9999	902	1.12
40%	264	9999	915	1.09
45%	286	9999	914	1.09
50%	312	9999	884	1.17
55%	342	9999	867	1.22
60%	377	54.49	864	1.23
65%	420	14.61	874	1.20
70%	474	7.28	894	1.14
75%	543	4.25	1013	0.89
80%	634	2.62	1258	0.60
85%	763	1.63	1398	0.50
90%	955	1.00	1357	0.53
95%	1275	0.58	1146	0.70
100%	1918	0.32	1474	0.46

Line from BUS 5 to BUS 2: Operation of Relays at BUS 5 – Current (A) and Trip Time (Sec)

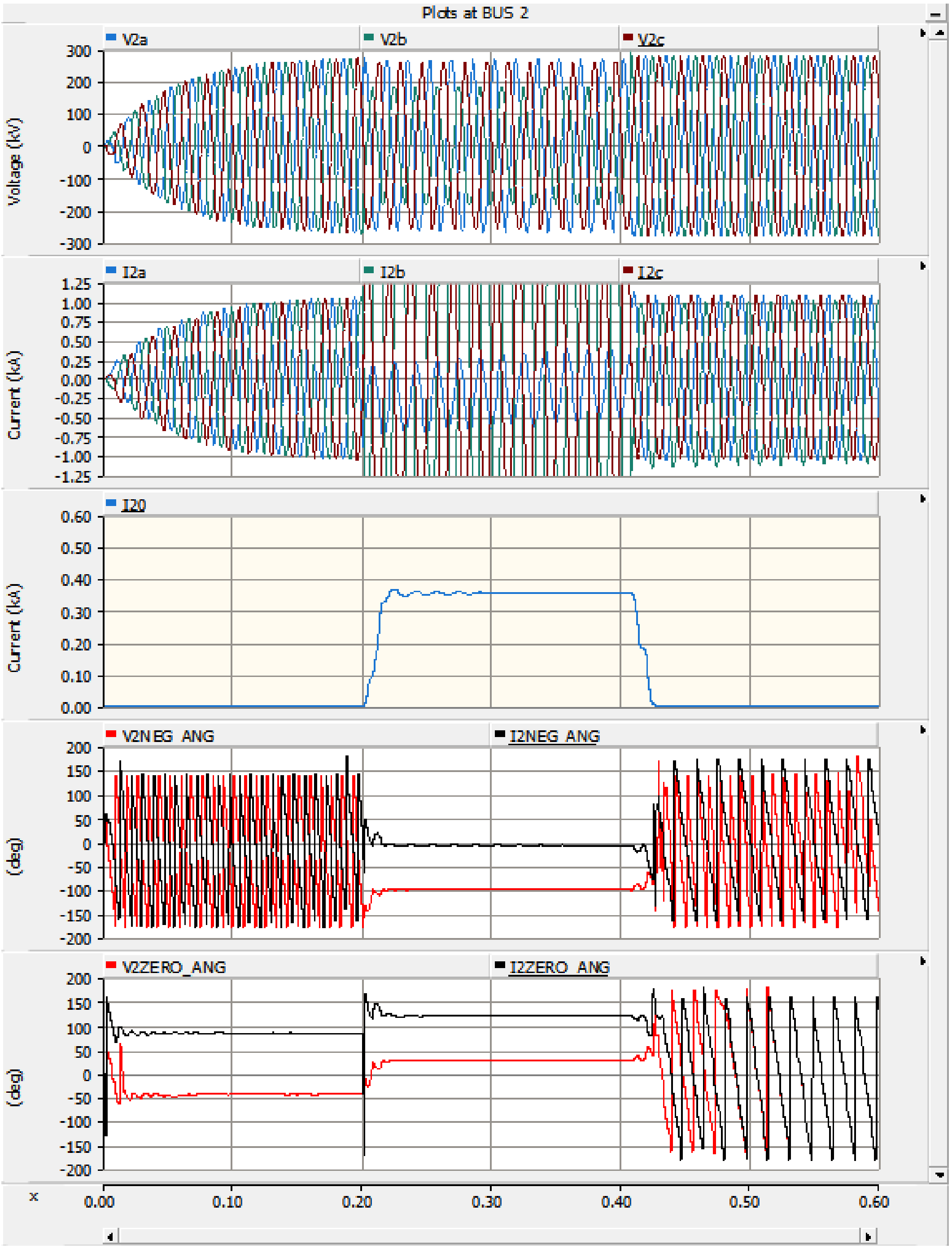
Fault Location from BUS 1	311C (Primary)			
	Without Mutual Coupling		With Mutual Coupling	
	Io	Trip Time	Io	Trip Time
BUS 1 End Opened				
0.5%	88	9999	376	56.8
5%	97	9999	407	18.9
10%	107	9999	445	10.0
15%	118	9999	487	6.4
20%	130	9999	534	4.5
BUS 2 End Opened				
80%	123	9999	70	9999
85%	124	9999	46	9999
90%	126	9999	63	9999
95%	127	9999	162	9999
99.5%	128	9999	169	9999

Line from BUS 5 to BUS 2: Operation of Relays at BUS 5 – Current (A) and Trip Time (Sec) – Line 1 Opened

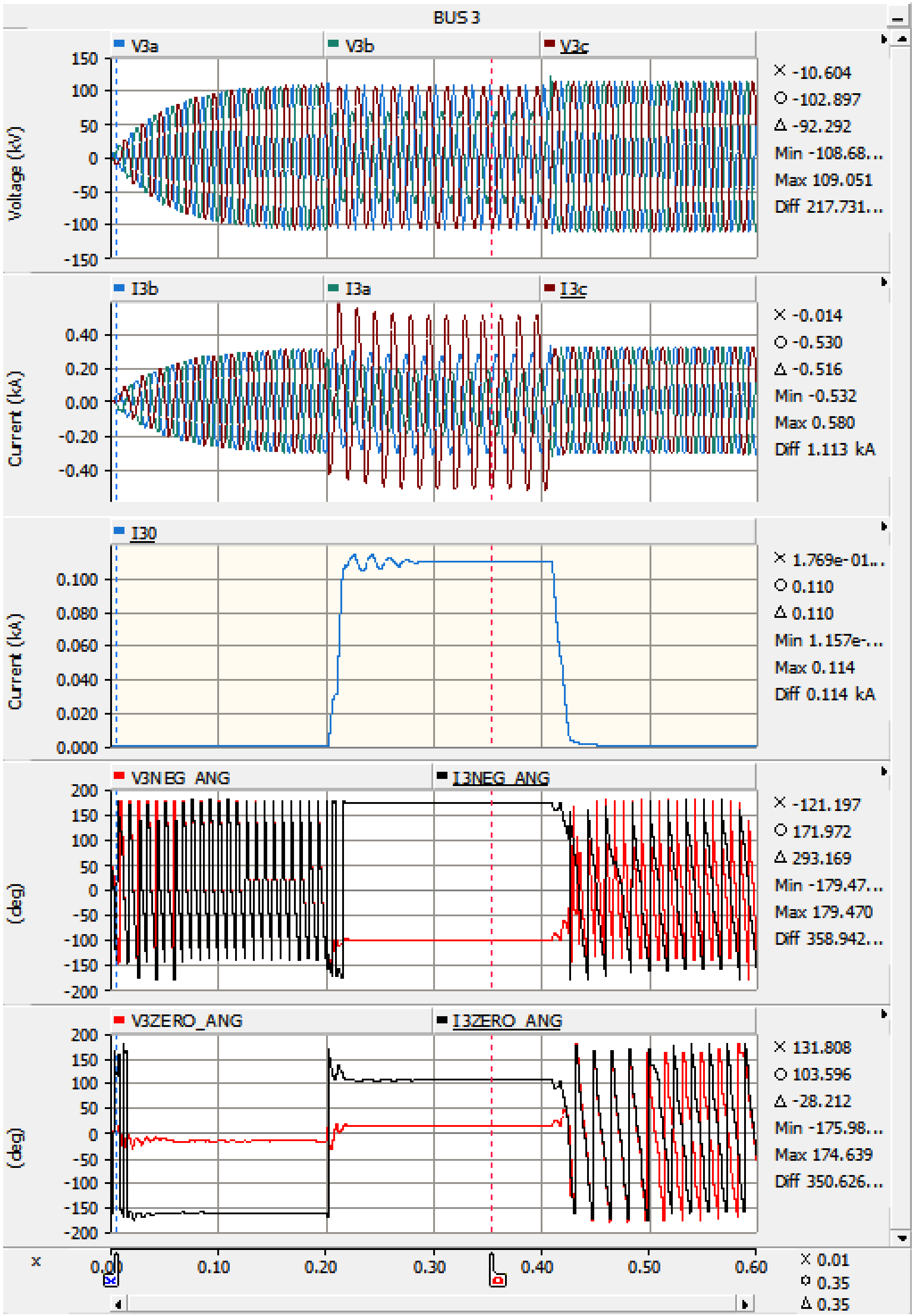
Appendix D
Time Domain Simulation-PSCAD EMTDC Results



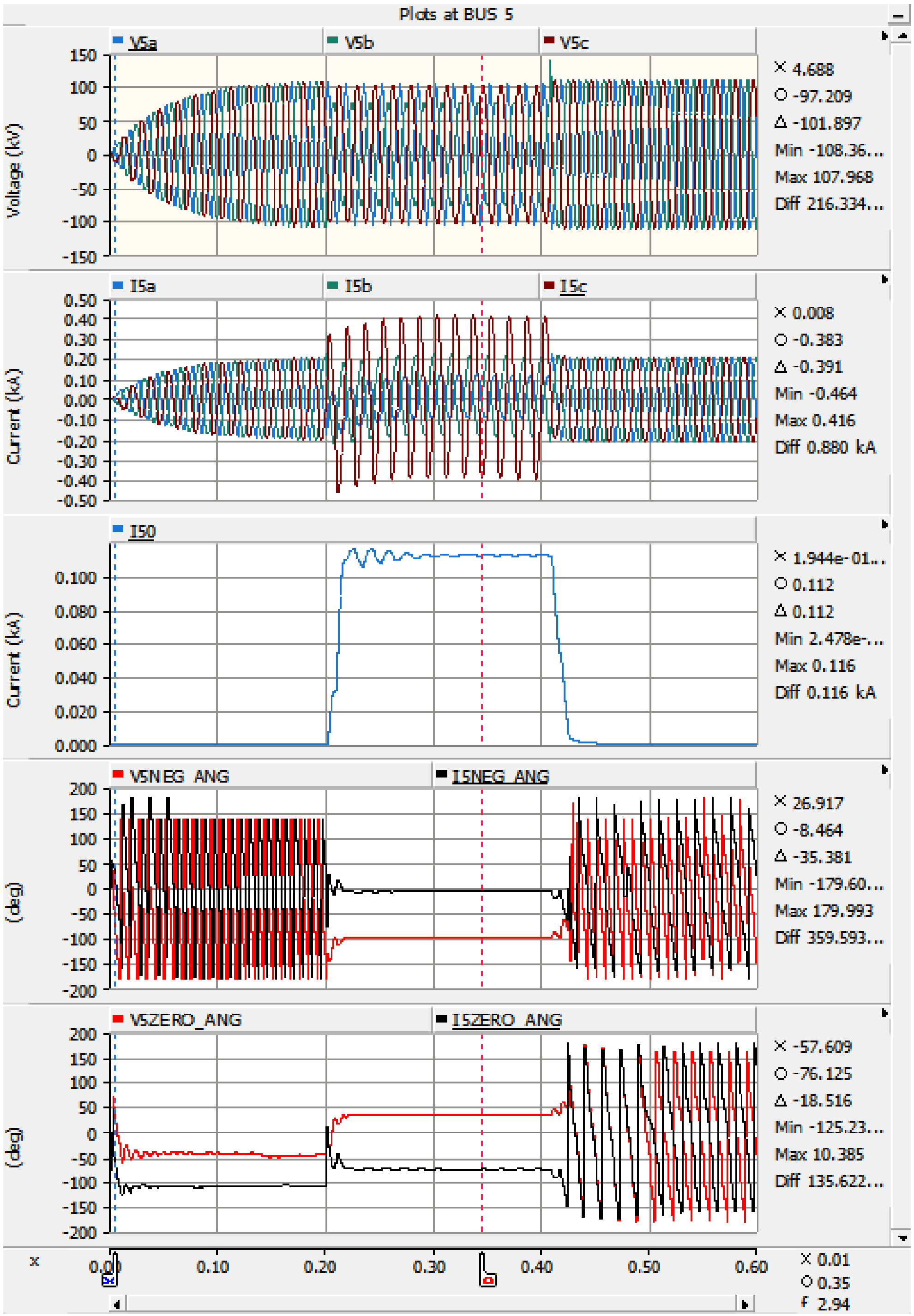
Current and voltage values for Relay at 138kV BUS 1 Station Protecting Line 1 (SLG Fault at BUS 1)



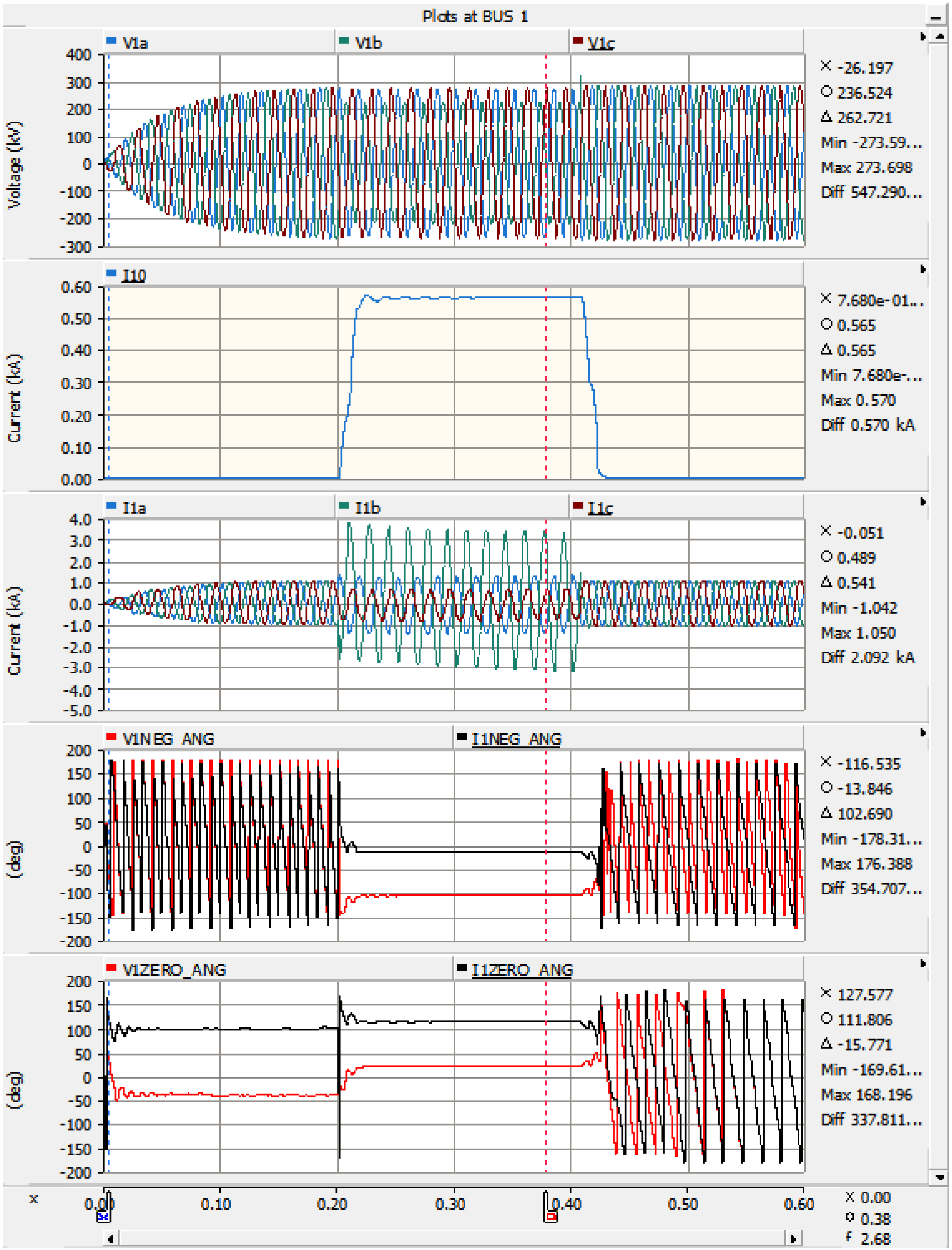
Current and voltage values for Relay at 138kV BUS 2 Station Protecting Line 1 (SLG Fault at BUS 1)



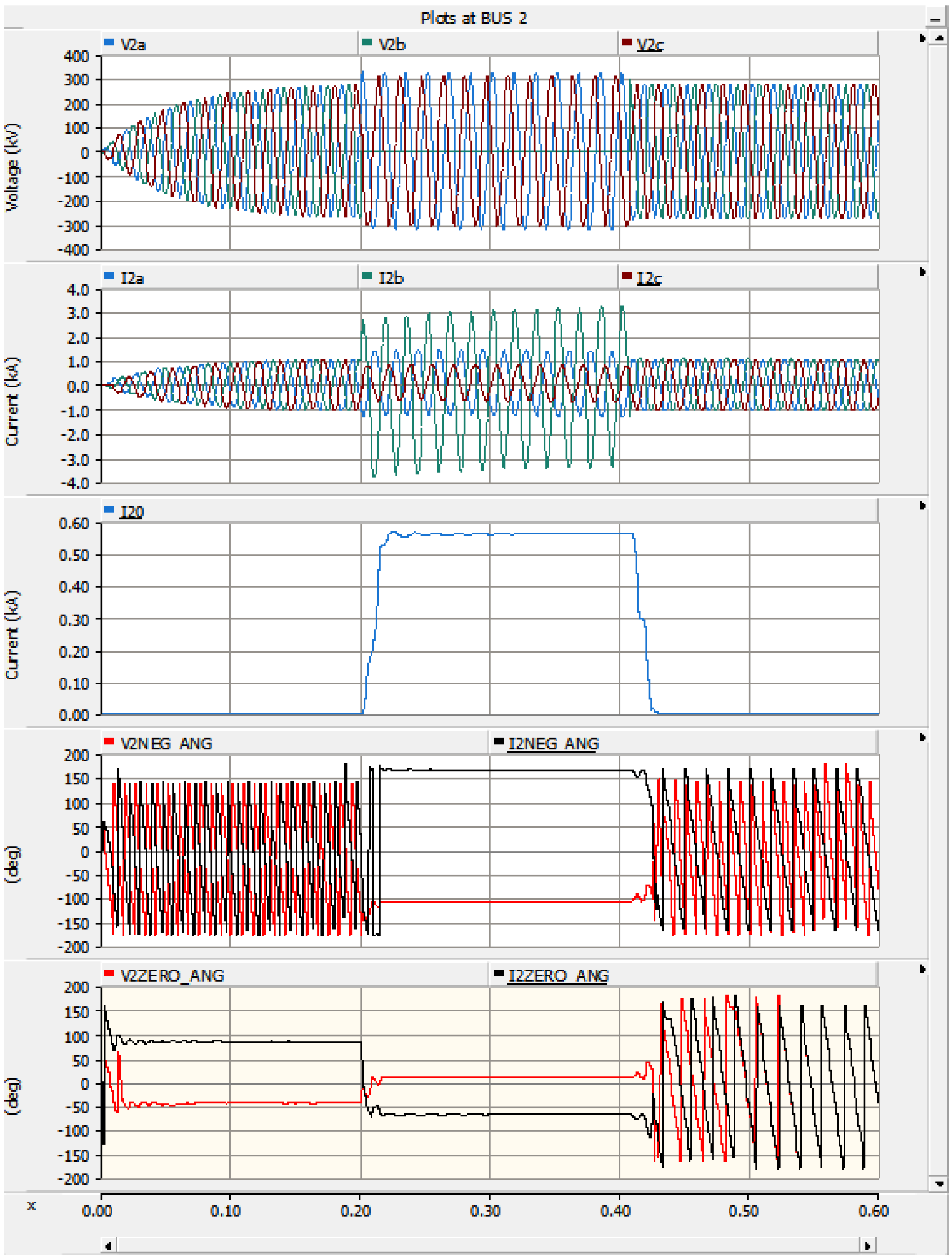
Current and voltage values for Relay at 138kV BUS 3 Station Protecting Line 2 (SLG Fault at BUS 1)



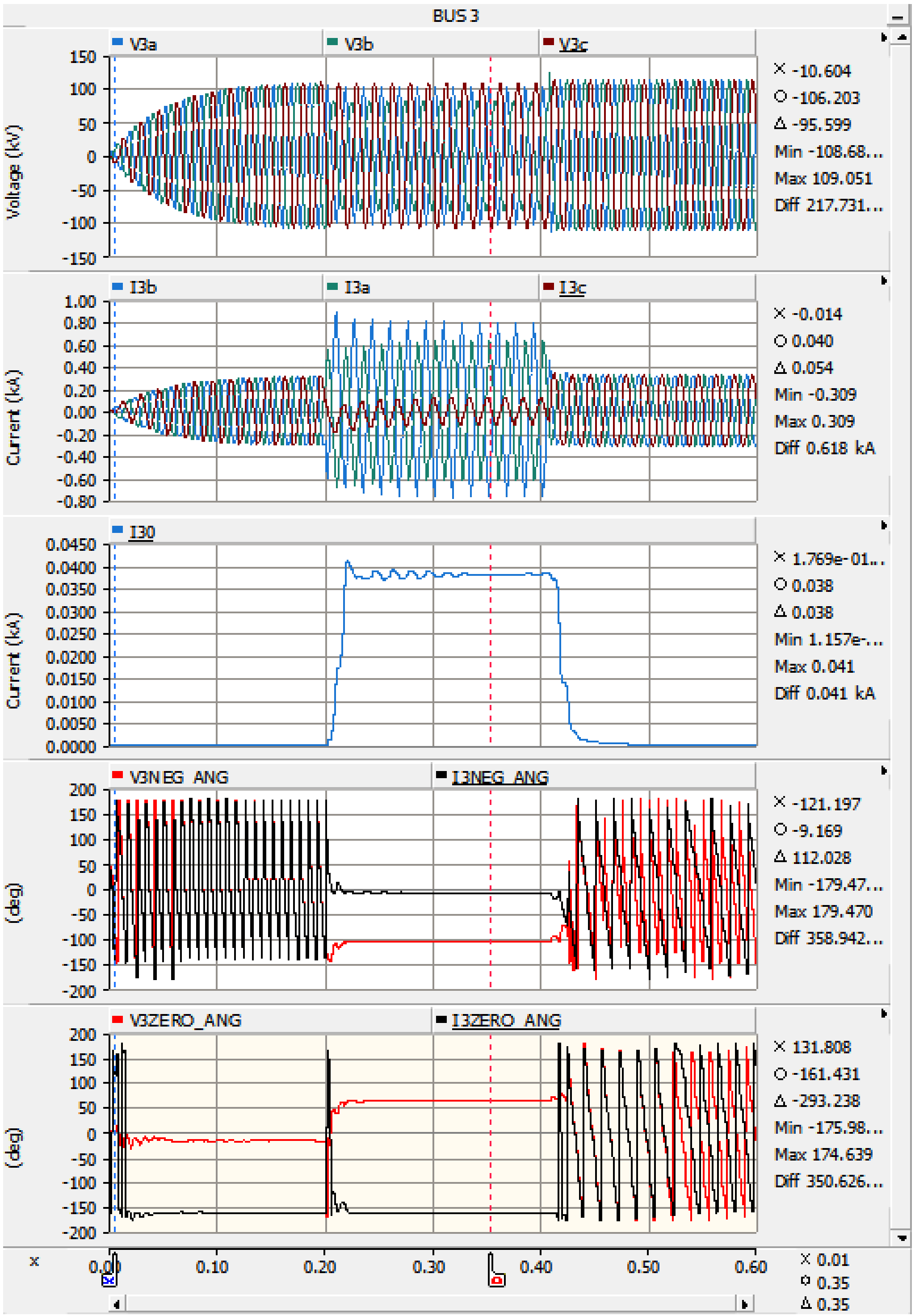
Current and voltage values for Relay at 138kV BUS 5 Station Protecting Line 3 (SLG Fault at BUS 1)



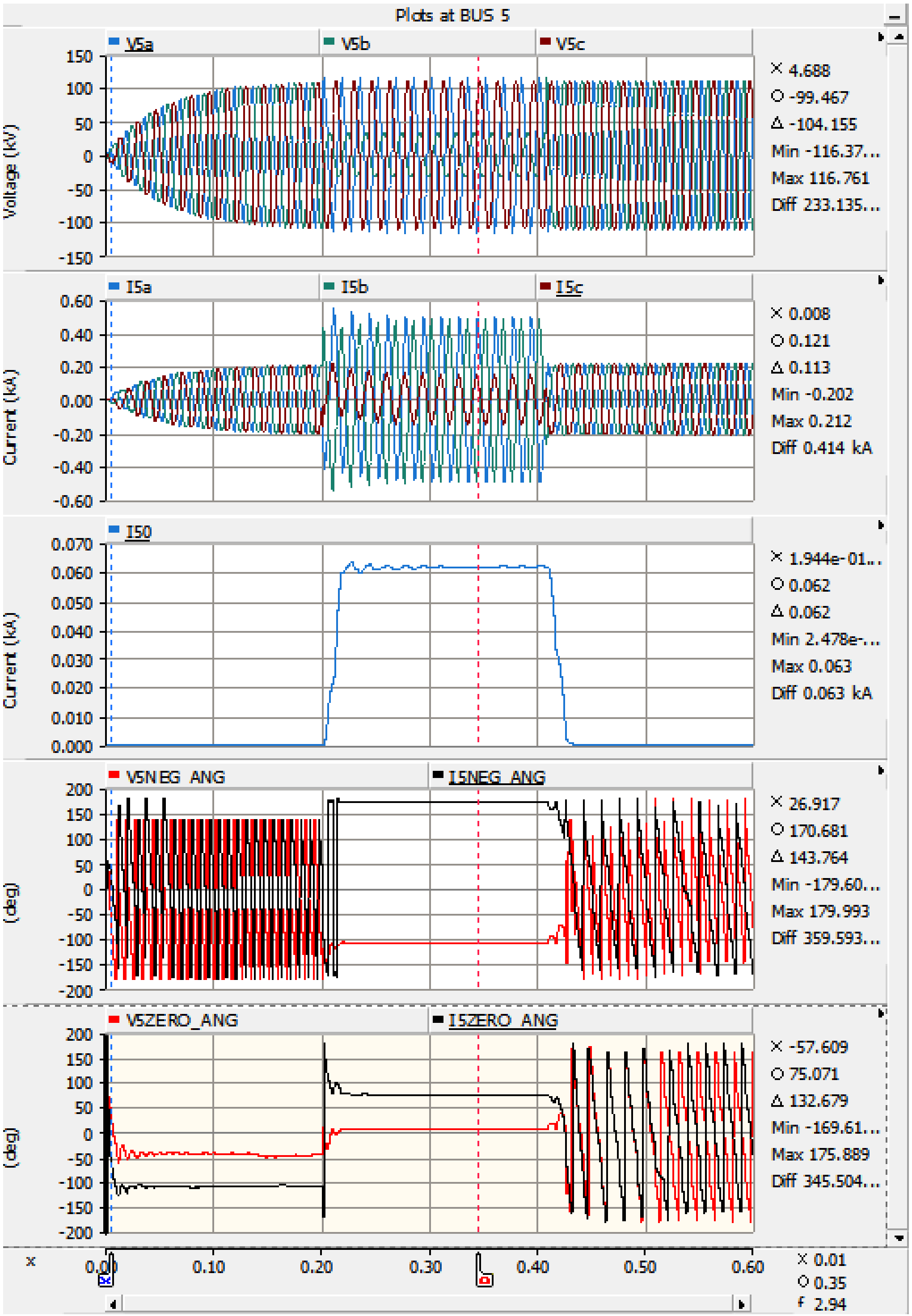
Current and voltage values for Relay at 138kV BUS 1 Station Protecting Line 1 (SLG Fault at BUS 2)



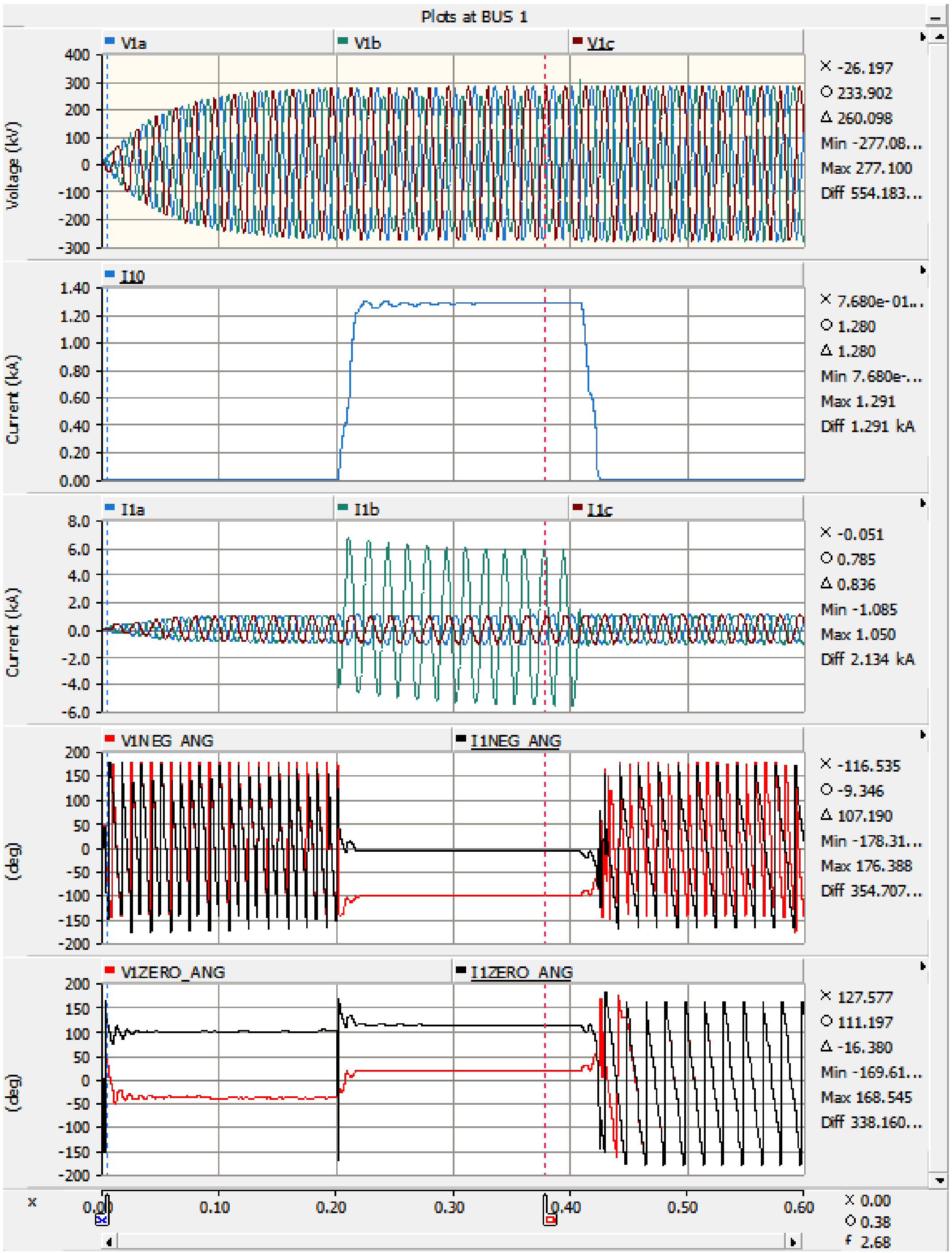
Current and voltage values for Relay at 138kV BUS 2 Station Protecting Line 1 (SLG Fault at BUS 2)



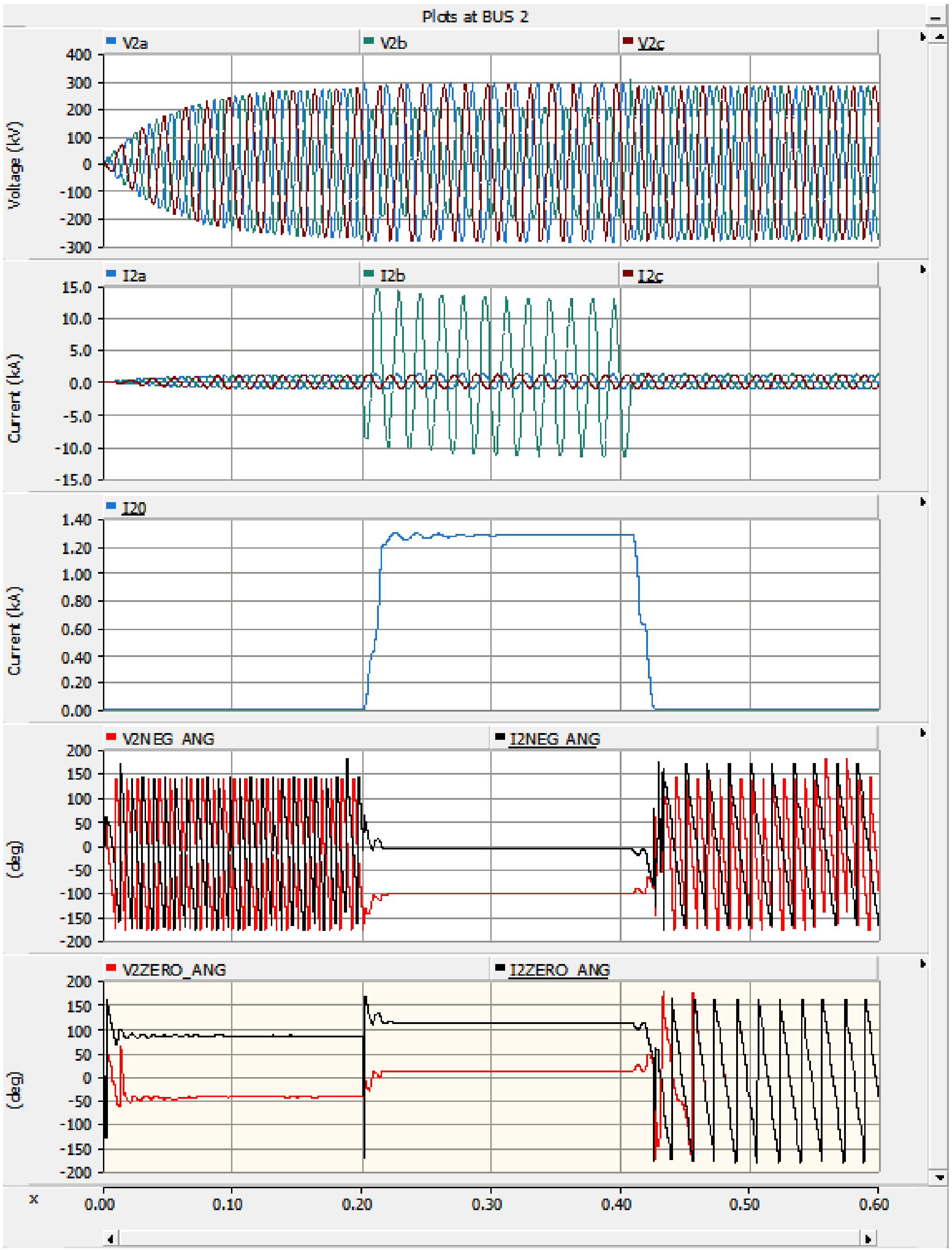
Current and voltage values for Relay at 138kV BUS 3 Station Protecting Line 2 (SLG Fault at BUS 2)



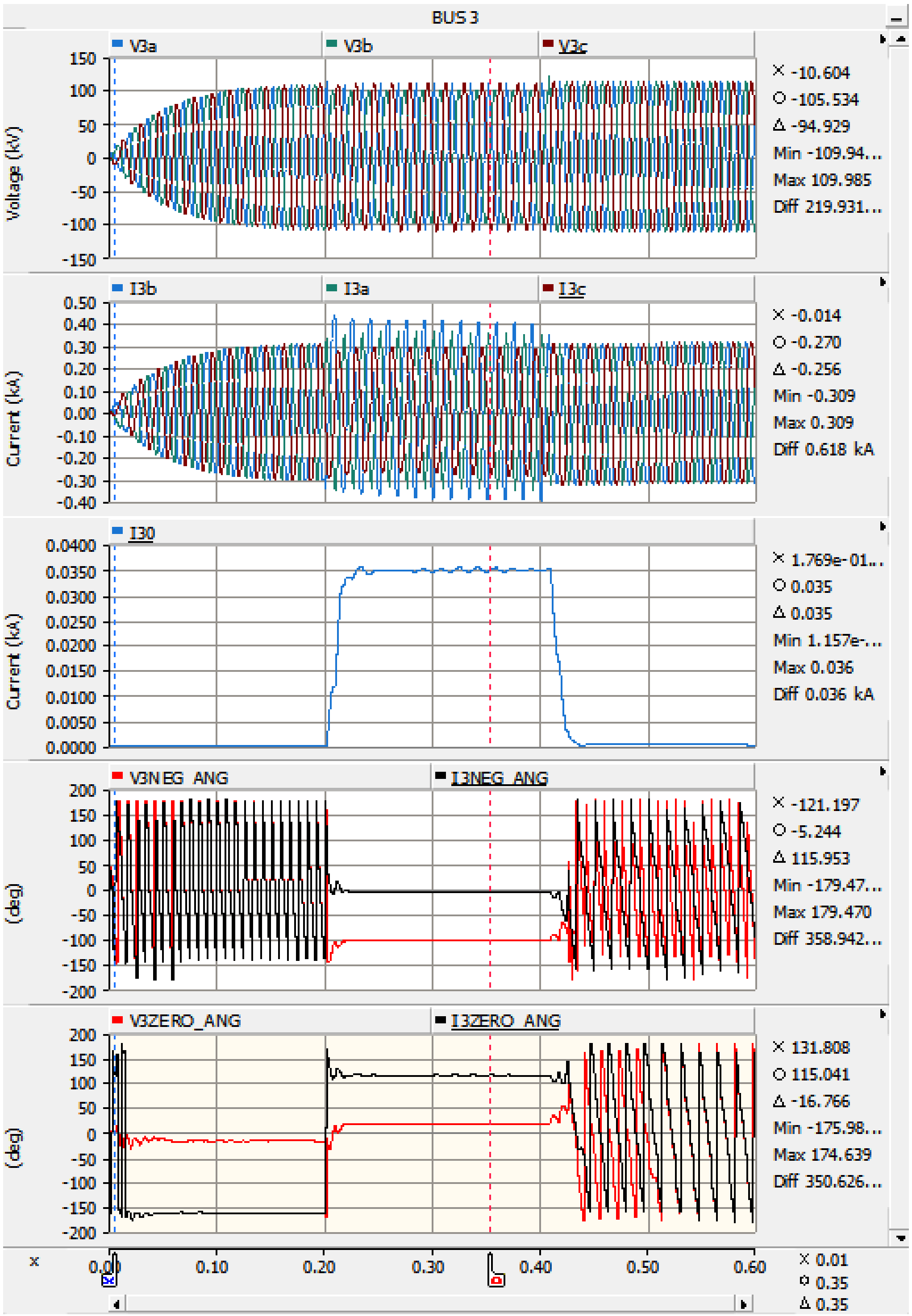
Current and voltage values for Relay at 138kV BUS 5 Station Protecting Line 3 (SLG Fault at BUS 2)



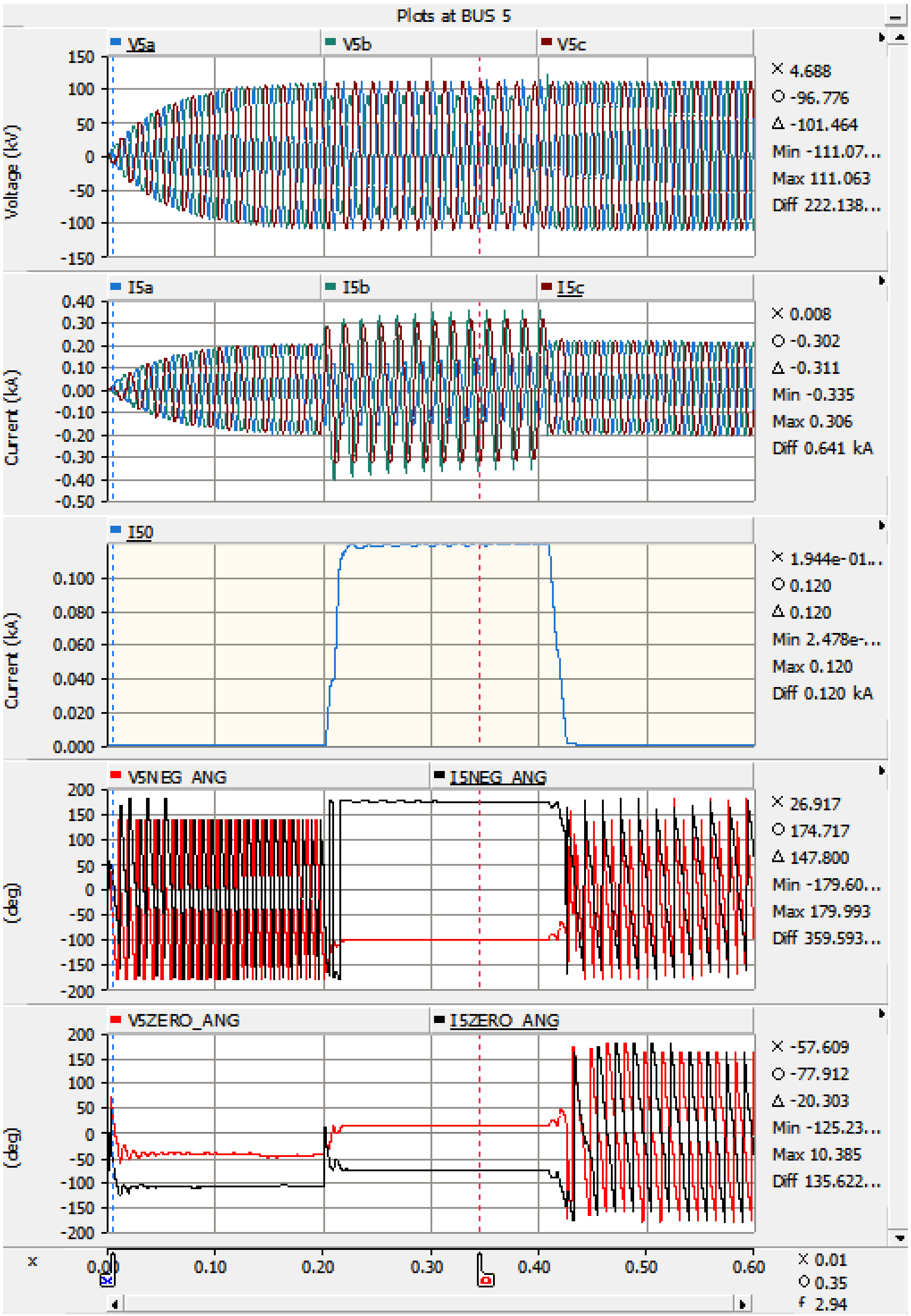
Current and voltage values for Relay at 138kV BUS 1 Station Protecting Line 1 (SLG Fault at 50% on Line 1)



Current and voltage values for Relay at 138kV BUS 2 Station Protecting Line 1 (SLG Fault at 50% on Line 1)



Current and voltage values for Relay at 138kV BUS 3 Station Protecting Line 2 (SLG Fault at 50% on Line 1)



Current and voltage values for Relay at 138kV BUS 5 Station Protecting Line 3 (SLG Fault at 50% on Line 1)

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