DESIGN OF A DIFFERENTIAL PROTECTION SCHEME FOR A 345 KV TRANSMISSION LINE USING SEL 311L RELAYS

by

TARANGINI KAROOR SUBRAHMANYAM

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Major Professor
Dr. Noel Schulz

Abstract

Transmission networks are an important part of an electric power system. They help transfer power from the point of generation (power plants) to the substation. In order to minimize losses during power transfer, the lines are operated at high voltages. The high voltage lines not only have a high power transmission capacity, but they are also prone to faults of larger magnitudes. Thus the occurrence of such faults results in a need for the faults to be cleared quickly in order to limit damage caused to the system. Hence, relays are installed at the Buses to provide protection to the lines. Transmission lines in a power system are most commonly protected by distance relays that use directional comparison schemes. However, due to the simplicity of line differential schemes, there has been an increase in the use of differential relays for complex networks. Moreover, since the relays require only current as the operating parameter, their settings can be determined easily.

This report discusses the design of a line current differential protection scheme for a transmission line using SEL 311L relays. The relay settings have been determined and then tested for seven fault scenarios, three internal fault points and four external fault points. To set and test the relays, AcSELerator Quickset, SEL 5030 and PowerWorld programs have been used. Real life power system is simulated with the help of SEL AMS (Adaptive Multichannel Source) that acts as the source to provide the required data to the relays. The relays trip and open the breaker contacts for an internal fault. During an external fault, the relays do not trip and the breaker contacts remain closed. The response of the relays in case of communication failures has been discussed.

Table of Contents

List of Figures

List of Tables

Acknowledgements

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Chapter 1 - Introduction

Transmission lines serve as interconnecting links in a power system and help to transmit power from generation to load. Hence, they are the most important part of a power system. They are usually operated at high voltage and low current to minimize the losses during power transfer (power lost is proportional to the square of current) and so, a fault on the transmission line must be identified and the faulted section isolated quickly to reduce equipment damage. Thus, design of a protection system consisting of appropriate switchgear and protective gear is required to ensure reliable operation of the system i.e., to reduce the duration of power outages and possible equipment damage, and provide best service to customers.

For protection at lower voltages, fuses are used. However, at high voltages, relays and circuit breakers are commonly used for protection of power systems. They can be classified into different types based on the operating parameters, construction and function. On the basis of function, the types of relays are overcurrent, differential, distance, definite time, and inverse time. While over-current, voltage, distance and directionality are powerful techniques, all of them involve some compromise between the objectives of reliability, security, speed, selectivity and economy [8]. On the other hand, differential protection is secure, reliable, fast, and economical. Thus it is one of the effective types of protection.

This report aims to design a protection and communication system for a 345 kV transmission line of a given power system. In order to protect the line, SEL (Schweitzer Engineering Laboratories) 311L relays have been used on either side of the transmission line. The relays provide differential and overcurrent protection as the primary and backup protection schemes, respectively.

First, transmission line protection has been discussed; its principles and differential protection theory. Second, protection system design has been considered. In order to use the SEL relays, the relay settings must be determined by performing fault calculations on the chosen system. The fault calculations were performed using Power World software, and fault currents were computed for balanced (three-phase) and unbalanced (single-line-to-ground and line-to-line) faults. Next, setting the differential relay and AMS (Adaptive Multichannel Source) has been included. The SEL AMS simulates conditions that exist in a power system with the help of the data inputted to it through SEL 5030 software. The relays have been tested for seven fault scenarios, three internal faults and four external faults. In each case, the relay response that is obtained by the indication of the LEDs on its front panel has been presented and thus verified. The case of communication failure between the relays has also been discussed. Then, conclusions and possible future work have been presented.

Chapter 2 - Transmission line protection

As discussed earlier, transmission lines transport power at high voltages from source to load and are the most significant component of power systems. In order to ensure uninterrupted power supply to consumers, the lines must operate with high reliability. A short circuit or fault in the line hampers system operation to a large extent. A fault is a sudden abnormal flow of current in the line due to a short circuit in the system. Some of the causes of transmission line faults are [9]:

1. Faulty equipment (switches, breakers, transformers, etc.)
2. Natural disasters (earthquakes, floods, etc.)
3. Weather (snow, wind, ice, etc.)
4. Animals (squirrels, birds, etc.)
5. Trees and lightning
6. Vandalism

Faults cannot be prevented; they can only be interrupted quickly in order to isolate the faulty section from the rest of the system so equipment damage is minimized and reliability of power system is not compromised. Hence, the design of protection system is vital to safe operation of transmission lines.

A basic protection scheme must have three basic components:

1. Instrument transformers
2. Relays
3. Circuit breakers

Instrument transformers can be either current transformers (CT) or voltage transformers (VT). In a differential protection scheme, only CTs are required. The function of the CT is to sense the current flowing in the line, convert it to a lower secondary value and feed it to the relay. The relay then has to determine whether the system is in fault condition or normal condition based on whether or not the current exceeds a set pickup value. Under fault conditions, the relay signals the circuit breaker. The circuit breaker opens and disconnects the faulted section from the rest of the system.

Ideally, a relay must have the following characteristics [1]:

1. Selectivity: The relay must trip only when there is a fault and not unnecessarily.
2. Reliability: The relay must operate dependably and accurately when a fault occurs, despite it having been inactive for a long time.
3. Sensitivity: The relay must be sensitive enough so that it trips immediately when the fault current exceeds a predefined threshold value.
4. Speed: The relay must be quick to respond under fault conditions to isolate the faulted part of the system and reduce damage caused to the system.
5. Economy: The relay protection scheme must not be too expensive to manufacture and implement.

Since it is nearly impossible to attain all the above features, a compromise has to be made when designing the protection scheme.

Differential protection principles

As the name suggests, differential protection is based on the principle that the algebraic sum of all currents in the zone of protection is ideally zero in all cases except for internal faults. Figure 2.1 shows the general scheme of differential protection. The current transformers (CT) on either side of the protected element are connected by pilot wires and the operating coil of the relay is placed between the pilot wires. The relay operates or trips when a difference current $I_1' - I_2'$ flows through the relay operating coil. I_1 and I_2 are the line currents or primary currents, while I_1' and I_2' are the secondary currents of the CTs respectively.

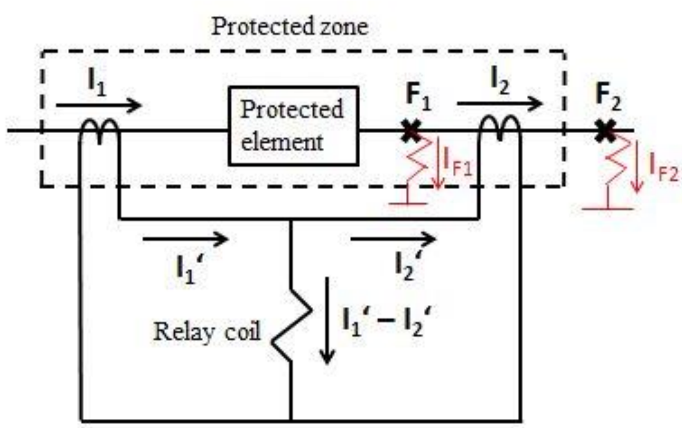

Figure 2.1 Differential protection

CTR or current transformer ratio is the ratio of primary or input current to secondary or output current of the CT. Hence, CTR = I_P / I_S. For ease of understanding, both the CTs are assumed to have the same CT ratio, or, (I_1 / I_1') = (I_2 / I_2'). A fault that occurs anywhere inside the zone of protection is called an internal fault (point F_1 in Fig 2.1) and that which occurs outside the protected zone is called an external fault (point F_2 in Fig 2.1).

Under normal conditions or for external faults, the currents I_1 and I_2 are equal in phase and magnitude. The secondary currents I_1' and I_2' are also equal (as both CTs have the same CTR) and keep circulating between the two CTs. Therefore, I_1' - I_2' = 0 and no current flows through the relay coil. This causes the relay to continue to remain inoperative. However, when internal faults occur, currents I_1 and I_2 are not equal as some current I_{F1} flows through the fault. Correspondingly, I_1' and I_2' are no longer equal as in the previous case and a difference current I_1' - I_2' flows through the relay coil. This causes the relay to trip and send a signal to the circuit breaker to open.

Thus, the internal and external fault conditions can be summarized as follows.

Under normal conditions or for an external fault, $|I_1' - I_2'| = 0$.

For an internal fault, $|I_1' - I_2'| \neq 0$.

But, these conditions are not the best to determine relay operation in real life or non-ideal situations. This is due to the fact that even under normal conditions, a small magnitude of difference current flows through the relay coil because of CT saturation errors and currents flowing through shunt elements in the protected zone. Hence, even when there is no fault, I_1' - I_2' is not exactly zero. Therefore, in order to accommodate the above conditions that are present in non-ideal situations, the relay is designed to operate if the differential current exceeds the pickup value of the relay. Pickup value of a relay is defined as the minimum current value that qualifies relay tripping.

This chapter discussed the principles of transmission line protection. The need for a protection scheme and necessary characteristics of an ideal protection system were presented. Then, the general working principle and trip conditions of a differential relay were explained. The next step is to review the theory of operation of the SEL 311L relay as it slightly differs from the general differential protection scheme. The coming chapter will explain in detail the working of differential elements present in the SEL 311L relay and how the relays are set up to provide differential protection to a model transmission line.

Chapter 3 - Differential protection scheme in SEL 311L relay

As discussed previously, differential protection is a viable option when high accuracy and fault clearing speed are desired. Line current differential scheme is superior to distance and directional comparison schemes in selectivity, sensitivity, speed of operation and protection of multi terminal lines, non-radial systems and long transmission lines [8].

This project makes use of SEL 311L relays in order to provide line current differential protection to a transmission line. The theory of operation of a SEL 311L relay is unique, i.e., instead of computing the difference of the current phasors at the local and remote ends, it calculates the ratio of the phasors and uses the alpha plane in order to determine the location of the fault. This chapter discusses in detail the line current differential scheme of SEL 311L relay.

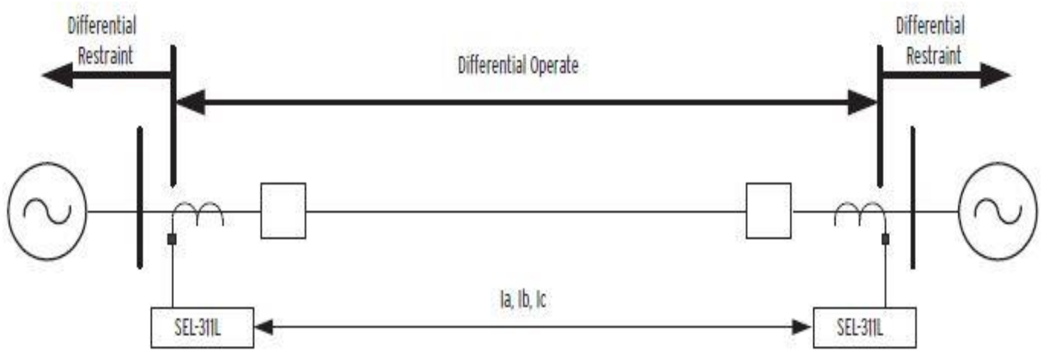

Figure 3.1 Operate and restraint regions [4]

Figure 3.1 shows differential operate and restraint regions and how the relays are setup to provide differential protection to the line. The relays are stationed at two ends of the line and time synchronized samples of current phasors at both ends are exchanged through a fiber optic communication channel. The relays must trip for faults that occur in the operate region and remain inactive for those occurring in the restraint region.

Theory of operation-Alpha plane

The differential elements in SEL 311L relay operate by checking the vector ratio of the local and remote currents I_L and I_R, respectively on a complex plane called the 'Alpha Plane'. As shown in Figure 3.2, the alpha plane is a phasor plot of the ratio I_R / I_L. There is a separate alpha plane for currents in each phase, as well as negative and zero sequence currents.

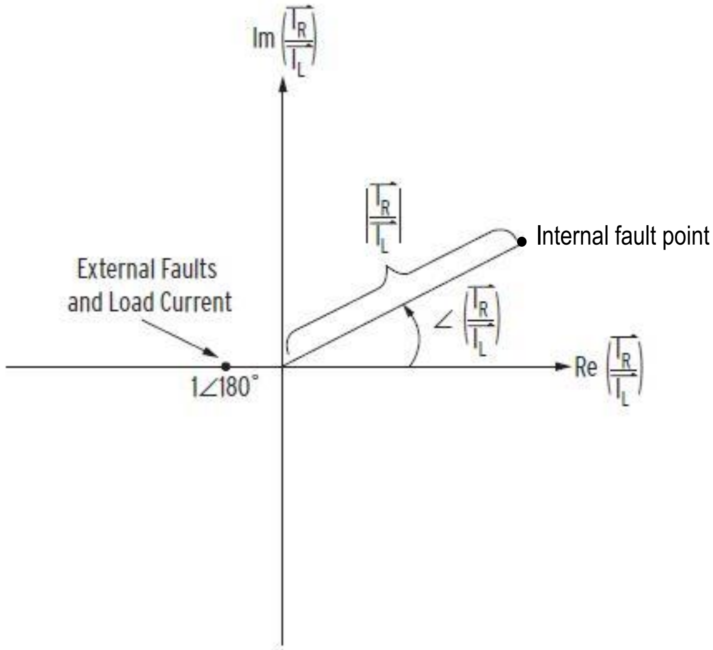

Figure 3.2 Alpha plane for phase A[3]

Figure 3.2 is the alpha plane plot for phase A. It is a complex plot where the real and imaginary parts of the remote-to-local current ratio are represented by the X and Y axes respectively. The way in which fault points for different scenarios (internal and external faults) are marked on the alpha plane is discussed below.

External fault and normal conditions

When a fault occurs anywhere outside the zone of protection, it is considered as an external fault and the relay must not trip for such faults. In Figure 3.3, the fault lies outside the transmission line, thus making it an external fault.

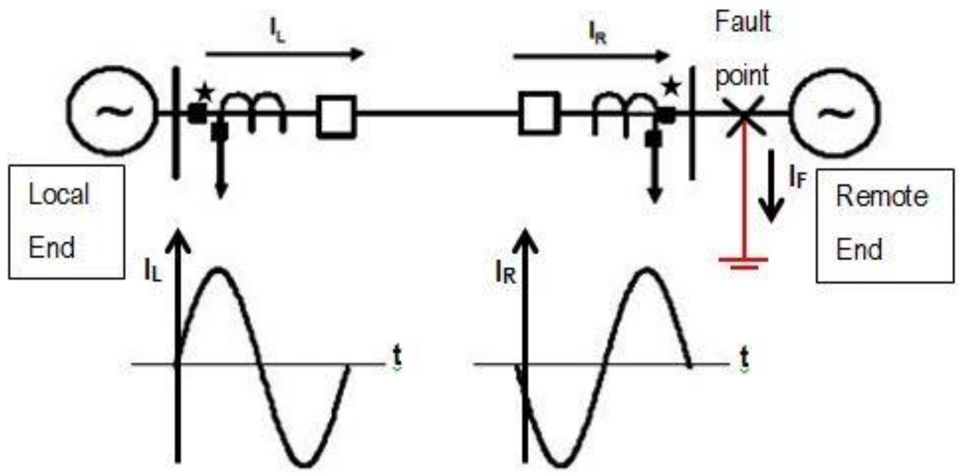

Figure 3.3 External fault [5]

In this case, as shown above, I_L flows into the line but I_R flows away from the line. The star symbol denotes the polarity of the CTs and it can be seen that the CTs are of opposite polarity. This means that currents entering the line will be considered to be positive (or phase 0˚) and those leaving will be considered to have a negative direction (or phase 180˚). Thus, the currents at two ends are 180˚ out of phase for external faults. Since, in an ideal situation, the line is assumed to be lossless, the magnitudes of local and remote currents are equal. Assume the magnitude of line current to be 'I'. Then, the remote-to-local current ratio is as follows:

For phase A, $\frac{I_{RA}}{I_{LA}} = \frac{I\angle 180^\circ}{I\angle 0^\circ} = 1\angle 180^\circ$ or $-1+j0$

For phase B, $\frac{I_{RB}}{I_{LB}} = \frac{I\angle 180^\circ}{I\angle 0^\circ} = 1\angle 180^\circ$ or $-1+j0$

For phase C, $\frac{I_{RC}}{I_{LC}} = \frac{I\angle 180^\circ}{I\angle 0^\circ} = 1\angle 180^\circ$ or $-1+j0$

This is the case even for normal operation or no-fault situations. The current ratio for normal and external fault conditions is -1+j0 as explained above and thus is marked one unit to the left of the origin on the X axis or real axis as shown in Figure 3.2. For phases B and C, this point lies at the same position, i.e., at -1+j0 on the respective alpha plane plots of the two phases.

Internal fault

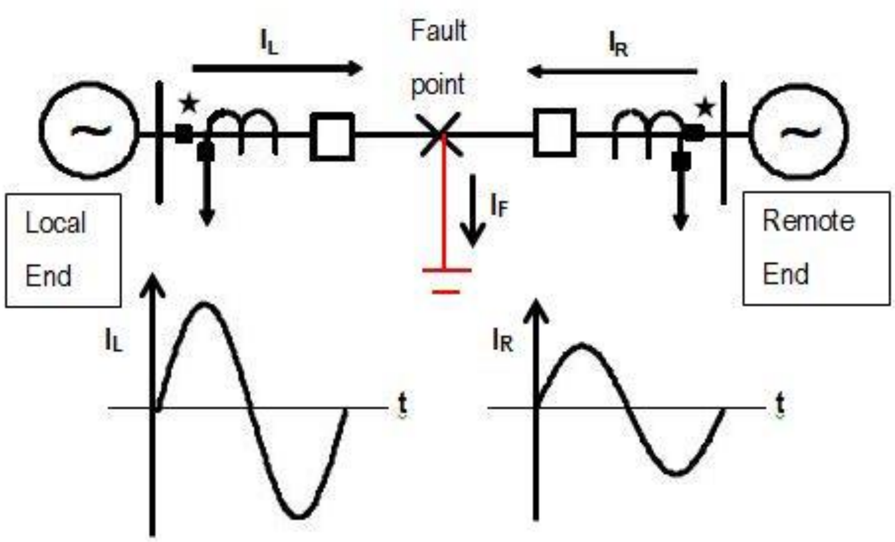

Figure 3.4 Internal fault [5]

As discussed previously currents entering the line will be considered to be positive (or phase 0˚) and those leaving will be considered to have a negative direction (or phase 180˚). For an internal fault, as shown in Figure 3.4, the currents I_L and I_R flow into the line towards the fault. Thus, the currents are almost in phase with each other. Since a part of either currents flows into the faulted section of the line, there is a difference in the magnitudes of currents at local and remote ends. This is denoted by the current waveforms shown in Figure 3.4. An arbitrary internal fault point for a SEL 311L relay is shown on the right half of alpha plane (Figure 3.2). The length of the trajectory and its deviation from the X-axis signifies the magnitude and phase angle of the vector current ratio respectively.

Modified Alpha plane

The conditions discussed above are valid in ideal situations i.e., for lossless lines. However, this is not possible in real life since losses are bound to occur in transmission lines. So, even under normal operation or external faults, the magnitude of remote and local currents will not be exactly equal. There will also be a slight difference in phase due to different source angles at two ends of the line. This means that the point denoting external faults and normal operation will no longer lie at -1+j0, but slightly displaced from it. The displacement varies with the losses occurred and the location of fault. The alpha plane in Figure 3.2 must thus be modified to operate in non-ideal situations.

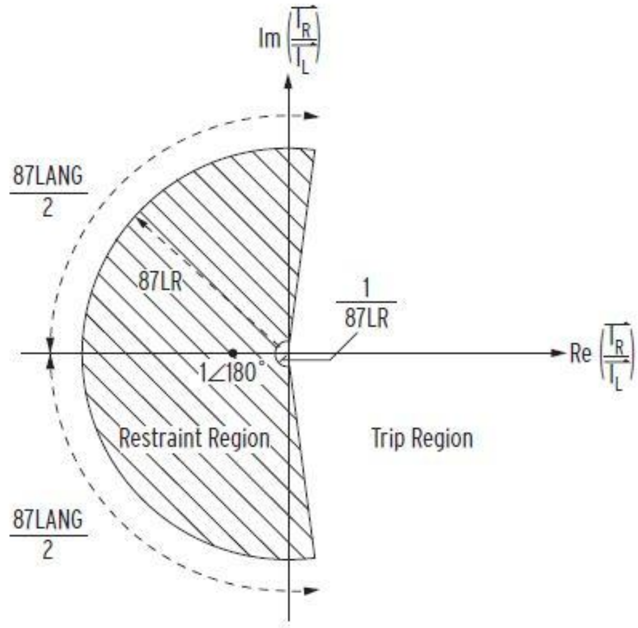

Figure 3.5 Alpha plane with trip and restraint regions

The restraint region is the area on the alpha plane where the relay is inoperative. For the SEL 311L relay, the restraint region is semi annular and it surrounds the ideal external fault point in such a way that even errors due to CT saturation and channel asymmetry are accommodated. This increases the accuracy of the relay. The modified alpha plane with designated trip and restraint regions is shown in Figure 3.5. The angle of the restraint region is determined by the setting 87LANG and its extent is determined by setting 87LR.

For the relay to trip, two conditions must be satisfied:

1. The vector ratio (I_R/I_L) must lie in the trip region of alpha plane
2. The difference current must exceed the pickup value of the relay

The pickup value is set based on the fault calculations performed on the system which will be discussed in the coming chapters. Therefore, when a fault occurs, the relay checks these two conditions to determine whether or not to operate.

This chapter presented an insight into the operation of differential scheme of protection of the SEL 311L relay. The alpha plane and its modifications to include line losses, CT saturation etc., were explored. The next step is to figure out the settings of the relay by performing fault and load flow analysis of the model power system considered. Then the experimental setup of the relay and other required components has been discussed.

Chapter 4 - Design of line current differential protection scheme

Line current differential protection is the easiest communication assisted tripping scheme [8] as it is simple to configure and depends on current alone to act as the operating parameter. This chapter discusses the protection of a transmission line using two such differential relays, SEL 311L7 and SEL 311L1. Figure 4.1 illustrates how the relays are placed in a real time environment to protect the transmission line from Bus 5 to Bus 4.

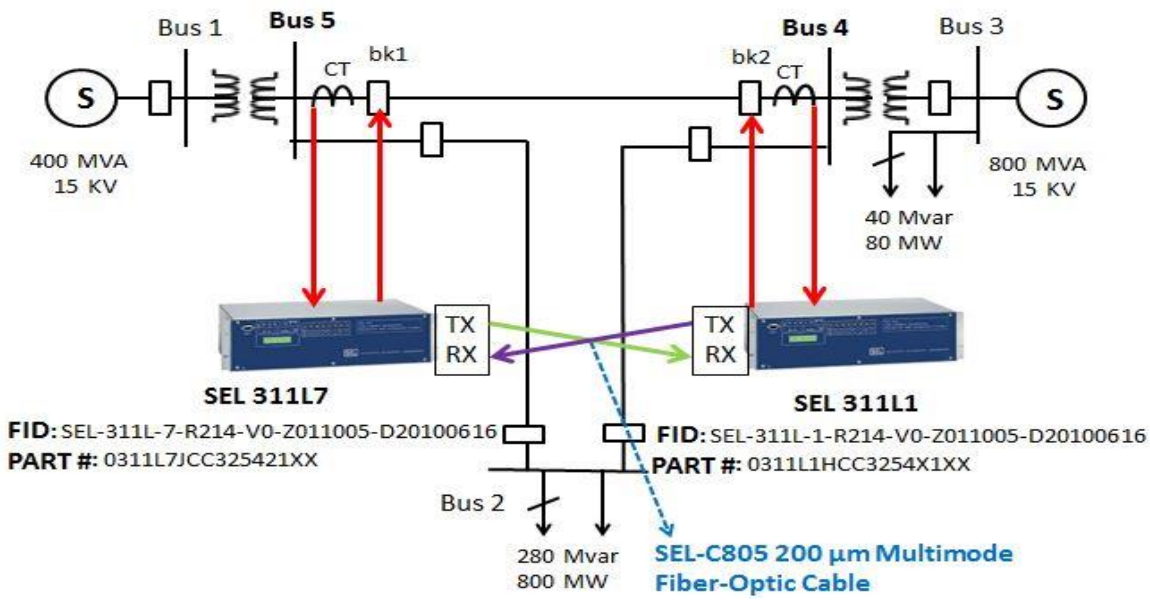

Figure 4.1 Power system and relays

The relays are connected at both ends of the line, i.e., SEL 311L7 relay at Bus 5, and SEL 311L1 relay at Bus 4. The currents flowing in a 345kV line are relatively large and the relays are not made to handle that level of currents. Hence, the current transformer at each end steps down the line current to a much lower secondary output value of 0 to 5amps AC, scaled proportionally, and sends it to the relay. This stepped down current is then converted into an analog signal and analyzed by the relays and a trip/close signal is sent to the 125V DC circuit breakers depending on the fault condition. For this project, the real time on-field conditions were simulated using the SEL-RTS, which is a relay test system used for testing protective relays. It consists of a device called an AMS (Adaptive Multichannel Source) and the SEL 5401 software to operate the AMS. In order to simulate an actual fault condition, PowerWorld software is used to perform load flow analysis and fault analysis to obtain information regarding the normal line currents and fault currents, respectively. This data is used as input to the AMS using the SEL 5401 software. The AMS then simulates three-phase current waveforms similar to those that would be supplied by the current transformer at each end and transmits it to the relay. Thus, a fault condition is simulated. The relay processes the information received from the AMS and exchanges it with the relay at the other end using the direct fiber channel thereby enabling communication assisted protection. This chapter describes in detail the steps involved in the design of the protection scheme.

Power System circuit and data

The power system considered in this report has five Buses, two generators, two transformers, five transmission lines and two loads as shown in Figure 4.2. The design of a line current differential protection scheme for the transmission line from Bus 5 to Bus 4 will be discussed in this chapter.

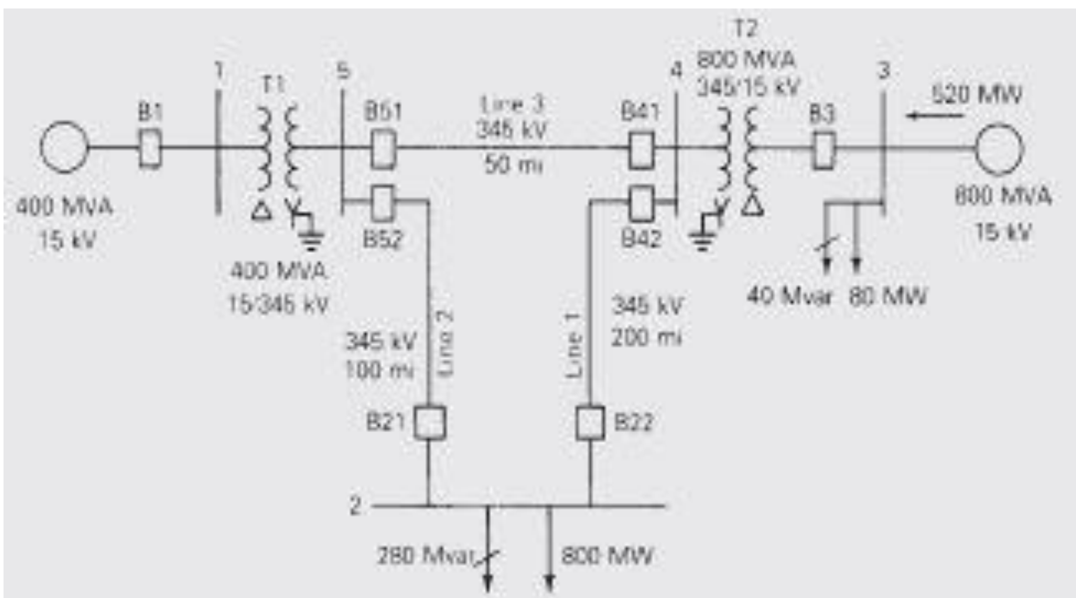

Figure 4.2 Test Case Power system [1]

Input data

Input data for the chosen power system is listed in table 4.1. It consists of the information regarding the Buses, transformers and transmission lines in the system. Based on this data, the system was developed in PowerWorld and then load flow analysis and fault analysis were performed on it.

Table 4.1 Input data for the system [1]

BUS input data

BUS	Type	V (p.u.)	δ (deg)	P_G (p.u.)	Q_G (p.u.)	P_L (p.u.)	Q_L (p.u.)	Q_{gmax} (p.u.)	Q_{gmin} (p.u.)
1	Slack	1.0	0	-	-	0	0	-	-
2	Load	-	-	0	0	8.0	2.8	-	-
3	Constant voltage	1.05	-	5.2	-	0.8	0.4	4.0	-2.8
4	Load	-	-	0	0	0	0	-	-
5	load	-	-	0	0	0	0	-	-

Line input data

BUS-to-BUS	R' (p.u.)	X' (p.u.)	G' (p.u.)	B' (p.u.)	Maximum MVA (p.u.)
2-4	0.0090	0.100	0	1.72	12.0
2-5	0.0045	0.050	0	0.88	12.0
4-5	0.00225	0.025	0	0.44	12.0

Transformer input data

BUS-to-BUS	R (p.u.)	X (p.u.)	G_C (p.u.)	B_M(p.u.)	Maximum MVA (p.u.)
1-5	0.00150	0.02	0	0	6.0
3-4	0.00075	0.01	0	0	10.0

Sequence data

Sequence data for the system can be obtained by opening the fault analysis dialog of the system in PowerWorld. The positive, negative and zero sequence impedances of generators, transformers and transmission lines in the system are listed in Table 4.2.

Table 4.2 Sequence data for the system

Apparatus	**Rating**	**Configuration**	**Positive (p.u)**		**Negative (p.u)**		**Zero (p.u.)**	
			R	X	R	X	R	X
Generator at BUS 1	400 MVA 15 kV	Neutral grounded with bolted impedance	0	1	0	1	0	0.5
Generator at BUS 3	800 MVA 15 kV	Neutral grounded with bolted impedance	0	1	0	1	0	0.5
Transformer 1	400 MVA 15/345 kV	Delta-grounded wye	0.0015	0.02	0.0015	0.02	0.0015	0.02
Transformer 2	800 MVA 345/15 kV	Wye grounded-delta	0.00075	0.01	0.00075	0.01	0.00075	0.01

Line 1 (BUS 2 and 4)	345 kV	200 mi	0.009	0.1	0.009	0.1	0.0225	0.25
Line 2 (BUS 2 and 5)	345 kV	100 mi	0.0045	0.05	0.0045	0.05	0.01125	0.125
Line 3 (BUS 4 and 5)	345 kV	50 mi	0.00225	0.025	0.00225	0.025	0.005625	0.0625

Transmission line data

The protection scheme was designed for the transmission line from Bus 5 to Bus 4 and the information corresponding to this line is listed in Table 4.3.

Table 4.3 Transmission line data

Line-line voltage	345 kV (Base line-line voltage)
Total power	100 MVA (Base MVA)
Line length	50 miles
Current transformer ratio	100
Per unit impedance	R’=0.00225 X’=0.025

Transmission lines of length between 50 mi and 150 mi are considered as medium transmission lines and their single phase equivalent circuit can be represented by a nominal T or π configurations. In this project, the line is considered to be modeled in a π configuration as shown in Figure 4.3.

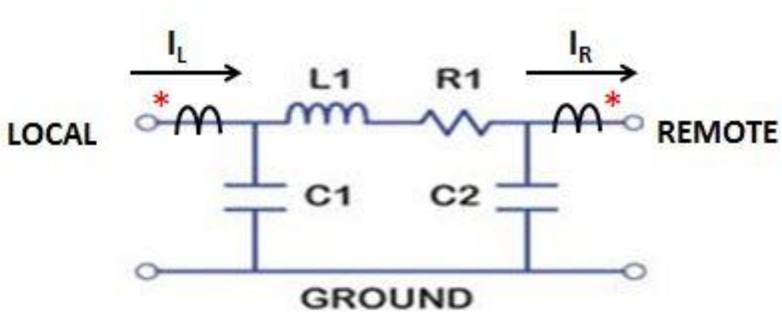

Figure 4.3 Transmission line π model

For an ideal transmission line, there are no losses, and so currents at both ends of the line are equal, or $I_L = I_R$. Also, since there are no shunt components there is a phase difference of exactly 180˚ between currents at the two ends under normal conditions and external faults. However, practically, losses are bound to occur in a transmission line due to the resistance it offers to current flow. This means that $I_L \neq I_R$. From the π-model of the line, it can be seen that the capacitors provide a leading power factor. Hence, the conditions for external and internal faults must be modified accordingly. So, for internal faults, phase difference between I_L and I_R is not exactly 0˚, but slightly more than that and for external faults, the phase difference is not exactly 180˚, but slightly less than that. The modified trip conditions are represented by Figure 4.4 and will be used as reference for setting the relay.

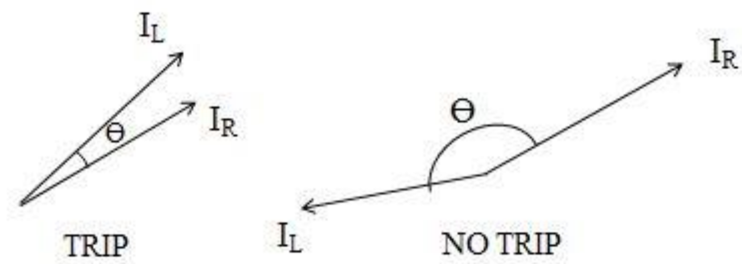

Figure 4.4 Trip conditions for π-modeled transmission line

Load flow and fault analysis

The power system discussed above was modeled in PowerWorld and fault analysis was performed after solving the system for single solution using Newton's method. Results of load flow and fault analysis were used to set up the AMS and relay, respectively. Figure 4.5 shows the system modeled in PowerWorld.

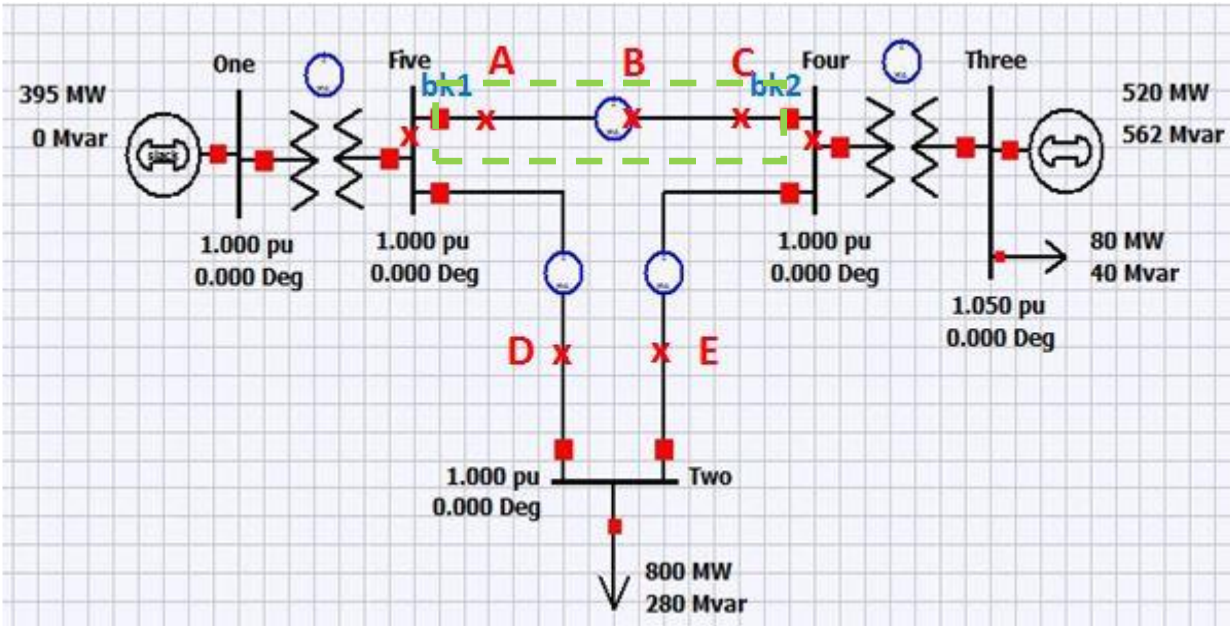

Figure 4.5 System in PowerWorld

The red crosses denote the seven points in the system where fault analysis was performed. Points A, B, and C lie along the line at 25%, 50%, and 75%, respectively from Bus 5. Points D and E lie at 50% of transmission lines 5-2 and 4-2, respectively. The remaining two points are Bus 5 and Bus 4. The rectangular box drawn between the two breakers denotes the zone of protection for the transmission line, meaning that the relays must trip for a fault that occurs at any point in the zone (internal faults) and must not trip for faults at points outside the zone (external faults). Hence, the relay must trip for faults at A, B, and C and must restrain for faults at D, E, Bus 5, and Bus 4.

Load flow analysis

Results of load flow analysis are used to obtain the line currents, or the currents that flow through the CTs at the local and remote ends of the transmission line. Thus, the values of currents in the system during normal conditions, or in pre-fault state are obtained. The real or active power in a three phase system is given by the equation:

$$P = \sqrt{3}UI\cos(\delta - \beta - 30) \qquad (4.1)$$

Where, P = real power flowing along the line in kW

I = line current in Amps

U = line-line voltage in kV

δ = line-line voltage angle in degrees

β = line current angle in degrees

Rewriting the above equation,

$$\beta = \delta - 30 - \cos^{-1}\left(\frac{P}{\sqrt{3}UI}\right) \qquad (4.2)$$

P, U, I, and δ are obtained from load flow analysis as shown in Figures 4.6, 4.7 and 4.8; P and I are obtained from the branch information dialog of the transmission line, while U and δ are obtained from the Bus information dialogs of Buses 5 and 4. Therefore, β for phase A can be computed.

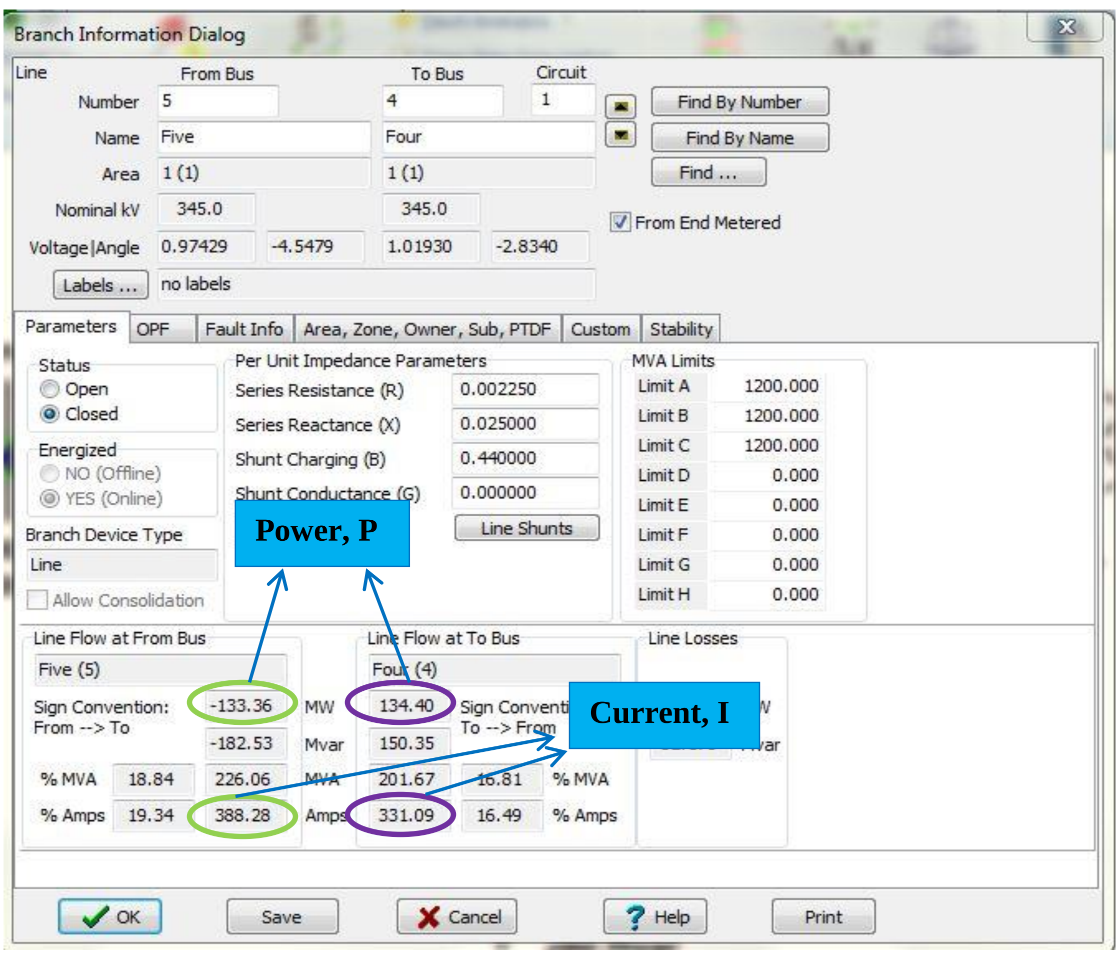

Figure 4.6 Branch information dialog of transmission line

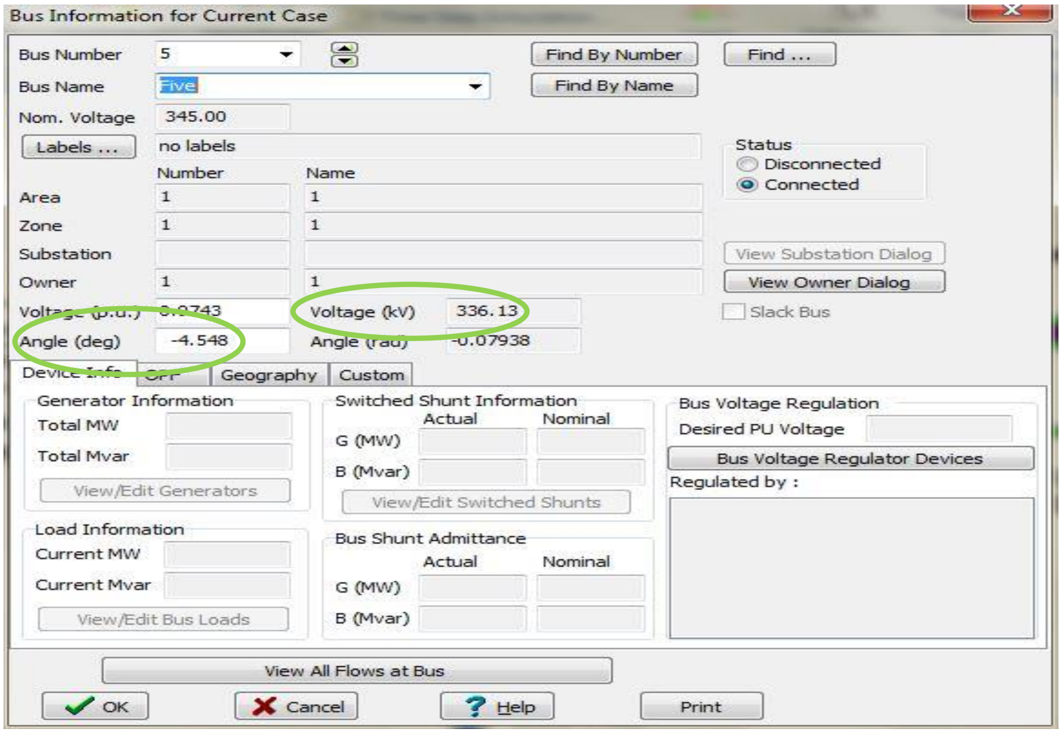

Figure 4.7 Bus information dialog for Bus 5

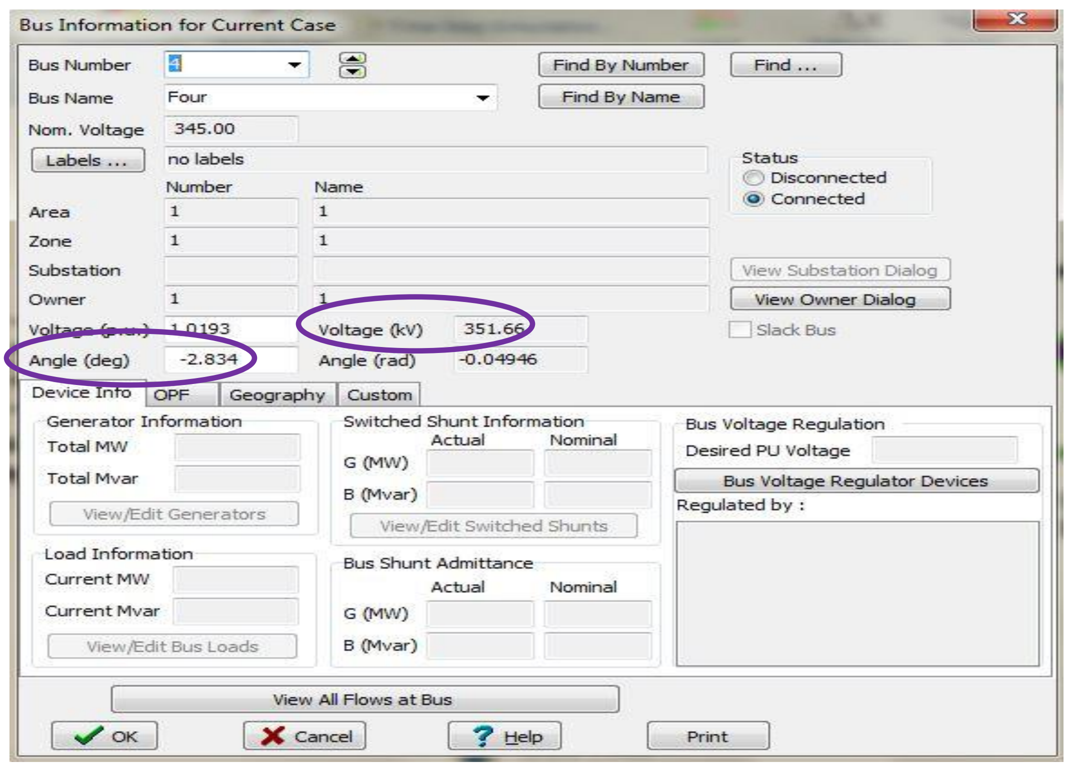

Figure 4.8 Bus information dialog for Bus 4

From the above figures, for Bus 5,

P = -133.36 MW = -133360 kW

U = 336.13 kV

I = 388.28 A

δ = -4.548˚

Using equation 4.2, $\beta = -4.548 - 30 - \cos^{-1}(\frac{-133360}{\sqrt{3}\times 336.13\times 388.28})$ = 91.6˚

Hence, line current in phase A at Bus 5 is 388.28∠121.6˚. The phase rotation is considered to be ABC, so the current angle 'β' for the other two phases (phase B and phase C) can be computed by subtracting and adding 120˚, respectively. Therefore, the angle of line current in phase B is 91.6 – 120 = -28.4˚, and that of line current in phase C is 91.6 + 120 = 211.6˚. By repeating the process with values at Bus 4, the line currents for Bus 4 can be computed. The three-phase line currents seen by the two relays are listed in Table 4.4.

Table 4.4 Line currents

Location of relay	**Line current (Amps∠˚)**			
	I (Amps)	**∠A˚**	**∠B˚**	**∠C˚**
Bus 5	388.28	91.6	-28.4	211.6
Bus 4	331.09	-81.04	-201.04	38.959

Fault analysis

After obtaining the load flow solution of the system modeled in PowerWorld, fault analysis was performed. Fault analysis is the analysis of power system parameters when a fault occurs anywhere in the system. The fault analysis tool in PowerWorld can analyze both balanced and unbalanced faults.

Balanced or 3-phase fault is a fault that affects all three phases equally. This means that short has occurred between the three phases, i.e., from phase A to phase B to phase C. Unbalanced faults are of three types:

i. Single-line-to-ground (SLG) – A fault that occurs between any one phase and the ground is called an SLG fault. By default, PowerWorld computes an SLG fault assuming it to have occurred between phase A and ground.

ii. Line-to-line (LL) – A fault that occurs between any two phases is called an LL fault. By default, PowerWorld computes an LL fault assuming it to have occurred between phases B and C.

iii. Double-line-to-ground (DLG) – A fault that occurs between any two phases and the ground is called a DLG fault. By default, PowerWorld computes a DLG fault assuming it to have occurred from phase B to phase C to ground.

Thus, after performing fault analysis, fault currents were computed for 3-phase, SLG and LL faults at the seven different positions: points A, B, C, D, E, Bus 5, and Bus 4. It was observed that the minimum fault current was obtained for a line-to-line fault on the system. In order to set the relays, the minimum fault current was used because if the relay is configured to trip for a minimum fault, it will definitely trip for higher fault currents. Hence, the results of line-to-line fault analysis were used to set the relays and are listed in Table 4.5.

Table 4.5 Line-to-line fault currents

Fault Location	**Relay location**	**Primary Fault current (Amps∠°)**		
		I_A (A)	**I_B (A)**	**I_C (A)**
A	BUS 5	388.28∠91.60°	773.81∠-110.34°	615.73∠39.89°
B			718.53∠-109.30°	561.40∠38.24°
C			667.45∠-107.89°	509.50∠36.70°
Bus 5			757.19∠32.08°	853.81∠-120.87°
Bus 4			620.07∠-106.09°	459.51∠35.23°

D			567.30∠23.28°	639.38∠-119.79°
E			235.54∠-64.00°	155.57∠-49.90°
A	BUS 4	331.09∠-81.04°	827.52∠-144.82°	870.80∠57.47°
B			881.17∠-143.87°	925.90∠57.06°
C			936.35∠-142.88°	983.11∠56.79°
Bus 5			774.91∠-145.77°	817.20∠58.05°
Bus 4			586.94∠73.04°	486.15∠-141.30°
D			569.67∠-154.05°	590.96∠59.04°
E			210.15∠115.37°	136.10∠150.23°

Configuring the SEL 311L differential relay

The SEL 311L7 and SEL 311L1 relays must be configured so they provide differential protection to the transmission line. To set up the relays, necessary components are:

1. SEL 311L7 relay
2. SEL 311L1 relay
3. SEL C805 200µm Multimode fiber optic cable
4. SEL C662 cable
5. AcSELerator Quickset software
6. Laptop

Relay settings

Time synchronized samples of current magnitude and phase at both ends of the line must be exchanged between the two relays in order to compute the current ratio and plot it on the alpha plane thus enabling it to determine whether or not a fault has occurred and then take corresponding action. This is done by connecting a multimode fiber optic cable between the relays and thereby establishing communication between them. The SEL 311L7 relay (at Bus 5) was connected to a laptop with the SEL C662 cable. Using the AcSELerator quickset software, communication was established between the relay and the laptop and then the settings were fed to the relay. Tables 4.6 and 4.7 show the settings of relays at Bus 5 and Bus 4 respectively.

Table 4.6 Relay settings at Bus 5

Group 1 General settings	
Relay Identifier Labels	
RID Relay Identifier	SEL 311L7
TID Terminal Identifier	Bus 5, BK 1
Current transformer ratio and Application settings	
CTR Local Phase CT ratio, CTR:1	100
APP Application	87L
Line Current Differential Settings	
E87L	2
EHST	2
EHSDTT	N
EDD	Y
ETAP	N
EOCTL	N
PCHAN	X
EHSC	Y
CTR_X	100
87L Setting	
Minimum Difference Current Enable Level Settings	
87LPP	4.7
87L2P	0.5
87LGP	0.5
CTALRM	4.3
Restraint Region Characteristic Settings	
87LR	6.0

87LANG	195
Logic 1	
Trip/Comm.-Assisted Trip Logic	
TR	87L
ULTR	TRGTR
Output Contact Equations	
OUT101	TRIP
OUT102	CLOSE
Channel X	
EADDCX	Y
TA_X	1
RA_X	2

Table 4.7 Relay settings at Bus 4

Group 1 General settings	
Relay Identifier Labels	
RID Relay Identifier	SEL 311L1
TID Terminal Identifier	Bus 4, BK 2
Current transformer ratio and Application settings	
CTR Local Phase CT ratio, CTR:1	100
APP Application	87L
Line Current Differential Settings	
E87L	2
EHST	2
EHSDTT	N
EDD	Y
ETAP	N
EOCTL	N
PCHAN	X
EHSC	Y

CTR_X	100
87L Setting	
Minimum Difference Current Enable Level Settings	
87LPP	4.0
87L2P	0.5
87LGP	0.5
CTALRM	3.6
Restraint Region Characteristic Settings	
87LR	6.0
87LANG	195
Logic 1	
Trip/Comm.-Assisted Trip Logic	
TR	87L
ULTR	TRGTR
Output Contact Equations	
OUT101	TRIP
OUT102	CLOSE
Channel X	
EADDCX	Y
TA_X	2
RA_X	1

Some calculations were required to configure the relays so they work with the conditions at hand, and have been discussed below.

Calculation of 87L settings

87LPP is the value of secondary difference current in amps which qualifies tripping when the alpha plane ratio lies outside the tripping region [3]. This parameter must be set above the maximum load current or current flowing in the line under normal conditions. Hence, 87LPP is set at 20% above maximum load current.

$$87LPP = \frac{\max load\ current \times 1.2}{CTR} \tag{4.3}$$

At Bus 5, the maximum load current is 388.28A and the CTR is 100. Hence, 87LPP = 4.7.

At Bus 4, the maximum load current is 331.09A and the CTR is 100. Hence, 87LPP = 4.0.

87L2P denotes the secondary negative sequence difference current in amps which qualifies tripping when the alpha plane ratio lies outside the tripping region. This parameter must be set above expected maximum line charging current unbalance. Typically, it is set at 10% of nominal current, i.e., 0.5A for a 5A relay [3].

87LG detects high impedance ground faults and is set to its minimum value of 0.5A.

CTALRM denotes phase difference current alarm pickup and should be set above max load to alarm on CT error [3].

$$CTALRM = \frac{\max load\ current \times 1.1}{CTR} \tag{4.4}$$

Hence, CTALRM is set to 4.3 at Bus 5 and to 3.6 at Bus 4.

Settings for the outer radius and angular extent of the restraint region, 87LR and 87LANG, respectively, are set at their default values.

Communication protocol

The SEL C805 200µm multimode fiber optic cable is connected between ‘Channel X’ of the two relays such that the TX port of each relay is connected to RX port of the other as shown in Figure 4.9. When communication is established between the relays, LEDs for TX and RX will light up as shown in Figure 4.10.

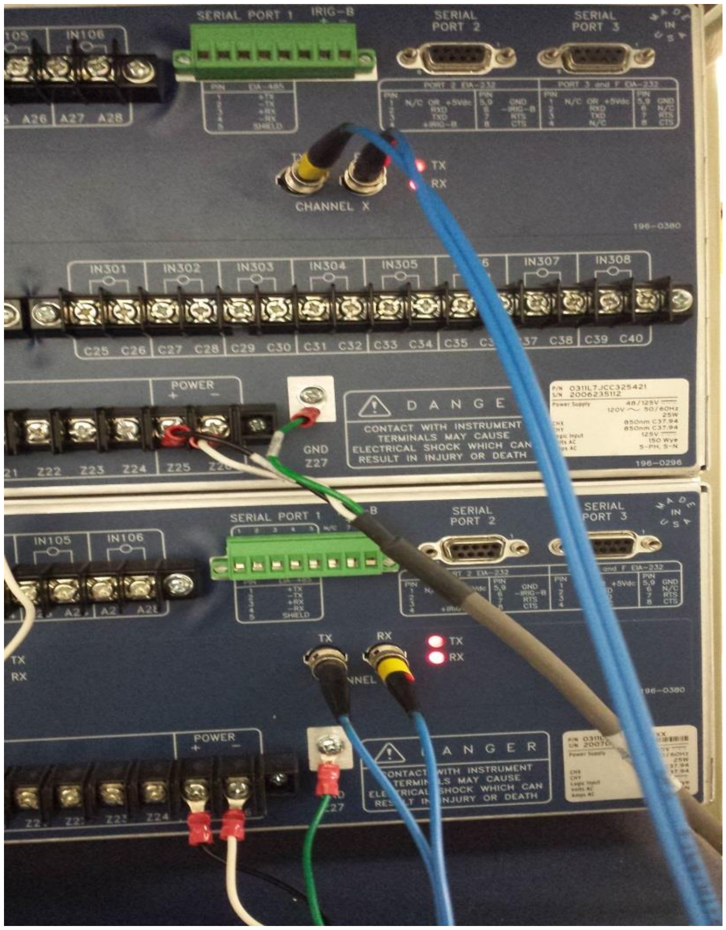

Figure 4.9 Communication between relays established

Figure 4.10 LEDs light up

In cases where the communication channel fails, or one of the relays stops working, the 87CH FAIL LED on the front panel of the relays will light up to denote that a communication failure has occurred and that the relays are no longer communicating. A communication failure has been simulated by disconnecting the transmission part of the cable at one relay (Figure 4.11) and it can be seen that the LED lights up to signify communication problems(Figure 4.12).

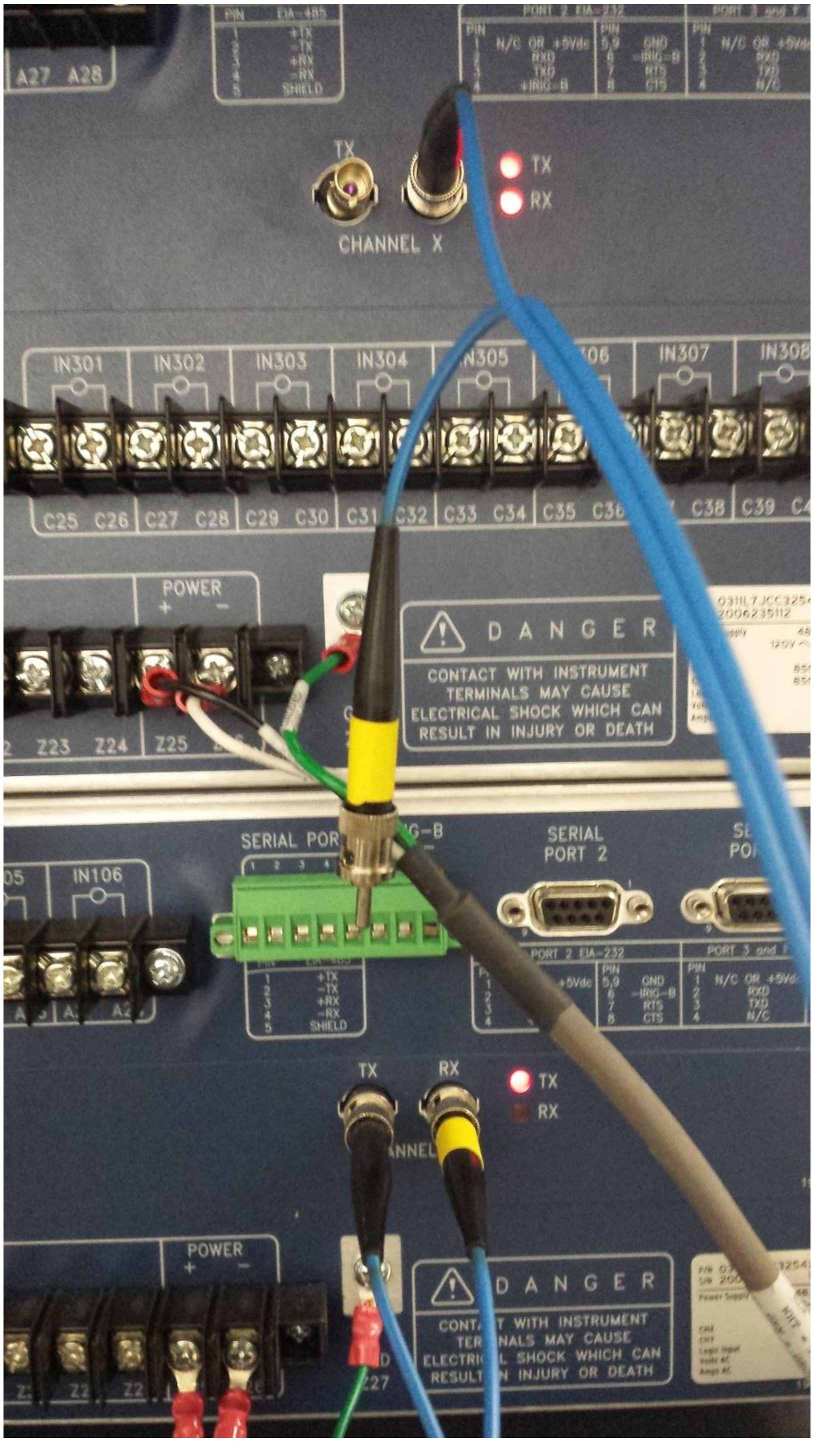

Figure 4.11 Simulate communication failure

Figure 4.12 Relay front panels showing communication failure

Source settings

The SEL AMS simulates currents that flow in each phase of the line. Therefore, when connected to the relays, the AMS simulates conditions in an actual power system so that relay performance can be tested. Results of load flow analysis and fault analysis offers the value of currents in pre-fault and fault state, respectively. These currents must be converted to secondary values and then sent to the AMS using SEL 5401 software.

Calculation of secondary currents

For both relays, assume current transformer ratio, CTR = 100. Hence,

$$Secondary\ current = \frac{Primary\ current}{CTR} = \frac{Primary\ current}{100} \tag{4.5}$$

In the pre-fault stage, currents seen by the relays are currents at maximum load situation, i.e., line currents during normal conditions. Hence, using equation 4.5, pre-fault secondary currents are calculated from Table 4.4.

Table 4.8 Prefault secondary currents

Relay location	**Prefault secondary currents (Amps∠°)**		
	I_A	**I_B**	**I_C**
Bus 5	3.88∠91.60°	3.88∠-28.4°	3.88∠211.6°
Bus 4	3.31∠-81.04°	3.31∠-201.04°	3.31∠38.96°

Similarly, currents during fault state tabulated in Table 4.5 are converted to secondary values using equation 4.5.

Table 4.9 Fault secondary currents

Fault Location	**Relay location**	**Secondary Fault current (Amps∠°)**		
		I_A (A∠°)	**I_B (A∠°)**	**I_C (A∠°)**
A	Bus 5	3.88∠91.60°	7.74∠-110.34°	6.16∠39.89°
B			7.19∠-109.30°	5.61∠38.24°
C			6.67∠-107.89°	5.09∠36.70°
Bus 5			7.57∠32.08°	8.54∠-120.87°
Bus 4			6.20∠-106.09°	4.59∠35.23°
D			5.67∠23.28°	6.39∠-119.79°
E			2.35∠-64.00°	1.55∠-49.90°
A	Bus 4	3.31∠-81.04°	8.27∠-144.82°	8.71∠57.47°
B			8.81∠-143.87°	9.26∠57.06°
C			9.36∠-142.88°	9.83∠56.79°
Bus 5			7.75∠-145.77°	8.17∠58.05°
Bus 4			5.87∠73.04°	4.86∠-141.30°

D			5.69∠-154.05˚	5.91∠59.04˚
E			2.10115.37˚	1.36∠150.23˚

In the post-fault state, after the fault has occurred, the breaker will open and remain open until a maintenance person arrives at the fault site to manually close the breaker. During this state, all the currents are zero.

Configuring the AMS

In order to configure the AMS, SEL 5401 software was used and secondary currents seen by the relay during pre-fault, fault and post-fault states for different fault scenarios were provided to the relays. The AMS was connected to the laptop using SEL C662 cable and SEL 5401 software was used to create pre-fault, fault and post-fault states for the relays during various fault scenarios (different fault points). The images of setting files for the AMS for Bus 5 and Bus 4 for the various fault points are listed in Appendix A. The setting files were then downloaded to the laptop.

Experimental setup and procedure

Components required to run the experiment are:

1. SEL 311L7 relay
2. SEL 311L1 relay
3. SEL AMS – 2
4. SEL C662 cable – 4
5. SEL C805 200μm Multimode fiber optic cable
6. Ribbon cable
7. Wires
8. AcSELerator Quickset software
9. SEL 5401 software
10. Laptop – 2
11. Mirror mouse

Figure 4.13 shows how components are set up in order to perform the experiment and demonstrate the differential scheme of protection.

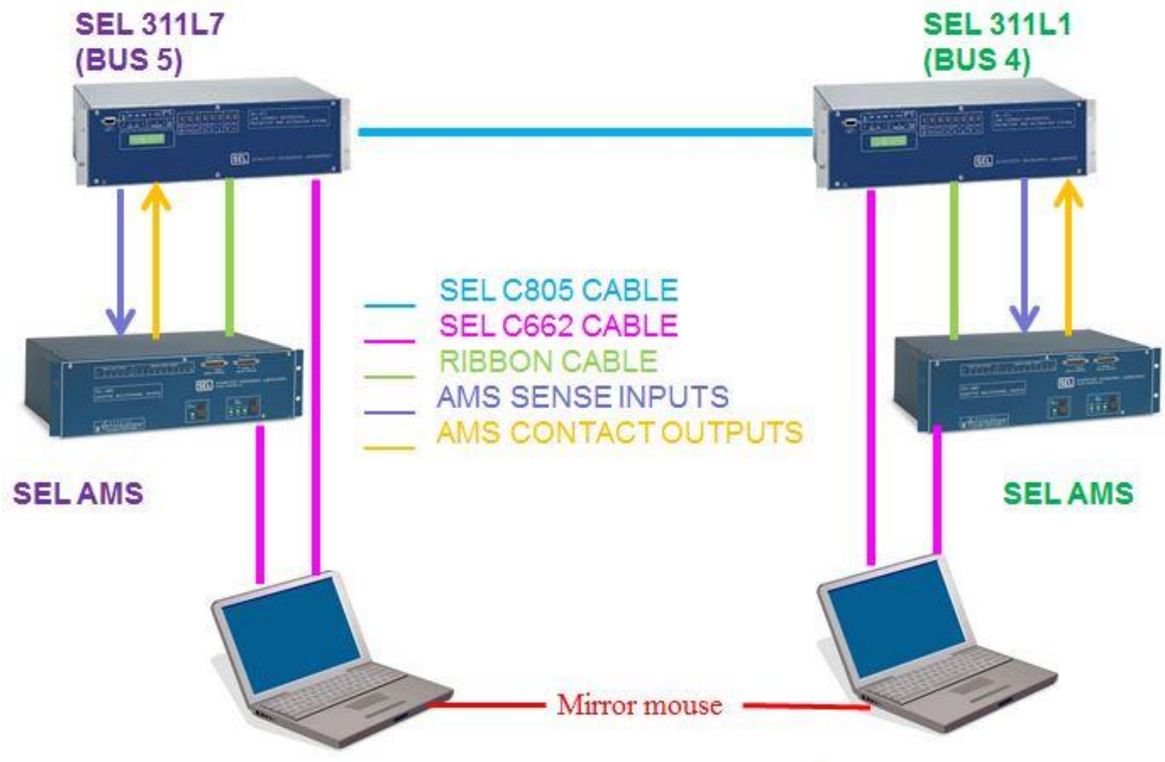

Figure 4.13 Experimental setup

The mirror mouse is a setup of two regular computer mice connected with their left buttons wired together so that when the mirror mouse is connected between the laptops, a click can be made on both laptops simultaneously. This is important because when running tests on the AMS, test files need to be sent to both relays at once so that the relays see fault currents at the same time. To test the relays, the equipment is connected as shown in Figure 4.13 and all the components are switched on. In order to simulate the fault conditions, the AMS test files for a particular fault point are pulled up on the laptop screens and with a click of the mirror mouse, the test files are loaded and run simultaneously. After the test is finished running, the relay either trips or remains inactive depending on whether or not it is an internal fault point. If a fault has occurred, the relay trips, and the type of fault is displayed on the front LED screen of the relay. The status of the breaker contacts is displayed on the front LED screen of the AMS.

Chapter 5 - Results

This chapter shows the results obtained in the seven fault scenarios considered. In each case, a picture of the front panel of both relays is presented from which the status of the relay (trip or no trip) can be determined. In the pictures, Bus B and Bus C refer to Bus 5 and Bus 4 respectively.

For faults at locations A, B, and C, the relay must trip for a line-to-line fault and breakers at both ends of the line must be opened, thus isolating the faulted line. As shown in Figure 5.1, the LEDs for ‘trip’ and ‘87’ on both relays are turned on which means that the relays have tripped by the criteria that must be satisfied for differential protection scheme. The LEDs for ‘B’ and ‘C’ are also turned on, implying that a line-to-line fault has occurred on phases B and C. On the front panel of the AMS, there are LEDs that denote sense input status (relay status) and contact output status (breaker status). The LEDs for relay status are turned on, signifying that the relays connected to that AMS have tripped and the LEDs for breaker status are turned off, meaning that the breaker is opened.

For faults at D, E, Bus 5, and Bus 4, the relay must not trip and breakers at both ends of the line must remain closed. As shown in Figure 5.2, the LED for ‘trip’ is not turned on for either relay, implying that neither relay trips. Also, on the AMS, it is observed that the LED for relay status is turned off, meaning that the relay hasn’t tripped. The LED for breaker status is turned on, signifying that the breaker contacts remain closed.

Thus, the relays have been set up to provide line current differential protection to the transmission line from Bus 5 to Bus 4 of the power system in Figure 4.2.

Figure 5.1 Front panel of relays and AMS for faults at A, B, and C

Figure 5.2 Front panel of relays and AMS for faults at D, E, Bus 5, and Bus 4

Chapter 6 - Conclusions and future work

Transmission line protection is necessary to improve and maintain stability of power systems. Differential protection is widely used as the preferred scheme of protection where faults must be cleared quickly and where protection coordination becomes difficult with time delayed schemes, and multi-terminal systems. This report discussed the design of a line current differential protection scheme for a 345 kV transmission line. SEL 311L relays were used in conjunction with SEL-AMS to simulate a power system and test out the performance of designed protection scheme.

First, a background was provided on the theory of transmission line protection and the differential protection scheme in particular. Then, the system under consideration was described, data given was analyzed and load flow analysis was performed on the system followed by fault analysis. The resulting data was used to determine settings of relay and AMS respectively. The experimental setup was then discussed and fault conditions simulated for the occurrence of fault at seven different locations in the power system. Lastly, the results obtained in each case were specified.

Some challenges were encountered in this design project. Firstly, in order to perform the experiment, the appropriate software for operating the relay, and AMS, i.e., AcSELerator Quickset and SEL 5401- Test system software had to be studied and understood. Next, the right parameters had to be derived for setting the relays. This required that a few calculations be performed. Then, the setting files for each fault point had to be sent to both the sources (i.e., AMS) at the same instant of time to make both relays sense the same type of fault. This proved to be a bit difficult as even a difference of seconds in sending the inputs to the sources resulted in each relay seeing a different fault. Finally a mirror mouse was assembled and used to send the setting files simultaneously.

A possible extension of the work presented in this report could be to configure and setup the SEL-RTAC (Real Time Automation Controller) in conjunction with the relays to provide integrated system security and web based HMI (Human Machine Interface) applications.

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Appendix A - AMS Setting files

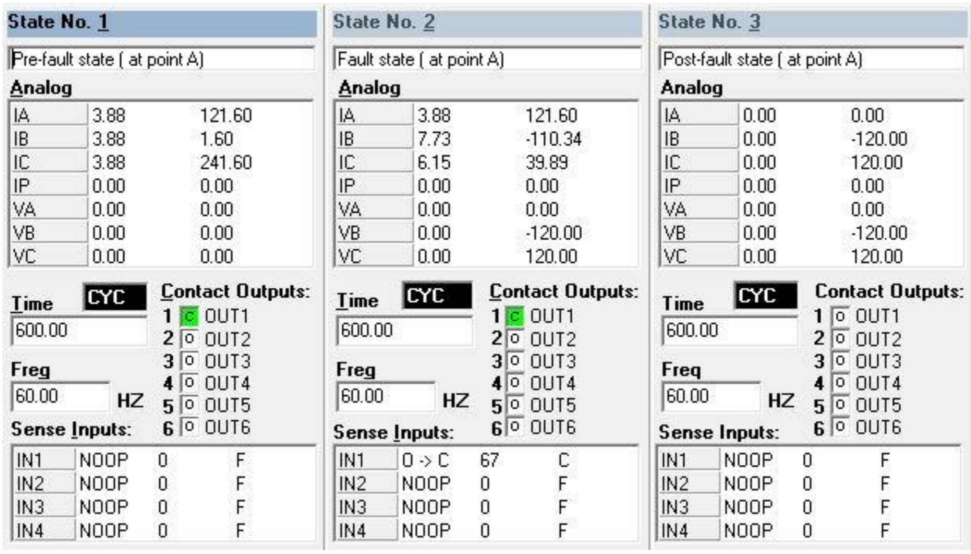

Figure A.1 AMS setting file for Bus 5 for fault at A

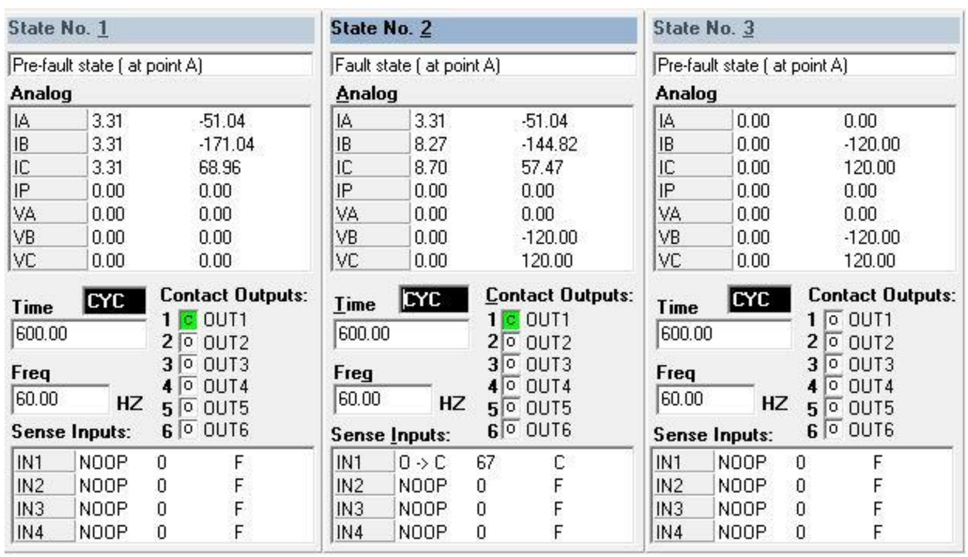

Figure A.2 AMS setting file for Bus 4 for fault at A

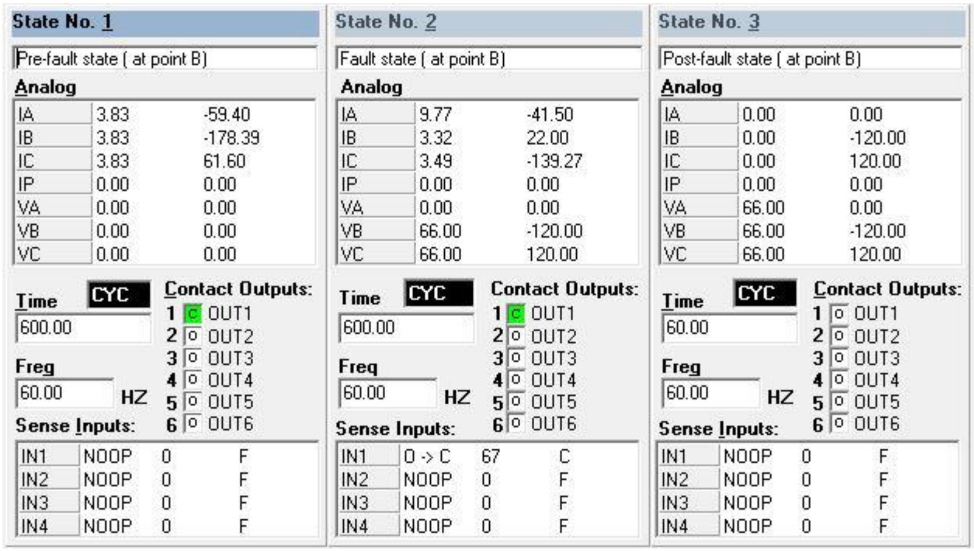

Figure A.3 AMS setting file for Bus 5 for fault at B

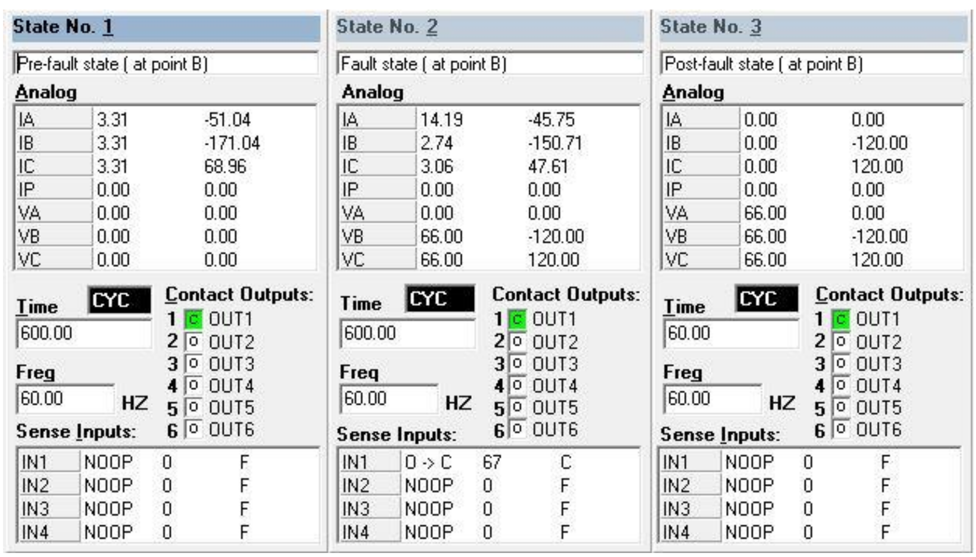

Figure A.4 AMS setting file for Bus 4 for fault at B

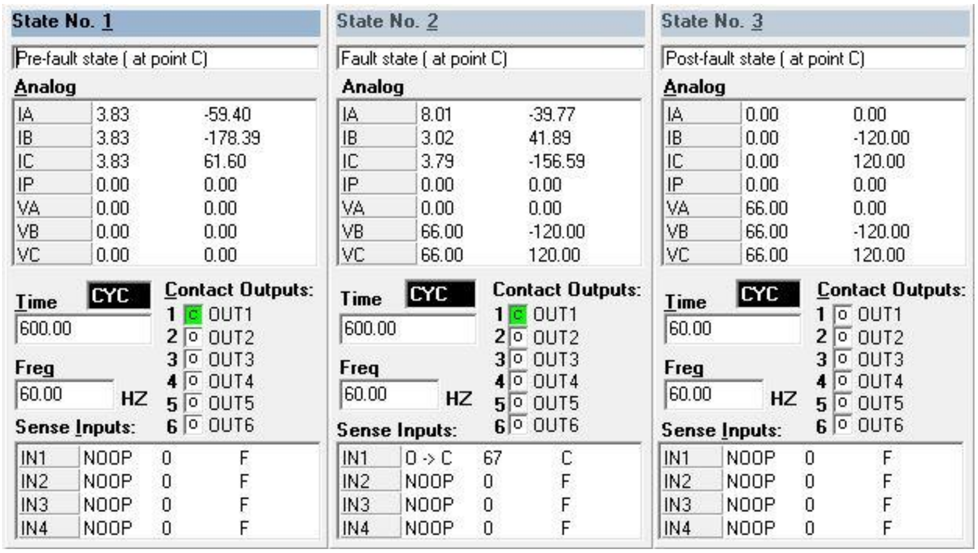

Figure A.5 AMS setting file for Bus 5 for fault at C

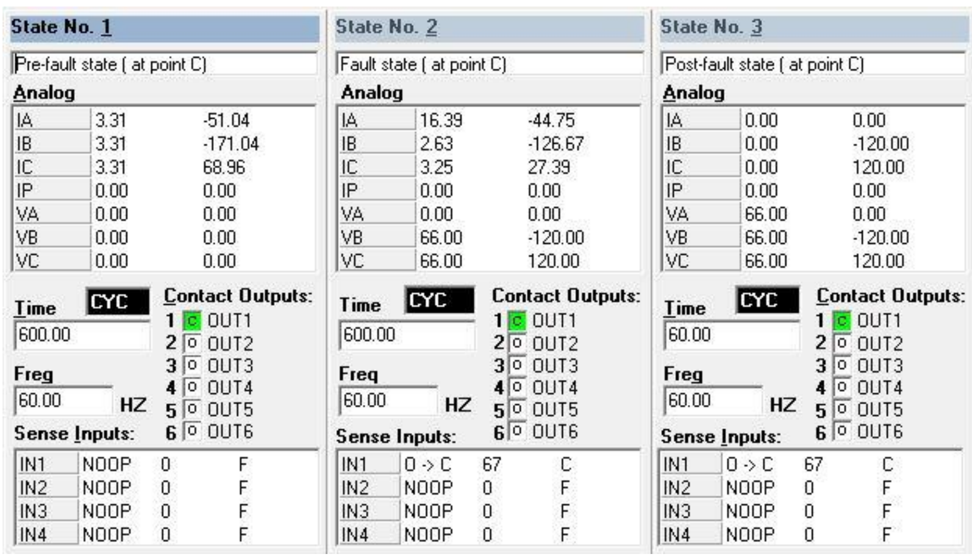

Figure A.6 AMS setting file for Bus 4 for fault at C

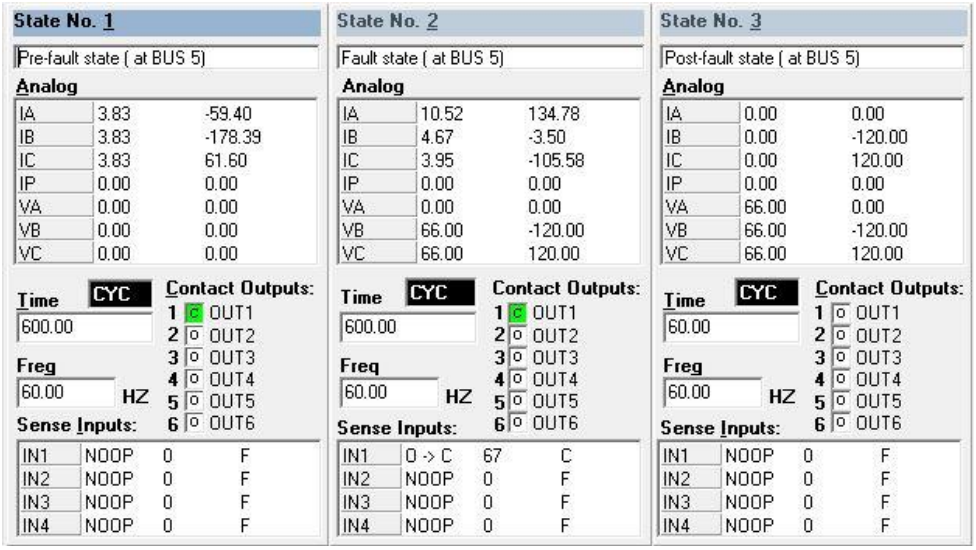

Figure A.7 AMS setting file for Bus 5 for fault at Bus 5

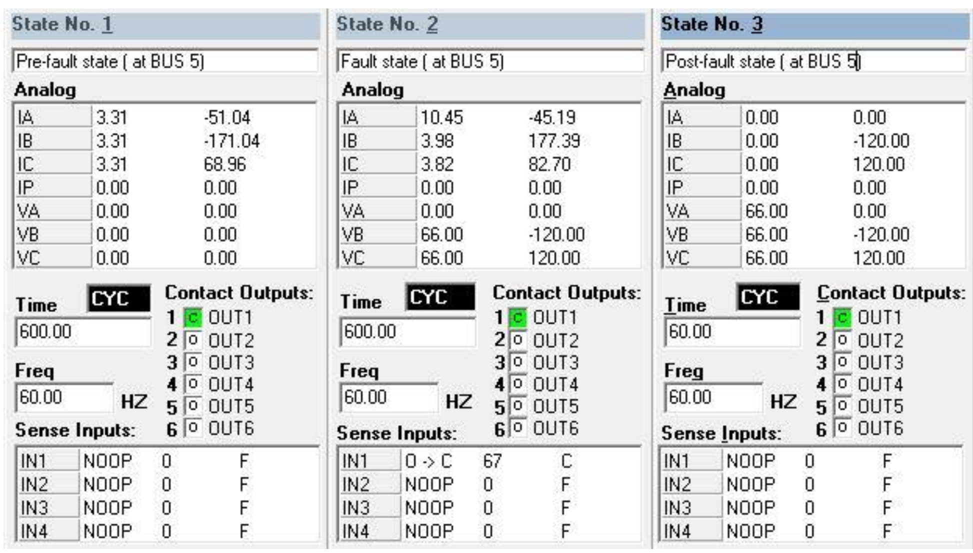

Figure A.8 AMS setting file for Bus 4 for fault at Bus 5

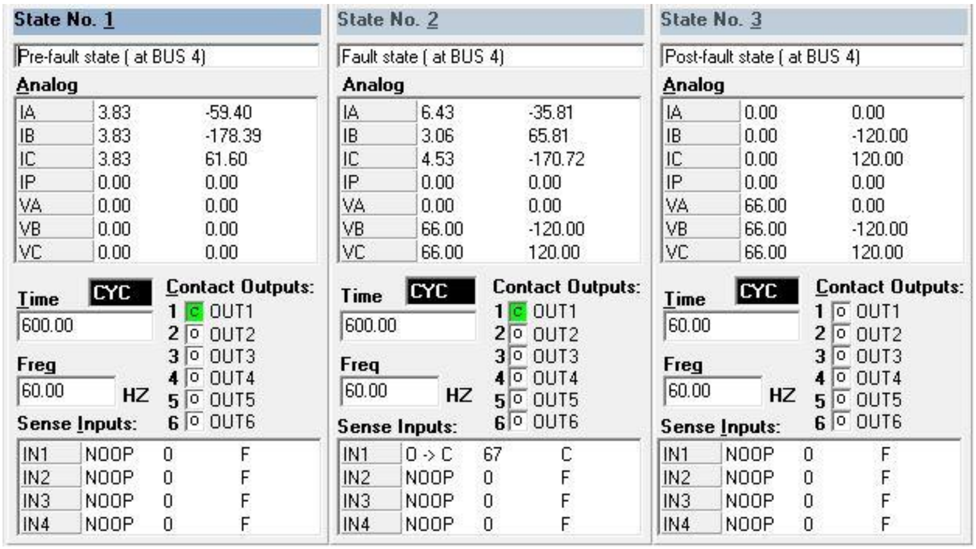

Figure A.9 AMS setting file for Bus 5 for fault at Bus 4

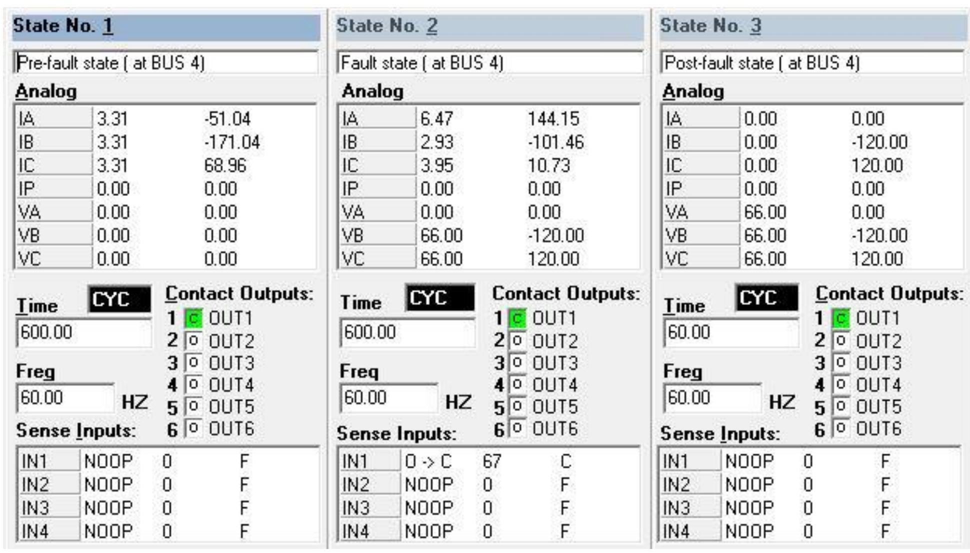

Figure A.10 AMS setting file for Bus 4 for fault at Bus 4

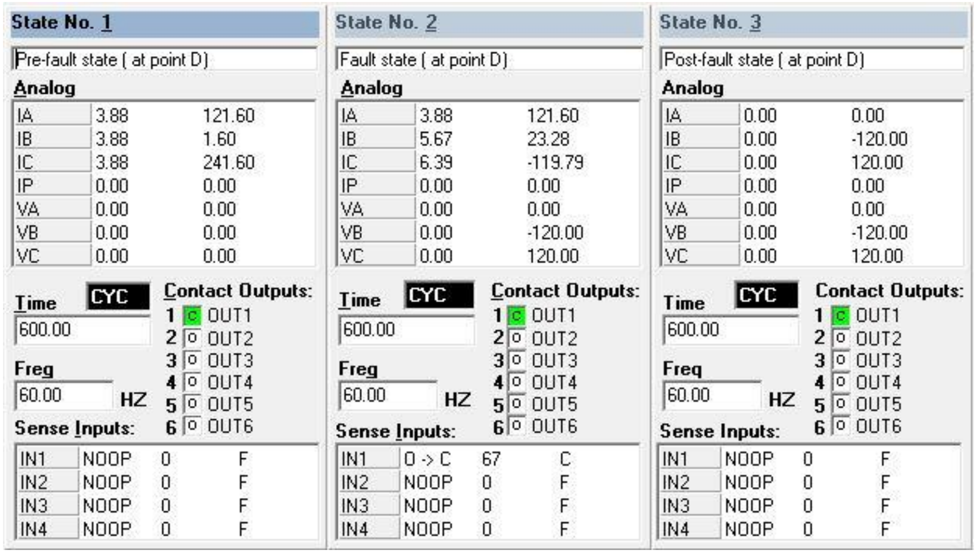

Figure A.11 AMS setting file for Bus 5 for fault at D

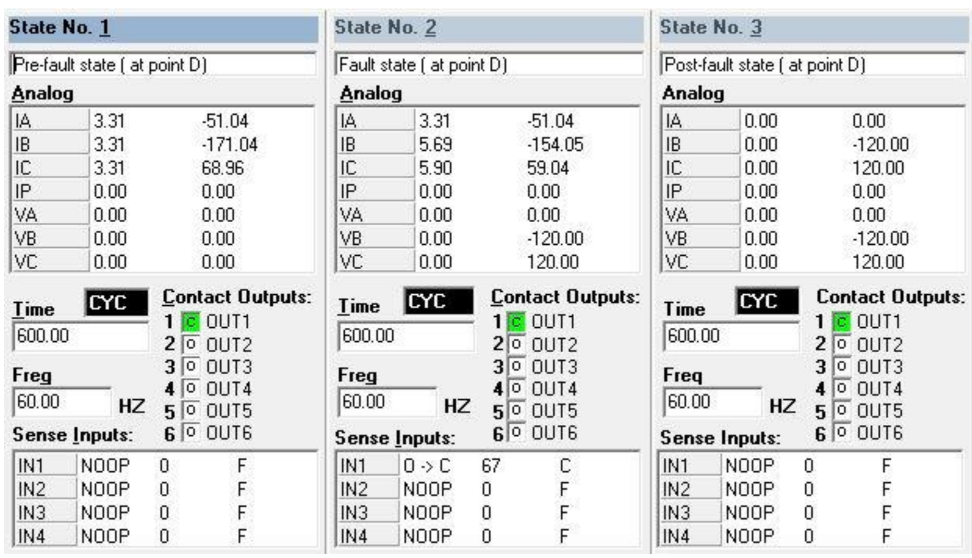

Figure A.12 AMS setting file for Bus 4 for fault at D

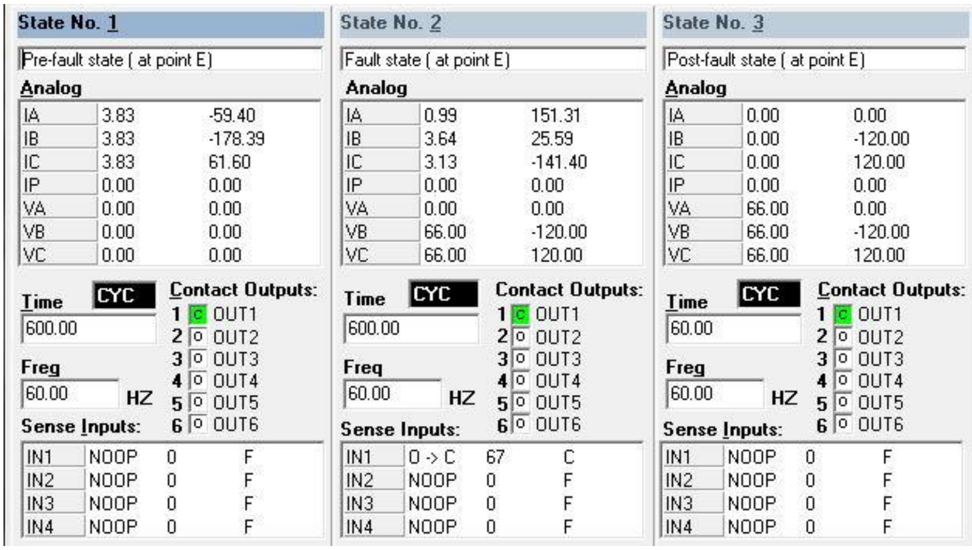

Figure A.13 AMS setting file for Bus 5 for fault at E

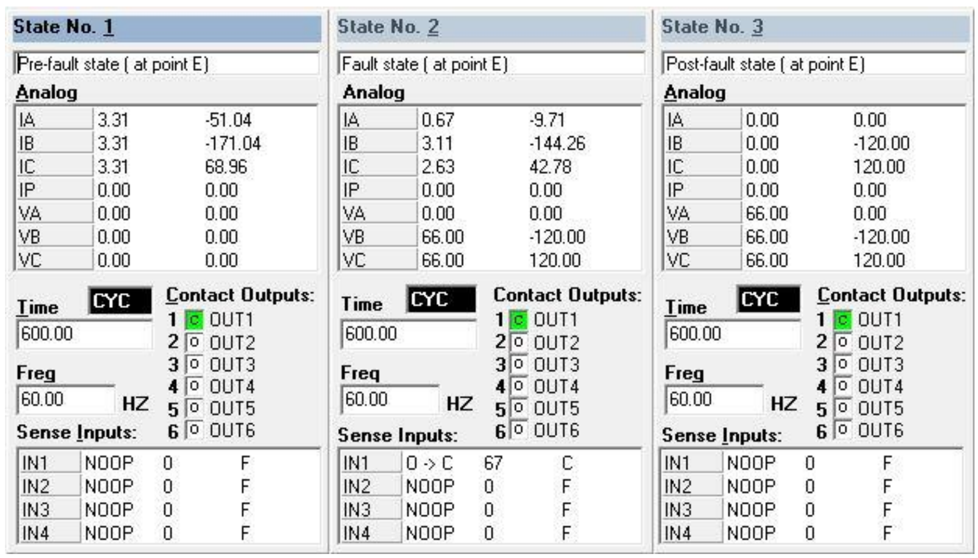

Figure A.14 AMS setting file for Bus 4 for fault at E