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Modelling of three zones distance relay with auto-recloser function using PSCAD/EMTDC™ simulation: an active learning tool

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Protection is a very important aspect of power system. To an undergraduate and post graduate student, the learning of the course poses a major challenge, as often the course treatment is not backed up with field visits, simulation, demonstrations etc. Modern simulation tools can be used as an active learning tool, to augment class room teaching. Further, simulations results can be demonstrated without expensive infrastructure and drastically improve the level of understanding of the subject. This paper presents a systematic approach using simulation through PSCAD™, to enhance the teaching-learning experience of transmission line protection using distance relay with auto-recloser feature. The response of the protection system is studied and analyzed when a fault occurs in the system. Simple exercises are posed to augment the self-learning experience of the student to further strengthen the concept of the topic.

Keywords: *Auto-recloser, three zone distance relay, permanent faults, PSCAD/EMTDC™ software, temporary fault*

1.0 INTRODUCTION

The objective of a protection scheme is to keep the power system stable by isolating only the components that are under fault, whilst leaving as much of the network as possible still in operation. Whenever there is a fault the protective relay detects the fault and generates a trip signal to operate the breaker. There are various types of protection relays. Distance relay is most commonly used to protect transmission lines. They respond to the impedance between the relay location and the fault location. As the impedance per km of a transmission line is fairly constant, these relay respond to the distance to a fault on the transmission line [1-4].

About 80-90 % of the faults occurring are transient in nature. The timing of opening and closing of the breaker depends upon whether the fault is temporary or permanent. A circuit breaker is equipped with auto-recloser mechanism that can automatically close the breaker after it has been opened due to a fault. The auto-recloser allows a selected number of attempts to restore service after adjustable time delays. For example a recloser may have 2 or 3 "fast" reclose operations with a few seconds delay, then a longer delay and one reclose; if the last attempt is not successful, the recloser will lock out and require human intervention to reset. If the fault is a permanent fault then the auto-recloser will exhaust its pre-programmed attempts to re-energize the line and remain tripped off until manually commanded to try again. In distribution systems, a maximum of three consecutive reclosures are allowed. The multiple reclosures help in burning out the objects responsible for the fault, say, a tree branch, and thus clearing out the fault. In contrast, in

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transmission systems because reclosures impose arduous duty to the circuit breakers and other elements of the power system due to high levels of fault MVA, only one reclosure is permitted [5-6].

In order to understand the concept of protection it is important for the students to have a practical experience of the same by implementing the theoretical concept on a practical system. Since it is very difficult to mimic the actual power system in a scaled down manner in the laboratory, the student is often left with misunderstood concepts and misinterpretations. Simulation is an effective alternative to scaled down hardware to illustrate the various relaying concepts of the power system. Simulation tools such as MATLAB™, PSCAD™, PSIM™ etc, can be used as teaching aids to augment the understanding of the power system relaying concepts. The advantage of simulation tools is that the learner can actually observe the time domain voltages and currents, the overvoltage and under-voltage conditions, the transient spikes produced by the fault conditions, unbalance created, operation and effect of protective devices [7-8].

This paper presents the systematic procedure to aid the teaching of relaying concept with auto-recloser function using PSCAD/EMTDC™.

2.0 MODEL OF DISTANCE RELAY FOR TRANSMISSION LINE PROTECTION

Distance relays are normally used to protect transmission lines. A distance relay, as its name implies, has the ability to detect a fault within a pre-set distance along a transmission line or power cable from its location. Every power line has a resistance and reactance per kilometer related to its design and construction hence its total impedance is a function of its length.

Table 1, lists the presence of sequence components, of voltage and current, during various faults and its statistics. It is clear that the positive sequence component is the only component which is present during all faults. Thus, it would be prudent to measure positive sequence impedance between the relay location and the fault so as to cater to every fault. Power systems have been in operation for over a hundred years now. Accumulated experience shows that all faults are not equally likely.

TABLE 1

PRESENCE OF SEQUENCE COMPONENTS IN VARIOUS FAULTS AND STATISTICS WITH REFERENCE TO TYPE OF FAULT

Fault	+ ve Seq.	- ve Seq.	zero Seq.	Proba-bility. of occur -ance	Severity
L-G	Yes	Yes	Yes	85%	Least Severity
L-L	Yes	Yes	No	8%	
L-L G	Yes	Yes	Yes	5%	
L-L-L	Yes	No	No	2%	Most Severity

Single line to ground faults (L-G) are the most likely whereas the faults due to simultaneous short circuit between all the three lines, known as the three- phase fault (L-L-L), is the least likely. This is depicted in Table 1. The severity of the fault can be expressed in terms of the magnitude of the fault current and hence it's potential for causing damage. In the power system, the three-phase fault is the most severe whereas the single line-to-ground fault is the least severe [3, 4].

Phase fault (L-L): The ratio of difference of positive and negative sequence voltages and currents gives the desired value of positive sequence impedance between the relay location and the fault point as shown in equation 1

$$Z = \frac{V_{a1} - V_{a2}}{I_{a1} - I_{a2}} \qquad ....(1)$$

The line voltages V_a, V_b, V_c can be expressed in terms of zero (V_{a0}), positive (V_{a1}), negative(V_{a2}) sequence components as shown in equations 2-4

$$V_a = V_{a0} + V_{a1} + V_{a2} \quad ....(2)$$

$$V_b = V_{a0} + a^2V_{a1} + aV_{a2} \quad ....(3)$$

$$V_c = V_{a0} + aV_{a1} + a^2V_{a2} \quad ....(4)$$

Since,

Therefore, $V_{a1} - V_{a2} = \frac{V_b - V_c}{a^2 - a}$;

where, $a = 1\angle 120^\theta$ ....(5)

Similarly $I_{a1} - I_{a2} = \frac{I_b - I_c}{a^2 - a}$ ....(6)

Hence $\frac{V_{a1} - V_{a2}}{I_{a1} - I_{a2}} = \frac{V_b - V_c}{I_b - I_c} = Z_1$ ....(7)

Thus, a distance measuring unit with voltages of $(V_b - V_c = V_{bc})$ and current of $(I_b - I_c)$ will measure positive sequence impedance up to fault point Z_1, in case of phase b-c faults as shown in equation 7. Similarly, V_{ab}, $(I_a - I_b)$ and V_{ca}, $(I_c - I_a)$ for phase a-to-b and phase c-to-a faults [3].

Ground faults (L-G): In case of ground faults

$$V_{a0} + V_{a1} + V_{a2} = I_{a1}Z_1 + I_{a2}Z_1 + I_{a0}Z_0 \quad ....(8)$$

However $V_{a0} + V_{a1} + V_{a2} = V_a$ ....(9)

From equation 8 and 9

$$V_a = I_{a1}Z_1 + I_{a2}Z_1 + I_{a0}Z_0 - I_{a0}Z_1 + I_{a0}Z_1 \quad ....(10)$$

Since, $Z_2 = Z_1$

$$V_a = (I_{a1} + I_{a2} + I_{a0})Z_1 + I_{a0}Z_0 - I_{a0}Z_1 \quad ....(11)$$

$$V_a = I_aZ_1 + I_{a0}(Z_0 - Z_1) \quad ....(12)$$

$$V_a = \left(I_a + \frac{Z_0 - Z_1}{Z_1} I_{a0} \right) Z_1 \quad ....(13)$$

$$I_{a0} = \frac{I_a + I_b + I_c}{3} \quad ....(14)$$

Since, $I_{res} = I_a + I_b + I_c$

$$V_a = \left(I_a + \frac{Z_0 - Z_1}{3Z_1} I_{res} \right) Z_1 \quad ....(15)$$

$$Z_1 = \frac{V_a}{\left(I_a + \frac{Z_0 - Z_1}{3Z_1} I_{res} \right)} \quad ....(16)$$

Where, $k = \frac{Z_0 - Z_1}{3Z_1}$

$$Z_1 = \frac{V_a}{(I_a + kI_{res})} \quad ....(17)$$

Thus, a distance measuring unit with voltages of (V_a) and current of ($I_a + KI_{res}$) will measure positive sequence impedance up to fault point Z_1, in case of phase a-to-g faults as per the equation 17. Similarly, V_b, $(I_b + KI_{res})$ and V_c, $(I_c + KI_{res})$ for phase b-to-g and phase c-to-g faults.

Figure 1. shows the distance relay logic for the protection of transmission line from all types of faults. The OR gate will issue the trip command to the circuit breaker in case of fault [3, 4]. The positive sequence impedance is calculated in real time and when it is below the pre-set value, the distance relay gives a command to operate the circuit breaker. This model is used in developing the distance relay logic in PSCAD /EMTDC™.

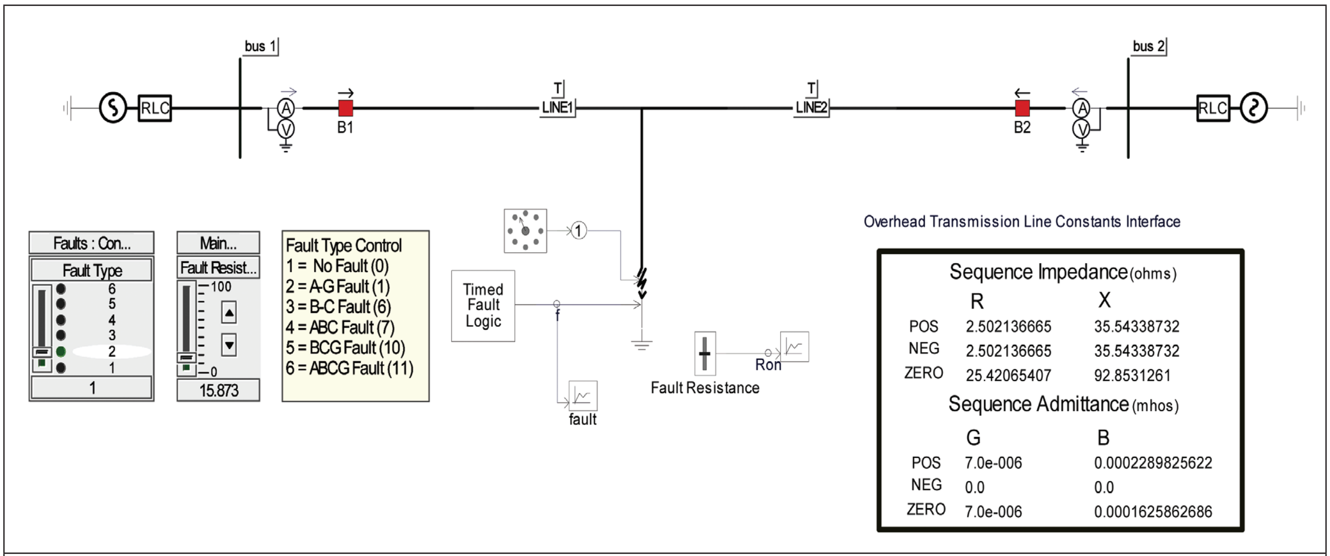

FIG. 1 SINGLE LINE DIAGRAM OF TRANSMISSION LINE WITH FAULT LOGIC BLOCK

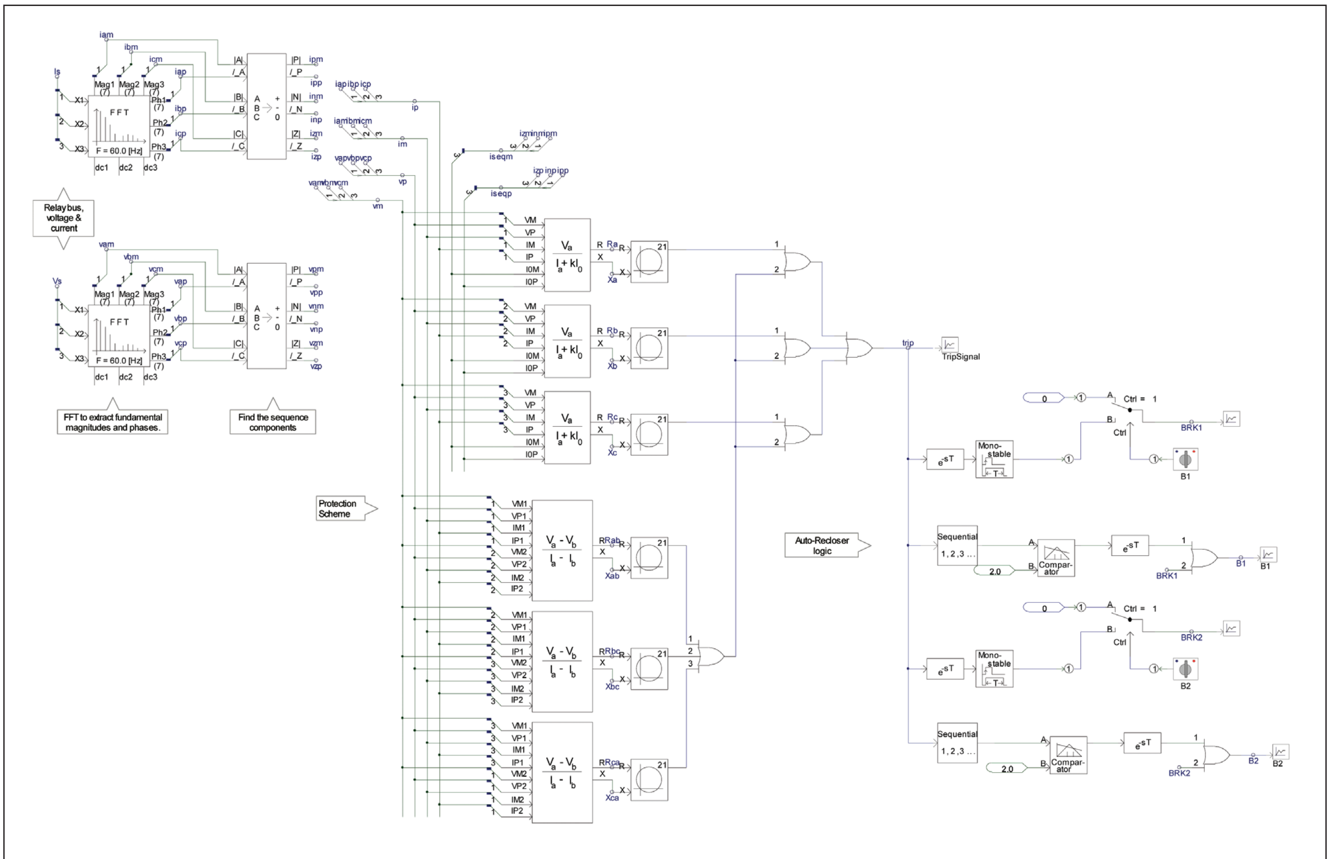

FIG. 2 COMPLETE PROTECTION SCHEME OF A THREE-PHASE LINE USING DISTANCE RELAY AND AUTO-RECLOSER LOGIC

3.0 CASE STUDIES

In order to study the functioning of the distance relays, a typical 230 kV, 100 kM transmission line has been modelled in PSCAD™ [9-11]. The transmission line is connected between two buses Bus 1 and Bus 2. Bergeron model is used to model all the three phase transmission line in PSCAD/EMTDC™ using given data in Appendix A. It is based on the distributed LC parameter and travelling wave line model, with lumped resistance. It represents the L and C elements of PI section in distributed manner. This model is suitable for studies where the fundamental frequency load flow and relay studies is most important [7].

The generator G_1 is rated 100 MVA, 230 kV, 60 Hz and generator G_2 is rated 100 MVA, $230\angle 20°\ kV$, 60 Hz are connected to bus 1 and bus 2 respectively. The single line diagram of the 100 kM long transmission line provided with the breakers at both ends is shown in Figure 1. The fault occurs at 65 kM from bus 1. The fault type can be controlled through the rotary switch and the duration of fault can be controlled through timed fault logic.

On-line frequency scanner (FFT) is the module designed to give the magnitudes and phases of the voltages and current measured by multi-meter connected to bus 1, by using the magnitudes and phase of the sequence filter find out the sequence component i.e. positive, negative and zero sequence components of the same currents and voltages [9].

Mho relay which is designed in PSCAD/ EMTDC™ as per the logic discussed in section 2.0. The logic for ground fault and phase fault is shown. Thus, in all, six distance measuring units each set at Z_1 (set impedance), the positive-sequence impedance of the line section, are sufficient for complete protection against all the ten shunt faults, as shown in Figure 2. To produce the trip signal on the occurrence of the fault, the trip signal is given to B1 and B2 supported with auto-recloser function logic. However, the operation of the breakers is controlled by signal BRK1 and BRK2 which are obtained from the OR gate used in the sequential circuit.

The logic of auto-recloser is also needs to be developed in PSCAD, as it is not available as a built-in function. The function of auto-recloser is to close the breaker, after it is opened by the relay on the occurrence of fault, with a delay of 1 sec. If the fault is temporary and gets cleared in 1 sec., the breakers remain closed and the supply to the system is restored. If it is a permanent fault, on closing the breaker, the relay again senses the fault and opens the breaker permanently. The logic building for the auto-recloser function, for different cases is presented in the subsequent sections, along with detailed results [12-14].

3.1 Mho relay with Auto-recloser; Temporary fault

On the occurrence of fault, the distance relay detects the fault and issues trip command to the circuit breakers B2 and B2. Since the breaker operating time should be 60 ms. The two breakers open to clear A-G fault at 0.26 ms. After a delay of dead time (1 second) due to auto-recloser function, the circuit breaker closes its contacts and the contacts remain closed as the fault is transient fault and is cleared at 0.8 seconds.

Fault specifications:

- Ground fault (A-G) is at transmission line T1
- Time to apply Fault-0.2 seconds
- Duration of Fault 0.05 seconds (Approx. 3 cycles)

The voltage and current waveforms captured at bus 1, for this fault are as shown in Figure 3. Since it is A-G fault, the voltage of phase-A has dropped and current of phase-A has increased during 0.2-0.05 seconds as seen in 3 (a) and 3 (b) respectively.

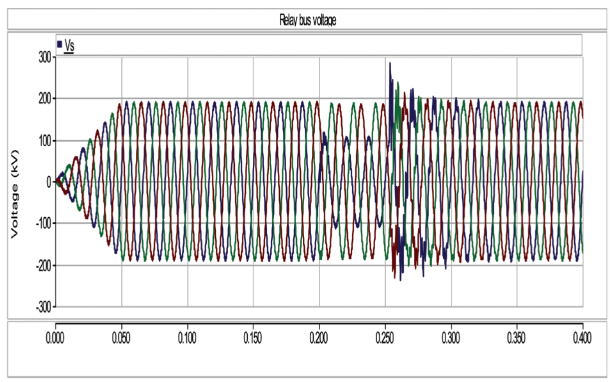

FIG. 3 (A) VOLTAGE WAVEFORM AT BUS 1 FOR TEMPORARY A-G FAULT

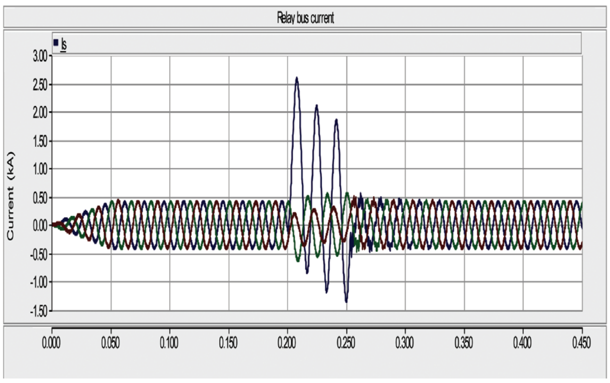

FIG. 3 (B) CURRENT WAVEFORM AT BUS 1 FOR TEMPORARY A-G FAULT

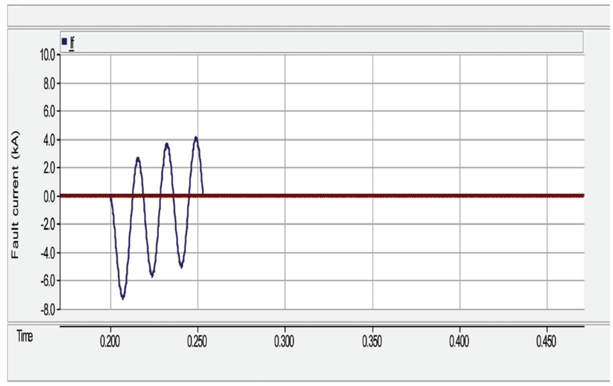

FIG. 4 (C) MAGNITUDE OF FAULT CURRENT FOR TEMPORARY A-G FAULT

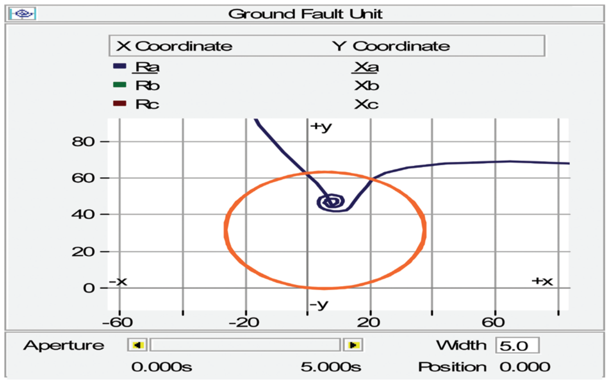

FIG. 4 (A) MHO TRAJECTORY OF GROUND FAULT UNIT

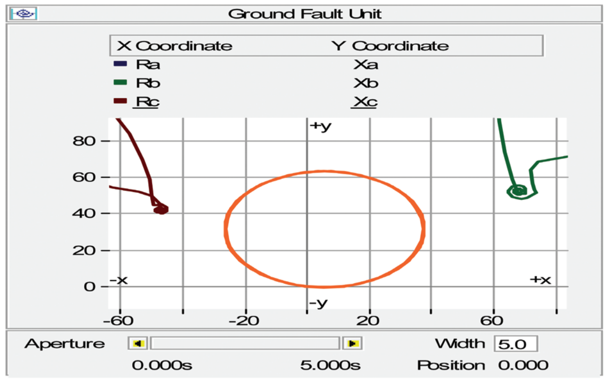

FIG. 5 (A) MHO TRAJECTORY OF GROUND FAULT UNIT

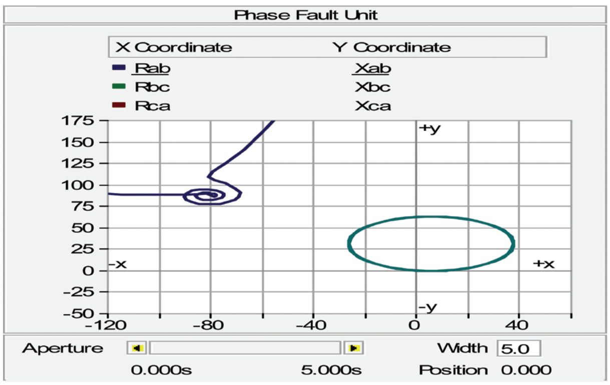

FIG. 4 (B) MHO TRAJECTORY OF PHASE FAULT UNIT

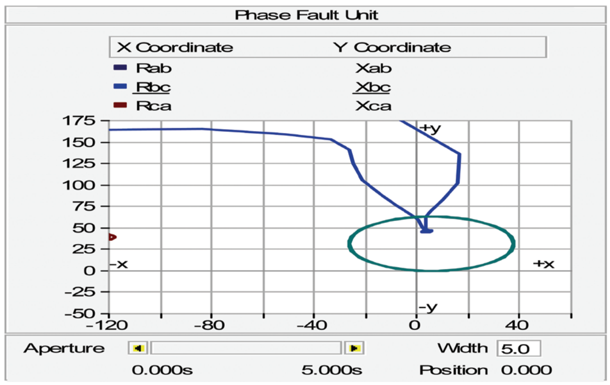

FIG. 5 (B) MHO TRAJECTORY OF PHASE FAULT UNIT

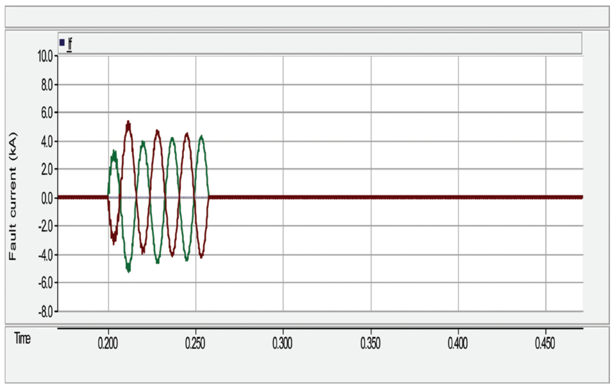

FIG. 5 (C) MAGNITUDE OF FAULT CURRENT FOR TEMPORARY A-B FAULT

When ground fault (A-G) occurs the zone trajectory of Mho relay for ground fault unit shown in Figure 4(a). The circle shows the region of operation of the distance relay and the fault location. Since the fault is within the relay reach, the relay operates. Figure 4(b) shows the zone trajectory of Mho relay for Phase fault unit, shows the fault is outside the relay reach. The magnitude of fault current for A-G fault is shown in Figure 4(c).

When phase fault (A-B) occurs the zone trajectory of Mho relay shown in Figure 5(b). The circle shows the region of operation of the distance relay and the fault location. Since the fault is within the relay reach, the relay operates. Figure 5(a) shows the zone trajectory of Mho relay for ground fault unit, shows the fault is outside the relay reach. Figure 5(c) shows the magnitude of fault current for A-B fault.

The Auto- recloser logic is developed in PSCAD as shown in Figure 2 and discussed below:

For temporary fault, the trip signal is a pulse as shown in graph Figure 6(a). On receiving the trip signal time delay blocks (T.D.-1 & T.D.-2) give a time delay of 60 ms so that breakers open after a delay of 60 ms. The mono-stable blocks (M.S-1 & M.S-2) makes the duration of trip pulse to 1 second. This ensures that the breaker B1 & B2 remain open for one second. The trip signal is also given to the sequential block which increments by one on the change in the input, i.e. trip signal. Thus at 0.2 sec., the output of sequential block is land again at 0.28 sec when trip signal becomes zero from 1, the output is 2. In case of temporary fault, trip signal is only one pulse hence output of sequential block will not be more than 2. The output of sequential block is given to comparator whose one input is set at 2. It is configured to give an output 1 when sequential output is more than 2 and output 0 if it is less than 2. In case of temporary fault, the outputs of COM-1 and COM-2 are zero. These outputs are given to time delay blocks (T.D.-3 & T.D.-4), to get a time delay of 1 sec. The delayed output from time delay block and signal from Breaker is given to OR gate. The outputs of two OR gate (2 &3) will control the operation of breakers B1 and B2. Since in this case the outputs of T.D -3 and 4 are zero, the breaker operation is controlled through the signal BRK1 and BRK2. The sequence of operations for the transient fault and their corresponding output waveforms are as summarized below:

Time of fault occurrence at 0.2 sec and initiates trip signal as shown in Figure 6(a).

Mono-stable vibrator gives a signal at 0.26 sec for a period of 1 sec. So that breaker does not close before 1 sec of opening (Figure 6(b)).

The output of sequential is 2 due to two operations; first opening and then closing of breakers (Figure 6(c)).

The output of comparator circuit is 0, since the output of sequential is 2 (Figure 6(d)).

Breakers B1 and B2 operations are due to signal BRK1 and BRK2 received from relay logic. Thus Breakers open at 0.26 sec and remains open till 1.26 sec. After 1.26 sec. breakers will close (Figure 6 (e), (f)).

Since the fault duration is 0.05 sec, it gets cleared before 1.26 sec and thus relay will not issue any trip signal to the breakers and they continue to remain close.

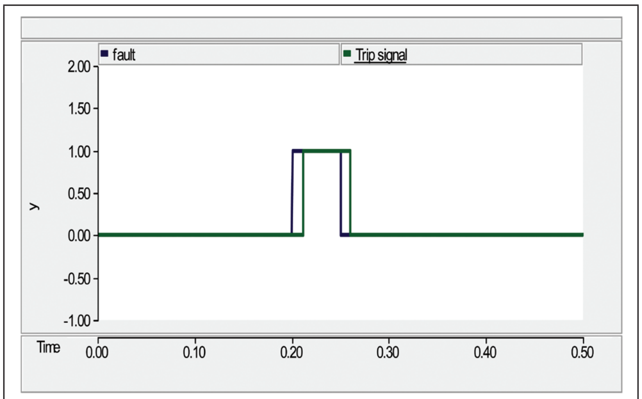

FIG. 6 (A) WAVEFORM OF FAULT AND TWO PULSES OF TRIP SIGNAL

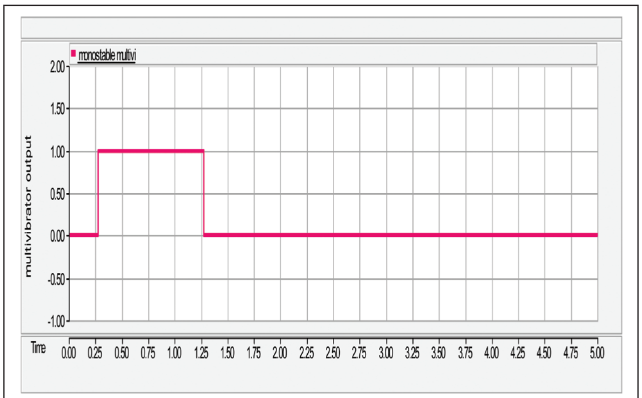

FIG. 6 (B) WAVEFORM OF MONO-STABLE VIBRATOR

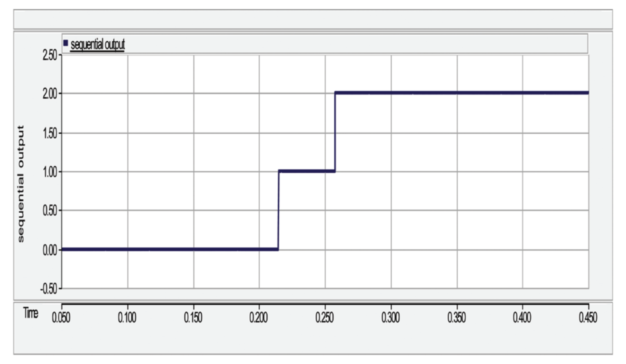

FIG. 6 (C) WAVEFORM OF SEQUENTIAL OUTPUT

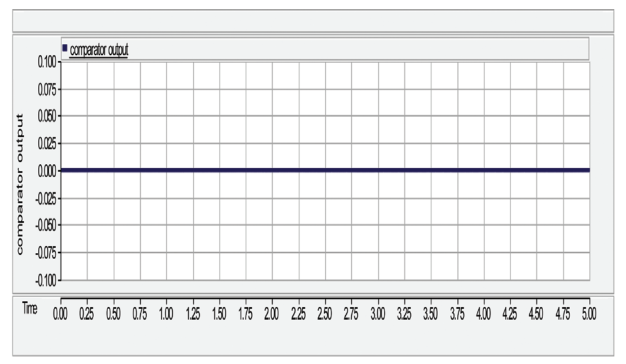

FIG. 6 (D) WAVEFORM OF COMPARATOR OUTPUT

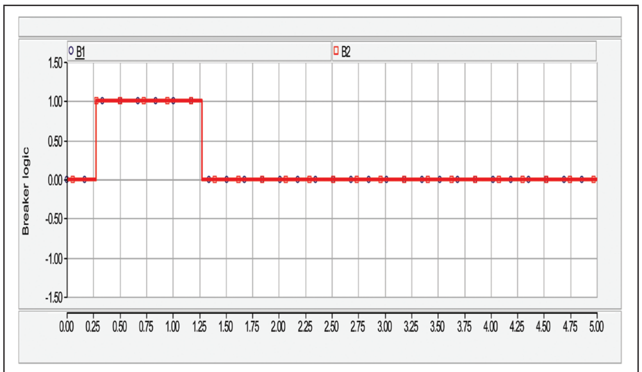

FIG. 6 (E) WAVEFORM OF THE BREAKERS, B1 AND B2 OPERATION

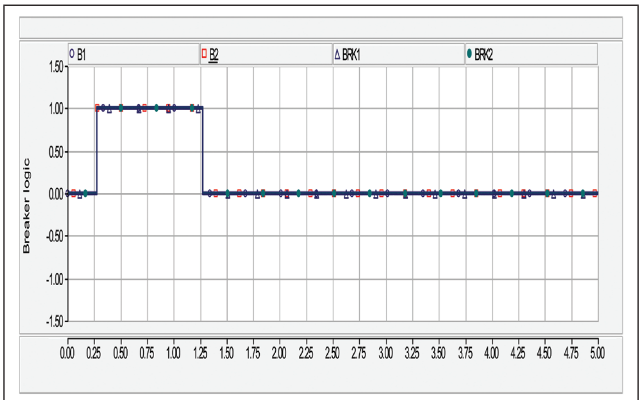

FIG. 6 (F) WAVEFORM OF THE BREAKERS, B1 AND B2 OPERATION ARE DUE TO SIGNAL BRK1 AND BRK2 RECEIVED FROM RELAY LOGIC

3.2 Mho relay with Autorecloser; Permanent fault

Fault specifications:

- Ground fault (A-G) is at transmission line T1
- Fault starts at 0.2 seconds.
- Duration of fault up to duration of simulation run

A permanent A-G fault is created on the transmission line at a distance of 65 kM from the bus1. The fault is initiated at 0.2 sec. The voltage and current waveforms captured at bus1, for this case are as shown in Figure 7. Since it is A-G fault, the voltage of phase-A has dropped and current of phase-A has increased at 0.2 seconds as seen in Figure 7(a) and 7(b) respectively.

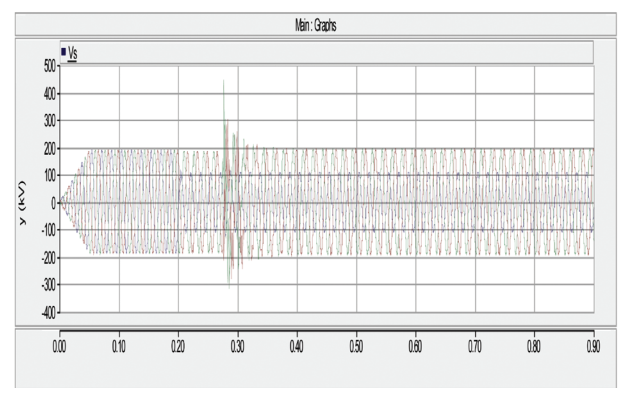

FIG.7 (A) VOLTAGE WAVEFORM AT BUS 1 FOR PERMANENT A-G FAULT

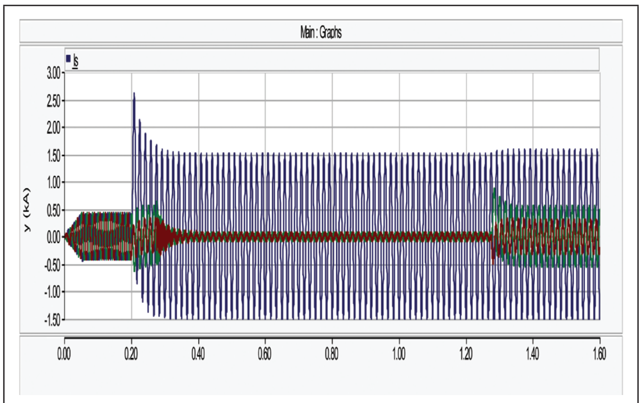

FIG. 7 (B) CURRENT WAVEFORM AT BUS 1 FOR PERMANENT A-G FAULT

The distance relay issues trip command to the breaker as shown in Figure 8(a). For permanent fault also, breakers close after 1 sec of opening, as in the case of temporary fault. On closing of breakers, transmission system gets energized and the fault is again seen by the relay. The relay again issues trip signal to the breakers as shown in Figure 8(a). Thus in case of permanent fault trip signal consists of two pulses. The output of sequential block will be four as seen from the waveform shown in Figure 8(d). Thus the output of comparator will be high. This is given to the OR gate after a delay of 60 ms. This logic captures the second pulse of trip and opens the breaker after 60 ms of the second trip signal. Initially the breaker operation is controlled from the first trip signal and after first recloser; it is controlled by the second trip signal which is processed properly by the developed logic. The processed signal is the output of the OR gate. It thus opens the breaker again permanently. The sequence of operations for the permanent fault and their corresponding output waveforms are as summarized below:

- Time of Fault occurrence 0.2 sec and initiates trip signal as shown in Figure 8(a).
- Mono-stable vibrator gives a signal at 0.26 sec (after a delay of 60 ms) for a period of 1 sec. So that beaker does not close before 1 sec of opening (Figure 8 (b)).
- Breaker opens at 0.26 sec and remains open till 1.26 sec. After 1.26 sec. breaker will close (Figure 8(c)). Since the fault is permanent, relay will again issue a trip signal to the breakers (Figure 8(a)).
- Mono-stable vibrator again gives a signal at 0.26 sec (after a delay of 60 ms) for a period of 1 sec (Figure 8 (b)).
- The output of sequential logic is 4 as it sees four operations; first opening, closing then again opening and closing of breakers (Figure 8 (d)).
- The output of comparator circuit is 1, since the output of sequential is 2 (Figure 8 (e)).
- Breakers B1 and B2 operations is due to signal from comparator logic. Thus Breakers open permanently at 1.32 sec (Figure 8 (f)).

Thus the second trip signal is detected by sequential- comparator logic circuit. A delay of 60 ms is provided to the trip signal, in order to open the breakers after a delay of 60 ms of the second trip and the breakers are open permanently.

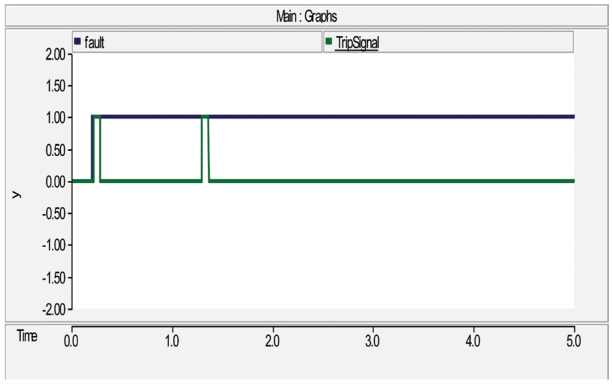

FIG. 8 (A) WAVEFORM OF PERMANENT FAULT AND TWO PULSES OF TRIP SIGNAL

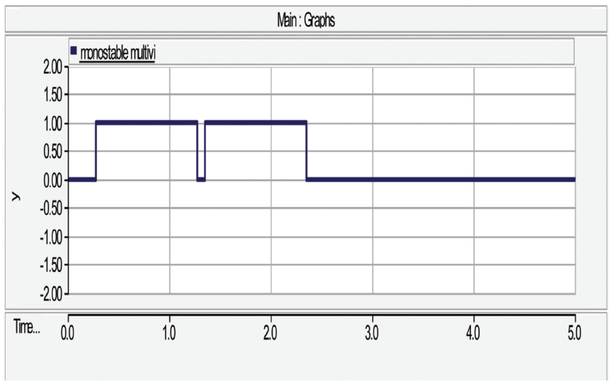

FIG. 8 (B) WAVEFORM OF MONO-STABLE VIBRATOR

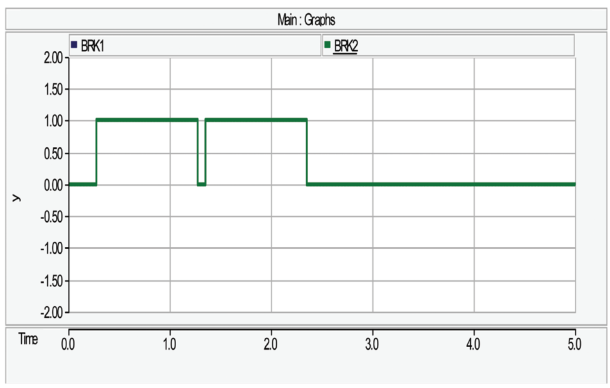

FIG. 8 (C) WAVEFORM OF SIGNAL BRK1 AND BRK2 RECEIVED FROM RELAY LOGIC

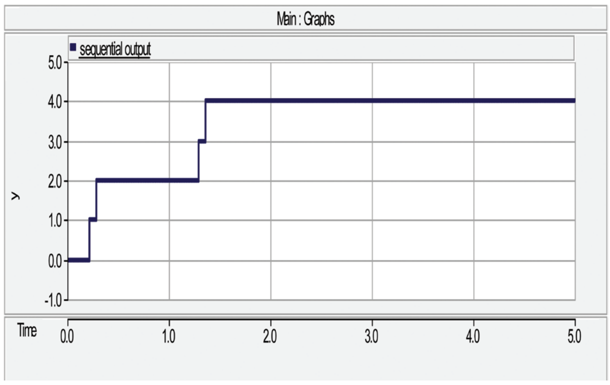

FIG. 8 (D) WAVEFORM OF SEQUENTIAL OUTPUT

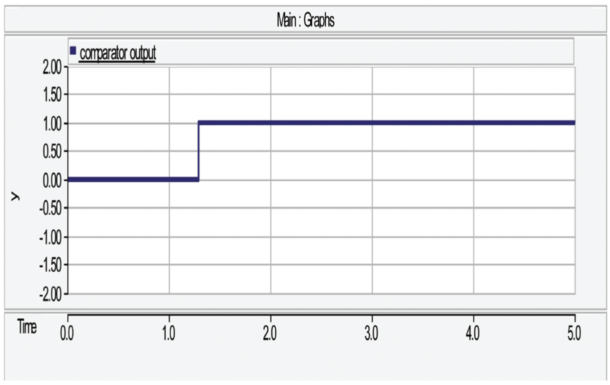

FIG. 8 (E) WAVEFORM OF COMPARATOR OUTPUT

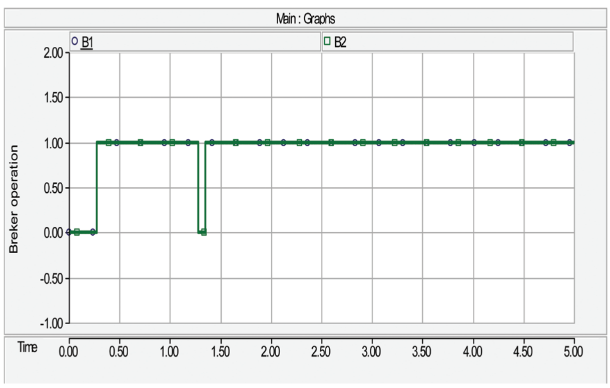

FIG. 8 (F) WAVEFORM OF THE BREAKERS B1 AND B2 OPERATION

The case studies discussed above clearly illustrate the operation of distance relays with auto-recloser facility under transient and permanent faults. The case studies simulate a real power system, thus enhancing the theoretical concept of auto-recloser, to the student. Now some extended exercises which the facilitator can assign to the students are, to generate three zones, 3 X 6 = 18, measuring units will be required. This is a rather costly affair! Therefore, schemes, which save upon the number of measuring units, have been devised. One popular idea, known as the switched distance scheme uses only three measuring units, but switches the inputs to them with the help of fault detector. This brings down the number of measuring units from 18 to 9.

3.3 Three Zones Protection

Distance relays will have instantaneous directional zone 1 protection and one or more time delayed zones. The tripping signal produced by zone 1 is instantaneous; it should not reach as far as the busbar at the end of the first line so it is set to cover only 80-85 per cent of the protected line. The remaining 20-15 percent provides a factor of safety in order to mitigate against errors introduced by the current and voltage transformers, and line impedance calculations. The 20-15 percent at the end of the line is protected by zone 2, which operates in time delay (t_2) in seconds. Zone 3 provides the back-up and operates with a time delay of t_3 seconds. Three protection zones in the direction of the fault are used in order to cover a section of line and to provide back-up protection to remote sections [9-11]. In the majority of cases the setting of the reach of the three main protection zones is made in accordance with the following criteria;

Zone 1: This is set to cover between 80 and 85 percent of the length of the protected line;

Zone 2: This is set to cover all the protected lineplus 50 per cent of the shortest next line

Zone 3: This is set to cover all the protected lineplus 100 per cent of the second longest line plus 25 per cent of the shortest next line.

Mho relay characteristics for three zones of protection as shown in the Figures 9 and 10.

For variation of Power angle from 20 to 60 deg, relay deviations is more severe and relay cause maloperate shown in Figure 9. Single line to ground fault with different fault resistance were applied on the transmission line shown in Figure 10, when the fault resistance from 50 to

20 Ω the relay detects the fault in another zone, due to increase in fault resistance, mho relay maloperates.

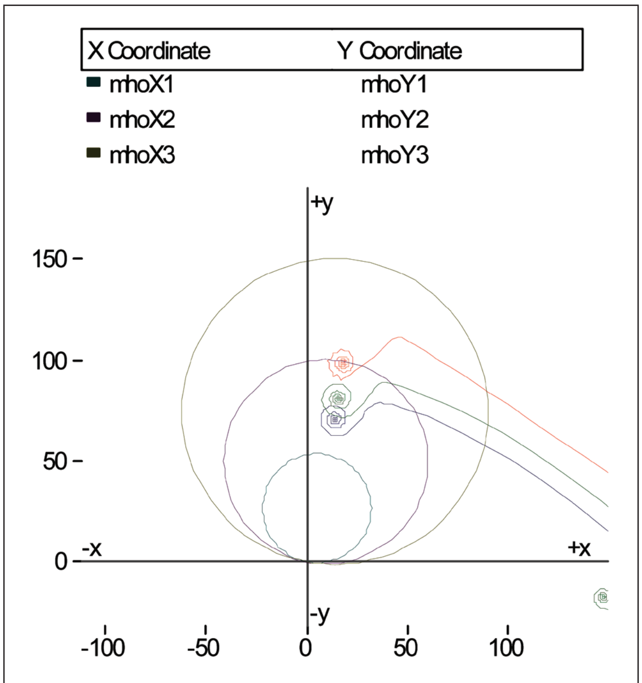

FIG. 9 APPARENT IMPEDANCE TRAJECTORY OF A-G MEASURING UNIT FOR VARIATION OF POWER ANGLE (LEGEND: RED =20°, GREEN=40°, BLUE=60°)

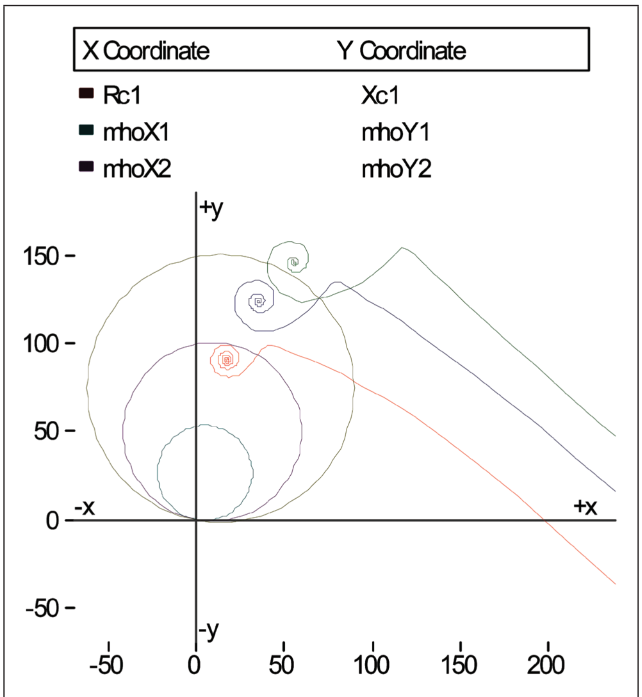

FIG.10 APPARENT IMPEDANCE TRAJECTORY OF A-G MEASURING UNIT FOR DIFFERENT FAULT RESISTANCE (LEGEND: RED=50Ω, BLUE= 30Ω, GREEN = 20Ω)

Some extended exercises which the facilitator can assign to the students are simulating the above system for different types of faults, and study the behaviour of the distance relay.

- Change the location of the fault and simulate
- Change the relay setting and observe
- Compare the system performance, with and without auto-recloser facility.

4.0 CONCLUSION

This paper presents a systematic approach for teaching of transmission line protection, using three zones protection of distance relays with auto-recloser, through simulation to undergraduate and post graduate students. *PSCAD/EMTDC™* has been used as the simulation tool, though the method is similar if any other tools such as PSIM, NETPLAN etc. are used. The distance relay is modelled in *PSCAD/EMTDC™* as described by mathematical equations. The auto-recloser function is modelled to help the students to understand its operation for permanent and temporary faults. *PSCAD/EMTDC™* is an easy tool, due to the vast library capabilities present and the drag and drop approach used to build networks. Similar simulation exercises can be developed for other power system applications.

APPENDIX A

Study System Data of Figure 1.

Elements of Study System	Parametric quantity
Equivalent Source (2)	System Voltage = 230 KV System Frequency = 60 Hz Posit. Sequence Impedance $Z_1 = 25.9\angle 80°\Omega$ Zero Sequence Impedance $Z_0 = 25.9\angle 80°\Omega$

Figure A.1 shows the physical structure of the Bergeron model transmission line. By utilizing of transmission line in PSCAD with proper tower configuration and height of conductor and ground wire as shown in the Figure A.1

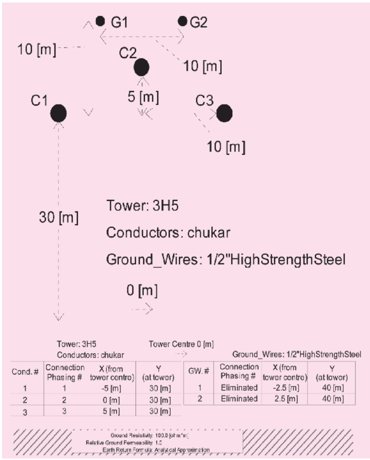

FIG. A.1. PHYSICAL STRUCTURE OF BERGERON MODEL TRANSMISSION LINE

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