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Distance Protection Scheme For a Medium Voltage Power Distribution System

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***Abstract*–Power system protection is a significant area which needs a lot of attention. The key aim of using power system protection is to isolate the faulty section from the system to make the rest of the network work without any disturbance. Moreover, it is used for the protection of power system and prevent the flow of fault current. It is an essential component of power system security and stability. Owing to the probability of sudden faults and disturbances, it is vital that appropriate protection schemes are designed to counteract these faults and disturbances to provide uninterrupted supply to customers. This paper attempts to design a distance protection scheme for a Medium Voltage distribution network using DIgSILENT Power Factory Software. It is expected that this work may help researchers in protection design to come up with innovative ideas to apply on distribution networks of various topologies in the future.**

Keywords-Distance protection; distribution network; faults; power system protection; power system security

I. INTRODUCTION

Due to ever increasing consumption of conventional energy sources which include fossil fuels like coal, natural gas and oil, there is an urgent need to move towards alternative sources of energy [1]. Solar energy is one of the best sources of renewable energy. If utilized appropriately, it can benefit the energy sector significantly.

Electrical power systems typically operate at various voltage levels ranging from 230 V to 500 kV or even greater than this. Electrical apparatus used may be utilized in various forms i.e., they may be enclosed (e.g., motors, generators, pad mounted transformers etc.) or placed in open atmosphere (e.g., transmission lines or pole-mounted transformers). All such equipment undergoes irregularities and discrepancies in their life due to numerous reasons. These reasons can be natural or man-made. Natural reasons may include faults due to lighting, falling trees, flying objects, tornadoes, or earthquakes. Manmade reasons may include human error or car accidents etc. For instance, a worn-out bearing of a DC motor may be the reason behind overloading or over-heating of the motor. A tree falling on an overhead power line may result in a fault. A lightning strike (which is obviously an act of Nature) can lead to insulation damage and, in turn, insulation failure. Pollution may negatively affect performance and operation of line insulators which may cause breakdown. Over frequency of a generator may result in a mechanical or structural failure of its turbine leading to tripping of an alternator. On the contrary, low frequency operation will decrease the life of the turbine and hence it should be prevented. It is essential to avoid these irregular and unwanted operating regions for protection of the equipment. Even more significant is safety of the work personnel which may be threatened due to contact with live parts having fault current in them. Currents, even of the order of about 50 mA, are enough to cause lethal damages. Whenever human security is compromised or there is a likelihood of equipment failure, it is mandatory to isolate and de-energize the electrical equipment. In short, every electrical equipment must be checked for protection and must offer human safety under abnormal operating conditions. This important and sensitive role comes under the jurisdiction of electrical protection systems. It incorporates equipment protection and system protection [1-2].

In a typical protection system, there are many essential elements. Relay is the backbone of this system. A relay is a logical element or device which processes the inputs (typically voltages and currents) from the system and provides a trip decision if a fault is present within the relay's desired zone of protection. IEEE defines relay as ‘‘an electric device that is designed to respond to input conditions in a prescribed manner and, after specified conditions are met, to cause contact operation or similar abrupt change in associated electric control circuits.’’ A conceptual diagram of relay is shown in Fig. 1. The relay takes the current and voltage input signals from its Current Transformer (CT) and Potential Transformer (PT). CT and PT are the devices which help the relay in forming its decision. They are collectively termed as instrument transformers. They step down high magnitudes of voltages and currents to a measurable value. Normally CT has a turns ratio of 100:5. Sometimes, 100:1 is also used depending on the application. Usually, PT has a turns ratio of 100:1, although some other ratios are also used. Details of construction and mechanism of instrument transformers will not be discussed in this paper as this is not the purpose here. As a simple example, consider Fig. 2, a relay R_1 is used to protect the transmission line having fault F_1. A similar system is connected at the other end of the transmission line relay R_3 to open circuit from the other end. To examine the condition of the electrical equipment, relay detects current through a CT and voltage through a PT, also known as Voltage Transformer (VT) [2-3].

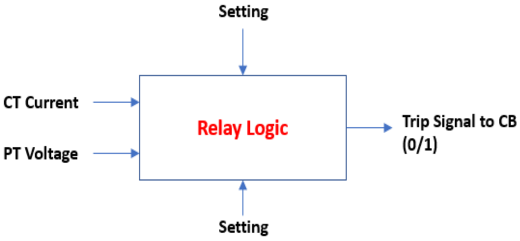


Fig. 1. Conceptual relay diagram

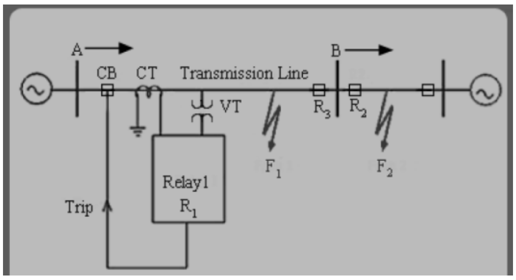


Fig. 2. Typical relaying system

II. Desirable Performance Characteristics of Protection Schemes

Designed protection schemes must have some essential performance features. They are mentioned below [3]:

A. Selectivity

This feature requires that a protection system should disconnect only the faulted portion of power system. In other words, relays should not operate for the faults for which they are not intended to operate.

B. Dependability

This is defined as the ability of protective relay to detect and disconnect all faults within the protection zone. For instance, if a relay “R” is designed to protect 70% of a transmission line, it should accurately trip for any fault within its zone.

C. Security

It is the ability of the relay to reject all power system events and transients which are not part of fault. This prevents healthy part of the system to disconnect needlessly. Dependability and security are often collectively known as ‘reliability’ of protection system.

D. Sensitivity

Sensitivity means that the relays that are intended to operate for a given fault condition have a stronger inclination to operate for that condition than other (typically remote) relays. This feature allows that, no matter what the magnitude of the fault current is, or the fault location on the protected power system element, the intended relays will “see” the fault more strongly.

E. Speed

The protection system should remove the fault in the minimum possible time. If planned time delays are required, they should be accurate. For instance, in a distance protection scheme, if Zone 2 is set to operate after 5 cycles, it should do so accurately.

F. Cost

The protection system should provide maximum security at minimum expense. The components used should not be redundant.

III. Factors Affecting Protection System

Some factors which may impact the design of protection system are elaborated below [3].

A. Economics

Faults and disturbances are comparatively uncommon; therefore, it can be easily concluded that there is no need to make expense on protection issue because there have not been any protection related issues. The Protection Engineer hopes that there will be no need to operate protection, and everything will run smooth but when problems does happen, protection is essential for maintaining the life and quality of the system.

B. Personality

Type, location, and timing of a fault or non-permittable condition in the power system is random. The number of likelihoods is immeasurable. Accordingly, the Protection Engineer must plan and design the protection system for the actions with maximum likelihood, based on history of faults, expected probabilities that seem most probable to happen, and the suggestions of equipment manufacturer. This is what make protection a complex combination of art and science. As nature (or personality) of every Protection Engineer varies, so is the protection design criteria set by him or her changes and consequent actions and results are based on this behavior. Though there is a lot of technology and practices which are uniform for every fault case, protection systems still lack following standards. Therefore, protection replicates the personality of the Protection Engineers which makes the art and science of equipment protection quite fascinating.

C. Location of Input and Disconnecting Devices

Protection design is only applicable to places in the system where there is presence of circuit breakers, isolators, or alike devices to allow isolation of the faulted area and where CT and VT, when needed, are accessible to provide data regarding faults and disturbances in the power network. Effective collaboration amongst system operators, network planners and Protection Engineers is significant to enable ideal operating environment of the equipment in the power network.

D. Available Indicators of Fault

The faults or unwanted conditions must deviate from the normal operating conditions to observe a notable difference. Some “change” in some quantities is essential for the relay to operate. Typically, these quantities are current, voltage, impedance, and reactance. Any significant change in these will drastically help the relay in detecting abnormalities and hence they can be utilized for accurate working of protective relay. The critical factor in this selection and application of protection is first to find out what amounts of the quantities are available to differentiate between acceptable and unacceptable conditions. Then, a relay can be found or designed accordingly. If there is no substantial difference between acceptable and unacceptable conditions, protection of the system may be operating at its moderate condition at best, or it may not operate at all. For instance, consider a distribution system, where car accidents, falling trees, sandstorms, tornadoes, or snowstorms may cause a “live” line to be on the ground. This is completely unacceptable, but in this situation, it may be probable that the fault current can be quite less and all other system constraints such as voltage, power, and frequency, may remain within allowed limits. Therefore, in such scenarios, no “change” in the measurable quantities exist for any kind of relay to sense and isolate the unacceptable conditions.

IV. FAULT TYPES

There are two broad classes of faults: Shunt faults and Series Faults. Shunt faults include single line to ground (LG), line to line (LL), double line to ground (LLG) and three phase bolted faults (LLL). Open conductor faults and high impedance faults come under the heading of series faults. Commonly, two types of faults are studied in research literature: three phase symmetrical faults and single line to ground fault. Mostly papers have covered shunt faults [4]. Table I shows statistics of occurrence for shunt faults.

TABLE I. STATISTICS FOR VARIOUS FAULTS

Fault type	Occurrence probability (%)	Severity
LG	85	Least
LL	8	↓
LLG	5	
LLL	2	Most

Furthermore, the probability of faults on different elements of the power system also varies. The transmission and distributions lines which are subjected to harsh environmental conditions are most likely to be exposed to faults. Indoor equipment such as underground cables and power generators is least prone to be subjected to faults. The fault statistics regarding various power system elements are shown in Table II [4].

V. SOURCES OF FAULT

There are many sources of faults including natural events, physical accidents, equipment failure and mis operation [3-6]. They are shown in Fig. 3 (Appendix). As evident from Fig. 3, a lot of natural events are responsible for faults. They include but are not limited to Lighting, wind, snowstorms, explosions, falling trees and flying objects. Falling trees are a major cause of high impedance faults. Insulation failure and human error are also major culprits in causing system faults.

TABLE II. FAULT STATISTICS FOR VARIOUS ELEMENTS

Power System Element	Probability of Faults (%)
Overhead Lines	50
Underground Cables	9
Transformers	10
Generators	7
Switchgears	12
CT, PT, Relays etc.	12

VI. DESIGN OF PROTECTION SCHEME

In this paper, a distance protection scheme has been designed to protect the lines of a Medium Voltage (MV) distribution network. MV distribution network of 11 kV is modelled using DIgSILENT Power Factory software. Although there are many commercial softwares available for carrying out this design procedure, DIgSILENT is gaining popularity due to its efficient and user friendly features especially regarding power system protection and load flow analysis. The concept of zones is described in Fig. 4 [7].

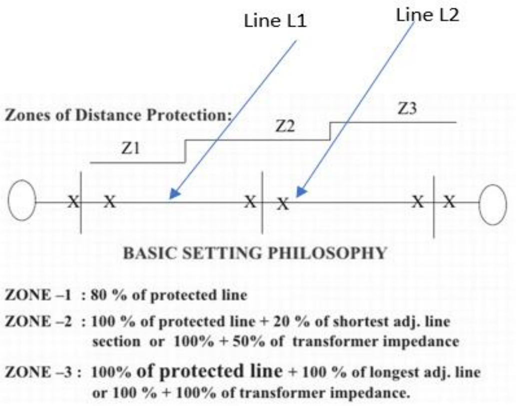


Fig. 4. Zones of distance protection

As evident from Fig. 4, Zone 1 cover 80% of the line to be protected. Let’s denote this line by, say, L1. L2 is the line adjacent to L1. Zone 2 covers 80% of the first line (L1) and 20% of the next line (L2). As we have no transformer in the designed scheme in this paper, so we will follow only the rules related to lines. Zone 3 cover L1 and L2 and about 40% of the third line L3. Although this number can be increased to 100% as shown in Fig. 4, but this entirely depends on our needs. In this paper, it is chosen to be at 40%.

Performance of distance relay is defined in terms of reach accuracy and operating time. Reach accuracy links the actual ohmic reach of the relay under realworld conditions with the relay setting value in ohms. Reach accuracy chiefly relies on the voltage value offered to the relay under faulty circumstances. The impedance measuring techniques employed in the designs of relay also have an influence. Operating times can change with change in fault current, change in the position of the fault comparative to the relay setting and the change in the point on the voltage wave at which the fault takes place. Contingent on the measuring techniques used in designing the relay, measurement of signal transient errors, for instance those errors reproduced by Coupling Capacitor Voltage Transformers or saturating CTs, can also unfavorably postpone relay operation for faults which are quite near to the reach point [8].

A few numerical relays measure the absolute impedance of the fault and based on this measurement; a decision is made whether operation is essential according to impedance limits defined on the R-X (Impedance) diagram. Distance numerical relays do not measure absolute impedance. Instead, they make a comparison between the measured value of fault voltage with an exact replica voltage derived from the fault current and the zone impedance setting to decide whether the fault is within zone or not. Distance relay impedance comparators are classified according to polar characteristics, the number of signal inputs, and the method through which signal comparisons are carried out. The most common types compare either the relative amplitude or phase of two input quantities to attain operating characteristics that are either straight lines, trapezoids or circles when plotted on an R-X diagram [8-10].

The model of the designed network is shown in Fig. 5 (Appendix). It has been built using DIgSILENT Power Factory [11]. As evident from Fig. 5, there are 5 buses in the distribution network. Each bus is operating at 11 kV. There is 1 MW inductive load (power factor 0.8) at Bus 3 and Bus 4. The length of each distribution lines is 5 Kilometers. The modelling of lines is done according to “Lumped Parameters” i.e., we are considering nominal-pi model of lines. Rated voltage of all line is 11 kV and rated current is 1 kA. Suppose we want to protect Line 1, Line 2 and 40% of Line 3. We will achieve this design with the help of distance relay installed at Bus 1 i.e., beginning of Line 1.

To begin the design process, we first carry out AC load flow analysis to confirm that all bus voltages and angles are within the required range and power flow solution (using Newton Raphson Method) converges. This is confirmed by Fig. 6 (Appendix). After successfully carrying out load flow, we turn our attention towards the major objective: performing short circuit analysis and designing the distance relaying scheme. There are several relay models in DIgSILENT Library, but this paper uses Schweizer SEL-321 to perform the required distance protection design. The time delay coordination between Zones 1, 2 and 3 have been set with the help of DIgSILENT software. Zone 2 has been set to delay Zone 1 by 10 cycles and Zone 3 has been set to delay zone 1 by 15 cycles for all types of faults (phase and ground). Although, these can be changed for each kind of fault, we have set it the same for simplicity and comparing results.

VII. SIMULATIONS

Although the designed scheme works for any kind of fault, the accuracy of design has been demonstrated for two faults: three phase fault and single line to ground fault. The reason is that three phase fault is the worst case in which there is maximum fault current and single line to ground is the most probable fault. Hence, both extremes have been considered.

Case 1: Three Phase Fault midway between Bus 1 and Bus 2

In the first case, a three-phase bolted fault (i.e., solid three phase fault with no fault impedance) occurs exactly between Line 1 and Line 2 (i.e., at 50% distance from Bus 1 and Bus 2). Appendix (Fig. 7) shows the settings needed for placing a fault on the system. International Electrotechnical Commission (IEC) 60909 method has been employed for calculation of fault currents, although other methods may be used which may give slightly different results. The resulting Impedance Diagram (or more commonly known as R-X Diagram) is shown in Fig. 8. The three concentric circles represent the three zone of protections: Outer circle being Zone 3 and inner one being Zone 1. The center one represents Zone 2. The R-X diagram also clearly show the fault is within Zone 1.

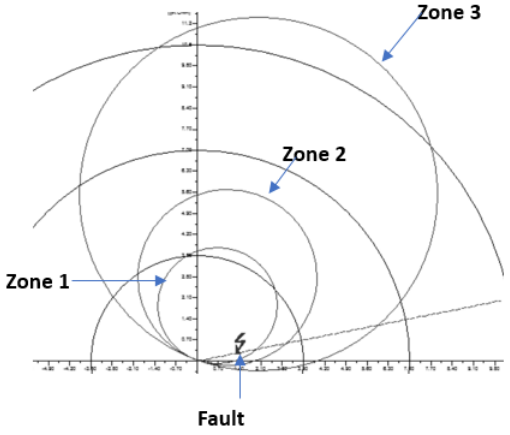
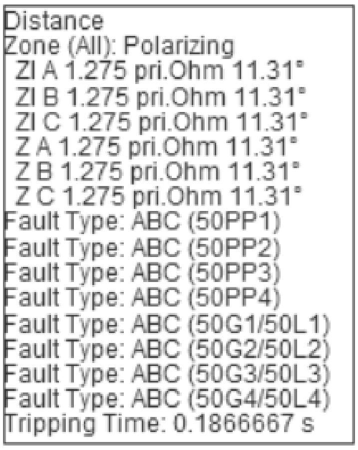


Fig. 8. R-X diagram

Fig. 9 (Appendix) shows the time distance diagram. It is evident that Zone 2 operated after Zone 1 and Zone 3 after Zone 2. The software also shows us the tripping time for this fault. Fig. 10 shows that in this case, the relay trips at 0.1866 seconds after the occurrence of fault. It also indicates fault type is ABC i.e., three phase fault as we simulated. 50PP represent relay settings for “phase faults” and 50G/50L represent relay settings for “ground faults”. These settings have been shown in Fig. 11-12 (Appendix).



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Distance
Zone (All): Polarizing
  ZI A 1.275 pri.Ohm 11.31°
  ZI B 1.275 pri.Ohm 11.31°
  ZI C 1.275 pri.Ohm 11.31°
  Z A 1.275 pri.Ohm 11.31°
  Z B 1.275 pri.Ohm 11.31°
  Z C 1.275 pri.Ohm 11.31°
Fault Type: ABC (50PP1)
Fault Type: ABC (50PP2)
Fault Type: ABC (50PP3)
Fault Type: ABC (50PP4)
Fault Type: ABC (50G1/50L1)
Fault Type: ABC (50G2/50L2)
Fault Type: ABC (50G3/50L3)
Fault Type: ABC (50G4/50L4)
Tripping Time: 0.1866667 s
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Fig. 10. Tripping time

Case 2: Three Phase Fault at Bus 4

In the second case, three phase fault is placed at Bus 4 (outside of Zone 3). The R-X Diagram is shown in Fig. 13.

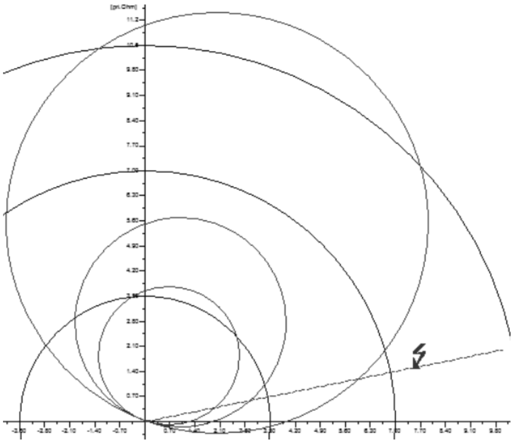
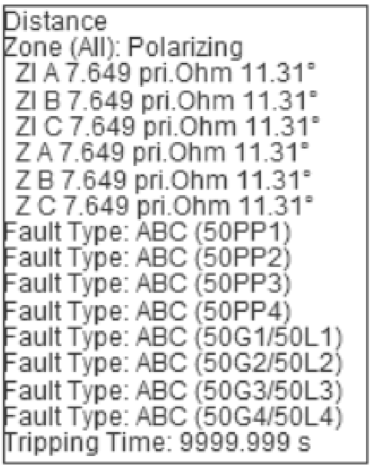


Fig. 13. R-X diagram

As expected, the relay will not trip as the fault is out of the protection zone. Hence, the software displays the tripping time as “9999.999s” (Fig. 14) which indicates it will not trip.



```
Distance
Zone (All): Polarizing
  ZI A 7.649 pri.Ohm 11.31°
  ZI B 7.649 pri.Ohm 11.31°
  ZI C 7.649 pri.Ohm 11.31°
  Z A 7.649 pri.Ohm 11.31°
  Z B 7.649 pri.Ohm 11.31°
  Z C 7.649 pri.Ohm 11.31°
Fault Type: ABC (50PP1)
Fault Type: ABC (50PP2)
Fault Type: ABC (50PP3)
Fault Type: ABC (50PP4)
Fault Type: ABC (50G1/50L1)
Fault Type: ABC (50G2/50L2)
Fault Type: ABC (50G3/50L3)
Fault Type: ABC (50G4/50L4)
Tripping Time: 9999.999 s
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Fig. 14. Tripping time

Case 3: LG Fault between Bus 2 and Bus 3

Now we put a single line to ground fault between Bus 2 and Bus 3. The resulting R-X diagram is shown in Fig. 15. We observe that fault is shown in two different places on the diagram it involves both phase and ground and DIgSILENT treats each of them separately as the settings of relay for each fault (phase and ground) have been performed individually.

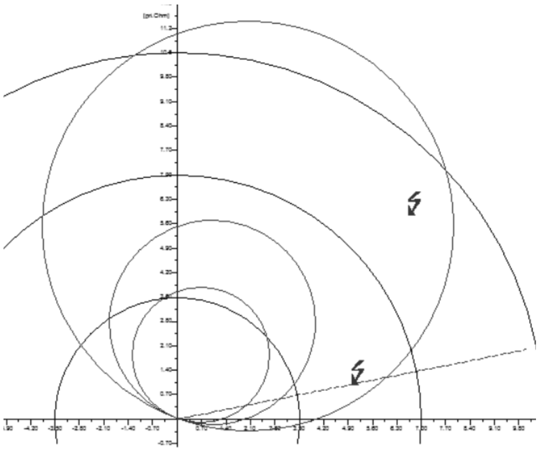
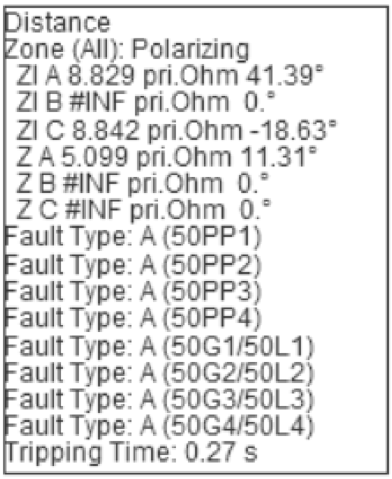


Fig. 15. R-X diagram

The tripping time as shown by Fig. 16 is 0.27s (about 13 cycles) The delay is since fault is much farther away from the previous case and hence, it takes a longer time to clear. Moreover, it is between Zone 2 and Zone 3, hence there is delay in fault clearing according to the settings we did.



```
Distance
Zone (All): Polarizing
  ZI A 8.829 pri.Ohm 41.39°
  ZI B #INF pri.Ohm  0.°
  ZI C 8.842 pri.Ohm -18.63°
  Z A 5.099 pri.Ohm 11.31°
  Z B #INF pri.Ohm  0.°
  Z C #INF pri.Ohm  0.°
Fault Type: A (50PP1)
Fault Type: A (50PP2)
Fault Type: A (50PP3)
Fault Type: A (50PP4)
Fault Type: A (50G1/50L1)
Fault Type: A (50G2/50L2)
Fault Type: A (50G3/50L3)
Fault Type: A (50G4/50L4)
Tripping Time: 0.27 s
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Fig. 16. Tripping time

Case 4: LG Fault at Bus 4

In the last case, a single line to ground fault is placed outside Zone 3 (i.e., at Bus 4). As expected, the relay does not trip (Fig. 17) as confirmed by the tripping time (Fig. 18).

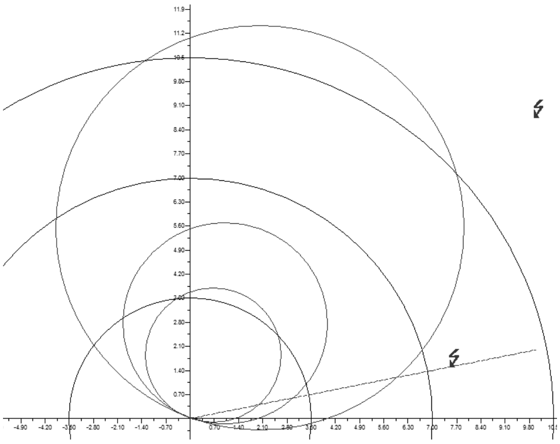


Fig. 17. R-X diagram

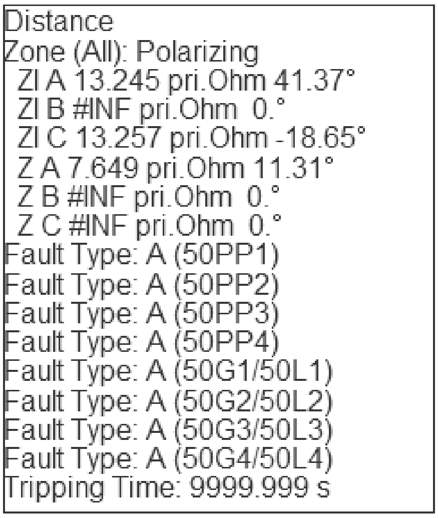

Distance
Zone (All): Polarizing
ZI A 13.245 pri.Ohm 41.37°
ZI B #INF pri.Ohm 0.°
ZI C 13.257 pri.Ohm -18.65°
Z A 7.649 pri.Ohm 11.31°
Z B #INF pri.Ohm 0.°
Z C #INF pri.Ohm 0.°
Fault Type: A (50PP1)
Fault Type: A (50PP2)
Fault Type: A (50PP3)
Fault Type: A (50PP4)
Fault Type: A (50G1/50L1)
Fault Type: A (50G2/50L2)
Fault Type: A (50G3/50L3)
Fault Type: A (50G4/50L4)
Tripping Time: 9999.999 s

Fig. 18. Tripping time

VIII. RESULTS AND DISCUSSION

As evident from the above-mentioned simulations, it can be conclusively said the designed distance protection scheme works accurately. If there is any kind of fault that lies in the zones of protection, the relay will trip, and fault will not propagate on the system. If the fault is outside the zone of protection, relay will not trip. This is confirmed by time-distance diagram as well as impedance (R-X) diagram.

Moreover, further the fault from the relay, the greater the time to clear it. The time delay settings of zones have also been verified through simulations. The summary of distance relay timings and impedance values (primary and secondary) for both phase and ground faults are shown in Table III (Appendix).

This study provided simulation results for distance protection for a MV radial distribution system. This can be a remarkable starting point for researchers in the domain of power system short circuit evaluation. Recent research [12-23] strongly indicates that there is a lot of potential work which needs to be explored in this crucial domain, especially in regard to distance protection of distribution networks with distributed generation (DG).

IX. CONCLUSION AND FUTURE WORK

The paper discussed the design of distance protection scheme applied to a MV distribution network using DIgSILENT Power Factory Software. The results obtain validate the accurate design of the scheme. Whenever there is fault within the relay zone of protection, the relay trips. If the fault is out of the zone, it does not trip. As a future research work, distance schemes can be designed for meshed distribution networks as opposed to the conventional radial topology and effect of infeed from other generation sources such as induction or synchronous generators can be considered.

REFERENCES

[1] Lecture notes on power system protection. [Online]. http://nptel.ac.in/downloads/108101039/

[2] M.V. Andreev and A. S. Gusev, “Simulations of differential protections of transformers in power systems,” *13th International Conference on Developments in Power System Protection*, 2016, pp. 1-14.

[3] L. Blackburn, Protective Relaying Principles and Applications, Boca Raton, FL: CRC Press, 3rd Edition, 2007. ISBN: 9781420017847.

[4] Classification of faults. [Online]. http://yourelectrichome.blogspot.com/2011/09/classificafion-of-shunf-faults.html

[5] M.A. Ohrstrom, “Fast fault detection for power distribution systems,” Licentiate Thesis, Royal Institute of Technology (KTH), Stockholm, 2003.

[6] T. -C. Peng, D. Tzelepis, A. Dysko, and I. Glesk, “Assessment of fault location techniques in voltage source converter based HVDC systems,” *IEEE Texas Power and Energy Conference (TPEC)*, 2017, pp. 1-6.

[7] A mini project on transmission line protection. [Online]. https://www.slideshare.net/moiz89/protection-of-transmission-linesdistance-relay-protection-scheme

[8] Principles and characteristics of distance protection. [Online]. http://electrical-engineering-portal.com/principles-characteristics-distance-protection

[9] G. Song, “Protection performance of traditional distance relays under wind power integration,” *13th International Conference on Developments in Power System Protection*, 2016, pp. 1-6.

[10] S. H. Horowitz and A.G. Phadke, Power System Relaying, 4th Edition, 2014, Wiley.

[11] DIgSILENT PowerFactory User Manual, DIgSILENT GmbH, 2018. [Online]. Available: https://www.digsilent.de/en/downloads.html

[12] W. -H. Kim, J. -Y. Kim, W. -K. Chae, G. Kim and C. -K. Lee, “LSTM-based fault direction estimation and protection coordination for networked distribution system,” *IEEE Access*, vol. 10, pp. 40348-40357, 2022.

[13] M. M. Keramat and M. Hosein Fazaeli, “The new adaptive protection method for the compensated transmission lines with the series capacitor in a high share of wind energy resources by using PMU data,” *7th Iran Wind Energy Conference (IWEC2021)*, 2021, pp. 1-6.

[14] H. Ebrahimi, A. Yazdaninejadi, S. Golshannavaz and S. Teimourzadeh, “An ENS-Oriented voltage protection scheme for inverter-based generators in active distribution networks,” *IEEE Transactions on Smart Grid*, vol. 13, no. 4, pp. 2639-2649, Jul. 2022.

[15] S. M. Saad et al., “An improved overcurrent-distance coordination strategy to minimize cascaded tripping problem in protection of distribution systems: a case study for the Libyan distribution system,” *IEEE 1st International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering*, 2021, pp. 554-558.

[16] K. Pandakov and H. K. Hoidalen, "Distance protection with fault impedance compensation for distribution network with DG," *IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2017, pp. 1-6.

[17] V. Telukunta, J. Pradhan, A. Agrawal, M. Singh, and S. G. Srivani, "Protection challenges under bulk penetration of renewable energy resources in power systems: A review," *CSEE Journal of Power and Energy Systems*, vol. 3, no. 4, pp. 365-379, Dec. 2017.

[18] C. Lal, S. Sarangi, S. R. Mohanty, and A. K. Singh, "ANN based adaptive mho distance protection in distribution network with distributed generations," *IEEE 7th Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON)*, 2020, pp. 1-6.

[19] A. M. Tsimtsios and V. C. Nikolaidis, "Setting zero-sequence compensation factor in distance relays protecting distribution systems," *IEEE Transactions on Power Delivery*, vol. 33, no. 3, pp. 1236-1246, Jun. 2018.

[20] D. Todorov and B. Gilev, "Fault section estimation in electric power distribution system with Elman neural network," *20th International Symposium on Electrical Apparatus and Technologies (SIELA)*, 2018, pp. 1-4.

[21] U. Shahzad, "Transient stability risk assessment framework incorporating circuit breaker failure and severe weather," *Australian Journal of Electrical and Electronics Engineering*, vol. 19, no. 2, pp. 137-148, 2022.

[22] U. Shahzad, "A review of challenges for security-constrained transmission expansion planning," *Journal of Electrical Engineering, Electronics, Control and Computer Science*, vol. 7, no. 2, pp. 21-30, 2021.

[23] U. Shahzad and S. Asgarpoor, "A comprehensive review of protection schemes for distributed generation," *Energy and Power Engineering*, vol. 9, no. 8, pp. 430–463, 2017.

APPENDIX

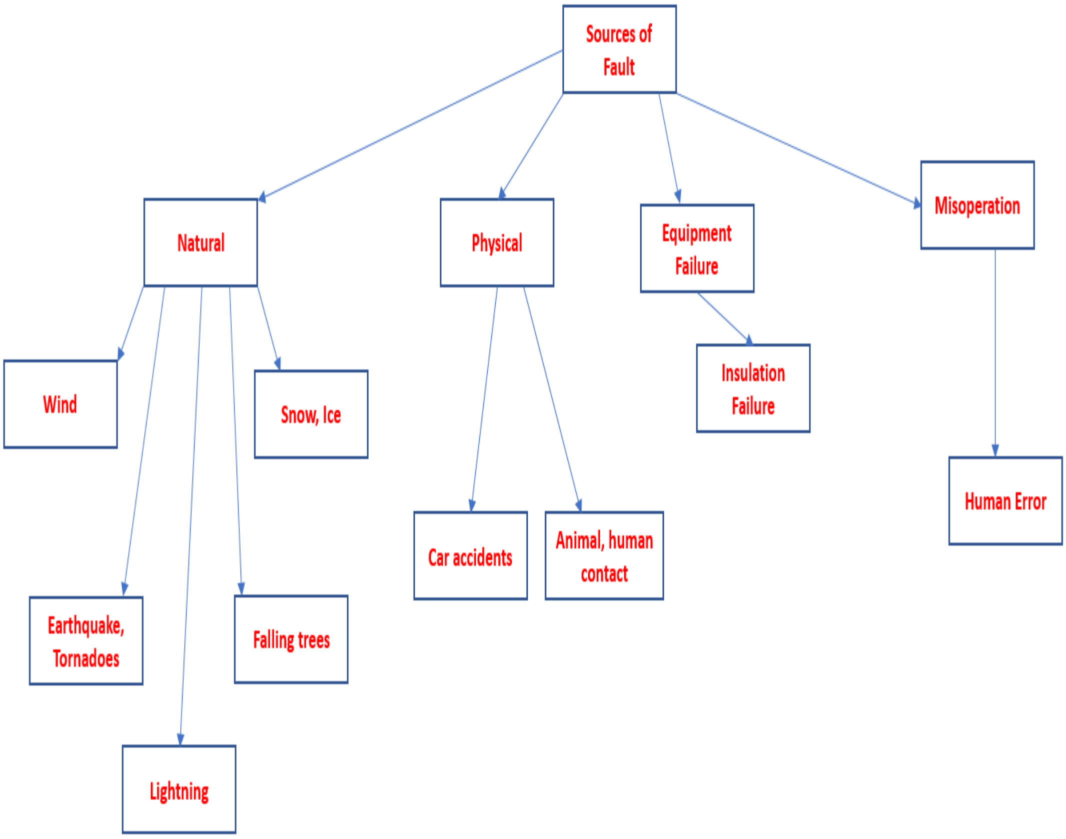


Fig. 3. Major sources of fault

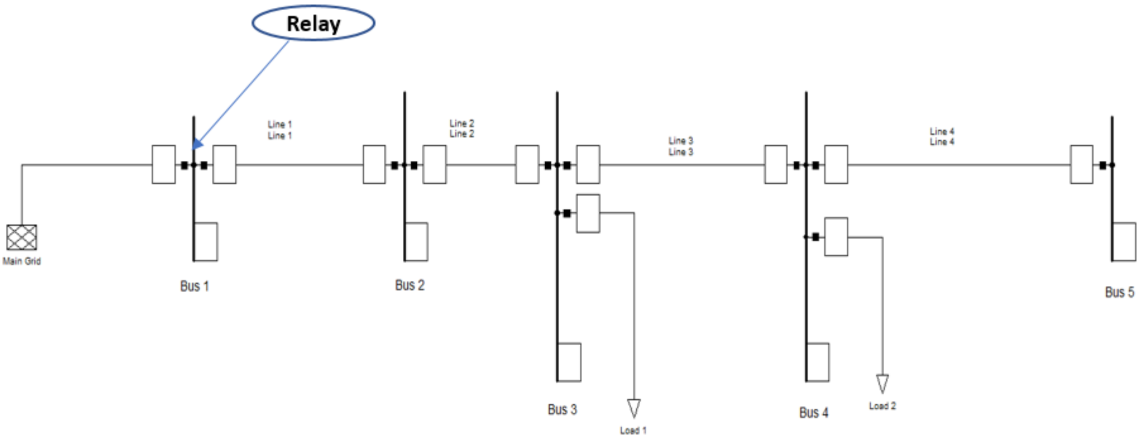


Fig. 5. Medium Voltage (11kV) power distribution network simulated on DIgSILENT

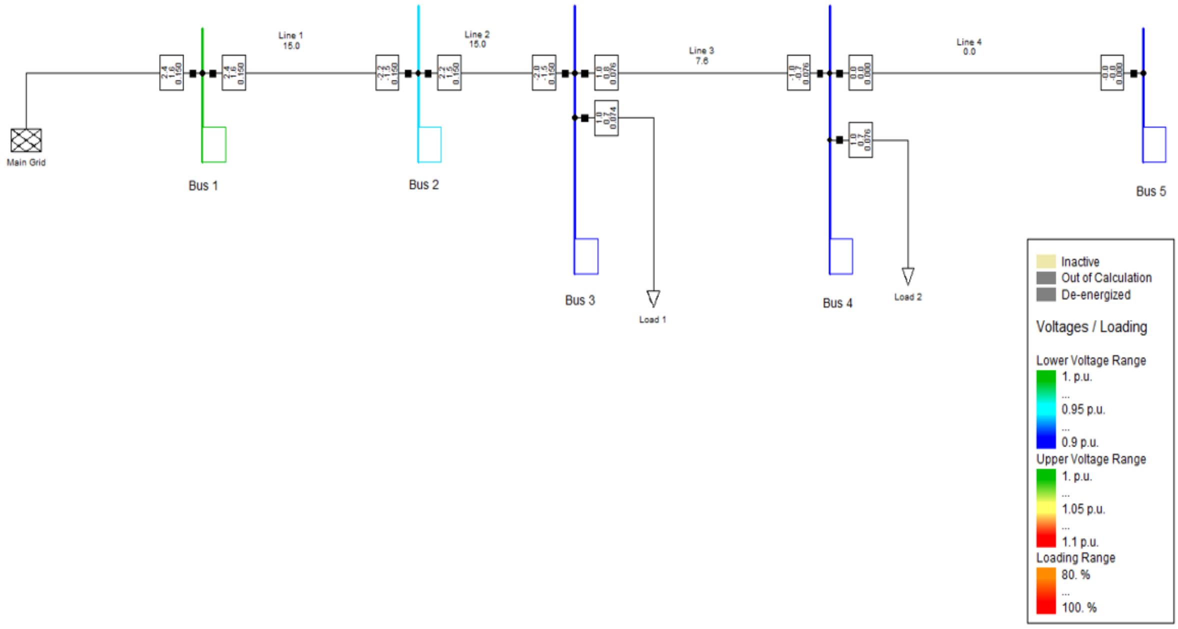
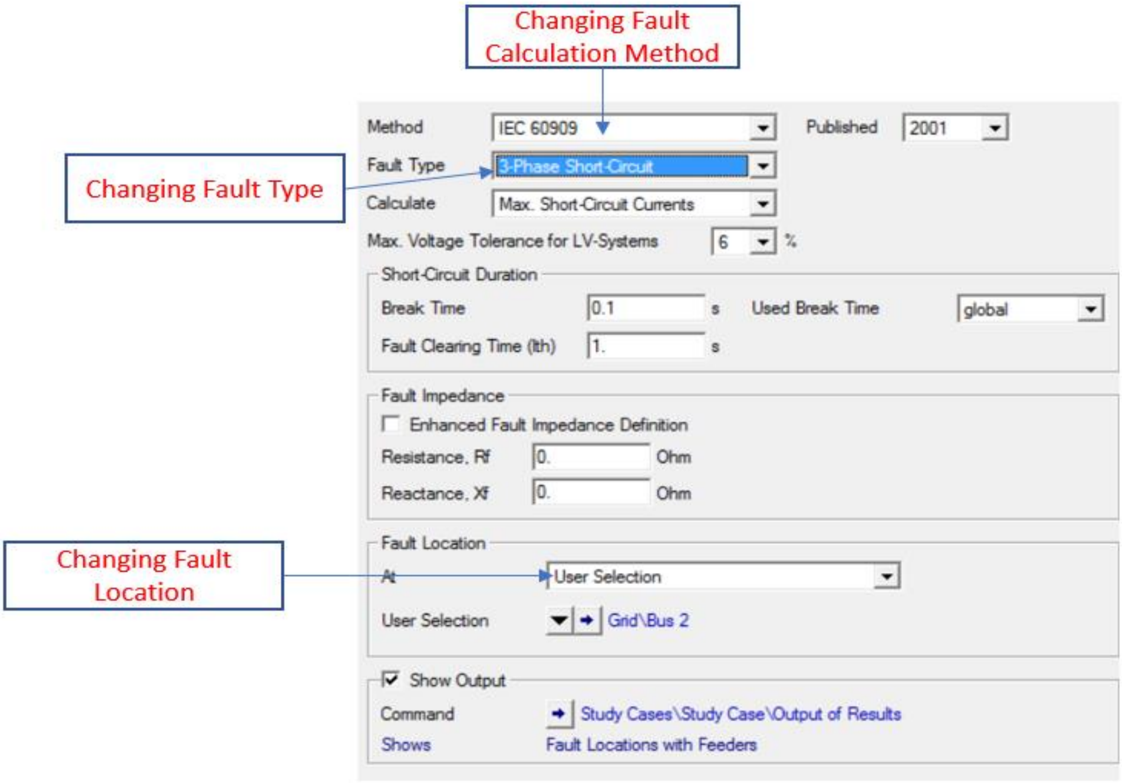


Fig. 6. Load flow analysis



Method: IEC 60909
Published: 2001
Fault Type: 3-Phase Short-Circuit
Calculate: Max. Short-Circuit Currents
Max. Voltage Tolerance for LV-Systems: 6 %

Short-Circuit Duration
Break Time: 0.1 s
Used Break Time: global
Fault Clearing Time (Ith): 1. s

Fault Impedance
☐ Enhanced Fault Impedance Definition
Resistance, Rf: 0. Ohm
Reactance, Xf: 0. Ohm

Fault Location
At: User Selection
User Selection: Grid\Bus 2

☑ Show Output
Command: Study Cases\Study Case\Output of Results
Shows: Fault Locations with Feeders

Fig. 7. Performing fault analysis

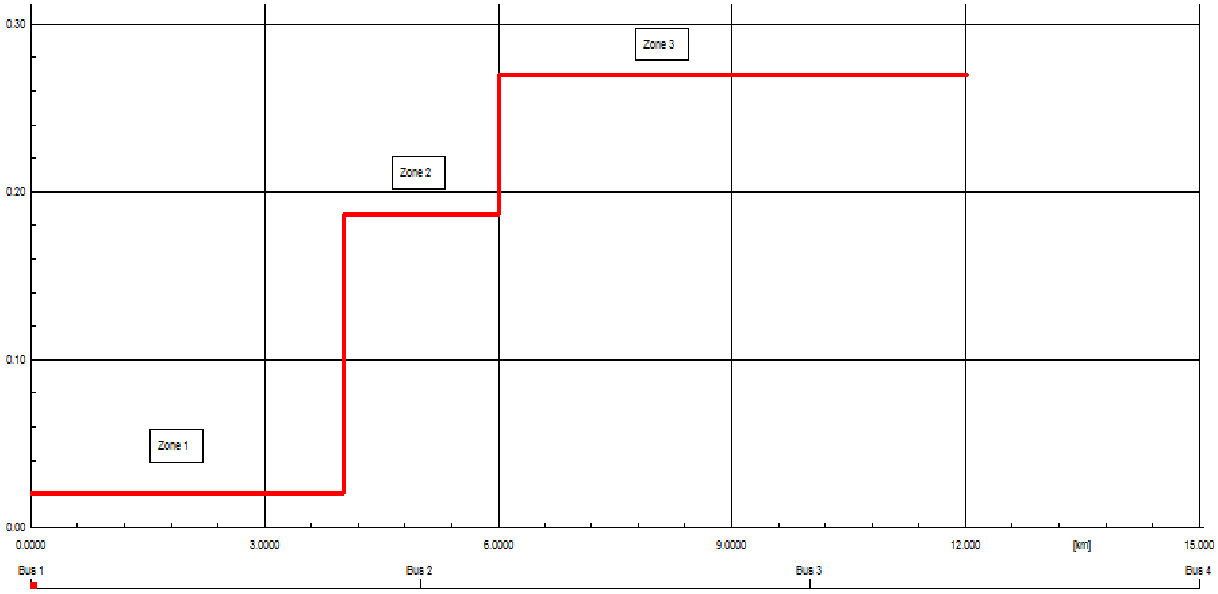
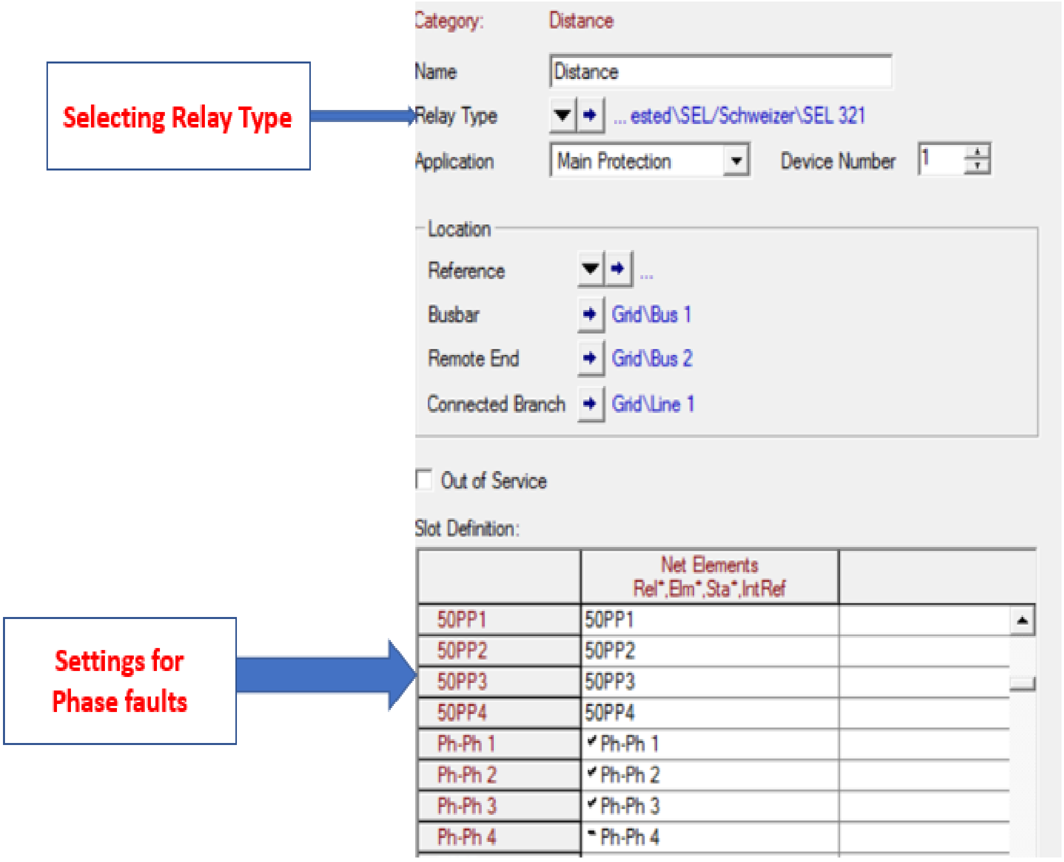


Fig. 9. Time distance diagram



Category: Distance

Name: Distance

Relay Type: ... ested\SEL/Schweizer\SEL 321

Application: Main Protection

Device Number: 1

Location

Reference: ...

Busbar: Grid\Bus 1

Remote End: Grid\Bus 2

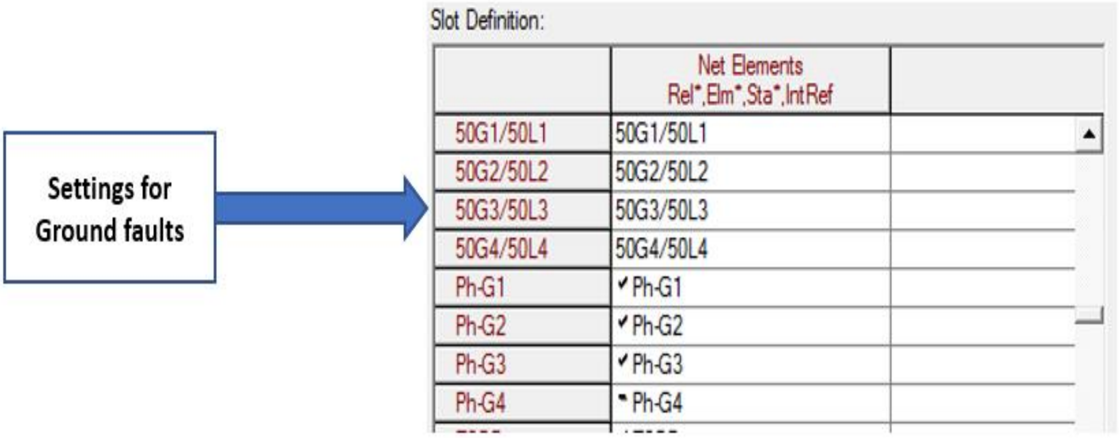
Connected Branch: Grid\Line 1

☐ Out of Service

Slot Definition:

	Net Elements Rel*,Elm*,Sta*,IntRef	
50PP1	50PP1	
50PP2	50PP2	
50PP3	50PP3	
50PP4	50PP4	
Ph-Ph 1	✓ Ph-Ph 1	
Ph-Ph 2	✓ Ph-Ph 2	
Ph-Ph 3	✓ Ph-Ph 3	
Ph-Ph 4	- Ph-Ph 4	

Fig. 11. Relay settings for phase faults



Slot Definition:

	Net Elements Rel*,Elm*,Sta*,IntRef	
50G1/50L1	50G1/50L1	
50G2/50L2	50G2/50L2	
50G3/50L3	50G3/50L3	
50G4/50L4	50G4/50L4	
Ph-G1	✓Ph-G1	
Ph-G2	✓Ph-G2	
Ph-G3	✓Ph-G3	
Ph-G4	▪Ph-G4	

Fig. 12. Relay settings for ground faults

TABLE III. RELAY IMPEDANCE VALUES AND TIME SETTINGS

	Protection Device	Location	Branch	Manufacturer	Model	Stage (Phase)	Impedance [pri. Ohm]	Impedance [sec. Ohm]	Angle [deg]	Time	Directional	Stage (Earth)	Impedance [pri. Ohm]	Impedance Z [sec. Ohm]	Angle [deg]	Time	Directional
1	Distance	Bus 1	Line 1		SEL 321	Ph-Ph 1	3.930	3.573	70.00	0.00	Forward	Ph-G1	3.930	3.573	70.00	0.00	Forward
						Ph-Ph 2	5.900	5.364	70.00	0.17	Forward	Ph-G2	5.900	5.364	70.00	0.17	Forward
						Ph-Ph 3	11.800	10.727	70.00	0.25	Forward	Ph-G3	11.800	10.727	70.00	0.25	Forward