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Fault Detection and Protection Methodologies for High Voltage AC Transmission Lines

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Abstract

For electrical power transmission system, a high voltage protection scheme provides prevention against the hazards in the form of lightning, ferranti effect, and power fluctuations. When these conditions occur, the power system can experience an over voltage which may be two to three times greater than its rated value. During these kinds of abnormal conditions, protective relays play a crucial role in protecting the system. In this work, the authors have analyzed the performance of four different relays (overcurrent, over/under voltage, distance, and differential relays). Analyses are based on the operating time under different faults occurring on 80-250 km long 400 kV high voltage AC transmission lines. MATLAB has been used to model and analyze the system for identifying different types of faults in a transmission line. The main objective of this work is to compare the operating times of the most important four relays under conditions of single line to ground fault (LG), three phase fault (LLLG) and double phase to ground fault (LLG). In this situation, the system outputs are observed under normal, fault, and no-fault conditions, and the response time is calculated to turn on a circuit breaker. It is envisioned that this work will be one-stop source of guidance for protection engineers to select proper relays for the newly installed power systems.

Key Words: transmission lines, over and under voltage relay, differential relay, faults; protection

1. Introduction

For efficient transmission of electric supply from generation site to the consumer, all major and minor components of power system play very important role. However, among all these components, most important and sensitive is fault protective relay. Faults can be of many types like phase-to-phase fault, two phase-to-ground fault, and three phase faults. However, the most common type is single line to ground fault [1]. All these faults result in the disturbance of power supply to the consumer and lead to the inconvenience. These faults in power system could cause economic losses. Economic losses could be due to either damage of power system or short fall of electricity at consumer's side. It is important to protect the HV transmission lines when fault is occurred

The most common types of fault occurring in a power system are categorized as [2]:

- Single line to ground fault (LG).
- Three phase fault (LLLG).
- Double line to ground fault (LLG).

The values of current and voltage can be used to locate the presence of an error/ fault in the system in small transmission lines. While for the long transmission lines, distance relays are optimal option for their protection [3].

Different types of relays have been designed to protect the power system from different faults which have various specific operating phenomena. Many relays have been tested for fault detection performance using different methods in past. Transmission lines were tested using different methodologies like an ANN based relay which is specifically designed for faults identification of 400kVAC transmission line. This technique is based on ANN software and elaborates the impedance relay protection in lines. Furthermore, a lot of work has been done on digital differential relays to show its performance and efficiency over the conventional differential relay, concluding that performance and operating time of digital differential relay is better than the conventional differential relay. However, the algorithm and structure of modern digital differential relays are complex than the conventional relays [4]. Numerical overcurrent relay is tested in operational prospective using MATLAB/ Simulink model for the discrete current input values [5]. Distance relay (normally called as Impedance relay) can be designed on MATLAB/Simulink model [6, 7]. If third harmonic affects the relay voltage limit then relay trips [8]. Furthermore, the over and under voltage relays are tested for the transmission line protection [9]. This analysis has been done by choosing a single relay model for specific fault conditions in transmission line. Differential relay is used to measure the current and/or voltage value at feeding and load end to determine the difference between any of two quantities. It works on the principle that the values of current and voltage at the feeding end must be equal to the values at the load end. If these values are not equal then the relay will trip [10]. Distance/Impedance relay works on the principle of impedance, where relay is inserted, and the fault occurs. Impedance is measured by pointing the current and voltage as the fundamental quantities (Z=V×I). If the values of any of current and/or voltage are deviated from their nominal rated values, then the value of the impedance will be changed, and the relay will get the signal to trip. While over-current relay is used for current fault detection when current rises from a specific value. Over-current relay is an adjusted value relay in which a plug value is set as threshold. Plug value is a rated value for over-current relay operation if the value of the system exceeds from the plugged value, then the relay will trip. Over and under voltage relay operates on the principle of specific voltage value detection. When the value of voltage goes above or below the rated value, the over and under voltage relay instantly trips.

In a power system, the protection is done either on the generating side which includes the grid station or at the transmission side which includes the protection of the generator system, transformer, and transmission lines etc. The protection is done by keeping the voltage and current values between a bearable range during power (P=V x I) transfer for maintaining a voltage or current level in the transmission system. In case of faults, a large amount of current will start to flow in power lines [11]. For the protection of such scenario, over-current protection relay is inserted which will detect the fault and initiate the circuit breaker (CB) operation of cutting off the passage of current flow into the circuit. In case of voltage fault, under/ over voltage relays are used [12].

This research is carried out to satisfy the curiosity that which relay has the shortest operating time under same fault conditions in a high voltage power system. The considered relay types for this study are differential relay, distance/impedance relay, overcurrent relay, and under and over voltage relay. MATLAB Simulink models for the mentioned relay types are designed to check their operation in three-phase (LLLG), double line to ground (LLG), and single line to ground (LG) fault conditions in transmission lines and their operating time values are measured. A comparative analysis is also carried out based on their measured operating time to conclude that which relay type is the best for high voltage transmission lines.

2. Methodology

The single line diagram of system under consideration is shown in Fig.1. Protection models are designed using four different relay types to achieve the aimed objective. The designed models are described as:

- Protection model using differential relay
- Protection model using distance/ impedance relay
- Protection model using over and under voltage relay
- Protection model using over-current relay

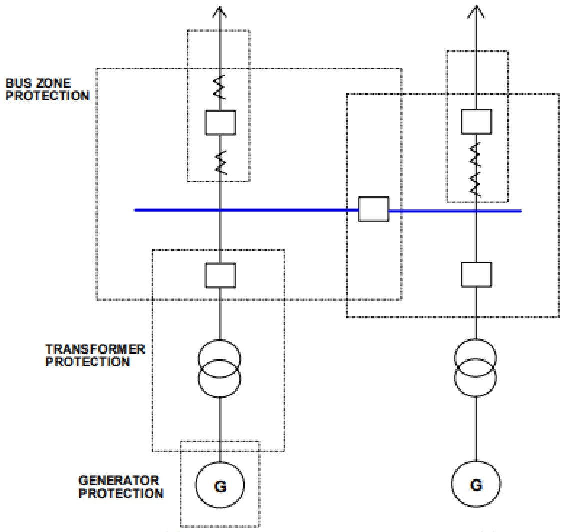

Fig. 1: Single line diagram of whole system

2.1 Protection model using differential relay

Using the differential relay scheme, transmission protection model of single-line diagram is designed with its certain characteristic value.

MATLAB Simulink model is designed to explain the working of differential relay at the fault conditions in [13]. In transmission pi line model, three faults have been introduced in the zone of transmission line, generated faults are LLLG, LLG and LG faults. To determine the fault occurring and the circuit breaker (CB) operating time, the results are obtained from the scope in the form of waves. The MATLAB Simulink model is designed to check the desired fault conditions and CB operating time in the transmission line as shown in Fig.2.

2.2 Protection model using distance/ impedance relay

Single line diagram of distance/ impedance relay is shown in Fig.3. The distance relay is tested for pre-fault conditions and after fault have been generated in the transmission line.

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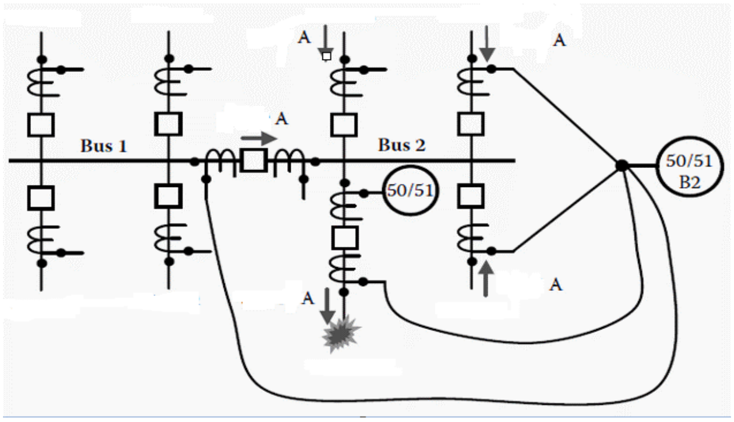


Fig. 2: Single-line diagram of differential relay-based transmission protection model

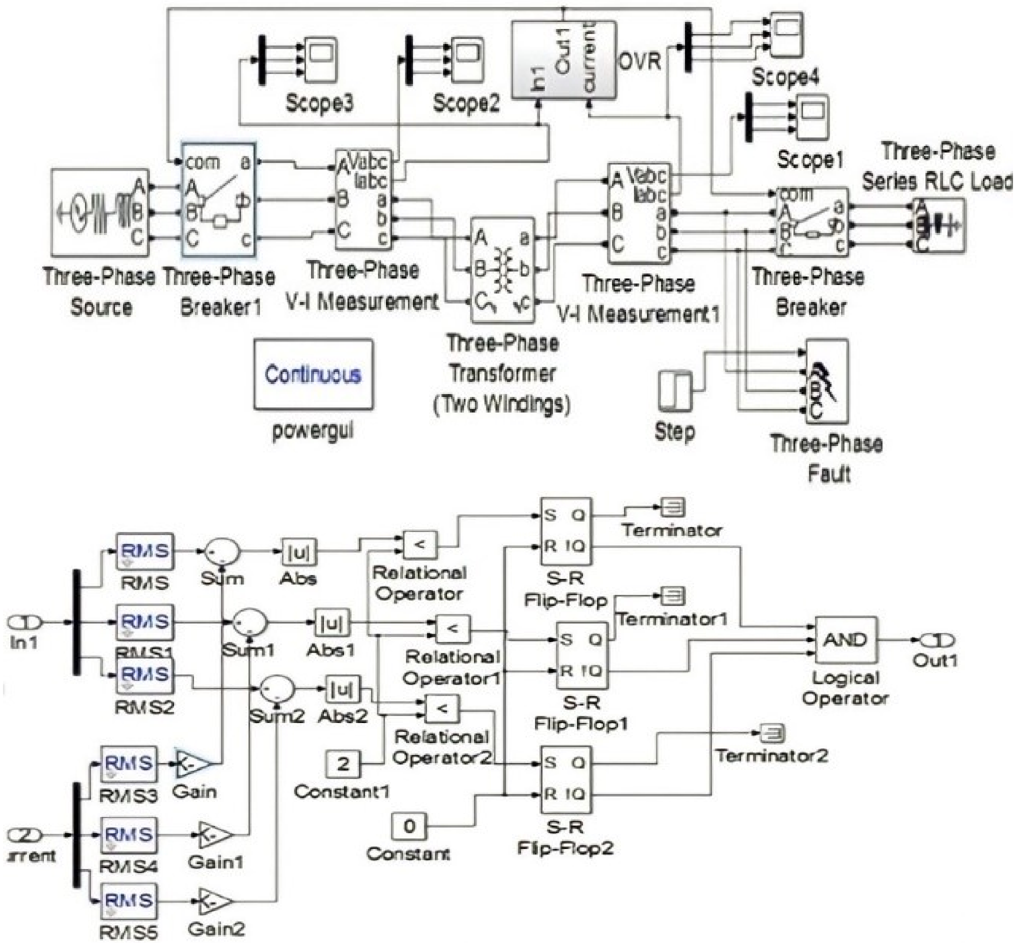


Fig. 3: MATLAB Simulink based Transmission line model for differential relay

2.2.1 Characteristics of conventional distance relay

There are following characteristics of conventional distance relay

- Distance relays that emulate traditional relay's impedance, do not measure absolute impedance.
- The fault level is determined based on the difference between the measured fault voltage and replica voltage derived from the fault current and the zone impedance setting.

Distance relay impedance comparators are classified according to the polar characteristics they have, how many inputs they have, and how they compare signals.

2.2.2 Characteristics of modern distance relay

Following are characteristics of modern distance relay:

- Starting relays, sometimes called fault detectors, have the main function of controlling the relay timing, allowing the measurement relay to extend its reach into zone two and zone three.
- In a distance scheme, tripping relays, zone timers, starting relays, and impedance measuring units are included.
- Any network needs a range of schemes to meet its economic and technical requirements.
- Low voltage, medium voltage, and high voltage systems may be classified into three main groups based on the protection schemes employed to meet their protection requirements.

Conventional distance relay has been used instead of modern distance relay as the existing one is the conventional system.

The transmission line model of distance/ impedance relay is designed on the MATLAB Simulink as shown in Fig.4. When the fault is occurred, relay generates signal to operate circuit breaker and protect the circuit against fault. Conventional distance relay has been replaced with the modern digital relay which works faster than the conventional distance relay. The MATLAB Simulink models have been designed to study the behavior of relay when the fault occurs in the circuit [7, 14].

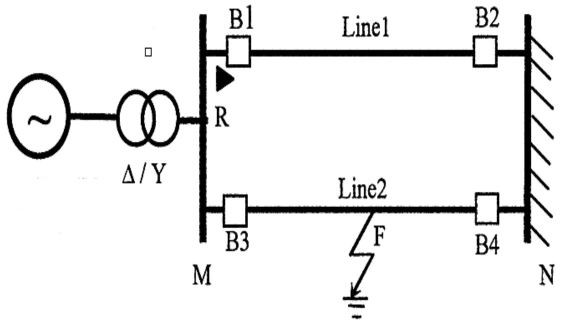
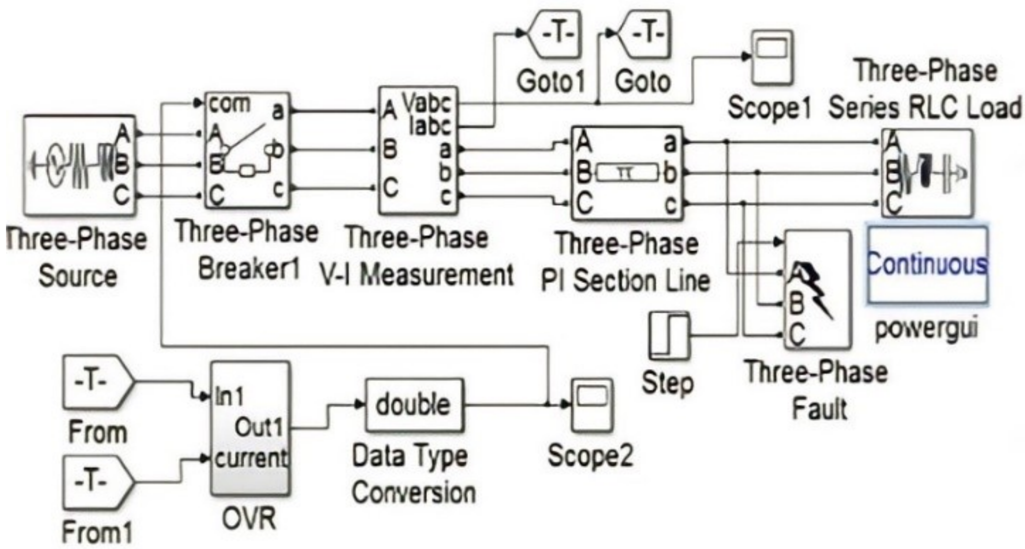


Fig. 4: Single line diagram of conventional distance/ impedance relay-based transmission protection model



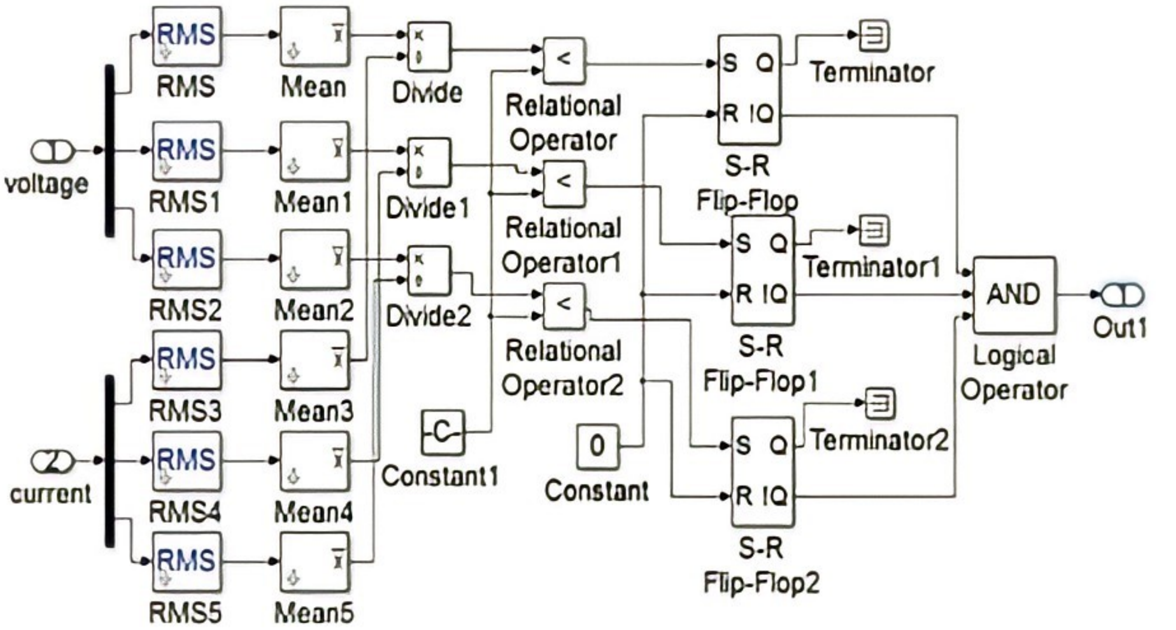


Fig. 5: MATLAB Simulink based transmission line model for distance/ impedance relay

2.3 Protection model using over and under voltage relay

Single-line diagram of under and over voltage relay is shown below in Fig.5, and MATLAB Simulink based designed transmission line model for under and over voltage relay is shown in Fig.6.

In the case of over and under voltage relay, MATLAB/ Simulink models have been designed which are given a rational operator for both over and under value conditions and checked alternatively [7, 8, 15-17]. The designed model is inserted in power transmission line for the protection purpose to check its operation.

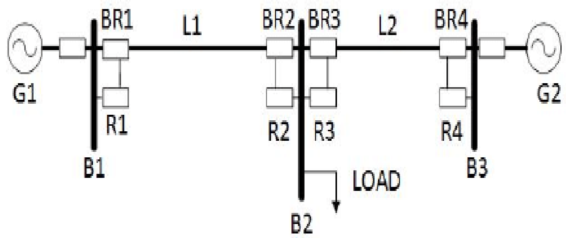
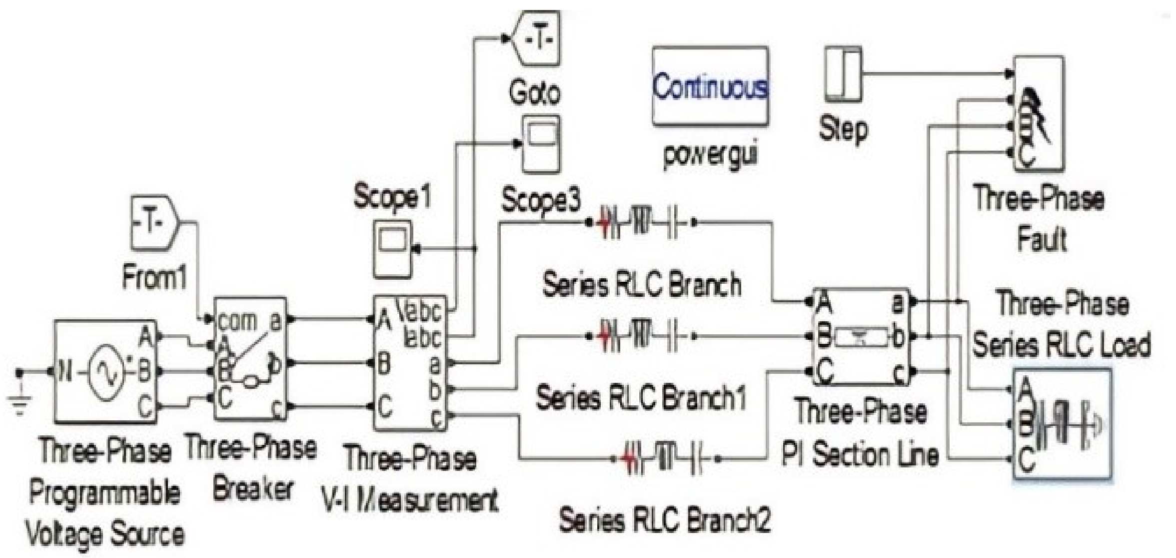


Fig. 6: Single-line diagram of over and under voltage relay-based transmission protection model



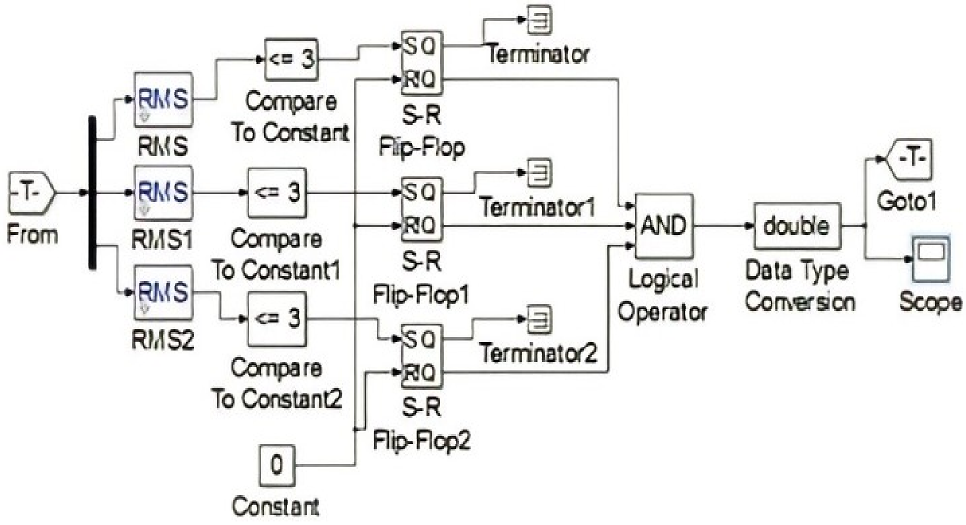


Fig. 7: Over and under-voltage relay-based transmission protection model using MATLAB Simulink

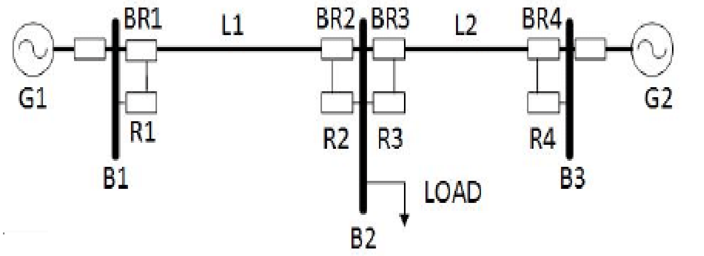


Fig. 8: Single-line diagram of conventional over current relay-based transmission protection model

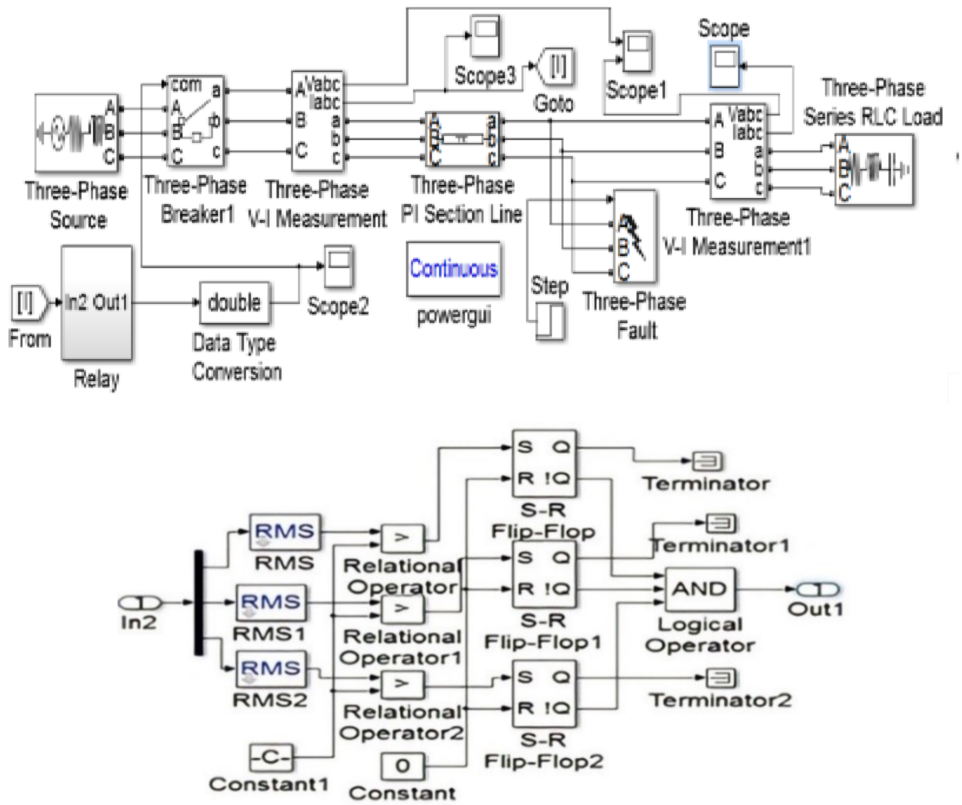


Fig. 9: Over-current relay-based transmission protection model using MATLAB Simulink

3. Results and discussion

Reduction in operating time is calculated for four different transmission line protection relays using mathematical set of equations and developed simulation models (described in section 2). Calculated and simulation outcomes are discussed below.

3.1 Differential relay presence effect on power transmission line fault

Firstly, the operating time of the relay in single line to ground fault condition is calculated. For differential relay maximum driving voltage at load side is, V_d=30000V. At over-loading state in relay, the assumed current exceeds by 25%. The reduction in operating time delay is calculated using

Equation (1):

$$t_{R.B} = \frac{0.14(tsm)}{(psm)^{0.02}-1} \quad (1)$$

Where

$$psm = \frac{V_{relay}}{ps}$$

and

V_{relay} = 300V, ps = 1V, t_{cb} = 0.5s, V_{max} fault=300V

$$T_{total} = t_{cb} + t_{cb}$$

$$T_{total} = 0.511s$$

Thus, operating time of differential relay for LG fault is~ 0.5s. Similarly, operating time for LLLG and LLG fault have been calculated.

The values were inserted in designed Simulink transmission line model, and the fault condition was generated to check the behavior of nominal values of current/voltage. As the fault condition occurs at a step of 0.5s, the rated values of the current/voltage started to deviate as shown in Fig.10.

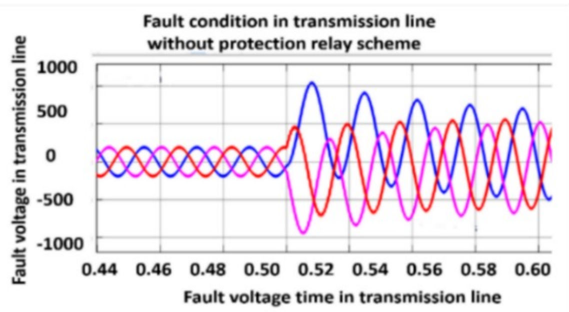


Fig. 10: Fault current analysis in transmission line without protection scheme

Fault voltage increases up to 25%V in transmission line without protection relay scheme that has been shown in figure.

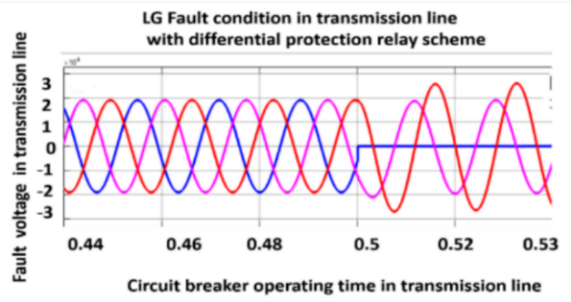


Fig. 11: Fault current analysis in transmission line in case of LG fault condition with differential protection scheme

Operating time is 0.5 seconds and fault volateg increases up to 2.5%V in case of LG fault condition using differential protection relay scheme.

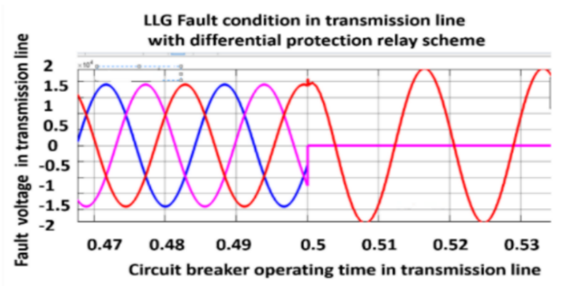


Fig. 12: Fault current analysis in transmission line in case of LLG fault condition with differential protection scheme

When LLG fault is generated, circuit breaker operating time is 0.5 seconds and fault voltage increases up to 2V using differential protection realy scheme.

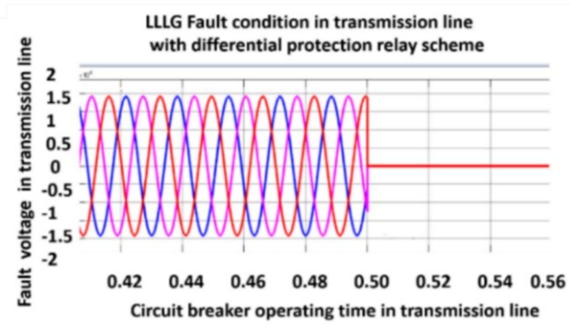


Fig. 13: Fault current analysis in transmission line in case of LLLG fault condition with differential protection scheme

When LLLG is generated, the circuit breaker operating time is 0.5 seconds and fault voltage increases up to 1.5V using differential protection relay scheme.

Table 1: Operating time of differential relays for transmission fault

Relay protection Schemes	Circuit Breaker operating time for LLLG fault	Circuit Breaker operating time for LLG fault	Circuit Breaker operating time for LG fault
Differential relay scheme	0.5s	0.5s	0.5s

3.2 Distance/ impedance relay presence effect on power transmission line fault

To calculate operating time, let the value of the nominal current exceed up to 25% from rated value. By using equation (1), the reduction in operating time is calculated for distance relay by changing certain parameters as I_{relay}=15A, ps=1A, I_{OC}=150A instead of using V_{relay}= 300V, and ps=1V, and total calculated operating time of over and under voltage relay is 0.525s. Here, MATLAB is also used for calculation of operating time of distance relay when LG, LLG and LLG faults are generated.

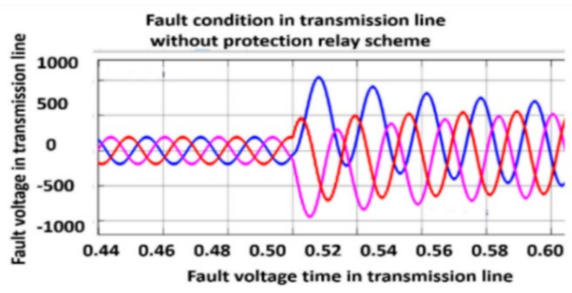


Fig. 14: Fault current analysis in transmission line without protection scheme

Fault voltage increases up to 800V in transmission line without protection relay scheme that has been shown in figure.

When LG fault is generated, the circuit breaker operating time is 0.52 seconds using differential protection relay scheme.

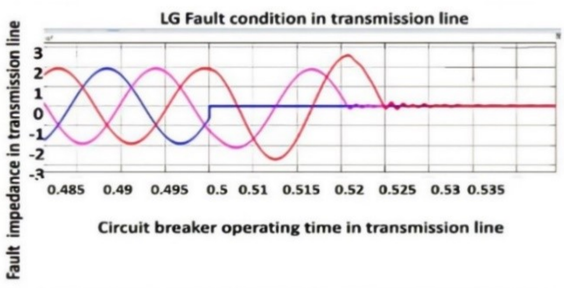


Fig. 15: Fault current analysis in transmission line in case of LG fault condition with distance/ impedance protection scheme

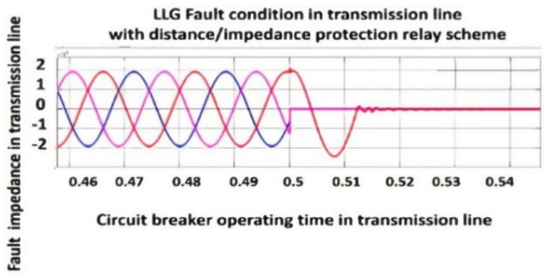


Fig. 16: Fault current analysis in transmission line in case of LG fault condition with distance/ impedance protection scheme

When LLG fault is generated, the circuit breaker operating time is 0.5125 seconds using differential protection relay scheme.

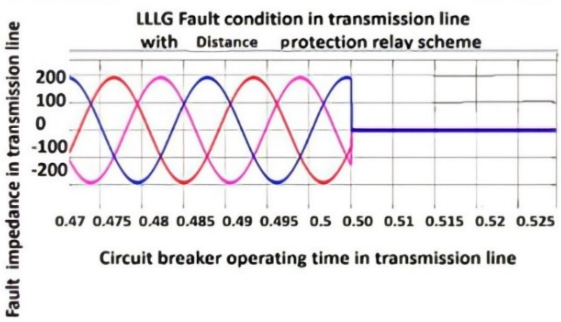


Fig. 17: Fault current analysis in transmission line in case of LLLG fault condition with distance/ impedance protection scheme

When LLLG fault is generated, the circuit breaker operating time is 0.5 seconds using differential protection relay scheme. In case of LLLG fault, the circuit breaker operates exactly at 0.5s of the fault conditions while in case of LLG fault the circuit breaker does not operate exactly at 0.5s but it takes a delay and operates at 0.5125s. This means at this condition distance relay do not operate instantly to remove the fault. In case of LG fault, the CB operates at 0.52s which takes longer time to operate than in the case of two other faults when fault occurs at 0.5s. All the results are reported in the Table for comparison.

Table 2: Operating time of distance or impedance relays for transmission fault

Relay protection Schemes	Circuit Breaker operating time for LLLG fault	Circuit Breaker operating time for LLG fault	Circuit Breaker operating time for LG fault
Distance or Impedance relay scheme	0.5s	0.5125s	0.525s

3.3 Over and under voltage relay presence effect on effect on power transmission line fault

In case of LLG fault, which most commonly occurs, the maximum driving voltage at load side is 4000V. At overloading in relay let current exceed 25% of nominal value. When current value is less than 25% of nominal value, it is considered under voltage condition and when current exceed 25% of nominal value, it is considered as over voltage condition. By using equation (1), calculate the reduction in operating time for over and under voltage relay by changing certain parameters as V_{relay}= 9.37V and ps = 0.8V and total calculated operating time of over and under voltage relay is 0.525s. MATLAB is used to calculate operating time when LG, LLG and LLG faults are generated at 0.5s.

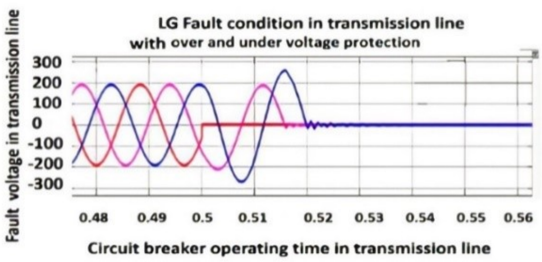


Fig. 18: Fault current analysis in transmission line with over and under voltage protection scheme in case of LG fault condition

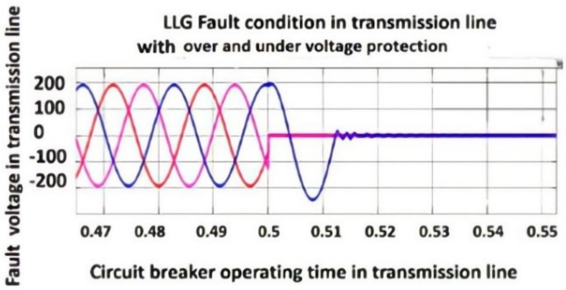


Fig. 19: Fault current analysis in transmission line with over and under voltage protection scheme in case of LLG fault condition

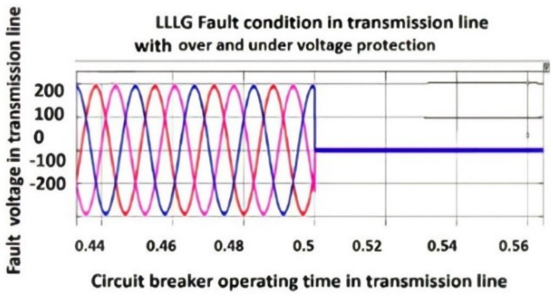


Fig. 20: Fault current analysis in transmission line with over and under voltage protection scheme in case of LLLG fault condition

When LLLG fault occurs, the relay trips and CB operates at 0.5s and protects the system without any delay in the operation. However, in case of LG fault, the relay operates at 0.529s with a delay time of 0.029s and in case of LLG fault the circuit breaker operates at 0.512s, with the delay of 0.012s.

In both cases when the relay operated as under voltage, it trips as the value of voltage gets down from rated value and in case of over voltage condition the relay trips when the value of voltage gets more than that of the rated value.

Table 3: Operating time of over and under voltage relays for transmission fault

Relay protection Schemes	Circuit Breaker operating time for LLLG fault	Circuit Breaker operating time for LLG fault	Circuit Breaker operating time for LG fault
Over and under voltage relay scheme	0.5s	0.525s	0.515s

3.4 Over-current relay presence effect on effect on power transmission line fault

While calculating the operating time for line-to-ground (LG) fault, the maximum driving current at load side in system=80A. At overloading in relay assume current exceeds 25%. By using equation (1) calculate the reduction in operating time for distance relay by changing certain parameters such as I_{relay}=30A, ps=1A, tsm=0.01s instead of I_{relay}=15A ps=1A I_{OC}=150A and total calculated operating time of over and under current relay is 0.519s. Relay operating time of overcurrent relay in the case of LG fault= 0.519s. The results have been drawn with three phase faults in the system while checking the behavior with and without relay operations.

Here MATLAB is also used to calculate operating time of CB when LG, LLG, LLLG faults occurred at 0.5s.

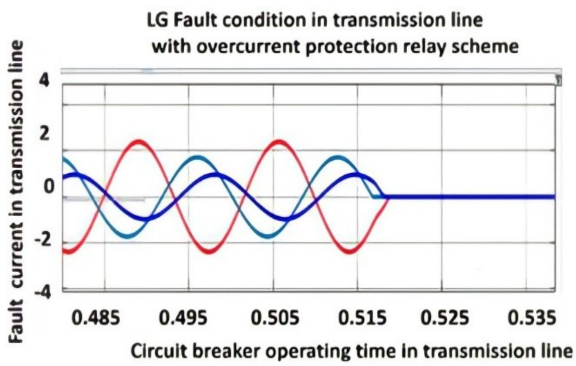


Fig. 21: Fault current analysis in transmission line with overcurrent protection scheme in case of LG fault condition

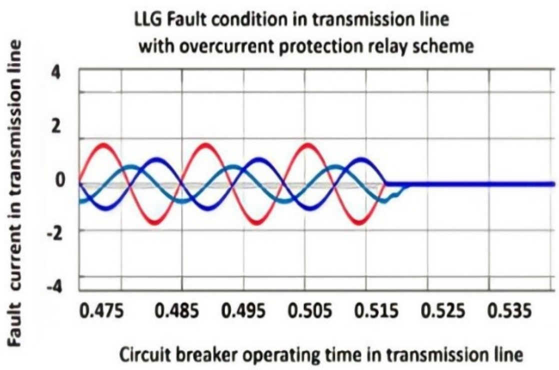


Fig. 22: Fault current analysis in transmission line with overcurrent protection scheme in case of LLG fault condition

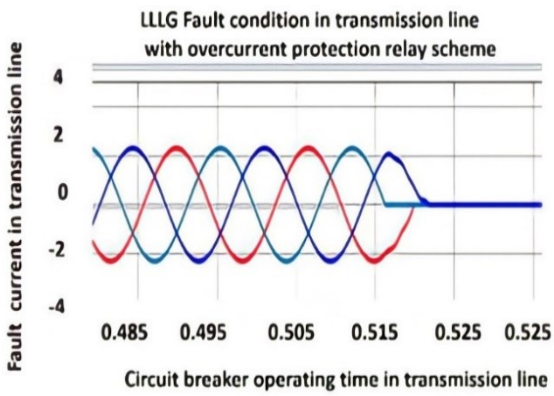


Fig. 23: Fault current analysis in transmission line with overcurrent protection scheme in case of LLLG fault condition

For all cases of LG, LLG and LLLG faults, CB operated at 0.519s with the delay of 0.019s which means the overcurrent relay never operates instantly at fault condition (as fault condition is 0.5s). It will always take time to operate and clear the fault in all LLLG, LLG, and LG conditions. This means overcurrent relay is less effective in clearing fault quickly.

Table 4: Operating time of over current relays for transmission fault

Relay protection Schemes	Circuit Breaker operating time for LLLG fault	Circuit Breaker operating time for LLG fault	Circuit Breaker operating time for LG fault
Over current relay scheme	0.519s	0.519s	0.519s

4. Comparative analysis of four protection relay model

The operating time of four different relays are calculated using the MATLAB models and concluded that differential relay is 97.56% better than Distance/Impedance relay in terms of operating time. Similarly, over and under voltage relay operated at different operating time for all three faults and on an average, it operates at 0.513s which is still higher than differential relay operating time and differential relay is 97.46% better in its operation compared to over and under voltage relay. At the end overcurrent relay operated at similar delayed value for all three types of faults. This means that overcurrent relay never operates instantly in any type of fault condition. Thus, the differential relay is 96.34% better than overcurrent relay in its operating time. However. the differential relay is better to protect fault inside the zone which cannot operate properly in the outside of a protective zone. All the operating times of above mentioned four relays for all three types of faults (LLLG, LLG and LG) are given below in Table 5.

5. Conclusion

Under fault conditions, the circuit breaking times of four relays (differential relay, distance, or impedance relay, over and under voltage relay, over current relay) have been calculated and compared. LG, LLG, and LLLG faults are considered in this work. The results of the MATLAB simulations indicate that all considered relays operated instantly for the LLLG fault, except for the overcurrent relay, which took a time gap of 0.019 seconds. The differential relay operated the CB at the exact time of 0.5s in the case of LLG fault, but all other relays took a time delay of 0.0125s in the case of LG fault. The differential relay was the only one showing a time delay in operating time in the third case of LG fault. When circuit breaking time is considered, differential relay performed better than distance or impedance relays, over and under voltage relays, and over current relays. However, there is a problem associated with differential relays, which is that they are not capable of detecting faults and swings in transmission lines. There are times when a swing occurs in which the nominated current or voltage rises from its rated value for a brief period and then falls back to its rated value. As differential relays are instantaneous, they will operate in swing conditions. In contrast, overcurrent relays always operate with a time delay, which raises the percentage of risk when the system is highly sensitive to faults. During LG faults, over and under voltage relays operated faster than during LLG faults, while distance/impedance relays operated faster than during LG faults.

6. Future Scope of the Work

This work can be extended to analyze future relays, to compare their operating times with the present relays, and to calculate their efficiency. For transmission lines protection, the current relay scheme can be extended to future technologies. In transient analysis, comparison could be made with the neural network protection scheme and FFT-based techniques.

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Table 5: Operating time of all relays for transmission line faults

Relay protection Schemes	Circuit Breaker operating time for LLLG fault	Circuit Breaker operating time for LLG fault	Circuit Breaker operating time for LG fault
Differential relay scheme	0.5s	0.5s	0.5s
Distance or Impedance relay scheme	0.5s	0.5125s	0.525s
Over and under voltage relay scheme	0.5s	0.525s	0.515s
Over current relay scheme	0.519s	0.519s	0.519s

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