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Modeling of relay protection of electric power system using Matlab/Simulink

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Abstract. The criteria for evaluating protective relaying devices encompass verifying both their design and application performance. Utilizing modeling and simulation techniques enables cost-effective completion of substantial design, evaluation, and testing tasks for physical relays and power systems. To effectively design, set, test, and evaluate protective relays, one requires software tools proficient in modeling both the protective relays of various designs as well as the surrounding power system. In this article, the authors present new models of protection that allow to simulate the overcurrent relay (51), instantaneous overcurrent relay (50) and differential relay (87) by using Matlab/Simulink. Initially, a methodology that presents how to build a library, including the different models and their communication architectures. Secondly, a case study in 220 kV transmission systems is selected as an example for fault simulation and relay testing for each relay model and the coordination protection. The simulation results are given and a description of how this case study can be used to compare protection schemes. In particular, the new contribution of this article is that the overcurrent relay is built based on a mathematical model according to IEC 60255 and IEEE C37.112-1996 standards. The results have shown that the difference between the proposed model and theoretical calculations is very small.

Keywords: power system simulation, relay protection, differential relay, over-current relay, coordination protection.

Classification numbers: 4.2.3, 4.8.3, 4.8.4

1. INTRODUCTION

Electrical systems are essential to the functioning of our modern society, providing reliable and efficient electricity to consumers, transport and industries. However, the operation of these systems is vulnerable to faults, either due to equipment failures, external incidents, natural disasters, or by misoperation of the system caused by operators' negligence. This can result in permanent damage to electrical system components leading to considerable costs for their replacement and longer disconnection times for customers. This sets a requirement for a power system to detect and isolate faults in the network. This is achieved by using relay protection systems. It works by continuously monitoring the electrical signals and parameters of the system and recognizing any abnormal conditions that may arise. When a fault is detected, the relay protection system isolates the affected part of the network, preventing further damage, and restoring the system to a safe and stable state.

In research on relay protection systems, testing on the system is very dangerous and requires high costs. Therefore, to study relay protection systems, simulation is very important, it allows for the testing and optimization of protection schemes in a safe and controlled environment. Through simulation, engineers can evaluate the effectiveness of different protection schemes in detecting and isolating faults and optimizing their settings and configurations for specific power system conditions. It is an essential tool in the study of relay protection systems, allowing engineers to design, optimize and evaluate protection schemes, while ensuring the safe and reliable operation of electrical power systems. Therefore, there is a lot of research into the application of software for relay protection simulation, such as EMTP, ETAP, PowerFactory [1, 2, 3]. In school and industry, simulation tools based on Matlab/Simulink [1 - 11] are becoming popular for engineering applications. This software enables the creation of detailed models of electrical systems and relay protection systems, allowing engineers to analyze protection system performance under a variety of fault conditions.

In [4], this study only simulating overcurrent protection with characteristic curve according to IEC 60255 standard. While publications [5, 6] focuses on simulating differential protection for stator winding generator and transformers; [7] focuses on modeling of a distance relay. Paper [8] presents setting of relay protection of electric power systems based on its mathematical models. With the desire to build simulation relay models on the basis of mathematical models for the purpose of study relay protection systems, in this article, the authors present new models of protection that allow to simulate the overcurrent relay (51), instantaneous overcurrent relay (50) and differential relay (87) by using Matlab/Simulink. In particular, the new contribution of the article is that the overcurrent relay is built on the basis of a mathematical model according to IEC 60255 and IEEE C37.112-1996 standards. Some examples and simulation results are also provided to test the accuracy and efficiency of these models. These models can be used to simulate the protection of various elements such as lines, transformers, busbars, etc.

This article is arranged as follows. The working principle of the overcurrent relays and differential relay is discussed in details in section 2. Section 2 also presented Matlab/Simulink module of these relays. For testing and simulation of the protection relay, an electrical system is selected as the protection object, it is represented in section 3. Finally, conclusions are given in Section 4.

2. OVERCURRENT RELAYS AND DIFFERENTIAL RELAY

2.1. Overcurrent relays

As the name states, overcurrent relays are protective devices used in electrical power systems to detect an over-current flowing through a circuit and trip the circuit breaker to isolate the faulty section from the rest of the system. This relay uses current inputs from a CT and compares it to a predetermined threshold value. If the current exceeds this threshold, the relay will activate and send a trip signal to the circuit breaker, which opens its contact to disconnect the protected equipment.

Overcurrent relays can be classified into two types: instantaneous and time-delayed. Instantaneous relays operate as soon as the current exceeds a preset value, while time-delayed relays have a delay before tripping, which allows temporary overcurrents without interrupting the system.

The time-delayed is classified into two types: Definite Time Overcurrent Relay (DTOC) and Inverse Definite Minimum Time (IDMT) Overcurrent Relay. The first operates with a fixed time delay. The relay will trip after a fixed time delay when the current exceeds the preset value. It is typically set to allow for system coordination with other protective devices. The second operates with an inverse time characteristic. The operating time of the relay is inversely proportional to the fault current. If the fault current is higher, the operation time will be less, and vice versa [3-6]. Features of the IDMT overcurrent relay depend on the standard type selected for relay operation. These standards can be ANSI, IEEE or user-defined [13, 14]. Relay calculation uptime using characteristic curves and corresponding parameters [1, 2, 4, 8, 10]. Any mentioned above criteria can be used to perform a characteristic curve for overcurrent relays. Then the overcurrent relay will calculate the corresponding uptime for that particular characteristic curve.

According to IEC 60255 or BS142 [13, 14], the characteristics of the IDMT relay are represented by the following equation:

$$T = \frac{k}{(\frac{I}{I_s})^{\alpha} - 1}.TMS \tag{1}$$

where: *T:* Relay operation time; *k:* Constant for relay characteristic; I_s: Relay pickup setting; *I:* Current input to the relay; *α:* Constant representing inverse time type (α > 0); *TMS:* Time multiplier setting controls the relay tripping time.

By using the appropriate TMS settings, classification of the protected network system can be achieved [14]. The range of TMS is usually 0.1 to 1.0 second. Different types of curves can be obtained by varying *α* and *k* [14]. Table 1 below shows the values of *α* and *k* for each curve.

Table 1. Different types of inverse characteristics curves according to IEC 60255.

Relay Characteristic Type	**α**	**k**
Standard inverse	0.02	0.14
Very inverse	1	13.5
Extremely Inverse	2	80
Long Inverse	1	120

According to IEEE C37.112-1996 [13], the characteristics of the IDMT relay are represented by the following equation:

$$T = (\frac{A}{(\frac{I}{I_s})^{p} - 1} + B).TD \tag{2}$$

where: *A:* Time factor for over-current trip; *I:* Current input to the relay; *Is:* Relay pickup setting; *p:* Exponent for inverse-time; *B:* Timer coefficient for over-current trip; *TD:* Time dial.

Different types of curves can be obtained by varying *A*, *B* and *p* [13]. Table 2 below shows the values of *A*, *B* and *p* for each curve.

Table 2. Different types of inverse characteristics curves according to IEEE C37.112-1996.

Relay Characteristic Type	A	B	p
Moderately inverse	0.0515	0.114	0.02
Very inverse	19.61	0.491	2.0
Extremely inverse	28.2	0.1217	2.0

2.2. Differential relay

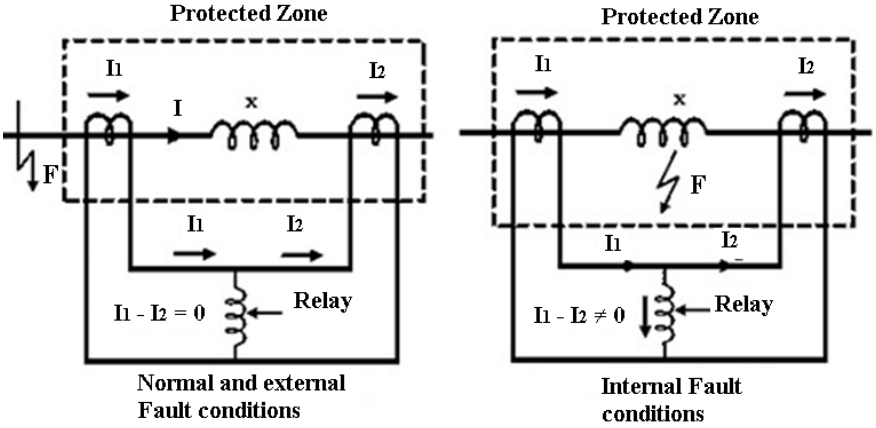


Figure 1. Differential relay working principle.

Differential relays are protective relays used in electrical systems to detect and protect against internal faults in electrical equipment, such as lines, transformers, generators, motors and busbars. It operates by measuring the current difference between two points in the system and tripping the breaker if this difference exceeds a preset value [5, 6, 9, 10].

The differential relay provides high sensitivity and selectivity in detecting faults within the protected zone, as it only responds to the difference in current between two points, regardless of the magnitude of the current. This makes it a necessary protective device for critical and high-value equipment in power systems.

The circuit employs two current transformers (CTs) positioned at each end of the designated section for protection. Positioned between these CTs, the relay coil is directly connected to the equipotential point, ensuring no current flows through the relay coil under normal conditions (Fig. 1). This setup is designed to prevent relay malfunction.

Under both normal and external fault conditions in the circuit, the current entering the protected region is equal to the current exiting the protected region ($I_1 - I_2 = 0$). Consequently, no current flows through the relay coil, rendering it inactive. Thus, the relay remains out of service during such conditions.

Similarly, in the event of an internal fault as depicted in the above diagram, the current entering the protected region differs from the current exiting it ($I_1 - I_2 \neq 0$). This disparity in current flows is termed as circulating current, and it is directed to the operating coil of the relay. The relay functions if the operating torque surpasses the restraining torque in this scenario.

2.3. Matlab/Simulink module of relays

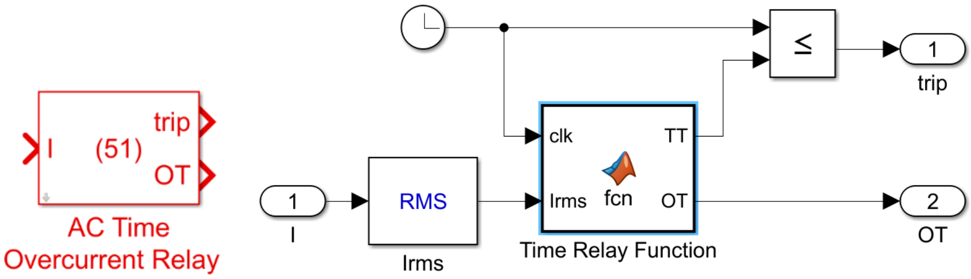
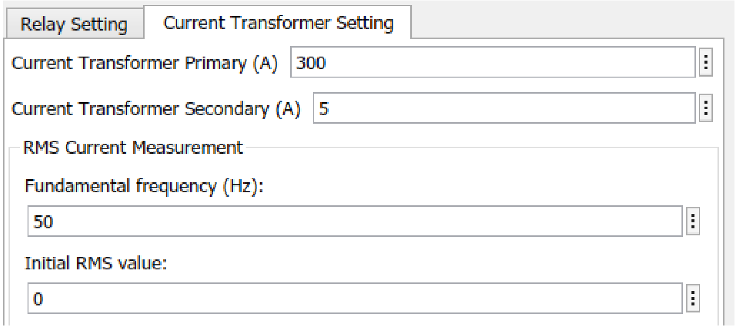


Figure 2. Representation of overcurrent relays module and detail.



Current Transformer Primary (A) 300

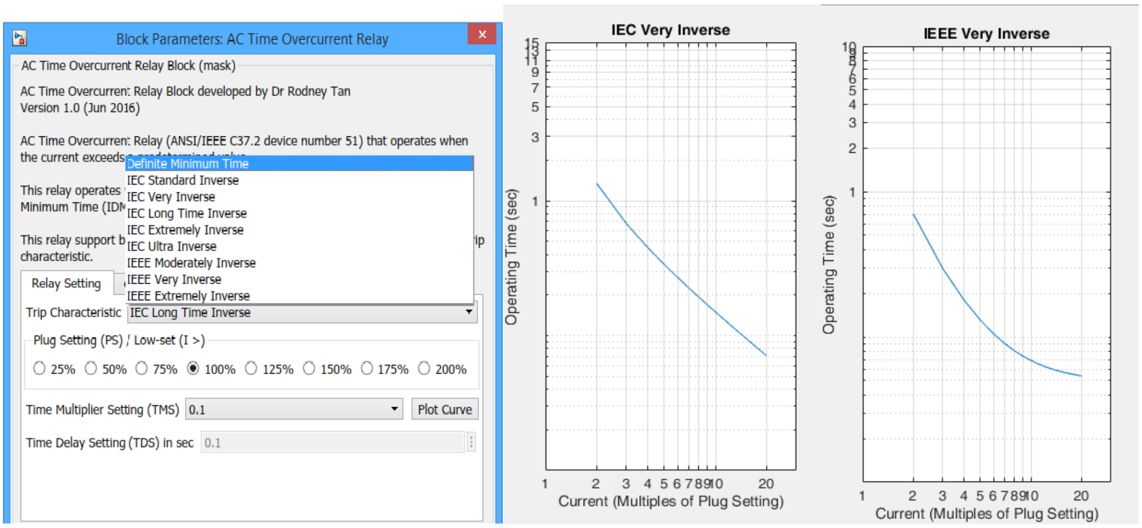
Current Transformer Secondary (A) 5

RMS Current Measurement

Fundamental frequency (Hz): 50

Initial RMS value: 0

Figure 3. Selects the ratio of CTs.


Block Parameters: AC Time Overcurrent Relay

AC Time Overcurrent Relay Block (mask)

AC Time Overcurrent Relay Block developed by Dr Rodney Tan
Version 1.0 (Jun 2016)

AC Time Overcurrent Relay (ANSI/IEEE C37.2 device number 51) that operates when the current exceeds

This relay operates
Minimum Time (IDM

This relay support b
characteristic.

Trip Characteristic: IEC Long Time Inverse

Plug Setting (PS) / Low-set (I >): ○ 25% ○ 50% ○ 75% ● 100% ○ 125% ○ 150% ○ 175% ○ 200%

Time Multiplier Setting (TMS): 0.1

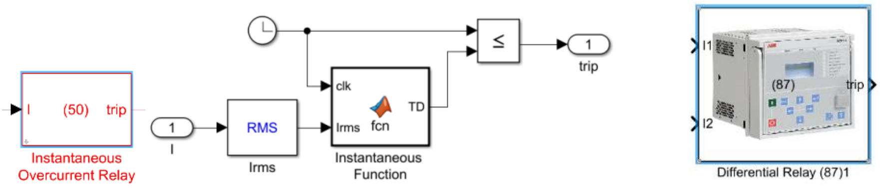
Time Delay Setting (TDS) in sec: 0.1

a. b. c.

Figure 4. a) Setting the time operation and choosing the inverse characteristic curves. b) IEC very inverse and characteristic curves and IEEE very inverse and characteristic curves.

Representation of overcurrent relays (51) module is shown in Fig. 2. The module consists of CTs and overcurrent relays (Fig. 3). The current signal is calculated RMS value, compared with the preset value. The operation time is determined by the time characteristic according to

IEC 60255 standard. If any phase currents exceed the preset value, the relay will activate and send a trip signal to the circuit breaker, which opens its contact to disconnect the protected equipment. The operation time is set on through select the Time Multiplier Setting (TMS) and the trip characteristics (Fig. 4). To view the characteristics curves, select the "Plot Curve" button (Fig. 4a), Fig. 4b and Fig. 4c illustrate the IEC very inverse and IEEE very inverse characteristic curves, respectively.



a) b)

Figure 5. a) Representation of instantaneous overcurrent relays module and detail; b) Representation of differential relay module.

The configuration of instantaneous overcurrent relay is similar to the overcurrent relays but without the time delay (Fig. 5a).

Differential relay operates similarly but with the inputs are the difference between the two currents. The operation time can be selected instantaneously or with time delay (Fig. 5b).

3. SIMULATION AND RESULTS

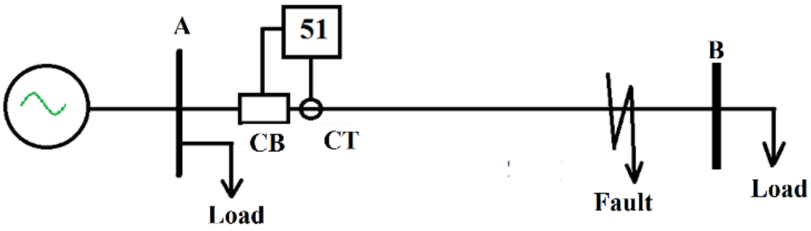


Figure 6. One phase diagram of a transmission system.

For testing and simulation of the protection relay, an electric network is used as shown in Fig. 6. The parameters of the simulation system are as belows:

- Source: 230 kV, 50 Hz, Ssc = 750 MVA, X/R = 8.
- Load A: 100 MW and 72 MVAr, Load B: 45 MW and 30 MVAr.
- Transmission line: 80 km
- R_0 = 0.108 (Ω/km) , L_0 =1.345 (mH/km), C_0 = 9.483 (nF/km).

3.1. Overcurrent relays simulation

In order to ensure a safe, reliable and fast operation of the relay protection, it is necessary to determine the working state parameters of the power system, including full-load current, short-circuit current largest and smallest. The current transformer ratio is selected and a suitable pickup value and time multiplier settings on that basis. The Matlab/Simulink simulation is shown in Fig. 7. The full load current in steady-state mode and the fault current in short-circuit mode simulation results and are shown in Fig. 8 and Fig. 9. Table 3 shows the results of power system analysis and settings of the overcurrent relay model which are based on this results.

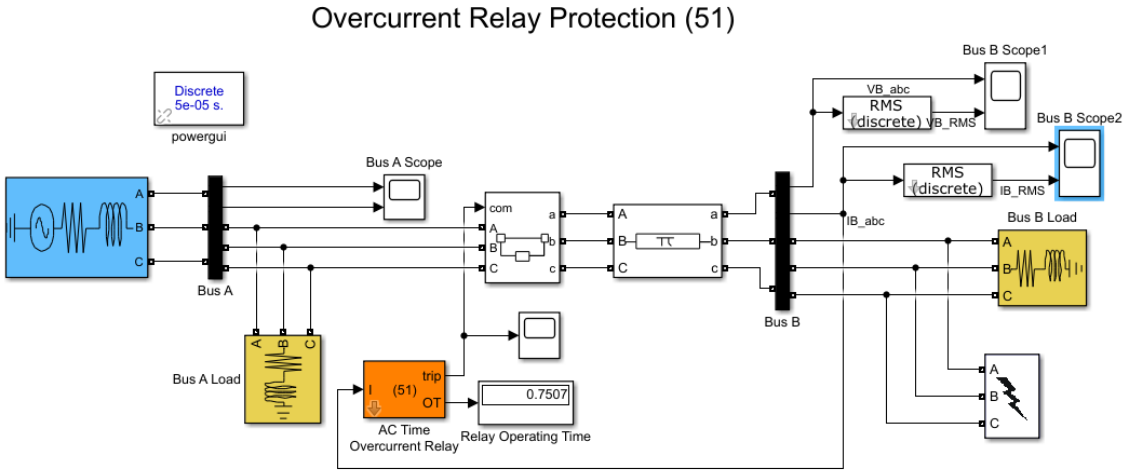


Figure 7. The Matlab/Simulink simulation model.

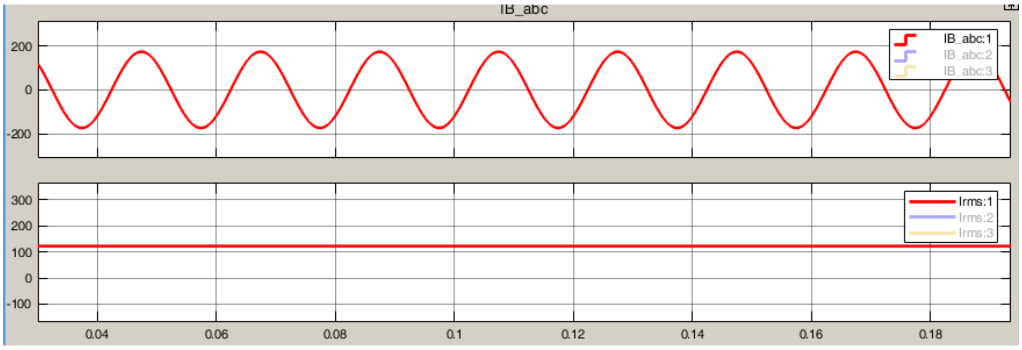


Figure 8. Instantaneous waveform and RMS waveform of full load current.

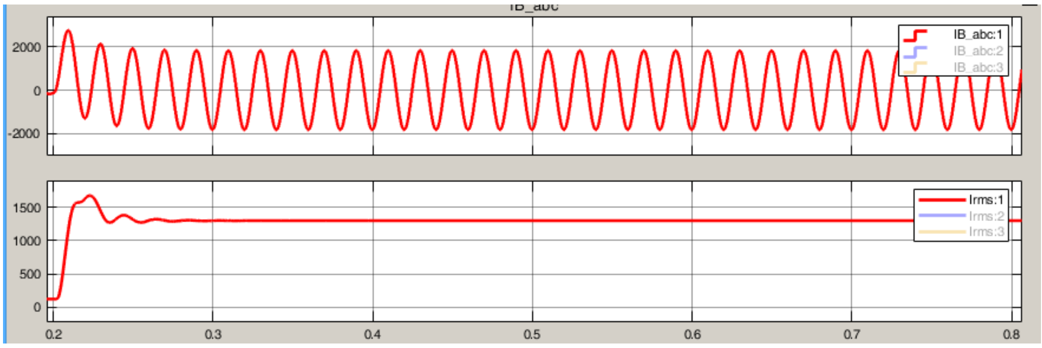


Figure 9. Instantaneous waveform and RMS waveform of largest short-circuit current (Three phase fault).

Table 3. Power system analysis and relay settings.

Measurements		**Relay settings**	
Full load current	122 A	Current Transformer Ratio	300:5
Consider the starting current	221 A	Pickup Value	5 A
Maximum Fault Current	1677 A	Minimum current which relay trip	300 A

In the test case model, the three phase fault was applied at t= 0.2 sec. If choosing the definite time, the operating time always is the preset time when the current through CT is larger than 300 A. The results for Very Inverse characteristic curves are shown in Fig. 10 and Fig. 11. In other cases of characteristic curves, the simulation results are shown in Table 4.

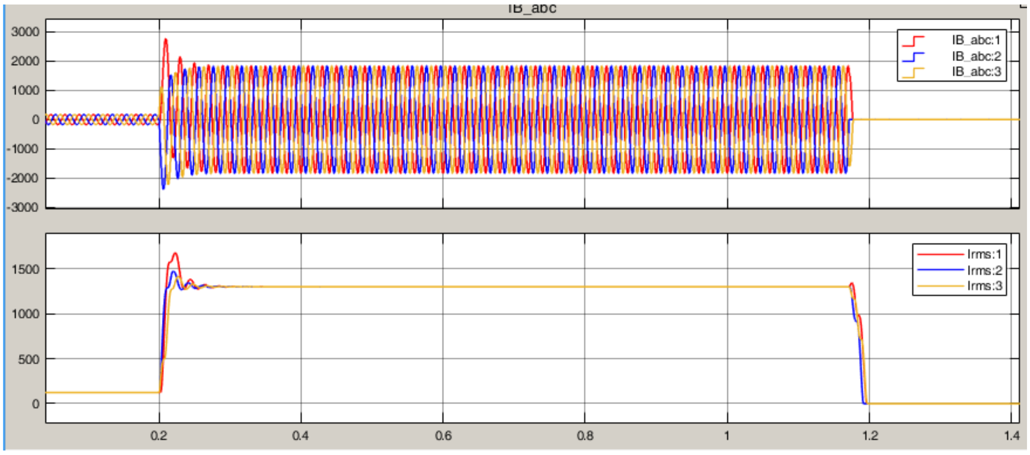


Figure 10. Instantaneous waveform and RMS waveform of short-circuit current in the case of overcurrent relay trip.

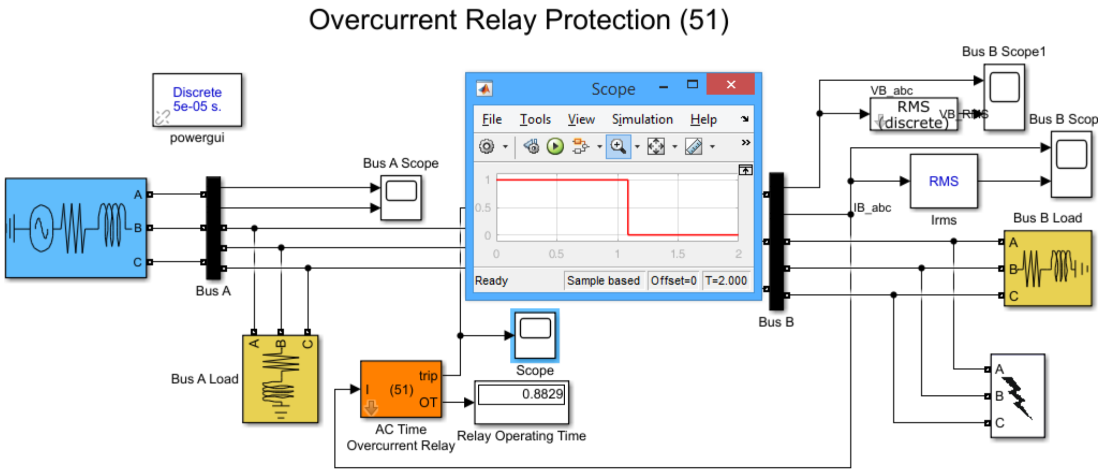


Figure 11. Display the Operating time and Trip signal time in the case of choosing the Very Inverse characteristic.

Table 3. The simulation result of the proposed relay with many characteristic curves and the ideal calculations.

Measurements		**Operating time**	**Ideal operating time**	**Trip signal time**	**Ideal trip signal time**
IEC 60255 standard	Standard Inverse	1.200	1.1994	1.4022	1.400
	Very Inverse	0.8829	0.8824	1.0854	1.0829
	Extremely inverse	0.7943	0.7934	0.9968	0.9943
	Long time inverse	7.8480	7.8427	8.0507	8.0427
IEEE C37.112-1996 standard	Moderately inverse	0.4755	0.4754	0.6780	0.6754
	Very inverse	0.3420	0.3418	0.5445	0.5418
	Extremely inverse	0.3165	0.3162	0.5190	0.5162

Where:

- The ideal results are calculated using Eg. (1) (in the case of IEC 60255 standard) or Eg. (2) (in the case of IEEE C37.112-1996 standard).
- Trip signal time = Time at which fault is detected + Operating time.

Table 4 also shows the comparison of results from the proposed model with the theoretical calculations. The reason for this difference is due to the delay in RMS analysis and information processing that determines the time of the fault.

3.2. Instantaneous overcurrent relay simulation

In this case, the test system was as the previous but using the instantaneous overcurrent model (50) (Fig. 12). The three phase fault happened at t = 0.2 sec. Simulation results of instantaneous overcurrent protection are shown in Fig. 12 and Fig. 13. As a result, although it means instantaneous, the fault is cleared after 0.0288 sec.

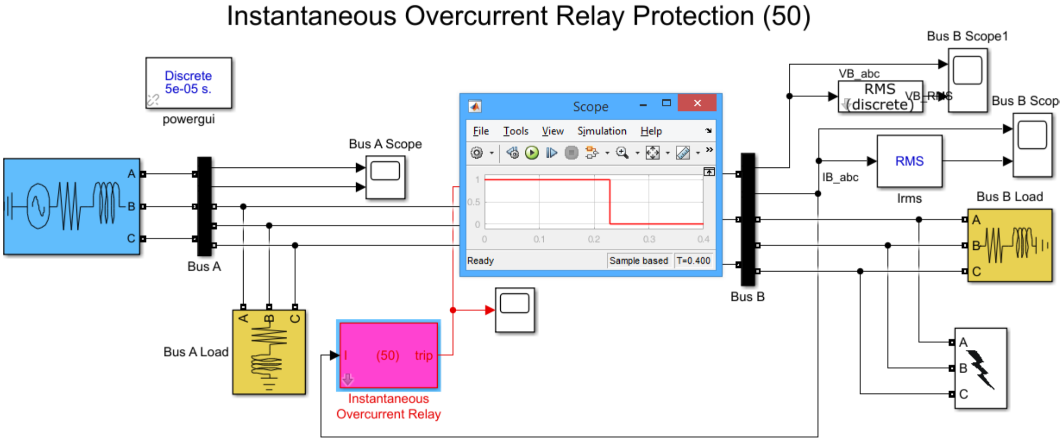


Figure 12. Test the operation of instantaneous overcurrent relay.

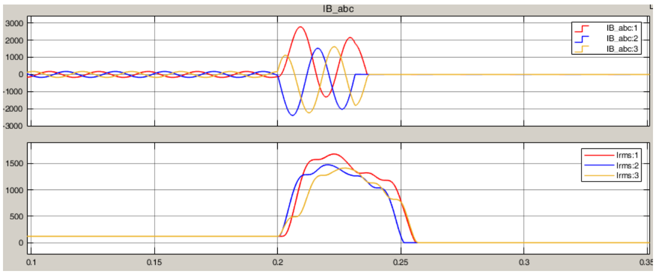


Figure 13. Instantaneous waveform and RMS waveform of short-circuit current in the case of instantaneous overcurrent relay protection.

The relay needs time to analyze the RMS of currents and process data, so there is a certain delay. This is consistent with the operation of relay protection in the real system.

3.3. Differential relay simulation

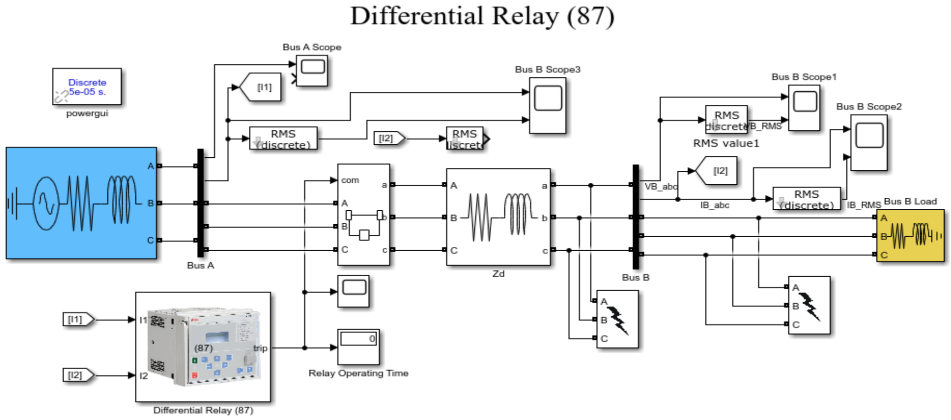


Figure 14. Test the operation of the Differential relay.

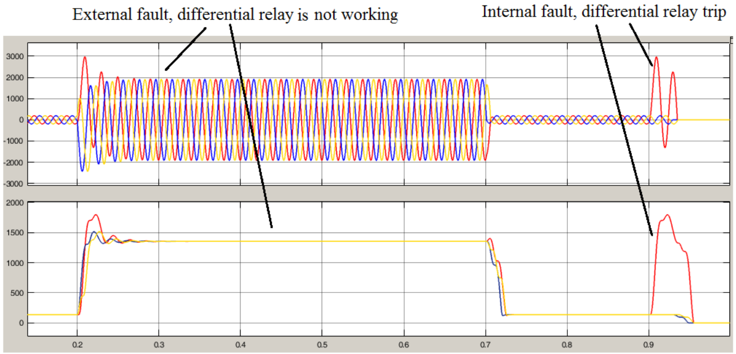


Figure 15. Instantaneous waveform and RMS waveform of short-circuit current in the case of Differential relay protection.

In this case, the same system without the load at begin of the line using the differential relay model (87) (Fig. 14). To test the operation of differential relay, two faults are applied, the first is an external fault and the second is internal fault (Fig.14). The first happens at 0.2 sec to 0.7 sec, the second happens at 0.9 seconds. According to the principle of Differential relay, in the case of an external fault, the current entering and leaving the protected zone of the system is not different due to the fault, the relay is not working. However, in the case of an internal fault, the current becomes unequal and the differential relay will detect this difference and starts operating. Simulation results of the Differential relay are shown in Fig. 15. From 0.2 sec to 0.7 sec, the external fault occurs, the current uprise but the relay is not working because the current from two CTs is equal. Whereas, the internal fault occurs at 0.9 sec, the differential relay detects this difference and sends a trip signal to the circuit breaker, and the fault is cleared at 0.9258 sec.

3.4. The coordination protection of relays

The disadvantage of the differential relay is that it does not work with an external fault. Therefore, the design should be coordinated with other types of protection, such as overcurrent relay. Fig. 15 illustrates the coordination protection of differential relay and overcurrent relay in a power system supplying two loads (with the same parameters of power systems and the first load is 30 MW and 20 MVAr, and the second load is 15 MW and 10 MVAr). Assume the fault occurs at 0.2 sec (the external fault with differential relay) on the second load and the internal fault occurs at 0.9 sec.

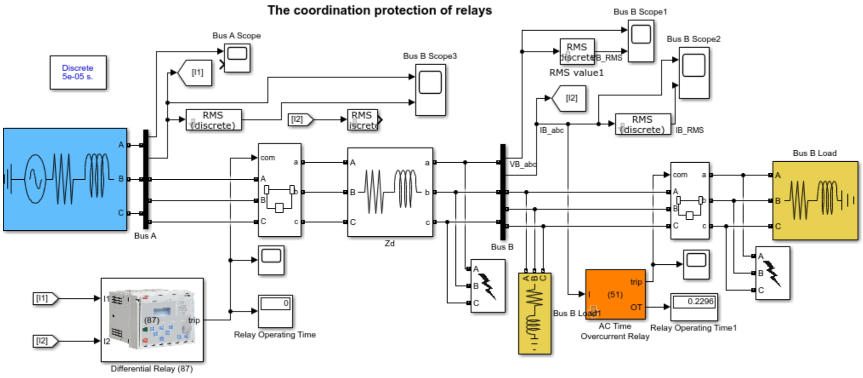
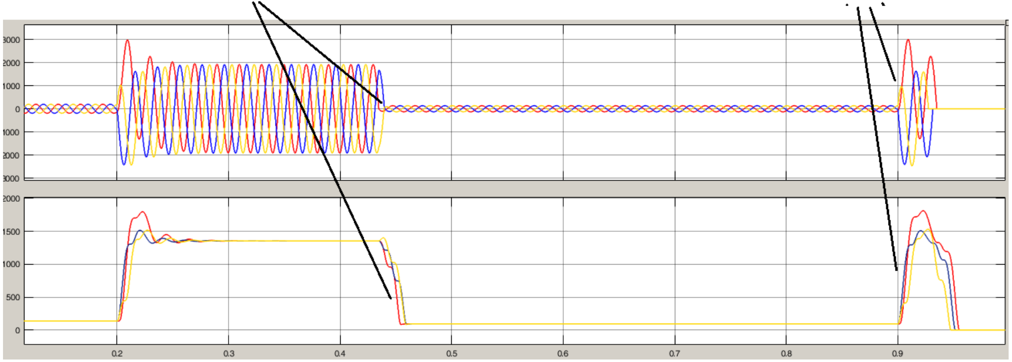


Figure 16. Test the coordination protection of relays.


External fault, differential relay does not work, but the overcurrent relay active and trip after 0.23 sec

Internal fault, differential relay trip

Figure 17. Instantaneous waveform and RMS waveform of short-circuit current in the case of coordination protection of differential relay and overcurrent relay.

The simulation results of the coordination protection of relays are shown in Fig. 16. When the external fault occurs, the differential relay does not work but the overcurrent is activated and trips after 0.23 sec, isolating the fault to ensure the system is in normal operation. When the internal fault occurs at 0.9 sec, the differential relay detects and active, the fault is cleared at 0.9258 sec (Fig. 17).

4. CONCLUSIONS

This article presents the modeling of overcurrent and differential relays in Matlab/Simulink. The overcurrent relay model is designed with the features of instantaneous, time-definite, and inverse definite minimum time (IDMT) characteristics according to IEC 60255 and IEEE C37.112-1996 standards. These models are tested in the 220 kV transmission systems for each relay model and the coordination protection. The results have shown that the difference between the proposed model and theoretical calculations is very small. It was also proved the correctness of the proposed relay model. These models can help protection engineers effectively enhance the performance of the digital protective relay design, selection, and settle setting.

The models proved to work accurately in the simulation environment. Although, the author will expect to extend the tests by adding hardware-in-the-loop, to evaluate the actual operating times of an electric power system.

Credit authorship contribution statement. Vo Tien Dung: Methodology, investigation, resources, formal analysis, preparation of the draft, revision of the article. Thai Huu Nguyen and Tran Duy Trinh: Formal analysis.

Declaration of competing interest. The authors declare that they have no conflicts of interest in relation to this article.

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