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Effect of Load Variation and Fault Resistance on the Operation Time of IDMT Overcurrent Relay

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ABSTRACT

Fault can occur in power system due to many factors such as lightning, tree or crane encroachment, animal intervention, human error etc. Each fault occurrence has its own fault resistance value, and this value is unknown to the protection relay used to the protect the circuit. Besides that, the connected load in power system is dynamic where the value is changing over time. It is very important for the protection relay to be as reliable as it can so that the fault can be isolated as soon as possible when a fault occur. This paper study the effect of fault resistance value and load variation on IDMT overcurrent relay operation time. This relay is used to protect the line from fault occurrence where the higher the fault current, the faster the operation time will be. MATLAB Simulink has been used to model the transmission line, source, connected load and IDMT overcurrent relay. Faults simulations were conducted for various fault resistance and load values and the effects on relay operation time have been analysed. From the results, it was found that, the higher the fault resistance, the higher the operation time while the higher the value of connected load at the end of the line, the faster the relay operation time.

1. Introduction

Faults can occur between phases, between a phase and the ground, or in both scenarios. Various factors contribute to faults, including a lightning strike on a phase conductor, contact with a tree on the line, insulation failure of cables and winding, incorrect installation sequence, and machinery malfunctions [1]. The fault current, also known as the short-circuit current, has the potential to compromise the stability of the power system, resulting in uneven current flows [2]. This abnormal current state poses a risk of damaging the equipment. Additionally, during fault conditions, high currents may lead to overheating, potentially causing fire or explosions.

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To address this issue, protection relays can be employed to safeguard the power system against damage resulting from faults. There are three primary types of protection relays: overcurrent relay [3], impedance-based relay [4], and differential relay [5]. This research specifically focuses on the overcurrent relay. Overcurrent relays can be classified into two categories: instantaneous relays and time-dependent relays [6]. The instantaneous overcurrent relay activates without any time delay once the fault current surpasses the preset current threshold [7]. In contrast, time-dependent relays operate with an adjustable time delay [8]. Definite time [9] and inverse time [10] overcurrent relays fall under the category of time-dependent relays. During a fault condition, a definite time overcurrent relay initiates its operation after a specified time, determined by the relay's time setting.

The inverse time overcurrent relay initiates its operation upon reaching the pickup current and subsequently triggers a trip after a designated time delay, where the operation time is inversely proportional to the fault current value. The higher the fault current, the quicker the operation time of the inverse time relay. The correlation between the operation time and the fault current value is illustrated through various time-current characteristic curves [11]. An example of an inverse time overcurrent relay is the Inverse Definite Minimum Time (IDMT) relay [12]. Notably, it incorporates an additional feature: when the fault current exceeds a certain threshold, the operation time deviates from the characteristic curve, and the tripping signal is dispatched after the set definite minimum time has elapsed.

In this research, the IDMT relay has been selected for safeguarding the transmission line. Numerous studies have delved into the application of IDMT relays, including the work presented by Hussin *et al.,* [13]. This particular research involved the design of a three-phase source, circuit breaker (CB), IDMT overcurrent (OC) relay, distributed parameter line, three-phase load, and fault using MATLAB Simulink software. The OC relay subsystem was utilized to identify fault occurrences and compute the relay's operation time. The analysis encompassed variations in fault type, distribution line length and time multiplier setting (TMS). The findings demonstrated the feasibility of utilizing MATLAB Simulink for modeling and simulating IDMT overcurrent relays. It's worth noting that the simulation time is contingent on the complexity of the model.

Digital signal processing (DSP) was employed by Goh *et al.,* [14] to model the IDMT overcurrent relay. The relay model was constructed using MATLAB Simulink and subsequently transferred to the TMS320F2812 DSP board. The outcomes revealed that the operation times generated by the DSP board were consistent with those obtained from the simulation. This validation underscores the effectiveness of the DSP board as a reliable relay processor.

Ensuring the reliability of a protection scheme to safeguard the circuit is paramount, ensuring that the scheme operates according to its intended function and achieves the desired action [15]. Numerous factors can influence the reliability of an overcurrent relay, including harmonic effects [16], load [17], current transformer saturation [18], integration of distributed energy (DG) sources [19], contribution from induction motors [20], inrush current occurrences [21], and various other considerations.

The current transformer (CT) serves the purpose of stepping down the primary current to a lower value that is compatible with the relay. However, improper installation of the CT, including choosing an unsuitable size and specification, may lead to saturation. A MATLAB model was created by A. L. M. Coelho and P. M. Silveira to study how CT behavior affects overcurrent relays [22]. Low fault currents and standard burdens allowed the relay to function well even during CT saturation. However, higher fault currents, DC components, and specific CT conditions notably affected relay response.

Inrush current, characterized by a short-term but significantly high magnitude of current, occurs during the energization of apparatus like transformers, reactors, and capacitors. Due to its substantial magnitude compared to the steady-state value, inrush current has the potential to trigger the relay to trip without any conditions. Research conducted by Yang *et al.,* [23] revealed that varying transformer closing instances resulted in different amplitudes of inrush current. The researchers concluded that the relay might malfunction when exposed to the highest amplitude of inrush current at specific closing times.

Induction motors contribute to the transient current in short-circuit situations. This transient current has the potential to modify the operation times of overcurrent relays, leading to a misalignment between primary and backup relays. To address this challenge, a dynamic model of the overcurrent relay, considering the influence of the induction motor, was introduced by M. G. Maleki *et al.,* [20]. An optimization-based approach, incorporating a novel set of constraints, was employed to establish updated coordination settings. This method effectively resolved the issue of false trips that occurs when employing conventional coordination methods.

Ilik and Arsoy [24] investigated the impact of integrating distributed generation (DG) on a directional overcurrent protection scheme within a radial network. The analysis unveiled that the coordination of upstream relays could be jeopardized due to the changing connections of DG sources, making it susceptible to fluctuations in the fault contributions from these sources.

The value of fault resistance is unknown to the protection relay. As fault current traverses the fault resistance, completing the fault impedance loop during fault occurrences, numerous studies have delved into understanding the impact of variations in fault resistance on the accuracy of protection relays. Notably, research in this domain has been conducted, with previous studies [25-27], particularly focusing on impedance-based relays.

The investigation outlined by Khoa *et al.,* [25] indicated that various single-end impedance-based methods, including the simple reactance method, Takagi method, modified Takagi method, and Eriksson method, were significantly impacted by an increase in fault resistance. Furthermore, as highlighted by the research conducted by Ghorbani *et al.,* [26] certain zone 1 faults exhibited an amplification of fault resistance due to infeed from a remote source. This led to a calculated impedance seen by the relay that was higher than the actual value. Consequently, the faults were incorrectly located in zone 2, causing delayed relay operation. The analysis conducted by Adrianti *et al.,* [27] emphasized that distance relays are ill-suited for deployment in distribution systems. This is because these relays can severely underreach, mainly attributed to the smaller impedance of distribution lines compared to transmission lines. Additionally, in distribution systems, the majority of the impedance measured by the relay is dominated by fault resistance, further compromising the relay's accuracy.

Overcurrent relays function by continuously measuring the current value and are configured based on a pickup current setting, with or without a time setting. Due to their current-based operation, limited research specifically examines the impact of fault resistance on their operation time. While some references incorporate fault resistance in their methods [28-31], none have delved into the variation of fault resistance and its influence on operation time of IDMT relay. Similarly, the effect of load, which fluctuates over time and is unknown to the installed overcurrent relay, has been investigated by several researchers. However, existing studies primarily focus on fixed load types [8,32-34]. Consequently, this paper seizes the opportunity to explore the impact of both varying load and fault resistance on the operation time of the Inverse Definite Minimum Time (IDMT) overcurrent relay. The research commenced with the modeling of a three-phase radial transmission line, incorporating an Inverse Definite Minimum Time (IDMT) overcurrent relay, using MATLAB Simulink software. Subsequently, the designed model was employed to simulate diverse fault conditions, enabling the analysis of the influence of load variation and fault resistance on the relay's operation time. It is important to note that the scope of this study is confined by a limitation, wherein only the standard inverse (SI) characteristic is modeled for the relay.

2. IDMT Overcurrent Relay

As one of inverse time relay, this relay has two main settings which are plug setting (PS) and time multiplier setting (TMS). TMS is used to adjust the delay time of the relay. It has a setting range from 0 to 1. The lower the value, the faster the operation time. PS is used to determine the current setting (pickup current) of the relay to detect the fault occurrence. The equation for pickup current is shown by Eq. (1). The $CT_{secondary}$ is the value of rated current for the secondary side of the current transformer (CT) where the value is 1 or 5 A.

$$I_P = PS\ X\ CT_{secondary} \tag{1}$$

Next is the determination of multiple of fault current over pickup current which is also called as plug setting multiplier (PSM). PSM equation is shown by Eq. (2). $I_{F(s)}$ is the secondary value of the fault current. This value can be gained from the measured primary fault current, $I_{F(p)}$ using Eq. (3).

$$PSM = \frac{I_{F(s)}}{I_P} \tag{2}$$

$$I_{F(s)} = \frac{I_{F(p)}}{CT\ ratio} \tag{3}$$

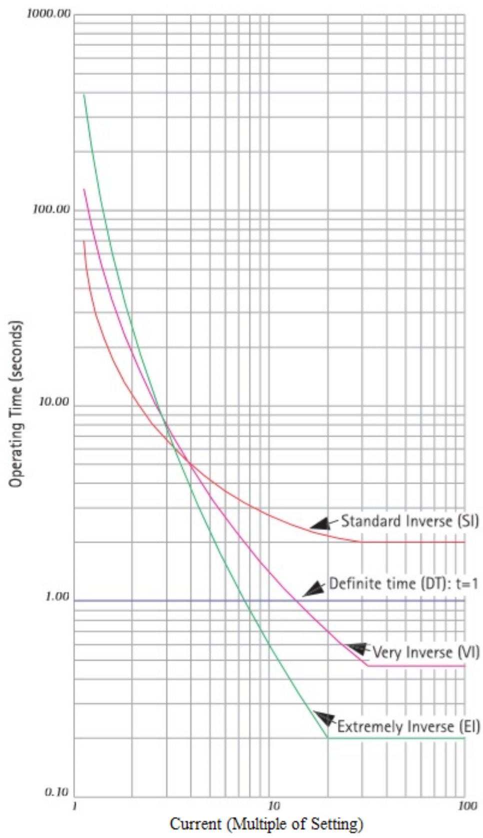

Fig. 1. Time-current characteristic of IEC standard for IDMT overcurrent relay [13]

Figure 1 shows the time-current characteristic (TCC) for inverse time overcurrent relay based on IEC Standard with four types of characteristics. The operation time is inversely proportional to the multiple of current setting. Different characteristics have different operation times for the same multiple of fault current over pickup current. The higher the gradient of the curve, the faster the relay operates.

All the curves can be represented by Eq. (4) where this equation is used to determine the operation time of IDMT relay for different time-current characteristics. The constants for the different curves can be referred from Table 1.

$$t(s) = \frac{k}{PSM^{\alpha}-1} xTMS \tag{4}$$

Table 1
Constants for different characteristics in IED standard

Type of Curves	k	α
Standard / normal inverse	0.14	0.02
Very inverse	13.5	1
Extremely inverse	80	2
Long time inverse	120	1

Since only standard inverse was referred, Eq. (4) can be written as in Eq. (5) for standard inverse curve.

$$t(s) = \frac{0.14}{PMS^{0.02}-1} xTMS \tag{5}$$

3. Modelling and Simulation of IDMT Overcurrent Relay and Transmission Line

Figure 2 shows the model of three-phase transmission line with IDMT overcurrent relay which have been constructed using MATLAB Simulink software. The model consists of three-phase source (substation), current measurement, IDMT relay, circuit breaker, transmission line, fault connection and three-phase load. When a fault occurs, the fault current will be higher than the pickup current and the relay will send a trip signal to open the circuit breaker to isolate the line. The parameters for the simulation model are listed in Table 2.

Figure 3 shows the blocks inside IDMT relay subsystem. Each phase has its own overcurrent element (OC R, OC Y and OC B). Each of these phase overcurrent elements has its own operation time calculator, fault detector and trip signal. All those three trip signals from all the phase overcurrent elements are fed to an OR gate. A trip signal from any phase overcurrent element will make the three-phase circuit breaker to be tripped and all the three phases will be opened including the un-faulted phases. All the phase overcurrent elements have similar block configuration and the blocks inside OC R subsystem is shown in Figure 4.

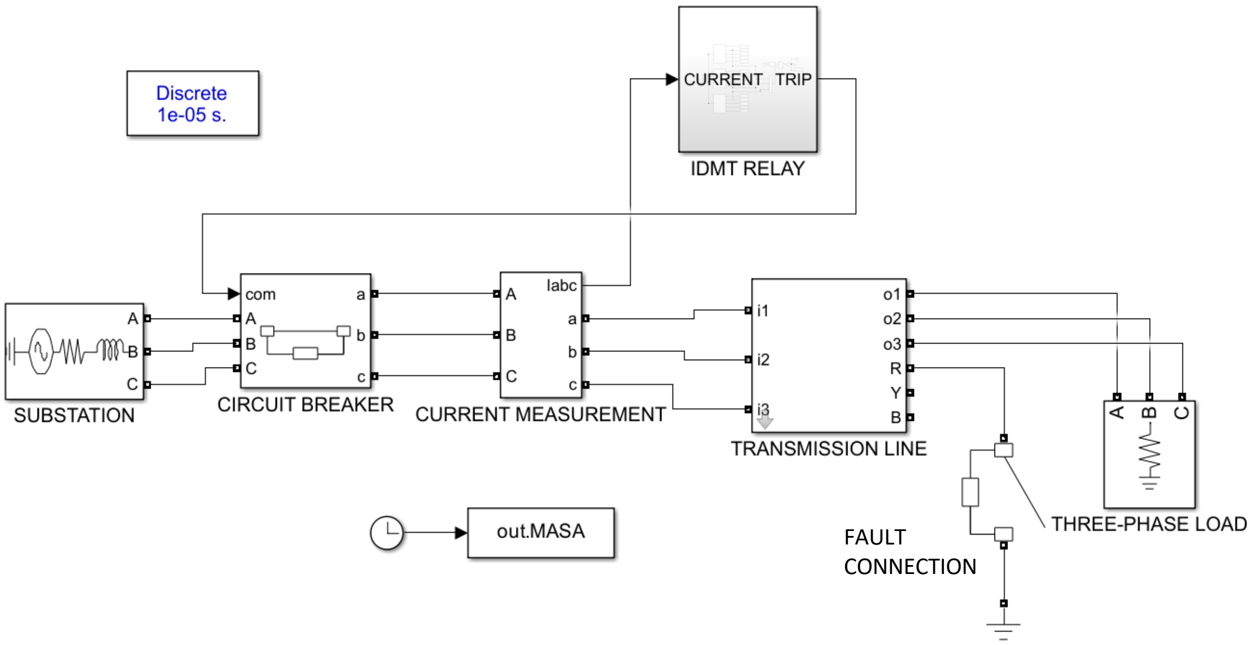

Fig. 2. Simulation model of transmission line and IDMT overcurrent relay

Table 2
Parameters for the simulation model

Parameters	Values
Phase-to-Phase Voltage, V_{rms}	220 kV
Frequency, f	50 Hz
Line CT Ratio	300/1 A
Line Positive-Sequence Resistance, R_1	0.0748746 Ω/km
Line Zero-Sequence Resistance, R_0	0.2199746 Ω/km
Line Positive-Sequence Inductance, L_1	1.27085 mH/km
Line Zero-Sequence Inductance, L_0	4.26289 mH/km
Line Positive-Sequence Capacitance, C_1	2.33471 nF/km
Line Zero-Sequence Capacitance, C_0	1.46429 nF/km
Line Length	100 km

Referring to Figure 4 which is for red phase overcurrent element, firstly, the input current (IR) will be converted to its rms value (RMS block). Then the primary RMS value is converted to its secondary value by dividing with the CT ratio. To get the pickup current, the plug setting (PS) is multiplied with the secondary rated current of current transformer (CTS). Next, the secondary RMS value of input current ($IR_{secondary}$) is checked whether it exceeds the pickup current (I_{pickup}) or not (relational operator). If the value exceeds the pickup current, the timer will be started (integrator). The operation time calculator is used to calculate the operation time based on fault current value using Eq. (5) for standard inverse curve. Once the time of the timer exceeds the calculated operation time, the trip signal will be sent to the circuit breaker to isolate the line.

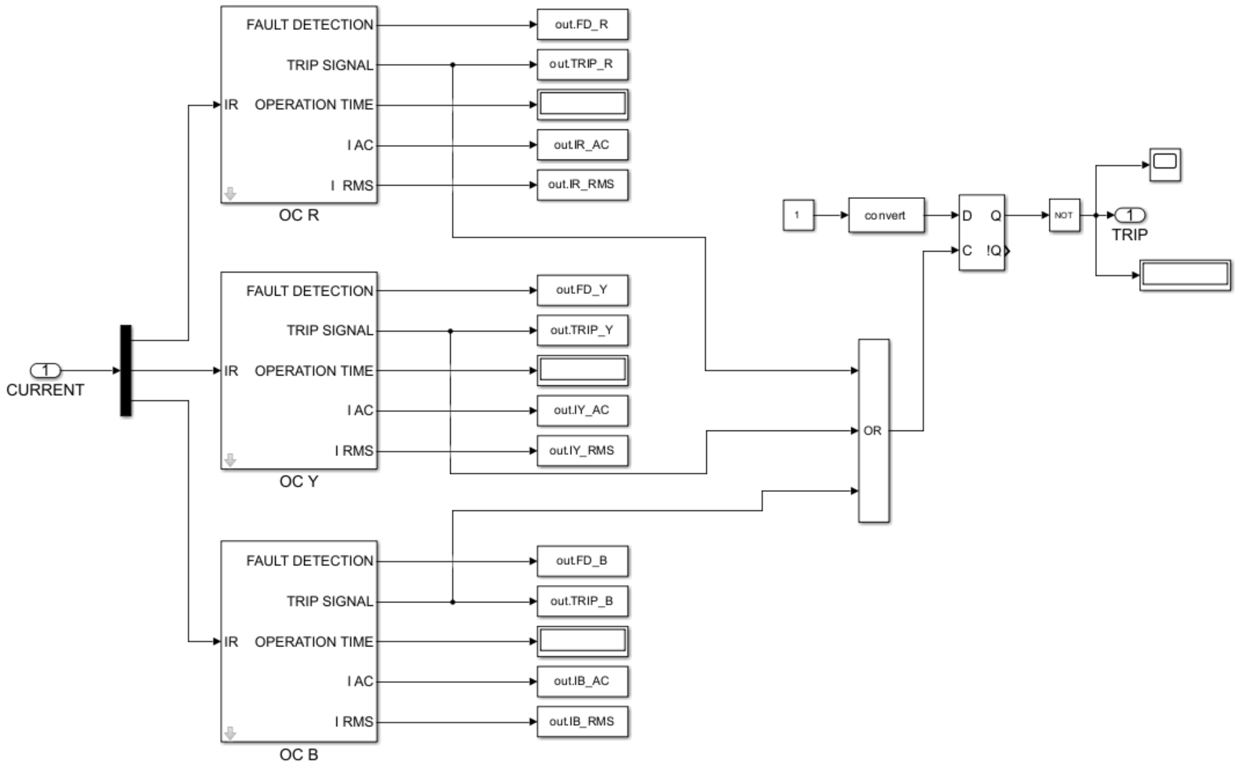

Fig. 3. The blocks inside IDMT overcurrent relay subsystem

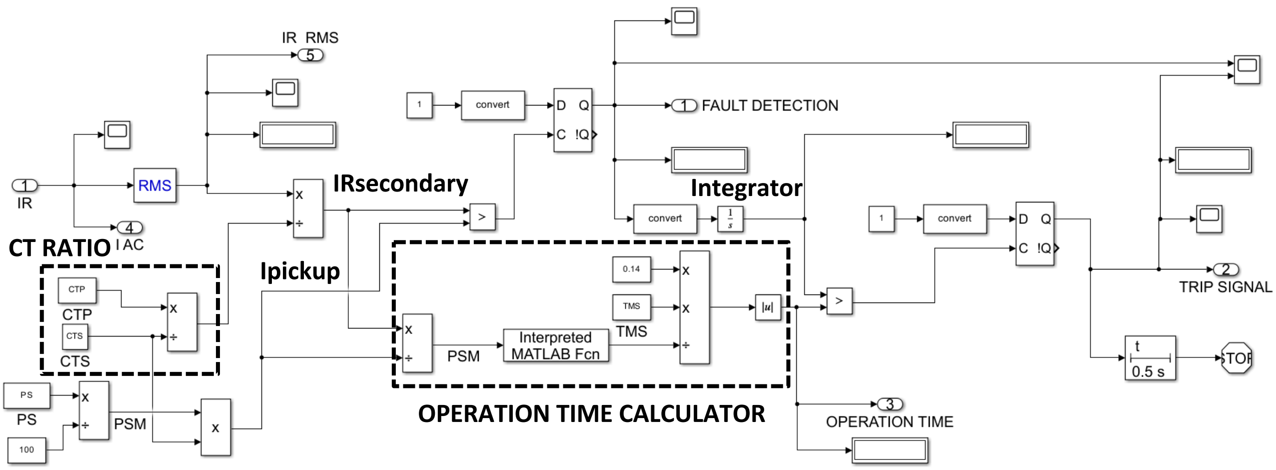

Fig. 4. The blocks inside OC R subsystem

4. Results and Discussion

This section presents the results of testing the IDMT overcurrent relay. Firstly, the results for an example of overcurrent relay operation are shown and discussed. Then, the results of the test on different fault resistance values and load variation are shown and the effects on relay operation time are discussed. All the tests are based on IDMT overcurrent relay standard inverse characteristic.

4.1 Single-Line-to-Ground (SLG) Fault at Red Phase

Before the simulation model can be used for various fault conditions, a single-line-to-ground fault was simulated to confirm the waveforms produced by the overcurrent relay which was developed using Simulink is correct. A red phase-to-ground permanent fault with 30 Ω fault resistance was simulated at 70 km from the substation. The fault was initiated at 0.2 s. For this test, the PS and TMS of the relay were set as 130 % and 0.3, respectively. Figure 5 shows the AC waveform of the current.

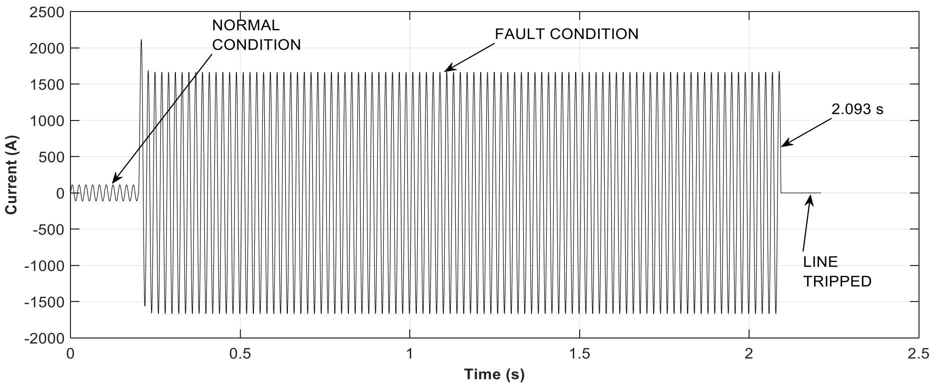

Fig. 5. AC waveform of the red phase current

Firstly, the waveform is in normal condition. At around 0.2 s, the current suddenly increased to a very high value due to the fault occurrence. Then, at 2.093 s, the current became zero because the line has been tripped by the relay after the operation time of the relay has been elapsed. The RMS waveform for the current is shown in Figure 6. Similar with previous figure, the RMS current suddenly increased at 0.2 s and the RMS fault current value is 1177.35 A. After the operation time of the relay has been elapsed, the tripping signal was sent at 2.097 s. After that, RMS current became zero once the breaker has been fully opened.

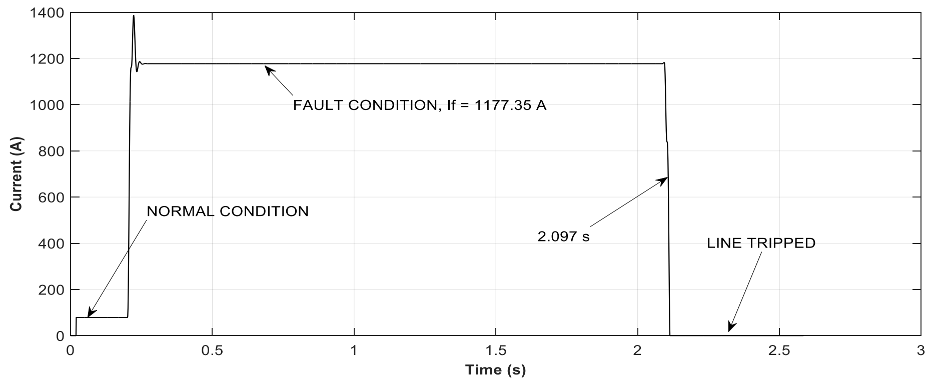

Fig. 6. RMS waveform of the red phase current

Fault detection signal is shown in Figure 7. The fault has been detected at 0.2051 s. The fault was detected after the fault current of 1177.35 A (Figure 6) exceeded the primary current setting (1.3 x 300 = 390 A). The relay then sent a trip signal after the operation time of the relay has been elapsed. Figure 8 shows the trip signal which was sent at 2.085 s. From Figure 7 and 8, the operation time of the relay is 1.8799 s (2.085 s – 0.2051 s).

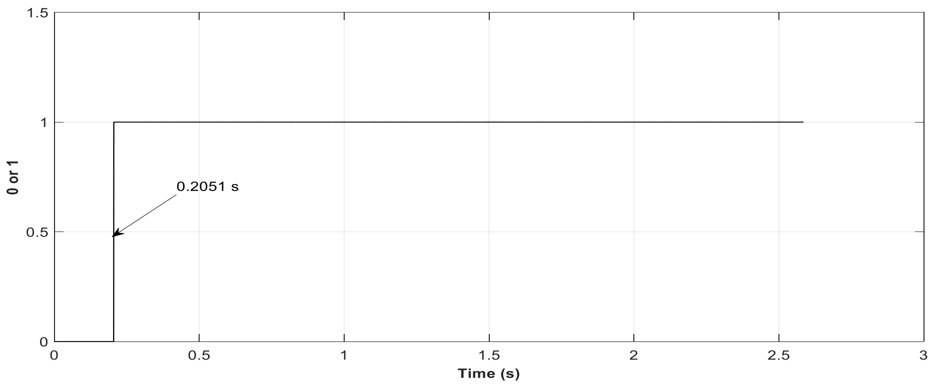

Fig. 7. Fault detection signal

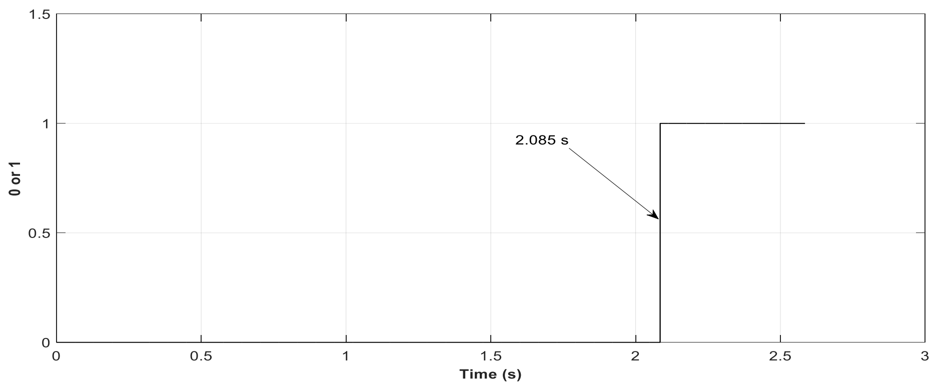

Fig. 8. Trip signal

To confirm the accuracy of the operation time, the operation time from simulation can be compared with the calculated operation time using Eq. (5) based on the fault current value and relay settings. The calculation is shown as follows:

$$t(s) = \frac{0.14}{\left(\frac{1177.35}{1.3\ x\ 300}\right)^{0.02} - 1}\ x\ 0.3 = 1.8797\ s$$

The calculated operation time is 1.8797 s which is approximately equal with the operation time from simulation (1.8799 s) with absolute difference of 0.0002 s which is very small.

4.2 Simulation Results for Fault Resistance Variation

Next is the test to study the effect of fault resistance on overcurrent relay operation time. The faults have been fixed to yellow-to-ground fault type, 80 km from local substation and occurred at 0.5 s. The fault resistance has been varied from small to high fault resistance values and the results is shown in Figure 9. In this test, the relay has been set with PS of 125% and TMS of 0.2.

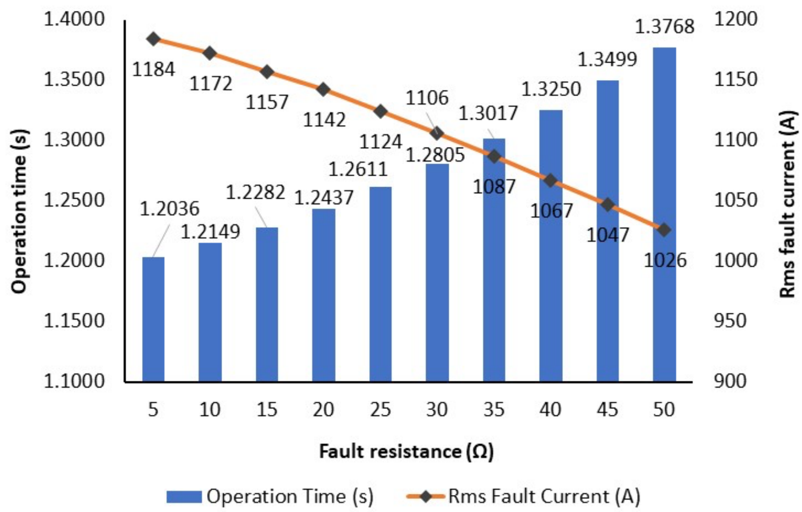

Fig. 9. Results of relay operation time and RMS fault current for different fault resistance values

From Figure 9, it can be concluded that, with the increases of fault resistance values, the RMS fault current decreases although all the faults occurred at the same location. As the consequence, the operation time of the relay to send a trip signal to isolate the fault increases with the increase of fault resistance values. This will make the relay becoming less sensitive to the faults with higher fault resistance values. Fault resistance is an unknown value and is dependent on the nature of the fault such as due to lightning, tree or crane touching the live line etc.

4.3 Simulation Results for Load Variation

In power system, load is normally connected through a transformer. The total load connected at a transformer normally dynamic and always changing with time. This is because, the transformer is connected to various load locations with different sizes. Thus, this test was conducted to study the effects of different total load values on the operation time of the relay.

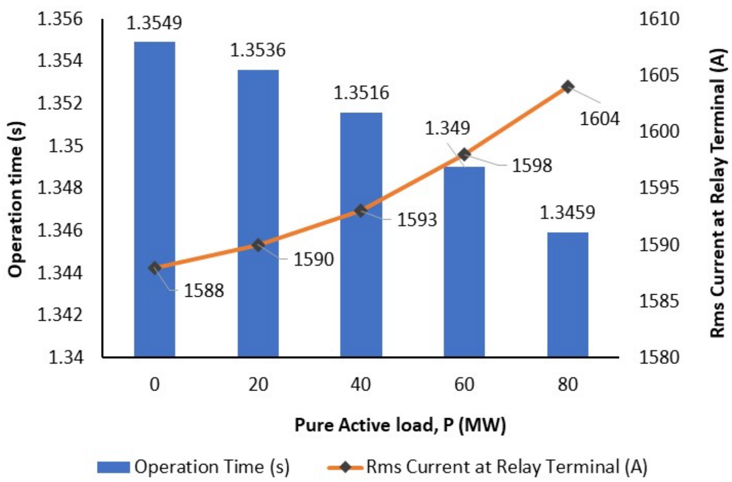

Fig. 10. Results of relay operation time and RMS current at relay terminal for purely active load variation

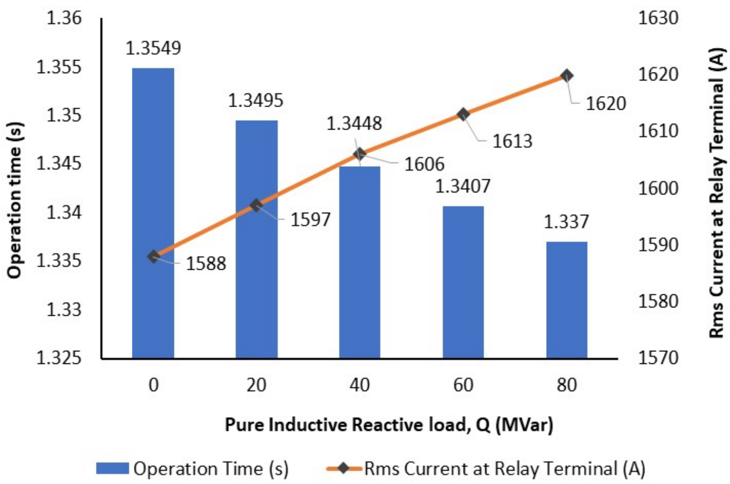

Fig. 11. Results of relay operation time and RMS current at relay terminal for purely inductive reactive load variation

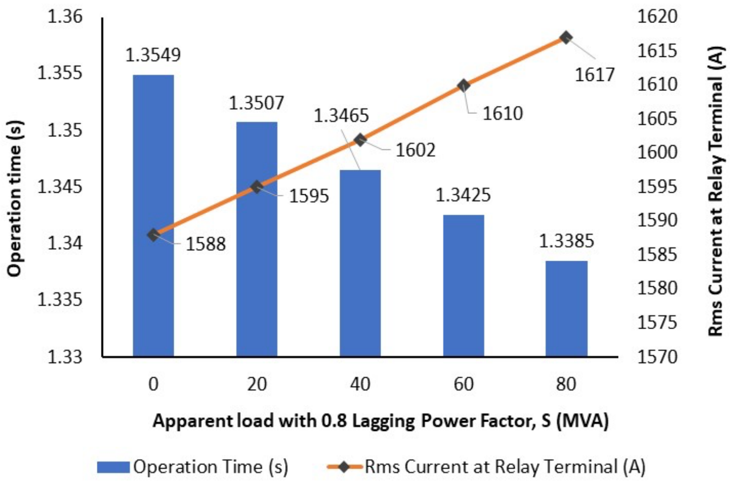

Fig. 12. Results of relay operation time and RMS current at relay terminal for variation of apparent load with 0.8 lagging power factor

The load here is configured in radial connected system as shown in Figure 2. Different load locations and configurations might have different effects. The effects of total load variation on the operation time of the relay are shown in Figure 10, 11 and 12 for purely active load, purely inductive reactive load and apparent load with 0.8 lagging power factor, respectively.

From all three load conditions, it can be concluded that with the increases of load, the RMS current measured at relay terminal also increases. This is because, the RMS current measured at relay terminal is the combination of fault current which flows through the fault point and load current which flows through the connected load. Thus, the higher the load current, the higher the RMS current measured at relay terminal. As the consequence, operation time of the relay for all three load conditions decreases with the increase of total connected load.

5. Results and Discussion

This paper has successfully studied the effects of fault resistance values and load variation on the operation time of IDMT overcurrent relay. First, the developed model has been tested on single line-to-ground fault to confirm the correctness of the model for simulating different fault conditions. Next, for the test on different fault resistance values, it can be concluded that the higher the fault resistance values, the higher the operation time of the relay which will make the relay to be less sensitive. From the results shown in Figure 9, the operation time for fault resistance of 50 Ω is 0.1732 s slower than the operation time for 5 Ω (1.3768 s – 1.2036 s) which is about 8.66 cycles for 50 Hz system. Then, for load variation, the higher the volume of connected load, the faster the operation time of the relay due to higher RMS current measured at relay terminal. For future recommendations, other factors which can gave effects on operation time of the relay can be studied such as inrush current, distributed energy connection etc.

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