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Research Article

Performance Evaluation of Overcurrent Relay Coordination on 20-kV Busbar and Feeders

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ABSTRACT

The coordination of Overcurrent Relays (OCR) in power systems is crucial to ensure selectivity and reliability. Mis-coordination between OCRs on the 20-kV busbar and feeders can significantly reduce system performance, often due to improper determination of pick-up values and Time Multiplier Setting (TMS). Previous studies mostly focused on protection coordination for a single feeder and relied solely on simulation. This study evaluates OCR coordination on the 20-kV busbar and five feeders connected to the Unit I transformer at Secang Substation by combining manual analysis and Electrical Transient Analyzer Program (ETAP) simulations, validated against IEEE Std 242-2001. This integrated approach provides more reliable insights than earlier works limited to single-feeder coordination or software-only methods. Evaluation was conducted through short-circuit current analysis and Time Current Characteristic (TCC) curves, yielding pick-up and TMS values that produce Coordination Time Intervals (CTI) in compliance with IEEE Std 242-2001. Results indicate that the busbar OCR achieved a pick-up of 0.566 and a TMS of 0.236. For the feeders, SCG 10 achieved 0.27 and 0.173; SCG 03 yielded 0.5025 and 0.147; SCG 05 produced 0.441 and 0.153; SCG 07 yielded 0.35 and 0.165; and SCG 08 achieved 0.5535 and 0.137. Applying these settings produced CTI values exceeding the minimum requirement of 0.3 seconds. This evaluation demonstrates that coordinated OCR settings can improve reliability in 20-kV distribution systems and reduce the risk of widespread outages due to protection failures.

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1. INTRODUCTION

The demand for electrical energy in the current era of technological advancement continues to increase. This condition must be supported by the reliability of the power system, including its protection system [1]. A reliable protection system can detect faults at an early stage and subsequently isolate them to prevent the disturbance from spreading to unaffected areas [2]. This aspect is particularly crucial in distribution systems to ensure the continuous availability of electrical energy for consumers [3].

One of the primary protection devices in a 20-kV distribution network is the Overcurrent Relay (OCR) [4]. This protective device requires precise settings in its operation to ensure proper coordination. Such proper coordination is intended to enable the protection system to function optimally, thereby minimizing disturbances [5].

Efforts to optimize the coordination of Overcurrent Relay operations have been carried out by [6][7]. Their study highlights that short-circuit analysis and assessment of existing components are essential to obtain accurate inputs for setting relay protection coordination. The coordination of OCRs in a network is considered reliable when the primary relay can quickly isolate faults within its designated zone, while the backup relay operates after a predetermined delay if the primary relay fails to function [8][9].

However, amid the increasing complexity of modern distribution systems, a major issue that frequently arises is the miscoordination between primary and secondary protection [10]. This issue also occurs in the operation of Overcurrent Relays. The miscoordination in question refers to discrepancies in the operating times between protection relays [11].

Regarding the issue of miscoordination, several previous studies have shown that the primary cause of miscoordination between Overcurrent Relays is the improper configuration of the pick-up setting and Time Multiplier Setting (TMS) [12]. An excessively small TMS difference between the main OCR and the backup OCR has the potential to cause operational miscoordination [13][14].

Various previous studies have been conducted regarding the coordination of protection systems in 20-kV distribution networks. These studies have been carried out through theoretical approaches as well as by utilizing software tools [15]-[17]. However, most of these studies remain general in nature, focusing on a single feeder network, and have not specifically analyzed the potential non-selectivity of relay coordination on the 20-kV busbar and feeder sides [18][19].

Therefore, this study aims to evaluate the coordination performance of Overcurrent Relays (OCR) on the 20-kV busbar and feeders connected to Transformer Unit I at the Secang Substation through a combination of manual analysis and ETAP-based simulation. The research focuses on determining the optimal OCR settings, including pick-up current and Time Multiplier Setting (TMS), assessing the Coordination Time Interval (CTI) in accordance with IEEE Std 242-2001[20], and analyzing the influence of pick-up and time-dial variations on the Time Current Characteristic (TCC) curves [21]. In addition, this study seeks to identify and minimize potential protection selectivity errors arising from improper OCR settings. Through the evaluation process, this research is expected to contribute to enhancing the reliability of the electrical distribution system. The contribution lies in the protection system by ensuring the achievement of optimal coordination performance of Overcurrent Relays on the 20-kV busbar and feeders. In addition, this study is expected to provide readers with valuable information and insights into topics relevant to the discussion of Overcurrent Relay coordination performance.

2. RESEARCH METHODS

2.1 Literature Study

The literature study was conducted by reviewing theoretical foundations to address the problems and achieve the objectives of the research. The study focused on books and journals relevant to the topic of protection system coordination, particularly Overcurrent Relays in electrical power systems.

2.2 Data Collection

The research was conducted at the 150-kV Secang Substation, located at Jl. Nasional No.14 24, Payaman, Ngadirojo, Secang District, Magelang Regency, Central Java. The data used in this study consisted of secondary data collected from PT PLN (Persero) UP3 Magelang and PT PLN (Persero) UPT Salatiga. Data collection was carried out through planned observations and interviews with employees at the research site.

The data used in this study were obtained through direct observation of relay settings and operational records at the Secang Substation, complemented by interviews with operational personnel. To ensure reliability, the collected data were cross-checked with official technical documents from PT PLN (Persero) UP3 Magelang and PT PLN (Persero) UPT Salatiga. The data were then validated by comparing the observed values with calculations based on the IEEE Std 242-2001 standard. In addition, the results of manual calculations were verified using simulation software, thereby strengthening the credibility and validity of the data.

2.3 Simulation of Existing OCR Coordination

The simulation of Overcurrent Relay coordination on the 20-kV busbar and feeder under existing conditions was carried out to determine the initial performance of the OCR coordination currently installed in the field. The simulation was performed using ETAP software, with component specifications adjusted according to the technical field data that had been collected.

2.4 OCR Resetting Calculation

The OCR resetting calculation was carried out through several stages to obtain the values of primary Iset, secondary Iset, pick-up current, and Time Multiplier Setting (TMS) as input variables.

2.4.1 Source Impedance Calculation

The source impedance represents the generator's capability to influence fault current levels. This calculation involves determining the short-circuit impedance at both the 150-kV and 20-kV sides [22].

2.4.2 Transformer Impedance Calculation

The transformer impedance value affects the magnitude of the fault current that can be transferred from the primary side to the secondary side. In calculating transformer impedance, the reactance is considered, while the resistance can be neglected due to its relatively small value.

2.4.3 Feeder Impedance Calculation

The total impedance value of a feeder is influenced by several factors, such as network configuration, feeder length, and conductor size. The feeder impedance calculation depends on the impedance value per kilometer of the feeder itself.

2.4.4 Equivalent Impedance Calculation

The equivalent network impedance is obtained by summing the impedance components from the source to the fault location. Since the impedances from the source to the fault point are connected in series, the equivalent impedance can be calculated through direct addition.

2.4.5 Fault Current Calculation

In the design and operation of an electric power system, analyzing the potential occurrence of short-circuit faults is essential. The results of this analysis significantly influence the design and configuration of the protection equipment used. Types of short-circuit faults include single line-to-ground faults, line-to-line faults, double line-to-ground faults, and three-phase faults. In accordance with the operating principle of the OCR, which only detects two-phase and three-phase short-circuit faults, this study only considers these two types of faults.

A line-to-line (two-phase) fault occurs when one phase becomes shorted to another phase without connection to ground. For a two-phase fault there is no zero-sequence component, and the positive- and negative-sequence components are connected in parallel. The magnitude of the two-phase fault current can be determined from the Equation (1).

$$I_f = \frac{V_{ph-ph}}{Z_1+Z_2} \quad (1)$$

with : I_f : fault current
V_{ph-ph} : phase-to-phase voltage
$Z1$: positive-sequence impedance
$Z2$: negative-sequence impedance

A three-phase short-circuit fault is a symmetrical fault, meaning that the current and voltage in each phase remain balanced after the fault occurs. Therefore, the magnitude of the three-phase fault current can be analyzed using only the positive-sequence component. The equation to determine the three-phase fault current is as in Equation (2).

$$I_f = \frac{V_{phasa}}{Z_1} \quad (2)$$

with : I_f : fault current
V_{phasa} : phase-to-neutral voltage
Z_1 : positive-sequence impedance

2.4.6 Calculation of Pick-Up Current and TMS

Based on the operating principle of the inverse-time overcurrent relay, the relay operating time is strongly influenced by the magnitude of the fault current. Therefore, determination of the optimal OCR settings must take into account the transformer's rated current, the CT ratio, and the expected range of fault currents.

There are two core parameters to be considered: the pick-up current setting and the time-dial setting. The pick-up or operating current is the threshold that determines when the relay should operate once the current reaches a specified value. The pick-up current value depends on the selection of the tap on the current transformer (CT). The OCR current setting can be calculated using the Equations (3) – (5).

$$I_{set(prim)} = 1{,}2 \times I_{b\,max} \quad (3)$$

$$Pick\text{-}up = \frac{I_{set(prim)}}{I_{n\,CT}} \quad (4)$$

$$I_{set(sec)} = I_{set(prim)} \times \frac{1}{CT\ ratio} \quad (5)$$

with : $I_{\mathrm{b\,max}}$: maximum load current (A)
$I_{set(prim)}$: primary current setting (A)
$I_{set(\mathrm{sec})}$: secondary current setting (A)
$I_{n\,CT}$: nominal current of current transformer (A)
CT ratio : ratio of current transformer

Next, based on the magnitudes of the short-circuit fault currents that have been determined, the relay time-setting values can be established using the Equation (6).

$$TMS = \frac{T \times \left[\left[\frac{I_{fault}}{I_{set}}\right]^{\alpha} - 1\right]}{\beta} \tag{6}$$

with : T : trip time (s)
TMS : Time Multiplier Setting
I_{fault} : short-circuit fault current (A)
I_{set} : relay pick-up current setting (A)
α, β : constants (determined according to the relay characteristic curve type)

The values of the constants α and β for each curve type are presented in Table 1 [7].

Table 1. Values of α and β based on curve types

Curve Types	α	β
Standard invers	0.02	0.14
Very Invers	1	13,2
Extremely Invers	2	80
Long Invers	1	120

2.5 Simulation of OCR Coordination Evaluation Results

The simulation of the evaluation results is performed using ETAP software. The input variables for the components used in this simulation are derived from the evaluation calculations conducted in the previous stage.

2.6 Program Code Design in Octave

In this study, Octave software is utilized as a computational tool. In addition to manual calculations, a program code will be developed to generalize the calculation of pick-up current and time dial settings, enabling its application to other case studies.

2.7 Evaluation Result Analysis

Based on the research problems and objectives defined in this study, the analytical technique used is regression analysis. This regression technique is applied to determine the causal relationship between the pick-up current and time dial setting values as independent variables, and the resulting OCR coordination curve as the dependent variable.

The analysis focuses on the Time Current Characteristic (TCC) curve and the Coordination Time Interval (CTI) of OCR coordination obtained from ETAP software simulations. The TCC curves and CTI tables will then be compared with the IEEE Std 242-2001 standard. The OCR settings are considered optimal if the TCC and CTI results meet the standard criteria. However, if the OCR coordination curve does not comply with the standard, adjustments to the OCR current and time settings will be performed.

The minimum standard value of the Coordination Time Interval based on IEEE Std 242-2001 is presented in Table 2 [23].

Table 2. Minimum CTI IEEE Std 242-2001

Downstream	Upstream			
	Fuse	Low-voltage breaker	Electro-mechanical relay	Static relay
Fuse	CS	CS	0,22 s	0,12 s
Low-voltage circuit breaker	CS	CS	0,22 s	0,12 s
Electromechanical relay (5 cycles)	0.20 s	0.20 s	0.30 s	0.20 s
Static relay (5 cycles)	0.20 s	0.20 s	0.30 s	0.20 s

3. RESULTS AND DISCUSSION

3.1 Research Results

The performance evaluation of the Overcurrent Relay (OCR) coordination on the 20-kV busbar and feeders was carried out on feeders connected to Unit I Transformer at Secang Substation. The evaluation process involved resetting the OCR on the 20-kV busbar side and the OCR at the base of each feeder. This resetting process was conducted through several stages, including literature review, data collection, calculation, simulation, and analysis, with the objective of ensuring that the coordination between the two relays complies with the standards specified in IEEE Std 242-2001.

3.1.1 Dataset

The transformer used as the object of this research is the Unit I Transformer at Secang Substation. The specification of the Unit I Transformer at Secang Substation, obtained from the attached nameplate, is presented in Table 3.

Table 3. Transformer specification

No.	Parameter	Value
1.	Brand/Serial Number	UNINDO /P060LEC764-05
2.	Power Rating	60 MVA
3.	Voltage Rating	150/20 kV
4.	Current Rating	230.9/1732.1
5.	Frequency	50 Hz
6.	Phase	3
7.	Impedance	12.14 %
8.	Cooling Type	ONAN/ONAF
9.	Configuration	STAR-STAR (YNyn0+d)
10.	Manufacturer	ALSTOM
11.	Year of Manufacture	2014

The technical data of the existing OCR settings on the 20-kV busbar and the feeders connected to Transformer Unit I of Secang Substation are presented in Table 4.

Table 4. Setting OCR existing

Parameter	Existing OCR Data	
	20-kV Busbar	Feeders
Brand	SCHNEIDER	SCHNEIDER
Type	MiCOM P141	MiCOM P123
I *pick-up*	1.04	0.6
TMS	0.15	0.15
Characteristic	Standard Invers	Standard Invers
CT ratio	2000/5	800/5

Transformer Unit I at Secang Substation supplies five feeders, namely SCG 03, SCG 05, SCG 07, SCG 08, and SCG 10. Their specifications are shown in Table 5.

Table 5. Feeder specification

Parameter	Value
Voltage	20 kV
Conductor Length	SCG 03 = 21.678 km SCG 05 = 25.175 km SCG 07 = 15.104 km SCG 08 = 61.032 km SCG 10 = 39.233 km
Conductor Size	240 mm^2
Cable Type	AAAC
Positive Sequence Impedance (Ohm/km)	0.1344 + j0.3158
Zero Sequence Impedance (Ohm/km)	0.2824 + j1.6034

The maximum load current data on the feeders used in this study were collected during the period from January 2025 to May 2025 at 10:00 AM and 7:00 PM on each feeder connected to Transformer Unit I at Secang Substation. The detailed data on peak load or maximum load for each feeder are presented in Table 6.

Table 6. Peak load data of each feeder

Feeder	Peak Load (A)
SCG 10	122
SCG 03	335
SCG 05	294
SCG 07	130
SCG 08	369
20-kV Busbar	942

Furthermore, the impedance data and short-circuit current on the 150-kV side of the Secang Substation are presented in Table 7.

Table 7. Short-circuit test data of Secang Substation

Parameter	Value
Substation	Secang
Voltage	150 kV
Positive Sequence Impedance	0.004344 + j0.042194
Negative Sequence Impedance	0.004392 + j0.042444
Zero Sequence Impedance	0.018566 + j0.087637
Single-Phase Short-Circuit Current	7,27 kA
Three-Phase Short-Circuit Current	9,97 kA

3.1.2 Simulation of the Existing Protection System

The initial simulation was carried out using ETAP software to analyze the coordination of the Overcurrent Relay (OCR) on the 20-kV busbar and feeders in the existing system. The input parameters of the components used in the simulation were adjusted based on the technical data that had been collected. The circuit to be simulated is presented in Figure 1.

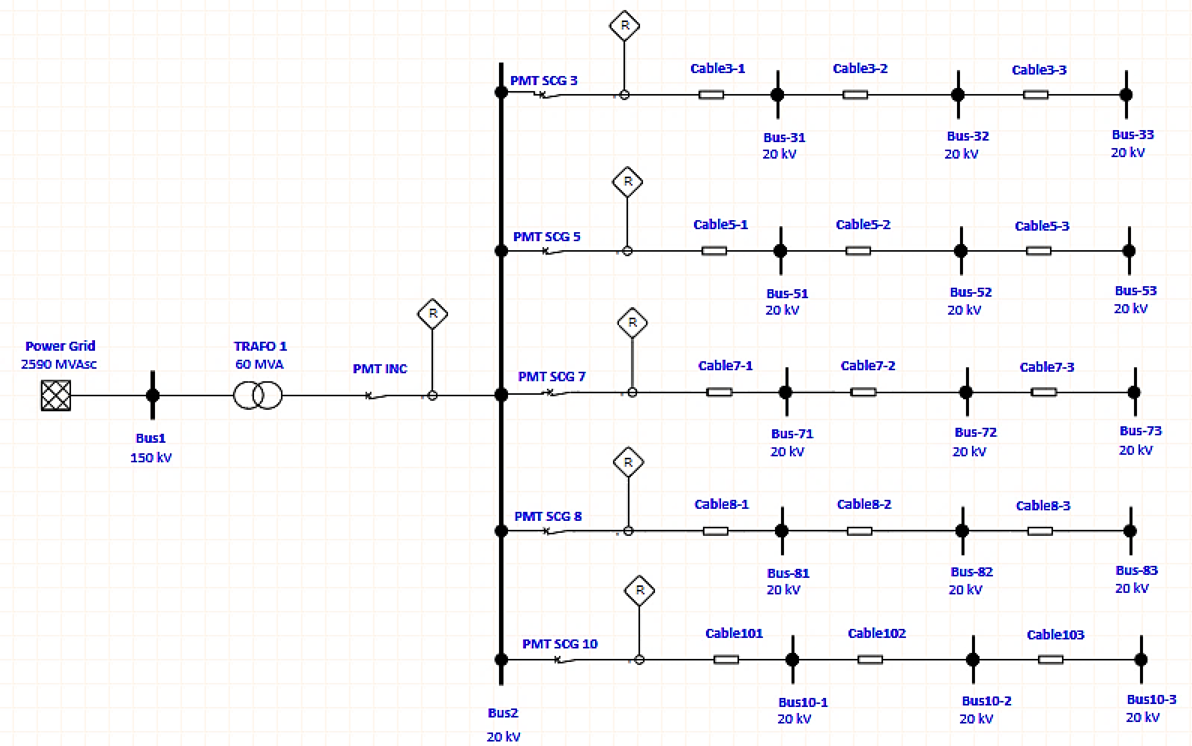

Figure 1. Protection system simulation circuit

Subsequently, a Star-Protection & Coordination simulation was carried out by applying a three-phase short-circuit fault. The fault simulation was applied to the SCG 10 feeder as a sample to evaluate the performance of the OCR on the feeder side. The selection of a single sample was due to the fact that all OCRs on the feeder side have identical characteristics, setting values, and CT ratios. Consequently, the resulting TCC curves are identical across all feeders, indicating that the protection system performance on the SCG 10 feeder is representative of all feeders connected to Transformer Unit I of Secang Substation.

The practice of sampling protection components with identical characteristics and settings has also been conducted by Reda [7], who stated that protection system coordination analysis can be simplified through grouping of relays with identical settings. With such simplification, the analysis results of one relay are considered representative of other relays with the same characteristics and settings.

The results of the Star-Protection & Coordination simulation, which show the operating sequence and the generated Time Current Characteristic (TCC) curve on the SCG 10 feeder, are illustrated in Figure 2.

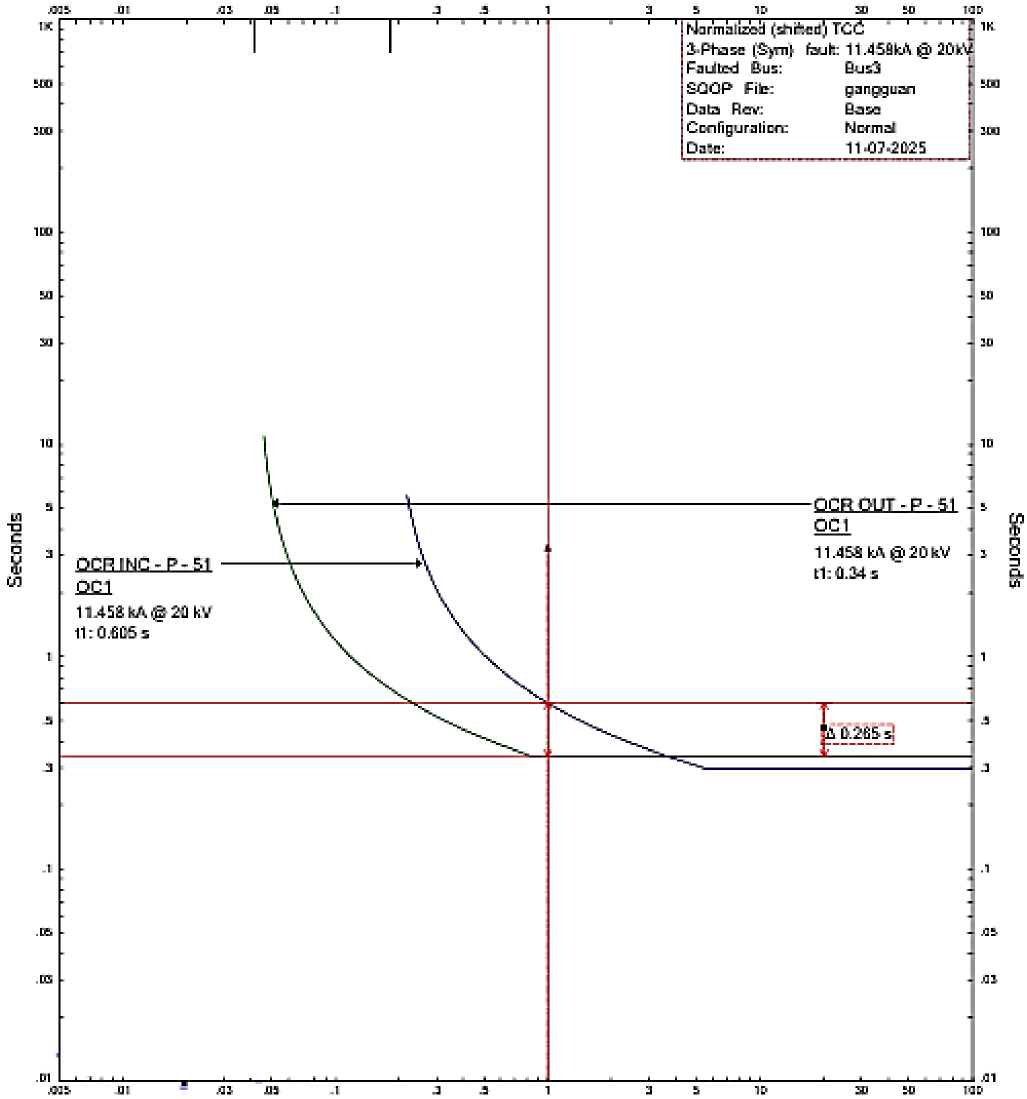

Figure 2. CTI TCC curve existing protection system

The simulation results in Figure 2 above show the Time Current Characteristic (TCC) coordination curves of the OCR on the 20-kV busbar, represented by the blue curve (OCR INC – P-51 OC1), and the OCR on the SCG 10 feeder, represented by the green curve (OCR OUT – P-51 OC1). The x-axis of the curve represents the fault current values, while the y-axis represents the relay operating time.

Under the simulated three-phase fault condition occurring at Bus 3, located at 1% of the total length of the SCG 10 feeder (0.4 km), it is observed that the OCR on the feeder side operates within 0.34 s, while the OCR on the 20-kV busbar side operates within 0.605 s. The time difference between the two OCR operations is 0.265 s. These results indicate that the Coordination Time Interval (CTI) between the 20-kV busbar OCR and the feeder OCR does not meet the minimum CTI requirement specified in IEEE Std 242-2001, as shown in Table 2. The table states that protection systems utilizing electromechanical relays on both upstream and downstream sides must have a minimum operating time interval of 0.3 s.

Furthermore, based on Figure 3, it can be observed that the two resulting curves intersect at a certain fault current point. This indicates an overlap in the coordination curves, which implies a potential miscoordination between the OCR on the 20-kV busbar side and the feeder. The red-circled area in the figure highlights a range of fault currents where the 20-kV busbar OCR may operate faster than the feeder OCR.

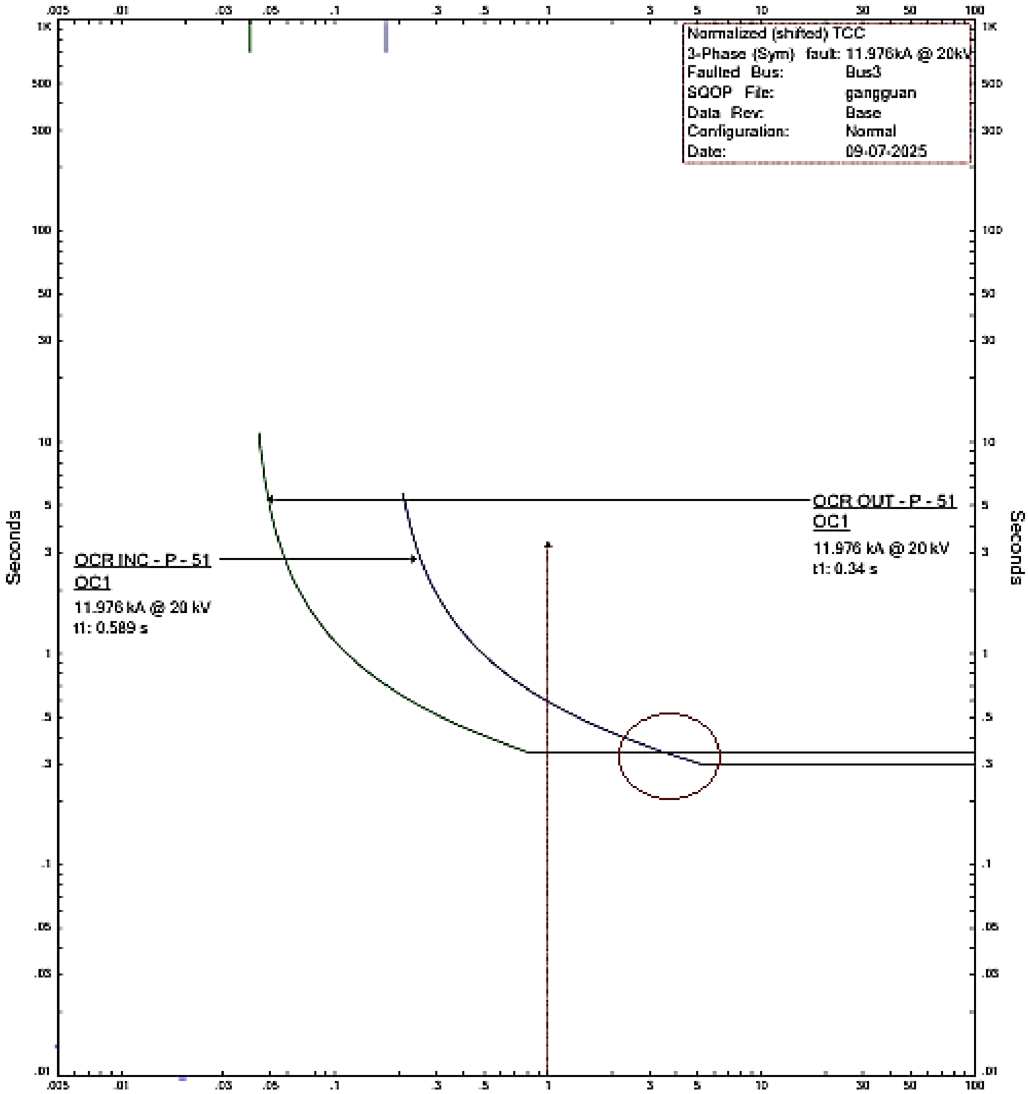

Figure 3. TCC Curve Existing Protection System

The intersection of the curves indicates the need for an evaluation of the relay coordination settings. This evaluation is intended to eliminate the intersection points of the coordination curves, thereby ensuring the selectivity of the protection system under all possible fault current conditions. The evaluation will be carried out to determine the optimal pickup current and time multiplier setting (TMS) values for the OCR on both the 20-kV busbar side and the feeder.

3.1.3 Overcurrent Relay Setting Calculation

The OCR setting calculation is carried out to obtain the optimal values of primary current setting (Iset primary), secondary current setting (Iset secondary), pick-up current, and Time Multiplier Setting (TMS). The OCR setting calculation begins with the determination of the short-circuit fault current that may occur on the feeder network. The short-circuit current value can be obtained by considering the source impedance, transformer impedance, feeder impedance, and the equivalent impedance of the entire network.

After the impedance values were calculated, the equivalent impedance was obtained, representing the overall magnitude of impedance in each feeder network. The impedance values for each feeder at distances of 1% (near-end), 50% (mid-line), and 100% (far-end) are shown in Table 8.

Table 8. Equivalent Impedance Value

Feeders	Equivalent Impedance		
	1% Distance (near-end)	50% Distance (mid-line)	100% Distance (far-end)
SCG 10	0.0524 + j1.086	2.636 + j7.158	5.272 + j13.353
SCG 03	0.0282 + j1.029	1.456 + j4.386	2.913 + j7.809
SCG 05	0.0336 + j1.042	1.691 + j4.938	3.383 + j8.913
SCG 07	0.02 + j1.01	1.015 + j3.348	2.03 + j5.733
SCG 08	0.082 + j1.156	4.101 + j10.601	8.305 + j20.478

After all the determining factors have been identified, the maximum and minimum short-circuit fault currents that may occur on each feeder connected to Transformer Unit I at the Secang Substation can then be calculated. Subsequently, the relationship between the impedance values and the resulting fault current magnitudes can be analyzed. The three-phase short-circuit current values and two-phase short-circuit current values for each feeder, with fault locations determined based on the impedance calculation distances, are shown in Table 9.

Table 9. Short-circuit current values

Feeders	Three-Phase Short-Circuit Faults (kA)			Two-Phase Short-Circuit Faults (kA)		
	1%-Distance	50%-Distance	100%-Distance	1%-Distance	50%-Distance	100%-Distance
SCG 10	10.632	1.514	0.804	9.196	1.311	0.697
SCG 03	11.214	2.499	1.385	9.712	2.164	1.200
SCG 05	11.076	2.212	1.211	9.592	1.916	1.049
SCG 07	11.426	3.301	1.899	9.895	2.858	1.644
SCG 08	9.967	1.016	0.529	8.632	0.88	0.458

After the maximum and minimum short-circuit fault current values for each feeder have been determined, the next step is to calculate the setting variables of the Overcurrent Relay (OCR). The determination of the OCR setting values must ensure that the relay does not operate at the maximum load current but can operate at the minimum fault current. Therefore, the pick-up current value must be set so that the primary setting current (Iset) is above the maximum load current and below the minimum fault current. This approach ensures that the OCR can accommodate maximum load while remaining responsive to minimum fault currents. To guarantee a safe operational margin against load fluctuations and maintain operational sensitivity, a multiplying factor of 1.2 times the maximum load current is selected [6].

Based on the application of the OCR relay implemented in the field and its adjustment with the simulation in the ETAP software, the variable used to determine the OCR current setting (Iset) is the primary nominal current value of the Current Transformer (CT) in use. Thus, the primary Iset value is obtained from the ratio between the load fluctuation tolerance and the primary nominal current of the CT. The CT current rating used in this evaluation process remains the same as the CT rating installed in the field. Therefore, the determination of the pick-up coefficient will be adjusted by considering both the maximum load current and the CT rating being used.

The T (base time) value used in calculating the Time Multiplier Setting (TMS) for the feeder-side OCR is 0.3 seconds, while the base time for the 20-kV busbar OCR is set to 0.7 seconds. This choice is based on the system requirement that the 20-kV busbar side OCR, which functions as a backup relay, have a slower operating time than the feeder-side relays. Choosing a larger TMS for the backup relay will improve protection coordination, but it must remain within the allowable protection operating range of 0–1[13][24].

Using Equations (3) through (6) together with the collected data, the calculated settings for primary Iset, secondary Iset, pick-up, and TMS are summarized in Table 10.

Table 10. Comparison of Existing OCR Settings and Evaluation Results

OCR	Existings OCR Setting				OCR Setting Based on Evaluation			
	$I_{set(prim)}$ (A)	$I_{set(\sec)}$ (A)	Pick-Up	TMS	$I_{set(prim)}$ (A)	$I_{set(\sec)}$ (A)	Pick-Up	TMS
SCG 10	480	3	0.6	0.15	146.4	0.915	0.183	0.191
SCG 03	480	3	0.6	0.15	402	2.513	0.5025	0.147
SCG 05	480	3	0.6	0.15	352.8	2.205	0.441	0.153
SCG 07	480	3	0.6	0.15	156	0.975	0.195	0.192
SCG 08	480	3	0,6	0.15	442.8	2.767	0.5535	0.137
20-kV Busbar	2080	5.2	1.04	0.15	1132	2.83	0.566	0.236

3.1.4 Simulation of OCR Coordination Evaluation Result

The protection system simulation from the evaluation results was conducted to analyze the level of improvement in the performance of OCR coordination on the 20-kV busbar and feeders connected to Transformer Unit I at Secang Substation. The system simulation was carried out using ETAP software, with the OCR setting values applied based on the evaluated results.

By applying the evaluated setting values, the expected conditions were achieved on feeders SCG 03, SCG 05, and SCG 08. The Coordination Time Interval (CTI) between the OCR curve on the 20-kV busbar and the OCR on the SCG 03 feeder was found to be 0.348 s. For the SCG 05 feeder, the CTI was 0.337 s, and for the SCG 08 feeder, the CTI reached 0.407 s. These CTI values meet the minimum requirement of 0.3 s as specified in IEEE Std 242-2001. In addition, no curve overlapping was observed between the two OCR curves. This indicates that there is no potential for relay miscoordination.

However, for feeder SCG 10 with a pick-up value of 0.183 and a TMS of 0.191, as well as for feeder SCG 07 with a pick-up value of 0.195 and a TMS of 0.192, the resulting Coordination Time Interval (CTI) values do not meet the minimum required threshold.

The Time-Current Characteristic (TCC) curve result for the coordination between the OCR on the 20-kV busbar and the feeder SCG 10 is shown in Figure 4.

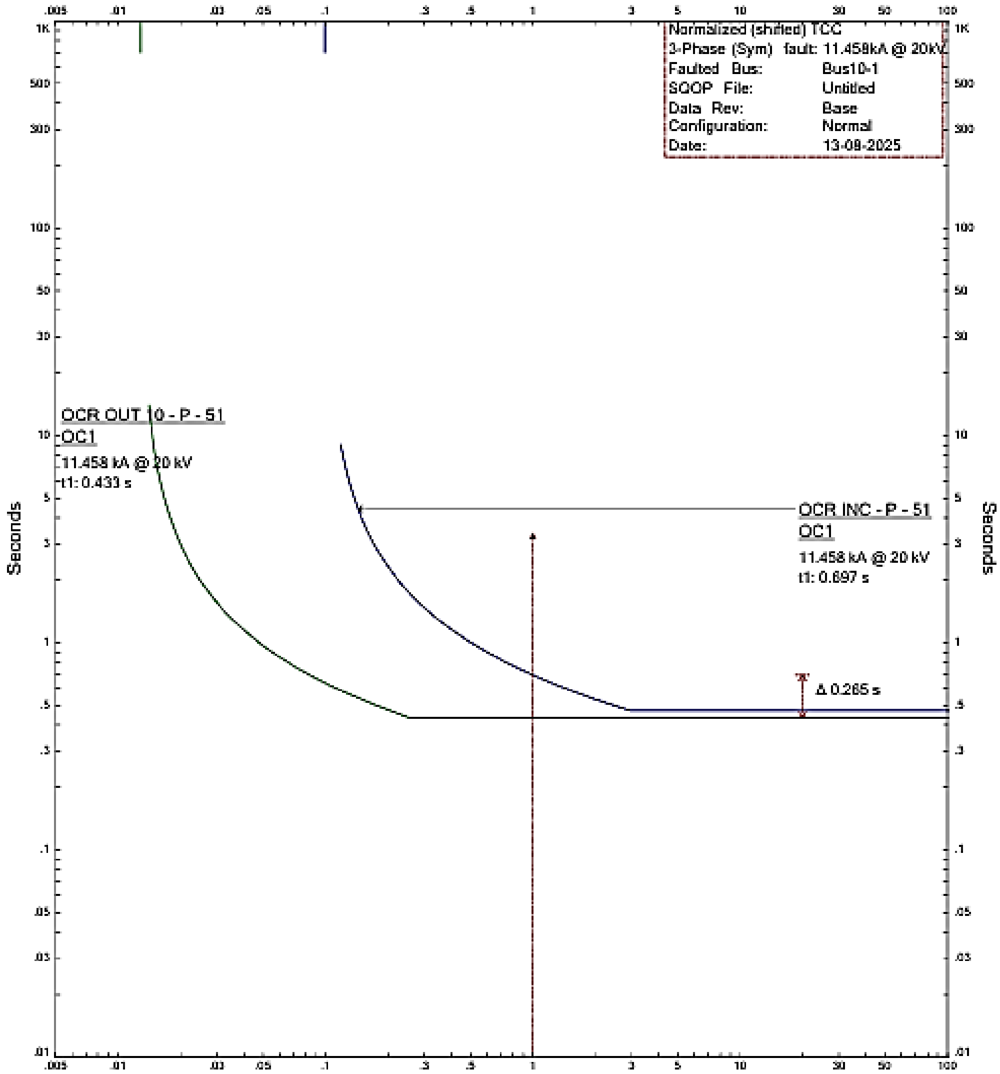

Figure 4. TCC Curve of OCR SCG 10 and OCR 20-kV Busbar

Under the three-phase short-circuit fault scenario at a distance of 1%, the feeder OCR operates within 0.433 seconds, while the 20-kV busbar OCR operates within 0.697 seconds. The resulting Coordination Time Interval (CTI) between the two relays is 0.265 seconds. This CTI value does not meet the minimum standard specified in IEEE Std 242-2001, which is 0.3 seconds. Although there is no curve overlapping between the two relays, a CTI value below 0.3 seconds may lead to mis-coordination [6]. Therefore, an adjustment of the relay settings is required to achieve the minimum CTI threshold.

According to Bui [12], the factors that can hinder OCR coordination include the relay operating time, the selection of the pick-up value (multiplier), the curve coefficient, and the Time Multiplier Setting (TMS). Hence, an optimization will be carried out to improve the operating time difference (CTI) between the feeder OCR as the primary relay and the 20-kV busbar OCR as the backup relay.

After the adjustment, the obtained values are primary Iset of 216 A, secondary Iset of 1.35 A, pick-up of 0.27, and TMS of 0.173. By applying these settings, the CTI value achieved is 0.306 seconds, which meets the minimum standard specified by IEEE Std 242-2001.

Meanwhile, for feeder SCG 07, the TCC curve result for the coordination with the OCR on the 20-kV busbar is presented in Figure 5.

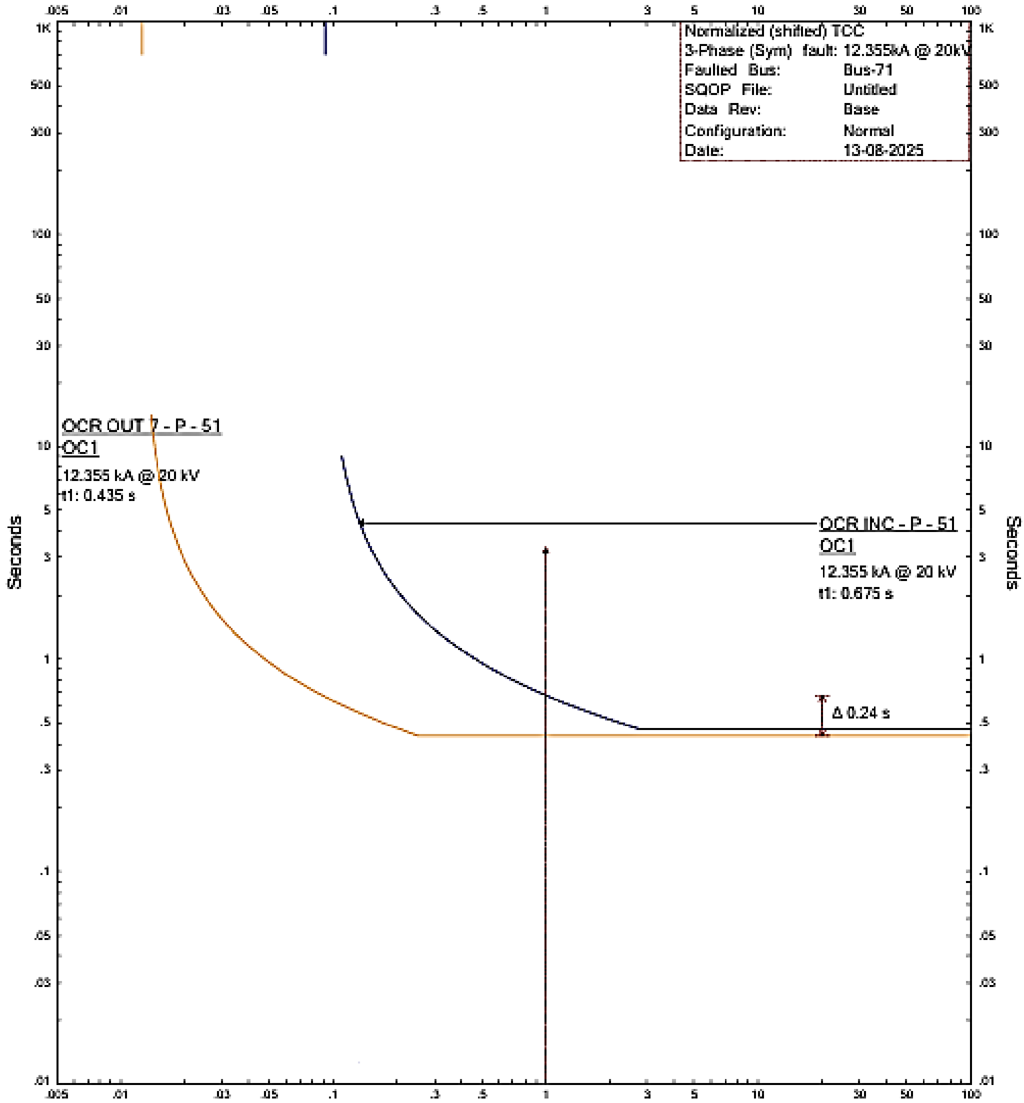

Figure 5. TCC Curve of OCR SCG 07 and OCR 20-kV Busbar

By applying the same adjustment scenario as implemented for feeder SCG 10, feeder SCG 07 achieved a primary Iset of 280 A, secondary Iset of 1.75 A, pick-up of 0.35, and TMS of 0.165. These settings resulted in a CTI value of 0.301 seconds, which meets the minimum CTI requirement specified by IEEE Std 242-2001.

3.1.5 Program Code Design in Octave

The Octave program was developed to generalize the calculation of overcurrent relay coordination for other case studies. The program includes a Graphical User Interface (GUI) to facilitate ease of use. The GUI will support the data input process for the variables required in the OCR coordination calculations. The stages of the designed program code process are illustrated in Figure 6.

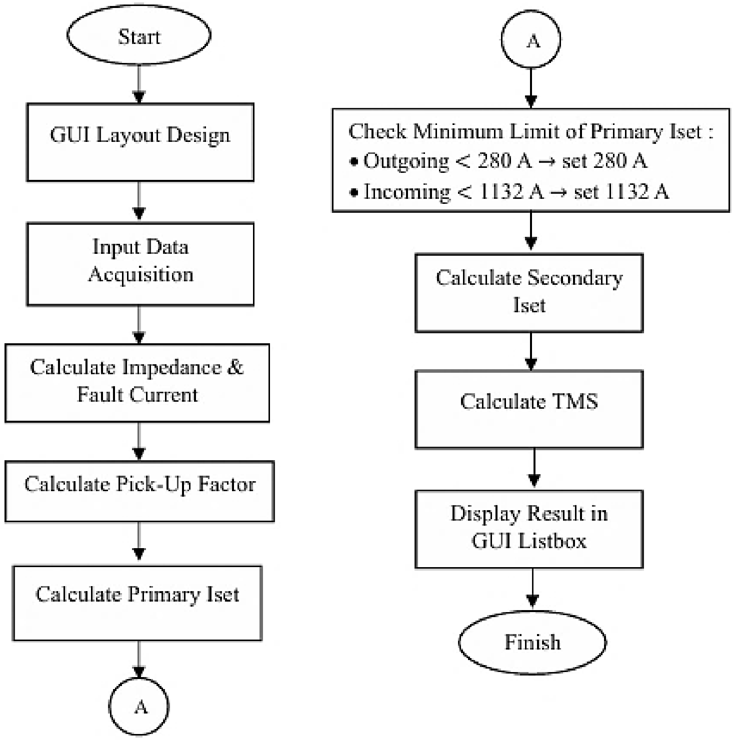

Figure 6. Algorithm of the OCR setting calculation program

3.2 Discussion

Based on the simulation of the existing conditions using the collected data, it was found that the Coordination Time Interval (CTI) between the 20-kV busbar OCR curve and the feeder-side OCR curve does not meet the requirements specified in the IEEE Std 242-2001 standard. According to this standard, a protection system utilizing electromechanical relays on both the downstream and upstream sides must have a minimum CTI value of 0.3 seconds. Meanwhile, the CTI value obtained from the existing system was 0.265 seconds. In addition, there is an overlapping of the Time Current Characteristic (TCC) curves between the feeder OCR, which functions as the primary protection relay, and the 20-kV busbar OCR, which serves as the backup protection relay. This condition indicates a potential occurrence of relay miscoordination.

An evaluation of the Overcurrent Relay (OCR) coordination performance on the 20-kV busbar and feeders has been carried out. The coordination performance between the 20-kV busbar OCR and the feeder OCRs connected to Transformer Unit I at the Secang Substation was evaluated by adjusting the relay settings. The evaluation process began with calculating the maximum and minimum short-circuit fault currents that could occur within the network. The calculation results for each feeder show that the maximum fault current occurs during a three-phase short circuit at 1% of the feeder length (near-end), while the minimum fault current occurs during a two-phase short circuit at 100% of the feeder length (far-end). This analysis indicates a negative correlation between the magnitude of the fault current and the distance of the fault location from the upstream point of the network. Fault current values decrease significantly as the fault location moves farther from the source. These results are consistent with the findings of Reda [7], who reported that fault currents decreased from approximately 9.16 kA at location F1 (near-end) to 0.797 kA at location F5 (far-end) due to increased line impedance with distance from the source. When compared quantitatively, the results of this study exhibit a similar trend, for example, on the SCG 10 feeder, the maximum three-phase fault current of 10.632 kA at 1% (near-end) decreases to 0.804 kA at 100% (far-end).

In another study conducted by Sun [9], who performed an OCR coordination analysis on a 22-kV distribution system using ETAP software, it was reported that the fault current ranged from 8.10 kA (for three-phase faults near the source) to 3.25 kA (for two-phase faults at the far end of the network), with Coordination Time Interval (CTI) values between 0.28 and 0.33 seconds. In comparison, the CTI range obtained in this study was 0.32–0.41 seconds, indicating a more conservative coordination margin. This difference is primarily attributed to the higher feeder impedance and longer line length at the Secang Substation, which increase the total system reactance and consequently extend the relay operating time.

The maximum and minimum fault current values are essential to determine, as the OCR setting parameters are highly influenced by these two factors. Determining the pick-up setting of the OCR is influenced by two main parameters: the minimum fault current and the maximum load current [11]. This means that the primary Iset value must be set above the maximum load current and below the minimum fault current. This approach ensures that the relay can handle the maximum load current while remaining sensitive to the minimum fault current. Therefore, the primary Iset value should be set above the maximum load current and below the minimum fault current. In this study, a multiplication factor of 1.2 was applied to the maximum load current to determine the primary Iset value [6].

Based on the compiled load current data for each feeder and the calculated fault current values, the pick-up and TMS setting parameters were determined for each feeder OCR and the 20-kV busbar OCR. As a result, the 20-kV busbar side yielded a pick-up value of 0.566 and a TMS of 0.236. For feeder SCG 03, the pick-up and TMS values obtained were 0.5025 and 0.147, respectively. Feeder SCG 05 produced a pick-up of 0.441 and a TMS of 0.153, while feeder SCG 08 had a pick-up of 0.5535 and a TMS of 0.137. The coordination performance results between the 20-kV busbar OCR and the feeder OCRs of these three feeders indicate CTI values above 0.3 s, thereby satisfying the minimum CTI requirement specified in IEEE Std 242-2001. Moreover, no overlapping of the TCC curves was observed between the two OCRs, indicating that there was no potential protection miscoordination.

However, for feeder SCG 10 with a pick-up of 0.183 and TMS of 0.191, and feeder SCG 07 with a pick-up of 0.195 and TMS of 0.192, the resulting CTI values failed to meet the minimum required threshold. These results indicate a coordination mismatch when the primary Iset value is determined using a fixed multiplier factor of 1.2. This discrepancy can be attributed to the fact that feeders SCG 10 and SCG 07 have lower maximum load currents compared to the other three feeders connected to Transformer Unit I at the Secang Substation, leading to excessively low pick-up settings and consequently higher TMS values. This finding suggests that the selection of the load tolerance multiplier factor should not be universally set at 1.2[6], but should instead consider the specific load fluctuation characteristics of each feeder and be periodically validated through system performance testing.

Based on the pick-up and TMS parameters used as input for the OCR settings, challenges in OCR coordination primarily arise from variations in relay operating times, the selection of pick-up multipliers, curve coefficients, and TMS values. In this study, a multiplication factor of 1.2 was applied to determine the pick-up current setting based on the maximum load current, resulting in a pick-up current of 0.566 A for the 20-kV busbar OCR. In comparison, Bui [12] reported that for a 22-kV distribution system integrated with distributed generation, the optimal multiplier factor ranged between 1.15 and 1.25, producing pick-up current settings between 0.54 A and 0.58 A. The close quantitative agreement between these values confirms that the selected 1.2 multiplier lies within the optimal coordination range. However, Bui's study also highlighted that a slightly lower multiplier (1.15) minimizes time overlap between primary and backup relays, whereas a higher value (1.25) provides additional stability under variable fault conditions. Therefore, the selection of 1.2 in the present work represents a balanced compromise that ensures adequate sensitivity without compromising coordination reliability.

After conducting an analysis by adjusting the pick-up and TMS values, it was found that the failure to meet the minimum CTI requirement on feeders SCG 10 and SCG 07 was primarily due to excessively high TMS values. In inverse-type OCRs, the TMS value is inversely proportional to the pick-up setting, which itself depends on the feeder's maximum load current. According to Foqha [10], the pick-up current should be selected within a range defined by its lower limit, the maximum load current and its upper limit, the minimum fault current, to maintain proper sensitivity and selectivity. Quantitatively, this range ensures that the relay operates with sufficient margin, typically setting the pick-up value between 1.25 and 1.5 times the maximum load current, while keeping it below the minimum fault current observed under short-circuit conditions. In comparison, the results of this study align with that principle, where feeders exhibiting lower maximum load currents consequently produced lower pick-up settings and higher TMS values, leading to a reduced CTI margin.

4. CONCLUSION

Based on the data collected and the analysis conducted during the evaluation of the coordination performance of Overcurrent Relays (OCR) on the 20-kV busbar and feeders, it can be concluded that the Time Current Characteristic (TCC) curves of the two OCRs in the existing protection system indicate non-compliance of the Coordination Time Interval (CTI) with the minimum threshold of 0.3 s specified in IEEE Std 242-2001. In addition, curve overlapping was observed, indicating a potential for protection miscoordination. Following the evaluation, the CTI values obtained exceeded the minimum threshold specified in IEEE Std 242-2001, and the overlapping between the two OCR curves was eliminated. The analysis of the relationship between pick-up current and Time Multiplier Setting (TMS) on the standard inverse TCC curves shows that excessively small pick-up values result in larger TMS values. This causes the TCC curve of the feeder OCR, acting as the primary relay, to approach that of the 20-kV busbar OCR, acting as the backup relay, thereby failing to meet the minimum CTI requirement. Conversely, by increasing the pick-up value of the feeder OCR, the TMS can be reduced, allowing the TCC curves of the relays to be separated with a time interval that complies with the standard.

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