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Coordination Analysis of Overcurrent Relays (OCR) and Directional Ground Relays (DGR) for Transformer Protection at Segoromadu Substation, Gresik

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Abstrak

Transformator merupakan komponen vital dalam penyaluran energi listrik yang rentan terhadap gangguan arus lebih dan hubung singkat, terutama pada gardu induk. Dalam penelitian ini, dilakukan analisis koordinasi Over Current Relay (OCR) dan Directional Ground Relay (DGR) untuk melindungi transformator di Gardu Induk Segoromadu, Gresik. Analisis ini bertujuan menentukan setting optimal OCR dan DGR, serta menguji keandalan proteksi daripada peralatan pengaman. Pengukuran dilakukan dengan menghitung arus gangguan hubung singkat tiga fasa, dua fasa, dan satu fasa ke tanah, serta pengaturan waktu relai. Hasil simulasi menunjukkan bahwa setting yang tepat pada OCR dan DGR dapat meningkatkan keandalan dan keamanan sistem proteksi gardu induk dalam menjaga pasokan energi yang stabil. Temuan ini memberikan kontribusi penting dalam meningkatkan performa sistem proteksi dan dapat menjadi acuan untuk pengembangan sistem proteksi di gardu induk lainnya

Abstract

Transformers are vital components in the distribution of electrical energy that are susceptible to overcurrent and short circuit disturbances, especially in substations. In this study, an analysis of the coordination of Over Current Relay (OCR) and Directional Ground Relay (DGR) was conducted to protect transformers in the Segoromadu Substation, Gresik. This analysis aims to determine the optimal settings of OCR and DGR, as well as to test the reliability of protection rather than safety equipment. Measurements were made by calculating the short circuit current of three phases, two phases, and one phase to ground, as well as the relay time settings. The simulation results show that the right settings on OCR and DGR can improve the reliability and safety of the substation protection system in maintaining a stable energy supply. These findings provide an important contribution in improving the performance of the protection system and can be a reference for the development of protection systems in other substations.

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Introduction

The electric power distribution system is a process of sending electric power through several stages starting from the generation, transmission and distribution systems. Each stage uses equipment so that the electric power reaches consumers reliably, safely and efficiently.

The components in the electric power distribution process at the substation are equipment that has an important role, one of which is a transformer or commonly called a transformer. Power transformers are one of the sensitive components in the electric energy channel and are susceptible to interference both inside and outside the transformer itself (Widagdo *et al.*, 2023). Transformers are very vital equipment in the distribution of electricity. does not rule out the possibility of interference, especially short circuits caused by excess current. This interference can be in the form of a 3-phase, 2-phase, or 1-phase to ground short circuit. The interference that occurs can be predicted, so that to prevent it, appropriate and reliable safety equipment or protection systems are needed (Widagdo *et al.*, 2024). Protection is a form of protection against equipment to avoid damage and ensure the continuity of a reliable electric power system. The protection system must be able to work to cut off the interference current that appears in the system quickly and selectively (Widagdo *et al.*, 2024). Protection systems, in addition to securing electrical equipment against interference, also function to localize interference, thereby minimizing the impact on other parts of the system. Therefore, protection is very necessary in the power system (Widagdo *et al.*, 2024).

In previous research by (Nursalim *et al.*, 2019), the results of the OCR settings are based on parameters such as short circuit current, relay location, and relay working time. The settings obtained are as follows: Relay Bus 1 FCP with a pickup current (I_P) of 3 A and Time Multiplier Setting (TMS) of 0,1 s, Relay Bus Auxiliary I with I_P of 2 A and TMS 0,21 s, Relay Bus Outgoing 1 with Ip of 0,6666 A and TMS 0,30 s, and Relay Bus G1 with I_P of 1 A and TMS 0,45 s. The relay on the pump motor is set with a faster operating time because its location is further downstream with a smaller short circuit current. The inter-relay delay time setting (Δt) is 0,204 to 0,34 seconds, in accordance with the IEEE 242-1986 standard which recommends a delay time for digital relays in the range of 0,2–0,4 seconds. Next is a research conducted by (Imawan *et al.*, 2023) who conducted a study on the coordination of Non-Cascade Overcurrent Relays on Power Transformer III at the 150 kV Tanggul Main Substation, Power Transformer III is equipped with an overcurrent relay protection system which aims to detect fault currents that exceed the specified current setting. This Overcurrent relay has two coordination patterns, namely cascade and non-cascade pattern coordination, with the non-cascade pattern considered more optimal because it is able to cut off faults faster. The non-cascade pattern overcurrent relay setting provides better protection on the incoming and 22kV feeder sides, because the incoming PMT works depending on the overcurrent relay time.

Pasaribu (2021) also conducted a study on Over Current Relay Analysis in the 20 kV distribution network at PT. Pelindo 1 Belawan Branch, the study obtained calculation results with data in the field that were not in the appropriate condition (there were differences), so it can be concluded that the Over Current Relay setting value at PT. Pelindo 1 was reset, and after the reset, until now the protection relay is still in good condition. Yusmartato (2016) conducted a study on the analysis of overcurrent and ground fault relays on feeders at the Lamhotma Main Substation. From his findings, calculations can be seen that the magnitude of the short circuit current is influenced by the distance of the fault point, the further the distance of the fault point, the smaller the short circuit current, and vice versa, the closer the distance of the fault point, the greater the value of the short circuit current.

This study aims to analyze the coordination between Overcurrent Relays (OCR) and Directional Ground Relays (DGR) in protecting transformers at the Segoromadu Substation, Gresik. The research involves collecting technical data from the substation, conducting simulations using power system analysis software, and evaluating relay coordination performance based on applicable standards such as IEEE and IEC. The approach offers a significant contribution by ensuring that OCR and DGR operate optimally in detecting and isolating disturbances without causing unnecessary interruptions to the power supply. The novelty of this research lies in the integration of software-based simulations with real-world scenario testing, resulting in adaptive and efficient protection strategies. The findings of this study are expected to provide practical recommendations for substation operators and power system managers to enhance the reliability of transformer protection systems, ultimately supporting the overall stability of the electrical power system.

Method

This research focuses on evaluating the coordination of Overcurrent Relays (OCR) and Directional Ground Relays (DGR) to enhance transformer protection at the Segoromadu Substation, Gresik. Given the critical role of transformers in ensuring a stable power supply, effective protection systems are essential to mitigate potential risks from overcurrent and ground faults. The study adopts a systematic approach, including the collection of substation operational data, simulation of relay settings using advanced power system software, and a thorough analysis of relay coordination based on established protection standards. These methods aim to optimize the protection system's performance and ensure minimal disruption in case of faults.

2.1 Impedance Value

Short circuit fault current is a condition where the conductor cable touches another conductor cable or the ground. In this condition, the magnitude of the value due to the disturbance will be calculated. A short circuit fault occurs when the basic insulation between phase wires or between phase wires and the ground is compromised, leading to an overcurrent fault due to the resulting excess current. Such faults can cause disrupt the stability of the power system if not promptly addressed. Before calculating the fault current, the impedance value is first needed using the following equation (Afif *et al.*, 2023):

a. Source Impedance

$$Z_s(\Omega) = \frac{(kV_{L-L})^2}{MVA_{SC}-} \tag{1}$$

Where,

kV_{L-L} : Base Voltage

Zs : Source Impedance

MVA_{SC} : Short Circuit Current on Transformer

b. Power Transformer Impedance (Afif *et al.*, 2023):

$$Z_{1T} = Z_{2T} \tag{2}$$

$$Z_{0T} = 3 \times Z_{1T} \tag{3}$$

Where,

Z_1 : Positive Sequence Impedance Transformer

Z_2 : Negative Sequence Impedance Transformer

Z_0 : Zero Sequence Impedance Transformer

c. Feeder Impedance (Afif *et al.*, 2023):

$$Z_{1f} = Z_{2f} = R_1 \times jX_1 \times L \tag{4}$$

$$Z_{0f} = R_0 \times jX_0 \times L \tag{5}$$

Where,

Z_{1f} : Positive Sequence Impedance Feeder

Z_{2f} : Negative Sequence Impedance Feeder

Z_{0f} : Zero Sequence Impedance Feeder

L : Feeder Length

d. Total Impedance (Afif *et al.*, 2023):

$$Z_{1total} = Z_{2total} = Z_s + Z_{1T} + Z_{1p} \tag{6}$$

$$Z_{0total} = Z_{0T} + 3Z_n + Z_{0p} \tag{7}$$

$$Z_n = \frac{R_0}{Z_{dasar}} \tag{8}$$

Where,

Z_{1total} : Positive Sequence Total
Z_{2total} : Negative Sequence Total
Z_{0total} : Zero Sequence Total
Z_n : Grounding Impedance

2.2 Short Circuit Fault Current

After calculating the impedance, the next step is to calculate the fault current using the following equation (Novia *et al.*, 2023):

a. 3 Phase Short Circuit Fault

$$I_{SC} = \frac{E_\alpha}{Z_1 + Z_f} \tag{9}$$

b. 2 Phase Short Cicuit Fault

$$I_{SC} = \frac{E_\alpha}{Z_1 + Z_2 + Z_f} \tag{10}$$

c. Phase-Earth Short Circuit Fault

$$I_{SC} = \frac{E_a}{Z_1 + Z_2 + Z_0 + Z_f} \tag{11}$$

Where,

I_{hs} : Short Circuit Current
Z_1 : Positive Sequence Impedance Total (pu)
Z_2 : Negative Sequence Impedance Total (pu)
Z_0 : Zero Sequence Impedance Total (pu)
Z_f : Short Circuit Impedance
E_a : Base voltage

2.3 Over Current Relay (OCR)

Over Current Relay (OCR) is a protection device that functions to detect excess current, either due to short circuit or overload that can cause damage to equipment in the protected power system. OCR acts as the main or backup protection device. OCR is required to be able to work according to the previously set time (Ramlan & Noor, 2022). The ability of OCR (Overcurrent Relay) to detect fault current depends on the current transformer, as it accurately measures the current flowing through the system and provides the necessary input for the relay to detect and respond to fault conditions. Furthermore, OCR can give a command to PMT to trip according to the required settings. According to British standards, the calculation of the current setting is 1,05 to 1,3 times the peak current (Prastyo & Wati, 2024).

$$I_{set\,primer} = 1{,}05\ s/d\ 1{,}3\ \times I_{max}(A) \tag{12}$$

$$\mathrm{I_{set\,secondary}} = \mathrm{I_{set\,primer}}\frac{1}{\mathrm{n_{CT}}} \tag{13}$$

To calculate the trip time, you can use the following equation (Ibrahmusa et al., 2023):

$$TMS = \frac{\left[\left(\frac{\mathrm{I_f}}{\mathrm{I_{set}}}\right)^{\alpha}\right] - 1}{\beta} \times t \tag{14}$$

$$t = \frac{\beta}{\left[\left(\frac{\mathrm{I_f}}{\mathrm{I_{set}}}\right)^{\alpha}\right] - 1} \tag{15}$$

Where,

I_{max} : Peak Current

t : Time Set to Relay

TMS : Standard Time Settings

I_f : Maximum Fault Current

I_{set} : Current Set to Relay

2.4 Directional Ground Relay (DGR)

Ground fault relay, or DGR (Directional Ground Relay), works on a similar principle to OCR, but there are differences in its use. If the OCR relay detects a short circuit between phases, while the DGR detects a short circuit from phase to ground and its direction (Anthony *et al.*, 2022). When a single-phase to ground fault occurs on the customer side connected to several feeders, analysis can be done quickly using the DGR (Directional Grounding Relay) because this relay is equipped with directional capabilities, allowing it to identify the fault's location and direction of the fault current, facilitating faster fault isolation and protection coordination. To calculate the DGR current setting, the equation is used (Prasetijo *et al.*, 2020):

$$I_{set\,primer} = 0{,}06\ s/d\ 0{,}12\ \times I_f \tag{16}$$

$$\mathrm{I}_{\mathrm{set\,secondary}} = \mathrm{I}_{\mathrm{set\,primer}} \frac{1}{\mathrm{n_{CT}}} \tag{17}$$

To calculate the trip time, you can use the equation (Nainggolan *et al.*, 2024):

$$TMS = \frac{\left[\left(\frac{\mathrm{I_f}}{\mathrm{I_{set}}}\right)^{\alpha}\right] - 1}{\beta} \times t \tag{18}$$

$$t = \frac{\beta}{\left[\left(\frac{\mathrm{I_f}}{\mathrm{I_{set}}}\right)^{\alpha}\right] - 1} \tag{19}$$

Where,

t	: Time Set to Relay
TMS	: Standart Time Settings
I_f	: Smallest Ground Fault Current
I_{set}	: Current Set to Relay

Results and Discussion

This section presents the results of the coordination analysis between Overcurrent Relays (OCR) and Directional Ground Relays (DGR) for transformer protection at the Segoromadu Substation, Gresik. The analysis focuses on assessing the effectiveness of the relay settings in detecting and isolating faults while minimizing unnecessary disruptions. The results obtained from the simulations and calculations will be discussed in detail, highlighting the impact of different relay coordination strategies on system reliability and transformer protection. This section also includes a comparison of the theoretical performance with practical outcomes, providing insights into improvements for the protection scheme.

3.1 Calculating Source Impedance

Based on the data obtained for the short circuit current on the 150 kV primary side bus at the Segoromadu Main Substation is 37,96 kA, the following calculation can be made:

a. Primary Side Short Circuit 150 kV

$$\begin{aligned} MVA_{SC} &= \sqrt{3} \times kV \times I_{SC} \\ &= \sqrt{3} \times 150\ kV \times 37{,}96\ kA \\ &= 9862{,}297\ MVA \end{aligned}$$

b. Primary Impedance

$$Z_{primer} = \frac{{kV_{(primer)}}^2}{MVA_{SC}}$$

$$= \frac{150^2}{9862{,}297} = 2{,}28\ \Omega$$

c. Secondary Impedance

$$Z_{Sekunder} = \frac{{kV_{(sekunder)}}^2}{{kV_{(primer)}}^2} \times X_{s(primer)}$$

$$= \frac{20^2}{150^2} \times 2{,}28 = 0{,}04\ \Omega$$

3.2 Calculating Transformer Reactance

In the Transformer specification data, the reactance is known to be 12.408%. Furthermore, to find out the value of positive sequence reactance, negative sequence reactance, and zero sequence reactance in Ohm (Ω), it is necessary to calculate the value of Ohm (Ω) at 100%.

$$X_{t(100\%)} = \frac{{kV_{(secondary)}}^2}{VA_{transformer}}$$

$$= \frac{20^2}{60} = 6{,}6\ \Omega$$

For the transformer reactance value in positive and negative sequence reactance (X_{t1} = X_{t2}) can be calculated as follows.

$$X_{t1} = X_{t2} = Transformer\ Reactance\ (\%) \times X_{t(100\%)}$$

$$= 12{,}408\% \times 6{,}6\ \Omega = 0{,}82\ \Omega$$

Because the transformer that supplies the feeder does not have a delta winding in its circuit, namely the YnYnO winding, so the magnitude of X_{t0} ranges from 9 to 14 × X_{t1}. So in this calculation the value of X_{t0} is approximately 10 × X_{t1}. So for the reactance value of the transformer in the zero sequence (X_{t0}) can be calculated as follows:

$$X_{t0} = 10 \times X_{t1}$$

$$= 10 \times 0{,}82 = 8{,}2\ \Omega$$

3.3 Calculating Feeder Impedance

To calculate the impedance value of the feeder depends on the value of the impedance per kilometer of the feeder, where the value is determined by the configuration used for the distribution network, with impedance consisting of positive sequence impedance (Z_1), negative sequence impedance (Z_2) and zero sequence impedance (Z_0).

Table 1. Positive, Negative and Zero Sequence Impedance Value Data

No.	Feeder	Positive and Negative Impedance Sequence	Zero Impedance Sequence
1.	Gramitama 4	0,4866 + 0,6277j	1,4598 + 1,883j
2.	Sentolang	1,2339 + 0,4749j	3,7016 + 1,4246j
3.	Pangsud	1,5378 + 0,4466j	4,6134 + 1,3397j
4.	Gulomantung 2	1,1314 + 0,4621j	3,3943 + 1,3862j
5.	Gramitama 3	0,2922 + 0,3878j	0,8766 + 1,1634j
6.	Gramitama 2	0,2922 + 0,3878j	0,8766 + 1,1634j
7.	Gramitama 1	0,2922 + 0,3878j	0,8766 + 1,1634j

Based on Table 1, the impedance values of the feeders for positive sequence, negative sequence and zero sequence can be calculated for the fault location in the location area with a distance of 0%, 25%, 50%, 75% and 100% of the feeder length, so that the impedance value of each feeder can be calculated as follows:

a. Positive and Negative Sequence Impedance:

$$Z_1 = Z_2 = \%\, feeder\ length\ \times Z/km$$

b. Zero Sequence Impedance:

$$Z_0 = \%\, feeder\ length \times Z/km$$

In Table 2 below are the calculation results for the Positive Sequence Impedance, Negative Sequence Impedance, and Zero Sequence Impedance values for the fault location areas at 0%, 25%, 50%, 75%, and 100%. These values represent the impedance measurements at various points along the faulted section, providing essential data for fault analysis and protection coordination in the system. By analyzing the impedance at different fault locations, it becomes possible to determine the fault type, severity, and appropriate protective measures, ensuring the reliability and stability of the electrical network.

Furthermore, the impedance variations at different fault locations provide insights into the electrical characteristics of the network under fault conditions. These measurements are crucial for accurately pinpointing the fault location, as they help in identifying discrepancies between the expected and actual impedance values. Such analysis enables the implementation of adaptive protection schemes and enhances the precision of fault isolation, minimizing the risk of system-wide outages and ensuring a quicker restoration of service.

Table 2. Positive, Negative and Zero Sequence Impedance Data with Percentage of Feeder Length

No	Feeder	% Length	Z_1 and Z_2	Z_0
1.	Gramitama 4	0	0	0
		25	0,1217 + 0,1569j	0,3649 + 0,4708j
		50	0,2433 + 0,3139j	0,7299 + 0,9415j
		75	0,3649 + 0,4708j	1,0948 + 1,4123j
		100	0,4866 + 0,6277j	1,4598 + 1,8830j
2.	Sentolang	0	0	0
		25	0,3085 + 0,1187j	0,9254 + 0,3562j
		50	0,6169 + 0,2375j	1,8508 + 0,7123j
		75	0,9254 + 0,3562j	2,7762 + 1,0685j
		100	1,2339 + 0,4749j	3,7016 + 1,4246j
3.	Pangsud	0	0	0
		25	0,3845 + 0,1117j	1,1533 + 0,3349j
		50	0,7689 + 0,2233j	2,3067 + 0,6698j
		75	1,1534 + 0,3349j	3,4601 + 1,0048j
		100	1,5378 + 0,4466j	4,6134 + 1,3397j
4.	Gulomantung 2	0	0	0
		25	0,2829 + 0,1155j	0,8486 + 0,3466j
		50	0,5657 + 0,2311j	1,6972 + 0,6931j
		75	0,8486 + 0,3466j	2,5457 + 1,0396j
		100	1,1314 + 0,4621j	3,3943 +1,3862j
5.	Gramitama 3	0	0	0
		25	0,0731 + 0,0969j	0,2192 + 0,2909j
		50	0,1461 + 0,1939j	0,4383 + 0,5817j
		75	0,2192 + 0,2908j	0,6575 + 0,8725j
		100	0,2922 + 0,3878j	0,8766 + 1,1634j
6.	Gramitama 2	0	0	0
		25	0,0731 + 0,0969j	0,2192 + 0,2909j
		50	0,1461 + 0,1939j	0,4383 + 0,5817j
		75	0,2192 + 0,2909j	0,6575 + 0,8725j
		100	0,2922 + 0,3878j	0,8766 + 1,1634j
7.	Gramitama 1	0	0	0
		25	0,0731 + 0,0969j	0,2192 + 0,2909j
		50	0,1461 + 0,1939j	0,4383 + 0,5817j
		75	0,2192 + 0,2909j	0,6575 + 0,8726j
		100	0,2922 + 0,3878j	0,8766 +1,1634j

Based on the data shown in Table 2, it can be seen that the magnitude of the Positive Sequence, Negative Sequence and Zero Sequence impedance values have different impedance values depending on the length of the feeder. The further from the supply voltage, the greater the impedance value, and conversely the closer to the supply voltage, the smaller the impedance value. This impedance value will be used as a reference for calculating the equivalent impedance of the network.

3.4 Calculating Network Equivalent Impedance

The next step is to calculate the magnitude of the equivalent impedance from the point of disturbance to the source. Since the magnitude of the Positive Sequence Equivalent Impedance is equal to that of the Negative Sequence Equivalent Impedance (Z_{1eq} = Z_{2eq}), the following equation is applied:

$$\begin{aligned} Z_{1eq} = Z_{2eq} &= Z_{secondary(20\,kV)} + X_{t1} + Z_{1(feeder)} \\ &= 0{,}04j + 0{,}82j + Z_{1(feeder)} \\ &= 0{,}86j + Z_{1(feeder)} \end{aligned}$$

To calculate the value of the Zero Sequence Equivalent Impedance (Z_{0eq}) based on the neutral grounding system of the main substation, the value of the grounding resistance is 500 Ω, the calculation can be done using the following equation:

$$\begin{aligned} Z_{0eq} &= X_{t0} + 3RN + Z_{0(feeder)} \\ &= 8{,}2j + (\ 3 \times 500\ ) + Z_{0(feeder)} \\ &= 8{,}2j + 1500 + Z_{0(feeder)} \end{aligned}$$

Based on the calculation data in Table 3, the values of Positive Sequence impedance, Negative Sequence impedance, and Zero Sequence impedance differ. These equivalent impedance values will be used in subsequent calculations to determine the magnitude of the short-circuit current. This step is crucial for accurately assessing the system's response during fault conditions.

The variations in the sequence impedance values highlight the unique characteristics of the network under different operating conditions. Positive Sequence impedance typically represents the normal operating conditions of the system, while Negative Sequence impedance reflects the system's response to unbalanced faults, such as line-to-line faults. Meanwhile, Zero Sequence impedance provides insights into the network's behavior ground fault conditions, which are essential for evaluating the system's grounding and fault current paths.

These impedance values play a critical role in determining the magnitude and distribution of short-circuit currents across the network. By accurately calculating these currents, it becomes possible to evaluate the thermal and mechanical stresses imposed on electrical equipment, such as transformers, circuit breakers, and transmission lines. This ensures that all components are adequately rated to withstand fault conditions, maintaining the system's integrity and safety. Moreover, the calculated short-circuit current magnitudes serve as a foundation for optimizing the coordination of protective devices. Proper coordination ensures that the nearest protective device to the fault operates first, minimizing the impact on the rest of the system and reducing downtime.

Table 3. Network Equivalent Impedance Calculation Result Data

No.	Feeder	%Length	$Z_{1eq} = Z_2eq$	Z_{0eq}
1.	Gramitama 4			
		0	0,86j	1500+8,2j
		25	0,1216+1,0169j	1500,3649+8,6707j
		50	0,2433+1,1738j	1500,7299+9,1415j
		75	0,3649+1,3307j	1501,0948+9,6122j
		100	0,4866+1,4877j	1501,4598+10,083j
2.	Sentolang			
		0	0,86j	1500+8,2j
		25	0,3084+0,9787j	1500,9254+8,5561j
		50	0,6169+1,0974j	1501,8508+8,9123j
		75	0,9254+1,2161j	1502,7762+9,2684j
		100	1,2339+1,3349j	1503,7016+9,6246j
3.	Pangsud			
		0	0,86j	1500+8,2j
		25	0,3844+0,9716j	1501,1533+8,5349j
		50	0,7689+1,0833j	1502,3067+8,8698j
		75	1,1533+1,1949j	1503,4600+9,2047j
		100	1,5378+1,3066j	1504,6134+9,5397j
4.	Gulomantung 2			
		0	0,86j	1500+8,2j
		25	0,2828+0,9755j	1500,8485+8,5465j
		50	0,5657+1,0910j	1501,6971+8,8931j
		75	0,8485+1,2065j	1502,5457+9,2396j
		100	1,1314+1,3221j	1503,3943+9,5862j
5.	Gramitama 3			
		0	0,86j	1500+8,2j
		25	0,0730+0,9569j	1500,2191+8,4908j
		50	0,1461+1,0539j	1500,4383+8,7817j
		75	0,2191+1,1508j	1500,6574+9,0725j
		100	0,2922+1,2478j	1500,8766+9,3634j
6.	Gramitama 2			
		0	0,86j	1500+8,2j
		25	0,0730+0,9569j	1500,2191+8,4908j
		50	0,1461+1,0539j	1500,4383+8,7817j
		75	0,2191+1,1508j	1500,6574+9,0725j
		100	0,2922+1,2478j	1500,8766+9,3634j
7.	Gramitama 1			
		0	0,86j	1500+8,2j
		25	0,0730+0,9569j	1500,2191+8,4908j
		50	0,1461+1,0539j	1500,4383+8,7817j
		75	0,2191+1,1508j	1500,6574+9,0725j
		100	0,2922+1,2478j	1500,8766+9,3634j

3.5 Calculating Short Circuit Fault

a. 3-Phase Short Circuit Fault

To determine a 3-phase short circuit fault using the equation in (9), the current value can be calculated when the fault occurs at 100% of the distance along the Gramitama 4 feeder.

$$I_{SC\ (3-Phase)} = \frac{11547{,}005}{\sqrt{0{,}4866^2 + 1{,}4877^2}} = 7.377{,}064 \text{ A}$$

Table 4. Results of Calculation of 3 Phase Short Circuit Current for All Feeders

No.	Feeder	% Length	$Z_{1eq} = Z_2 eq$	$I_{SC\ (3-Phase)}$
1.	Gramitama 4			
		0	0,86j	13426,7504
		25	0,1216+1,0169j	11274,4416
		50	0,2433+1,1738j	9632,1458
		75	0,3649+1,3307j	8367,9431
		100	0,4866+1,4877j	7377,0647
2.	Sentolang			
		0	0,86j	13426,7504
		25	0,3084+0,9787j	11252,3420
		50	0,6169+1,0974j	9171,7345
		75	0,9254+1,2161j	7555,7935
		100	1,2339+1,3349j	6352,1193
3.	Pangsud			
		0	0,86j	13426,7504
		25	0,3844+0,9716j	11050,3704
		50	0,7689+1,0833j	8692,1708
		75	1,1533+1,1949j	6952,8467
		100	1,5378+1,3066j	5722,2095
6.	Gulomantung 2			
		0	0,86j	13426,7504
		25	0,2828+0,9755j	11368,4829
		50	0,5657+1,0910j	9395,5548
		75	0,8485+1,2065j	7828,0549
		100	1,1314+1,3221j	6635,7559
7.	Gramitama 3			
		0	0,86j	13426,7504
		25	0,0730+0,9569j	12031,4627
		50	0,1461+1,0539j	10852,6671
		75	0,2191+1,1508j	9856,3466
		100	0,2922+1,2478j	9010,1453
8.	Gramitama 2			
		0	0,86j	13426,7504
		25	0,0730+0,9569j	12031,4627
		50	0,1461+1,0539j	10852,6671
		75	0,2191+1,1508j	9856,3466
		100	0,2922+1,2478j	9010,1453
9.	Gramitama 1			
		0	0,86j	13426,7504
		25	0,0730+0,9569j	12031,4627

		50	0,1461+1,0539j	10852,6671
		75	0,2191+1,1508j	9856,3466
		100	0,2922+1,2478j	9010,1453

b. Phase – Earth Short Circuit Fault

To determine a phase-earth short circuit fault using the equation in (11), the current value can be calculated when the fault occurs at 100% of the distance along the Gramitama 4 feeder.

$$I_{SC(phase-earth)} = \frac{3\times\frac{20000}{\sqrt{3}}}{2\times(04866+1,4877j)+(1501,4598+10,083j)} = 23,055\ \text{A}$$

Table 5. Result of Calculation of Phase – Earth Short Circuit Fault

No.	Feeder	% Length	$(2\times \boldsymbol{Z_{1eq}})+(\boldsymbol{Z_{0eq}})$	$\boldsymbol{I_{SC(phase-earth)}}$
1.	Gramitama 4			
		0	1500+9,92j	23,0935
		25	1500,6082+10,7046j	23,0840
		50	1501,2165+11,4892j	23,0746
		75	1501,8247+12,2738j	23,0651
		100	1502,4330+13,0584j	23,0557
2.	Sentolang			
		0	1500+9,92j	23,0935
		25	1501,5423+10,5136j	23,0697
		50	1503,0847+11,1072j	23,0459
		75	1504,6270+11,7008j	23,0222
		100	1506,1694+12,2944j	22,9986
3.	Pangsud			
		0	1500+9,92j	23,0935
		25	1501,9222+10,4782j	23,0638
		50	1503,8445+11,0364j	23,0343
		75	1505,7667+11,5946j	23,0048
		100	1507,689+12,1529j	22,9754
4.	Gulomantung 2			
		0	1500+9,92j	23,0935
		25	1501,4142+10,4976j	23,0716
		50	1502,8285+11,0752j	23,04991
		75	1504,2428+11,6528j	23,0281
		100	1505,6571+12,2304j	23,0064
5.	Gramitama 3			
		0	1500+9,92j	23,0935
		25	1500,3652+10,4047j	23,0878
		50	1500,7305+10,8895j	23,0821
		75	1501,0957+11,3742j	23,0764
		100	1501,461+11,859j	23,0708
6.	Gramitama 2			
		0	1500+9,92j	23,0935
		25	1500,3652+10,4047j	23,0878
		50	1500,7305+10,8895j	23,0821
		75	1501,0957+11,3742j	23,0764
		100	1501,461+11,859j	23,0708
7.	Gramitama 1			
		0	1500+9,92j	23,0935
		25	1500,3652+10,4047j	23,0878

50	1500,7305+10,8895j	23,0821
75	1501,0957+11,3742j	23,0764
100	1501,461+11,859j	23,0708

3.6 OCR and DGR Settings

To adjust the current value on the incoming side (20 kV voltage side), first calculate the nominal current value using the following equations (12)-(17):

Table 6. Transformer Rating Specification

Transformer Capacity	60 MVA
Based Voltage	150/20 kV
CT Ratio	2000 : 5

a. Calculating Nominal Current (20 kV Side):

$$I_{nom(20\text{ kV})} = \frac{\text{kVA}}{\sqrt{3}\times\text{kV}}$$

$$= \frac{60.000}{\sqrt{3}\times 20} = 1.732,0508\ A$$

b. Calculating Current Setting on Primary Side:

$$\text{I set}_{(\text{primer})} = 1,05\times\ \text{I}_{\text{nom}}$$

$$= 1,05\times 1.732,0508 = 1.818,65\ \text{A}$$

c. Calculating Current Setting on Secondary Side:

$$\text{I set}_{(\text{secondary})} = \text{I set}_{(\text{primer})}\times\frac{1}{\text{CT Ratio}}$$

$$= 1.818,65\times\frac{5}{2000} = 4,5466\ A$$

d. Time Multiplier Setting (TMS)

The 3-phase short circuit fault current at the fault location area at 0% of the feeder length is selected as the fault current used to calculate the TMS (Time Multiplier Setting) on the overcurrent relay on the incoming side of the 20 kV power transformer unit 2. The working time of the incoming side overcurrent relay is obtained as the standard working time value, namely +0.4 seconds.

t incoming = 0,3 + 0,4 = 0,7 second

$$\text{TMS} = \frac{\left[\frac{I_{fault}}{I_{set}}\right]^{n} - 1}{k}\times t$$

$$= \frac{\left[\frac{13.426,750}{1.818,65}\right]^{0,02} - 1}{0,14}\times 0,7 = 0,204$$

$$t = TMS \times \frac{k}{\left(\frac{I_{Fault}}{I_{set}}\right)^{n} - 1}$$

$$= 0{,}204 \times \frac{0{,}14}{\left(\frac{13.426{,}750}{1.818{,}65}\right)^{0{,}02} - 1} = 0{,}7\ second$$

The overcurrent relay setting on the feeder side is calculated based on the full load current value on each feeder. For the standard inverse relay characteristic, the overcurrent setting value is between 1,05 to 1,3 times the full load current. With a full load current of 281 Ampere and a CT ratio of 400 to 5, the overcurrent setting on the Gramitama 4 feeder side is as follows:

$$1{,}05 \times I_{FL}$$
$$1{,}05 \times 281\,A = 295{,}05\,A$$

The current value of 295,05 Amperes is the setting value on the primary side. If a short-circuit fault current equal to or greater than this value occurs, the overcurrent relay at the feeder position will detect it and issue a command to trip the circuit breaker (CB), thereby protecting other equipment and ensuring safe operation. However, if the short-circuit fault current is below 295,05 Amperes, the overcurrent relay on the feeder side will not activate.

a. Secondary Side Current Setting Value

The calculation of the current setting value $I_{Set(sec)}$ for the Gramitama 4 Feeder can be determined using Equation (16), as follows:

$$I_{set\ (sec)} = I_{set(primer)} \times \frac{1}{CT\ Ratio}$$

$$I_{set\ (sec)} = 295{,}05 \times \frac{1}{400/5}$$

$$= 295{,}05 \times \frac{5}{400} = 3{,}69\,A$$

b. Instant Current Adjustment on the Feeder Side

The instant current setting on the feeder side is obtained based on the value of the full load current on the feeder. The value of the primary instant current and the secondary instant current on the feeder can be calculated using the following equation:

$$I_{instan\ (primer)} = 1{,}6 \times I_{FL}$$

$$= 1{,}6 \times 281 = 449{,}6\,A$$

$$I_{instan\ (sec)} = 449{,}6 \times \frac{1}{400/5}$$

$$= 449{,}6 \times \frac{5}{400} = 5{,}62\,A$$

These calculations are critical for ensuring the effective operation of protective relays in the power system. The instant current setting determines the threshold at which the relay will trip to isolate the faulted section, preventing further damage to equipment and minimizing disruptions to the network. The proper selection of CT ratios and setting values is essential to maintain accuracy and reliability in fault detection, as well as to avoid nuisance tripping under normal load or transient conditions. This ensures the protection system's ability to respond promptly and accurately during abnormal events.

Table 7. Instant Current Calculation Results Data and Feeder Setting Current

Feeder	$I_{set(prim)}$	$I_{set(sec)}$	$I_{ins(prim)}$	$I_{ins(sec)}$
Gramitama 4	295,05	3,69	449,6	5,62
Sentolang	234,15	2,93	356,8	4,46
Pangsud	149,1	1,86	227,2	2,84
Gulomantung 2	172,2	2,15	262,4	3,28
Gramitama 3	215,25	1,35	328	2,05
Gramitama 2	225,75	1,41	344	2,15
Gramitama 1	218,40	1,37	332,8	2,08

In Table 7, it can be seen that the calculation results above will be used as a basis for calculating TMS (Time Multiplier Setting) and the value of the relay working time on the feeder side. The fault current selected to determine the value of the TMS (Time Multiple Setting) of the 20 kV feeder side overcurrent relay is a three-phase short circuit fault current at a location of 100% of the feeder length, with the relay operating time set at t = 0,3 seconds. The calculation of the TMS (Time Multiple Setting) value can use the following equation.

$$\text{TMS} = \frac{\left[\frac{I_{fault}}{I_{set}}\right]^{n} - 1}{k} \times t$$

$$= \frac{\left[\frac{9010{,}15}{218{,}4}\right]^{0{,}02} - 1}{0{,}14} \times 0{,}3 = 0{,}165499$$

$$\text{T} = TMS \times \frac{k}{\left(\frac{I_{Fault}}{I_{set}}\right)^{n} - 1}$$

$$= 0{,}165499 \times \frac{0{,}14}{\left(\frac{9010{,}15}{218{,}4}\right)^{0{,}02} - 1} = 0{,}3\ second$$

The operating time (T) is subsequently calculated using the TMS and the same current ratio raised to the characteristic exponent, along with k. The result, T = 0.3 seconds, aligns with the desired tripping time for the relay under the given fault conditions. These calculations are essential for ensuring that the relay operates correctly, tripping within a precise time frame to isolate the fault while maintaining proper coordination with upstream and downstream protection devices. This minimizes system disruption and ensures selective fault clearing.

Table 8. Comparative Data of OCR Calculation Results and Existing

Feedrer	OCR (Standard Inverse)			
	Current		TMS	
	Existing	Resetting	Existing	Resetting
Gramitama 4	400	295,05	0,15	0,142494
Sentolang	400	234,15	0,15	0,146227
Pangsud	400	149,1	0,15	0,162164
Gulomantung 2	400	172,2	0,15	0,162164
Gramitama 3	400	215,25	0,15	0,166170
Gramitama 2	400	225,75	0,15	0,164382
Gramitama 1	400	218,4	0,15	0,165499

Table 9. Comparative Data of DGR Calculation Results and Existing

Penyulang	DGR (Standard Inverse)			
	Current		TMS	
	Existing	Resetting	Existing	Resetting
Gramitama 4	4	11,5	0,2	0,039884
Sentolang	4	11,5	0,2	0,039884
Pangsud	4	11,5	0,2	0,039884
Gulomantung 2	4	11,5	0,2	0,039884
Gramitama 3	4	11,5	0,2	0,039884
Gramitama 2	4	11,5	0,2	0,039884
Gramitama 1	4	11,5	0,2	0,039884

From Table 8 related to the calculation results and existing, there are several values that are different from the calculation results with existing data. The setting current value on the standard inverse overcurrent relay, the existing data is 400 A, while the data according to the calculation varies for each feeder depending on the size of the full load current on each feeder varying from 149,1 A to 295,05 A. Likewise for the setting current on Instantaneous, there are also differences. The TMS (Time Multiple Setting) value on the existing is 0,15, the same for all feeders, while the calculation data varies between 0,142494 to 0,166170. From Table 9 which explains the calculation results and existing for the DGR relay, there are several different values from the calculation results with existing data. The setting current value on the DGR standard inverse relay, the existing data is 4 A, while the data according to the calculation has the same value for each feeder of 11,5 A. Likewise for the TMS (Time Multiple Setting) Value, there is also a difference. The TMS (Time Multiple Setting) value on the existing is 0,2 the same for all feeders, while the calculation data obtained a value of 0,03988 the same for each feeder.

Conclusion

The results of the research that has been done show a significant difference between the existing data and the calculation results in the relay settings. In the standard inverse overcurrent relay, the existing current setting value is 400 A, while the calculation results vary between 149,1 A to 295,05 A, with the existing TMS of 0,15 different from the calculation results ranging from 0,142494 to 0,166170. Meanwhile, in the DGR relay, the existing current setting value of 4 A is different from the calculation results which show a uniform value of 11,5 A, and the existing TMS of 0,2 is also different from the calculation results of 0,039884. This difference indicates a mismatch that can affect the performance of the protection settings.

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