Performance Evaluation of Overcurrent Relay and Ground Fault Relay Coordination in Distribution Feeder

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ABSTRACT

Reliable and sustainable electrical distribution systems require effective protection measures against internal and external disturbances, especially short-circuit disturbances, to avoid damage to the equipment. Overcurrent relays (OCR) and ground fault relays (GFR) play an important role in the safety of the distribution network. To improve performance, evaluation of relay coordination is essential. During the short circuit, the nearest relay to the fault point is activated first and the backup relay is activated if the fault current exceeds the adjustment of the main relay. Coordination ensures that timely signaling is sent to interrupt the circuit. Inspection of the OCR relay revealed that it did not comply with the IEC 60255 standard and consequently adjusted the classification time to 0.402 seconds. Similarly, the results of the GFR relay inspection did not meet the standards and required an adjustment of the evaluation time to 0.492 seconds. Resolving these deviations is crucial to maintaining the reliability and compliance of the distribution network with industry standards, ensuring that the protection relays respond quickly and effectively to disturbances, thereby preventing possible damage to equipment.

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1. INTRODUCTION

The electricity system must be reliable and capable of meeting the electricity demand constantly [1]. One of the supports is a good protection system. Protection systems are a means of preventing or limiting damage caused by interference [3] to devices and ensuring the continuity of electrical distribution in substations [2]. Almost all electrical circuit failures in the electrical distribution system are short circuit failures. If not removed immediately, the equipment will damage itself. Short circuit failures in substations are three-phase failures, two-phase failures, and single-phase ground failures [3]. Protection relays are used to overcome disturbances in the distribution system. Protection relays are electrical equipment designed to separate parts of the electrical system when there are disturbances in the system. In order to achieve high system reliability, safety relays with good selective capabilities are required, as rapid and precise safety measures will minimize the isolation of disturbances. The most used protection relays are the overcurrent relay (OCR) and ground fault relay (GFR). These two protection devices are installed on the input and output sides of the substation; therefore, the relay coordination on the input and output sides must be maintained, as the coordination between the relays determines the reliability of the protection system [6-7].

The setting of the OCR on the self-serving power distribution network was determined by determining the value of the adjustment of the current and time multiplier (TMS) of each OCR on the network. Under existing conditions, if the nearest OCR fails to function when interference occurs, it does not meet the protection coordination requirements. There was an OCR with a time classification and an overlapping coordination curve. This configuration is required so that the nearby OCR can work without interference. When the primary relay failed and no overhang curve was found, backup protection was implemented in a coordinated sequence. The time classification was based on the IEEE 242-1986 standard [8], which was 0.2-0.4 seconds [6]. The ground fault relay is a protection relay that is used to detect and protect ground faults, especially those involved in one or two phases. It works by preventing the electricity network from being interrupted by problems between phases or three phases and operates in a single direction. The relay is usually installed on high- and medium-voltage systems, including safety transformers, to ensure the protection of electrical equipment in the event of ground-phase faults [5].

Current differential protection schemes apply to medium voltage distribution systems to maintain as much energy as possible for loads and distribution units during defects [3]. Differential relays of the conventional two-terminal current percentage are used to form sequential time-current coordinated differential protection zones. Several times, different elements in each protection zone are delayed, which guarantees coordination with adjacent protection equipment of the area, and continuity between different protection zones [9].

In the context of a comprehensive evaluation of the protection mechanisms, the integration of the AC microgrid into the distribution network can provide insight into the dynamics of the interaction of the microgrid and contribute to improving the protection system of the distribution network [10]. Changes in the layout of the distribution network can have a significant impact on coordination and protection measures. To modernize the microgrid protection system, various protection strategies have been proposed, including DC/AC systems, communication frameworks, synchronized machines, and distributed generation based on inverters (IBDGs). These microgrids are classified as integral components of the overall protection framework.

Conventional overcurrent protection techniques in generator-assisted distribution networks can impede relay coordination, resulting in lower network reliability [11]. To address this problem, protective coordination strategies using double direction closure (DSDR) have been developed to improve the effectiveness of fuse storage systems. These DSDR protection strategies allow network operators to achieve flexible coordination coverage and precise protection settings according to coordination requirements. The effectiveness of the proposed protection system has been confirmed by standard IEEE systems and comparative analysis. Furthermore, the document emphasizes the economic aspects of designing protection strategies that involve fewer protective devices [12].

The superconducting fault current limiter (SFCL) causes a delay in OCR operation due to minimal error currents and has a negative impact on the coordination of energy distribution network protection systems [13]. These delays in the OCR pathway prolong the exposure time of neighboring power plants to asymmetric fault currents. In the case of asymmetric ground faults, the OCR index is used to compensate for barriers introduced by SFCL. The recommended OCR index contains all resistance components derived from the voltage and current measured in the distribution system and the SFCL [14]. To demonstrate the effectiveness of this algorithm, simulations were performed using power system computer aided design (PSCAD) to analyze the protective coordination between OCR and SFCL in the electricity distribution system [15].

In order to address the growing current failures in power distribution systems caused by the interconnected operation of high-capacity generators, superconductor fault current limiters are being investigated as protection devices [16]. This integration into the electrical distribution system can lead to malfunction or non-operation of protection relays and interfere with their coordination. To evaluate the operation of fault current limiters and coordinate protection between OCRs and network distribution circuit voltage components, overcurrent voltage relays are used. PSCAD simulations are used to examine the optimization of the proportional voltage coefficient of the OCR voltage component, with the aim of improving the protection coordination between the OCR [17].

Modern electricity networks require flexible energy use, but high energy penetration rates are the common source of wind and solar power, and this presents a challenge [18]. The network plays an essential role in the development of robust and sustainable electricity systems, especially in high intermittent renewable energy. To overcome these complex problems, and especially to increase energy production, public utilities and consumers must strictly demand distribution systems [19].

In order to ensure effective coordination of the protection relays, the closest relay to the source of disturbance is activated, and a circuit breaker trip command is issued when the electrical system encounters a problem. If the main relay is susceptible to interference or malfunction, the second relay or the backup relay will start to run. Evaluation of the coordination of installed protection relays is essential to maintain and improve the performance of the protection system.

2. RESEARCH METHOD

The protection system is a way to prevent or limit damage caused to electrical equipment due to interference to ensure the continuity of the electrical distribution [19]. Protection relays are electrical devices that detect disturbances in electrical systems. When the relay feels a disturbance, it automatically disconnects the circuit breaker and commands it to separate the affected part of the system. A protection relay is an OCR and GFR [21][22].

An overcurrent relay, or better known as an OCR, is a piece of equipment that detects overcurrent, which is caused by a short circuit between phases that can damage the electrical system equipment within its security area [12]. To adjust the OCR current value, equation (1) is:

$$I_{setOCR\,(feeder)} = 1.1 \; x \; I_{load} \tag{1}$$

The setting on the side of the *incoming,* equation (2) is:

$$I_{setOCR\,(incoming)} = 1.2 \; x \; I_{nominal} \tag{2}$$

Ground fault relay (GFR) basically has the same working principle as OCR but has differences in its use. If OCR detects a short-circuit current between phases, then GFR detects a short-circuit current from one phase to ground [6]. Setting the GFR current on the feeder side of equation (3) is:

$$I_{setGFR\,(feeder)} = 0.1 \; x \; I_{load} \tag{3}$$

On the side of *incoming,* equation (4) is:

$$I_{setGFR\,(incoming)} = 0.1 \; x \; I_{nominal\,trafo} \tag{4}$$

Time-Multiple Setting (TMS) is a time-multiple variable value used for setting protective relays. Inverse relays can be differentiated according to their working time characteristics [21] according to the IEC standard [23].

The protection system, which is placed sequentially along the distribution line, is arranged in such a way that it will work at a time grading according to the location of the protection relay against disturbances. Relays closest to the fault will operate faster than relays farther away. Meanwhile, if the relay does not work, the relay behind it will work longer. To determine the source impedance (Z_s) on the primary side, equation (5) is as follows.

$$Z_{s\,(primary)} = \frac{kV_{L-L\,(primary)}^2}{MVA_{SC}} \tag{5}$$

$Z_{s\,(primary)}$ is the source impedance on the primary side (Ω), kV $_{L-L}$ (primary) is the phase-to-phase voltage on the primary side (kV), MVA$_{sc}$ is the current capacity when a fault occurs.

To determine the source impedance value on the secondary side, equation (6) is:

$$Z_{s\,(secondary)} = Z_{s\,(primary)} \; x \; \frac{kV_{L-L\,(secondary)}^2}{kV_{L-L\,(primary)}^2} \tag{6}$$

$Z_{s\,(secondary)}$ is the source impedance on the secondary side (Ω), $Z_{s\,(primary)}$ is the source impedance on the primary side (Ω), $Z_{s\,(secondary)}$ is the source impedance on the secondary side (Ω), $Z_{s\,(primary)}$ is the

source impedance on the primary side (Ω), kV L-L (secondary) is the phase-to-phase voltage on the secondary side (kV), kV L-L (primary) is the phase-to-phase voltage on the primary side (kV).

When calculating the impedance of a transformer, the reactance value is taken, while the resistance is ignored because it is small. The following is how to find the impedance values for a positive sequence, a negative sequence, and a zero sequence. To calculate the positive and negative sequence impedance of a transformer, equation (7) is as follows.

$$Z_{t1} = Z_{t2} = \%Z \; x \; \frac{kV_{L-L}^2}{MVA} \tag{7}$$

Z_{t1} is the positive sequence impedance of the transformer (Ω), Z_{t2} is the negative sequence impedance of the transformer (Ω), %Z is the percentage of transformer impedance (%), kV L-L = phase-to-phase voltage (kV), MVA = power transformer capacity (MVA). To calculate the zero sequence impedance of a transformer (Z_{t0}) the equation (8) is as follows:

$$Z_{t0} = 3 \; x \; Z_{t1} \tag{8}$$

Where:
Z_{t0} = Transformer zero sequence impedance (Ω)

Feeder impedance is divided into positive sequence, negative sequence, and zero sequence impedance. To calculate the positive and negative sequence impedance values of the feeder, equation (9) is:

$$Z_{L1} = Z_{L2} = Z_{1 \; conductor} \; x \; l \tag{9}$$

Z_{L1} is the impedance of the positive sequence feeder (Ω), Z_{L2} is the impedance of the negative sequence feeder (Ω), Z_1 The conductor is the impedance of the positive sequence feeder wire (Ω/km), l is the length of the channel (km). To calculate the zero sequence impedance value of the feeder, equation (10) is:

$$Z_{L0} = Z_{0 \; conductor} \; x \; l \tag{10}$$

Z_{L0} is the zero-sequence impedance of the feeder (Ω), Z_0 conductor is the zero-sequence impedance of the feeder wire (Ω/km).

To calculate the equivalent positive sequence and negative sequence impedance, equation (11) is:

$$Z_1 = Z_2 = Z_s + Z_{t1} + Z_{L1} \tag{11}$$

Z_1 is the equivalent positive sequence impedance (Ω), Z_2 is the equivalent negative sequence impedance (Ω), Zs is the source impedance (Ω), Z_{t1} is the positive sequence impedance of the transformer (Ω), Z_{L1} is the positive sequence impedance of the feeder (Ω).

To calculate the zero sequence equivalent impedance, equation (12) is:

$$Z_0 = 3R_N + Z_{t0} + Z_{L0} \tag{12}$$

Z_0 = Equivalent zero sequence impedance (Ω), RN = soil resistance (Ω), Z_{t0} = Transformer zero sequence impedance (Ω), Z_{L0} = feeder zero sequence impedance (Ω).

To obtain the value of the three-phase short circuit fault current, equation (13) is:

$$I_{f,3\phi} = \frac{V_{L-N}}{Z_1} \tag{13}$$

$I_{f,3\phi}$ is the three-phase short circuit fault current (A), V_{L-N} is the phase to neutral voltage (V), Z_1 is the positive sequence impedance (Ω). To obtain the value of the two-phase short circuit fault current, equation (14) is:

$$I_{f,L-L} = \frac{V_{L-L}}{Z_1 + Z_2} \tag{14}$$

$I_{f,L-L}$ is the two-phase short circuit fault current (A), V_{L-L} is the phase-to-phase voltage (V), Z_1 is the positive sequence impedance (Ω), Z_2 is the negative sequence impedance (Ω). To obtain the value of the single phase short-circuit fault current to ground, equation (15) is:

$$I_{f,L-G} = \frac{3 \, x \, V_{L-N}}{Z_1 + Z_2 + Z_0} \tag{15}$$

$I_{f,L-G}$ is the single phase short circuit fault current to ground (A), V_{L-N} is the phase to neutral voltage (V), Z_1 is the positive sequence impedance (Ω), Z_2 is the negative sequence impedance (Ω), Z_0 is zero sequence impedance (Ω).
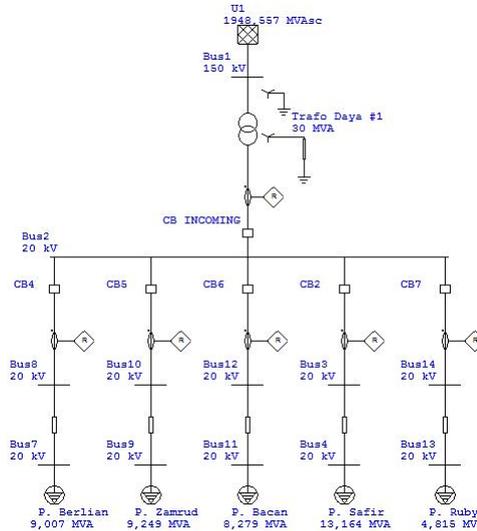

Figure 1. Diagram feeder of PK substation

Figure 1 is a single line diagram of the PK substation using the ETAP 12.6.0 programme to run simulations of short circuit faults and relay coordination. The data entered are the reset data. The results of the relay simulation are then compared with the relay data installed in the field.

Table 1. Over current relay

Incoming side		Feeder side	
Brand	Schneider	Brand	Schneider
Type	P142	Type	P142
Curve	IEC-*Standard Inverse*	Curve	IEC-*Standard Inverse*
CT ratio	1000: 1	CT ratio	400: 5
I_{set} (A)	1000	I_{set} (A)	352
I_{relay} (A)	1	I_{relay} (A)	4.4
TMS	0.22	TMS	0.13

Table 2. Ground fault relay

Incoming side		Feeder side	
Brand	Schneider	Brand	Schneider
Type	P142	Type	P142
Curve	IEC-*Standard Inverse*	Curve	IEC-*Standard Inverse*
CT ratio	1000: 1	CT ratio	400: 5
I_{set} (A)	100	I_{set} (A)	32
I_{relay} (A)	0.1	I_{relay}(A)	0.4
TMS	0.23	TMS	0.12

The evaluation of the coordination of OCR and GFR in the PK substation is by collecting data from the substation, transformer data, load data, feeder line data and relay data. The data in table 1 and table 2 will be used to calculate the equivalent impedance, short-circuit current, and TMS. Technical data on installed equipment includes installed power under three-phase short circuit conditions is 1948.557 MVA at a nominal voltage of 150 kV, power transformer capacity is 30 MVA, voltage on the secondary side is 20 kV at a nominal current of 866.02 ampere. The type of conductor used is AAAC with a size of 240 mm2, positive and negative sequence impedance $0.1344+j\,0.3158$ Ω/km, and a zero-sequence impedance $0.2824+j1.6034$ Ω/km.

3. RESULTS AND DISCUSSION

Short-circuit fault current calculations and OCR and GFR resetting are carried out. After that, a short circuit fault simulation will be performed, a relay coordination simulation, and the OCR and GFR curves will be displayed on the incoming and feeder sides. The simulation results before and after the reset will be compared. Using equation (5), the source impedance (Z_s) is as follows:

$$Z_{s\,(primary)} = 11.55\,\Omega$$

To convert the impedance on the primary side to the secondary side using equation (6), then:

$$Z_{s\,(secondary)} = 0.205\,\Omega$$

The positive and negative sequence impedance values of the transformer are obtained using equation (7):

$$Z_{t1} = Z_{t2} = 1.66\,\Omega$$

The transformer has a YY(d) winding connection which has a delta winding in it, the magnitude of Z_{t0} is three times the positive sequence impedance of the transformer. So, by using Equation (8) we have the following.

$$Z_{t0} = 3\,x\,1.66 = 4.98\,\Omega$$

The feeder chosen as a reference is a sapphire feeder. The positive sequence, negative sequence, and zero sequence impedances of the feeder are calculated using equation (9) and (10):

$$Z_1 = Z_2 = (0.1344 + j0.3158)\,x\,64$$
$$= 8.6016 + j20.2112\,\Omega$$
$$Z_0 = (0.2824 + j1.6034)\,x\,64$$
$$= 18.0736 + j102.6176\,\Omega$$

The feeder impedance values for fault locations with a distance of 0% and 100% of the feeder length in positive sequence and negative sequence are as follows:

$$Z_{1(0\%)} = 0$$
$$Z_{1(100\%)} = 100\%\,x\,(8.6016 + j20.2112)$$
$$= 8.6016 + j20.2112\,\Omega$$

The feeder impedance values for fault locations with a distance of 0% and 100% of the zero-sequence feeder length are as follows:

$$Z_{0(0\%)} = 0$$
$$Z_{0(100\%)} = 100\%\,x\,(18.0736 + j102.6176)$$
$$= 18.0736 + j102.6176\,\Omega$$

The equivalent impedance is calculated by adding the source impedance on the 20 kV side, the transformer impedance, and the feeder impedance. Equation (11) is used to calculate the equivalent impedance of positive sequence and negative sequence:

$$Z_{1(0\%)} = j1.865 + 0 = j1.865\,\Omega$$
$$Z_{1(100\%)} = j1.865 + 8.6016 + j20.2112$$

$$= 8.6016 + j22.0762 \ \Omega$$

Equation (12) is used to calculate the equivalent impedance of the zero sequence:

$$Z_{0(0\%)} = 120 + j4.98 + 0 = 120 + j4.98 \ \Omega$$
$$Z_{0(100\%)} = 120 + j4.98 + 18.073 + j102.6176$$
$$= 138.0736 + j107.5976 \ \Omega$$

If the equivalent impedance value according to the fault location has been obtained, then the next step is to calculate the short-circuit fault current. The three-phase short circuit fault current is calculated using equation (13):

$$I_{f,3\phi(0\%)} \quad = 6.191.42 \ A$$
$$I_{f,3\phi(100\%)} = 487.36 \ A$$

The two-phase short circuit fault current is calculated using equation (14):

$$I_{f,L-L(0\%)} = 5.361.93 \ A$$
$$I_{f,L-L(100\%)} = 422.07 \ A$$

Single phase short circuit fault current to ground is calculated using equation (15):

$$I_{f,L-G(0\%)} = 279.74 \ A$$
$$I_{f,L-G(100\%)} = \ 155.73 \ A$$

Feeder side OCR current adjustment

$$I_{set} = 418 \ A$$

The TMS OCR setting on the feeder side at the specified working time (t) is 0.3 seconds.

$$0.3 = \frac{0.14}{\left(\frac{6.260}{418}\right)^{0.02} - 1} \ x \ TMS$$
$$TMS = 0.12$$

Adjustment of feeder side GFR current;

$$I_{set} \ = 38 \ A$$

The specified working time (t) is 0.5 seconds;

$$0.5 = \frac{0.14}{\left(\frac{287}{38}\right)^{0.02} - 1} \ x \ TMS$$
$$TMS = \ 0.15$$

Incoming side OCR current adjustment;

$$I_{set} \ = 1.2 \ x \ 866.02 = 1.039.224 \ A$$

The TMS OCR setting of the incoming side at the specified working time (t) is 0.3 + 0.4 seconds.

$$0.7 = \frac{0.14}{\left(\frac{6,260}{1.039.224}\right)^{0.02} - 1} \ x \ TMS$$
$$TMS = 0.184$$

Adjusting the incoming side GFR current;

$$I_{set} \ = 0.1 \ x \ 866.02 = 86.6 \ A$$

The working time (t) set is 1 second;

$$1 = \frac{0.14}{\left(\frac{287}{86.6}\right)^{0.02} - 1} \; x \; TMS$$

$$TMS = 0.173$$

Figure 2 (a) simulates the coordination of OCR in three-phase short circuits. The relay sequence is that relay 2 sends a signal to CB 2 to drive, and relay 1 sends a signal to CB 2. Figure 2 (b) is the OCR working time coordination curve of the input and output sides of the three-phase short circuit when a short circuit error occurs. The work time of the second relay is 0.302 seconds, and the first relay is 0.704 seconds. Therefore, we get a time of 0.402 seconds.
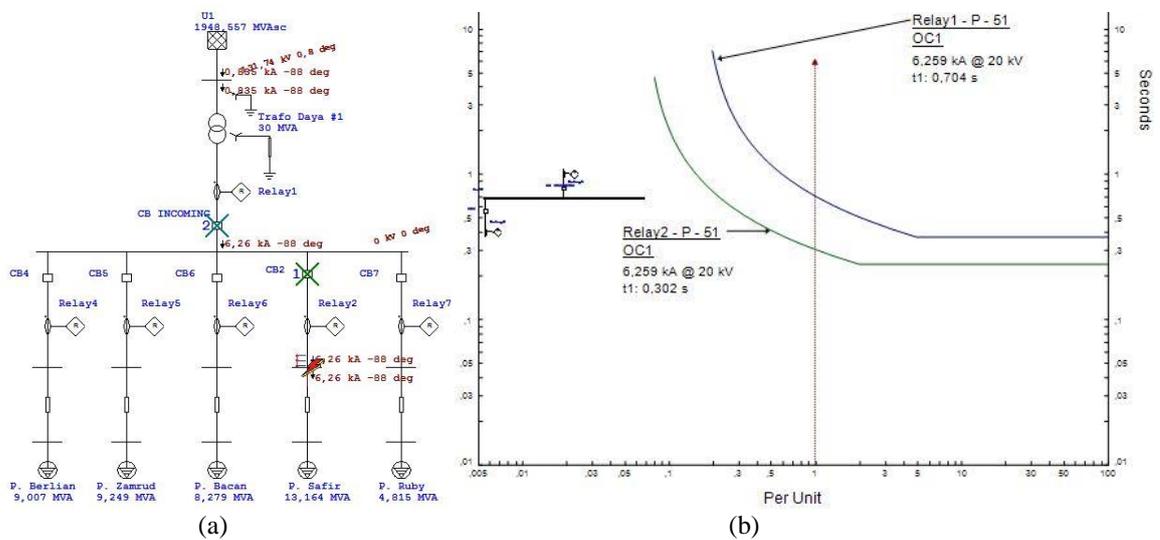

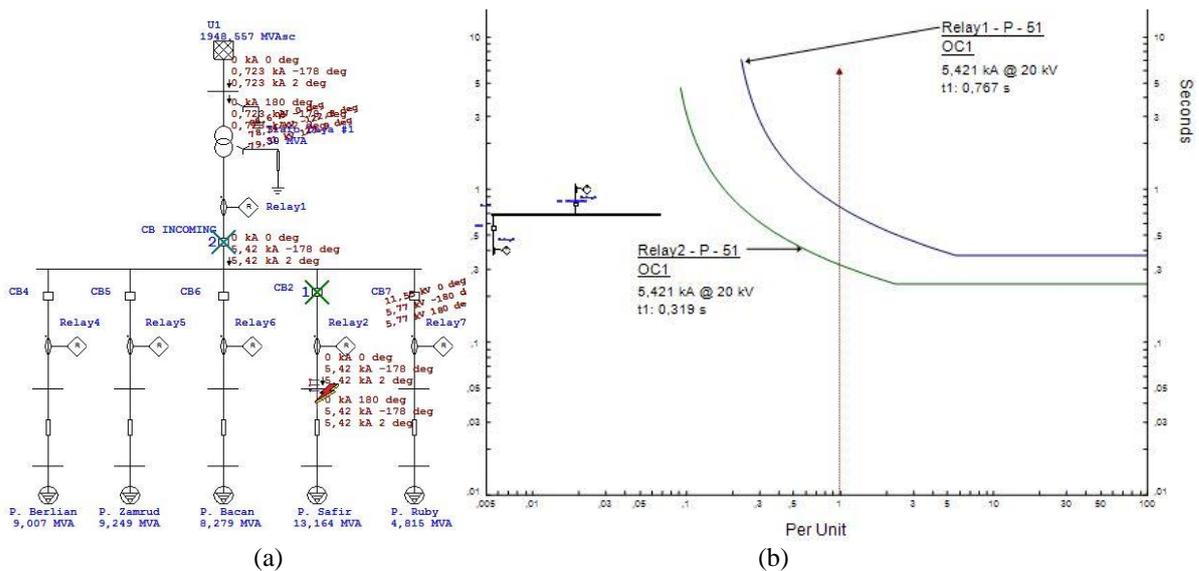**Figure 2.** (a) Simulation of OCR coordination when three phase faults; (b) Time coordination curve

Figure 3. (a) OCR coordination simulation when phase-to-phase fault (b) time coordination curve

Figure 3 (a) is a simulation of OCR coordination when a two-phase short circuit occurs. The relay sequence that works is that relay 2 gives a signal to CB 2 to trip, then relay 1 gives a signal to the incoming CB to trip. Figure 3 (b) is the OCR working time coordination curve of the input and output

sides of the feeder when a two-phase short circuit malfunction occurs. The working time of relay 2 was 0.319 seconds, while relay 1 was 0.767 seconds. Therefore, the time rating value is 0.448 seconds.
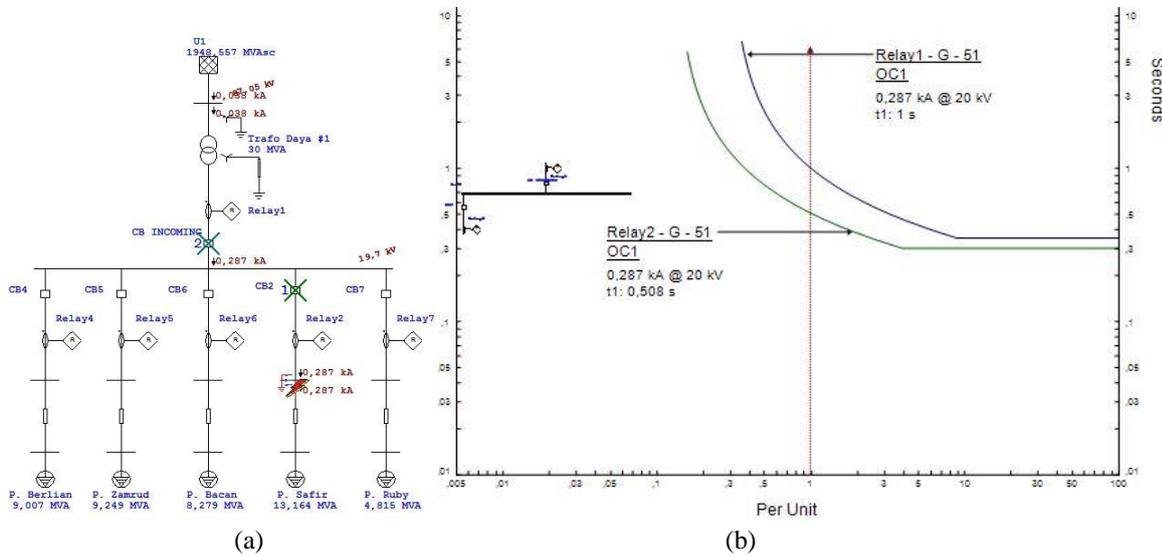

Figure 4. (a) GFR coordination simulation when single phase ground fault (b) Time coordination curve

Figure 4 (a) is a simulation of GFR coordination when a single-phase short circuit to the ground occurs. The relay sequence that works is that relay 2 gives a signal to CB 2 to trip, then relay 1 gives a signal to the incoming CB to trip. Figure 4 (b) is the GFR working time coordination curve on the feeder side and on the incoming side when a single phase short circuit to ground fault occurs. The working time of relay 2 is 0.508 seconds and relay 1 is 1 second. Therefore, we get a time-grading value of 0.492 seconds. It can be concluded that after resetting the relay has a time grading that complies with IEC 60255 [24], which is 0.4 - 0.5 seconds. The installed relay also works according to its settings. When the short circuit fails, the closest relay will be activated. If the magnitude of the current failure exceeds the subsequent configuration of the backup relay, the backup relay will respond within the specified time parameters according to the recommendations of IEC 60255.

4. CONCLUSION

Analysis of short-circuit failure simulations shows that the farther away the failure point is from the power source, the lower the corresponding fault current. In contrast, when the fault point is closer to the power source, the current value of the fault is higher. As the existing OCR time classification does not meet the IEC 60255 standards, adjustments are made. The evaluation results show that OCR's work time on the top of the entry is 0.704 seconds, and the working time on the top of the feeder is 0.302 seconds. The time distribution between the OCRs complies with IEC 60255 standards in the range of 0.402 seconds. The GFR time classification under current conditions also does not comply with the IEC 60255 standards, so the GFR has been redesigned to make the GFR working time 1 second from the source and 0.508 seconds from the source. The calculation time between GFR is strictly in accordance with IEC 60255 standards, which is 0.492 seconds. Finally, after evaluating the coordination of the OCR and GFR protection relays in the distribution feeder, the relays were adjusted to IEC standards to improve the protection device performance. Future research could study the optimization techniques of OCR and GFR relay coordination to improve performance according to existing standards.

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