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Protection Coordination Method Using Symmetrical Components in Loop Distribution System

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Abstract: Power utilities worldwide commonly use the radial distribution system because of its advantages of being simple in structure and having relatively inexpensive installation costs. It has a disadvantage in that its power supply reliability is low because the load side of the fault section will suffer from an outage in the event of a fault in the system. However, recently, with ICT (Information and Communication Technologies) development, system reliability is required to be high as the outage-susceptible loads increase. In addition, the increase in the connection of distributed resources such as renewable energy and electric vehicles is making it impossible to predict the power flow and reducing line utilization. Therefore, a loop power distribution system is proposed as a measure to solve this problem. Because all buses (nodes) in a loop distribution system have two or more power supply routes, they are more reliable than the radial system. It allows them to improve line utilization by connecting lines with different load peak times. However, in the case of a fault in the loop distribution system, the fault current is supplied from both directions, making it impossible to properly isolate the fault section with the protection method of the conventional distribution system. The permissive overreach transfer trip (POTT) method using communication to compensate for the limitations of conventional protection devices, and the other method using directional distance relay, is proposed. However, these methods operate by determining the direction of the fault current but have a disadvantage. It is difficult to detect a fault due to the effects of ground faults and distributed generation (DG) occurring in other lines. Therefore, in this paper, we propose a protection coordination algorithm that uses the negative-sequence component of voltage and current that occur when an unbalanced fault occurs, rather than the determination of the directionality and use of communication. To validate this, we configured a system using PSCAD/EMTDC (Manitoba Hydro International Ltd., Winnipeg, Manitoba, Canada), a system analysis program package and verified the results depending on the type of faults with the proposed algorithm.

Keywords: protection coordination; loop distribution system; symmetric component; distributed generations

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1. Introduction

The radial distribution system currently accounts for more than 99% of distribution lines used by power companies worldwide because of its advantages of being simple in structure and having relatively inexpensive installation costs compared to other methods. However, it has a significant disadvantage in terms of supply reliability. It is impossible to supply power to the healthy section downstream of the fault section, although the fault is eliminated from the system. Furthermore, with the development of ICT technology, as facilities to be interconnected to the distribution system become more complex and advanced, they also are becoming more susceptible to outage, so higher reliability is required. The tendency of power flows to the distribution system is diversified by increasing distributed resources such as various DGs and electric vehicles [1,2]. Problems that affect line utilization include over-voltage and low-voltage occurring on the line and excess capacity of distribution line [3,4].

One solution to the problem is to configure the power distribution system into a loop structure. All buses (nodes) in the loop distribution system have two or more power supply routes. Each connection element has a connection point in two or more directions to minimize the outage section. However, a system fault occurs and thus has a higher level of reliability than the radial system. A low voltage drop at the ends of the lines is realized through bidirectional current distribution even during constant operation. At the same time, they can reduce overall peaks when the lines are interconnected at different peaks per hour, thereby increasing line utilization and expanding the acceptability of distributed resources [5,6]. This structure is not used well because of the high installation cost compared to the conventional radial system. However, as the DG supplement increases, the radial system's limitations occur, and interest in a loop distribution system increase. However, in the loop structure, it is difficult to apply the conventional protection coordination due to the diversification of fault currents. Conventional protective devices used in radial systems are either non-directional or react only to one-way fault currents and may lead to failure to detect the bidirectional fault current or non-function or malfunction by falsely detecting the fault current. However, it is not a fault section. This can cause significant damage to electrical equipment and interconnected lines [7–10].

To make up for this, protection coordination suitable for the loop method is proposed. The most commonly used method is the POTT, which uses one-to-one communication between circuit breakers to exchange trip signals and blocking signals. When the fault in the forward direction is detected in the directional relay installed on the circuit breaker (CB), it isolates only the fault section by sending a trip signal. Whereas when the fault in the reverse direction is detected, sending a blocking signal to prevent malfunction of CB [11–13]. However, this method is based on one-to-one communication that cannot determine the fault section for the ground fault current generated on other distribution lines and may cause CB malfunction. Moreover, it is difficult to detect a High Impedance Fault (HIF) with a minimal fault current.

There is also a method of detecting a fault section using a distance relay, mainly used in the transmission system [14–16]. The distance relay detects and isolates the fault section when a fault occurs within the preset area set by calculating the impedance to the fault location. However, using the distance relay has the disadvantage of not accurately detecting the fault location since it affects the equation for determining impedance to the fault location when DGs are interconnected to the distribution line, or the size of the fault resistance becomes large. Another method is to isolate the fault section using the ratios of the zero-sequence component and positive-sequence component of the fault current [17]. When a fault is detected, this method pre-activates the breaker at the end of the preset system. Afterward, it converts the loop system into a temporary radial system. It then detects and isolates the fault section using the ratios of the positive-sequence component and zero-sequence component [18–20]. This method activates the circuit breaker without considering the load interconnected to the line in the process of converting the system into a temporary radial system. Consequently, overload of the line can be induced. It also has the disadvantage of not handling short circuits because it uses a zero-sequence current that does not occur in the event of a short circuit.

In this paper, we propose a method of using a negative-sequence component of current and voltage to compensate for this. Unlike the zero-sequence component, the negative-sequence component appears in all asymmetry faults. In addition, due to the characteristics of the negative-sequence component, the closer the fault location, the larger magnitudes of the voltage and current, but their magnitudes become smaller as the fault location moves toward the substation. Moreover, the closer the positive-sequence component is to the fault location, the smaller its magnitude.

Therefore, we propose an algorithm for phase to ground fault and phase to phase short circuit. This algorithm makes use of the characteristics of the negative and positive-sequence components of current. In addition, by multiplying the current ratio by voltage ratio, a situation due to the current fluctuation is prevented, and fault detection is facilitated. Using the proposed protection method, it is possible to detect a ground fault and phase-to-phase short circuit and HIF, which is difficult to detect due to the minimal magnitude of fault current by the current protection coordination method. When a HIF occurs, although the overall magnitude of the current is the same, the magnitude of the negative-sequence component increases as it approaches the fault location as described above, making this idea applicable. Lastly, the method we propose has the advantage of isolating the fault section without determining the direction of the fault current, reducing additional facilities because it does not use communication.

2. Conventional Protection Coordination

However, as shown in Figures 1 and 2, if the relay installed in the recloser (REC) and CB can be detected only a unidirectional fault current, the range of outages can be expanded by a malfunction or non-function of CB.

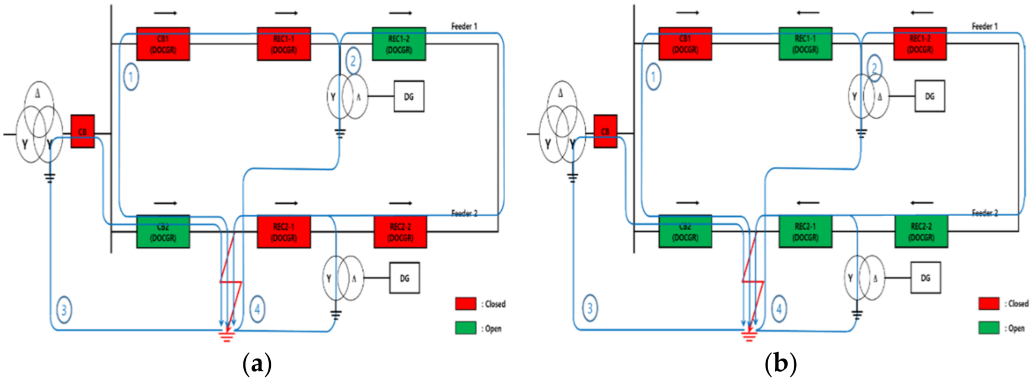


Figure 1. Flow diagram of fault current (ground fault); (**a**) Setting in the direction of the load side (**b**) Setting in the direction of the generation side.

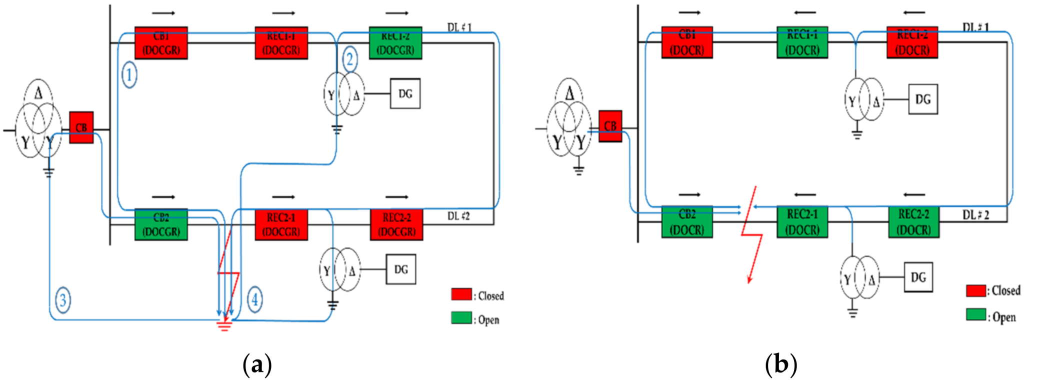


Figure 2. Flow diagram of fault current (phase-to-phase short circuit); (**a**) Setting in the direction of the load side; (**b**) Setting in the direction of the generation side.

As shown in both (a) in Figures 1 and 2, when the DOCGR is set in the load side direction, the circuit breaker on the right side of the fault location is inoperable, and the fault current from the interconnected transformer on line 1 causes a malfunction, which operates the REC 1–2, expanding the outage section. As shown in both (b), when the direction is set to the generation side, CBs at both ends of the fault location operate; when the DG is interconnected to line 1, the REC 1–1 operates. In this way, directional relays (DOCR and DOCGR) cannot be installed in the loop distribution system; as in this alternative, the following protective equipment is installed as alternatives.

Figure 1 shows the flow of the fault currents in the event of a ground fault in the loop system. The fault current flows across almost all sections of the distribution line, starting from the fault location through the grounding of the main transformer and the grounding of a distributed generation-connected transformer. In addition, if a phase-to-phase short circuit occurs, all CBs on the distribution line experienced a fault current due to the current supplied from the substation and the fault current supplied from DG. Assume that relay only measures one direction. In the Figure 1, the relay installed on the distribution line detects a fault current flowing from the substation side to the load side in Figure 1a. Furthermore, in Figure 1b, it was set to detect the fault current flowing from the load side to the substation side.

2.1. Distance Relay

The distance relay sets a zone from the relay and operates when the impedance occurs within the preset zone. By setting the distance ratios of buses A to B as n in Figure 3, the zone of distance relay is set as nZ_R. Generally, it is divided into three regions: if n is less than 0.8, then it is set to Zone 1; if n is between 1.2 and 1.5, then it is set to Zone 2; Zone 3 is set to where n is 2 or more, or maybe set to detect a fault in the reverse section of the bus. The type of the distance relay includes impedance, Mho, reactance and quadrilateral, depending on the operating characteristics that set the zone by being installed at the entrance of the distribution line or between CB and REC [21,22].

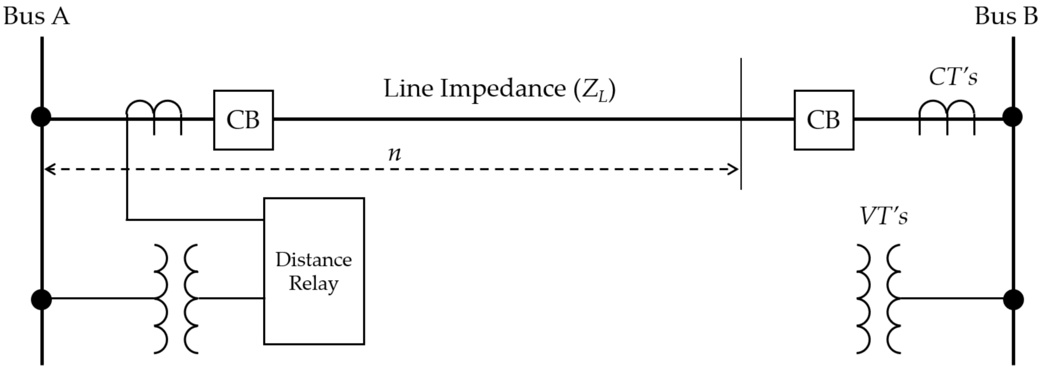


Figure 3. Distance relay between bus A and bus B.

When a fault occurs at any point R of line, impedance Z_R from the distance relay installation point to the fault is calculated as in Equation (1) from the ratio of voltage and current.

$$Z_R = \frac{V}{I} \times \frac{\frac{1}{PT_{ratio}}}{\frac{1}{CT_{ratio}}} = Z_L \times \frac{CT_{ratio}}{PT_{ratio}} \tag{1}$$

Z_R = Impedance measured by the distance relay
Z_L = Line impedance

The impedance Z_R to the fault location increases as the fault location becomes distant from the distance relay. Assuming that the setting impedance in the relay is Z_T, if $Z_R < Z_T$, it determines that this is a fault within its zone and operates instantaneously. On the contrary, if $Z_R > Z_T$, it determines that this is a fault outside its zone, and delayed operation is performed.

2.2. Pilot Wire Communication Method

In order to isolate the fault section, this method uses forward or reverse fault currents that use one-to-one communication-based POTT between CBs of the system where the communication line is installed, as in Figure 4. When a fault occurs between CB, the directional relay (67) installed in CB detects the fault and sends a trip signal to the other CB located at the other end. In other words, it detects a forward fault in CB, receives a trip signal from the other circuit breaker located at the other end and then opens a CB according to the AND condition. When a fault occurs outside CB, on the left side of bus A, CB B detects the forward fault and then sends a trip signal to CB A. However, CB A detects the reverse fault and prevents the operation of CB B by sending a blocking signal without sending a trip signal to CB B.

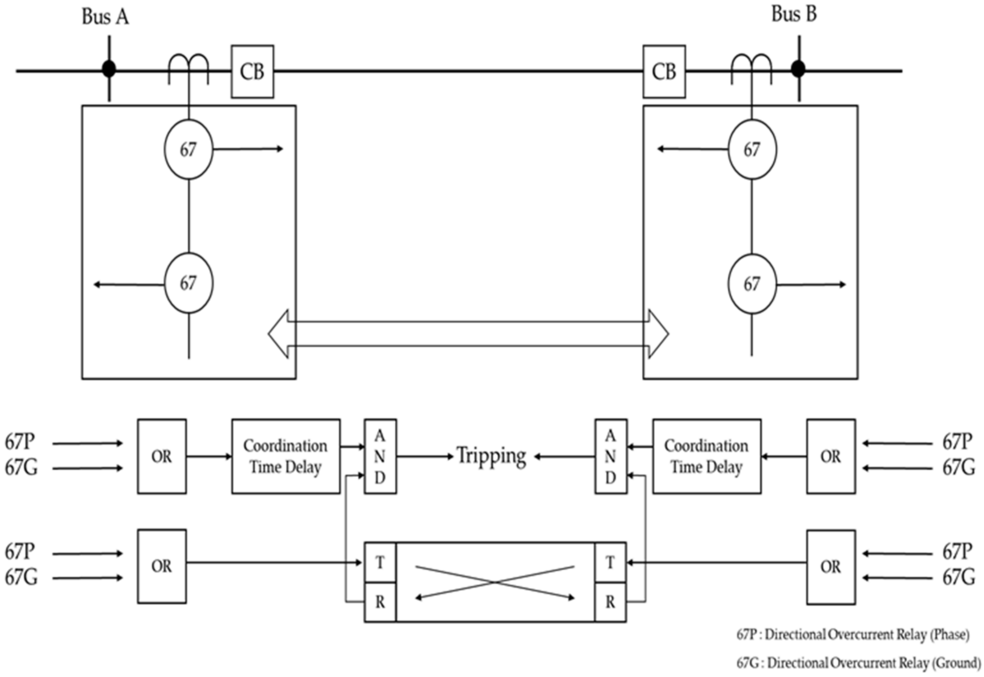


Figure 4. Principle of POTT [4].

2.3. HIF (High Impedance Fault)

When a ground fault arc caused by an open phase occurs in the system, the shoulder occurs in the current waveform [23,24]. Using this, it is possible to determine whether the system's arc generates via correlation analysis or FFT (Fast Fourier Transform). When an arc is detected in the neutral line, but the protection device does not operate, it must be determined as a HIF, and the system must be temporarily changed to the radial system by opening all the interconnection switches or CB. After being changed to a radial system, the interconnection equipment is inserted by analyzing the non-voltage section for each line to determine the line that contains the HIF section (in some cases, it is difficult to determine the fault section due to DG. Hence it is necessary to immediately input the interconnection switch to allow the open sequence to proceed). Finally, a fault section is derived by confirming the voltage on the primary and secondary sides and opening the protective device one by one from the end of the line containing the fault section during the opening sequence.

3. Problems in Conventional Protection Coordination

The distance relay has a significant dependence on voltage and current measured in the PT and CT of a relay because a distance relay uses the fault impedance measured from a relay to set a zone. When an error occurs in voltage and current measurement, underreach or overreach of a relay can cause malfunction or non-function. Furthermore, when the DG is interconnected to a loop system, DG supplies fault current to a fault location. Therefore, the infeed effect can be generated because an impedance (Z_{add}) affects Z_R measured in a relay, as shown in Figure 5.

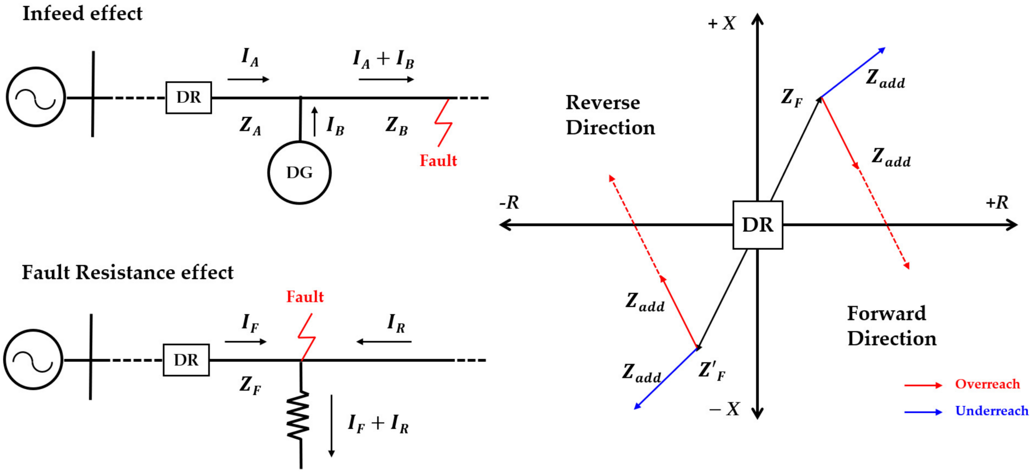


Figure 5. Limit of the distance relay.

Moreover, the fault resistance effect occurs due to the fault resistance. An additional impedance $Z_{add} = \left(\frac{I_A}{I_B} \times R_f\right)$ results in an underreach or overreach of a relay, as the current is bidirectionally supplied to a fault location [18].

In addition, the protection method of the POTT is based on one-to-one communication and is a method of operating when CBs at both ends pick up a forward fault. However, when DG is interconnected to a loop system or a ground fault occurs on the external line, malfunction may occur due to a fault current flowing through the interconnection transformer grounding of DG.

When a fault section is not isolated or is widened due to malfunction or non-function of CB, the range of outage increases, and the reliability of the entire system decreases. In addition, when switching to the temporary radial system to eliminate the fault, overload may occur depending on the load interconnected to the distribution line of the healthy phase. Accordingly, to reduce the outage range and improve the system's reliability, a fault must be accurately picked up, and only the fault section must be isolated.

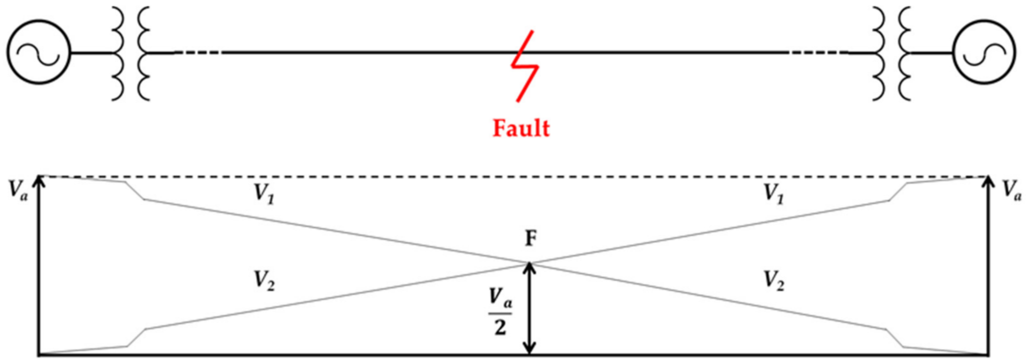
4. Proposed Protection Algorithm

The symmetric component of voltage and current is derived using Equation (2).

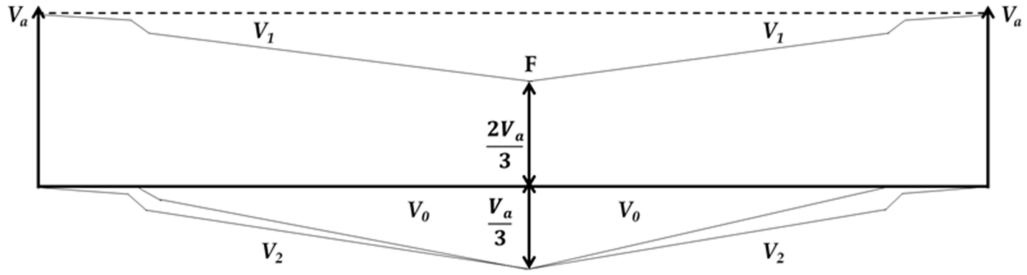
$$\begin{aligned} I_1 &= \tfrac{1}{3}\left(I_A + aI_B + a^2 I_C\right),\ V_1 = \tfrac{1}{3}\left(V_A + aV_B + a^2 V_C\right) \\ I_2 &= \tfrac{1}{3}\left(I_A + a^2 I_B + aI_C\right),\ V_2 = \tfrac{1}{3}\left(V_A + a^2 V_B + aV_C\right) \\ I_0 &= \tfrac{1}{3}(I_A + I_B + I_C),\ V_0 = \tfrac{1}{3}(V_A + V_B + V_C) \end{aligned} \tag{2}$$

As can be seen from the Equation (2), the characteristic of the symmetric component is that in the normal operation, only the positive-sequence component exists, and the negative and zero-sequence component does not exist. However, if a fault occurs, the magnitude of the negative and zero-sequence components increases because an imbalance occurs. Since the imbalance is most significant at fault, its value is the largest. Conversely, the unbalance is negligible on the substation side, so the magnitude is almost zero. Positive-sequence components have opposite characteristics. Since there is almost no unbalance on the substation side, it is the largest in magnitude and decreases in magnitude as it approaches fault. This content is represented in Figure 6. The magnitudes of the positive-sequence component V_1 and negative-sequence component V_2 increase and decrease opposite each other.

There is a limit to detecting both a ground fault and a phase-to-phase short circuit using a zero-sequence component because a zero-sequence component occurs only in the case of a ground fault. However, when an asymmetric fault occurs in the system, the negative-sequence component and zero-sequence of current and voltage occur. Therefore, this paper proposes a method for detecting faults using the current and voltage of a negative-sequence component generated from all asymmetric faults.



(a) : Phase to Phase Fault



(b) : Ground Fault

Figure 6. Size of voltage symmetric component by fault; (**a**) Phase to Phase Fault; (**b**) Ground Fault.

Figure 6 shows that a fault occurred in the middle of the distribution line with a power source at both ends. Since the voltage drop is negligible as it is closer to the substation side, only a positive-sequence component exists, and it is almost the same as the magnitude of the phase voltage. However, as it approaches the fault location, the magnitude of the positive-sequence component becomes smaller due to voltage unbalance. Conversely, the negative-sequence component hardly exists on the substation side, where the voltage drop is negligible. However, as it approaches the fault, the magnitude increases and becomes equal to the positive-sequence component.

When a fault occurs, as shown in Figure 6, the negative-sequence component of voltage increases as it approaches the fault location. On the contrary, the positive-sequence component decreases as it approaches a fault location. When a fault occurs in a line, the magnitude of voltage varies, as shown in Figure 6. In the case of a positive-component V_1, it is measured the largest on a substation side, and magnitude decreases as it approaches a fault location. In the case of a short-circuit in Figure 6a, it is the half magnitude of phase voltage at a fault location. In the case of a negative-sequence V_2, the magnitude increases as it goes to a fault location, contrary to normal operation. It has almost zero magnitudes on normal operation. However, when a fault occurs, it increases to half of the phase voltage in the case of a short-circuit. In the case of a ground fault in Figure 6b, the magnitudes of a positive-sequence, negative-sequence and zero-sequence component are all the same at the fault location. however, closer to the substation side, magnitude of zero and negative-sequence is decrease and positive-sequence increases

The magnitude of the current is also measured similarly shown in Figure 6. Thus, a magnitude of the negative-sequence component increase as they approach the fault location and decrease as they become distant from the fault location. Conversely, a positive-sequence component decreases as it approaches a fault location [22].

In this paper, we propose a method of isolating the fault section using the characteristics of symmetric components. Fault picked up by calculating the ratio of the negative-sequence current and positive-sequence current. However, a current ratio fluctuates rapidly in the process of CB and REC operation. Therefore, a calculated value can be measured to infinity or zero. Therefore, multiplying the ratio of the negative-sequence voltage and positive-sequence voltage by a calculated value, thereby quickly detecting a fault and preventing it from being output to an infinity value. The reciprocal of a calculated value is set as the operation time of CB and REC. A calculated value becomes more significant as it is closer to the fault section and smaller as it is farther from the fault section. Thus, CB and REC close to the fault section is first opened and isolates only the fault section.

$$I_P\left(=\frac{I_2}{I_1}\right)\times\frac{V_2}{V_1} \tag{3}$$

I_p = Ratio of the positive-sequence current and negative-sequence current
I_1 = Magnitude of the positive-sequence current
I_2 = Magnitude of the negative-sequence current
V_1 = Magnitude of the positive-sequence voltage
V_2 = Magnitude of the negative-sequence voltage

4.1. Ground Fault/Phase-to-Phase Short Circuit

When a ground fault occurs, the positive-sequence, negative-sequence and zero-sequence components, which are symmetric components of the current, are all measured. Previously, to detect a ground fault, a current zero-sequence component flowing through the neutral line had to be measured, so ground relay is needed. However, using the algorithm that we propose does not require installing an additional device for measuring the zero-sequence component because this method can detect the fault by using the negative-sequence component, not by using the zero-sequence component, and allows the isolation of a fault section using the conventional equipment without the need to install any additional equipment.

Moreover, in the case of a phase-to-phase short circuit, the fault section can be isolated using the method we propose because the negative-sequence component and positive-sequence component occur. According to the characteristics of the symmetric component mentioned above, the ratio of a negative-sequence component by a positive-sequence component increases as it approaches a fault location. In the case of a phase-to-phase short circuit, since there is no current flowing in the neutral line, the current ratio value is used to pick up a fault. If this value does not reach a specific range, it is not determined as a fault because it means that a negative-sequence current does not increase more than a specific value. However, if the ratio value exceeds a certain range, it is determined that a fault has occurred, and the algorithm is performed. Therefore, as with the ground fault, a phase-to-phase short circuit can be detected and isolated using the proposed algorithm. Thus, it is possible to detect both ground fault and phase-to-phase short circuits without additional equipment.

4.2. HIF (High Impedance Fault)

When a HIF occurs, the fault current undergoes minor changes, and the voltage does not fluctuate. Therefore, conventional methods of detecting faults by magnitudes and phases of current and voltage are not suitable for detecting a HIF. However, the proposed algorithm detects a fault using the symmetric components of the negative-sequence component and the positive-sequence component of current and voltage. Therefore, when a fault is detected in the neutral line, HIF can be detected. However, the value of the negative-sequence component is tiny and may not reach the set value. As shown in Figure 7, if a fault current is detected on the Y-side grounding of the substation and the voltage of the negative-sequence component does not reach a specific value, in order to facilitate fault detection, the constant value is multiplied by the voltage value if a negative-sequence component of voltage magnitude is less than a certain value. This value is finally multiplied by a ratio value of current to calculate the final value.

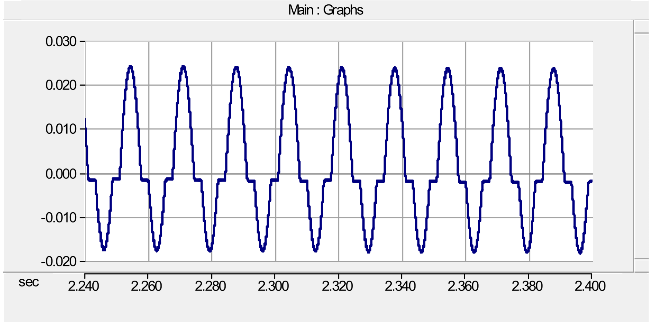


Figure 7. HIF current waveform measured from the neutral line of the main transformer.

HIF uses a fault resistance of 30–100 Ω in a common ground fault. However, the arc current due to HIF consists of sparks and sustained arcs and has very intermittent and random characteristics. Therefore, we implemented a HIF model based on the theory of A. E. Emanual to model and accurately all possible fault currents, as shown in Figure 8. It consists of two DC power supplies, V_p and V_n, connected in reverse parallel by two diodes. Diodes determine the direction of the AC voltage passing through the DC power supply, and the breakdown point where the air insulation is broken may be determined by the size of the DC power supply. A high-resistance ground fault occurs between a conductor wire and an object with high resistance impedance, and thus, it is half-wave asymmetry within one cycle due to the material difference between the anode and cathode [23,24].

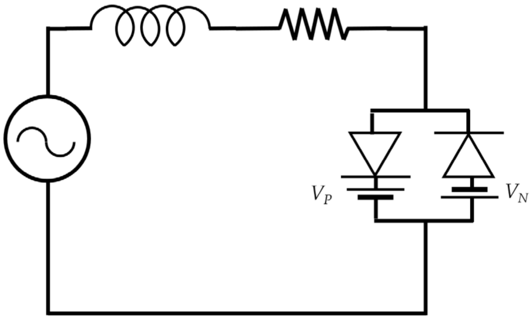


Figure 8. HIF model of A.E. Emanual [23,24].

4.3. Algorithm

The proposed algorithm proceeds according to the sequence of Figure 9. For fault pickup, the algorithm distinguishes between ground failure and phase-to-phase short circuit. In the case of a ground fault, a fault pickup occurs as the current measured on the grounding of the main transformer exceeds a specific value (=20 A), which makes the ground fault algorithm operate, thereby calculating the values of the currents of negative-sequence component/positive-sequence component (I_p) and the ratio of the negative-sequence and positive-sequence voltage (V_2/V_1). In the HIF, the magnitude of voltage and current is measured to be smaller than the single-line-ground fault. Therefore, if a voltage of a negative-sequence component is smaller than a specific value (=500 V), multiplying by ten (=constant) makes it easier to detect the fault. When a phase-to-phase short circuit occurs, no current is detected in the neutral wire. Therefore, the ratio of current and voltage is used for fault pickup. When a phase-to-phase short circuit occurs, negative-sequence increases, positive-sequence decreases. When a value of ratio of voltage and current exceeds a specific value, it is determined as a fault, and an algorithm is performed.

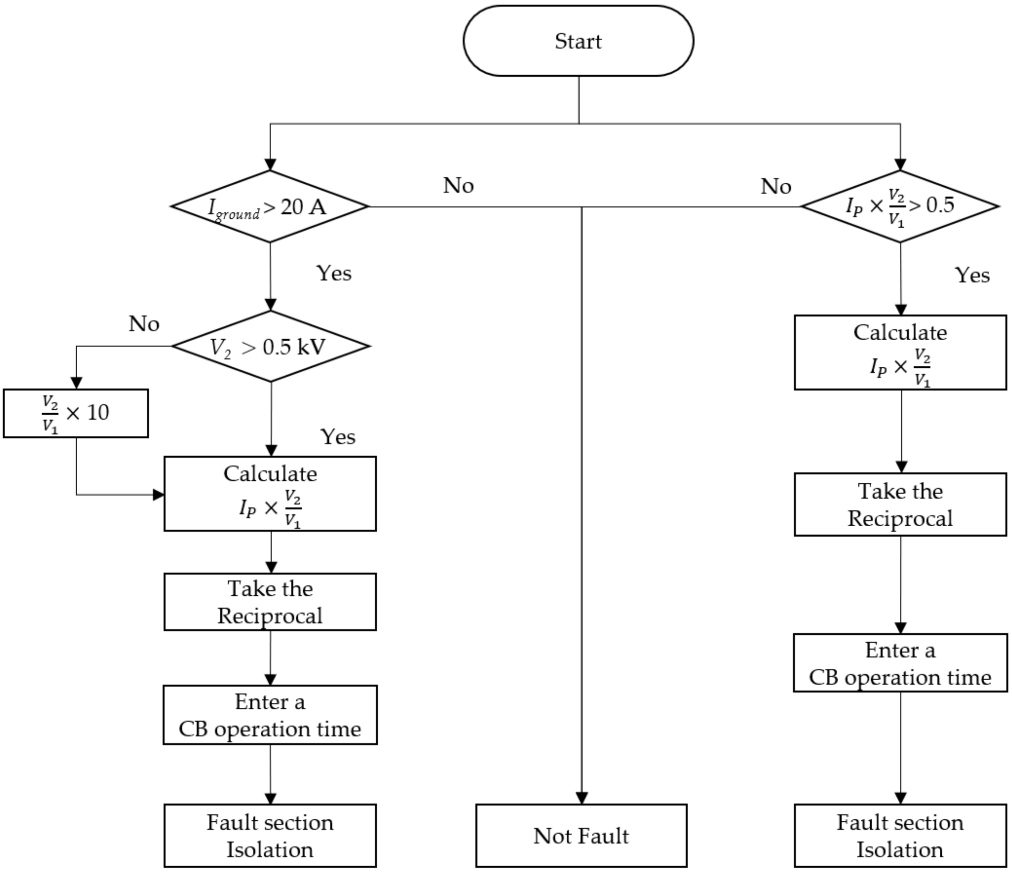


Figure 9. Block diagram of algorithm.

When the calculated value is finally output, it is necessary to multiply this value by ten (or any constant) to take the reciprocal and set this to the operating time of CB. The reason for multiplying by constant is to accelerate the operating time of CB. If the magnitude of a calculated value is large, the operating time of CB is shortened. It has similar characteristics to TCC (Time–Current Curve applied to a conventional OCR. Although other CBs measure a similar value in a loop distribution system, the other CB does not operate because the fault pickup is not made in the healthy section below the operated CB when CB with a significant calculated value is operated.

5. Simulation and Analysis

In this chapter, we conduct simulations to verify the proposed algorithm and analyze results. To this end, we modeled a PCS-based DG interconnected to a loop distribution system by using the PSCAD/EMTDC program tool. The proposed algorithm yields the same result regardless of fault location. Therefore, we fixed the fault location and performed a simulation depending on the type of fault.

5.1. Distribution System Configuration and Fault Scenario Settings

As shown in Figure 10, we configured the distribution line in a loop system with interconnection points connected to the switch and installed a CB and three RECs on each line. The components that make up the system, including DG, were set as shown in Table 1, DG is interconnected to feeder 2, and the fault is set to occur in feeder 1 between REC 1–3 and REC 1–4. The scenario was set to allow a fault to occur in 1 s, last 0.5 s and then eliminated itself. In the case of a ground fault, when a fault current is detected on the Y-side grounding of the main transformer and each CB and REC's neutral line for fault pickup, the algorithm operates to isolate the fault section. In addition, in a phase-to-phase short circuit in which the fault current is not detected on the ground, the fault pickup is set to be performed when a proposed positive-sequence component and negative-sequence component values ratio exceeds a specific value.

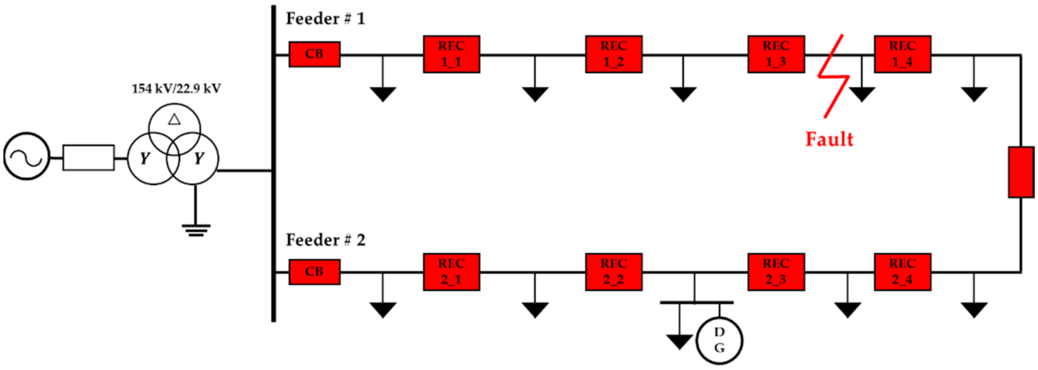


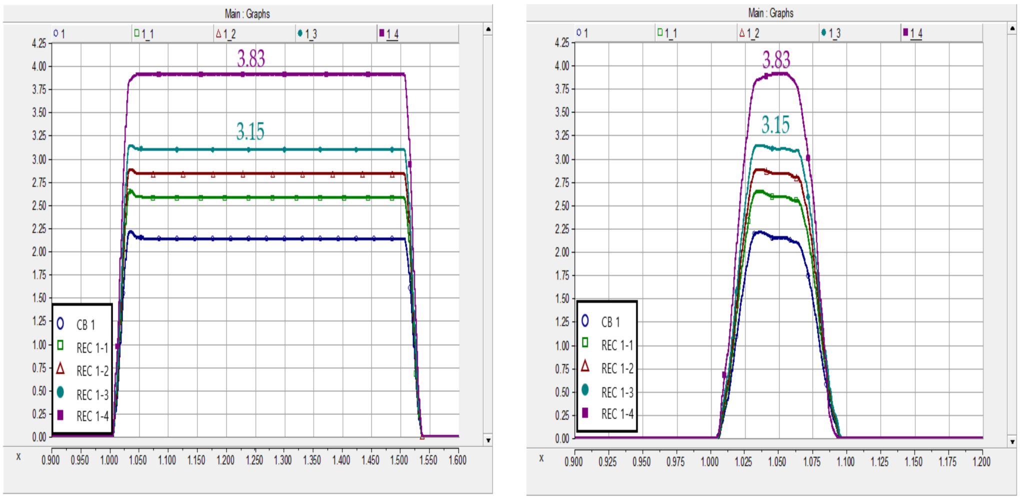
Figure 10. Configuration diagram of loop distribution system.

Table 1. Specifications of the system model components.

Index	**Value**	**Remark**
	154 kV Grid Source	
Positive Sequence %Z	0.08 + j0.99	100 MVA Based
Zero Sequence %Z	0.34 + j1.69	
	3-Winding Transformer (154 kV/22.9 kV/6.6 kV)	
Rated Power	45/60 MVA	45 MVA Based
Positive Sequence %X_{1--2}	j16.16	
Positive Sequence %X_{2-3}	j6.69	
Positive Sequence %X_{3-1}	j25.38	
Type	$Y - Y_g - \triangle$	
	Distribution Generation (22.9 kV)	
Rated Power of DG	1 MVA (0.5 M × 2)	
Transformer Connection	$Y_g - \triangle$	
Positive Sequence %X	j 0.05	
	Line Impedance (CNCV)	
Positive Sequence %Z	1.7828 + j1.7848	
Zero Sequence %Z	2.4617 + j5.4421	
	Fault resistance (Ω)	
Short-circuit	0.1 Ω	
Single Line Ground Fault	0.1 Ω	
High Impedance Fault	150 Ω	

5.2. Simulation Consequences

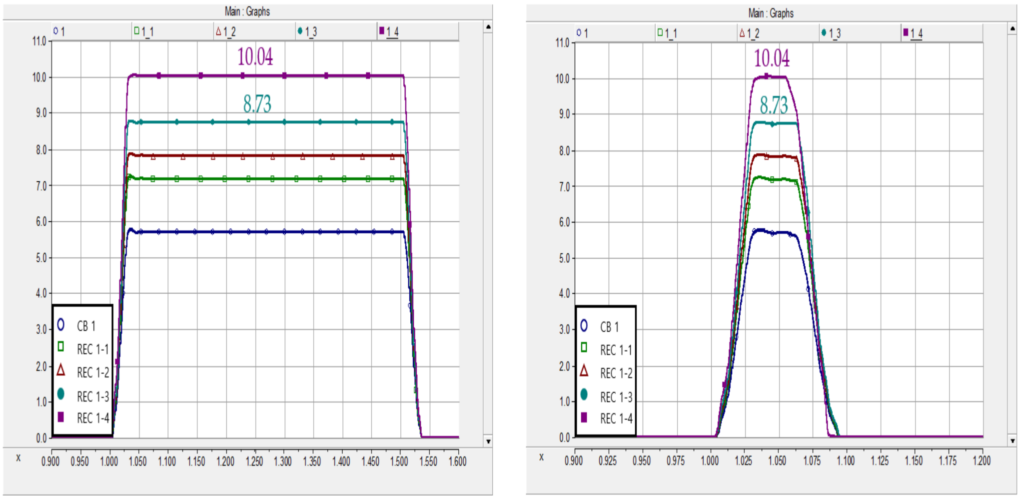
Figure 11 shows the measured value of fault current ratio when the proposed fault isolating method is applied to the phase-to-ground fault that occurred in a loop distribution system. The x-axis represents time, and the y-axis represents the ratio of voltage and current. The left side of Figure 11 shows the measured values before applying the algorithm to a fault. The right side of Figure 11 shows that the first CB, measured as 3.83, operates in 26 ms by applying the proposed algorithm. Although DG is interconnected by the operation of the REC 1–4, the supply path of a fault current is blocked, thereby preventing the fault current from flowing in the healthy section downstream of CB. Moreover, this shows that the second circuit breaker, measured at 3.15, operates in 30 ms to isolate the fault section.



(**a**) (**b**)

Figure 11. Ground fault simulation: measured values for each breaker of feeder 1. (**a**) Before applying algorithm; (**b**) after applying algorithm.

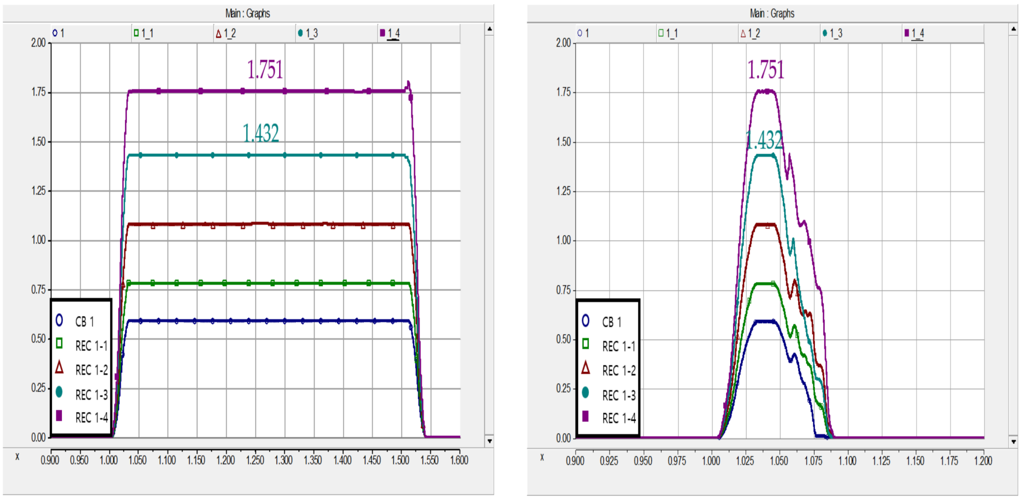
Figure 12 shows the measured value of fault current ratio when the proposed method is applied to the phase-to-phase short circuit that occurred in a loop distribution system. The x-axis represents time, and the y-axis represents the ratio of voltage and current. The left side of Figure 12 shows before applying the algorithm. The right side shows that the first CB (REC 1–4), measured at 10.04, operates in 10 ms using the proposed algorithm. The fault current does not flow in the healthy section below CB due to the REC 1–4. Therefore, the calculated value is not applied downstream of REC 1–4. This shows that the CB (REC1–3), measured at 8.73, operates in 12 ms to isolate the fault section.



(**a**) (**b**)

Figure 12. Phase-to-phase short circuit simulation: measured values for each breaker of feeder 1. (**a**) Before applying algorithm; (**b**) after applying algorithm.

Figure 13 shows the measured values when HIF occurs. The left side shows before applying the algorithm. The x-axis represents time, and the y-axis represents the ratio of voltage and current. The current and voltage of HIF do not change significantly; therefore, as suggested by the algorithm, the value is measured by multiplying a voltage ratio by ten. The right side shows that the first CB (REC 1–4), measured at 1.75, operates within 50 ms. Moreover, the second CB (REC1–3), measured at 1.432, operates in 65 ms to isolate the fault section.



(**a**) (**b**)

Figure 13. HIF simulation: measured value of feeder 1. (**a**) Before applying algorithm; (**b**) after applying algorithm.

6. Conclusions

The protection methods in the conventional loop distribution system are communication-based, and methods of isolating a fault section by exchanging a trip and blocking signal by detecting a forward fault current were mainly applied. They were also methods of using directional distance relays to detect the fault section by measuring impedance. However, these methods have the disadvantage of not detecting a fault or causing a malfunction resulting from the fault current flowing through the grounding of the interconnection transformer of DG. As a result, the extension of the outage section caused problems such as reduction in reliability and stability of the distribution system and limitation of interconnection DG to a loop system. This paper proposed isolating a fault section using symmetrical components of voltage and current to solve such problems. We propose an algorithm that isolates only the fault section without the additional determination of the directionality using the characteristics of the negative-sequence component, which increases as it approaches the fault location and decreases as it is farther from the fault location. The characteristics of the positive-sequence component, which decrease as it approaches the fault location. In addition, this algorithm is a method of inputting the reciprocal of the calculated value as the operating time of CB, and therefore, can isolate the fault section without additional communication equipment. A loop distribution system is modeled using the PSCAD/EMTDC(Manitoba Hydro International Ltd., Winnipeg, Manitoba, Canada) software package to validate the proposed algorithm. In addition, the controller is designed for an algorithm, and the operation of the proposed algorithm is verified by simulating the situation in which a fault occurred in the distribution line. Simulations have shown that, regardless of the type of asymmetric fault, the proposed algorithm operates to isolate only fault sections within 100 ms. This method compensates for the disadvantages of the POTT, which detects forward faults using communication and the distance relays that use impedance, thereby eliminating the need for additional equipment for determining directionality and the communication equipment. In this way, this method can isolate only the fault section, although a large-scale DG is interconnected and communication errors. Therefore, we expect that applying the proposed method to a loop distribution system will expand the spread of DG and increase the reliability of a distribution system.

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