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A Modified Selective Ground Relay for Ungrounded Distribution Systems

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Abstract - Selective ground relays (SGRs) are useful for distinguishing a faulted feeder from the sound feeders in ungrounded systems. However, they sometimes mis-operate due to human or device errors. Particularly, the reversed polarity of zero-sequence current transducers (ZCTs) is the most frequent cause of mis-operation. This paper presents a modified SGR for reducing the probability of mis-operations caused by the reversed polarity of ZCTs. The modification is achieved by introducing an adaptive time delay, which depends on the magnitude of the zero-sequence current and the phase angle deviation from the reference. The modified SGR was successfully demonstrated on a sample ungrounded system without mis-operation.

Keywords: Adaptive time delay, mis-operation, phase angle deviation, selective ground relay, ungrounded system, zero-sequence current transducer.

1. Introduction

Ungrounded systems are defined as systems of conductors with no intentional connections to the ground, except through potential measuring or other very-high-impedance devices. In reality, such systems are grounded through the distributed shunt capacitance of the conductors and current limiting resistors (CLRs), which cause the system to be neutral close to ground potential under normal conditions. When a single phase-to-ground fault occurs, the voltage between the faulted phase and ground collapses to near zero throughout the system.

Ungrounded systems have many advantages over solid and low-impedance grounding. A single phase-to-ground fault does not cause a high current to flow, because the current is limited by the distributed shunt capacitance and the CLR. The small fault current minimizes fault arcing and reduces personal safety hazards. In addition, power quality is improved with the elimination of momentary voltage sags caused by single phase-to-ground faults and the reduction of zero-sequence harmonic currents generated by converters and motor drives [1]. By contrast, during a fault the line-to-ground voltages for the other two sound phases increase to the line-to-line voltage potential, stressing the insulation of cables and other equipments connected to the system. This high voltage can initiate a second fault at the weakest insulation point in the system and larger, more damaging fault currents can occur. The second phase-to-ground fault will usually instigate high fault currents flowing between the two insulation failures and cause extensive damage to the system, requiring expensive repairs or an extended shutdown. Therefore, locating and repairing the first ground fault is of prime importance.

The ground relays for ungrounded systems must have high sensitivity because the fault current is very low compared to those of solidly grounded systems. One approach for detecting a ground fault in ungrounded systems is to use the fault-generated transient components of voltage and current [2, 3]. These methods have limited sensitivity, because high-resistance faults reduce the level of harmonics and attenuate the transient components of voltage and current. Another approach is to use the fundamental-frequency voltage and current components. The watt-metric method [4, 5] is a conventional solution, but its sensitivity is limited to fault resistances no higher than a few kilo-ohms. Other fundamental-frequency methods are based on the phasor measurement of the zero-sequence current and voltage using digital signal processing techniques [6-8]. The spread of high-performance microprocessors enables these methods to be implemented in real-time and increases sensitivity in addition to selectivity.

In Korea, selective ground relays (SGRs), which also operate based on the phasor measurement, are generally utilized to protect ungrounded distribution systems. Although SGRs are useful for distinguishing a faulted feeder

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from the sound feeders in ungrounded systems, they sometimes mis-operate due to human or device errors. The reversed polarity of zero-sequence current transducers (ZCTs) is the most frequent cause of mis-operation, although the system is always field-tested after installation to verify and confirm the correct operation of the relays and transducers.

This paper presents a method to prevent the SGRs from mis-operating due to the reversed polarity of ZCTs. For this purpose, we propose an adaptive time delay that has two components: one inversely proportional to the magnitude of the zero-sequence current and the other linearly proportional to the phase angle deviation from the reference. The performance of the modified SGR is evaluated for single phase-to-ground faults simulated using the Electro-magnetic transient program (EMTP). The evaluation results show that the modification prevented the SGRs from mis-operating due to the reversed polarity of ZCTs.

2. Power System Configuration

The ungrounded distribution system considered is operated radially with three feeders supplied by one substation transformer, as indicated in Fig. 1. The details of the system configuration follow.

- Substation transformer: 154 kV/22 kV, $Y-\Delta$ connected
  - Grounding potential transformer (GPT): $\frac{22}{\sqrt{3}}kV/\frac{190}{3}V$
  - Current limiting resistor (CLR): 8 Ω
  - ZCT: 200 mA/1.5 mA
  - Line: 58 mm2 aluminum cable steel reinforced (ACSR)

The total distribution line is 12 km in length, with 4, 5, and 3 km in the 1st, 2nd, and 3rd feeders, respectively. Assuming that a single phase-to-ground fault occurs on phase 'a' of the 1st feeder, F refers to the fault point located 2 km from the relaying point.

On delta-connected systems, since there is no wye point available for connection to ground, a ground must be created artificially. This can be done with the wye-broken delta connected GPT arrangement shown in Fig. 2. Generally, a GPT provides a high impedance path for zero-sequence currents so that the zero-sequence currents can flow into the ground at the fault point and back to the start point of the GPT. The impedance of the GPT to the normal current is high, so that when there is no fault in the system, only a small magnetizing current flows in the transformer winding. The wye-connected primary should be grounded solidly with a CLR connected across the bro-ken delta of the secondary windings, as shown in Fig. 2(a).

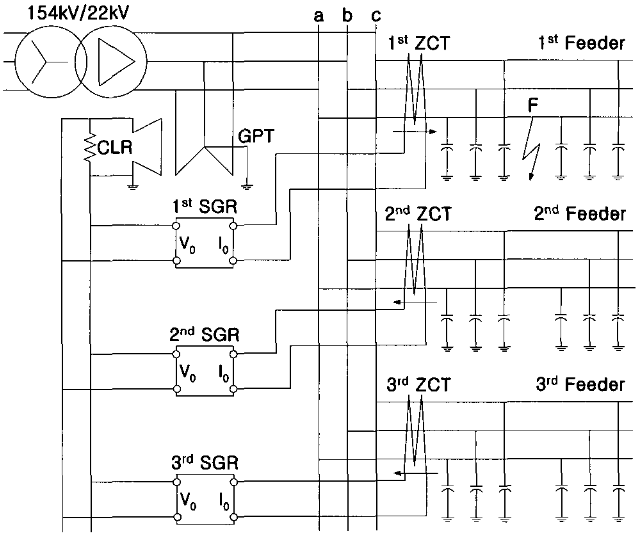
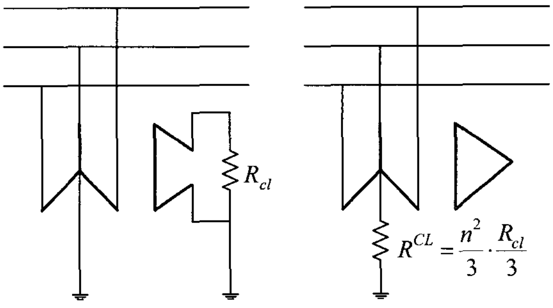


Fig. 1 Sample ungrounded distribution system.



(a) (b)

Fig. 2 Arrangement of GPT and CLR: (a) Wye-broken delta connection. (b) Equivalent wye-delta connection

The CLR connected at the secondary, R^{cl}, can be transformed to the equivalent grounding resistance connected at the primary, R^{CL}:

$$R^{CL}=\frac{n^2}{3}\cdot\frac{R^{cl}}{3} \tag{1}$$

where n is the turns ratio of the GPT. In Korea, the rated secondary voltage of the GPT is $\frac{190}{3}V$ and an impedance of 8 Ω is generally used for R^{cl} in ungrounded 22 kV systems. Therefore, the equivalent grounding resistance becomes

$$R^{CL}=\frac{1}{3}\cdot\left(\frac{22kV}{\sqrt{3}}/\frac{190V}{3}\right)^2\cdot\frac{8\Omega}{3}\cong 35.8\,k\Omega \tag{2}$$

Equation (2) indicates that the CLR has the effect of providing high resistance grounding for ungrounded systems.

The distributed shunt capacitance of an overhead line can be very high if considerable lengths are involved. The capacitance, which depends on the conductor size, insulation, and construction, can be obtained from the manufacturer or an approximate value can be calculated using appropriate formulas. The zero-sequence capacitance of 58 mm^2 ACSR is about 0.004 *μF/km*, which corresponds to 663.1 *kΩ/km* at 60 Hz.

3. System and Fault Characteristics

For the single phase-to-ground fault shown in Fig. 1, the sequence networks and their interconnections are shown in Fig. 3. It is well known that it is necessary to substitute $3R^{CL}$ for R^{CL} in the zero-sequence network in order to preserve equivalence. The following summarizes the notation used in Fig. 3.

Z_{Lk}^{Fm} : Impedance of the series inductance and resistance of the mth feeder.

Z_{Ck}^{Fm} : Impedance of the shunt capacitance of the mth feeder.

Z_{Dk}^{Fm} : Load impedance of the mth feeder.

Z_{Sk} : Source impedance, including the transformer impedance.

Z_G : Ground impedance at the fault point.

I_k^{Fm} : Current at the relaying point of the mth feeder.

I_{Gk} : Current at the fault point.

The letter k = 0, 1, and 2 denotes the zero, positive, and negative sequence, respectively.

In ungrounded systems, the capacitive impedance Z_{Ck}^{Fm} is very large, while the other impedances Z_{Sk}, Z_{Lk}^{Fm}, and Z_{Dk}^{Fm} are relatively small. Therefore, practically, Z_{C1}^{Fm} is shorted out by Z_{S1}, Z_{L1}^{Fm}, and Z_{D1}^{Fm} in the positive sequence network, and Z_{C2}^{Fm} is shorted out by Z_{S2}, Z_{L2}^{Fm}, and Z_{D2}^{Fm} in the negative sequence network. Compared to Z_{C0}^{Fm} and $3R^{CL}$ in the zero-sequence network, the other impedances are very small and can be neglected. This leads to the simplified network used to find the zero-sequence components, as shown in Fig. 4(a). From this Fig., the fault current is given by

$$I_F = 3I_{G0} = 3 \cdot \frac{E_S}{3Z_G + Z_{C0}^{Eq} // 3R^{CL}} \tag{3}$$

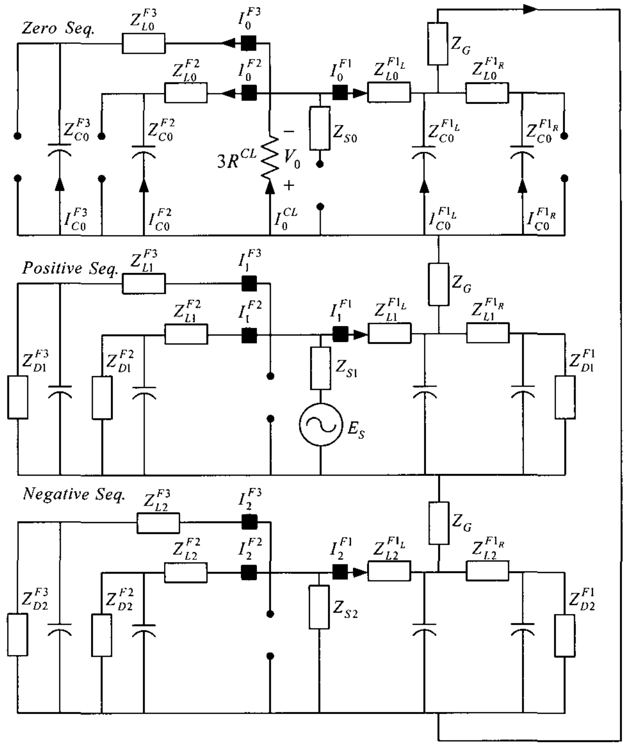
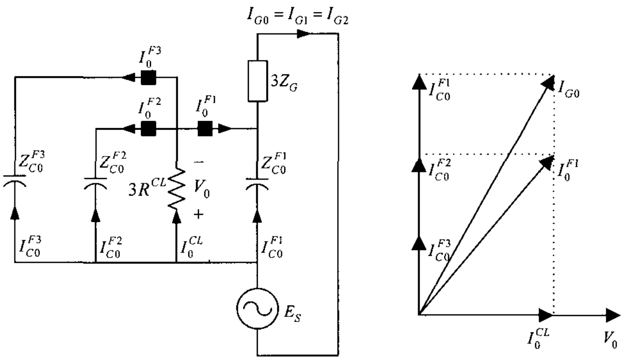


Fig. 3 Interconnections of the sequence networks for the single phase-to-ground fault



(a) (b)

Fig. 4 Simplification of Fig. 3: (a) Simplified network used to find the zero-sequence components. (b) Phasor diagram

where

$$Z_{C0}^{Eq} = \frac{1}{j\omega C_0^{Eq}} = \frac{1}{j\omega(C_0^{F1} + C_0^{F2} + C_0^{F3})}$$

According to the current divider rule, the zero-sequence current at the relaying point is given by

$$I_0^{F1} = I_{G0} \cdot \frac{Z_{C0}^{F1}}{Z_{C0}^{F1} + Z_{C0}^{F2} // Z_{C0}^{F3} // 3R^{CL}} \tag{4}$$

Since the capacitive current of the faulted feeder does not appear at the relaying point as shown in Fig. 4(b), I_0^{F1} is smaller than I_{G0} by I_{C0}^{F1}, which flows through the shunt capacitance of the faulty feeder itself.

4. Modified Selective Ground Relays

When a single phase-to-ground fault occurs at the 1st feeder in the ungrounded system shown in Fig. 1, the 2nd SGR should not operate. However, if the polarity of the 2nd ZCT is reversed, the 2nd SGR may mis-operate. As the main advantage of ungrounded systems is continuous service, the mis-operation probability of SGRs should be reduced as much as possible. For this purpose, we propose an adaptive time delay that is inversely proportional to the magnitude of the zero-sequence current and linearly proportional to the phase angle deviation from the reference. Since microprocessor-based SGRs work with the estimates of voltage and current phasors, we can use the information concerning phase angle in addition to the magnitude with high accuracy.

Fig. 5 indicates the operating characteristics of microprocessor-based SGRs. The mth SGRs will operate with a definite time delay, which is set from 0.1 to 10 s, only when all of the following conditions are satisfied [9]:

1) $\left|V_0^{Fm}\right| > V_{Set}^{Fm}$
2) $\left|I_0^{Fm}\right| > I_{Set}^{Fm}$
3) $|\theta_0^{Fm} - \theta_{Set}^{Fm}| < 90°$ where $\theta_0^{Fm} = \angle I_0^{Fm} - V_0^{Fm}$

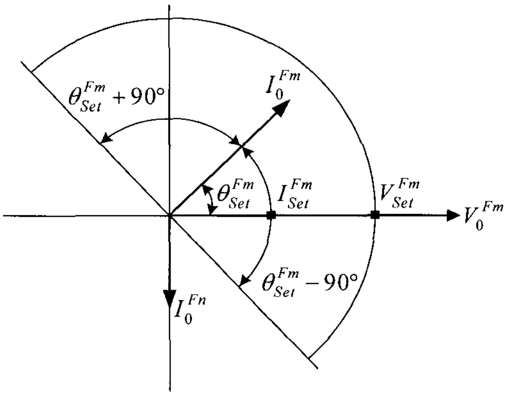


Fig. 5 Operating characteristics of microprocessor-based SGRs

Assume that a single phase-to-ground fault occurs at the mth feeder, not the nth feeder. Then, the nth SGR will not operate, although the first and second conditions above are satisfied, because the third condition is not satisfied: for example, θ_0^{Fn} and θ_{Set}^{Fn} are -90° and 45°, respectively. However, when the polarity of the nth ZCT is taken in the wrong way, θ_0^{Fn} becomes +90° and the nth SGR may mis-operate. This nuisance operation can be prevented by introducing a time delay between the operating times of the mth and nth SGRs. If there is a proper time delay between them, the mth SGR will operate before the mis-operation of the nth SGR, although the nth SGR is in the pick-up state. Subsequently, the nth SGR will return to the normal state and send an alarm signal to the operators, notifying them to check the polarity of the nth ZCT.

The adaptive time delay is determined based on the following two properties.

1) The zero-sequence current of the faulted feeder has a larger magnitude than those of the parallel sound feeders.
2) The phase angle of the faulted feeder is 60~85° depending on the CLR and the shunt capacitances of the parallel sound feeders, while those of the sound feeders are ±90° considering the reversed polarities of the ZCTs.

Using these properties the adaptive time delay T_{Set}^{Fm} is defined as

$$T_{Set}^{Fm} = T_{Mag}^{Fm} + T_{Ang}^{Fm} \tag{5}$$

where, T_{Mag}^{Fm} is the time delay inversely proportional to the magnitude of the zero-sequence current and T_{Ang}^{Fm} is linearly proportional to the phase angle deviation from the reference.

With reference to Fig. 4(a), the zero-sequence current of the faulted feeder can be generally expressed as

$$I_0^{Fm} = I_0^{CL} - \sum_{p=1,\neq m}^{N} I_0^{Fp} \tag{6}$$

where N is the total number of feeders connected to the system. From (6), it is easily found that the faulted feeder has the largest zero-sequence current of the N feeders. To insert this property into the operating time, the inverse time-current curve [10] is applied to T_{Mag}^{Fm}:

$$T_{Mag}^{Fm} = \frac{A}{(|I_0^{Fm}|/|I_{Set}^{Fm}|)^p - 1} + B \tag{7}$$

where A, B, and p are constants that provide selected curve characteristics. Of course, in order to implement the same operating characteristic as conventional SGRs, the definite time-current curve can be applied to T_{Mag}^{Fm}.

Although the inverse time-current curve is applied, it is impossible to guarantee enough time delay between the operating times of the mth and nth SGRs because the magnitude of the zero-sequence current depends on the ground impedance, Z_G. To ensure sufficient time delay, the phase angle is used for the adaptive time delay in addition to the magnitude of the zero-sequence current. As indicated in Fig. 6, T_{Ang}^{Fm} is linearly proportional to the phase angle deviation from the reference θ_{Set}^{Fm} and is given by

$$T_{Ang}^{Fm} = \frac{T_{90^\circ}}{90^\circ - \theta_{Set}^{Fm}} \times | \theta_0^{Fm} - \theta_{Set}^{Fm} | \qquad (8)$$

where

$T_{90^\circ} \geq \max_{m}(T_{CB}^{Fm})$

T_{CB}^{Fm} : Operating time of the circuit breaker installed at the mth feeder.

Note that the phase angle is independent of Z_G. Instead, the phase angle only depends on the CLR and the shunt capacitances of the parallel sound feeders. From (8), the nth SGR, which is connected to the mis-polarized ZCT, has a longer operating time than the mth SGR by a minimum of T_{90°.

Fig. 7 presents the flowchart of the modified SGR described in this section.

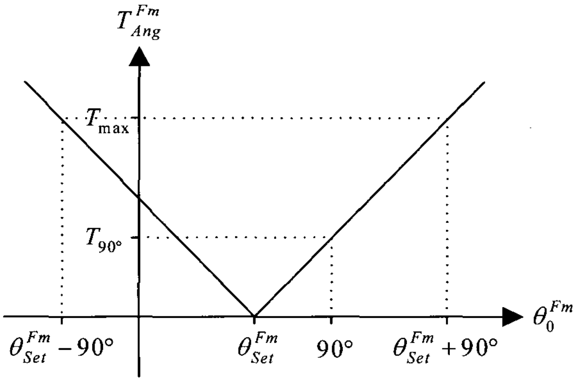


Fig. 6 Linear time-phase angle curve

5. Simulation Results

The performance of the proposed method was evaluated for single phase-to-ground faults on the ungrounded system shown in Fig. 1. EMTP was used to generate fault signal waveforms and the EMTP outputs were pre-conditioned using a second order Butterworth low-pass filter with a cutoff frequency of 600 Hz. Fig. 8 shows the waveforms of the zero-sequence voltage and currents. As expected, v_0^{F1} lags i_0^{F1} by 54°, while v_0^{F2} leads i_0^{F2} by 90°. It is also easily found that i_0^{F1} has a magnitude that is 1.97 times larger than i_0^{F2}.

The performance of the proposed method is illustrated conceptually by the representative simulations described in Table 1. It is assumed that the definite time delay is 0.5 s and the ground resistance at the fault point is 1 kΩ.

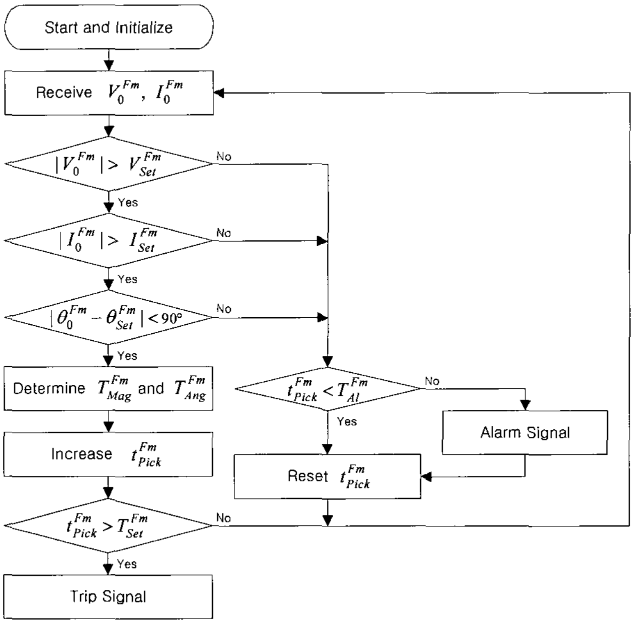


Fig. 7 Flowchart of the modified selective ground relay

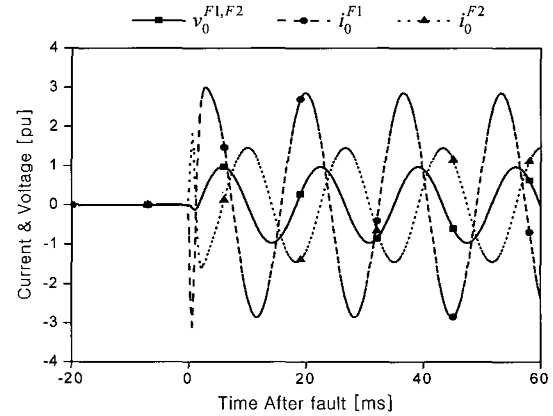


Fig. 8 Waveforms of the zero-sequence voltage and currents

5.1 Case 1

Fig. 9 indicates the state change of the 1st SGR when the definite time delay is used and the polarities of all ZCTs are normal. The 1st SGR operated normally, because all of the operating conditions are satisfied.

1) $|I_0^{F1}| > I_{Set}^{F1}$: 4.29 mA > 1.5 mA
2) $|V_0^{F1}| > V_{Set}^{F1}$: 175 V > 100 V
3) $|\theta_0^{F1} - \theta_{Set}^{F1}| < 90°$: $|0°| < 90°$

In the case of the 2nd and 3rd SGRs, the phase angle condition blocked their operations, so that they remained in the normal state.

5.2 Case 2

Fig. 10 shows the state change of the 2nd SGR when the definite time delay is used and the polarity of the 2nd ZCT is reversed. Due to the reversed polarity, the phase angle of the 2nd SGR satisfied the third operating condition. The magnitudes of the zero-sequence voltage and current also satisfied the first and second operating conditions, respectively.

1) $|I_0^{F2}| > I_{Set}^{F2}$: 2.18 mA > 1.5 mA
2) $|V_0^{F2}| > V_{Set}^{F2}$: 175 V > 100 V

Consequently, the 2nd SGR mis-operated.

5.3 Case 3

Fig. 11 shows the state changes of the 1st and 2nd SGRs when the adaptive time delay is used and the polarity of the 2nd ZCT is reversed.

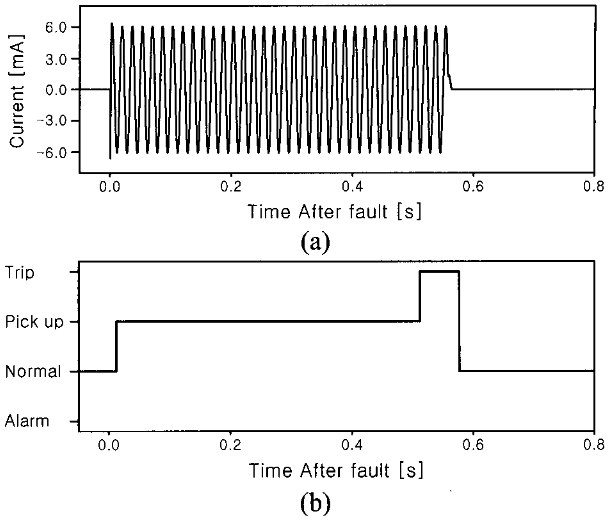
The following moderately inverse time-current curve is used for T_{Mag}^{Fm} :

$$T_{Mag}^{Fm} = \frac{0.0028}{(|I_0^{Fm}|/|I_{Set}^{Fm}|)^{0.02} - 1} \qquad (9)$$

Since the common operating times of air and vacuum circuit breakers are 40 ms and 50 ms, respectively, $T_{90°}$ is set to 50 ms. Although both the 1st and 2nd SGRs satisfy all of the operating conditions, the 2nd SGR has a much longer operating time than the 1st SGR due to the phase angle deviation and the smaller magnitude of the zero-sequence current. Consequently, after the 1st circuit breaker tripped, the 2nd SGR returned to the normal state without mis-operation and sent an alarm signal to the operators warning them to check the polarity of the ZCT.

Table 1 Simulation conditions

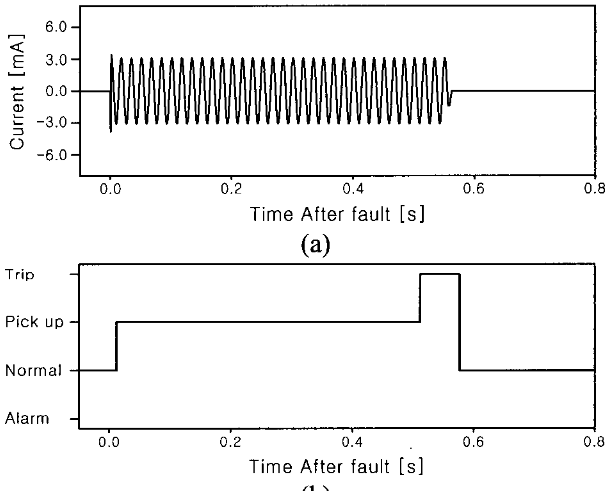
	Time delay	Polarity of the 2nd ZCT
Case 1	Definite	Normal
Case 2	Definite	Reversed
Case 3	Adaptive	Reversed



(a)

(b)

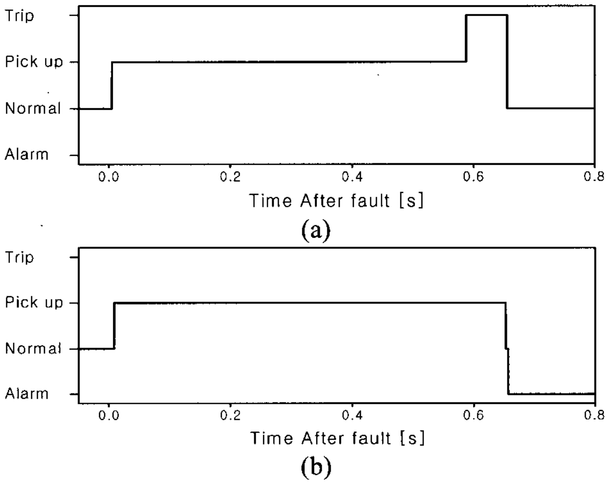
Fig. 9 Results for case 1: (a) Waveform of i_0^{F1}. (b) State change of the 1st SGR



(a)

(b)

Fig. 10 Results for case 2: (a) Waveform of i_0^{F2}. (b) State change of the 2nd SGR



(a)

(b)

Fig. 11 Results for case 3: State changes of the (a) 1st and (b) 2nd SGRs

6. Conclusions

A modified selective ground relay is proposed to reduce the probability of mis-operation caused by the reversed polarity of ZCTs. The modification is achieved by introducing an adaptive time delay, which is composed of two components: one inversely proportional to the magnitude of the zero-sequence current and the other linearly proportional to the phase angle deviation from the reference. For a single phase-to-ground fault in an ungrounded system, the modified SGR of the faulted feeder operates faster due to the adaptive time delay than that of the sound feeder sensed by the mis-polarized ZCT. Consequently, after the circuit breaker of the faulted feeder trips, the modified SGR of the sound feeder returns to the normal state without mis-operation.

The performance of the modified SGR was evaluated conceptually for the single phase-to-ground faults simulated using EMTP. The evaluation results show that the modification is useful for preventing SGRs from mis-operating due to the reversed polarity of ZCTs, although hardware implementation and field-testing will be required.

Acknowledgements

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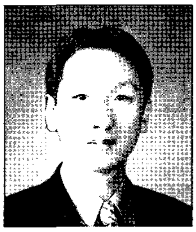

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