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Application of Fault Location Method to Improve Protect-ability for Distributed Generations

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Abstract - This paper proposes novel protection schemes for grid-connected distributed generation (DG) units using the fault location algorithm. The grid-connected DG would be influenced by abnormal distribution line conditions. Identification of the fault location for the distribution lines at the relaying point of DG helps solve the problems of the protection relays for DG. The proposed scheme first identifies fault locations using currents and voltages measured at DG and source impedance of distribution networks. Then the actual faulted feeder is identified, applying time-current characteristic curves (TCC) of overcurrent relay (OCR). The method considering the fault location and TCC of OCR might improve the performance of the conventional relays for DG. Test results show that the method prevents the superfluous operations of protection devices by discriminating the faulted feeder, whether it is a distribution line where DG is integrated or out of the line emanated from the substation to which the DGs are connected.

Keywords: Distributed Generations, Fault Location Algorithm, Overcurrent Relay

1. Nomenclature

V_{Si}	*i*-phase voltage measured at the relaying point
I_{Si}	*i*-phase current measured at the relaying point
I_{S0}, I_{S2}	Zero and positive sequence current at the local terminal
I_{r0}, I_{r2}	Zero and positive sequence current at the remote terminal
I_f	A-phase fault current
I_{f2}	Negative sequence fault current
Zl_0, Zl_1, Zl_2	Zero, positive, and negative sequence impedance of line
Z_S, Z_{S2}	Source impedance and negative sequence source impedance of local terminal
Z_r, Z_{r2}	Source impedance and negative sequence source impedance of remote terminal
R_f	Fault resistance
D	Fault distance from the local terminal
k	$(Zl_0 - Zl_1)/Zl_1$

2. Introduction

Recently, the majority of distributed generations (DG) are designed to be integrated into distribution networks. DG may make a contribution to improve quality of power, minimize peak loads, and eliminate the need for reserve margin [1, 2]. On the other hand, it can be influenced by abnormal grid conditions such as disturbances occurring in a neighboring feeder emanated from the substation to which the DGs are connected as well as in the power line integrated DG. The conventional protection schemes applied in the DG only monitors the variation of system parameters such as current, voltage, frequency, phase angle jump, and so on. Thus, those methods would be mal-operated for the disturbance occurred in the neighboring feeder [3-7].

Conventional protection schemes for DG are overcurrent relaying (51), overcurrent ground relaying (51G), under/over voltage relaying (27/59), and under/over frequency relaying (81U/O) [8]. In general, DG is isolated from power networks for the fault occurred in interconnected distribution feeders. This power islanding is defined by the condition that DG feeds the power to the networks without the utility supply as soon as possible in order to reduce the impact on DG. However, DG should be sustained at power networks for the fault in neighboring

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distribution feeders. When the fault occurs in the neighboring feeders, the above parameters monitored in the DG terminal may have varied until the fault is cleared by protective devices in the associated networks. However, the conventional protection method only monitors the variation of system parameters, and therefore it might mal-operate for the fault occurred in the neighboring distribution feeder. Thus, to improve the protection method for distributed generations, it is necessary to identify the fault location to determine whether it is the interconnected distribution feeder with DG or the neighboring feeder.

This paper proposes advanced protection schemes using the fault location algorithm and the overcurrent relaying algorithm to enhance the performance of conventional protection relays for DG. The method is based on the decrease of the magnitude of impedance calculated by current and voltage at the relaying point of DG. After fault occurrence, the impedance measured in DG may vary according to the fault position and the types. Thus, by monitoring the impedance variations in the DG, we can discriminate fault locations to see whether it is occurred in an associated feeder integrated with the DG or in neighboring ones. Basically, if the impedance calculated in the DG is much smaller than the interconnected line impedance, the trip signal is generated to disconnect the DG from the grid. While it is much larger than the line impedance, the DG is sustained at power networks. Finally, by considering the time current characteristics of OCR for distribution networks, we decide the fault in the boundary zone between the interconnected feeder and the neighboring one, to determine whether it is occurred in the line integrated with DG or not. We tested the proposed method using the actual distribution network of the Korea Electric Power Corporation (KEPCO). Test results indicated that the newly proposed protective function identified the faulted feeder correctively and does not mal-operate for the fault occurred in the neighboring feeder.

3. The Proposed Novel Protection Scheme for DG Using Fault Location and Overcurrent Relaying Algorithms

In this section, we will investigate the problems of conventional protective schemes for DG and describe the proposed method.

3.1 Conventional protection method of DG

Usually, DG has to be equipped with overcurrent-, over- and undervoltage, and over- and under frequency protection functions. This paper utilizes IEEE Std. 1547-2003 for protection and coordination of distribution networks integrated with distributed generators as a basic reference model for protective schemes of DG [9]. The standard recommends that the overcurrent value (*I*>), undervoltage value (*V*<), and overvoltage value (*V*>) should be set to 150%, 88%, and 110% of the rated values, respectively. The under frequency value (*f*<) and overfrequency value (*f*>) are to be set to 59.3 *Hz* and 60.5 *Hz*, respectively. However, these protective schemes simply follow the protection of industrial and commercial loads and the protective relaying functions just utilize the magnitude of current or voltage measured prior to DG. Such simple protective schemes do not consider the characteristics of DG interface and therefore usually makes frequent false tripping resulting from the faults or reclosing sequences of the neighboring feeders.

3.2 Fault distance calculation method

In this section, we investigate a fault location algorithm to restore power system availability and its possibility for application to the protection scheme of DG.

Figure 1 shows a single line-to-ground fault in a balanced three-phase system. To begin with, when the fault occurs in the power line, a-phase voltage at the measuring point is given as (1).

$$V_{Sa} = d \cdot Zl_1 \times (I_{Sa} + kI_{S0}) + I_f R_f \tag{1}$$

We can estimate the fault distance with (1). The phase voltage and current are also available from measurement. Most of the parameters in (1) are known values except for the resistance R_f and the current I_f. However the resistance R_f can be eliminated by the derivation from (2).

$$\begin{aligned} V_{Sa} &= d \cdot Zl_1 \times (I_{Sa} + kI_{S0}) + 3I_{f2}R_f \\ &= d \cdot Zl_1 \times (I_{Sa} + kI_{S0}) + \frac{3(B_1 + D_1)I_{S2}}{-dA_1 + B_1} R_f \end{aligned} \tag{2}$$

where, $A_1 = Zl_2$, $B_1 = Z_{r2} + Zl_2$, $D_1 = Z_{S2}$. The current I_f and distribution factor, D_f can be expressed by (3) and (4), respectively.

$$I_f = 3I_{f2} \tag{3}$$

$$D_f = \frac{I_{f2}}{I_{S2}} = \frac{I_{S2} + I_{r2}}{I_{S2}} = \frac{B_1 + D_1}{-dA_1 + B_1} \tag{4}$$

Equation (2) is rearranged to a second order polynomial with respect to the distance d as follows;

$$d^2(a_r - \frac{d_r}{d_i}a_i) + d(b_r - \frac{d_r}{d_i}b_i) + c_r - \frac{d_r}{d_i}c_i = 0 \tag{5}$$

where,
$$\begin{aligned} a_r + ja_i &= (I_{Sa} + kI_{S0})Zl_1A_1 \\ b_r + jb_i &= -(I_{Sa} + kI_{S0})Zl_1B_1 - V_{Sa}A_1 \\ c_r + jc_i &= V_{Sa}B_1 \\ d_r + jd_i &= -3(B_1 + D_1)I_{S2} \end{aligned}$$

The fault distance d can be obtained by solving (5) [10].

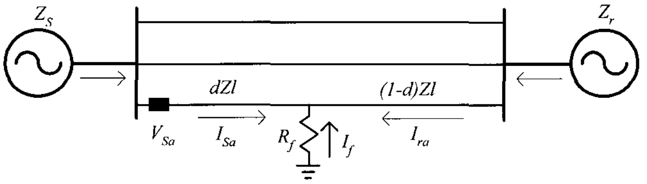


Fig. 1 Single line-to-ground fault on balanced system

3.3 Application feasibility of fault location algorithm to protective functions for DG

The fault location algorithms mentioned in the previous subsection are widely available to estimate the fault position. However, the conventional fault location method needs data from both the local and remote terminal of the power line to determine the exact fault location. The impedance Z_r is needed inevitably to find the exact fault position. It continuously changes according to the configuration of power system networks and the state of the generator. Thus, the conventional fault location algorithm has an unavoidable error due to the impedance Z_r. However, because the source impedance of the distribution network isn't much varied, the fault distance calculated in the terminal of DG is more precise than those of the transmission line. We should notice that the source impedance of the distribution networks is almost identical to that of the distribution transformer.

3.4 The proposed method

In this section, we describe the advanced protection method for DG adopting fault location algorithms and time-current characteristics of OCR applied in feeders. Fig. 2 presents a simplified equivalent circuit of distribution networks including DG. We assume that the DG is connected with a dedicated line due to the large generating power of the DG. After monitoring three-phase voltages and currents, we inspect an impedance variation with (5). In the first place, if the fault distance d is much shorter than the dedicated line length, the fault is affiliated with Z_1. The proposed method generates a trip signal disconnecting the DG as soon as possible to avoid negative impact of fault on the DG. In the second place, if the fault distance d is much longer than the length of the dedicated line, the fault comes under the category Z_3. In this case, the DG is sustained at power networks. Furthermore, if the d is calculated with Z_2, it is difficult to decide whether the fault occurs in the dedicated line integrated with DG or out of the line. For this case, we would like to place special emphasis on the time-current characteristics of OCR applied in the grid. In general, the current magnitude of a fault in the Z_2 is much larger, thus the circuit breaker disconnects the feeder or dedicated line quite rapidly. If the operation of protection devices for DG is delayed, then we can discriminate the fault position easily. In this paper, we propose advanced protection rules to enhance the performance of conventional protection relays for DG. Advanced protection rules are follows.

<u>*Advanced Protection Rules of DG*</u>

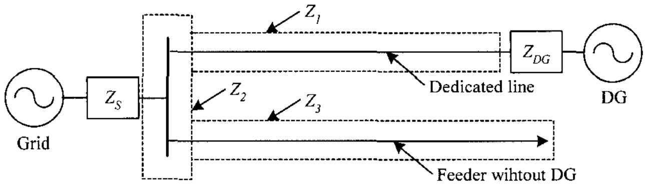
Rule 1: If *OCR* and *UVR* at DG detect the fault and the fault distance D is Z_1, the result is instantaneous trip.

Rule 2: If *OCR* and *UVR* at DG detect the fault and the fault distance D is Z_2, the result is delayed trip.

Rule 3: If *OCR* and *UVR* at DG detect the fault and the fault distance D is Z_3, the result is blocking trip.

Rule 4: If *UFR* or *OFR* detect the power islanding, the result is instantaneous trip.

The values for Z_1, Z_2, and Z_3 may be determined according to the reliability and selectivity of protection device in the DG. In this paper, we set the Z_1 and Z_2 with 90% and 110% of the total length of dedicated line, respectively. The Z_3 is assumed to be the longest line in feeders.



Z_1 : Instantaneous trip zone
Z_2 : Delayed trip Zone
Z_3 : Trip blocking Zone
Z_s, Z_{DG}: Source impedance of grid and DG

Fig. 2 A simplified one-line diagram of distribution network integrated with DG

4. Case Studies

We tested the proposed method with several kinds of network conditions including single line-to-ground fault at the neighboring feeder as well as dedicated line to see its superiority.

4.1 Modeling of Distribution Networks having DG

In this paper, with the aid of an EMTDC simulator, we model the Hoenggye distribution networks of KEPCO in Korea (which are composed of five feeders), simulate various operating conditions of DG, and also finally verify the feasibility of the proposed adaptive algorithm [11]. Fig. 3 shows the circuit diagram of the distribution network to which DG is connected. We assumed the DG with generators to be asynchronous generators and the transformers to be 690/22900 V step-up transformers. The technical data for distribution networks and asynchronous generators are provided in the Appendix. The 4-step capacitor banks are installed in front of the wind turbine generator in order to compensate for the reactive power consumed by the asynchronous generator. Capacitor banks are switched-in one by one as the generator's power increases. The capacity of the capacitors in a 4-step capacitor bank is assumed as 100 kvar.

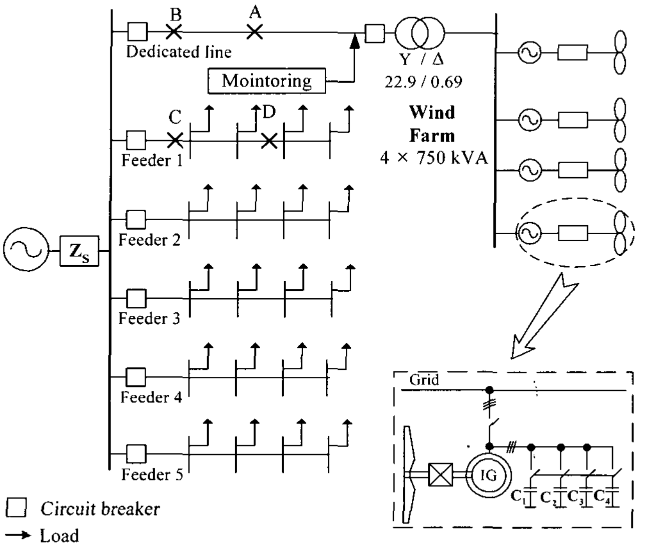


Fig. 3 Distribution networks model with the wind farm

4.2 imulation results

In this paper, we simulate single line-to-ground fault on the feeder locations of A, B, C, and D in Fig. 3 and test the proposed algorithm for these different cases. The faults on A and B locations represent the faults occurred on the feeder interconnected with DG, while the faults on C and D locations represent the faults occurred on the neighboring feeder. The objectives of the proposed algorithm are that for the faults on the interconnected feeder, it causes the DG to disconnect from the feeder as soon as possible, and for the faults on the neighboring feeder, it restrains unnecessary DG shutdowns or disconnections. Therefore, we can enhance the operational performance and availability of DG by applying the proposed algorithm.

4.3 Time-current characteristics of protection relay

In order to protect the distribution networks and DG, relays provide the intelligence for identifying fault conditions, for timing and reclosing, and for controlling the operation of a circuit breaker. There are many different shapes of time-current characteristics available, and the type chosen is dependent upon application. These relays can provide excellent coordination with fuses and reclosers in addition to providing load pick-up capability after an extended outage. The time-current characteristics of 51- and 51G-relay used in the Hoenggye distribution feeders and DG are represented in Table 1. In this table, the VI means very inverse, which is a characteristic type for operating time of the protective relay. The delayed time of the 27-, 59-, and 81-relay at DG are indicated in Table 2 [9].

Table 1 Delayed time of overcurrent relay

Feeder Name	Relay	Time Delay Setting (sec)						Instant - aneous (sec)	Curve Type
		150%	300%	500%	700%	1000 %	2000 %		
Dedicated Line	51	12.15	2.22	1.00	0.68	0.53	0.42	0.05	VI
	51G	13.88	2.53	1.13	0.78	0.62	0.48		
Feeder 1	51	12.15	2.22	1.00	0.68	0.53	0.42		
	51G	13.88	2.53	1.13	0.78	0.62	0.48		
Feeder 2, 3	51	12.15	2.22	1.00	0.68	0.53	-		
	51G	13.88	2.53	1.13	0.78	0.62	0.48		
Feeder 4, 5	51	10.42	1.90	0.85	0.60	0.45	-		
	51G	13.88	2.53	1.13	0.78	0.62	0.48		
DG Terminal	51	7.87	1.44	0.66	0.46	0.35	-		
	51G	5.82	1.09	0.49	0.34	0.26	0.2		

Table 2 Delayed time of over/under voltage relay at DG

Relay	Ranges of the voltage and frequency magnitude	Time Delay Setting (sec)
27	$V < 50\ \%$	0.16
	$50 \leq V < 88\ \%$	2.00
59	$110 < V < 120\ \%$	1.00
	$V \geq 120\ \%$	0.16
81	$f < 57$ or $f > 60.5$ Hz	0.16
	$57 < f < 59.3$ Hz	0.5

Figs. 4 and 5 show the operational characteristics of the proposed algorithm for the single line-to-ground faults of location A and D, respectively. For the fault of A that is occurred at 12 km apart from DG, which is within the DG interconnected feeder, the currents at the utility side and the DG side abruptly increased and voltage at DG decreased after fault occurrence. The conventional protective relay such as OCR and UVR applied in DG generates the trip signal after the pre-determined delay time as in Table I and II. However, the proposed algorithm makes a trip signal as soon as possible to protect the DG and the grid. In this paper, we disconnect the DG from the grid in case the fault distance is estimated with Zone 1 and the current and voltage come into the operating region of OCR and UVR for 50 msec. For the fault of D, which occurs out of the DG interconnected feeder, the algorithm restrains tripping until the protective relay of the neighboring feeder isolates the fault as shown in Fig. 5. We assumed that the fault is occurred at 33 km apart from the DG. In this case, the conventional UVR at DG may generate the trip signal at 2 sec after fault occurrence due to the voltage being smaller than the pickup value and the OCR applied in the grid delaying the operation. Test results presented in Figs. 4 and 5 verify the adapting capability of the algorithm for the fault conditions.

We also implement the strategies for "weak-zone," in which the fault location estimation can be unreliable, such as fault locations near the bus (Case B) and on the interconnected feeder but at different branches (Case C). For the faults on the weak-zone, the proposed algorithm makes a delayed trip by coordinating with the main OCR of the feeder at the bus. In this algorithm, the time-current curve of the DG coordinates to lie to the right of the TCC of the main OCR of the feeder; therefore, the algorithm does not make unnecessary trips before a fault is cleared by the main OCR. We delay the circuit breaker operation applied in the DG for 750 msec if the fault location is calculated with Zone 2, which is the weak-zone. In Fig. 6, since the fault occurs on the weak-zone Z2 of the dedicated line, the fault is cleared by the main OCR of the grid at 3.53 sec. After opening of the circuit breaker on the grid side, the DG generates the power without utility source, which is defined by power islanding. Thus, the 81-relay generates the trip signal at 3.72 sec. For the fault in Case C, the proposed protection scheme decides the fault with one occurred in neighboring Feeder 1 as shown in Fig. 7. Thus there is no unnecessary trip of DG. After fault clearance by the OCR in Feeder 1, the DG can supply power to the grid continuously.

5. Conclusions

In this paper, an advanced protection scheme is proposed to enhance the conventional protection algorithm for grid-connected DG. The proposed method adopts a fault location algorithm and considers the TCC of the OCR. Basically, the method discriminates the faulted feeder by monitoring the impedance variations in DG. If the impedance calculated in the DG is much smaller than the interconnected line impedance, the trip signal is generated to disconnect DG from the grid. Even though it is much larger than the line impedance, the DG is sustained at

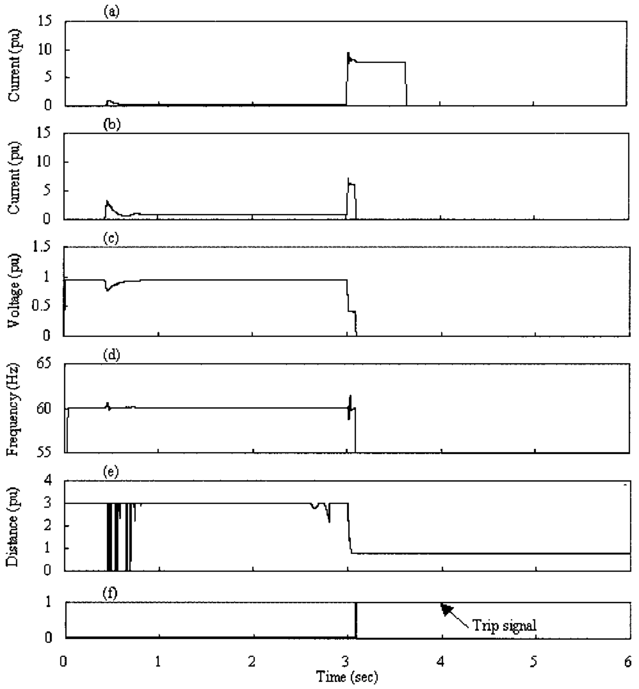


Fig. 4 Simulation results for Case A; (a) current at the utility, (b) current, (c) voltage, (d) frequency at the DG (e) fault location, and (f) final decision of the proposed method

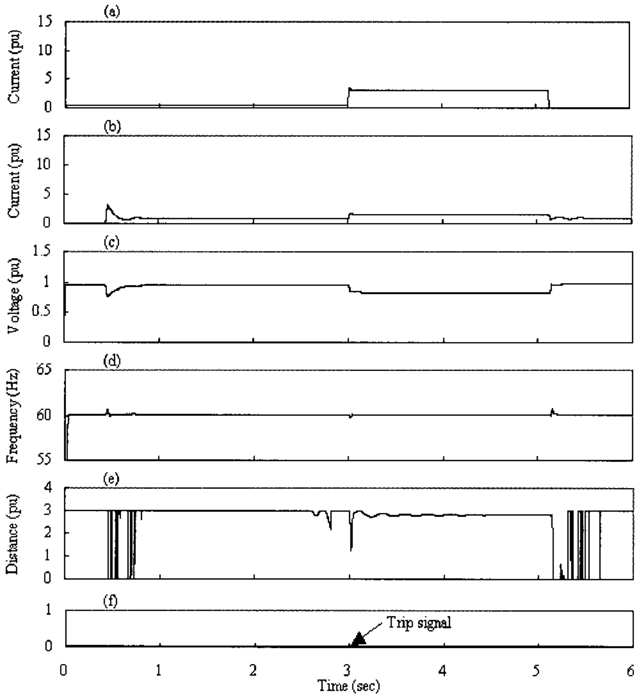


Fig. 5 Simulation results for Case D; (a) current at Feeder 1, (b) current, (c) voltage, (d) frequency at the DG (e) fault location, and (f) final decision of the proposed method

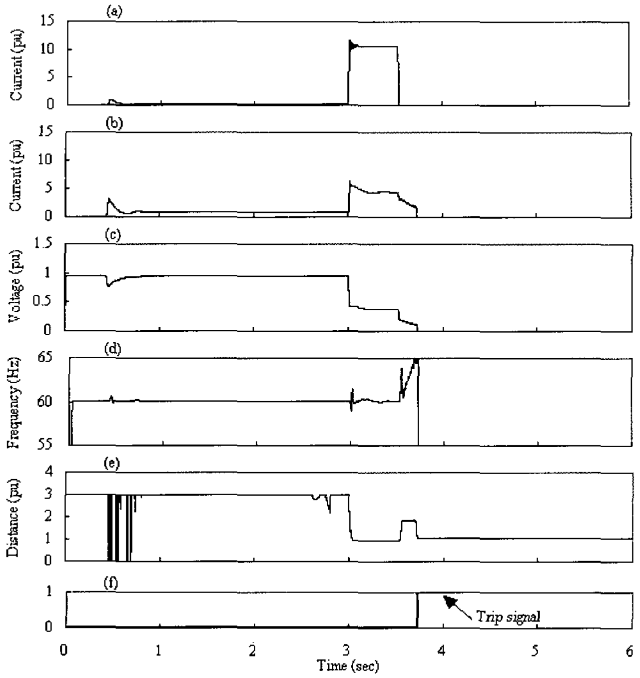


Fig. 6 Simulation results for Case B; (a) current at the utility, (b) current, (c) voltage, (d) frequency at the DG, (e) fault location, and (f) final decision of the proposed method

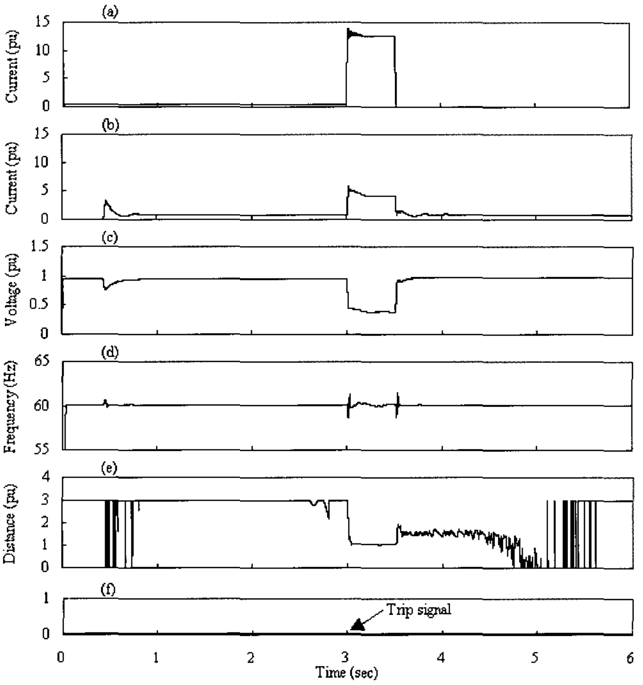


Fig. 7 Simulation results for Case C; (a) current at Feeder 1, (b) current, (c) voltage, (d) frequency at the DG, (e) fault location, and (f) final decision of the proposed method

power networks. Finally, by considering the time current characteristics of the OCR for distribution networks, we determine the fault to be in the weak-zone between the interconnected feeder and the neighboring feeder, being otherwise difficult to identify the actual fault location. The test results indicate that the newly proposed protective function identified the faulted feeder accurately and also that it does not mal-operate for the fault occurred in the neighboring feeder.

Though the proposed method could discriminate whether the fault occurs in the dedicated line integrated with DG or the neighboring feeder, it is somewhat difficult to estimate the fault location for the distribution line having load as well as DG and high impedance fault. In the future, we will research the improved algorithm for DG considering not only the load amount and high impedance fault, but also the configuration of distribution network and its protection devices such as recloser and sectionalizer.

Appendix

This appendix provides the technical data for Vestas V47-660 kW wound rotor type induction generator and distribution networks.

Table 3 Parameters of the Vestas V47-660 kW Induction Generator

Details	Wind Turbine
Rating	660 kW
Line to line voltage	690 V
Hz.	60
Pole No.	4
Base power	660 kW
Stator connection	Delta
Stator resistance	0.00393 Ω
Stator reactance	0.060 Ω
Rotor resistance, internal	0.00467 Ω
Rotor res. ext. (2% slip)	0.0070 Ω
Rotor res. ext. (10% slip)	0.06233 Ω
Rotor reactance	0.0067 Ω
Iron loss	0.081 Ω
Magnetizing reactance	3.13 Ω

Table 4 Technical Data of Distribution Networks

Details	Distribution Networks
Rated capacity per feeder	10 MVA
Rated line voltage	22.9 kV
Rated current	252 A
Nominal frequency	60 Hz

Line types	Three-phase overhead
Positive sequence source imp. of grid	0.082+j4.0 Ω
Zero sequence source imp. of grid	5.44 Ω
Load type	Spot loads
	All wye connected
	All constant kW, kvar
Loads in Feeder 1	5.5 MVA
Feeder 2	1.0 MVA
Feeder 3	1.1 MVA
Feeder 4	5.1 MVA
Feeder 5	6.5 MVA
Positive sequence line impedance	0.2+j0.39 Ω/km
Zero sequence line impedance	0.52+j1.19 Ω/km
Length of Feeder 1	22 km
Feeder 2	9.68 km
Feeder 3	4.75 km
Feeder 4	31.01 km
Feeder 5	58.40 km
Length of dedicated line	15 km

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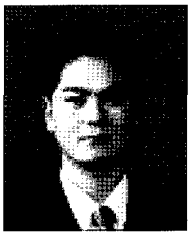

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