The FRTU-Based Intelligent Fault Location Determination Strategy in Ubiquitous Based Distribution Systems

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Abstract – This paper proposes a FRTU-based intelligent fault distance determination strategy in which each FRTU is able to avoid multiple estimations and reduce the level of estimation error by utilizing heuristic rules driven by voltage and current information collected by 1:1 communication with other FRTUs from the same zone in a ubiquitous-based distribution system. In the proposed method, each FRTU, at first, determines a fault zone and a fault path on the faulted zone based on the proposed heuristic rules which use its current data and the voltage data of its neighboring FRTUs as input data. Next, it determines the fault distance from its position based on the fault current estimated from the current data of the neighboring FRTUs. Finally, in order to prove the effectiveness of the proposed method, the diverse fault cases are simulated in several positions of the typical distribution system using the EMTP.

Keywords: Distribution System, FRTU, Fault Location, DAS, Ubiquitous-based System

1. Introduction

Distribution systems experience frequent outages as a result of exposure to accidents, such as car crashes and contact with trees because of their radial structure, and the fact that they pass through load areas such as city centers, forested regions, and coastal areas.

Electricity companies introduced the DAS (Distribution Automation System) to solve such problems, and greatly improved supply reliability by identifying the fault zone, separating the faulted zone from the feeder and then transferring the non-faulted zone to other feeders based on the remote monitoring and control function [1]. However, the service restoration of the fault zone is delayed because the fault location is identified by the patrol activity of the crew sent to the faulted zone. Also, in the case of a short-duration fault, whose importance increases from the viewpoint of electric power quality, the fault location cannot be identified because fault information is not furnished. As such, it is difficult to analyze the fault cause and then determine the corresponding strategy. Accordingly, a rapid and accurate determination method of fault location is required for the rapid restoration of the service and the enhancement of electric power quality.

Fault location determination methods can be classified into the traveling wave-based method and the impedance-based method. The traveling wave-based methods [2-4] are discriminated into the external wave injecting method and the generated wave analysis method according to the method of obtaining the signal from the fault location: the external wave injecting method can reduce uncertainty compared with the generated wave analysis method, but it has a disadvantage in that the signal injecting equipment must be installed in one or two terminals. On the other hand, the impedance-based method [5-7] is more practical than the traveling wave-based method because the fault location is estimated by the impedance computed from the measured voltage and current. However, the proposed methods [2-7] cannot be applied directly to distribution feeders including multiple branches and tapped loads because they are fault location determination methods for the transmission line. Thus, ref [8] proposed a fault distance determination method for the distribution feeder based on the fundamental frequency components obtained from the voltage and current measured in a substation bus. Ref [9] suggested fuzzy logic to process the uncertainty generated in the fault location determination of the radial distribution feeder. Also, ref [10] proposed the fault distance estimation method for distribution feeders considering the multi-phase branches and the dynamic characteristics of the load model based on the fundamental frequency components of the measured voltage and current in the bus. However, these methods may determine the multiple estimations and the estimation error caused by the multiple branches, tapped loads, and uncertainty of the load model by using the voltage and current measured from the position of the substation CB.

Accordingly, this paper proposes an FRTU-based intelligent fault distance determination strategy in which

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each FRTU is able to avoid the multiple estimations and reduce the extent of estimation error by utilizing its voltage and current as well as the voltage and current collected by 1:1 communication with other FRTUs of the same zone in ubiquitous-based distribution systems. In the proposed method, the FRTU, at first, determines a fault zone based on its current data and the voltage data of its neighboring FRTUs, and then minimizes the patrol scope of the crew by inferring a fault path on the faulted zone according to the proposed heuristic rules which use the voltage data of the neighboring FRTUs as input data. Finally, it determines the fault distance from its position based on the fault current estimated from the current data of the neighboring FRTUs. Finally, in order to prove the effectiveness of the proposed method, the diverse fault cases including single phase ground faults and phase to phase short faults are simulated in several positions of the typical distribution system using the EMTP.

2. Problem Definition

2.1 CB-based fault location determination method

A distribution system is operated as a radial structure starting from the CB of a distribution substation. A recloser is installed to clear a fault when a fault occurs on the feeder, switches are installed to separate the fault zone or scheduled outage zone from the feeder, and tie switches serve to transfer the un-faulted outage zone to other feeders.

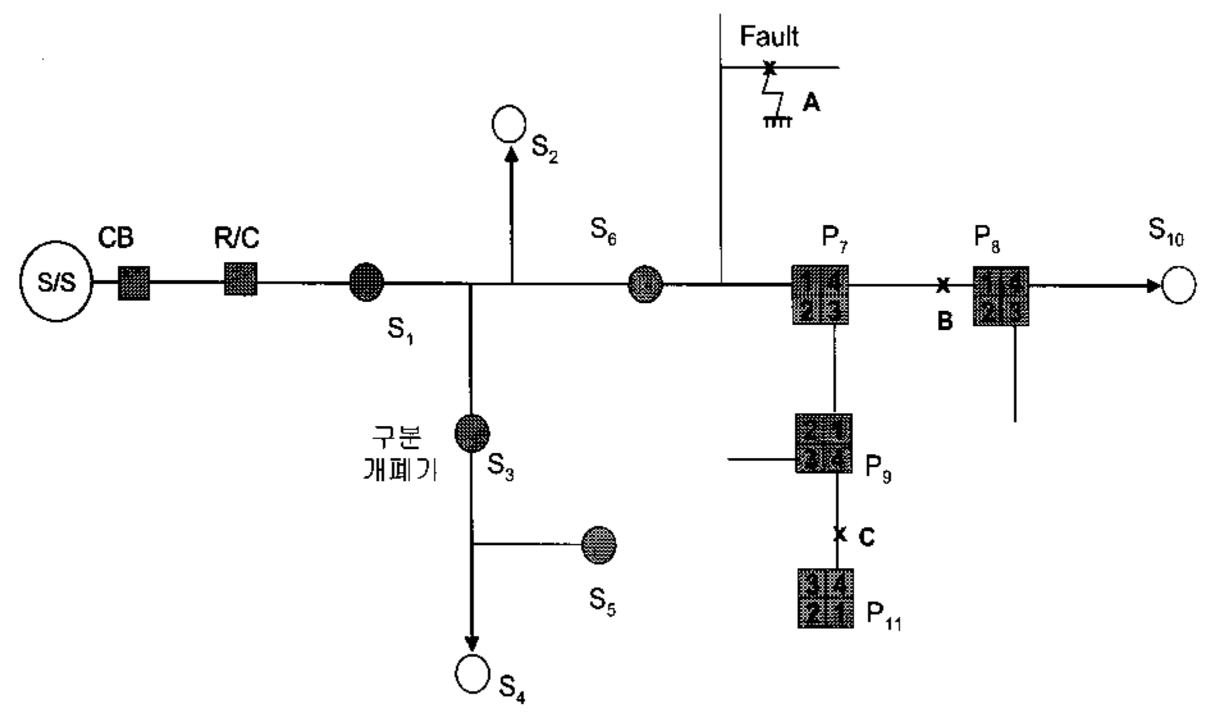


Fig. 1. Typical distribution system

Fig. 1 shows a typical distribution system. CB represents the feeder protection circuit breaker, R/C the recloser, S_i the ith overhead switch number, ● the closed overhead switch, ○ the opened overhead switch, and P_{ij} represents the jth circuit number of the ith multi-circuit switch. In particular, an FRTU (Feeder Remote Terminal Unit) is attached to each switch.

Feeder faults are distinguished into the short-duration fault and the permanent fault: the short-duration fault occurs frequently as compared with the permanent fault. In the case of a permanent fault which the recloser locks out, the fault zone can be easily identified because the switch FRTU records the fault information, and then sends the information to the DAS. However, the service restoration of the fault zone is delayed because the fault location cannot be identified in the fault zone. In the case of the short-duration fault, which is cleared during the reclosing operation of the recloser, it is difficult to identify the fault zone and fault location because the FRTU cannot send it to the DAS by not recording the fault information. Although the short-duration fault does not cause damage to the utility facility, its importance is increased from the viewpoint of power quality because it causes malfunctions of the computer-based or electronic switching equipment of the customer [8]. In order to release such quality problem, a corresponding strategy must be determined. Accordingly, to enhance the speed of service restoration to the fault zone and reduce the frequency of the short-duration fault, the location of both the permanent and short-duration faults must be identified and recorded in the distribution database.

Suppose the case wherein a fault occurs in point A of fig. 1. The existing CB-based fault location determination method estimates points A, B, and C within the fault distance boundary as the fault location because it measures the current and voltage in the substation CB position. At this time, the very difficult task of determining point A as the fault location from among the candidate set {A, B, C} is required. And, the voltage and current computation for the source bus of the fault zone, which must consider the various branches, tapped load and uncertainty of the load model, is required to approximate more accurately the fault distance. This problem can be solved by an FRTU-based fault location determination method according to the current and voltage of the FRTU. Of course, as the short-duration fault recording function must be implemented in the FRTU, it may perplex the system operator because the fault information is reported frequently in the DAS. Thus, the FRTU does not report the fault recording data to the DAS, but it sends the inferred fault zone and distance information from the data to the DAS and the crews near the feeder in order to analyze and identify the cause of the fault.

2.2 FRTU-based fault location determination

Recently, a ubiquitous-based system has been developed from the distribution system, in which the switch operation information can be exchanged freely between the FRTUs. Fig. 2 presents the composition of the ubiquitous-based distribution system, including the A/S (automatic switch).

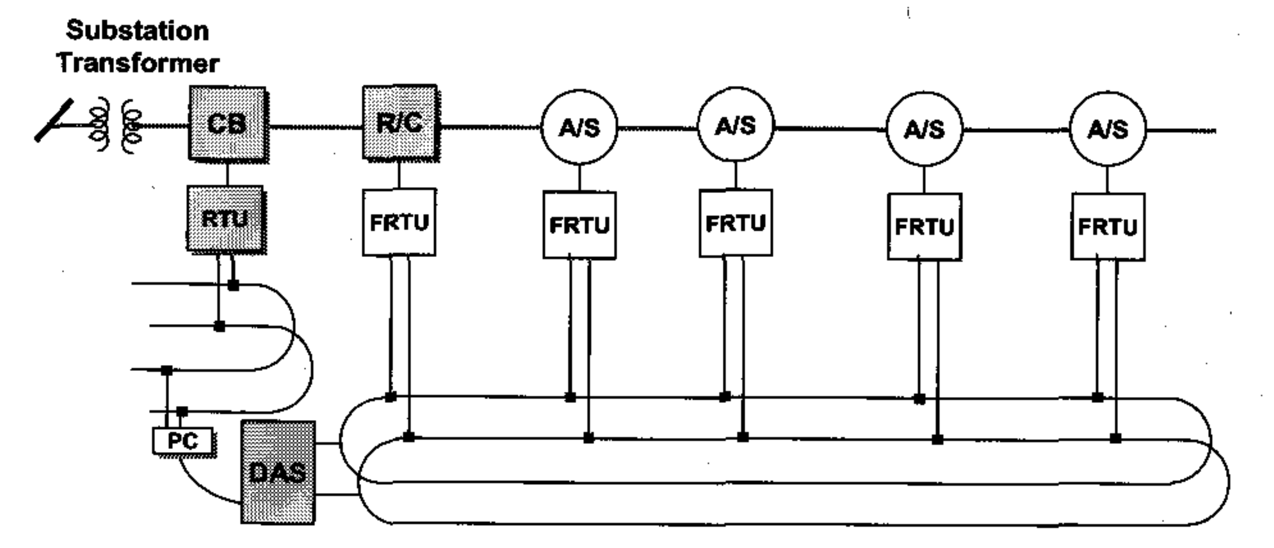


Fig. 2. The ubiquitous-based distribution system

The switch FRTUs are interconnected as an ethernet dual optic ring network as revealed in Fig. 2. As such, each FRTU can exchange at high speed diverse information such as the current, voltage, current direction, etc. with the other FRTUs. Therefore, it is possible to employ the FRTU-based fault location determination method using the current and voltage information obtained by 1:1 communication between the FRTUs.

With the proposed method, the FRTU is triggered by the fault current, and it determines the fault zone, fault path, and fault distance based on the heuristic rule, which is driven by the current and voltage collected from the neighboring FRTUs. So, the FRTU minimizes the patrol time taken by the crews to find the fault location within the fault zone.

3. Intelligent Fault Location Inferring Method

The proposed FRTU-based fault distance estimation method consists of a fault zone determination step, a fault path determination step, and a fault location determination step, which are based on the 1:1 communication between the FRTUs under the ubiquitous-based distribution system.

3.1. The fault zone determination

At first, when a short-duration fault or a permanent fault occurs, each FRTU experiencing the fault current determines the fault zone based on RULE 1], which is fired by the voltage information obtained by 1:1 communication with the load side FRTUs of the faulted zone.

RULE 1] If the FRTU experiences a fault current and more than one of the FRTUs within its self-load zone satisfy the nil-voltage condition, it determines the self-load zone as the fault zone. Here, the voltage condition is signified by $V_p > V_{basic}$, the nil-voltage condition by $V_p \leq V_{basic}$, and the self-load zone and load zone are connected directly to the FRTU. The V_p represents phase voltage.

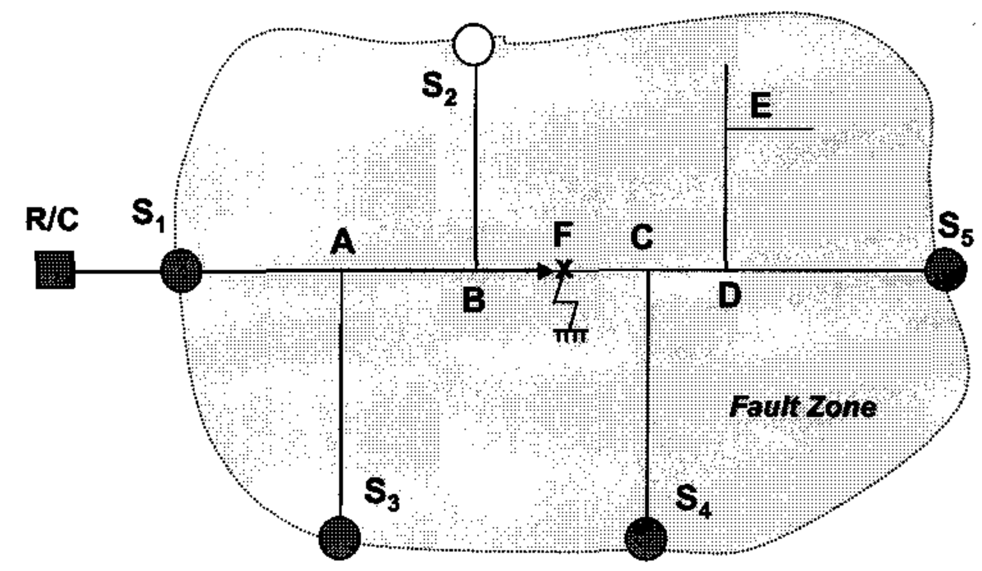


Fig. 3. The faulted zone topology

Fig. 3 shows the case in which a single phase ground fault occurs in the F position. At this time, switch S_1 of the source side experiences the fault current, but switches S_2 and S_3 do not experience the fault current and also satisfy the nil-voltage condition. On the other hand, switches S_4 and S_5, which are supplied from the F position, satisfy the nil-voltage condition. That is, the FRTU of the source switch S_1 of the fault zone experiences the fault current, and, more than one FRTUs , the FRTUs of the switches S_4 and S_5, of elements of its self-load zone switch set {S_2, S_3, S_4, S_5} satisfy the nil-voltage condition. Therefore, if the FRTU experiences the fault current, based on this rule, it can determine whether its self-load zone is the fault zone or not by checking the nil-voltage condition after collecting voltage data by 1:1 communication with its load zone FRTUs.

3.2. The fault path determination

After the fault zone has been identified, the fault path must be determined. Each FRTU has a switch information set of the self-load zone, arranged source side to load side according to the direction of the current flow in the main feeder. In the case of Fig. 3, the FRTU of switch S_1 saves the switch information set of the self-load zone as {S_3, S_2, S_4, S_5}. At this time, the fault path may be one among the path combinations made by switch S_1 and the switch information set {S_3, S_2, S_4, S_5}. This problem can be determined by RULES 2-4] using the voltage information collected by 1:1 communication with the elements of the switch information set.

RULE 2] The FRTU determines the path obtained by the last switch satisfying the voltage condition and the first switch satisfying the nil-voltage condition from among the paths of switch information set as the fault path.

RULE 3] The FRTU determines the branching point of the last switch among those switches as the starting point of the fault path when more than one switch satisfies the voltage condition.

RULE 4] The FRTU determines the branching point of the first switch among those switches as the ending point of the fault path when more than two switches satisfy the nil-voltage condition.

RULE 5] The FRTU determines the path from the branching point to the switch in the nil-voltage condition as the fault path when more than one switch satisfies the voltage condition in the load side of the switch that satisfies the nil-voltage condition.

RULE 6] The FRTU determines the branch line connected to the fault phase as the fault path when no switch satisfies the nil-voltage condition.

In Fig. 3, when a fault occurs in the F position, switches S_2 and S_3 in the source side from the F position do not experience nil-voltage. Therefore, neither $\{S_1, S_2\}$ nor $\{S_1, S_3\}$ may be the fault path. On the other hand, switches S_4 and S_5 in the load side from the fault position (F) satisfy the nil-voltage condition in the structure. Accordingly, based on the source switch, the path composed by the last switch from among the switches satisfying the voltage condition and the first among the switches satisfying the nil-voltage condition can be inferred as the fault path. That is, the FRTU can identify the path $\{S_2, S_4\}$ from switch S_2, which satisfies the voltage condition, and switch S_4, which satisfies the nil-voltage condition, as the fault path. RULE 2] is obtained from such structural characteristics.

In particular, when more than two switches satisfy the voltage or nil-voltage condition, the common main feeder can be inferred as the fault path. In Fig. 3, because switches S_3 and S_2 satisfy the voltage condition, the fault path is started from position B. This is defined as RULE 3]. Also, because switches S_4 and S_5 satisfy the nil-voltage condition, the fault path is finished in position C. This is defined as RULE 4]. Therefore, the main feeder section {B, C} of path $\{S_2, S_4\}$ can be determined as the fault path.

If a fault occurs in position E, the switch that satisfies the nil-voltage condition does not exist. At this time, it is certain that the fault occurred on the branch connected to the fault phase of source switch S_1 among candidate branches. This principle is represented by RULE 6]. However, in order to apply the rule, a dummy switch representing the branch terminal must be added to the switch information set of the FRTU.

3.3. The fault distance estimation method

The FRTU estimates the fault location after inferring the fault path by RULES 2-6]. Here, a practical method based on the fundamental voltage and current components is adopted as the fault distance determination method [8, 9]. The fault distance must be estimated differently according to the fault type. It can be broadly classified into the single phase ground fault and the phase to phase short fault. Equation (1) shows the fault distance estimation method to the single phase ground fault.

$$m = \frac{V_{pR} I_{mX} - V_{pX} I_{mR}}{R_1 (I_{mX} I_{kR} - I_{mR} I_{kX}) - X_1 (I_{mX} I_{kX} + I_{mR} I_{kR})} \quad (1)$$

In Equation (1), V_{pR} and V_{pX} represent the real part and the imaginary part of the fault phase voltage. I_{mR} and I_{mX} represent the real part and the imaginary part of the fault current $I_m = 3I_0$, and I_0 is zero sequence current. However, if fault resistance is great, fault distance m may be incorrect because of load currents flowing to multiple branches. Accordingly, fault current I_c is modified as Equation (2) to enhance the accuracy. In Equation (2), $I_{p(L),i}$ is the current collected by 1:1 communication with the ith switch FRTU and n represents the number of load side switches of the self-load zone.

$$I_m = I_p - \sum_{i=1}^{n} I_{p(L)i} \quad (2)$$

R1 and X1 symbolize the real part and the imaginary part of positive sequence impedance per km. I_{kR} and I_{kX} stand for the real part and the imaginary part of $I_k = I_p + \{(Z_0 - Z_1)/Z_1\} I_0$, and I_p, I_0, Z_0 and Z_1 represent the fault phase current, zero sequence current, zero sequence impedance per km and positive sequence impedance respectively.

In the event of a phase to phase short fault, double line ground fault, or three phase short fault, V_p, I_k and I_m must be replaced as the corresponding values, $V_p - V_q$, $I_p - I_q$, $\{(I_p - I_p^*) - (I_q - I_q^*)\}$. Here, p and q represent the phase experiencing the ground or short fault, where * signifies the pre-fault value.

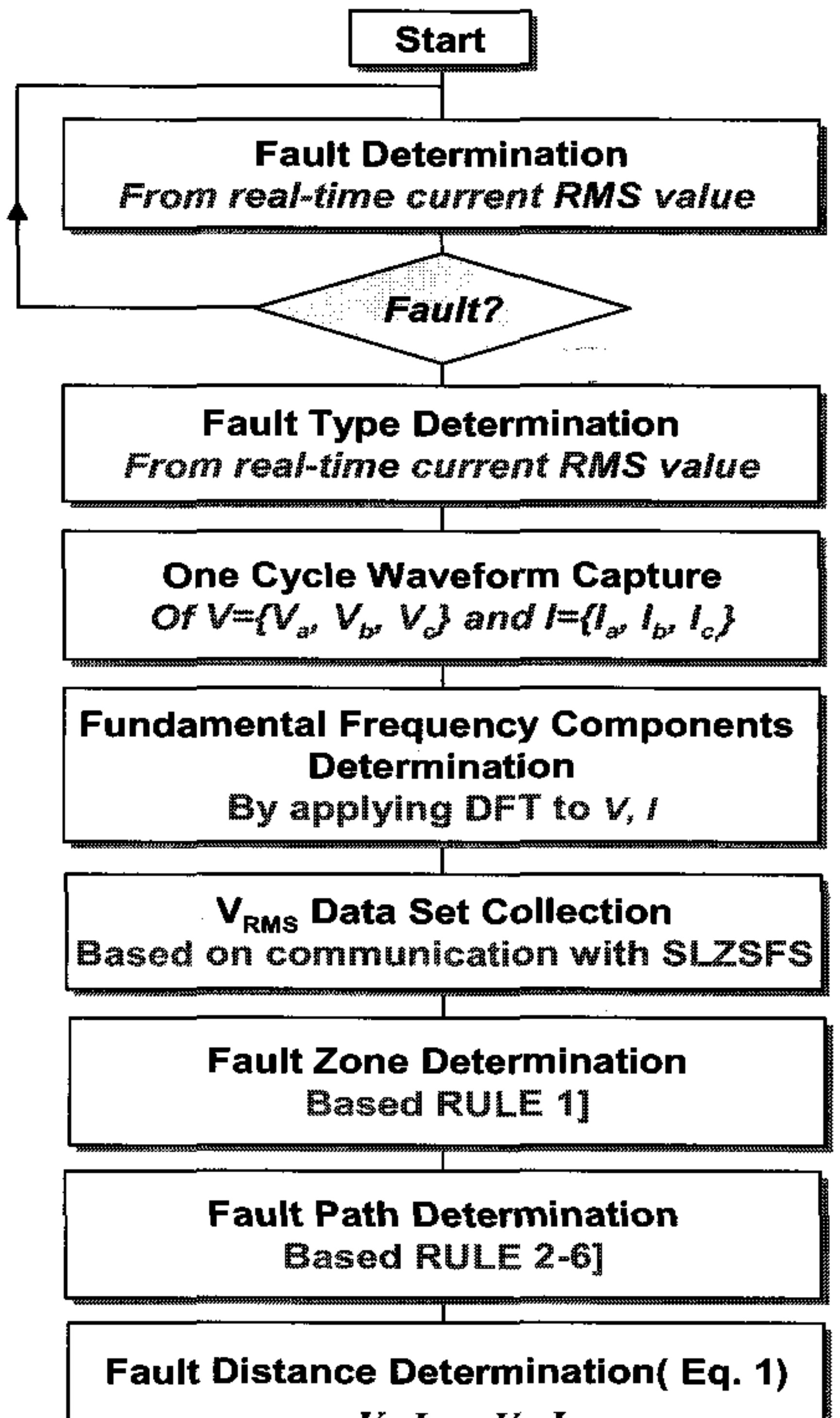
3.4. The fault location inferring procedure

Fig. 4 shows the FRTU-based intelligent fault distance estimation procedure that is proposed in this paper; in particular, it is explained by Steps 1-6 based on the single phase ground fault. In the case of a phase to phase short fault, the required data refers to Section 3.3.

Step 1] The FRTU determines whether the fault occurs or not from the current sample data furnished in real time. If the current satisfies the fault triggering condition, it determines the fault, and then proceeds to Step 2].

Step 2] The FRTU determines the fault type. According to which of I_a, I_b, I_c or I_n exceeds the setting value, it determines one from among the single phase ground fault, phase to phase short fault, double line ground fault, and three phase fault as the fault type. It then proceeds to Step 3].

Step 3] The FRTU collects a post-fault one cycle



$$m = \frac{V_{pR} I_{mX} - V_{pX} I_{mR}}{R_1 (I_{mX} I_{kR} - I_{mR} I_{kX}) - X_1 (I_{mR} I_{kR} + I_{mX} I_{kX})}$$

Fig. 4. The fault distance estimation procedure

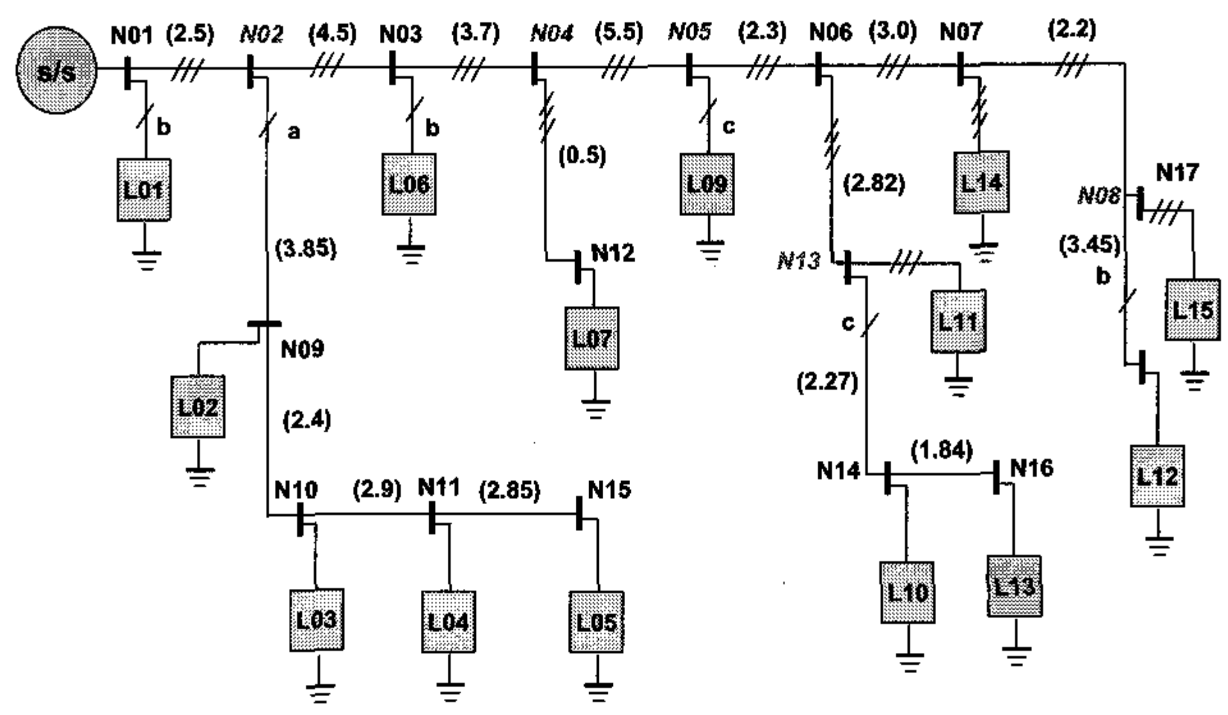


Fig. 5. Test distribution system

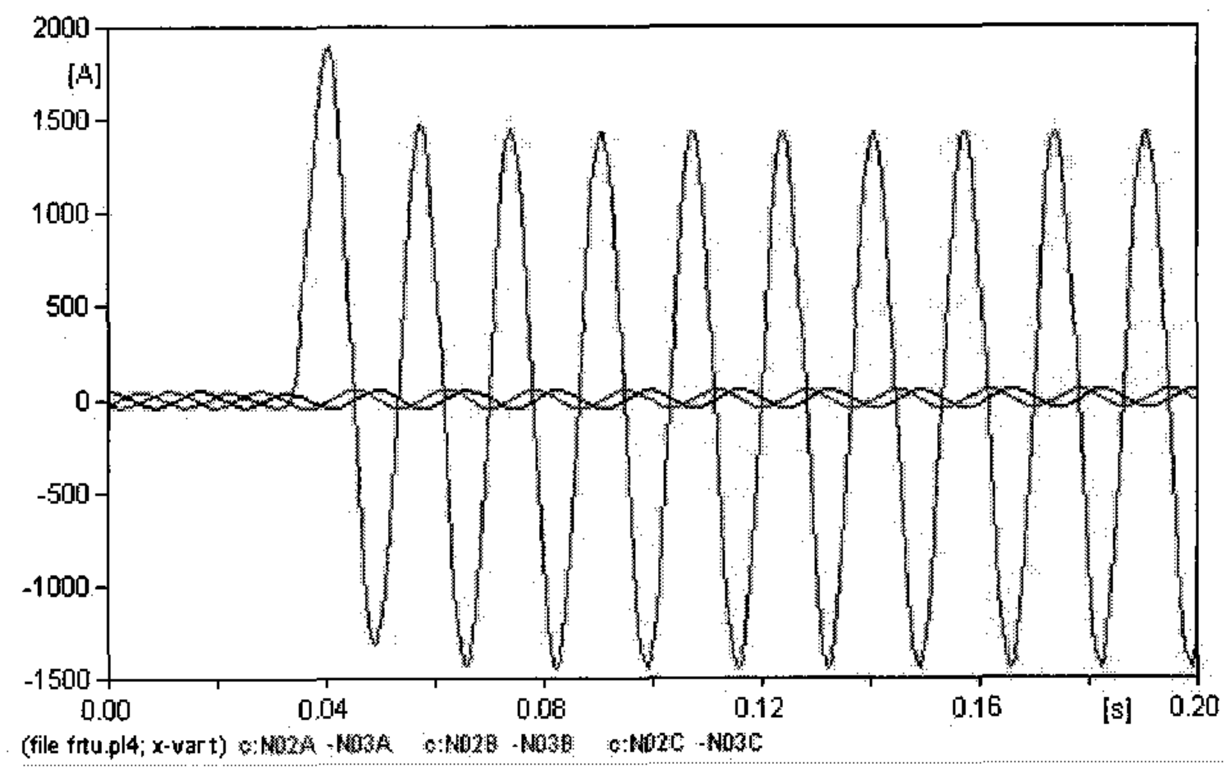


Fig. 6. Fault current waveform for fault case 2

waveform from the three voltages V_a, V_b, V_c, and the three currents I_a, I_b, I_c. Then, it obtains the fundamental frequency components by applying DFT (Digital Fourier Transformation) to those waveforms. It then proceeds to Step 4].

Step 4] The FRTU collects voltage V_{RMS} by 1:1 communication with the elements of the SLZSFS (Self-Load Zone Switch FRTU Set), after which it proceeds to Step 5].

Step 5] The FRTU determines the fault zone based on RULE 1] and the fault path based on RULES 2-6]. It then proceeds to Step 6].

Step 6] The FRTU estimates the fault distance by using Equation (1). If the work is finished, it goes back to step 1], and repeats the fault distance determination procedure.

4. Simulation Results

In this paper, the FRTU-based fault distance determination strategy was proposed. Accordingly, to show the effectiveness of the proposed method, the typical distribution is introduced, and several single phase ground faults and phase to phase short faults are simulated in any section on the test distribution system using EMTP. And, fault distance is estimated based on current and voltage waveforms obtained in switch bus other than CB bus (N01 bus), and then the obtained location is compared with the fault simulation location.

Fig. 5 shows the test distribution system introduced and modified from ref [10] for the evaluation of the method's effectiveness. In particular, buses N02, N04, N05, N13, and N08 symbolize the switch buses in which automatic switches for measuring the three phase current and voltage are simulated.

Table 1 presents the simulation results, in which A, B, C, and N of the fault type represent the phase. Fault cases 1, 2, and 3 simulate the single phase ground faults for the A, B, and C phases. Fig. 6 shows the current waveform of EMTP for fault case 2.

Fault case 4 simulates a short fault between phases A to B. Fig. 7 shows the current waveform of EMPT for fault case 4, where a 180°phase difference is identified between phases A and B. In those fault cases, the fault zone becomes the fault path because the fault zone consists of two switches.

However, in fault cases 5-8, the fault path is represented as a part of the fault zone. At first, the fault zone is defined as {N05, N13, N08} because the fault location is N06, N07, and N08. Here, N05 corresponds to the source switch and {N13, N08} to the self-load zone switch set. In fault case 5, where the fault location is N06, the self-load zone switch

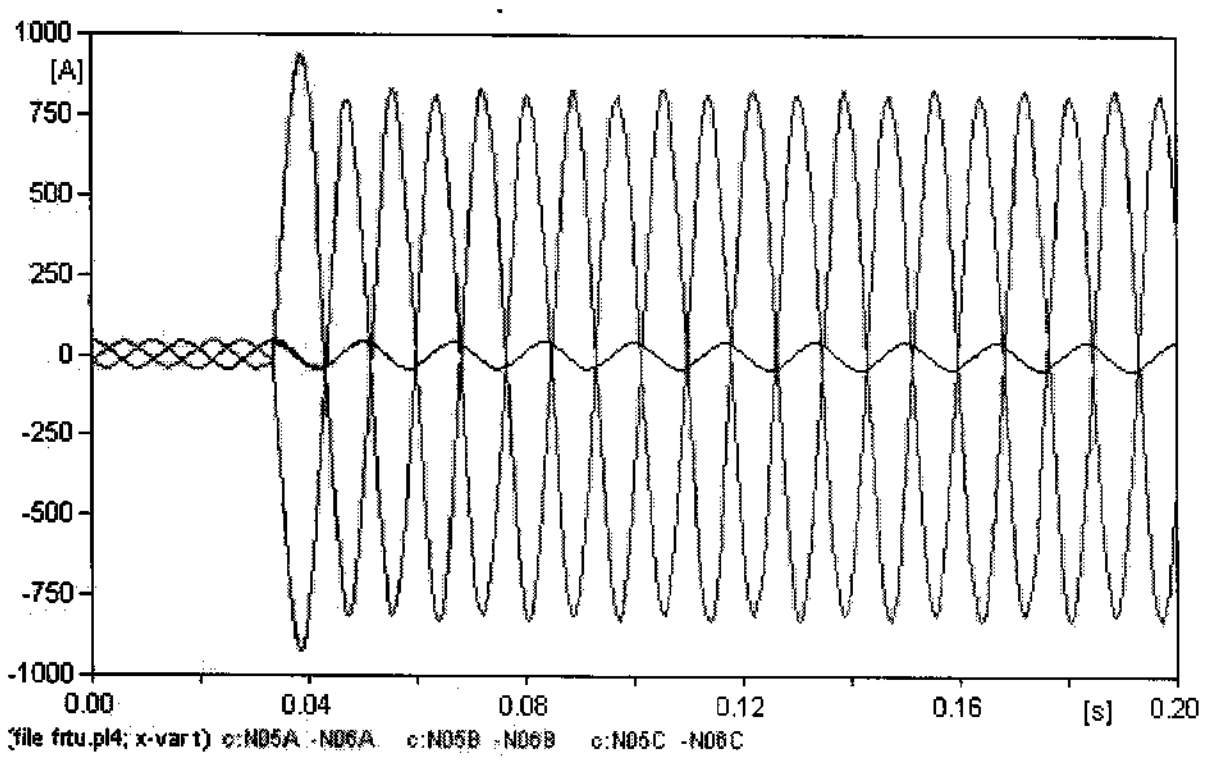


Fig. 7. Fault current waveform for fault case 4

Table 1. Simulation results

#	Fault Cases			Simulation Results					
	Fault Type	Fault Lo.	Length (km)	Fault Zone	Fault Path	Fault Resistance(Ω)			
						0	10	20	30
1	AN	N02	2.500	{N01,N02}	{N01,N02}	2.498	2,502	2,506	2,508
2	BN	N03	4.500	{N02,N04}	{N02,N04}	4.501	4.504	4.511	4.517
3	CN	N04	8.200	{N02,N04}	{N02,N04}	8.204	8.203	8.204	8.208
4	AB	N05	5.500	{N04,N05}	{N04,N05}	5.502	5.504	5.503	5.503
5	BC	N06	2.300	{N05,N13,N08}	{N05, ***N13(BP)***}	2.300	2.303	2.302	2.302
6	CA	N07	5.300	{N05,N13,N08}	{***N13(BP)***, N08}	5.297	5.285	5.291	5.290
7	AB	N08	7.500	{N05,N13,N08}	{***N13(BP)***, N08}	7.262	7.273	7.265	7.265
8	AN	N13	5.120	{N05,N13,N08}	{ ***N13(BP)***, N13}	5.223	5.224	5.291	5.442
9	AN	N05	5.500	{N04,N05}	{N04,N05}	5.495	5,499	5. 495	5.489
10	AN	N12	8.700	{N02,N04}	{N02,N04}	8.713	8.716	8.713	8.713
Averaged error [%]						-0.11	-0.07	0.08	0.39

set {N13, N08} experiences nil-voltage. Because N13 is the first switch among the nil-voltage switches, the fault path is determined as path {N05, N13} based on RULE 2]. Furthermore, more than two switches experience nil-voltage, so the fault path is started from N05 and finished at N06 based on RULE 4]. Accordingly, the fault path is inferred as {N05, ***N06***}. However, because N06 is not a switch bus, ***N06*** is represented as N13 (BP: Branching Point).

In the case of fault case 6 and fault case 7, the fault location is N07 and N08, respectively. Therefore, two switches {N05, N13} satisfy the voltage condition, and only switch N08 experiences nil-voltage. Therefore, the fault path is defined as path {N13, N08} based on RULE 2], because N13 is the first switch satisfying the voltage condition, and the fault path is reduced as path {***N06***, N08} based on RULE 3]. Here, ***N06*** is replaced as ***N13(BP)***. On the other hand, in the case of fault case 8, the fault path is initially determined as {N05, N13} based on RULE 2]. And then, because switch N08, which satisfies the voltage condition, exists in the load side of the nil-voltage switch N13, the final path is inferred as branch path {***N13(BP)***, N13} based on RULE 5].

The fault distance was then simulated. In the case of fault cases 5-7, the fault current I_c is computed from the current of the switch bus {N13, N08} to simulate the current obtained by 1:1 communication with the self-load side switches. The estimated results indicated the average errors of -0.11, -0.07, 0.08 and 0.39 [%] for the fault resistances 0, 10, 20, and 30(Ω), respectively. That is, an average degree of error ranging from a minimum of -0.07[%] to a maximum of 0.39[%] can be identified. Although in fault case 8 the fault resistance 30(Ω) showed an error of 6.29[%], the effectiveness of the proposed method was proved by showing the average error for all the fault cases of the fault resistance 0-30(Ω) as a maximum of 0.39[%].

5. Conclusions

This paper proposed an FRTU-based intelligent fault distance determining method based on data exchange between the neighboring FRTUs in a ubiquitous-based distribution system. The proposed method was designed with three FRTU-based steps; namely, the fault zone determination, the fault path determination, and the fault distance estimation step, in order to avoid the generation of multiple estimations and to reduce the estimation error. Several heuristic rules, based on fault current data and the voltage data of its neighboring FRTUs, were proposed to determine the faulted zone and the fault path. Furthermore, in the proposed method, the FRTU uses the current data collected by 1:1 communication with the neighboring FRTUs in order to estimate the fault current. Here, the heuristic rules were obtained from the feeder zone topology of the distribution system. Finally, in order to prove the effectiveness of the proposed method, diverse fault cases were simulated in several positions of a typical distribution system using EMTP. In the simulation results, the proposed heuristic rules based inference method demonstrated that multiple estimates can be avoided and the patrol scope minimized. Also, the effectiveness of the proposed method was proved by showing that the average degree of error for all fault cases of the fault resistance 0-30(Ω) falls within 0.39[%]

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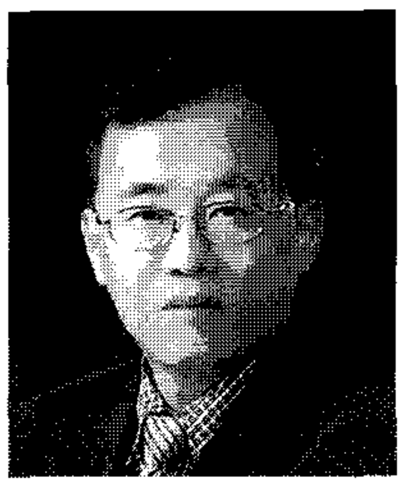

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