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# LSTM-Based Fault Direction Estimation and Protection Coordination for Networked Distribution System

**WOO-HYUN KIM[1], JU-YONG KIM[1], WOO-KYU CHAE[1], GEONHO KIM[1], AND CHUN-KWON LEE[2], (Member, IEEE)**

[1]Distribution Planning Laboratory, Korea Electric Corporation Research Institute, Daejeon 34056, South Korea
[2]Department of Control and Instrumentation Engineering, Pukyong National University, Busan 48513, South Korea

Corresponding author: Chun-Kwon Lee (ck.lee@pknu.ac.kr)

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**ABSTRACT** While the world's power distribution system resembles an intricate web-like structure, the most conventionally implemented distribution mechanism is the radial distribution system (RDS) where connection points for each distribution line are normally kept open. However, disadvantages regarding the traditional system have led to active research on establishing the networked distribution system (NDS), in which multiple circuits are interconnected with electricity as well as high-speed communication systems. The NDS offers multiple advantages including increased facility utilization, increased hosting capacity, and higher terminal voltage. Conversely, an unsolved issue prevails as the existing protection coordination method designed for the RDS is inadequate for fault occurrences in the NDS due to inaccurate fault direction identification. Hence, there is an urgent need for an alternative protection coordination method that allows high precision fault direction identification through communication. Moreover, the application of various existing technologies is hindered as the distance relay protection coordination algorithm malfunctions in situations where distribution lines are of short length, loads are dispersed onto multiple lines, and integration of distributed generation (DG) is frequent. Therefore, this paper presents a fault direction identification method that uses the waveform of the fault current based on long short-term memory (LSTM) neural network and a communication-based protection coordination scheme that can be applied in fault situations within an NDS.

**INDEX TERMS** Protection coordination, distribution system, closed-loop system, networked distribution system, fault direction, long short-term memory, deep learning neural network.

## I. INTRODUCTION

While the radial distribution system (RDS) is designed to supply the annual peak load since the maximum load is only required for a relatively short period during the year, the facility utilization rate is rather modest [1]–[3]. Facility utilization is anticipated to deteriorate due to the recent surge in distributed generation (e.g., solar power, wind power generation, etc.) and an increase in electric vehicle charging stations which induce large fluctuations in load. In addition, failures in distribution lines of the RDS result in a power outage lasting 3 to 5 minutes among all connected areas including those intact until the faulty section is disconnected, and an alternative power supply is provided to the sound sections (i.e., the load-side line in the faulty section) [4]–[7].

As an attempt to resolve the shortcomings of the RDS, the closed-loop system (CLS), an alternative approach that connects two unidirectional ends within the RDS, was introduced and subsequently demonstrated in distribution systems. Conversely, implementations of the approach failed to expand due to two major drawbacks [8], [9]. First, if a failure occurs at the substation, the load of both lines is supplied from the remaining intact substation, resulting in a reduced utilization rate of 50%. Second, the integration of distributed generation (DG) is not permitted within the CLS as the presence of multiple transformers for DG leads to malfunctions in the existing protection coordination algorithm.

Apart from the time-current curve (TCC)-based protection coordination method developed for the RDS, a protection

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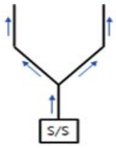
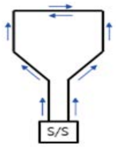
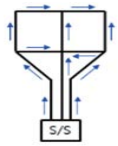
**TABLE 1.** **Comparison between distribution line operation methods.**

| | RDS | CLS | NDS |
|---|---|---|---|
| Scheme |  |  |  |
| Reliability | Low | Intermediate | High |
| Initial Cost | 1 | 1.2∼1.3 | 1.1 |
| Complexity of Design/Opeartion | Low | Intermediate | High |
| Utilization Rate | Low | Intermediate | High |
| Areas of Application | All | Suburban∼ Urban Areas (Underground) | All |
| Communication | Unnecessary | Required | Required |

coordination method utilizing a high-speed communication system has been developed and implemented for the CLS [10]. The approach indeed accomplished the task of minimizing the blackout area by opening each end of the failure point, should a fault occur. Despite the advantage, the inherent limitations of the CLS have most recently led to new approaches such as the multi-closed loop distribution system [11]–[14]. A system where electrical connections have been introduced among distribution lines of a dendritic nature is normally referred to as the meshed distribution system (MDS) [15]–[23]. Recently, research and demonstrations are actively being conducted regarding the networked distribution system (NDS), a distribution system that includes the integration of constant reciprocal communication and is optimized for protection coordination [24], [25].

A comparison between existing distribution systems and the NDS is presented in Table 1. In comparison to the RDS and CLS, the operation of the NDS can improve facility utilization through load sharing (or distributed resource sharing). In addition, the NDS can alleviate the occurrence of voltage fluctuations due to DG which is often encountered in existing distribution systems. Moreover, sharing power supply lines results in an increased hosting capacity [26]–[30]. Finally, in case of a failure, only the protection devices at each end of the failure point are opened to enable self-healing, thus the sound section on the load side of the failure point need not experience an interruption in the power supply.

Despite the advantages, NDS is yet to be implemented when a fault occurs within the NDS, the resulting fault currents rush to the fault point from multiple connected lines. Since the fault direction differs depending on the fault point, protection coordination methods built for the RDS are unsuitable for accurately distinguishing the faulty section. Multiple methods using directional relay and distance relay have previously been proposed to apply to the MDS. Among the proposed methods, distance relay can be successfully applied to spot loads, where the load is only connected to the bus, or when the distance between protection devices is sufficient. On the other hand, distance relay is inapplicable in situations where load and renewable energy sources are simultaneously connected to distribution lines of short length (1∼10km) due to the underreach.

Upon fault detection, the previous protection coordination method developed for the CLS allows the identification of fault direction, shares information regarding the fault via communication, determines the faulty section, and finally isolates the faulty section. However, if the protection coordination method fails in determining the fault direction, which is a principal factor in identifying the faulty section, the circuit breaker malfunctions. Consequently, simultaneous openings of the circuit breakers of the power system result in a power outage of large-scale. Several fault direction estimation techniques applicable to existing distribution power systems have been studied. A method of estimating the direction of a fault using the phase difference between the voltage and current of the distribution line is the most widely used method in the real distribution system [31]. Using phase difference method frequently malfunctions due to the influence of a three-phase ground fault, short circuit fault, or distributed generator that occurs near the voltage/current measurement point. The using only the phase of the current method calculates and compares the phase immediately before and after the fault detection by frequency or time-frequency analysis. Due to harmonics or disturbances, this approach is prone to fail to estimate the fault direction and necessitates the employment of additional digital filters to filter DC components created by incipient faults [32]–[34]. The current differential relay method, which is a method of detecting the position and direction of a fault using the magnitude or polarity of a current, is a protective cooperation method mainly used in a transmission system and has very high reliability [35]. This method is particularly effective for spot load systems, but cannot be used if there is a load or distributed power source in the section between protective devices, such as distribution systems, due to the underreach effect. Recently, methods for automatically estimating the fault direction of complex grids by adding machine learning-based techniques were investigated [36]–[38]. however, these approaches are in the early stage of the research, and the applied power distribution network is limited to RDS or CLS.

Hence, in this paper, a novel protection coordination method for the NDS based on long short-term memory (LSTM), which learns and estimates the time series data of the fault current waveform according to the time of occurrence, location, and condition of the fault is presented. The Recurrent Neural Network (RNN) is an efficient time-series data analysis model developed to model the relationship between input patterns when a correlation exists between the elements prior to and following the time-series data. LSTM is an algorithm that compensates for the limitations observed for the RNN, in that the preservation of information decreases as the distance from the current point increases. Because

**TABLE 2.** Minimum symmetrical component threshold of DOCR.

| Component | Description | Criteria |
|---|---|---|
| $3I1$ | Direction Identification of Positive-Sequence | 0.5 A |
| $3I0$ | Direction Identification of Zero-Sequence | 0.25 A |
| $V0$ | | 3.33% of $V_{norminal}$ |
| $I0/I1$ | | 9% of $I0/I1$ |

**TABLE 3.** Minimum symmetrical component threshold within the CLS.

| Component | Description | Criteria |
|---|---|---|
| $V1$ | Direction Identification in Short Circuit | 0.2 p.u. of $V_{rated}$ |
| $I1$ | | 20% of $I_{\phi}$ |
| $V0$ | Direction Identification in Ground Fault | 0.1 p.u. of $V_{rated}$ |

a separate structure determines whether to store historical time series data, LSTM shows excellence in the retention of relevant information [39]. Utilization of the LSTM algorithm is anticipated to yield significant reductions in error when determining fault direction, which is the major cause of circuit breaker malfunction issues in the existing CLS protection coordination algorithm. To verify the performance of the proposed algorithm, possible fault scenarios have been demonstrated in two distribution lines.

The remainder of this paper is organized as follows. Section II provides a problem formulation of existing protection coordination algorithms. In Section III, a novel LSTM-based distribution system protection coordination scheme is presented. An experimental simulation setup and corresponding results are discussed in Section IV. The paper is concluded in Section V.

## II. PROBLEM FORMULATION

A power system protection algorithm is largely divided into four steps: fault detection, fault re-assessment, identification of fault direction and faulty section, and subsequent blocking. A protection device detects a short circuit fault through the phase current ($I_{\phi}$), while the zero-sequence current ($I0$) is used for the detection of a ground fault. First, a current exceeding the $I_{\phi}$ (A, B, C; 400 Arms) or $I0$ (N; 75 Arms) of the circuit breaker is identified as a fault current.

Following fault current detection, the fault undergoes re-assessment. Most failures occurring in the distribution system are obvious failure situations that do not require the consideration of additional parameters. On the other hand, fault identification is oftentimes challenging due to a series of oscillations in the fault current caused by contact resistance at initial stages post-fault occurrence (1 to 5 cycles). Therefore, to prevent malfunctions in the protection coordination algorithm, the presumed fault is re-assessed post-detection through symmetric voltage and current components of the circuit breaker. The reliability of fault detection is enhanced after setting the minimum thresholds for the zero-sequence voltage ($V0$) in the case of a ground fault and the positive-sequence voltage ($V1$) and current ($I1$) in the case of a short fault. For the ground fault, since faults are detected through the $I0$ from the beginning, only the $V0$ is used for fault detection re-assessment. The minimum threshold values of the directional over-current relay (DOCR) for cases of short circuits and ground faults are presented in Table 2. In the existing protection cooperation algorithm designed based on DOCR, if either of the symmetric components of the measured current and voltage fails to exceed the threshold value after fault current detection, the incident is considered a failure in direction identification, and a trip signal is not issued. Subsequently, the circuit is automatically opened if the fault is not resolved within 200 ms. In short, if there is any uncertainty regarding the detected fault, the presumed fault is expected to be resolved through other sections. Conversely, if the fault persists, the circuit breaker is opened to ensure the stability of the system. Table 3 shows the minimum threshold value for fault direction identification in the CLS protection coordination algorithm. In the protection cooperation algorithm, the symmetric component threshold is set higher than the individual symmetric component thresholds of the DOCR to increase reliability when determining the direction of the fault current within a quick response time.

Then, the relay determines the fault direction by comparing the phase angle relation of the symmetric current components to voltage components. Fig. 1 illustrates the vector diagram and relation between different phasors in the short fault and the ground fault. Relays have an adjustable relay characteristic angle (RCA), which is the angle of the current compared to the angle of the voltage at which the relay operates with maximum sensitivity. In the event of a short circuit failure, $I1$ is typically highly lagging. The direction of the fault current is determined by calculating the torque of the relay internal voltage ($V1$-RCA) and $I1$. The torque product indicates the direction of fault current flow: a positive torque defines a forward fault and a negative torque defines a reverse fault. Therefore, the fault direction is calculated by comparing $I1$ with the positive area within ±90° of the RCA. As for the ground fault, the direction of the fault current can be estimated in a similar manner after the $V0$ is inverted (different RCA setting for $I0$) [40].

In succession to identifying the fault direction, each circuit breaker transmits a trip signal to the connected circuit breaker in the direction corresponding to the fault current via communication. Conversely, a block signal is transmitted to the connected circuit breaker in an opposite direction of the fault current. If trip signals are received from connected circuit breakers on each side, the circuit breaker is considered to be located in the faulty section, and the circuit is instantaneously opened. Fig. 2 shows the application of the existing CLS protection coordination method to a fault occurring between line 4 of circuit breaker A and line 1 of circuit breaker B. For

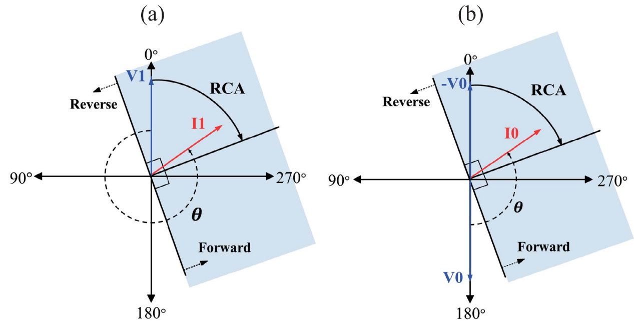



**FIGURE 1.** Direction identification using existing protection method: (a) direction of short circuit current; (b) direction of ground fault circuit.

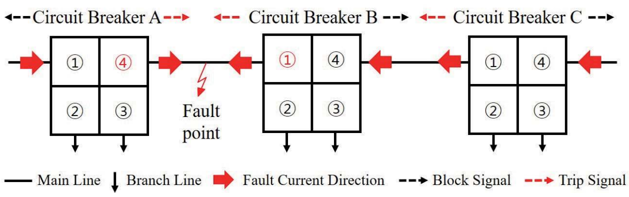



**FIGURE 2.** Communication-based protection coordination method.

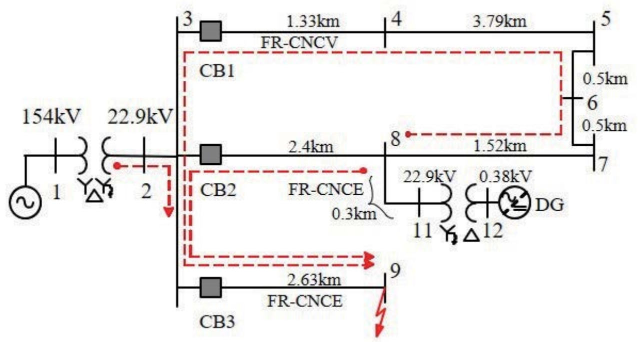



**FIGURE 3.** The failure of CLS integrated distribution generator.

the case of circuit breaker B in Fig. 2, since trip signals were received from both sides, it is regarded as a fault and only the breaker connected to line 1 is opened. The load of the branch lines does not experience a power outage.

However, there are two major limitations regarding the approach. First, when complete ground faults or short circuits are to occur in high proximity to a protection device, the fault direction cannot be determined as the magnitude of the fault resistance is small. Thus, the fault area fails to be minimized. In specific, for occurrences of 3-phase ground faults and 3-phase short circuits, if the fault resistance is low (0.1Ω or less), $V0$ and $V1$ converge close to "0 V", and thus the threshold value is not exceeded. For this case, fault direction is determined using the phase of the memory voltage measured 3 cycles earlier. However, since the memory voltage phase is a value at a steady-state and not a faulty state, the algorithm may malfunction if the phase of the $I0$ overlaps with the boundaries of fault direction identification. Second, the presence of multiple transformers for the integration of DG within a power system may lead to failures when using the algorithm. When a fault occurs, the fault current partially flows to the high-voltage side of the DG integrating transformer ($Y_g - \Delta$ connection). Therefore, while the $I0$ is detected, the $V0$ does not exceed the threshold, and thus the direction identification fails.

A case in which the protection device malfunctions due to a fault occurring in a separate line of the CLS is demonstrated in Fig. 3. In the presence of DG integration, if a failure occurs in a different line (CB3) connected to the same main transformer, $I0$ flows to three separate paths: bus 2-9, bus 11-8-9, bus 11-8-7-6-5-4-3-9. As a result, $I0$ measured at each circuit breaker is relatively small, and thus $V0$ falls below the threshold value. As the fault direction cannot be identified, the circuit breaker consequently malfunctions, resulting in a wide area power outage due to simultaneous openings of multiple circuit breakers.

## III. PROPOSED PROTECTION COORDINATION ALGORITHM

### A. FAILURE SITUATION CASES

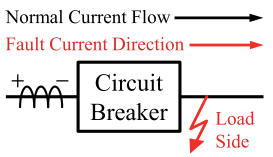
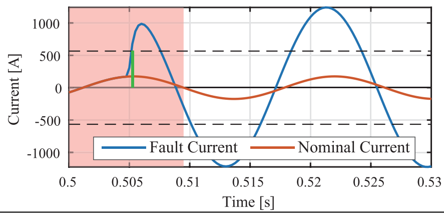
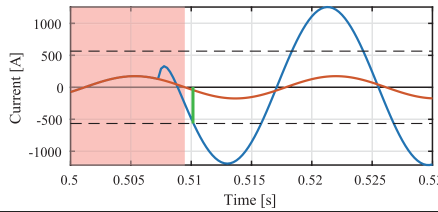
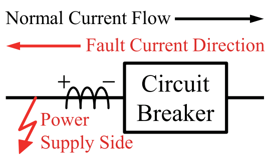
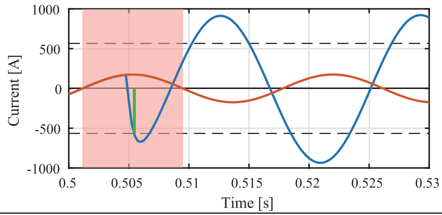
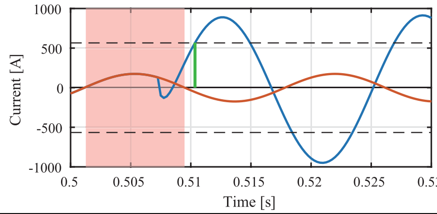
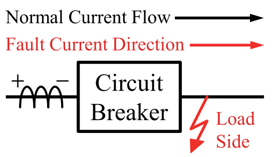
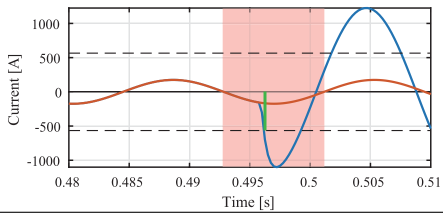
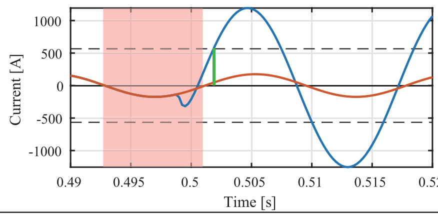
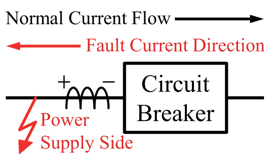
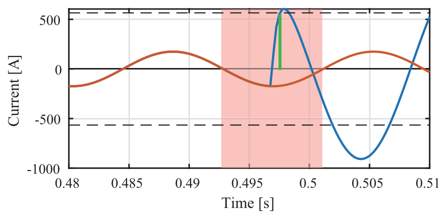
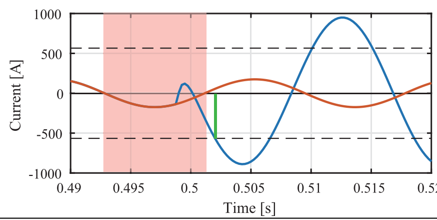
In bidirectional power distribution systems (e.g., CLS and NDS), the fault direction may be influenced by three major factors associated with the fault location and phase. First, the fault direction is highly dependent on the fault location (i.e., the power supply side (Upstream) or the load side (Downstream) of the protection device). Second, the fault direction depends on the phase sequence of the fault (i.e., a positive or negative phase sequence). Third, the direction of the fault current is divided into two cases regarding the difference in detection time (i.e., occurrence and detection may occur within the same half-cycle, or the fault current may be detected in the next half-cycle). In specific, if a fault current occurs near the zero-crossing point of the cycle, the fault current may fail to exceed the threshold. In this case, the fault current is expected to be detected in the subsequent half-cycle. The phase sequence and direction of a current in response to a fault situation are demonstrated in Table 4. The red line indicates the normal current (load current) waveform in absence of a fault, the blue line indicates the waveform of the fault current, and the green line indicates the phase sequence detected from the feeder remote terminal unit (FRTU).

The normal current direction ($C_{norm}$) is calculated by the phase difference between the voltage and the current monitoring for each circuit breaker in the distribution feeder system as follows:

$$C_{norm} = cos\{(\angle V_{5C} - RCA) - \angle I_{5C}\} \qquad (1)$$

where $\angle V_{5C}$ and $\angle I_{5C}$ are the phases of voltage and current at a steady-state before pickup 5 cycle, respectively. In this paper, the direction from the inside to the outside of the circuit breaker is defined as a forward direction as in the existing method. Each circuit breaker transmits a trip signal

**TABLE 4.** Current phase and direction according to fault situation.

| Polarity of the Fault | | Positive | |
|---|---|---|---|
| The Cycle of Fault Current Detection | | Same Half-Cycle | Next Half-Cycle |
| Fault Location |  |  |  |
| |  |  |  |
| Polarity of the Fault | | Negative | |
| The Cycle of Fault Current Detection | | Same Half-Cycle | Next Half-Cycle |
| Fault Location |  |  |  |
| |  |  |  |

in the forward direction and a blocking signal in the reverse direction.

When a fault is picked up, the polarity of the current ($Pol_{pu}$) and the before the half-cycle ($Pol_{hc}$) are extracted and compared as follows:

$$Pol_{pu} = i$$
$$Pol_{hc} = \frac{1}{32}\Sigma_{t=ZC_n}^{ZC_{n+1}} i_t \quad (2)$$

The sampling rate of the distribution feeder system used for protection cooperation is 3,840 Hz which is 64 samples per cycle. Therefore, the average value of the current during the half-cycle (32 samples) is calculated as the polarity before the half-cycle of fault pickup. $ZC_n$ and $ZC_{n+1}$ represent the time duration at which the current crosses zero. The number of $i_t$ should be more than 20 in order to reduce errors in transient conditions including inrush current, measurement errors, and DC components. Then, the direction of the fault current is opposite that of the normal current if the two polarities are the same, and the direction of the fault current is the same as that of the normal current if the two polarities are different. As result, it is feasible to determine the fault direction in the distribution system only using the fault current waveform. The proposed approach to estimate the fault direction can be uniformly applied regardless of the fault type, and all symmetric current components.

### B. LSTM-BASED FAULT CURRENT DETERMINATION ALGORITHM

An LSTM-based solution for time-series fault data analysis is presented in Fig. 4. The solution consists of layers of feature engineering, predictive model development, model optimization, and systematic evaluation.

- LSTM input layer: Features of the current waveform input data are extracted. When a fault occurs within the NDS, the protection coordination sequence of each circuit breaker operates. To determine the direction of the fault current, three parameters measured by the circuit breaker have been selected as inputs: the direction of current flow at steady-state ($C_{norm}$), the polarity at fault detection ($Pol_{pu}$), and the polarity of the preceding half-cycle ($Pol_{hc}$). The correlation between the fault direction and the steady-state current direction can be assessed by comparing the polarities of the fault detection point and the preceding half-cycle of the point of detection. The steady-state current direction is extracted through phase differences of the voltage and current among the 5 cycles preceding fault detection. Accordingly, three time-series parameters are extracted for the inputted current signals in the LSTM input layer.

- LSTM Hidden Layer: The hidden layer accepts data received from previous levels. Each hidden layer is the actual representation layer of the feature. The output of the previously hidden layer becomes the input of the next hidden layer. Through iteration, the weights of the hidden layer are continuously adjusted until the network converges.

- LSTM output layer: The outputs of the LSTM network are the estimated fault direction and fault detection time for each circuit breaker.

- Evaluation layer: After the last optimized parameters are applied to the LSTM estimation network, an optimal prediction result is obtained by calculating the mean squared error between the predicted data and the original data.

The time series dataset for LSTM network training was collected from 8 different fault current simulation cases. 8 fault case simulations were conducted to accumulate input data by altering the fault current from the minimum fault current detection value (400 A) to the most extreme case, the 3-phase fault (10 kA). The parameters of the LSTM network are adjusted and optimized using the adaptive moment estimation (ADAM) method. 128 mini-batch-sized feature data are randomly extracted for training. In addition, we set the initial learning rate to 0.001, the gradient decay factor to 0.9, and the squared gradient decay factor to 0.999.

### C. PROTECTION COORDINATION ALGORITHM

The complete protection cooperation algorithm using the proposed method is shown in Fig. 5 including the LSTM architecture, training, and fault direction estimation. The protection device of the system constantly monitors zero- or positive-sequences through the method of the symmetrical coordinate of the voltage and current. If a fault is detected whilst monitoring, the polarity at the point of detection is derived for direction identification, and the polarity of the mean value of current for the half-cycle preceding pick-up is then derived. Subsequently, based on the fault direction result derived from the LSTM network, the faulty section is determined through data sharing with the connected circuit breaker. If a fault is present within the identified section, it is immediately opened to minimize the faulty section. Finally, information on the status (e.g., circuit open, blockage failure, etc.) of the protection device is transmitted to the connected circuit breaker to decide whether the protection coordination had worked, and a backup sequence is prepared.

**TABLE 5.** Systematic parameters (impedance/reactance) of the target system.

| | Z1 | Z2 | Z0 |
|---|---|---|---|
| Source [P.U.] (@ 100MVA) | 0.00105+j0.01146 | | 0.00527+j0.029 |
| ACSR [P.U.] (@ 100MVA) | 0.086824+j0.228644 | | 0.034763+j0.074379 |
| | $X_{HM}$ | $X_{ML}$ | $X_{LH}$ |
| MTr #1, 2 [P.U.] (@ 60MVA) | j0.14496 | j0.0669 | j0.2538 |

## IV. PERFORMANCE EVALUATION

### A. SIMULATION SETUP

#### 1) TARGET SYSTEM

As shown in Fig. 6, the proposed protection coordination scheme was tested in the power distribution system of the IEEE 14-bus in which the distribution system voltage and frequency were modified to 22.9 kV, 60 Hz [3], [41]. Systematic parameters including a power source, main transformer (MTr), and distribution line (ACSR) are shown in Table 5. Z1, Z2, and Z0 are the positive, negative, and zero-sequence impedance of the distribution line, respectively. In addition, $X_{HM}$, $X_{ML}$, and $X_{LH}$ represent the reactance in the Y-Δ-Y connection (high-medium voltage, medium-low voltage, low-high voltage) for the removal of the third harmonic in the MTr.

Benchmark examples (e.g., power source, transformer, distribution line, etc.) registered in PSCAD's knowledge base have been used as the system parameters, and the PSCAD/EMTDC was utilized as the simulation tool. Parameters of the two transformers have been equally set since circulating currents, which may occur during parallel operation of transformers, are not considered in this paper. A spot load of 7 MVA and a 1 MVA distributed power source are connected to each bus, and a distributed load of 1 MVA is connected to each line. The total load of the system is 57 MVA, and if power is normally supplied from DG, each transformer will supply 25 MVA.

#### 2) RESULT IN NORMAL FAULT SITUATION

The duration for fault processing in the proposed protection coordination scheme is approximately 84 ms: the time required for pick-up following fault occurrence is 16.67 ms (60 Hz, 1 cycle), the average response time (i.e., time from pickup to direction identification and logic processing) is 20 ms, the average duration for the N:N communication between the connected protection devices is 5 ms, the average auxiliary relay operation time is 8 ms, and the average blocking time (i.e., contact opening and arc extinguishing time) is 34 ms. Based on this information, the duration from fault occurrence to the faulty section blocking according to the type and location of the simulated fault is summarized in Table 6. In Table 6, 1-4 DL refers to the distribution line connecting bus 1 and bus 4. Each fault was simulated at the 50% point of a distribution line connecting two buses. Regarding a general fault situation, the protection coordination was successful as only the circuit breakers at both ends of the failure point were opened.

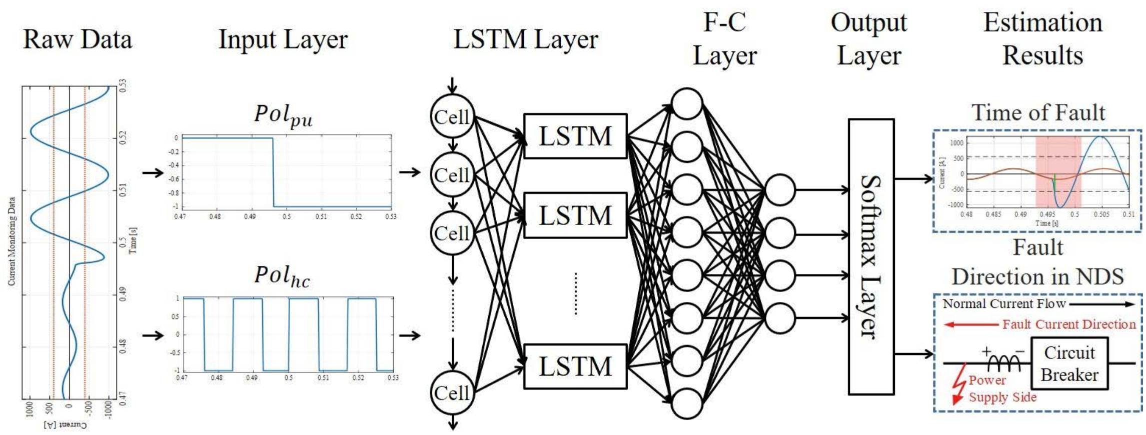



**FIGURE 4.** LSTM structure of fault current determination.

**TABLE 6.** Response time by fault impedance and type of fault [ms].

| Fault Type | 1-4 DL | | 1-5 DL | | 1-6 DL | | 2-3 DL | | 2-7 DL | | 3-4 DL | | 5-6 DL | | 6-7 DL | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (0.01∼5 Ω) | R3 | R6 | R1 | R10 | R2 | R13 | R4 | R9 | R5 | R16 | R8 | R7 | R11 | R12 | R14 | R15 |
| a-g | 84 | 95 | 74 | 74 | 74 | 74 | 74 | 74 | 88 | 100 | 88 | 87 | 799 | 79 | 74 | 72 |
| a-b-g | 85 | 99 | 84 | 95 | 74 | 76 | 76 | 76 | 89 | 102 | 85 | 86 | 86 | 86 | 87 | 84 |
| a-b-c-g | 81 | 90 | 78 | 80 | 79 | 79 | 78 | 76 | 86 | 99 | 76 | 84 | 84 | 85 | 80 | 85 |
| a-b | 83 | 94 | 71 | 71 | 71 | 71 | 71 | 71 | 81 | 99 | 84 | 85 | 85 | 85 | 76 | 76 |
| a-b-c | 80 | 90 | 78 | 80 | 79 | 79 | 83 | 86 | 86 | 97 | 74 | 81 | 84 | 81 | 78 | 78 |

**TABLE 7.** Response relay by the second problem with CLS.

| | | Existing Method | | Proposed Method | |
|---|---|---|---|---|---|
| Fault Type [0.01 Ω] | | a-b-c-g | a-b-c | a-b-c-g | a-b-c |
| Fault Location | 1-4 DL (R6) | R3, R8, R10, R15 | | R3, R6 | |
| | 1-5 DL (R10) | R1, R2, R13, R15 | | R1, R10 | |
| | 1-6 DL (R13) | R2, R13, R15 | | R2, R13 | |
| | 2-3 DL (R9) | R2, R3, R4, R5, R12 | | R4, R9 | |
| | 2-7 DL (R16) | R5, R10, R14 | | R5, R16 | |
| | 3-4 DL (R8) | R3, R4, R5, R8 | | R7, R8 | |
| | 5-6 DL (R12) | R1, R2, R11, R15 | | R11, R12 | |
| | 6-7 DL (R15) | R2, R14, R15 | | R14, R15 | |

**TABLE 8.** Simulation parameters for fault scenario 2.

| Fault Type | | | 3-Phase Ground Fault [0.01 Ω] | | 3-Phase Short Circuit [0.01 Ω] | |
|---|---|---|---|---|---|---|
| Fault Location | | | R2 | R13 | R2 | R13 |
| Phase Voltage [kV] | | A-N | 16.33 | 0.31 | 4.68 | 0.08 |
| | | B-N | 6.83 | 0.09 | 4.68 | 0.08 |
| | | C-N | 4.25 | 0.08 | 4.68 | 0.08 |
| Phase Current [kA] | | A | 12.55 | 5.09 | 4.03 | 1.64 |
| | | B | 7.50 | 3.05 | 4.03 | 1.64 |
| | | C | 3.68 | 1.48 | 4.03 | 1.64 |
| Symmetrical Component | Voltage [kV] | $V0$ | 3.14∠60° | 0.01∠32° | 0 | 0 |
| | | $V1$ | 8.47∠23° | 0.14∠-1° | 4.68∠-12° | 0.08∠-36° |
| | | $V2$ | 5.37∠52° | 0.01d27° | 0 | 0 |
| | Current [kA] | $I0$ | 1.05∠-12° | 0.4∠166° | 0 | 0 |
| | | $I1$ | 7.29∠-46° | 2.96∠133° | 4.03∠-81° | 1.64∠99° |
| | | $I2$ | 4.63∠-17° | 1.88∠162° | 0 | 0 |

### B. FAULT SCENARIO 1; THE FIRST DRAWBACK OF CLS PROTECTION COORDINATION

The operation of a circuit breaker in response to an occurrence of a ground fault in a separate line from the same bank (i.e., an external fault) was simulated. After connecting a distributed load of 5 MVA to one bus of the target system, the ground fault was simulated and repeated for all buses. When using the existing CLS protection coordination, it was demonstrated that the protection devices of the target system should not be triggered since an external fault had occurred, because the $I0$ was picked up while the $V0$ failed to exceed the threshold value (3.33% of 13.2 kV; 440 V) the result was instead a failure direction identification. On the other hand, when using the proposed method, the direction was successfully determined, and block signals between the protection devices resulted in the inactivity of protective devices.

### C. FAULT SCENARIO 2; THE SECOND DRAWBACK OF CLS PROTECTION COORDINATION

Table 7 shows the results for the application of existing and newly proposed protection coordination methods to simulations of a 3-phase ground fault or a 3-phase short circuit occurring right in front of the protection device of each line. When incorporating the existing method, the circuit breakers

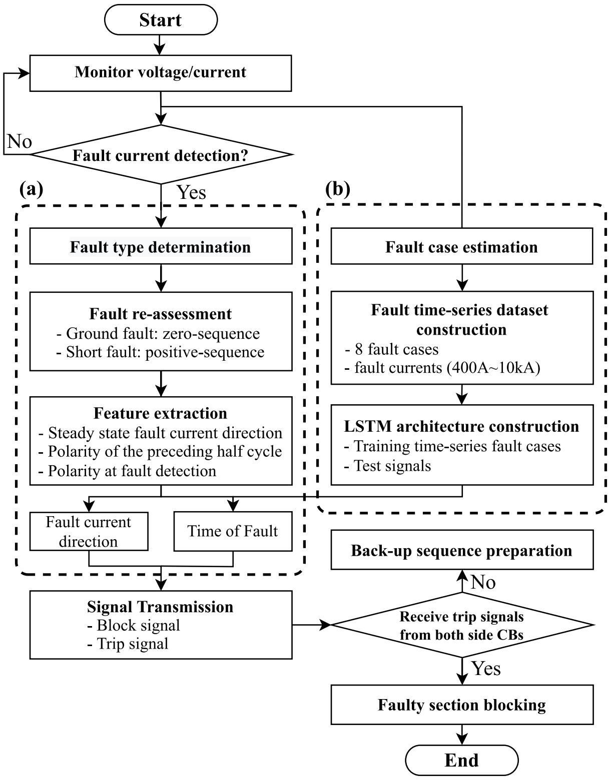



**FIGURE 5.** Proposed protection coordination algorithm; (a) Fault direction estimation with LSTM and (b) LSTM architecture training.

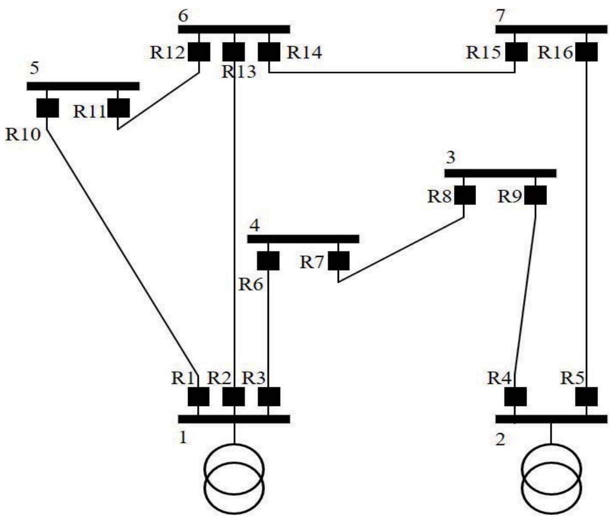



**FIGURE 6.** Target distribution system.

indiscriminately opened due to a failure in determining the fault direction, resulting in a wide area of power outage. However, when applying the proposed protection coordination method, only the circuit breakers in the faulty section were opened, and protection coordination was successful.

Among the multiple fault cases, the voltage and current (R2 and R13) were additionally measured for a fault occurring in front of R13 in a line connecting buses 1 and 6. The results which are depicted in Table 8, indicate that R2 successfully identified the 3-phase ground fault and the fault direction. In opposition, R13 failed to identify the fault direction as the $V0$ was 140 V while the $I0$ was picked up. Likewise, for the occurrence of a 3-phase short circuit, R2 operated normally, while R13 failed to do so as the $V1$ was measured to be 80 V. An alternative may be to modify the threshold value, but further research is inevitable since different values will need to be applied depending on the power system.

## V. CONCLUSION

When a fault occurs within the traditional dendritic power distribution system, a power outage is inevitable in sound areas as a time delay occurs during the processes of faulty section isolation and provision of alternative power supply to sound sections. Conversely, the faulty section is automatically isolated in the NDS, preventing occurrences of power outages within sound sections, and thereby ensuring enhanced reliability. Existing protection coordination methods designed for the RDS are inapt for the NDS, and existing communication-based protection coordination methods possess critical limitations. Hence, in this paper, a modified direction identification method has been proposed for the application to the NDS.

The proposed direction identification method is distinct from other conventional protection coordination algorithms as fault direction is determined solely through current waveforms. Since the phase difference between voltage and current is not required, the novel method is indeed anticipated to resolve drawbacks associated with existing methods and to bring about a number of benefits. In short, the proposed method holds the capacity of identifying a fault direction within a short time frame regardless of the magnitude of the voltage element, distribution line length, load type, or presence of DG integration within a power system. Future empirical studies on the NDS are planned to be conducted using the intelligent electronic device (IED) following optimization through real-time simulation (Hardware in the loop simulation, HILS).

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**WOO-HYUN KIM** received the B.S. and M.S. degrees in electrical engineering from Korea Maritime and Ocean University, Busan, South Korea, in 2019. He is currently a Researcher with the KEPCO Research Institute. His research interests include partial discharge, power quality, and protection coordination.

**JU-YONG KIM** received the M.S. and Ph.D. degrees from Kyungpook National University, Daegu, South Korea, in 1994 and 2007, respectively. He joined the KEPCO Research Institute, Daejeon, South Korea, as a Researcher, in 1994. He is currently the General Manager of the Smart Power Distribution Laboratory, Distribution Planning Group, KEPCO Research Institute. His research interests include DC distribution systems and DC microgrid.

**WOO-KYU CHAE** received the B.Eng. degree from Sungkyunkwan University, South Korea, in 2004, and the M.S. and Ph.D. degrees from Chungbuk National University, South Korea, in 2007 and 2020, respectively. He has been a Principal Researcher and an Electrical Engineer with the KEPCO Research Institute, South Korea, since 2004. His research interests include design and operation of meshed distribution grid, design and control of microgrid, and renewable energies. Recently, he is leading the project developing protection method and intelligent electronic device (IED) for meshed distribution grid. He is a Reviewer of the Korea Institute of Power Electronics and the Korea Institute of Illuminating and Electrical Installation Engineers.

**GEONHO KIM** received the B.E. degree from Ajou University, South Korea, in 2015, and the M.S. degree from Chungnam National University, South Korea, in 2021. He is currently a Senior Researcher with the KEPCO Research Institute. His research interest includes distribution system protection coordination.

**CHUN-KWON LEE** (Member, IEEE) received the B.S. degree from the School of Electrical Engineering, Inha University, Incheon, South Korea, in 2013, and the Ph.D. degree from the School of Electrical and Electronic Engineering, Yonsei University, Seoul, South Korea, in 2019. Upon his graduation, he joined the Department of Smart Distribution Laboratory, Korea Electric Power Corporation (KEPCO) Research Institute, as a Researcher, in 2019. He joined the Major of Control and Instrumentation Engineering, Pukyong National University, in 2021. His current research interests include the Internet of Things (IoT)-based electric equipment diagnosis and monitoring for condition-based maintenance, big data analysis, time-frequency analysis, and advanced signal processing technique with machine learning.