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Fault area estimation using traveling wave for wide area protection

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Abstract As the increasing number of Phasor Measurement Units (PMUs) are deployed, wide area protection in power systems has been gaining interest. In particular, fault detection, fault classification and fault area estimation are essential to reduce the damage of faults, and even prevent catastrophic cascades of failures. In this paper, we present a scheme for fault area estimation using PMUs and traveling wave theory. The purpose of this paper is to formulate a scheme for fault area estimation by calculating the approximate fault location based on traveling wave theory. This research has targeted at reliable operation of wide transmission system through the estimation of fault area. To verify the suggested scheme, the various simulations are performed in practical Korean power transmission system. The simulation results show that the proposed scheme has a good performance with high accuracy for estimating fault area.

Keywords Fault area estimation, Phasor measurement unit (PMU), Transmission line system, Traveling wave, Wide area protection

1 Introduction

Wide area protection schemes should be more intelligent to deal with new challenges, as the structure of power system have become more complex along with the development of distributed generations and renewable energy sources. Furthermore, the fast and accurate methods to detect faults, classify their types and locate them are crucial in wide area power systems. In order to address these challenges, the various practical researches related to the wide area protection schemes have been studied in many countries in the past few years [1–13].

In the 1980s, many researchers began studies on new technologies such as Power System Disturbance Monitor (PSDM), Frequency Disturbance Recorder (FDR), and PMUs based on the Global Positioning System (GPS) to prevent wide area blackout and to monitor, analyze and control wide area power grids [1, 2]. In U.S.A, Frequency Monitoring Network (FNET) has been constructed and is being operated by the Electric Power Research Institute (EPRI), Tennessee Valley Authority (TVA), and the IT Research Center at Virginia Tech University [5, 6].

In Korea, Korea-Wide Area Measurement System (K-WAMS) has been developed by Korea Electro- technology Research Institute (KERI), Korea Electric Power Corporation (KEPCO), Korea Electric Power Knowledge Data

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Network (KDN), and LS Industrial Systems (LSIS). K-WAMS monitors and evaluates wide-area power grids using the synchro-phasor of the voltages and currents measured by Intelligent Power system Information Unit (I-PIU) [7]. Recently, Wide Area Monitoring And Control (WAMAC) system has been considered as a new wide area protection system. According to the KERI's research result, WAMAC system is expected to detect unstable condition of power system beforehand and to prevent wide area outage from happening by blocking the faulted parts. In short, the various methods and systems are getting more attention because they could contribute to the prevention of cascaded power system failures [3–13].

As mentioned above, there are so many efforts to protect wide area power system. When these schemes are used as a kind of solution, the most important first step for protecting wide area power system is to detect the fault area. Once the accurate fault location is distinguished from wide area power system, it is possible to only separate the fault location. After the fault in power system is cleared, the restoration of power system will be achieved and then the wide area power system can come back to the steady state. In the series of process above, the discrimination of fault location is the most important basic stage for protecting power system.

In the past few years, fault location estimation has been performed in several methods, for example wavelet transform [14], fuzzy logic, neural networks [15], distributed parameter of transmission line [16], traveling wave method [17], prony method [18] and impedance method [19, 20]. Among them, the main fault location detection methods are impedance method and traveling wave method. Especially, the travelling wave fault location method has been widely applied in the power system because it's wide applicability and high accuracy [17].

Thus, this paper presents the technique to locate the fault area using traveling wave in Korean power transmission system. The proposed algorithm utilizes the application of PMUs and the propagation characteristics of traveling wave, and considers all areas in the Korean transmission system. 345 and 765 kV of Korean power transmission systems are modeled by using Electro Magnetic Transient Program - Restructured Version (EMTP-RV). In the case of modeling of target network, the main facilities such as the generators, transformers, loads and transmission lines are modeled based on real data provided by KEPCO and Korea Power Exchange (KPX). In the modeled Korean power transmission system, the total system is divided into 63 clusters where can happen the fault event. Also, PMUs are deployed to measure voltage and current of transmission line and the number of PMUs is calculated by applying the concept of Depth Of Unobservability (DOU). Based on these conditions, fault area is estimated by the traveling wave-based method described in Section 2. To validate the suggested algorithm, the various simulations including the line faults, generator trip and load shedding situations are conducted and the simulation results are analyzed.

2 Fault area estimation

2.1 Basic concept of fault area estimation

To achieve the fault area estimation in wide area network, this paper models the ultra-high voltages national wide transmission network of Korea using EMTP-RV. In the modeled transmission network, PMUs are deployed to measure the voltages and the currents of the transmission line connected to the bus. The output signal of the PMU which is installed on the bus and the adjacent bus could be supervised through the voltages and currents measured from each of PMU. The number of PMU to be installed in the network is 19 which are calculated based on the concept of DOU. The faults events are not only transmission line faults but also generator trip and load shedding situations. The travelling wave is applied in the modeled system for detecting fault area. The aim of this study is applying the travelling wave theory as an approximate fault area estimation technique rather than positioning exact location.

2.2 Selection of measurement points based on DOU

In general, the required number of PMUs to monitor the whole wide area network system is about 1/5–1/4 of a total number of buses in power system. In order to determine the optimal location for installing PMUs, the concept of observability is applied [21, 22]. The bus where the PMU is installed is called a directly observed bus. First neighbor buses of the directly observed bus are called observed buses, since their state can be obtained by PMU data and line parameters between directly observed buses. Other buses are called unobserved buses. DOU means the number of successive unobserved buses. This paper considers the concept of DOU for measuring of distance from observed buses to unobserved buses, as introduced in [21, 22].

The DOU concept is applied to select the optimal PMU measurement points in the power system. Figures 1 and 2 show the concepts of DOU 1 and DOU 2, respectively. In Fig. 1, the bus B and F are directly observed bus. Also, the bus A, C, E, and G indicate observed bus, and bus X is unobserved bus. This system is called DOU 1 system because the number of successive unobserved buses is one. In Fig. 2, the bus R and U are directly observed bus. Also, the bus Q, S, T, and V indicate observed bus, and bus Y

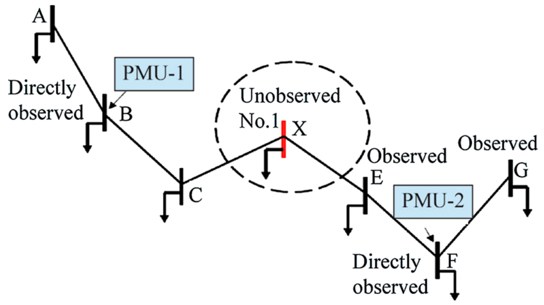

Fig. 1 Concept of DOU 1

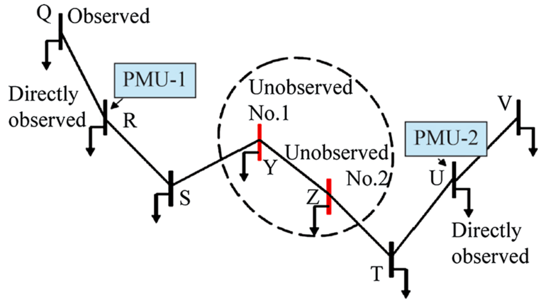

Fig. 2 Concept of DOU 2

and Z are unobserved bus. This system is called the DOU 2 system because the number of successive unobserved buses is two [24, 25].

According to the KEPCO's data, Korean power transmission system has 119 buses with 345 kV and 5 buses with 765 kV [23–25]. However, not all of them are taken into consideration in modeling. There are two cases where two buses were directly connected as a single bus. Two buses are considered as one single bus if the length of transmission line between them is less than a few kilometers for computational convenience. As a result, a total of 117 buses are included in the system modeling. The minimum number of PMUs required to monitor the whole system is calculated based on the DOU 1 system and DOU 2 system, as shown in Table 1. In this paper, DOU 1 is only considered because it gives better observability.

Table 1 Number of buses for two DOU cases

Cases	DOU 1	DOU 2
Directly observed bus	19	12
Observed bus	63	45
DOU 1 bus	35	44
DOU 2 bus	–	16
Total Number. of bus	117	117

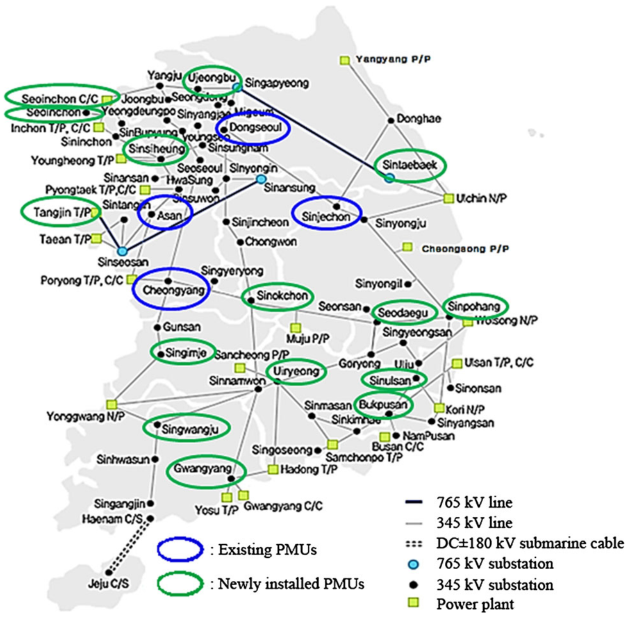

Fig. 3 Locations of PMUs in case of DOU 1

Figure 3 shows the locations of the PMUs in case of DOU 1. The blue and green ellipses indicate the existing PMUs and the newly installed PMUs, respectively.

2.3 Traveling wave theory and fault area estimation

The travelling wave theory has been applied to detect the fault occurrence and location for a long time. In this paper, the basic theory is applied for fault area estimation to reduce the sampling frequency level to 2.88 kHz, which is remarkable for identifying the fault area in the modeled system.

This method can detect the fault location and area by using the propagation velocity of traveling wave and the length of transmission line [26–28]. The estimation accuracy of fault area depends on the fault detection algorithm, the phase synchronization of the Global Positioning System (GPS) and the sampling frequency of Digital Fault Recorders (DFR) [22, 29].

Figure 4 illustrates a simple 2-bus transmission system to estimate the fault area using traveling wave. The parameter l means the line length between Bus 1 and Bus 2. If the fault occurs at a distance d from Bus 1 at time t_0, the DFRs immediately detect the line fault by obtaining fault signal.

The first detection time at Bus 1 and Bus 2 is t_{11} and t_{21}, respectively. The fault distance d can be derived as (3) based on (1) and (2).

$$d = v(t_{11} - t_0) \tag{1}$$

$$1 - d = v(t_{21} - t_0) \tag{2}$$

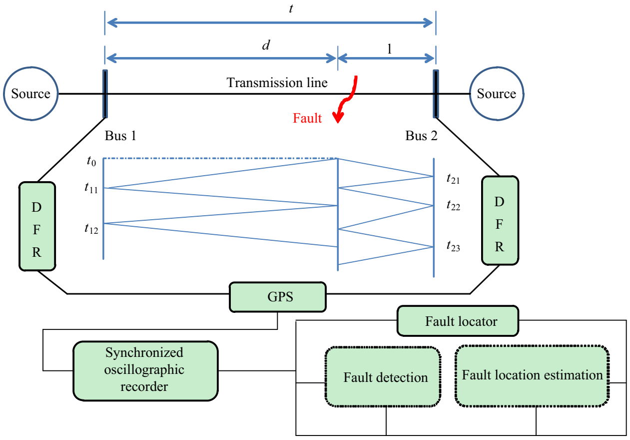

Fig. 4 Illustration of fault area estimation using traveling wave theory

$$d = \frac{l + (t_{11} - t_{21})v}{2} \tag{3}$$

where v means the propagation velocity of the traveling wave on the transmission line between Bus 1 and Bus 2.

If the error e called tolerance that occurs due to sampling frequency when applying traveling wave theory, it can be calculated as following equation.

$$|e| \cong \frac{\Delta t \cdot c}{2} \tag{4}$$

where c means the propagation velocity of light. For example, the tolerance will be 52.08 km when the sampling frequency is 2.88 kHz.

2.4 Fault area estimation in wide area network

The purpose of suggested scheme is not for detecting exact fault location but for estimating approximate fault location by the low level of the sampling frequency of the travelling wave system. In order to improve the accuracy of the fault location, Korean national wide transmission network is divided into 63 clusters as shown in Fig. 5. The 19 PMUs are installed to get the voltage signal from the network and they are synchronized with the GPS. The sampling frequency is selected based on the error about 52 km that is considered as a real distance between each PMU. The traveling wave is applied to locate the fault area in the modeled system. The initiated signal from the travelling wave source will be transferred to the fault position and will be reflected. Each PMU will detect the reflected signal and output signal which are voltage value measured from the PMU. This value will be used by the algorithm as voltage signal. The 19 PMUs have to be synchronized with the GPS in the modeled system. The algorithm is formulated to determine which cluster the fault is located in among the 63 clusters.

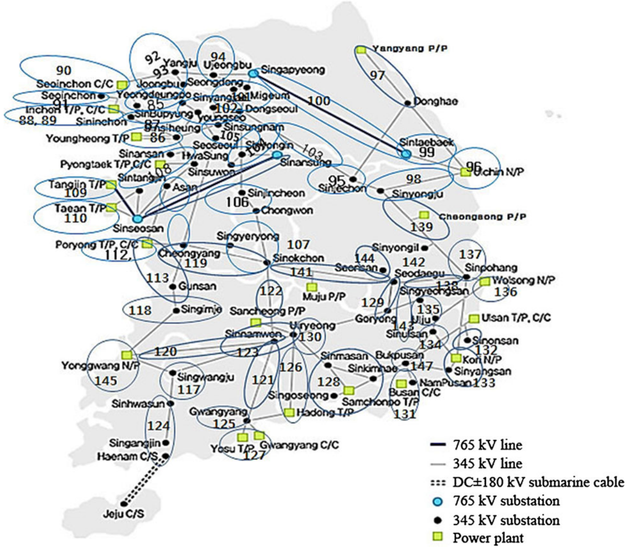

Fig. 5 Model system divided into 63 local areas

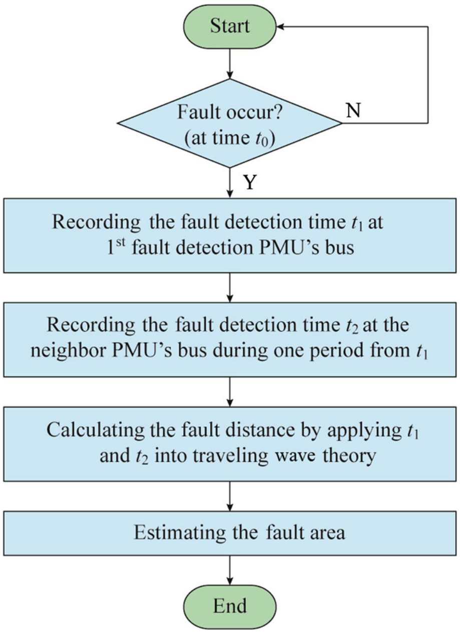

Fig. 6 Flow chart for estimating fault area

Figure 6 shows the algorithm for estimating the fault area. If the fault occurs at any area among the 19 areas, the PMU which is proximate to fault area will detect the fault firstly according to the traveling wave theory and classification method using Wavelet Singular Value Decomposition (WSVD). The voltage signal measured from PMU for the fault area estimation is processed. In the operation process of the algorithm, the threshold value is determined irrespective of voltage when there is white noise in signal and it is verified [30].

Since the fault is assumed to be in the vicinity of the first PMU, its neighbor PMUs need to calculate the fault distance from the first PMU. When the fault occurs between the first PMU and one of its neighbor PMUs, the fault distance is calculated according to (3).

If the calculated distance is below 50% of the real distance between the first PMU and the neighbor PMU, it is a valid fault distance. Otherwise, the fault is between the first PMU and another neighbor PMU. In this paper, the case study about fault area is only considered to Sinoxchun 3S. If Sinoxchun 3S is the place where the fault is firstly detected at time t_{18}, the fault distance from PMUs located in the vicinity of Sinoxchun 3S is calculated as shown in Table 2.

According to the traveling wave theory, the fault distance from Sinoxchun 3S in Table 2 should be between 0 and half of its real distance from Sinoxchun 3S if the fault occurs between Sinoxchun 3S and the corresponding neighbor PMU. However, when the fault does not occur between Sinoxchun 3S and the corresponding neighbor PMU, the calculated fault distance would have a minus value.

Based on the calculated fault distance in Table 2, the fault area can be estimated as shown in Table 3. The first column in Table 3 indicates the order of procedure in locating the fault area. Only if the first estimation order is not satisfied to corresponding condition, the condition of next order is examined. And then the algorithm determines the fault area where the condition of the order is satisfied. The orders for each scenario are set up with certain stages of repetition to find the fault area. This is because the propagation of voltage fluctuation created by a fault is hard to predict due to its non-linearity and dependency on the power system operating conditions. Therefore, some of the areas are examined more than once in the estimation procedure as shown in Table 3. When the nearby PMUs do not detect the fault, the fault distance from Sinoxchun 3S to each PMU in Table 3 is set to 0 as the fault distance is not calculated. The number 104 km of the order 3 and 4 in Table 3 means the distance from Sinoxchun 3S that distinguishes the area No. 106 from the area No. 146.

Table 2 Calculation of fault distance between Sinoxchun 3S and its neighbor PMUs

Neighbor PMU	Distance from Sinoxchun 3S (km)	Fault detection time	Fault distance from the Sinoxchun 3S to the neighbor PMU (km)
Seodaegu 3	l_{18_1}= 116.36	t_{18_1}	$L_{18_1} = \frac{l_{18_1}+c(t_{18}-t_{18_1})}{2}$
Singwangju 3	l_{18_2}= 156.20	t_{18_2}	$L_{18_2} = \frac{l_{18_2}+c(t_{18}-t_{18_2})}{2}$
Uiryeong 3	l_{18_3}= 161.42	t_{18_3}	$L_{18_3} = \frac{l_{18_3}+c(t_{18}-t_{18_3})}{2}$
Asan 3	l_{18_4}= 177.85	t_{18_4}	$L_{18_4} = \frac{l_{18_4}+c(t_{18}-t_{18_4})}{2}$
Chungyang 3	l_{18_5}= 183.18	t_{18_5}	$L_{18_5} = \frac{l_{18_5}+c(t_{18}-t_{18_5})}{2}$
Dongseoul 3	l_{18_6}=187.73	t_{18_6}	$L_{18_6} = \frac{l_{18_6}+c(t_{18}-t_{18_6})}{2}$
Singimje 3	l_{18_7}= 192.30	t_{18_7}	$L_{18_7} = \frac{l_{18_7}+c(t_{18}-t_{18_7})}{2}$
Dangjin TP7	l_{18_8}= 280.00	t_{18_8}	$L_{18_8} = \frac{l_{18_8}+c(t_{18}-t_{18_8})}{2}$

Table 3 Procedure of fault area estimation when the fault is firstly detected at Sinoxchun 3S

Order	Area no.	Area name	Fault distance from the Sinoxchun 3S to the neighbor PMU (km)
1	107	Sinoxchun 3S	In case that L_{18_1} and L_{18_8} are not calculated
2	112	Boryung T/P 3S Boryung C/C 3	$(0 < L_{18_4})$ and $(0 < L_{18_5})$
3	106	Sinjinchun 3 Chungwon 3 Ansung 3	$(0 < L_{18_8} < 104)$ and $(0 < L_{18_6})$
4	146	765 kV line between Sinansung and Singapyung	$(104 \le L_{18_8})$ or $(0 < L_{18_6})$
5	141	Sinoxchun 3S–Seodaegu 3	$0 < L_{18_1}$
6	122	Sinnamwon 3 area (Gwangju–Namwon–Oxchun)	$(104 \le L_{18_8})$ or $(0 < L_{18_6})$
7	112	Boryung T/P 3S Boryung C/C 3	$0 < L_{18_4}$
8	116	Singyeryong 3 Sinoxchun 3	$0 < L_{18_5}$
9	113	Boryung T/P 3 Chungyang S Gunsan 3	$0 < L_{18_7}$
10	107	Sinoxchun 3S	All previous conditions are not satisfied

3 Simulation and discussions

In this section, the modeling of Korean nationwide power transmission system in using EMTP-RV and the various simulations are discussed. The system parameters used in modeling are based on the real system data in PSS/E files provided by KEPCO and KPX [23–25].

3.1 Modeling of wide area transmission system in Korea

3.1.1 *Target network*

The nominal voltages of the power transmission system in Korea are composed of 154, 345, and 765 kV. The target network considered in this paper includes 345 and 765 kV transmission lines as shown in Fig. 7 [24, 25]. The transmission lines of 154 kV are treated as loads.

The total load is 54,647 MVA (The active power is 54,300 MW and the reactive power is 6150 Mvar). The total generation is 57,001 MVA (55,070 MW and 14,713 Mvar) and the loss of transmission lines over 154 kV transmission system is about 2%.

3.1.2 *Modeling of generator*

The target power transmission system has 159 generator units in total. Among them, 98 units are modeled with the full real data of KEPCO, while the other 61 units are missing some or all of their data, because some parts of the system were constructed many years ago. Therefore, four units of the Gwangyang Gas Turbines (G/T) and Unit 3 of the Gori Nuclear Power plant (N/P) are modeled using the data of other exciter and governor in their power plant complexes, respectively.

Eight units of the Seoinchun G/T are modeled with only generator and exciter data. Two units of the Cheongsong Power Plant (P/P), Units 1–4 of the Uljin N/P, Units 3 and 4 of the Yonggwang N/P, and two units of the Sancheong P/P are modeled only with generator and governor data. Units 1 and 2 of the Inchun G/T, six units of the POSCO Combined Combustion (C/C), the Pyungtaig C/C and nine units of the Thermal Power plants (T/P), four units of the the Yangyang P/P, Units 5 and 6 of the Uljin N/P, two units of the Yosu T/P, Units 1 and 2 of the Gori N/P, and nine units of the Ulsan C/C and T/P are modeled only with generator data. Finally, Units 3 and 4 of the Inchun T/P are modeled with the data of Unit 2 of the Yongnam T/P, which has similar characteristics

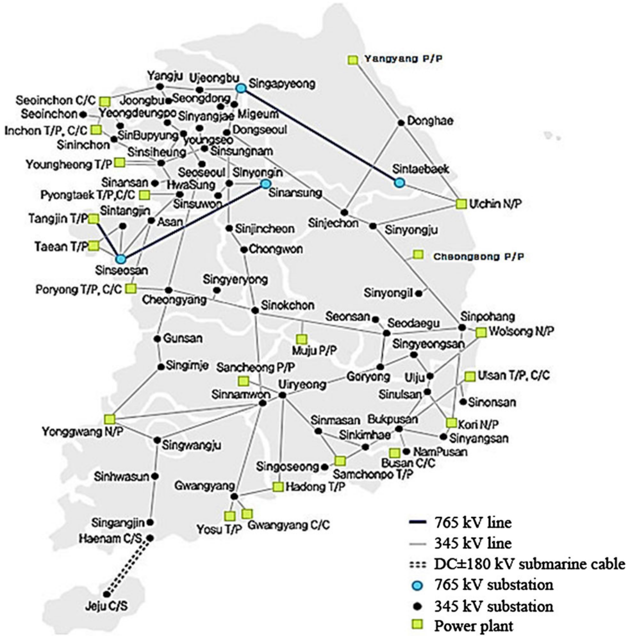

Fig. 7 345 kV and 765 kV Korean power transmission system

3.1.3 *Modeling of transformer*

450 transformers which include the main transformers and generator's step-up transformers are modeled. Based on the built-in transformer model in EMTP-RV, the necessary data such as the nominal voltage, capacity, frequency, and equivalent impedance are inputted. The tap positions are set to comply with the operating condition of the summer peak season according to the load flow data of the PSS/E.

3.1.4 *Modeling of transmission line*

The simulation time step is set to 13.88 μs to see the impact of fault propagation. The current signal travels 4.17 km per one time step. Therefore, the constant parameter (CP) model is applied to transmission lines longer than 10 km, even though CP models are generally applied to transmission lines longer than 100 km. On the other hand, the lines shorter than 10 km are modeled with the π model.

3.1.5 *Modeling of loads*

The static load model is used with steady-state load flow data such as the active power, reactive power, and voltages acquired by PSS/E simulations. Synchronized phasor angles of generators are also obtained from the load flow data of PSS/E, but they must be adjusted somewhat to make the system stable.

3.1.6 *Modeling and validation of wide area transmission system*

Figure 8 shows the wide area transmission system of Korea modeled by using EMTP-RV. The simulations are performed in steady state during 10 sec in order to validate the performance of the modeled network. The power system frequency of modeled transmission system is measured at nine buses: Dongseoul No. 1, Sinsiheung No. 3, Asan No. 3, Sinjechun No. 3, Chungyang No. 3, Seodaegu No. 3, Uiryung No. 3, Singoangju No. 3 and Bukbusan No. 3s.

Figure 9 shows the measured frequency range in the modeled network. The lowest frequency is 59.9931 Hz at the Uiryung No. 3, and the highest frequency is 60.0002 Hz at the Seodaegu No. 3. As a range of measured frequencies varies within less than 0.01 Hz, the modeled transmission network operates in a stable state.

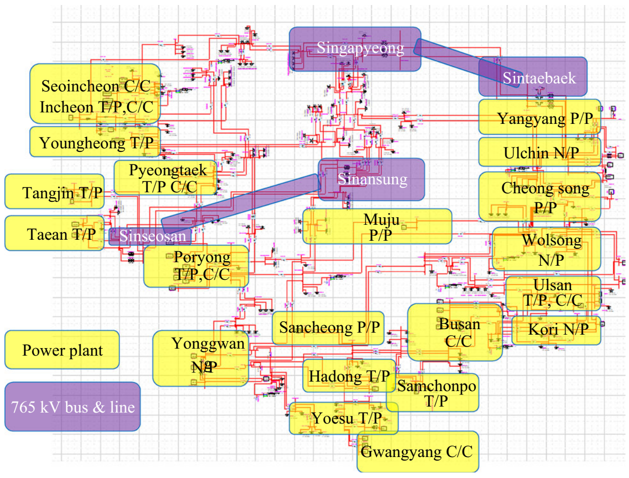

Fig. 8 Wide area power transmission system modeled by EMTP-RV

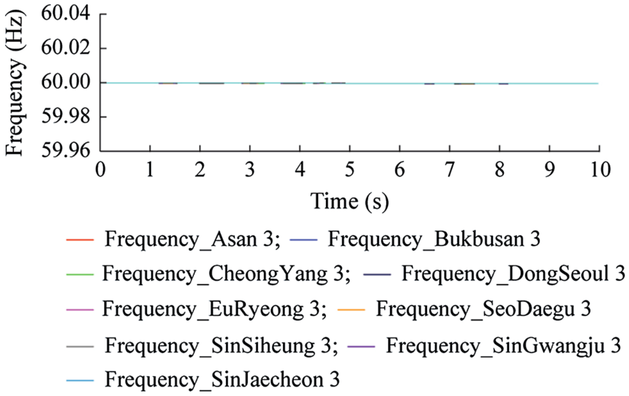

Fig. 9 Measured frequencies in the modeled system

Table 4 compares the measured voltages and the original PSS/E data. The average difference between two sets of voltages is 0.71%. From these results, it can be concluded that the wide area transmission system of Korea is well modeled.

3.2 Simulation results

As an example of fault area estimation, this paper presents the simulation results when the Double Line to Ground (DLG) fault with the fault resistance of 60 Ω at 0.502 sec occurs between the bus Chungwon 3 and the bus Sinjinchun 3. The exact fault area is 17.03 km from bus Chungwon 3 and 15 km from bus Sinjinchun 3.

Figure 10 shows the verification result of the proposed algorithm when DLG fault occurs between bus Chungwon 3 and bus Sinjinchun 3. As shown in Fig. 10, the fault area is being estimated by algorithm during 0.00356 sec from the fault time 0.502 sec and then the accurate fault area No. 106 is identified at 0.50556 sec. This shows that the algorithm can rapidly identify the exact fault area after the fault inception.

Table 4 Voltage difference between the modeled network and original data

Area name	Measured voltage (p.u.)	PSS/E voltage (p.u.)	Difference (%)
Boryung TP3	1.0282	1.0308	−0.25
Boryung TP3S	1.0273	1.0301	−0.27
Boryung CC3	1.0282	1.0308	−0.25
Boryung TP78	1.0213	1.0234	−0.21
Cheongsong PP	1.0325	1.0331	−0.05
Dangjin TP3	1.0084	1.0045	0.39
Dangjin TP7	1.0012	1.0017	−0.05
Gori #1	1.0237	1.0246	−0.09
Gori #2	1.0298	1.0276	0.21
Goangyang CC	1.0458	1.0323	1.3
Hadong TP3	1.0388	1.0322	0.64
Hadong TP3S	1.0389	1.0287	0.99
Inchun TP3S	1.0417	1.0314	1
InchunTP3	1.0393	1.0335	0.56
Mooju PP	1.0278	1.032	−0.41
Seobusan 3	1.0414	1.0321	0.9
Pyungtaig TP3	1.0155	1.0159	−0.04
Sanchung PP	1.0288	1.0241	0.46
Samchunpo TP	1.0216	1.0207	0.08
Seoinchun CC	1.0414	1.0309	1.02
Sininchun CC	1.0448	1.034	1.04
Taian TP3	1.0241	1.0343	−0.98
Taian TP3S	1.0231	1.034	−1.05
Uljin #1	1.0105	1.0316	−2.04
Uljin #2	1.0102	1.0314	−2.06
Uljin #3	1.0099	1.0332	−2.25
Ulsan TP	1.0342	1.0348	−0.06
Wolsung NP3	1.0215	1.0227	−0.12
Wolsung NP3S	1.0169	1.0234	−0.63
Yosu TP1	1.0179	1.0364	−1.79
Yangyang PP	1.0475	1.0306	1.64
Yeonggwang NP#1	1.0235	1.0295	−0.59
Yonggwang NP#2	1.0236	1.0297	−0.6
Yonggwang NP#3	1.0237	1.0311	−0.72
Yeongheong TP3	1.024	1.0251	−0.11
Average Difference (%)	0.71		

100 cases of faults are tested to verify the performance of the proposed algorithm: 1) 63 cases of line faults, including single-line-to-ground, double-line-to-ground, three-phase short, and double-line short; 2) 22 cases of generator trip, with the range of generation between 510–2400 MVA; 3) 15 cases of load shedding, with the

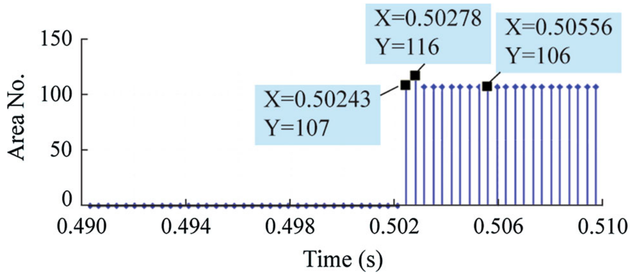

Fig. 10 Fault area when DLG fault occurs between Chungwon 3 bus and Sinjinchun 3 bus

Table 5 Simulation conditions and results

Fault type	Number of cases	Number of fault area estimation cases		
		Success	Marginal success	Fail
Line fault	63	52	7	4
Generator trip	22	17	2	3
Load shedding	15	8	5	2
Total	100	77	14	9

Note Success rate (including success and marginal success) = 91%

range of load between 210–360 MVA. The simulation conditions and results are presented in Table 5. The possibility of failure in the fault area estimation is just 9%. From these results, it can be seen that the proposed algorithm does not work well with small amounts of load shedding because they are too small to be observed in the power system. However, a larger amount of load shedding can be detected enough by the proposed algorithm.

The reasons of failures are considered as that the level of the sampling frequency of the travelling wave system, the influence of reflection /refraction of the traveling wave and the characteristics of the power transmission network. Optimizing the sampling frequency level and number of PMU are considered as the ways to improve the success rate of fault area estimation.

4 Conclusions

In this paper, the modeling of the 345 and 765 kV Korean nationwide power transmission system using EMTP-RV has been described based on real data in PSS/E files provided by KEPCO and KPX. To estimate the accurate fault area, the technique based on traveling wave is suggested. The proposed algorithm not only applies traveling wave theory and but also considers the application of PMUs and the concept of DOU. Based on the above contents, the verification of fault area estimation technique is conducted under various simulation conditions. As a result, the accuracy of fault area estimation tends to be very high (91%) for the all cases considered in this study. If the greater number of PMUs is installed in modeled system, the accuracy of fault area estimation will increase greatly. In addition, the reduction of the tolerance range in application of travelling wave theory will help to improve the performance of proposed algorithm.

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