

A Study on Frequency Monitoring System for Korean Wide-Area Power Protection based on Virtual FDR

Kwang-Ho Seok¹, Junho Ko¹, Chul-Won Park² and Yoon Sang Kim¹

¹*Department of Computer Science and Engineering, Korea University of Technology and Education, Cheonan, Korea*

²*Department of Electrical Engineering, Gangneung-Wonju University, Wonju, Korea
yoonsang@kut.ac.kr*

Abstract

This paper presents a frequency monitoring system for Korean wide-area power protection based on virtual FDR. The virtual FDR is introduced to enhance the simulation capability of frequency monitoring systems and consists of three parts: modeling, estimation, and simulation. Once a power grid model is obtained in the virtual FDR based on EMTP-RV, the frequency is estimated by DFT filtering and gain compensation based on real and imaginary filtering. Various disturbances and conditions are simulated using the data from the power grid model. The proposed FDR allows the monitoring system to display simulated disturbances and data, including voltages, currents, and frequencies. Various simulation results were given to show of the effectiveness of the proposed frequency monitoring system based on the virtual FDR.

Keywords: *frequency monitoring, wide-area protection, virtual FDR*

1. Introduction

Time-synchronized frequency estimation methods for GPS (global positioning system)-based frequency monitoring networks (FNETs) and phasor measurement units (PMUs) have recently been introduced. In the 1980s, researchers began studies on the frequency disturbance recorder (FDR), power system disturbance monitor (PSDM), and phasor measurement unit (PMU) based on GPS to prevent wide-area blackouts and to monitor, analyze, and control wide-area power grids [1-7]. In the United States, FNET has been constructed and is being operated by the Electric Power Research Institute, the Tennessee Valley Authority (TVA), and the IT Research Center at Virginia Tech University [8-10]. The FNET uses FDR to measure power system frequencies in more than 40 regions across the U.S. in real time. The measurements are synchronized by GPS and transmitted over the Internet to the central server.

In Korea, the Korea-Wide Area Measurement System (K-WAMS), developed by Korea Electrotechnology Research Institute (KERI), KEPCO KDN, and LS Industrial Systems, is currently in trial operation. K-WAMS monitors and evaluates wide-area power grids using the synchro-phasor of the voltages and currents measured by the intelligent power system information unit (I-PIU). However, it is believed that FNET should be applied for examining the dynamic characteristics of power grids during transient states and failures, since FNET can readily compile data from power grids to monitor frequencies and frequency deviations [11].

It is difficult to simulate various conditions and predict failures using conventional frequency monitoring, which merely displays required data and does not provide a general power grid model. To enhance simulation capability, this paper proposes a virtual FDR to complement the conventional monitoring system. The proposed virtual FDR is composed of three parts: modeling, estimation, and simulation. Modeling generates the virtual power grid model that replaces the real grid model. Estimation involves estimating frequencies from modeled data through DFT filtering and gain compensation using real and imaginary filtering based on our previous result in [12]. The third part is virtual simulation of various disturbances using the data from the virtual grid model when the real power grid is difficult to be linked. Various conditions (including generator rejection, load rejection, high impedance single line-to-ground fault, single line-to-ground fault, double line-to-ground fault, and triple line-to-ground fault) are simulated and studied to validate the proposed monitoring system based on the virtual FDR.

2. Proposed Frequency Monitoring System based on Virtual FDR

It is difficult to simulate various conditions and predict failures using frequency monitoring, which merely displays required data and does not provide a general power grid model. To enhance the simulation capability of frequency monitoring under various conditions, this paper introduces and proposed the concept of “virtual FDR” shown in Figure 1.

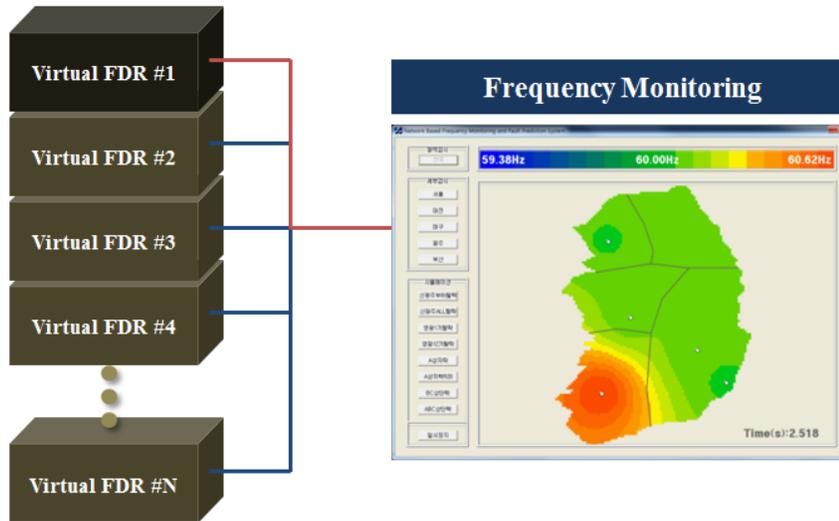


Figure 1. Frequency Monitoring System with Virtual FDR

2.1. Modeling

Modeling generates the virtual power grid model. In order to compile objective and reliable data, we used the EMTP-RV transient phenomenon analytical tool to model a 345 kV power grid in South Korea. We studied and modeled the generators and controllers installed in the grid to analyze their frequency characteristics. The power grid is modeled based on the data from the PSS/E program using EMTP-RV, as shown

in Figure 2. The 345 kV model consists of 154 generators that generate 57,654.76 MVA of power. The data acquired from the EMTP-RV is used in the virtual FDR.

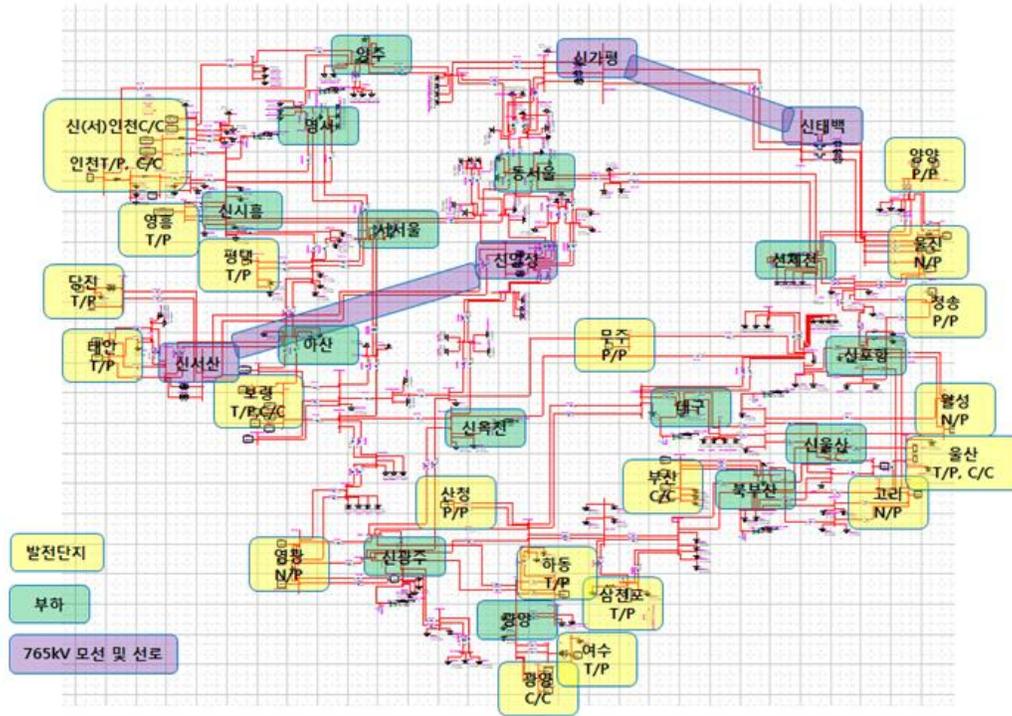


Figure 2. 345 kV Power Grid Model

2.2. Estimation

This part of the virtual FDR estimates the frequency from the modeled data. Most conventional techniques for measuring frequency and estimating frequency deviation require digital filtering and preprocessing. In addition, a trade-off between accuracy and calculation speed must be taken into account for real-time implementation. A frequency estimation algorithm must be able to measure not only regular frequencies under a normal state, but also irregular frequencies under transient states such as failures and load variations. However, widely-used frequency estimation techniques based on DFT filters are not capable of accurately measuring frequencies when they monotonically increase/decrease or transform into sinusoidal waves, creating estimation errors. In other words, frequency variation causes gain error, which undermines the accuracy of frequency estimation [13-17]. The frequency estimation algorithm we had previously proposed [12] was used for frequency estimation in the virtual FDR. By incorporating gain compensation of real and imaginary filters during frequency variation, the frequency estimation algorithm can improve accuracy and thus allow real-time implementation of conventional frequency estimation techniques based on DFT filters.

If we assume that deviation of occurred in the sinusoidal input with a regular frequency of 60 Hz, the input signal with deviated frequency can be written as Equation (1) [18 ~ 20].

$$V(t) = A \sin(2\pi(f + \Delta f)t + \theta) \quad (1)$$

Figure 3 displays the frequency response of the DFT filter for extracting the fundamental frequency. As it can be seen in Figure 3, the real and image parts obtained from the DFT filter during frequency variation include gain error, and the equation for calculating frequency estimation using DFT filter must be modified.

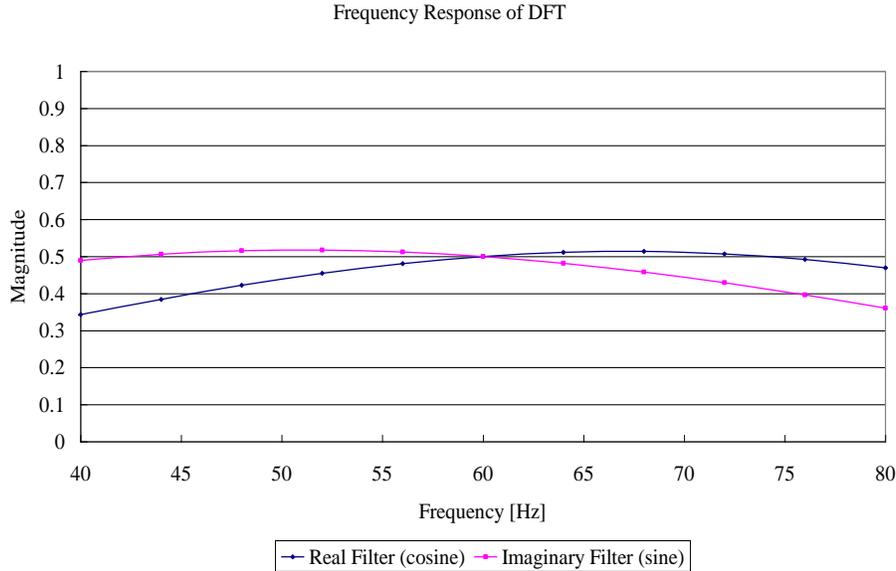


Figure 3. Frequency Response of DFT Filter

Equation (2) is the frequency response using the DFT digital filter, and its imaginary part filter is expressed as Equation (3). n is the number of sampling per period.

$$H(Z) = \sum_{k=0}^{n-1} V_k Z^{-k} \quad (2)$$

$$H_s(k) = \sin\left(\frac{2\pi k}{N} + \frac{\pi}{N}\right) \quad (3)$$

Multiplying Equation (3) and, the output of the imaginary part filter can be expressed as Equation (4).

$$H_s(k) = V(k) \sin\left(\frac{2\pi k}{N}\right) \cos\left(\frac{\pi}{N}\right) + V(k) \cos\left(\frac{2\pi k}{N}\right) \sin\left(\frac{\pi}{N}\right) \quad (4)$$

Performing Z-conversion of Equation (4) in the frequency domain yields Equation (5).

$$H_s(z) = \frac{1}{2} \sin\left(\frac{\pi}{N}\right) [V(ze^{\Omega_0}) - V(ze^{-\Omega_0})] + j \frac{1}{2} \cos\left(\frac{\pi}{N}\right) [V(ze^{\Omega_0}) + V(ze^{-\Omega_0})] \quad (5)$$

Where $V(z) = \frac{z - z^{-(N-1)}}{z + 1}$, $\Omega_0 = \frac{2\pi f_0}{f_s}$, and f_0 and f_s represent system and sampling frequencies, respectively. Rearranging $V(z)$ Equation (3) can be written as Equation (6).

$$H_s(z) = \frac{\sin\left(\frac{\Omega_0}{2}\right)(1 - z^{-N})(z + 1)}{z - 2 \cos \Omega_0 + z^{-1}} \quad (6)$$

Substituting $z = re^{j\Omega}$ ($r = 1$) into Equation (6), we obtain Equation (7).

$$H_s(e^{j\Omega}) = \frac{j2e^{-j\Omega(N-1)/2} \sin(\Omega_0/2) \sin(N\Omega/2) \cos(\Omega/2)}{\cos \Omega - \cos \Omega_0} \quad (7)$$

Repeating the processes of the imaginary part filter, the real part filter can be expressed as Equation (8).

$$H_c(e^{j\Omega}) = \frac{-2e^{-j\Omega(N-1)/2} \cos(\Omega_0/2) \sin(N\Omega/2) \sin(\Omega/2)}{\cos \Omega - \cos \Omega_0} \quad (8)$$

Substituting $\Omega = 2\pi f / f_s$, magnitudes of the compensated responses can be written as Equations (9) and (10).

$$|H_s(f)| = \frac{2 \sin(\pi f_0 / f_s) \sin(\pi N f / f_s) \cos(\pi f / f_s)}{\cos(2\pi f / f_s) - \cos(2\pi f_0 / f_s)} \quad (9)$$

$$|H_c(f)| = \frac{2 \cos(\pi f_0 / f_s) \sin(\pi N f / f_s) \sin(\pi f / f_s)}{\cos(2\pi f / f_s) - \cos(2\pi f_0 / f_s)} \quad (10)$$

The gain compensator of the DFT filter can be derived by performing Z-conversion of the sine and cosine filters and calculating the magnitudes and phases according to the frequency, resulting in Equations (11) and (12).

$$G_s(f) = T_0 [g(f - f_{sys}) - g(f + f_{sys})] / T \quad (11)$$

$$G_c(f) = T_0 [g(f - f_{sys}) - g(f + f_{sys})] / T \quad (12)$$

Where $|g(f)| = \frac{\sin(2\pi T_0)}{2\pi f T_0}$ and $T_0 = 0.5 / f_{sys}$.

2.3. Frequency Monitoring

Major parameters such as voltage, current, and frequency are presented in color graphs for monitoring. Examples of wide-area frequency and local-area power grid data monitoring are shown in Figure 4 and Figure 5, respectively. Regional frequency stabilities are indicated by colors on a 2-dimensional map, allowing the operator to monitor the overall status of power grids and any failure being propagated.

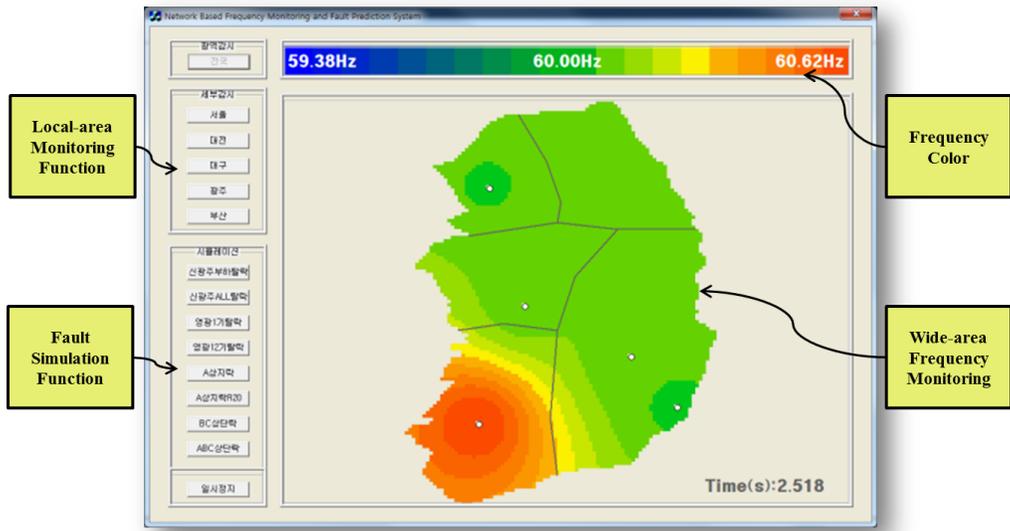


Figure 4. Wide-area Frequency Monitoring

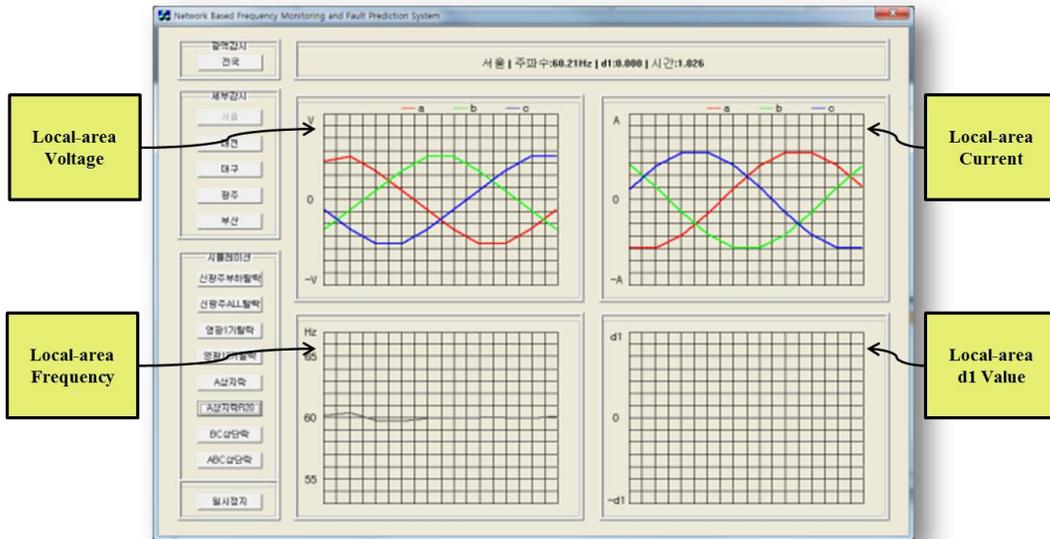


Figure 5. Local-area Power Grid Data Monitoring

Figure 5 shows the power grid data of a local area. Voltage, current, and frequency graphs are displayed to allow the operator to examine their variations in local areas.

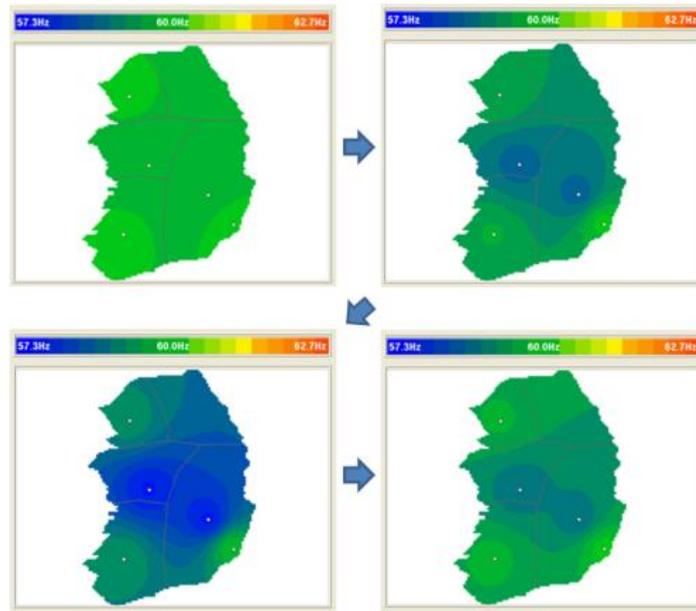


Figure 6. Example of Frequency Visualization

The fast frequency contour algorithm [21] is applied for frequency visualization, which can provide good visualization effects when there are a limited number of measurement devices. The fast frequency contour algorithm calculates the frequency by assigning weight factors based on the distance to the measurement device. Figure 6 displays an example of frequency visualization implemented by the fast frequency contour algorithm.

3. Simulation Results and Discussions

In this part of the virtual FDR, various disturbances are simulated in the virtual manner using the data from the virtual grid model when the real power grid is difficult to be linked. In order to simulate various disturbances and measure the corresponding parameters of the power grid, we hypothesized that FDRs are installed in five regions (Seoul, Daejeon, Gwangju, Daegu, and Busan) and collected data from each location. The selected regions are five major cities in South Korea that require analysis of effects from various forms of disturbance.

Once the power grid model based on EMTP-RV is obtained, the frequency is estimated through DFT filtering as well as gain compensation of real and imaginary filtering. Various disturbance conditions are simulated using the data from the power grid model. Finally, the virtual FDR transmits data into a monitoring system, displays simulated disturbances and data including voltages, currents, and frequencies. The virtual FDR performs three processes including the modeling, estimation and simulation.

The virtual FDR has a micro controller unit (MCU) and a GPS module. The MCU performs modeling, estimating, and simulation, and communicates with the server. The GPS module maintains time synchronization. Figure 7 and Figure 8 show the proposed

frequency monitoring system with the virtual FDR and a snapshot of the frequency monitoring system with virtual FDR embedded into one region.

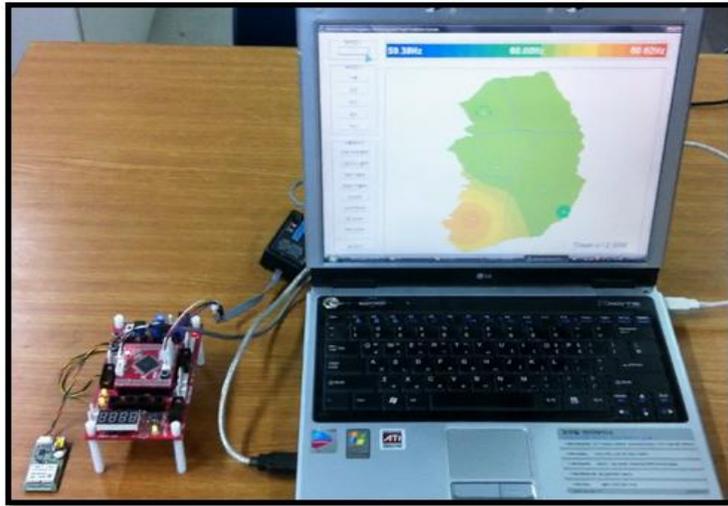


Figure 7. Monitoring with the Proposed Virtual FDR

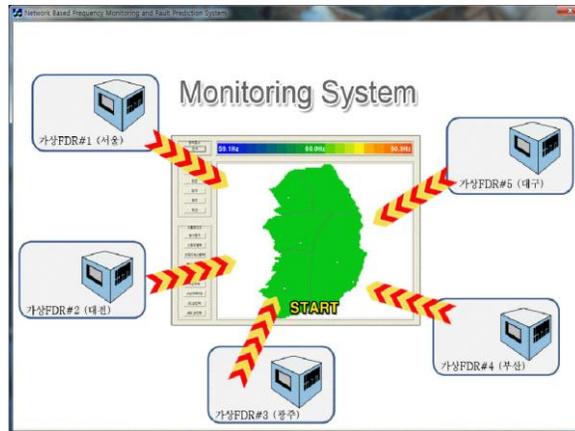


Figure 8. The Proposed Frequency Monitoring System with the Virtual FDR

By using the proposed monitoring system with virtual FDR, we studied simulation of various fault conditions as the followings:

- generator rejection,
- load rejection,
- high impedance single line-to-ground fault,
- single line-to-ground fault,
- double line-to-ground fault,
- triple line-to-ground fault

The following figures show frequency propagations that correspond to various fault conditions.

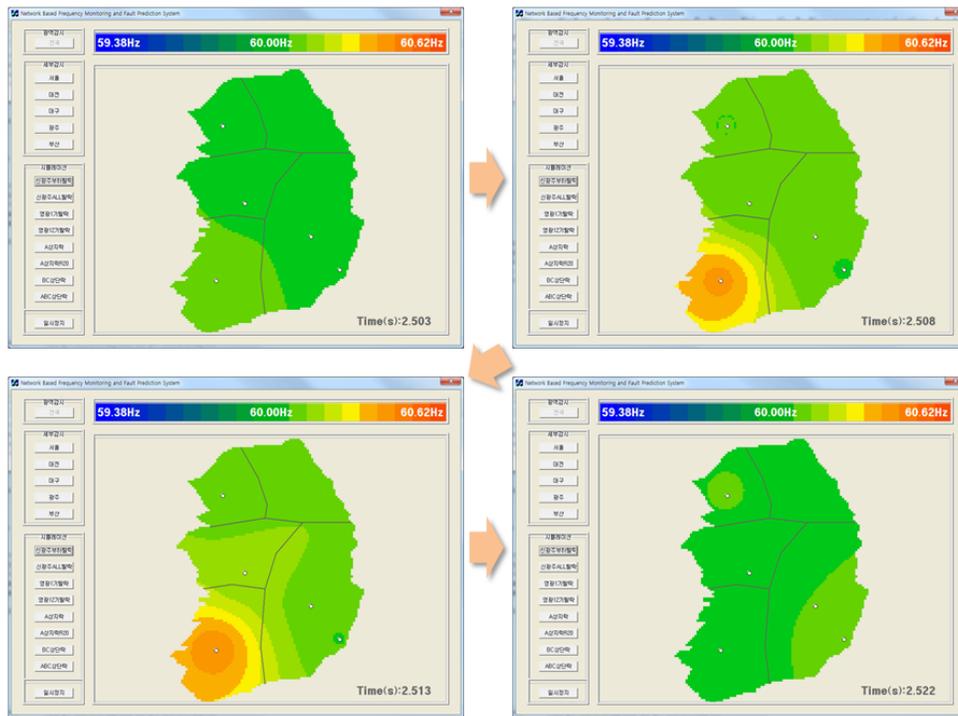


Figure 9. Simulation Result for 500mW load Rejection in Shinkwangju

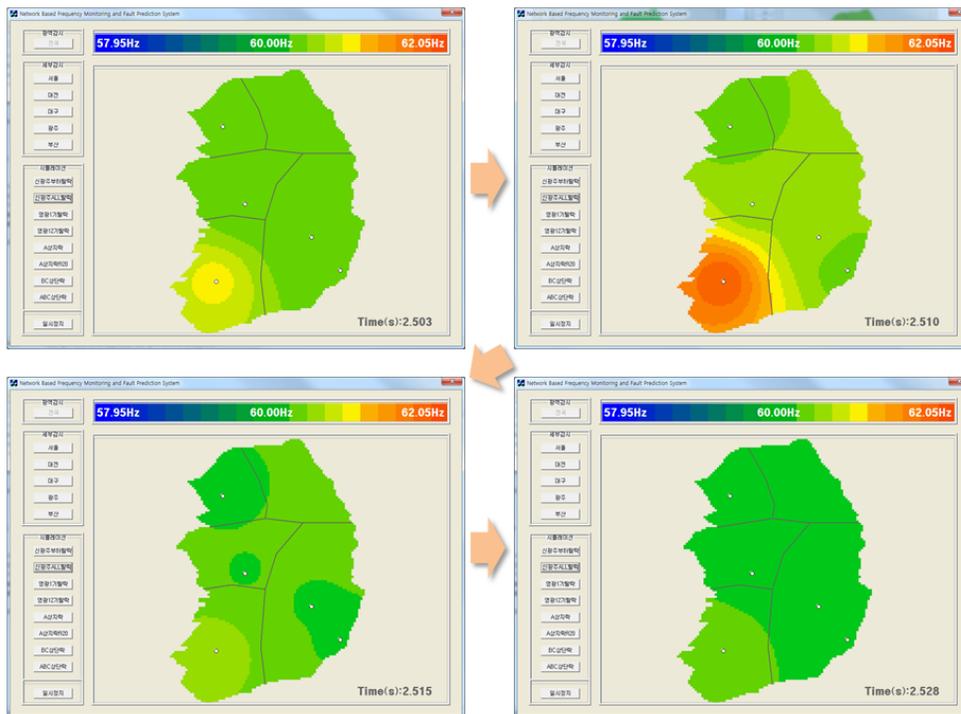


Figure 10. Simulation Result for Overall Load Rejection in Shinkwangju

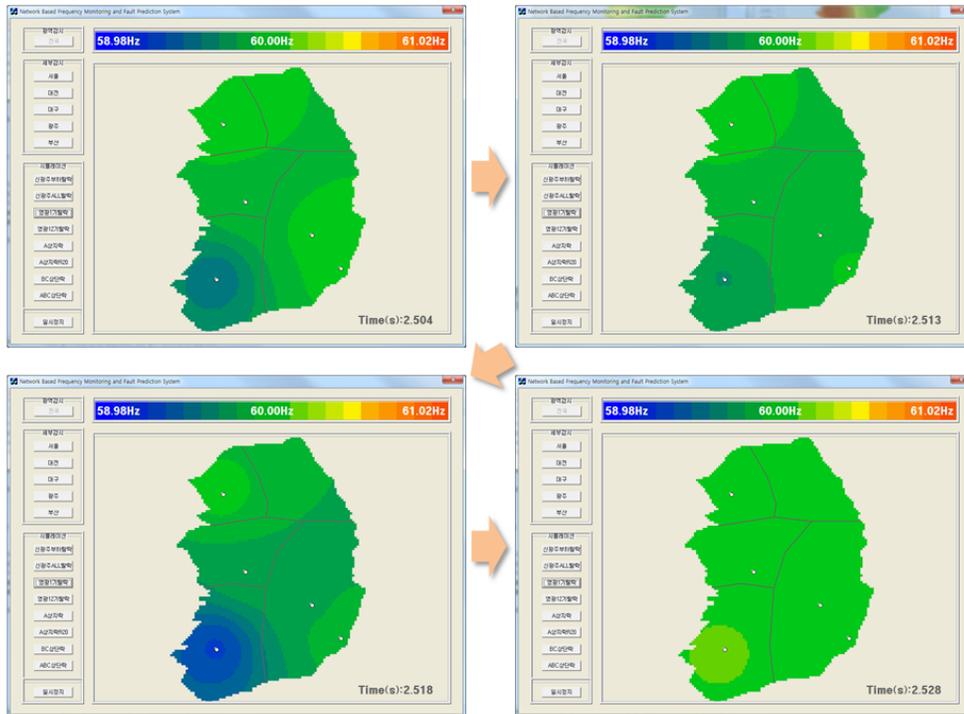


Figure 11. Simulation Result for Generator 1 Rejection in Yeonggwang

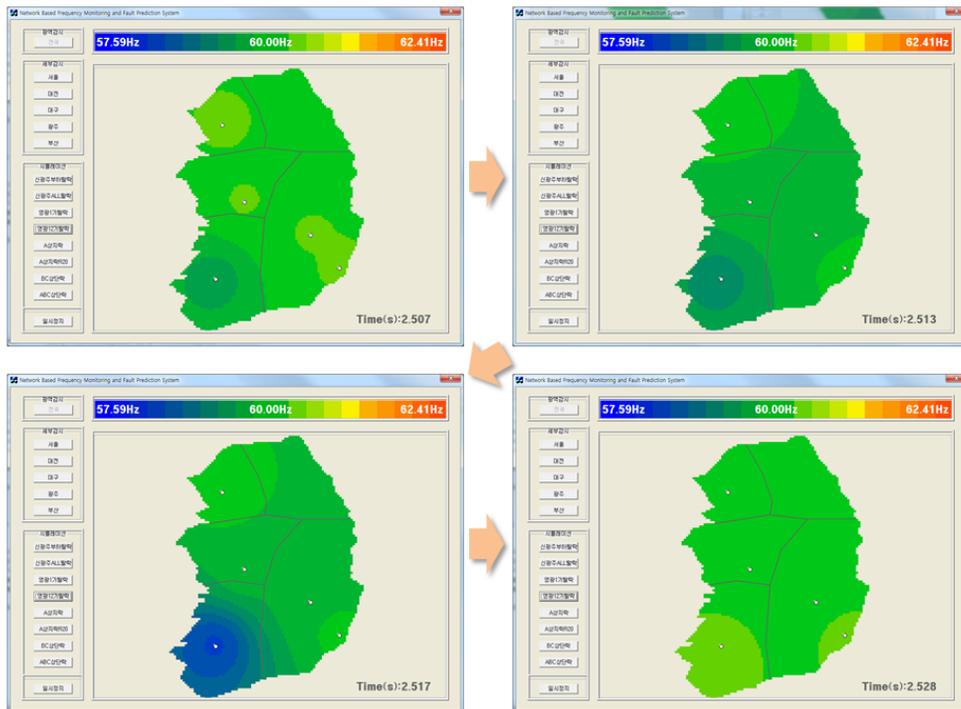


Figure 12. Simulation Result for Generator 1&2 Rejection in Yeonggwang

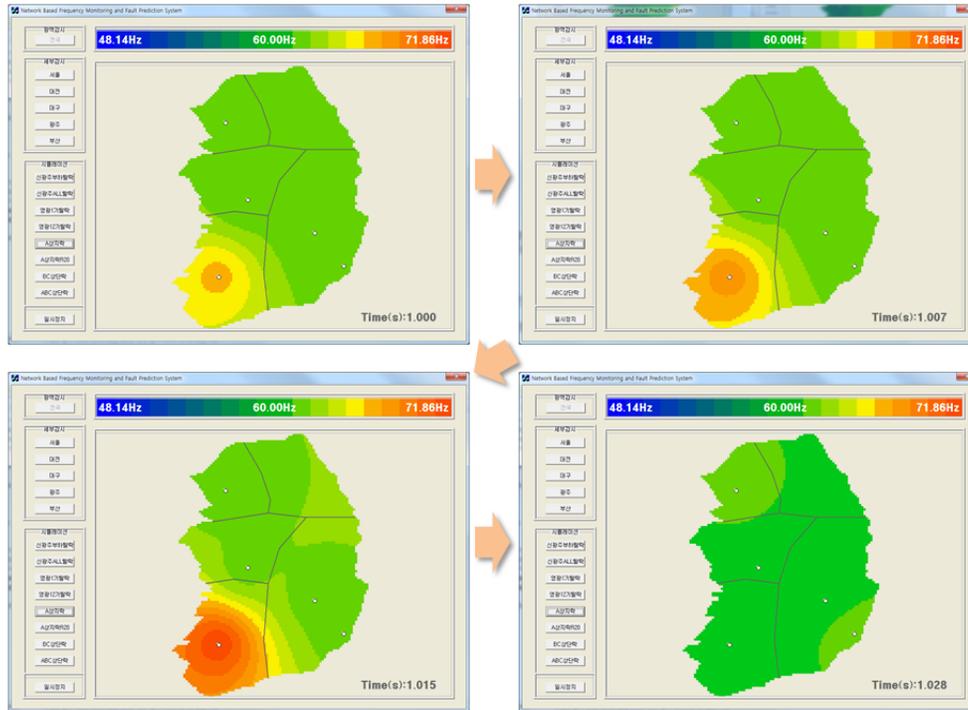


Figure 13. Simulation Result for Single Line-to-ground Fault between Yeonggwang and Shinkwangju

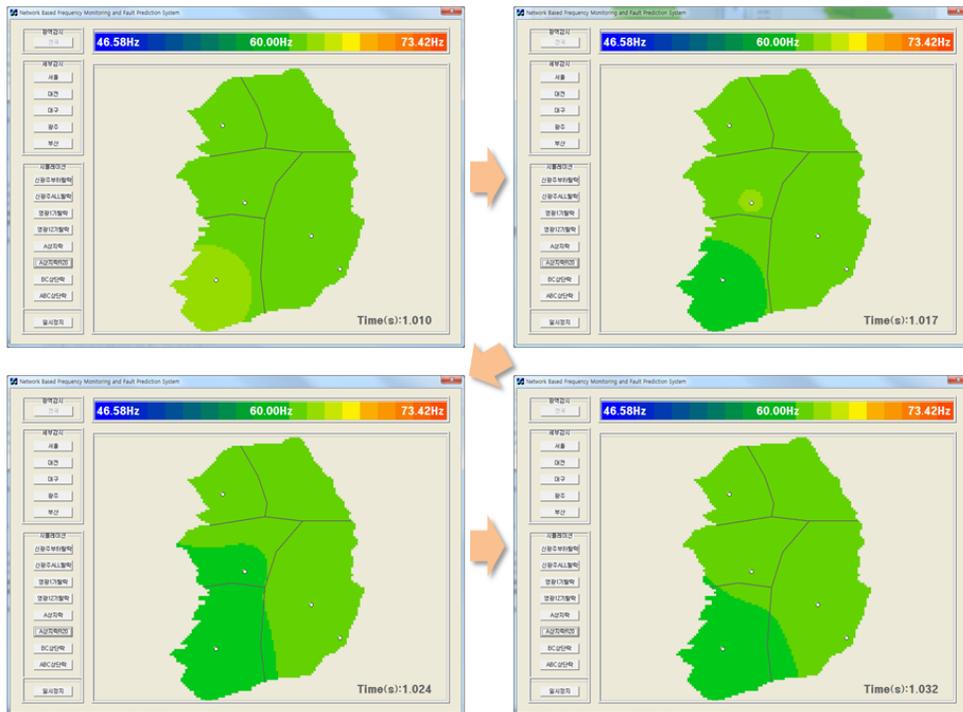


Figure 14. Simulation Result for High Impedance Single line-to-ground Fault between Yeonggwang and Shinkwangju

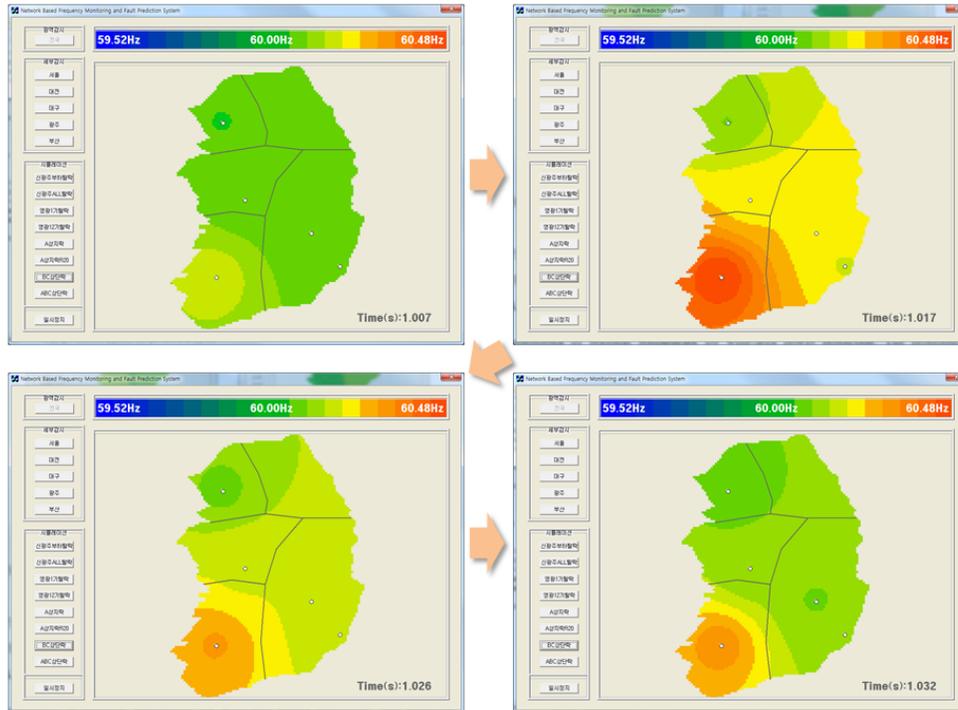


Figure 15. Simulation Result for Double line-to-ground Fault between Yeonggwang and Shinkwangju

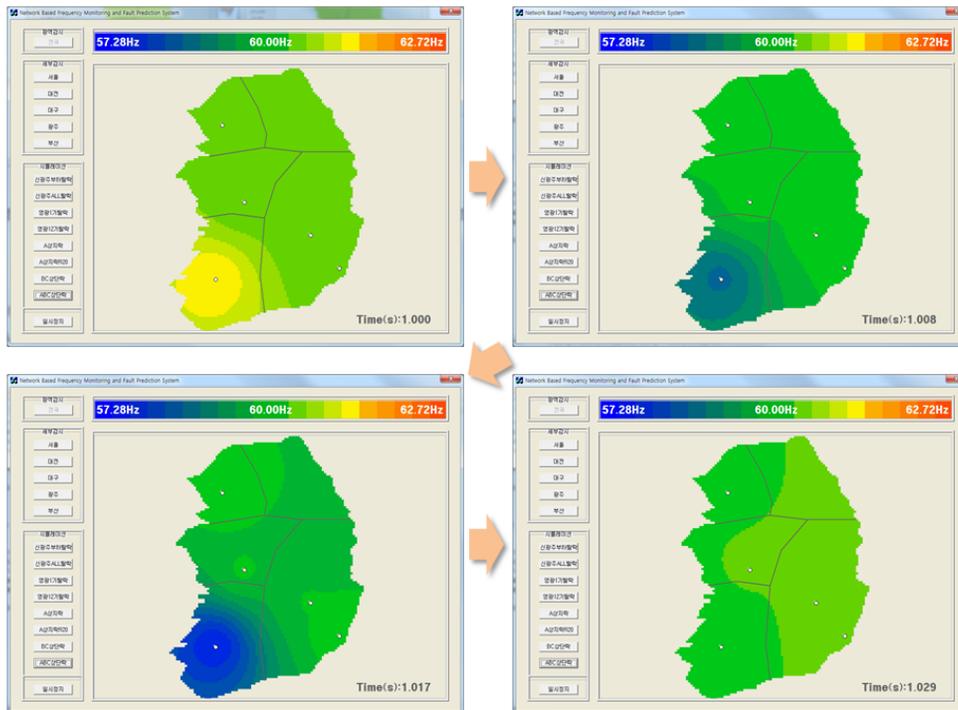


Figure 16. Simulation Result for Triple line-to-ground Fault between Yeonggwang and Shinkwangju

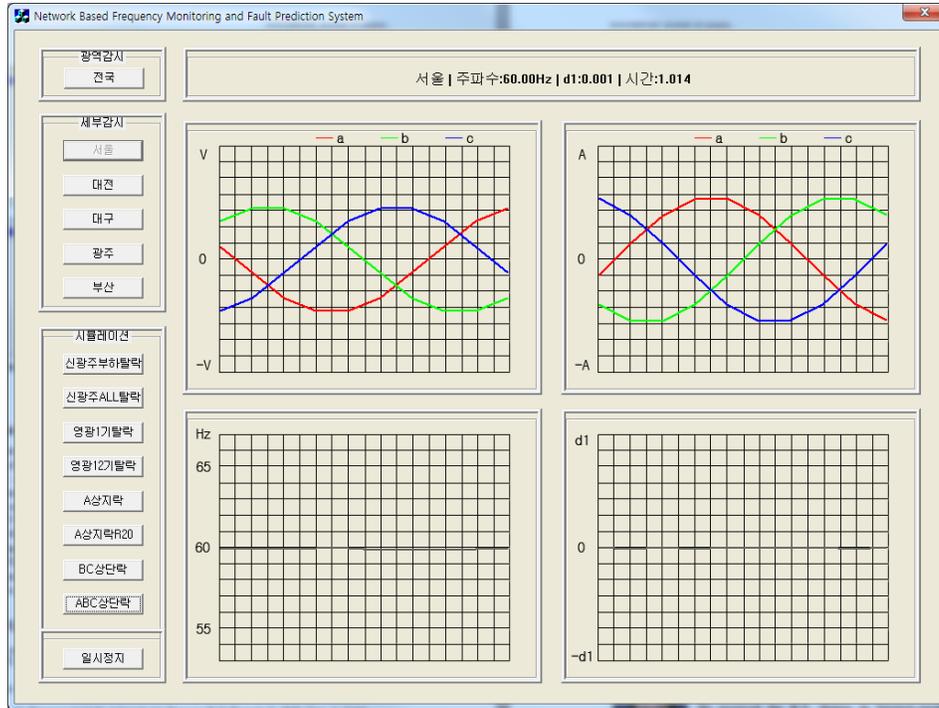


Figure 17. Simulation Result for Triple line-to-ground Fault between Yeonggwang and Shinkwangju (monitoring local area : Seoul)

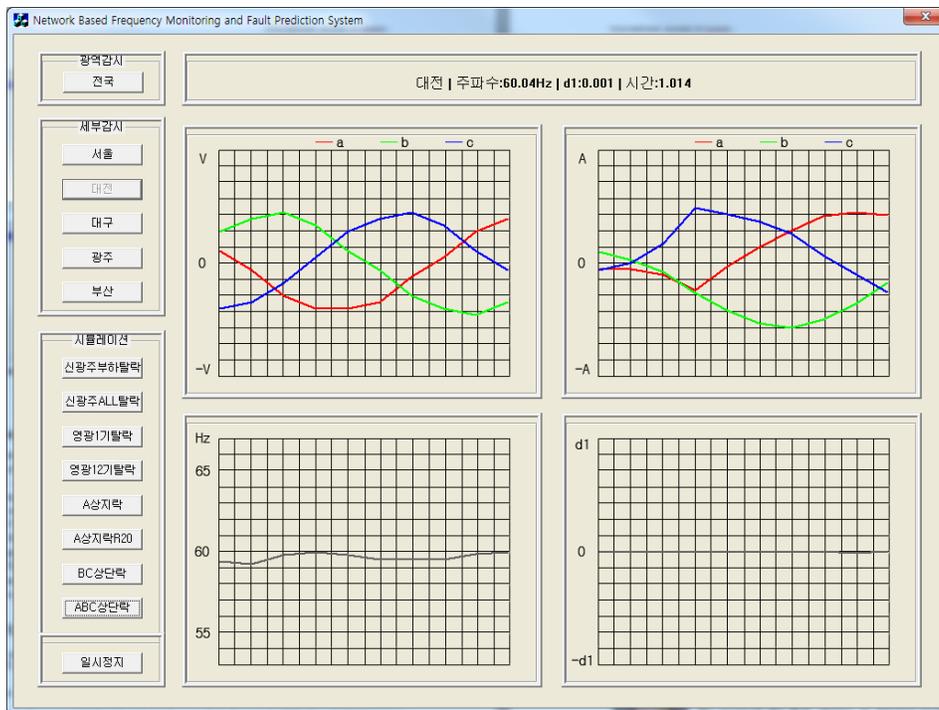


Figure 18. Simulation Result for Triple line-to-ground Fault between Yeonggwang and Shinkwangju (monitoring local area : Daejeon)

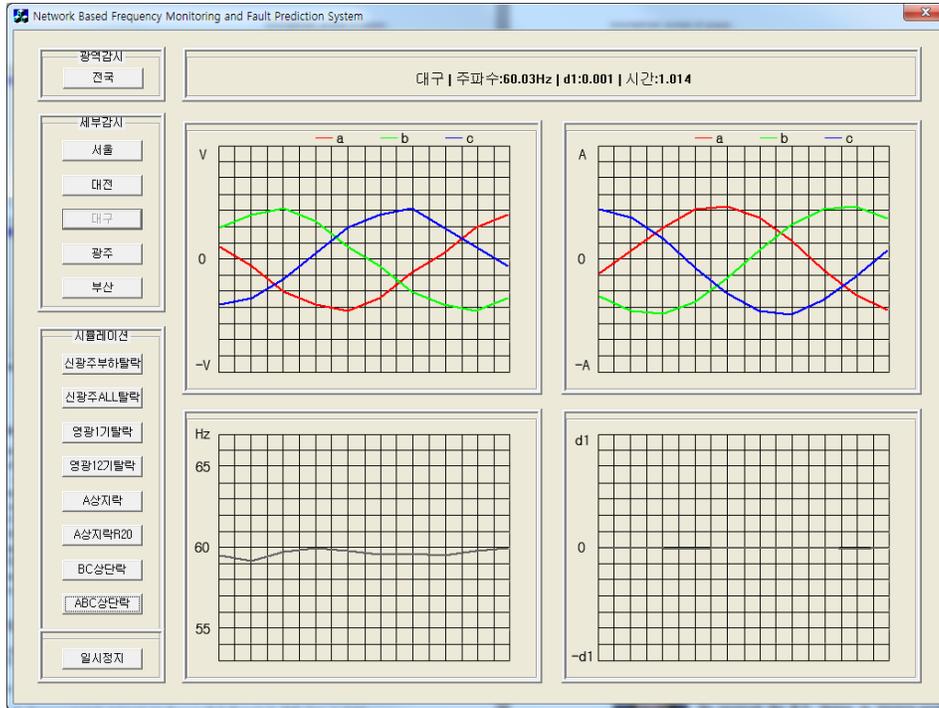


Figure 19. Simulation Result for Triple line-to-ground Fault between Yeonggwang and Shinkwangju (monitoring local area : Daegu)

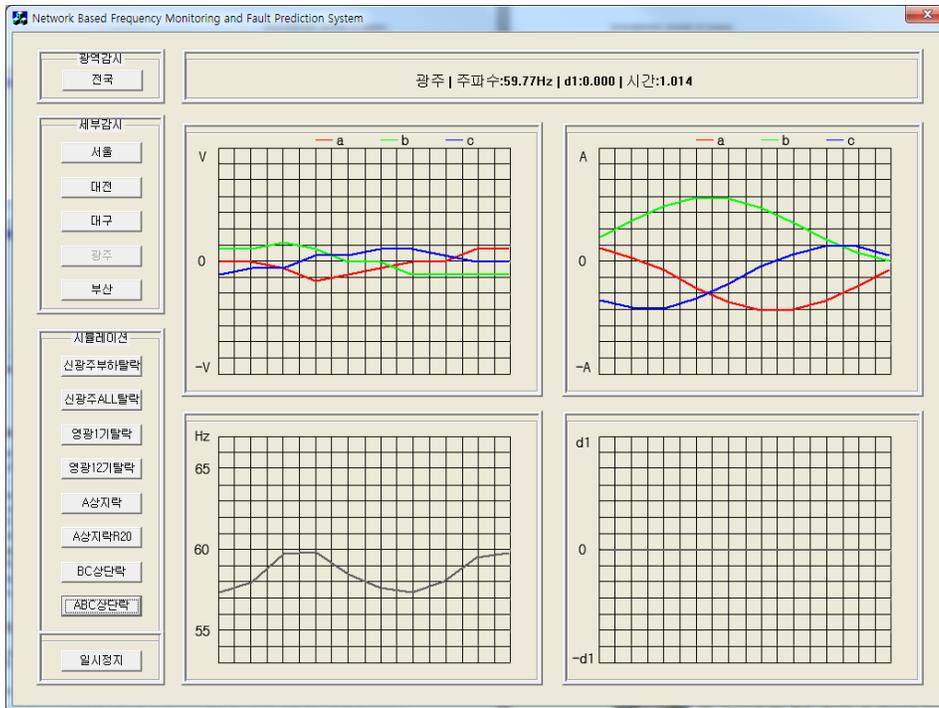


Figure 20. Simulation Result for Triple line-to-ground Fault between Yeonggwang and Shinkwangju (monitoring local area : Gwangju)

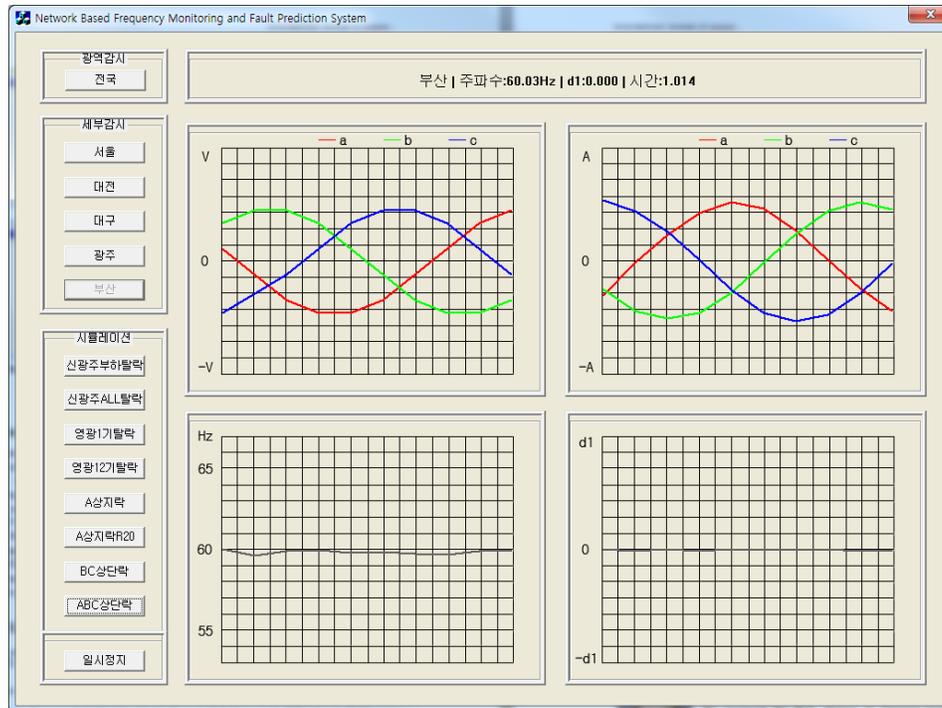


Figure 21. Simulation Result for Triple line-to-ground Fault between Yeonggwang and Shinkwangju (monitoring local area : Busan)

Figures (from 17 to 21) show the power grid data of a local area (Seoul, Daejeon, Gwangju, Daegu, and Busan). Voltage, current, and frequency graphs are displayed to allow the operator to examine their variations in local areas. Figures show simulation results in different monitoring region for triple line-to-ground fault between Yeonggwang and Shinkwangju.

4. Conclusions

By using virtual FDR, the proposed frequency monitoring system could enhance the simulation capability of conventional monitoring one. The proposed virtual FDR is composed of three parts: modeling, estimation, and simulation. A frequency monitoring system with the virtual FDR was implemented by modeling an actual 345 kV transmission system using EMTP-RV and by measuring voltages and currents in five regions in South Korea. The frequencies were estimated with a frequency estimation algorithm using gain compensation embedded in the virtual FDR. The virtual FDR allows the operator to view simulation processes under various fault conditions (such as generator rejection, load rejection, high impedance single line-to-ground fault, single line-to-ground fault, double line-to-ground fault, and triple line-to-ground fault).

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Authors



Kwang-Ho Seok

He received the B.S. degree in Internet-media engineering, from Korea University of Technology and Education (KUT), Korea, in 2007 and the M.S. degree in Information media engineering, from Korea University of Technology and Education (KUT), Korea, in 2009. Since 2009 to now, he has been Ph.D. student in Humane Interaction Lab (HILab), Korea University of Technology and Education (KUT), Cheonan, Korea. His current research interests include immersive virtual reality, human robot interaction, and power system.



Junho Ko

He received the B.S. degree in Internet-software engineering, from Korea University of Technology and Education (KUT), Korea, in 2009 and the M.S. degree in Information media engineering, from Korea University of Technology and Education (KUT), Korea, in 2011. Since 2011 to now, he has been Ph.D. student in Humane Interaction Lab (HILab), Korea University of Technology and Education (KUT), Cheonan, Korea. His research fields are artificial intelligence and vehicle interaction.



Chul-Won Park

He received the B.S., the M.S. and the Ph.D. degrees in electrical engineering from SungKyunKwan University, Seoul, Korea, in 1988, 1990 and 1996, respectively. From 1989 to 1993 he was an associate researcher at Lucky GoldStar Industrial Systems. From 1993 to 1996 he was a senior researcher at PROCOM system and lecturer at S.K.K. University. From 1997 to 2006 he was an Associate Professor at Wonju National College. He is currently a Professor in School of Electrical and Information Communication Engineering, Kangnung National University. His research interests include power IT, IED, power system modeling and control, and computer application to power system. He is a member of the KIEE.



Yoon Sang Kim

He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Sungkyunkwan University, Seoul, Korea, in 1993, 1995, and 1999, respectively. He was a Member of the Postdoctoral Research Staff of Korea Institute of Science and Technology (KIST), Seoul, Korea. He was also a Faculty Research Associate in the Department of Electrical Engineering, University of Washington, Seattle, USA. He was a Member of the Senior Research Staff, Samsung Advanced Institute of Technology (SAIT), Suwon, Korea.

Since March 2005, he has been an Associate Professor at the School of Computer and Science Engineering, Korea University of Technology Education (KUT), Cheonan, Korea. His current research interests include Virtual simulation, Power-IT technology, and device-based interactive application. Dr. Kim was awarded Korea Science and Engineering Foundation (KOSEF) Overseas Postdoctoral Fellow in 2000. He is a member of IEEE, IEICE, ICASE, KIPS and KIEE.