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고장 왜란 기록기를 위한 주파수 추정 기법의 비교 연구

Comparative Studies of Frequency Estimation Method for Fault Disturbance Recorder

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Abstract - Voltage and current phasor estimation has been executed by GPS-based synchronized PMU, which has become an important way of wide-area blackout protection for the prevention of expending faults in a power system. The PMU technique can not easily get the field data and it is impossible to share information, so that there has been used a FNET(Frequency Monitoring Network) method for the wide-area intelligent protection in USA. It consists of FDR(Fault Disturbance Recorder) and IMS(Information Management System). Therefore, FDR must provide an optimal frequency estimation method that is robust to noise and failure. In this paper, we present comparative studies for the frequency estimation method using IRDWT(Improved Recursive Discrete Wavelet Transform), FRDWT(Fast Recursive Discrete Wavelet Transform), and DFT(Discrete Fourier Transform). The Republic of Korea345[kV] power system modeling data by EMTP-RV are used to evaluate the performance of the proposed two kinds of RDWT(Recursive Discrete Wavelet Transform) and DFT. The simulation results show that the proposed frequency estimation technique using FRDWT could be the optimal frequency measurement method, and thus be applied to FDR.

Key Words : 345kV power system, DFT, EMTP-RV, FDR, FNET, FRDWT, Frequency estimation, IRDWT, GPS, PMU, Wide-area blackout protection, Wavelet Transform

1. Introduction

A wide-area protection relay intelligent technique has been used to improve the reliability of a power system and to prevent a blackout. Nowadays, voltage and current phasor estimation has been executed by GPS-based synchronized PMU, which has become an important way of wide-area blackout protection for the prevention of expending faults in a power system[1,2].

However, the PMU technique can not easily get the field data and it is impossible to share information, so that there has been used a FNET(Frequency Monitoring Network) method for the wide-area intelligent protection in USA. This technique is remarked for the prediction of the inception fault and for the prevention of fault propagation with accurate monitoring frequency and with frequency deviation. It consists of FDR(Fault Disturbance Recorder) and IMS(Information Management System)[3]. It is well-known that FNET will detect the dynamic behavior and the near real-time frequency information of the system. Therefore, FDR must provide an optimal frequency estimation method that is robust to noise and failure. In Korea, FNET has been studied since late 2000[4]. Frequency visualization tool was developed to use the wide-area frequency measurement value, which shows the real-time frequency to gradient color code and has made it possible to analyze an accident[5,6].

A well-known method, the Fourier Transform, has been used to analyze the transients and dynamic signal of a power system[7]. Kalman Filtering, Least Squares Method, and Artificial Neural Network were used for the analysis of power system signal. Especially, Fourier transform has been widely used because of low computation, but when the frequency is deviated, accuracy is reduced. Thus variable window technique[8] and advanced frequency estimation technique using gain compensation have been proposed an alternative to the Fourier transform[6,9,10].

For the past 20 years, much interest has been rapidly grown on the Wavelet as a new signal processing tool for a good diagnosis of transient signals. Wavelet Transform was applied at distance relay of multiple transmission line[11], voltage sag detection[12], generator internal fault detection[13], inrush detection of power transformer[14], ground fault detection of distribution systems[15], and power system diagnosis[16] due to a very good role in the singularity processing of the signal. Recently, it was shown that real-time implementation is possible in the phasor estimation of digital relay[17] and DC offsets[18] by greatly reducing the computation for real-time signal processing[19∼22].

In this paper, we present comparative studies on the

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frequency estimation method using IRDWT(Improved Recursive Discrete Wavelet Transform), the frequency estimation method using FRDWT(Fast Recursive Discrete Wavelet Transform)[6,10,19~22] and the one using DFT(Discrete Fourier Transform)[9]. 345[kV] power system modeling data of the Korea by EMTP-RV are used to evaluate the performance of the proposed two kinds of RDWT and DFT. The simulation results show that the proposed frequency estimation technique using FRDWT could be the optimal frequency measurement method, and thus be applied to FDR.

2. Frequency Estimation Method

2.1 Frequency Estimation Technique using Phase Angle Difference of Two Phasors

Correlating one cycle of reference fundamental frequency cosine and sine waveforms with the voltage signal, the real and imaginary components of the fundamental frequency, $V_{r1}^{12}(k)$ and $V_{i1}^{12}(k)$, presented in a voltage signal at any sampling instant for N = 12 are given by

$$\begin{aligned} V_{r1}^{12}(k) &= \frac{2}{12}[V_k - V_{k-6} \\ &\quad + 0.5\ (V_{k-10} - V_{k-8} - V_{k-4} + V_{k-2}) \\ &\quad + 0.866025404\ (V_{k-11} - V_{k-7} - V_{k-5} + V_{k-1})] \end{aligned} \tag{1}$$

$$\begin{aligned} V_{i1}^{12}(k) &= \frac{2}{12}[V_{k-9} - V_{k-3} \\ &\quad + 0.5\ (V_{k-11} + V_{k-7} - V_{k-5} - V_{k-1}) \\ &\quad + 0.866025404\ (V_{k-10} + V_{k-8} - V_{k-4} - V_{k-2})] \end{aligned} \tag{2}$$

where V_{k-n} is the sample at $(k-n+N)$th sampling instant.

To extract the fundamental frequency component using DFT filter, the real and imaginary parts computed using samples corresponding to the nth data window can be used to represent the signal in phasor form by the following equation (3):

$$\overline{V_n} = V_{rn} + jV_{in} \tag{3}$$

where V_{rn} and V_{in} are the real and imaginary parts computed using samples from the nth data window, respectively.

The phase angle difference, $(\theta_{n+1} - \theta_n)$, represents the rotation of the phasors as the data window is advanced by one sample. Finally, the frequency estimation $\hat{f}$ can be obtained by the following equation (4):

$$\hat{f} = \frac{\theta_{n+1} - \theta_n}{\frac{2\pi}{F_s}} \tag{4}$$

where F_s and $\hat{f}$ are the sampling frequency and the frequency estimation, respectively.

2.2 Improved Recursive Discrete Wavelet Transform

The performance of wavelet function depends on choosing a mother wavelet. The mother wavelet of IRDWT represents as the following:

$$\Psi(t) = \left(\frac{\zeta^3 t^3}{3} - \frac{\zeta^4 t^4}{6} + \frac{\zeta^5 t^5}{15}\right) e^{(-\zeta + j\omega_0)t} u(t) \tag{5}$$

Set $\zeta = \frac{2\pi}{\sqrt{3}}$ and $\omega_0 = 2\pi$ such that mother wavelet fills in the admissive condition. Fig. 1 shows the characteristic for mother wavelet in time domain.

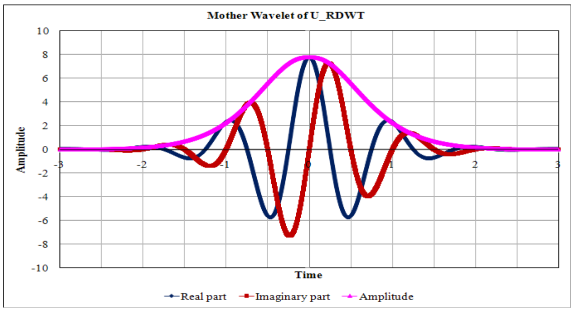


Fig. 1 Characteristic of mother wavelet transform of IRDWT

According to the displacement characteristics of z-transform, IRDWT can be expressed as equation (6). Thus, the wavelet coefficients can be implemented in real-time as it can use the historical data.

$$\begin{aligned} & W_\nu(kT,f) \\ &= \sqrt{f}\ T[a_1[\nu(k-1)T,f] + a_2[\nu(k-2)T,f] \\ &\quad + a_3[\nu(k-3)T,f] + a_4[\nu(k-4)T,f] + a_5[\nu(k-5)T,f]] \\ &\quad - b_1 W_{\nu,\Psi}[(k-1)T,f] - b_2 W_{\nu,\Psi}[(k-2)T,f] \\ &\quad - b_3 W_{\nu,\Psi}[(k-3)T,f] - b_4 W_{\nu,\Psi}[(k-4)T,f] \\ &\quad - b_5 W_{\nu,\Psi}[(k-5)T,f] - b_6 W_{\nu,\Psi}[(k-6)T,f] \end{aligned} \tag{6}$$

where, $\sigma = e^{-f\Delta T(\sigma - j\omega_0)}$

$a_1 = \sigma[(\sigma f\Delta T)^3/3 - (\sigma f\Delta T)^4/6 + (\sigma f\Delta T)^5/15]$

$a_2 = \sigma^2[2(\sigma f\Delta T)^3/3 - 5(\sigma f\Delta T)^4/3 + 26(\sigma f\Delta T)^5/15]$

$a_3 = \sigma^3[-6(\sigma f\Delta T)^3/3 + 22(\sigma f\Delta T)^4/6]$

$a_4 = \sigma^4[2(\sigma f\Delta T)^3/3 + 5(\sigma f\Delta T)^4/3 + 26(\sigma f\Delta T)^5/15]$

$a_5 = \sigma^5[(\sigma f\Delta T)^3/3 + (\sigma f\Delta T)^4/6 + (\sigma f\Delta T)^5/15]$

$b_1 = -6\sigma, b_2 = 15\sigma^2, b_3 = -20\sigma^3, b_4 = -6\sigma^4, b_5 = -6\sigma^5, b_6 = \sigma^6$

2.3 Fast Recursive Discrete Wavelet Transform

The mother wavelet of FRDWT represents as the following:

$$\Psi(t) = (1+\sigma|t|+\frac{\sigma^2 t^2}{2})e^{(-\sigma+j\omega_0)t}u(t) \tag{7}$$

Fig. 2 represents the mother wavelet transform in time domain at 60[Hz].

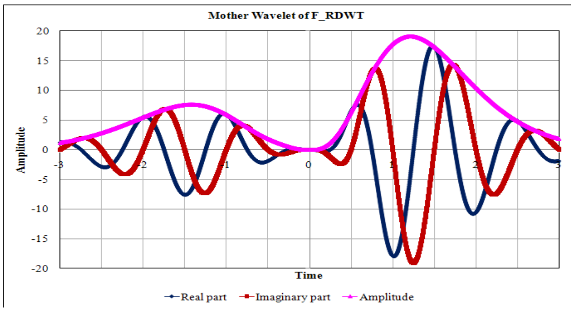


Fig. 2 Characteristic of mother wavelet transform of FRDWT

For the fixed frequency f, $W_\nu^+(kT,f)_k$ is the causal system output sequence, and $W_\nu^-(kT,f)_k$ is the non causal system output sequence. $W_\nu^+(kT,f)$ and $W_\nu^-(kT,f)$ are obtained by:

$$\begin{aligned} W_\nu^+(kT,f) &= \nu(kT)+a_1\nu[(k-1)T] \\ &+a_2\nu[(k-2)T]-b_1 W_\nu^+[(k-1)T,f] \\ &-b_2 W_\nu^+[(k-2)T,f]-b_3 W_\nu^+[(k-3)T,f] \\ W_\nu^-(kT,f) &= (a_1-b_1)\nu[(k+1)T]+(a_2-b_2)\nu[(k+2)T] \\ &+b_3\nu[(k+3)T]-b_1 W_\nu^+[(k+1)T,f] \\ &-b_2 W_\nu^+[(k+2)T,f]-b_3 W_\nu^+[(k+3)T,f] \end{aligned} \tag{8}$$

where, $\alpha = e^{-f\Delta T(\sigma - j\omega_0)}$

$$a_1 = \alpha(\frac{1}{2}(\sigma f T)^2+\sigma f T-2)$$

$$a_2 = \alpha^2(\frac{1}{2}(\sigma f T)^2-\sigma f T+1)$$

$$b_1 =-3\alpha, b_2 = 3\alpha^2, b_1 =-\alpha^3$$

The wavelet coefficients linked to a frequency f and a location kT is given by:

$$W_\nu(kT,f) = T\sqrt{f}\,[W_\nu^+(kT,f)+W_\nu^-(kT,f)] \tag{9}$$

2.4 Frequency Estimation by RDWT

The wavelet coefficients equation (6) and equation (9) lead to $E(k)$, $\theta(k)$, and $f(k)$. The estimation error can be written as equation (13). f_e is the estimated frequency.

$$E(k) = \frac{W\nu(kT)}{\nu(k)} \tag{10}$$

$$\theta(k) = \tan^{-1}\left(\frac{E(k+1)-E(k)}{\Delta T}\right) \tag{11}$$

$$f(k) = \frac{\left(\frac{\omega_0}{a}-\frac{\theta(k+1)-\theta(k)}{\Delta T}\right)}{2\pi} \tag{12}$$

$$E_{rr} = \frac{|f_e - f|}{f}\times 100\% \tag{13}$$

3. Simulation Studies

3.1 345[kV] Power System Modeling of Korea

To evaluate the performance of the proposed two kinds of RDWT and DFT, the Republic of Korea 345[kV] power system modeling data by EMTP-RV based on PSS/E program were used. 345[kV] power system consists of 154 generators, and the total generation is 57645.75[MVA]. A variety of disturbances such as generator rejection and load shedding were simulated. Simulation are performed on the assumption that FDR was installed at five locations (Seoul, Daejeon, Daegu, Gwangju, and Busan) as shown in Fig. 3, because the locations are the main areas where it is required to collect the signals, and thus analyze the effect on various disturbances. The sampling frequency of the test voltage data was set to 720[Hz][6,9,10].

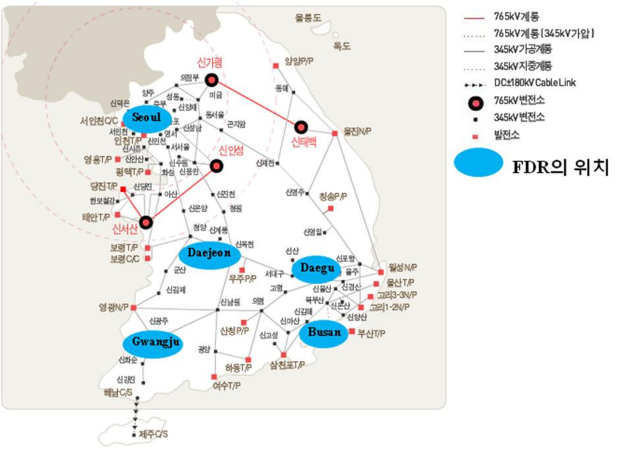
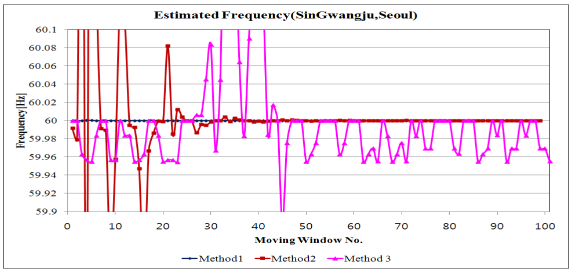


Fig. 3 Power system diagram of EMTP-RV

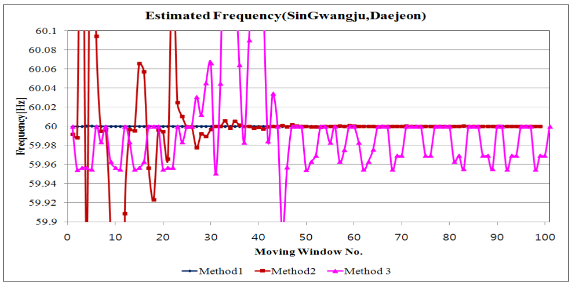
3.2 Performance Evaluation by 345[kV] Modeling

3.2.1 Load Shedding

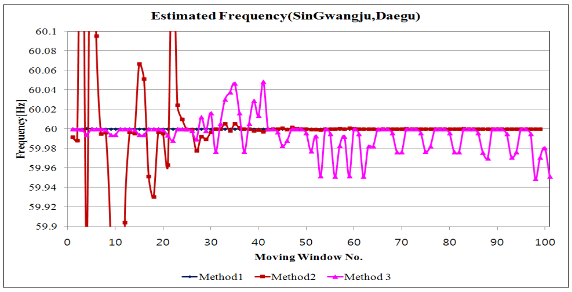
Fig. 4 shows the estimated frequency of A phase voltage by proposed two methods, when the entire load is shedding at the Gwangju[6]. In this paper, for better readability, we named the frequency estimation method using FRDWT as Method 1 and the frequency estimation



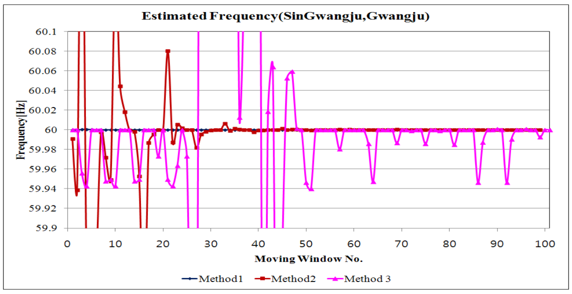
(a) In Seoul



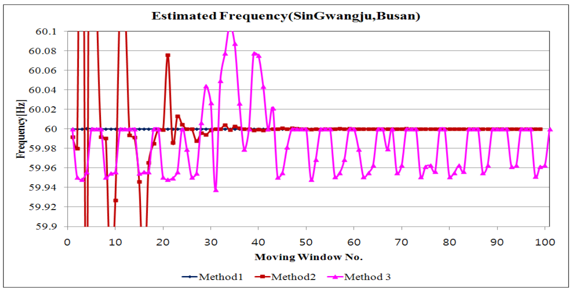
(b) In Daejeon



(c) In Daegu



(d) In Gwangju



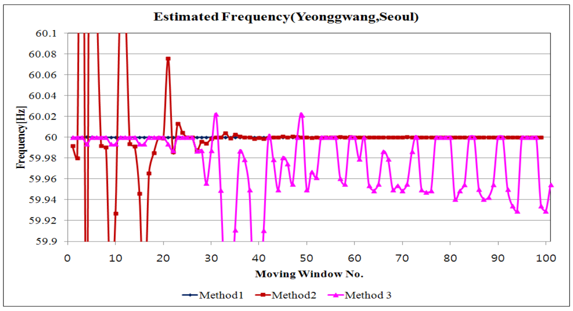
(e) In Busan

Fig. 4 Estimated frequency of load rejection

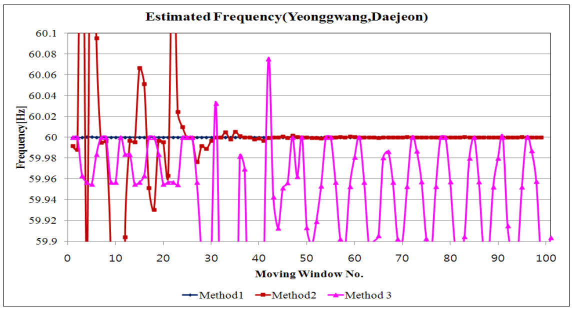
method using IRDWT as Method 2, respectively. In the same manner, we named the frequency estimation method using Phase Angle Difference of Two Phasors by DFT as Method 3. The estimated frequency using Method 2 shows gradually stabilizing after oscillating each about 1[Hz], 1.3[Hz], 1.3[Hz], 1.8[Hz], 1.2[Hz] in Seoul, Daejeon, Daegu, Gwangju, Busan during a two cycles after occur of the disturbance load shedding. The estimated frequency using Method 3 represents gradually stabilizing after oscillating each about 0.1[Hz], 0.3[Hz], 0.3[Hz], 1.8[Hz], 0.2[Hz] in Seoul, Daejeon, Daegu, Gwangju, Busan during a two cycles. Note that Method 1 represents good frequency estimation under both steady-state and dynamic conditions.

3.2.2 Generator Rejection

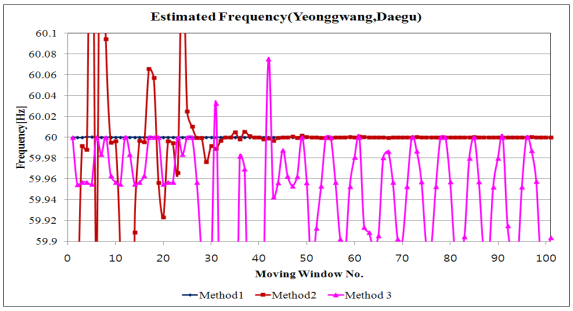
Fig. 5 represent the estimated frequency of A phase voltage by proposed two methods, in case of the first and second generator rejections at the Yeonggwang N/P[6]. The estimated frequency using Method 2 shows gradually stabilizing after oscillating each about 1[Hz], 1.5[Hz], 1.7[Hz], 2[Hz], 0.8[Hz] in Seoul, Daejeon, Daegu, Gwangju, Busan during a two cycle. The estimated frequency using Method 3 represents gradually stabilizing after oscillating each about 0.2[Hz], 0.5[Hz], 0.7[Hz], 2.4[Hz], 0.4[Hz] in Seoul, Daejeon, Daegu, Gwangju, and Busan during a two cycles. On the other hand, by Method 1 it is shown that better frequency estimation result can be obtained under both steady-state and dynamic conditions.



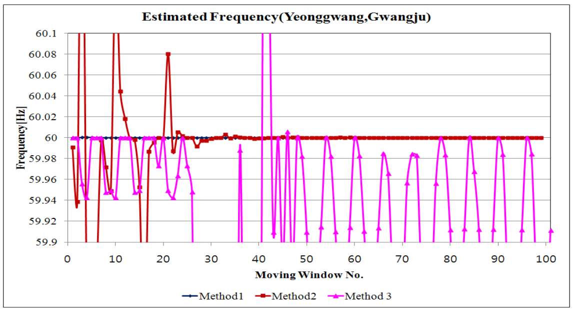
(a) In Seoul



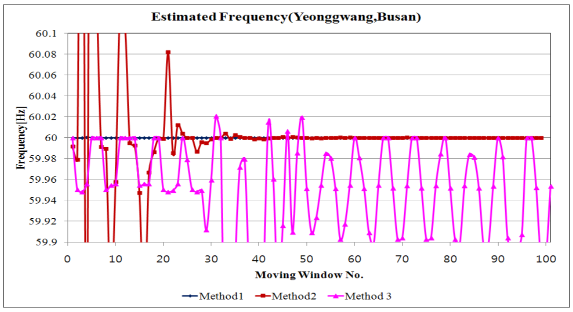
(b) In Daejeon



(c) In Daegu



(d) In Gwangju



(e) In Busan

Fig. 5 Estimated frequency of generator rejection

Following tables (Table 1, 2, and 3) represents the estimated frequency and error of several frequency estimation algorithms using the EMTP-RV 345kV modeling data. Table 1 means the maximum frequency value after the occurrence of the event. Table 2 shows the frequency value of 2 cycles elapsed after the event occurred.

Table 1 Estimated maximum frequency

Condition		Region	Method 1	Method 2	Method 3
Generator rejection	Yeonggwang #1,2	Seoul	60.02190	59.99672	60.00395
		Daejeon	60.07539	59.97665	60.00586
		Daegu	60.07535	59.98043	60.00579
		Gwangju	60.25843	59.97533	60.00198
		Busan	60.02077	59.96609	60.00378
Load shedding	Gwangju 1517MVA	Seoul	60.59270	60.11878	60.00130
		Daejeon	61.83804	60.19812	60.00180
		Daegu	61.71152	60.19565	60.00145
		Gwangju	70.66405	61.03175	60.00020
		Busan	61.07825	60.22111	60.00093

Table 2 Estimated frequency

Condition		Region	Method 1	Method 2	Method 3
Generator rejection	Yeonggwang #1,2	Seoul	59.94948	59.95112	60.00021
		Daejeon	59.91300	59.88034	60.00038
		Daegu	59.95647	59.88641	60.00037
		Gwangju	59.90955	59.78707	60.00015
		Busan	59.95119	59.90504	60.00022
Load shedding	Gwangju 1517MVA	Seoul	60.13926	60.02113	60.00000
		Daejeon	60.22195	60.11748	60.00000
		Daegu	60.26750	60.14545	60.00000
		Gwangju	59.63571	59.86206	60.00000
		Busan	60.10739	60.08802	60.00000

Table 3 Error of estimated frequency

Condition		Region	Method 1	Method 2	Method 3
Generator rejection	Yeonggwang #1,2	Seoul	0.084205	0.081452	0.000345
		Daejeon	0.144993	0.199431	0.000628
		Daegu	0.072548	0.189300	0.000608
		Gwangju	0.150748	0.354872	0.000242
		Busan	0.081343	0.158262	0.000370
Load shedding	Gwangju 1517MVA	Seoul	0.227052	0.035219	0.000006
		Daejeon	0.369913	0.195815	0.000008
		Daegu	0.445825	0.242431	0.000008
		Gwangju	0.607157	0.229902	0.000001
		Busan	0.175975	0.146700	0.000005

4. Conclusion

This paper presented comparative studies on three methods: Method 1(the frequency estimation method using IRDWT), Method 2(the frequency estimation method using FRDWT), and Method 3(the frequency estimation method using DFT). The Republic of Korea 345[kV] power system modeling data by EMTP-RV were used in order to evaluate the performance of the proposed two kinds of RDWT and DFT. From the simulation results of the generator rejection for the Republic of Korea power system, it was confirmed that as measurement point gets farther from the one of failure, then frequency vibrations are decreased. Overall, the frequency method using FRDWT can provide better accuracy and estimation velocity than the frequency estimation method using IRDWT or DFT under both steady-state tests and dynamic conditions such as load shedding and generator rejection.

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