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A Comparative Study on Frequency Estimation Methods

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Abstract – In this paper, a comparative study on the frequency estimation methods using IRDWT (Improved Recursive Discrete Wavelet Transform), FRDWT(Fast Recursive Discrete Wavelet Transform), and GCDFT(Gain Compensator Discrete Fourier Transform) is presented. The 345[kV] power system modeling data of the Republic of Korea by EMTP-RV is used to evaluate the performance of the proposed two kinds of RDWT(IRDWT and FRDWT) and GCDFT. The simulation results show that the frequency estimation technique based on FRDWT could be the optimal frequency measurement method, and thus can be applied to FDR(Fault Disturbance Recorder) for wide-area blackout protection or frequency measurement apparatus.

Keywords: Power information, 345kV power system, FDR, GCDFT, EMTP-RV, FRDWT, Frequency estimation, IRDWT, Wide-area blackout protection, Wavelet Transform

1. Introduction

A power system frequency is the major factor of power quality indicating abnormal states such as system disturbances [1]. It is used for synchronism check relay, frequency relay, and V/F relay to protect the over-excitation of power generation system when they are connected to both large centralized power generation and small distributed power generations [2, 3]. Under these conditions, a power system should maintain a nominal power system frequency. As well, frequency and frequency deviation accurately and quickly should be measured or estimated by the frequency measurement device. It is very significant to prevent wide spread accidents in power system [4].

For a long times, many techniques have been developed for the real-time frequency estimation in power systems. The IEEE PES has enacted an IEEE Std. C37.106-2003 about abnormal frequency protection [5]. Most of these techniques used the sampled and digitized methods to improve the performance of the zero-crossing detector using a zero-crossing time about the voltage signal. A well-known method, Fourier Transform, has been used to analyze the transients and dynamic signal of a power system [6]. Least squares method, Kalman filtering, and artificial neural network were used for tracking voltage phasor, and rate of change of frequency. Most notably, Fourier transform has been widely used because of low computation, but when the frequency is deviated, accuracy is reduced [7]. Thus new frequency tracking and phasor estimation algorithm by variable window [8] and advanced frequency estimation algorithm using gain compensation have been proposed as alternatives to the Fourier transform [9, 10].

For the past 20 years, much interest has been rapidly vested on the wavelet as a new signal processing tool for a quality diagnosis of transient signals. Wavelet transform was applied at distance relaying of combined transmission line [11], detection of voltage sag [12], synchronous generator protection [13], detection of transformer inrush current [14], and fault diagnosis scheme for power system relay protection [15]. As well, wavelets were applied for resonant grounded power distribution system relaying owing to a very good role in the singularity processing of the signal [16]. Recently, it is showed that real-time implementation is possible in the phasor estimation of IEDs [17] using discrete wavelet transform by greatly reducing the computation for real-time signal processing [18-23].

In this paper, a comparative study on the frequency estimation methods 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 GCDFT(Gain Compensator Discrete Fourier Transform) [9] are presented. The 345[kV] power system modeling data of the Republic of Korea by EMTP-RV is used to evaluate the performance of the proposed two kinds of RDWT (IRDWT and FRDWT) and GCDFT. The simulation results show that the frequency estimation technique based on FRDWT could be the optimal frequency measurement method, and thus can be applied to FDR(Fault Disturbance Recorder) for wide-area blackout protection or frequency measurement apparatus.

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2. Frequency Estimation Methods

2.1 Improved recursive discrete wavelet transform (IRDWT)

The performance of wavelet function depends on choosing a mother wavelet. The mother wavelet of IRDWT is given by

$$\psi(t) = (\frac{\zeta^3 t^3}{3} - \frac{\zeta^4 t^4}{6} + \frac{\zeta^5 t^5}{15})e^{(-\zeta + jw_0)t}x(t) \quad (1)$$

Set $\zeta = 2\pi/\sqrt{3}$ and $w_0 = 2\pi$ such that mother wavelet fills in the admissive condition. The characteristic for mother wavelet of IRDWT in time domain is illustrated in Fig. 1.

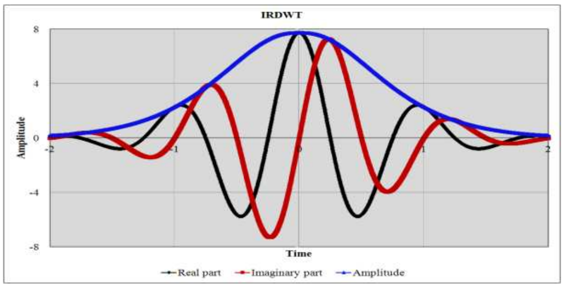


Fig. 1. Characteristic of mother wavelet transform of IRDWT

According to the displacement characteristics of z-transform, IRDWT is expressed by discrete Eq. (2). Therefore, the wavelet coefficients can be implemented in real-time as it can use the historical data.

$$\begin{aligned} & W_v(nT,f) \\ & = \sqrt{fT}\{a_1[x(n-1)T,f] + a_2[x(n-2)T,f] \\ & a_3[x(n-3)T,f] + a_4[x(n-4)T,f] + a_5[x(n-5)T,f]\} \\ & -b_1 W_{v,\psi}[(n-1)T,f] - b_2 W_{v,\psi}[(n-2)T,f] \\ & -b_3 W_{v,\psi}[(n-3)T,f] - b_4 W_{v,\psi}[(n-4)T,f] \\ & -b_5 W_{v,\psi}[(n-5)T,f] - b_6 W_{v,\psi}[(n-6)T,f] \end{aligned} \quad (2)$$

where,

$$\lambda = e^{-f\Delta T(\lambda - jw_0)}$$
$$a_1 = \lambda[(\lambda f\Delta T)^3/3 - (\lambda f\Delta T)^4/6 + (\lambda f\Delta T)^5/15]$$
$$a_2 = \lambda^2[2(\lambda f\Delta T)^3/3 - 5(\lambda f\Delta T)^4/3 + 26(\lambda f\Delta T)^5/15]$$
$$a_3 = \lambda^3[-6(\lambda f\Delta T)^3/3 + 22(\lambda f\Delta T)^4/6]$$
$$a_4 = \lambda^4[2(\lambda f\Delta T)^3/3 + 5(\lambda f\Delta T)^4/3 + 26(\lambda f\Delta T)^5/15]$$
$$a_5 = \lambda^5[(\lambda f\Delta T)^3/3 + (\lambda f\Delta T)^4/6 + (\lambda f\Delta T)^5/15]$$
$$b_1 = -6\lambda, b_2 = 15\lambda^2, b_3 = -20\lambda^3, b_4 = -6\lambda^4, b_5 = -6\lambda^5, b_6 = \lambda^6$$

2.2 Fast recursive discrete wavelet transform (FRDWT)

The mother wavelet of FRDWT is given by

$$\Psi(t) = (1 + \sigma|t| + \frac{\sigma^2 t^2}{2})e^{(-\sigma + jw_0)t}u(t) \quad (3)$$

The characteristic for mother wavelet of FRDWT in time domain at 60[Hz] is illustrated in Fig. 2.

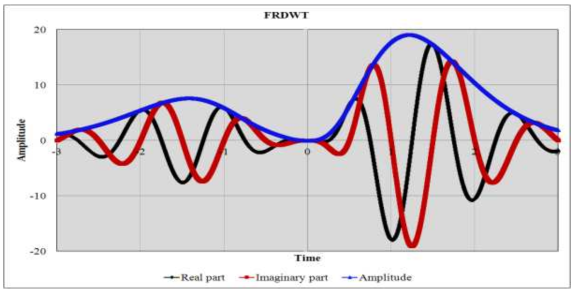


Fig. 2. Characteristic of mother wavelet transform of FRDWT

For the fixed frequency f, $\{W_v^+(nT,f)_k\}$ is the causal system output sequence, and $\{W_v^-(nT,f)_k\}$ is the non causal system output sequence. $W_v^+(nT,f)$ and $W_v^-(nT,f)$ are given by

$$\begin{aligned} W_v^+(nT,f) &= x(kT) + a_1 x[(n-1)T] \\ &+ a_2 x[(n-2)T] - b_1 W_v^+[(n-1)T,f] \\ &- b_2 W_v^+[(n-2)T,f] - b_3 W_v^+[(n-3)T,f] \end{aligned} \quad (4)$$

$$\begin{aligned} W_v^-(nT,f) &= (a_1 - b_1)x[(n+1)T] + (a_2 - b_2)x[(n+2)T] \\ &+ b_3 x[(n+3)T] - b_1 W_v^+[(n+1)T,f] \\ &- b_2 W_v^+[(n+2)T,f] - b_3 W_v^+[(n+3)T,f] \end{aligned}$$

where,

$$\alpha = e^{-f\Delta T(\sigma - jw_0)}$$
$$a_1 = \alpha(\frac{1}{2}(\sigma fT)^2 + \sigma fT - 2)$$
$$a_2 = \alpha^2(\frac{1}{2}(\sigma fT)^2 - \sigma fT + 1)$$
$$b_1 = -3\alpha, b_2 = 3\alpha^2, b_1 = -\alpha^3$$

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

$$W_v(nT,f) = T\sqrt{f}[W_v^+(nT,f) + W_v^-(nT,f)] \quad (5)$$

2.3 Frequency estimation by RDWT

The wavelet coefficients Eq. (2) and Eq. (5) lead to discrete signal $E(n)$, phase angle $\theta(n)$, and estimated frequency $f(n)$ as follows

$$E(n) = W_v(nT)/v(n) \tag{6}$$

$$\theta(n) = \tan^{-1}\left(\frac{E(n+1)-E(n)}{\Delta T}\right) \tag{7}$$

$$f(k) = \left(\frac{w_0}{a} - \frac{\theta(n+1)-\theta(n)}{\Delta T}\right)/2\pi \tag{8}$$

2.4 Gain compensator discrete fourier transform (GCDFT)

The frequency response of the real and imaginary parts corresponding to the fundamental frequency component in a voltage signal at any sampling instant for N = 12 is given by

$$\begin{aligned} X_{rl}^{12}(k) = \frac{2}{12}[&X_k - X_{k-6} \\ &+0.5(X_{k-10} - X_{k-8} - X_{k-4} + X_{k-2} \\ &+0.866025404(X_{k-11} - X_{k-7} - X_{k-5} + X_{k-1})] \\ X_{il}^{12}(k) = \frac{2}{12}[&V_{k-9} - V_{k-3} \\ &+0.5(X_{k-11} - X_{k-7} - X_{k-5} + X_{k-1} \\ &+0.866025404(X_{k-10} - X_{k-8} - X_{k-4} + X_{k-2})] \end{aligned} \tag{9}$$

The sample of the real and imaginary parts corresponding to the nth data window can be represented as the Eq. (10).

$$\bar{X} = X_{rn} + jX_{in} \tag{10}$$

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

The phase difference of the continuous discrete signal passed through the filter can be simply represented as the Eq. (11).

$$\theta_{n+1} - \theta_n = \tan^{-1}\left[\frac{X_{rn}X_{i(n+1)} - X_{in}X_{r(n+1)}}{X_{rn}X_{r(n+1)} - X_{in}X_{i(n+1)}}\right] \tag{11}$$

The final frequency value can be calculated using two phase differences as the Eq. (12).

$$\hat{f} = \frac{\dfrac{\theta_{n+1} - \theta_n}{2\pi}}{F_s} \tag{12}$$

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

The gain compensator of the DFT filter can be calculated by the calculation of the magnitude and phase according to frequency, after the z-transform of the sine and cosine filters as follow

$$A_s(f) = T_0[G(f - f_{sys}) + G(f + f_{sys})]/T \tag{13}$$

$$A_c(f) = T_0[G(f - f_{sys}) - G(f + f_{sys})]/T \tag{14}$$

where, $G(f) = \dfrac{\sin(2\pi f T_0)}{2\pi f T_0}$, $T_0 = 0.5/f_{sys}$

Finally, the compensation of estimation frequency can be computed by the gain compensator.

The estimation error can be represented as Eq. (15).

$$E_{rr} = \frac{|f_e - f|}{f} \times 100\% \tag{15}$$

where f_e is the estimated frequency.

3. Simulation Results and Discussions

3.1 The 345[kV] power system modeling of the republic of korea by EMTP-RV

In order to evaluate the performance of the proposed two kinds of RDWT and GCDFT, the 345[kV] power system modeling data of the Republic of Korea by EMTP-RV based on PSS/E program was used for the simulation [4, 6, 9, 10] (Fig. 3). The 345[kV] power system consists of 154 generators, governors, and exciters. The total generation was 57645.75[MVA]. Simulation was 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

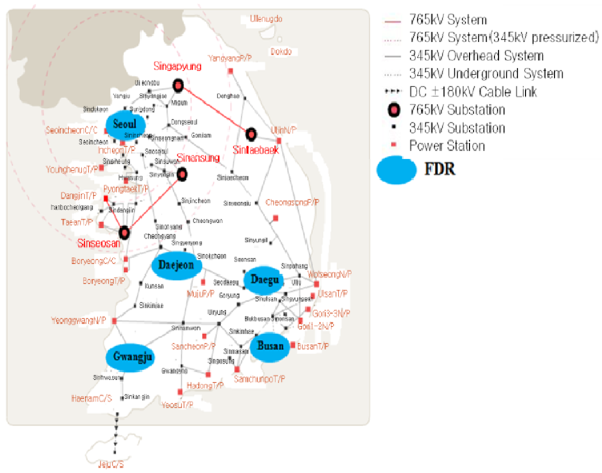


Fig. 3. Power system model of EMTP-RV

on various disturbances. The sampling frequency was set to 720[Hz].

3.2 Performance evaluation by 345[kV] modeling

In this subsection, simulation results on various disturbances such as generator rejection, load shedding, and three phase short fault are given and discussed.

3.2.1 Load Shedding

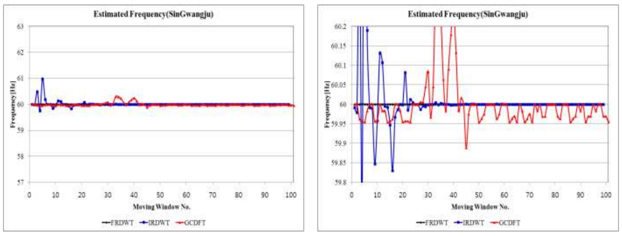
The estimated frequency of A phase voltage by the proposed three methods is shown in Fig. 4, when the entire load shedded at the SinGwangju [6]. In each city, the figure was displayed on the left side, enlarged figure was shown on the right. The estimated frequency using IRDWT shows gradually stabilizing after oscillating each about 1[Hz], 1.7[Hz], 1.8[Hz], 0.5[Hz], 1[Hz] in Seoul, Daejeon, Daegu, Gwangju, Busan during an instant of two cycles after occurrence of the disturbance load shedding. The estimated frequency using GCDFT represents gradually stabilizing after oscillating each about 0.5[Hz], 0.5[Hz], 0.3[Hz], 2.3[Hz], 0.2[Hz] in Seoul, Daejeon, Daegu, Gwangju, Busan during an instant of two cycles. Note that the frequency estimation by FRDWT represents good frequency estimation under both steady-state and dynamic conditions.

3.2.2 Generator rejection

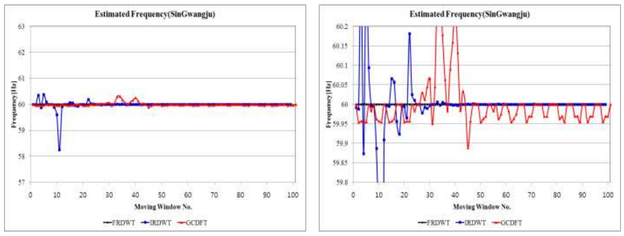
The estimated frequency of A phase voltage by the proposed three methods is shown in Fig. 5, in event of the first and second generator rejections at the Yeonggwang N/P[6]. The estimated frequency using IRDWT shows gradually stabilizing after oscillating each about 1[Hz], 1.5[Hz], 1.7[Hz], 2[Hz], 0.8[Hz] in Seoul, Daejeon, Daegu, Gwangju, Busan during an instant of two cycles after occurrence. The estimated frequency using GCDFT shows gradually stabilizing after oscillating each about 0.2[Hz], 0.6[Hz], 0.7[Hz], 2.4[Hz], 0.4[Hz] in Seoul, Daejeon, Daegu, Gwangju, and Busan during an instant of two cycles. On the other hand, the frequency estimation by FRDWT it is shown that better frequency estimation result can be obtained under both steady-state and dynamic conditions.

3.2.3 Three phase short fault

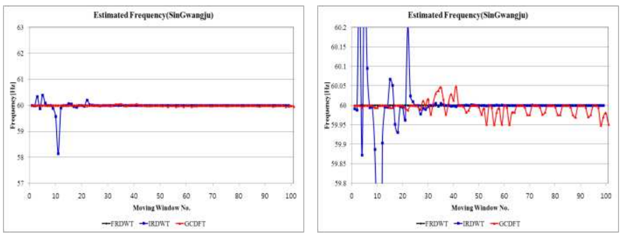
The estimated frequency of A phase voltage by proposed



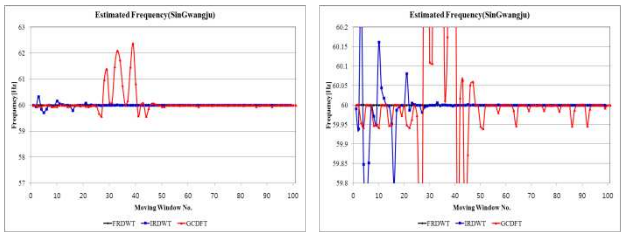
(a) In Seoul



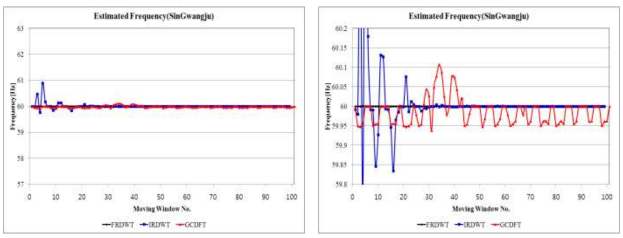
(b) In Daejeon



(c) In Daegu

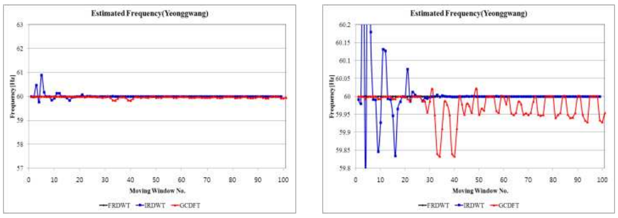


(d) In Gwandju

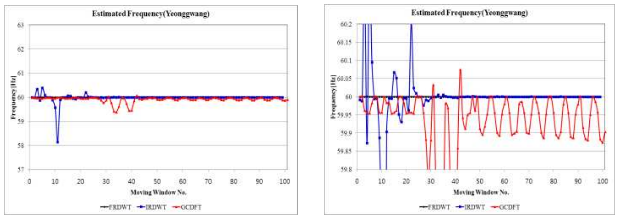


(e) In Busan

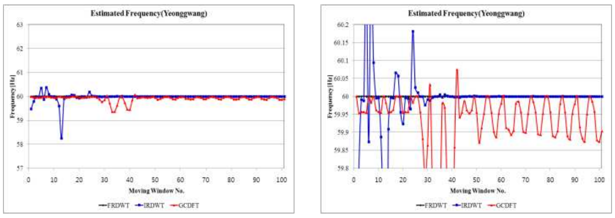
Fig. 4. Estimated frequency of load rejection (figures on the left provide full scale, whereas figures on the right provide enlarged scale)



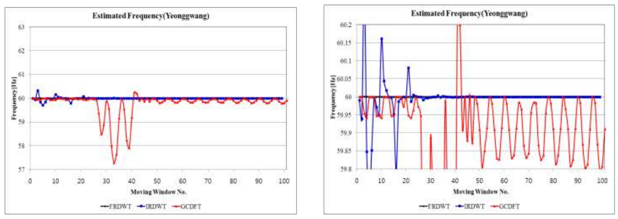
(a) In Seoul



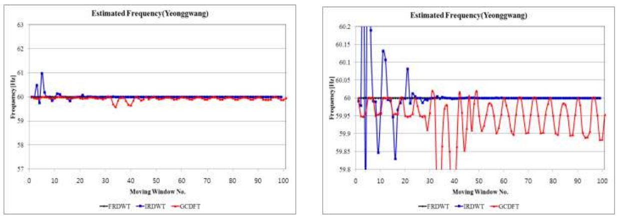
(b) In Daejeon



(c) In Daegu

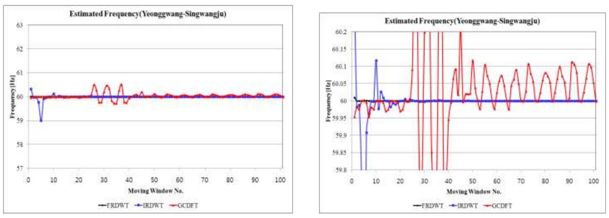


(d) In Gwandju

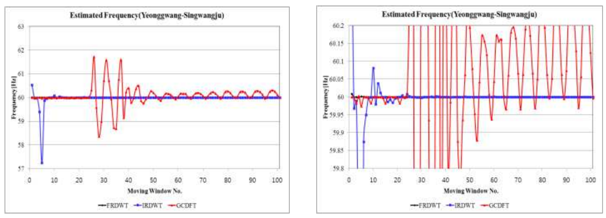


(e) In Busan

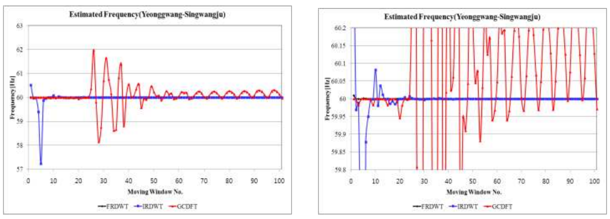
Fig. 5. Estimated frequency of generator rejection (figures on the left provide full scale, whereas figures on the right provide enlarged scale)



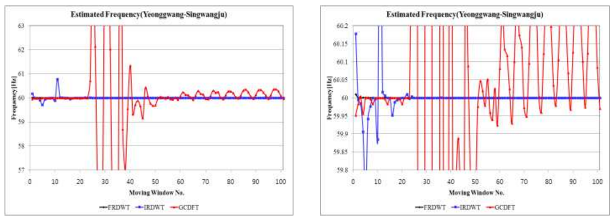
(a) In Seoul



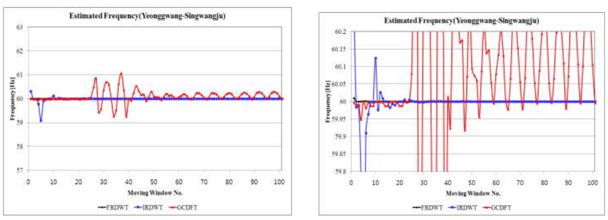
(b) In Daejeon



(c) In Daegu



(d) In Gwandju



(e) In Busan

Fig. 6. Estimated frequency of three phase short fault (figures on the left provide full scale, whereas figures on the right provide enlarged scale)

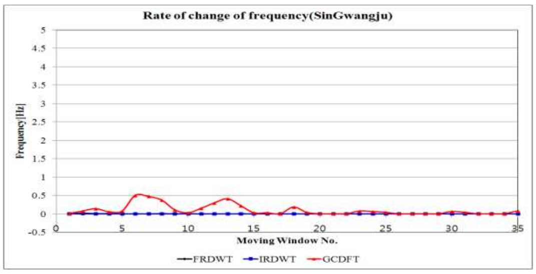
three methods is shown in Fig. 6, in event of three phase short fault between the Yeonggwang and Singwangju [6]. The estimated frequency using IRDWT shows gradually stabilizing after oscillating each about 1[Hz], 1.5[Hz], 1.7[Hz], 2[Hz], 0.8[Hz] in Seoul, Daejeon, Daegu, Gwangju, Busan during an instant of two cycles after occurrence. The estimated frequency using GCDFT represents gradually stabilizing after oscillating each about 0.5[Hz], 1.7[Hz], 2[Hz], 11[Hz], 1[Hz] in Seoul, Daejeon, Daegu, Gwangju, and Busan during an instant of two cycles. On the other hand, the frequency estimation by FRDWT it is shown that better frequency estimation result can be obtained under both steady-state and dynamic conditions.

The values of maximum frequency after the occurrence of the event are summarized in Table 1.

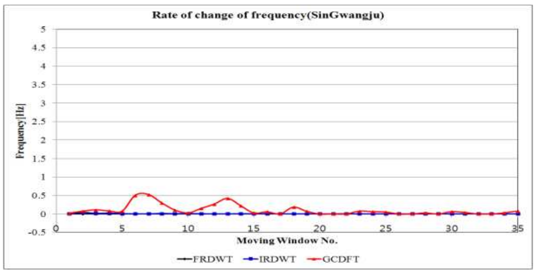
The rate of change of frequency during an instant of three cycles after occurred of the disturbance is illustrated in Fig. 7, in case of load shedding at the Yeonggwang. We can see that the rate of change of frequency using IRDWT is each about 0.01[Hz], 0.02[Hz], 0.01[Hz], 0.02[Hz], 0.03[Hz] in Seoul, Daejeon, Daegu, Gwangju, Busan during an instant of two cycles after occurrence. We can see that the rate of change of frequency using GCDFT is each about 0.5[Hz], 0.5[Hz], 0.1[Hz], 4[Hz], 0.25[Hz] in Seoul, Daejeon, Daegu, Gwangju, and Busan during an instant of two cycles. We can see that the rate of change of frequency using FRDWT is each about 0.005[Hz], 0.004[Hz], 0.003[Hz], 0.02[Hz], 0.002[Hz] in Seoul,

Table 1. Values of maximum frequency

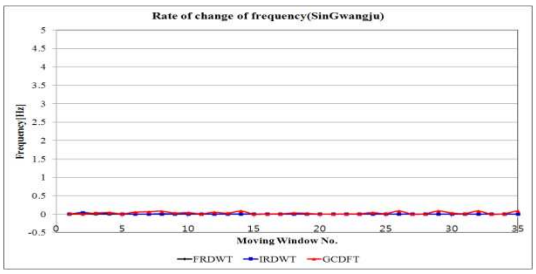
Condition		Region	FRDWT	IRDWT	GCDFT
Generator rejection	Yeonggwang # 1,2	Seoul	60.02190	59.99672	60.00395
		Daejeon	60.07539	59.97665	60.00586
		Daegu	60.07535	59.98043	60.00579
		Gwangju	60.25843	59.97533	60.00198
		Busan	60.02077	59.96609	60.00378
Load shedding	SinGwangju 1517MVA	Seoul	60.59270	60.11878	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
Three phase short fault	Yeonggwang – Singwangju	Seoul	60.00000	60.00130	60.50812
		Daejeon	60.00000	60.00180	61.72053
		Daegu	60.00000	60.00175	61.98829
		Gwangju	60.00000	60.00020	71.41243
		Busan	60.00000	60.00119	61.07169



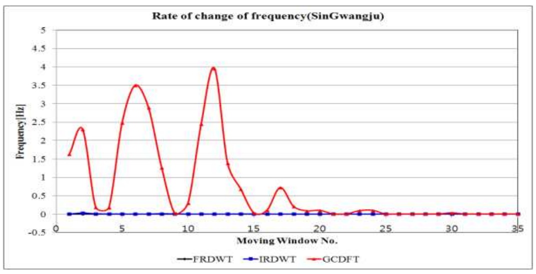
(a) In Seoul



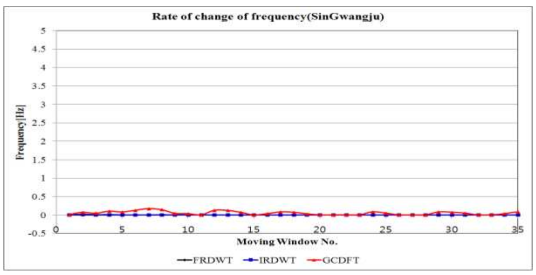
(b) In Daejeon



(c) In Daegu

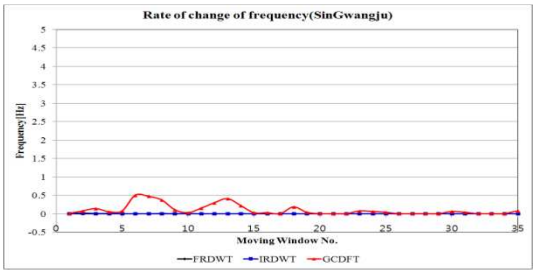


(d) In Gwangju

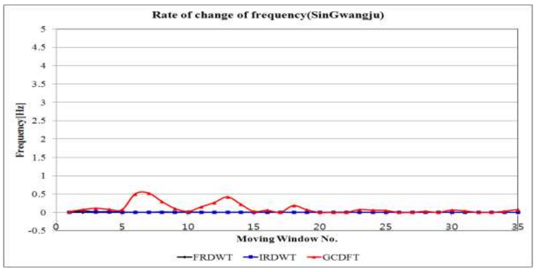


(e) In Busan

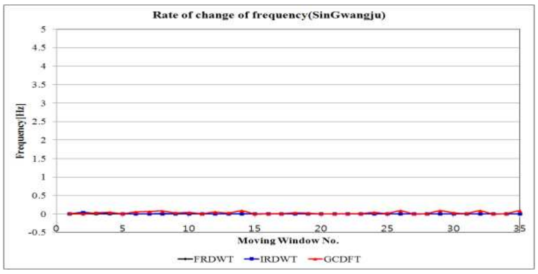
Fig. 7. Rate of change of frequency during load shedding



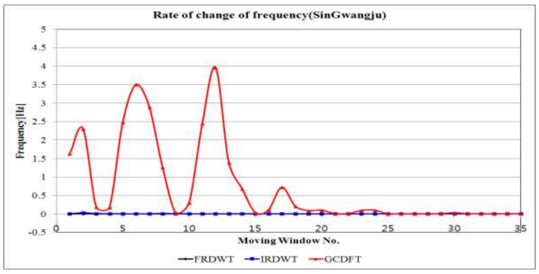
(a) In Seoul



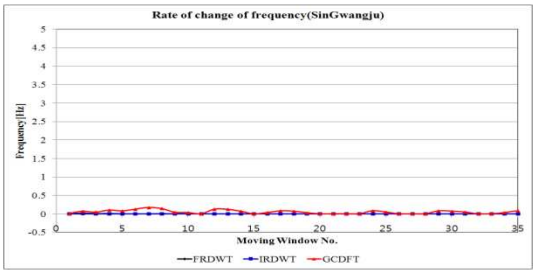
(b) In Daejeon



(c) In Daegu



(d) In Gwangju



(e) In Busan

Fig. 8. Rate of change of frequency during generator rejection

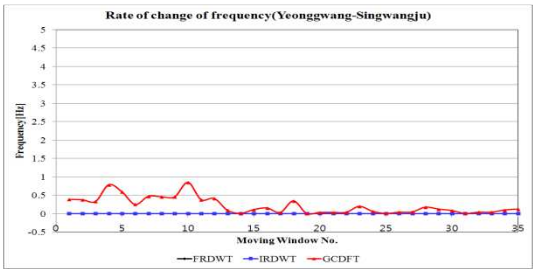
Daejeon, Daegu, Gwangju, Busan during an instant of two cycles after occurrence, too.

The rate of change of frequency during an instant of three cycle occurrence after occurred of the disturbance is showed in Fig. 8, in case of generator rejection at the Singwangju. The rate of change of frequency using GCDFT is each about 0.4[Hz], 1[Hz], 1.1[Hz], 4.5[Hz], 0.7[Hz] in Seoul, Daejeon, Daegu, Gwangju, and Busan during an instant of two cycles. The rate of change of frequency using IRDWT and FRDWT is very small in all of regions.

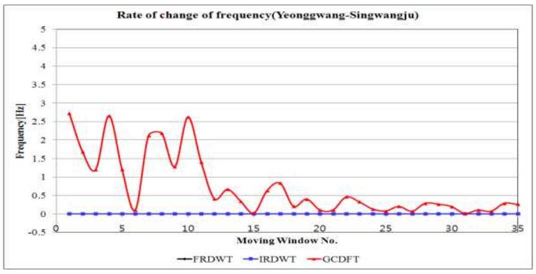
The rate of change of frequency during an instant of three cycle occurrence after occurred of the disturbance is represented in Fig. 9, in case of three phase short fault between the Yeonggwang and Singwangju. The rate of change of frequency using IRDWT is each about 0.001[Hz], 0.002[Hz], 0.002[Hz], 0.00[Hz], 0.001[Hz] in Seoul, Daejeon, Daegu, Gwangju, Busan during an instant of two cycles after occurrence. The rate of change of frequency using GCDFT is each about 0.8[Hz], 2.7[Hz], 3[Hz], 10[Hz], 1.7[Hz] in Seoul, Daejeon, Daegu, Gwangju, and Busan during an instant of two cycles. The rate of change of frequency using FRDWT is very small in all of regions during an instant of two cycles after occurrence.

4. Conclusion

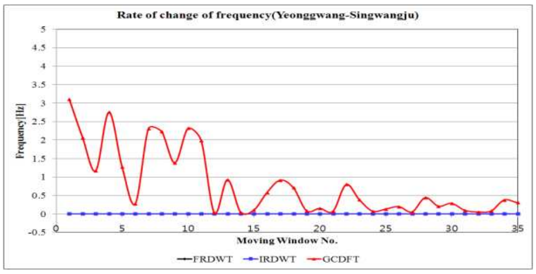
In this paper, a comparative study on three methods was presented: the frequency estimation method using IRDWT, the frequency estimation method using FRDWT, and the frequency estimation method using GCDFT. The 345[kV] power system modeling data of the Republic of Korea by EMTP-RV was used in order to evaluate the performance of the proposed two kinds of RDWT (IRDWT and FRDWT) and GCDFT. From the simulation results of the generator rejection, it was confirmed that as measurement point gets further away from the one of failure, then frequency vibrations are decreased. Likewise, in load shedding and three phase short fault, similar results was obtained. Observing the rate of change of frequency, the frequency variation is the most severed in Gwangju, because Gwangju is the nearest point of disturbance. In the



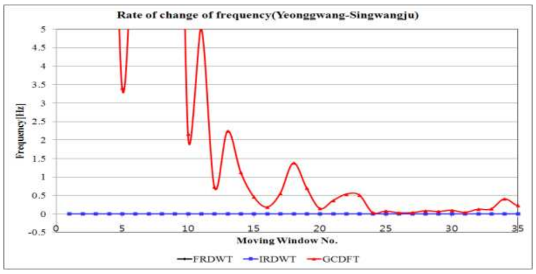
(a) In Seoul



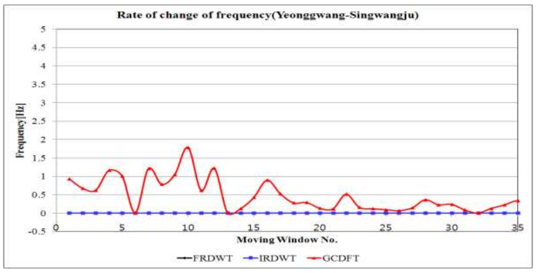
(b) In Daejeon



(c) In Daegu



(d) In Gwangju



(e) In Busan

Fig. 9. Rate of change of frequency during three phase short fault

case of three phase short fault occurrence, the frequency is gradually stabilized after about three cycles. Overall, the frequency estimation method using FRDWT can provide better accuracy and estimation velocity than the frequency estimation method using IRDWT or GCDFT under both steady-state tests and dynamic conditions such as load shedding, generator rejection, and three phase short fault. The future works includes the correlation between the measurement location and estimation effect.

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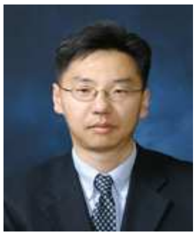

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