Advanced Frequency Estimation Technique using Gain Compensation

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***Abstract*—The frequency is an important operating parameter for protection, control, and stability of a power system. Due to the sudden change in generation and loads or faults in power system, the frequency is supposed to deviate from its nominal value. It is essential that the frequency be maintained very close to its nominal frequency. An accurate monitoring of the power frequency is essential to optimum operation and prevention for wide area blackout. As most conventional frequency estimation schemes are based on DFT filter, it has been pointed out that the gain error could cause the defects when the frequency is deviated from nominal value. This paper presents an advanced frequency estimation technique using gain compensation to enhance the DFT filter based technique. The proposed technique can reduce the gain error caused when the frequency deviates from nominal value. Simulation studies using both the data from EMTP-RV software and user defined arbitrary signals are performed to demonstrate the effectiveness of the proposed algorithm. The simulation results show that the proposed algorithm achieves good performance under both steady state tests and dynamic conditions.**

Keywords; DFT filter, EMTP-RV, Gain compensation, Frequency, Frequency estimation, Nominal frequency, Wide area blackout

I. INTRODUCTION

The frequency is an important operating parameter for protection, control, and stability of a power system [1]. The frequency as a key index of power quality can be indicative of system abnormal conditions and disturbances [2]. Due to the sudden change in generation and loads or faults in power system, the frequency is supposed to deviate from its nominal value. It is essential that the power frequency be maintained very close to its nominal frequency. In addition, the frequency measure devices and frequency tracking techniques should be fast and accurate in determining of frequency [3].

More recently, time synchronized phasor and frequency measurement methods for fault disturbance recorders (FDRs), phasor measurement unit (PMU) and intelligent power system information unit (iPIU) have been attracted. In the United States, frequency monitoring network (FNET) by careful monitoring of frequency and frequency deviation with high precision to a common reference of the GPS have become an important component of wide area measurements in power system [4-7]. In Korea, K-WAMS (Wide Area Measurement System) system has been developed last year [8-11].

After a microprocessor had been produced, many measurement and tracking techniques for frequency and frequency deviation have been reported in past three decades. Most of these techniques process the sampled and digitized values of the system voltage to frequency and frequency deviation measurement [12-13]. Meanwhile as most conventional frequency estimation techniques are based on DFT filter, it has been pointed out that the gain error for magnitude changes could cause the defects when the power system frequency is deviated from nominal value [14-17].

To improve the performance of DFT filter based techniques, this paper presents an advanced frequency estimation technique using gain compensation. To demonstrate the performances of the proposed algorithm, we used EMTP-RV simulation data and user defined arbitrary signals, which were sampled with 720Hz per cycle. The proposed technique can reduce the gain error caused when the power system frequency deviates from nominal value. This paper is organized as follows: In section 2, advanced frequency estimation algorithm with gain compensation is reviewed. In section 3, simulation studies are introduced and discussed. In section 4, results by the proposed algorithm are given.

II. ADVANCED FREQUENCY ESTIMATION ALGORITHM

A. *Frequency Estimation Technique using Phase Angle Difference of Two Phasor*

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

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

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

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

This work has been supported by KETEP (2008T100100131), which is funded by MKE(Ministry of Knowledge Economy)

For the extraction of fundamental frequency component using DFT filter, the real and imaginary parts computed using samples corresponding to n th data window can be used to represent the signal in phasor form by equation (3).

$$\overline{V_n} = V_{rn} + jV_{in} \qquad (3)$$

Where V_{rn} and V_{in} are the real and imaginary parts computed using samples from the n th data window. Similarly, V_{rn+1} and V_{in+1} are the real and imaginary parts computed using samples from the $(n+1)$ th data window.

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).

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

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

B. Advanced Frequency Estimation Algorithm with Gain Compensation

Consider that sinusoidal voltage signal can be expressed by equation (5).

$$v(n) = A\cos(2\pi n\frac{f}{f_s} + \theta) \qquad (5)$$

Where A and θ are the magnitude and the phase angle, respectively.

By applying frequency response of cosine filter to $v(n)$, equation (5) can be shown in equation (6). Similarly, frequency response of sine filter represents in equation (7).

$$v_c(n) = A_c \cos(2\pi n\frac{f}{f_s} + \theta) \qquad (6)$$

$$v_s(n) = A_s \cos(2\pi n\frac{f}{f_s} + \theta) \qquad (7)$$

Where, $A_c = A|H_c(f)|, A_s = A|H_s(f)|, \hat{\theta} = \theta - \pi\frac{f(N-1)}{f_s^2}$

And then, the ratio of magnitude of $v(n)$ can be expressed mathematically as

$$\frac{A_c}{A_s} = \frac{|H_c(f)|}{|H_s(f)|} = \frac{\tan(\frac{\pi f}{f_s})}{\tan(\frac{\pi f_0}{f_s})} \qquad (8)$$

From equation (8) the frequency f can be expressed as

$$f = \frac{f_s}{\pi}\tan^{-1}(\tan(\frac{\pi f_0}{f_s})\frac{A_c}{A_s}) \qquad (9)$$

Where f_0 is the fundamental frequency component.

From the combination of equation (6) and equation (7), an elliptic equation is expressed as

$$\left(\frac{v_c(n)}{A_c}\right)^2 + \left(\frac{v_s(n)}{A_s}\right)^2 = 1 \qquad (10)$$

By using the output of cosine and sine filter for $v(n)$ and $v(n-1)$, equation (10) can be expressed as

$$\begin{bmatrix} v_c^2(n) & v_c^2(n) \\ v_s^2(n-1) & v_s^2(n-1) \end{bmatrix} \begin{bmatrix} 1/A_c^2 \\ 1/A_s^2 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \qquad (11)$$

By arrangement of equation (11), the ratio of A_c to A_s can be expressed as

$$\frac{A_c}{A_s} = \sqrt{\frac{v_c^2(n) - v_c^2(n-1)}{-v_s^2(n) + v_s^2(n-1)}} \qquad (12)$$

Finally, substituting equation (12) into equation (9), we obtain an equation for frequency estimation with gain compensation.

$$f = \frac{f_s}{\pi}\tan^{-1}(\tan(\frac{\pi f_0}{f_s})\sqrt{\frac{v_c^2(n) - v_c^2(n-1)}{-v_s^2(n) + v_s^2(n-1)}} \qquad (13)$$

Fig. 1 shows flowchart of the advanced frequency estimation algorithm.

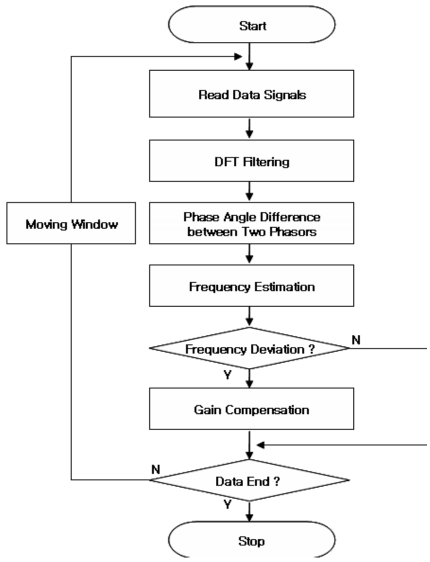


Figure 1. Flowchart of the advanced frequency estimation algorithm

III. Simulation Studies

Comprehensive evaluation of the proposed frequency estimation algorithm was carried out by conducting several test cases using EMTP-RV modeling data and user defined arbitrary signals.

A. Evaluation using EMTP-RV modeling data

The test voltage data were obtained from EMTP-RV simulation sampled with 12S/C. The 765kV T/L system in Korea is simulated by EMTP-RV software. Fig. 2 shows the power system model used for the simulation.

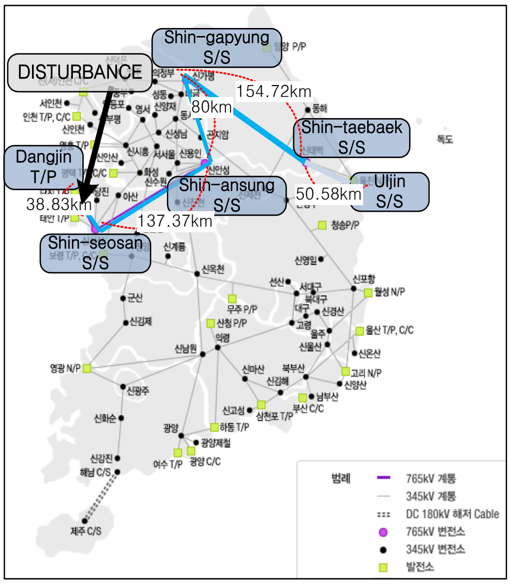
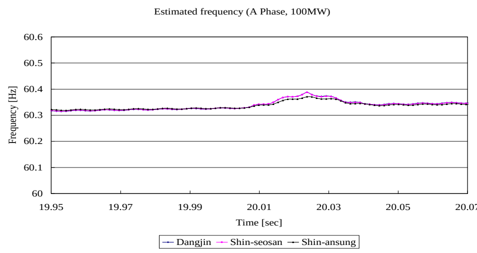


Figure 2. Power system model of EMTP-RV

The modeling for the governor and exciter of Uljin N/P and Dangjin T/P were obtained based on real data, and T/L between Shin-gapyung and Shin-ansung was simulated based on the places where the construction will be done. From the 765kV T/L system as shown in Fig. 2, voltages were measured of six regions (Dangjin, Shin-seosan, Shin-ansung, Shin-gapyung, Shin-taebaek, and Uljin) in case of 100MW load shedding and 400MW load shedding at Dangjin T/P. Fig. 3 shows the estimated each frequency for local area during 100MW load shedding at Dangjin. Fig. 4 shows the estimated each frequency for local area during 400MW load shedding at Dangjin. In these cases, inception time of disturbance by load shedding was at about 20sec. The frequencies using the proposed technique are estimated from the measured voltage data. As shown in Fig. 3 and Fig. 4, the magnitude of estimated frequency increases with the generating distortion of a voltage soon after the disturbance occurrence. We can see that the estimated frequency values reveal high accuracy. It is known that the estimated frequency variations show decrease according to distance increase from Dangjin. And the estimated frequency shows the more load shedding is increased, the more frequency oscillation is increased.



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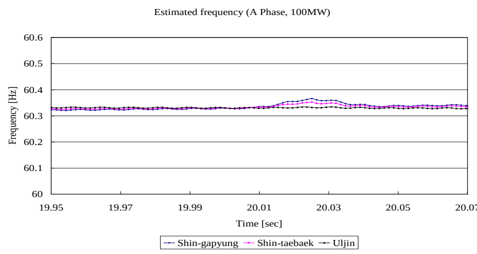
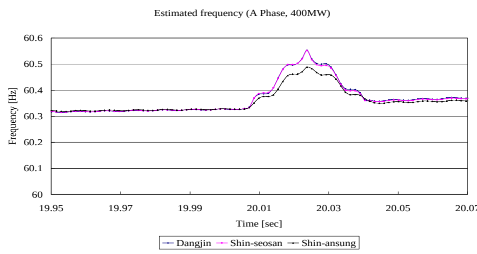


(b)

Figure 3. Estimated frequency during 100MW load shedding



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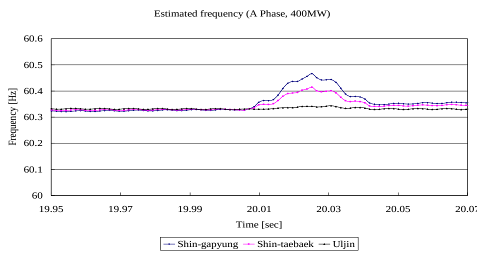


(b)

Figure 4. Estimated frequency during 400MW load shedding

B. Evaluation using user defined arbitrary signals

Seven signals with three conditions are tested to verify the proposed algorithm. Three conditions include the signal change in magnitude, harmonics change and frequency change. The sampling frequency is selected to be 720Hz.

The first test signal is assumed to magnitude change from 0.8pu to 1.2pu in 0.2pu step as the frequency and phase angle are unchanged. The result of frequency estimation using the proposed algorithm for the first test signal is shown in Fig. 5.

As shown in Fig. 5, the proposed algorithm represents good frequency estimation with the error less than ± 0.33Hz. We can see that the estimated frequency values reveal high accuracy after the magnitude change.

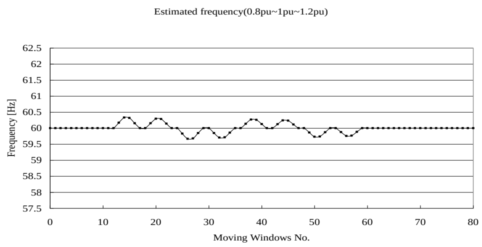
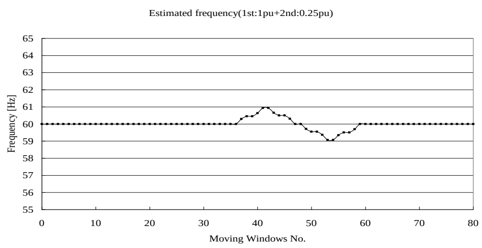


Figure 5. Estimated frequency during magnitude change

The test signals are assumed to harmonics change. First, second harmonic component is assumed to suddenly change from 0pu to 0.25pu. Second, third harmonic component is assumed to suddenly change from 0pu to 0.2pu. In this case, the result of frequency estimation using the proposed algorithm are shown in Fig. 6. We can see that the proposed algorithm represents good frequency estimation with the error less than ± 0.1Hz ~ ± 0.3Hz.



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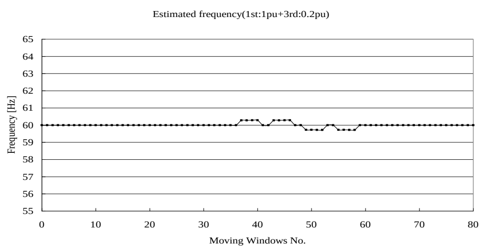
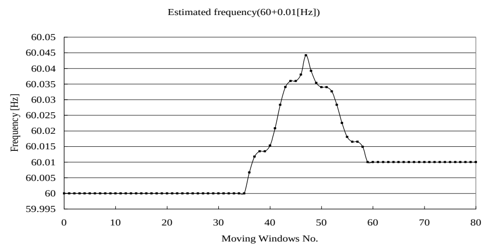


(b)

Figure 6. Estimated frequency during harmonics change

The third test signals are assumed to frequency changes from nominal frequency. Fig 7 shows the frequency estimation results obtained when the frequency is changed from the nominal frequency to various values such as 0.01Hz, 0.1Hz, 1Hz, and 6Hz. From Fig 7(a), it can be seen that the proposed technique estimates the frequency with maximum of 0.04Hz after the frequency is changed with 0.01Hz, and 60.01Hz is accurately estimated after 39ms, which 0.01Hz is reflected. From Fig 7(b), it can be seen that the technique estimates the frequency with maximum of 0.44Hz after the frequency is changed with 0.1Hz, and 60.1Hz is accurately estimated after 2 cycle, which 0.1Hz is reflected. From Fig 7(c), it can be seen that the technique estimates the frequency with maximum of 4.49Hz after the frequency is changed with 1Hz, and 61Hz is accurately estimated after 2 cycle, which 1Hz is reflected. From Fig 7(d), it can be seen that the technique estimates the frequency with maximum of 14.42Hz after the frequency is changed with 10% of the nominal frequency, and 66Hz is estimated after 2 cycle, which 6Hz is reflected. In summary, the proposed algorithm represents accurately good frequency estimation with the error of assumed frequency variation.



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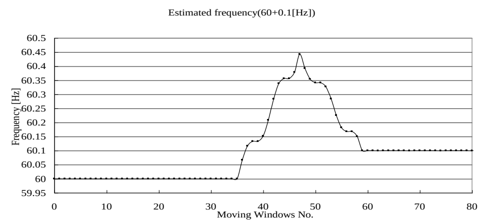

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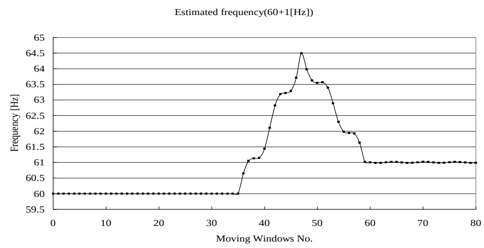
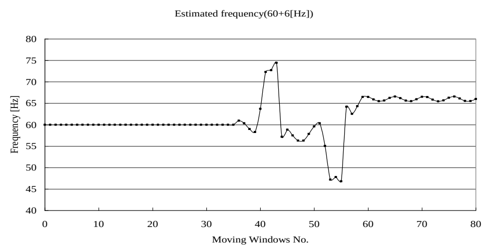


(c)



(d)

Figure 7. Estimated frequency during harmonics change

IV. Conclusion

In this paper, an advanced frequency estimation technique using gain compensation in order to reduce the gain error caused when the frequency is deviated from nominal value was developed. For the evaluation performance, we used voltage waveforms obtained from EMTP-RV simulation and user defined arbitrary signals. The various simulation results show that the proposed technique can provide better accuracy and higher robustness to harmonics and noise under both steady state tests and dynamic conditions.

Acknowledgment

This work was supported by the Development of Network Based Frequency Monitoring and Fault Prediction System for Wide Area Intelligent Relaying of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (2008T100100131).

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