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Full Length Research Paper

LabVIEW implement for distorted signal detection with robust complex extended Kalman filter

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This paper presents the personal computer (PC)-based LabVIEW as software to develop the algorithm of the robust complex extended Kalman filter (RCEKF) for detection of the parameters of voltage signal in power systems. The hardware of this paper is to take sample-and-hold card and DAQ (data acquisition) card for extracting the datum from the outside system to the PC, the program computes the amplitude, frequency and phase of the voltage signal with RCEKF. For validating the performance of RCEKF in this paper, the voltage signal from function generator and laboratory are applied to check the feasibility of algorithm firstly and then this application was also used in the TPC (Taiwan Power Company) secondary substation in Sijhou, Taiwan.

Key words: Complex Kalman filter, robust algorithm, voltage distorted signal, LabVIEW.

INTRODUCTION

The parameter of voltage signal includes amplitude, phase angle and frequency. The accuracy of extrapolating parameter is a very important issue for the application of power system. For example, from the measured voltage signal, the protective relay after signal management process shows how to make the exact judgment of system state and how to respond to action. From the literature review (Tadeusz and Jacek, 1997; Nishiyama, 1997), using the state variable types of the extended Kalman filter are real type and complex type in the application of signals extrapolation generally. The former uses the signal amplitude, frequency and phase angle as state variable. But this method in practical application, if signal is out of order, will result in the value of estimated value. The pitch of measured value and estimated value will increase gradually through tracking time. In order to develop the drawbacks as above, therefore, the complex extended Kalman filter is proposed (Dash et al., 2000) and is applied in the extrapolation of voltage distortion signal parameter. The main aim is to ensure exact and track the extrapolation distortion signal amplitude, phase angle, and frequency soon. But the complex extended Kalman filter is considered only on the linear part of equation during filtering process. When the parameter is abnormal, sometimes the nonlinear will take a great influence.

According to Huang et al. (2002), if there is an unusual signal in the system, the variation quantity will result in errors between the estimated value and the optimal value. This condition will cause the variable state which does not attach the optimal solution and it cannot estimate the parameter exactly. In order to solve this problem above, Huang et al. (2002) proposes a robust calculation method in the model of extended Kalman filter. Thus, it can be a state extrapolation application of power system. This effect is pretty good by simulating verification. But the robust calculation method is composed by exponential function in innate character. It is $\exp\left(-\left|y_k - H\tilde{x}_{k|k-1}\right|\right)$. The application meaning is that, the more there is a difference between measured value and estimated value, the less effect it has on extrapolation filtering. On the contrary, if there is a less difference between measured value and estimated value, it will keep the original effect verse extrapolation filtering. By applying the regression algorithm of extended Kalman filter, we can use this function to reduce the influence of weight of distortion. This paper has proposed this

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robust calculation approach of complex extended Kalman filter in signal extrapolation to improve performance. The application of signal extrapolation is only applied on the simulation stage (Ferreira, 1994; Xia, 1992; Hargrave, 1989; Mandal, 1995; Irving, 1998; Beides, 1991; Durgaprasad, 1998; Liu, 2001; Routray, 2002; Dash, 1999). But these approaches are seldom applied in practical measurement. Thus, each algorithm does not have practical verification in practical task.

The virtual instruments of LabVIEW by personal computer (PC) based are often applied in power system. The convenience and appetence in this application have been confirmed mostly. Thus, this paper uses the graphic control software of LabVIEW to finish the program of robust complex extended Kalman filter. This program used the practical measurement of three conditions as follows: Firstly, it has given the sine wave by function generator. Secondly, it has given the voltage signal of laboratory grid. Thirdly, it has given the voltage signal of Sijhou secondary sub-station in Changhua County of Taiwan power company (TPC). From the above items, it can verify algorithm practicality in practical measurement. This paper is organized as follows.

VOLTAGE SIGNAL OF COMPLEX EXTENDED KALMAN FILTER

An observable time-changing is regarded as a form of both real value z_k and noise v_k. The suffix *k* is hinted as time t_k. We can present this equation as follows.

$$\begin{aligned} y_k &= z_k + v_k \quad , \quad \mathrm{k} = 1, 2, 3, ..., \mathrm{N} \\ \mathrm{v_k} &\sim N(0, R_\mathrm{k}) \end{aligned} \tag{1}$$

For power system, the fact value of the above equation is presented by the time-changing function as follows.

$$z_k = \sum_{i=1}^{M} a_i \sin(\omega_i t_k + \phi_i) \tag{2}$$

Where; $\omega_i = 2\pi f_i$, $t_k = k\Delta t$, Δt presented the sampling interval, a_i, f_i, and ϕ_i are presented as the i order time-changing signal amplitude, frequency and phase angle. The noise v_k is Gaussian distribution, its mean value is zero and its variance is σ_v^2. The measurement error covariance of noise calculation

v_k is $R_k = E[v_k v_k^{*T}]$

Where the * and *T* are presented as conjugate complex number and matrix transpose, respectively.

Owing to the percentage of the other frequency part is different to fundamental frequency which is quite small in the time-changing voltage signal in power system. Thus, the part of signal harmonic can be neglected in this model. Thus, the presented equation of time-changing signals in equation (2) is simplified as single sinusoidal wave signal and presented as follows.

$$z_k = a_1 \sin\left(k\omega_1 \Delta T + \phi_1\right) \tag{3}$$

Where, ΔT is the sampling time, ω_1 is the fundamental angle frequency, ϕ_1 is the phase angle fundamental frequency.

Now, the equation (3) of state variable by complex style is presented as follows.

$$\begin{aligned} \alpha &= e^{j\omega_1 T_s} \\ u_k &= a_1 e^{j(k\omega_1 T_S + \phi_1)} \\ u_k^* &= a_1 e^{-j(k\omega_1 T_S + \phi_1)} \end{aligned} \tag{4}$$

Thus, the measurement value of single sinusoidal wave time-changing signal is presented by state variable u_k as follows.

$$\begin{aligned} x_{k+1} &= f(x_k) \\ y_k &= Hx_k + v_k \end{aligned} \tag{5}$$

Where, $x_k = \left[\alpha \ \mathrm{u_k} \ \mathrm{u_k^*}\right]^T = \left[x_{k(1)} \ x_{k(2)} \ x_{k(3)}\right]^T$

$H = \left[0 \ \ 0.5\mathrm{j} \ \ \text{-}0.5\mathrm{j}\right]$

To sum up, the equation is presented as complex matrix forming the following.

State equation $\begin{bmatrix} \alpha \\ u_{k+1} \\ u_{k+1}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & \dfrac{1}{\alpha} \end{bmatrix} \begin{bmatrix} \alpha \\ u_k \\ u_k^* \end{bmatrix} = Ax_k$

Measurement equation $y_k = \begin{bmatrix} 0 & 0.5i & -0.5i \end{bmatrix} \begin{bmatrix} \alpha \\ u_k \\ u_k^* \end{bmatrix} + v_k$

The state vector of extrapolation signal variable of Complex Extended Kalman filter is x_k. A is presented as state convert matrix in state equation. The regression procedure of extrapolation state process for Complex Extended Kalman filter is presented in the following equation.

$$\hat{x}_{k|k} = \tilde{x}_{k|k-1} + K_k\left(y_k - H\tilde{x}_{k|k-1}\right) \quad (6)$$

Where, $\hat{x}_{k|k}$ is the state variable after filtering, $\tilde{x}_{k|k-1}$ is the state variable after extrapolation, K_k is the Kalman gain, $y_k - H\tilde{x}_{k|k-1}$ is the innovation value.

State extrapolation

To calculate the extrapolation error covariance matrix $\mathrm{M}_{k+1|k}$ of state variable after extrapolation:

$$M_{k+1|k} = E\left[\left(x_{k+1} - \tilde{x}_{k+1|k}\right)\left(x_{k+1} - \tilde{x}_{k+1|k}\right)^{*T}\right] = F_k P_{k|k} F_k^{*T} \quad (7)$$

$$F_k = \frac{\partial\left(Ax_k\right)}{\partial x_k} \quad (8)$$

$$F_k = \begin{bmatrix} 1 & 0 & 0 \\ x_{k(2)} & x_{k(1)} & 0 \\ \frac{-x_{k(3)}}{x_{k(1)}^2} & 0 & \frac{1}{x_{k(1)}} \end{bmatrix}$$

State filtering: $P_{k|k}$ is the state variable error covariance after filtering. By using the least square method, we can gain K_k. The calculation is as follows.

$$P_{k|k} = \left[I - K_k H\right] P_{k|k-1}\left[I - K_k H\right]^{*T} + K_k R_k K_k^{*T} \quad (9)$$

$$K_k = P_{k|k-1} H^{*T}\left[HP_{k|k-1}H^{*T} + R_k\right]^{-1} \quad (10)$$

We can use equations (9) and (10) to be operated and get the error covariance of state variable after filtering.

$$P_{k|k} = P_{k|k-1} - K_k H P_{k|k-1} \quad (11)$$

The above equation, the Kalman K_k and error covariance of state variable after filtering $P_{k|k}$ are depended on the extrapolation value $\tilde{x}_{k|k}$. The frequency $\hat{f}_{(k)}$, amplitude $\hat{a}_{1(k)}$ and phase angle $\hat{\phi}_{1(k)}$ obtained at time k through the variable state $\hat{x}_{k(1)}$ and $\hat{x}_{k(2)}$ after filtering to get the optimal signal parameter extrapolation. The equation is depicted as follows.

$$\hat{f}_{(k)} = \frac{1}{2\pi\Delta T}\left[\mathrm{Im}\left(\ln \hat{x}_{k(1)}\right)\right] \quad (12)$$

$$\hat{a}_{1(k)} = \left|\hat{x}_{k(2)}\right| \quad (13)$$

$$\hat{\phi}_1 = \mathrm{Im}\left[\ln\left(\frac{\hat{x}_{k(2)}}{\left|\hat{x}_{k(2)}\right| \times [\hat{x}_{k(1)}{}^{k}]}\right)\right] \quad (14)$$

ANALYSES OF ROBUST COMPLEX EXTENDED KALMAN FILTER

In this paper, the proposed robust algorithm of Robust Complex Extended Kalman filter is the factor that restrains extraordinary variation by using exponential function. It can use this characteristic function to reduce the unfavorable system factor due to out of order. Thus, the stability of this approach characteristic is getting better. The dynamic state extrapolation stage of Robust Complex Extended Kalman filter is depicted as follows:

Step1: Input time-changing signals measurement value y_k, the initial value of state variable $\hat{x}_0$, the initial value of error covariance P_0 and the measured value of error covariance R_0.

Step 2: Begin to track at time $k = 0$.

Step 3: State extrapolates $\tilde{x}_k = A\hat{x}_{k-1}$.

Step 4: $F_k = \frac{\partial(Ax_k)}{\partial x_k}$ $M_{k+1|k} = F_k P_{k|k} F_k^{*T}$

Step 5: Measurement error covariance R_k

$$R_k = W_k^{-1}, \; W_k = W_k e^{-\left|y_k - H\hat{x}_{k-1}\right|}$$

Where, $e^{-\left|y_k - H\hat{x}_{k-1}\right|}$ is the robust exponential function of complex style. If it is real style, the robust exponential function is $e^{-\left|y_k - h\left(\hat{x}_{k-1}\right)\right|}$.

Step 6: The calculation of Kalman is shown as follows.

$$K_k = P_{k-1} H^{*T}\left[HP_{k-1}H^{*T} + R_k\right]^{-1}$$

Step 7: State filtering $\hat{x}_k = \tilde{x}_{k-1} + K_k\left(y_k - H\tilde{x}_{k-1}\right)$

Then, let us renew the P_k

Step 8: To judge time value k, we have to depend on, if there is a

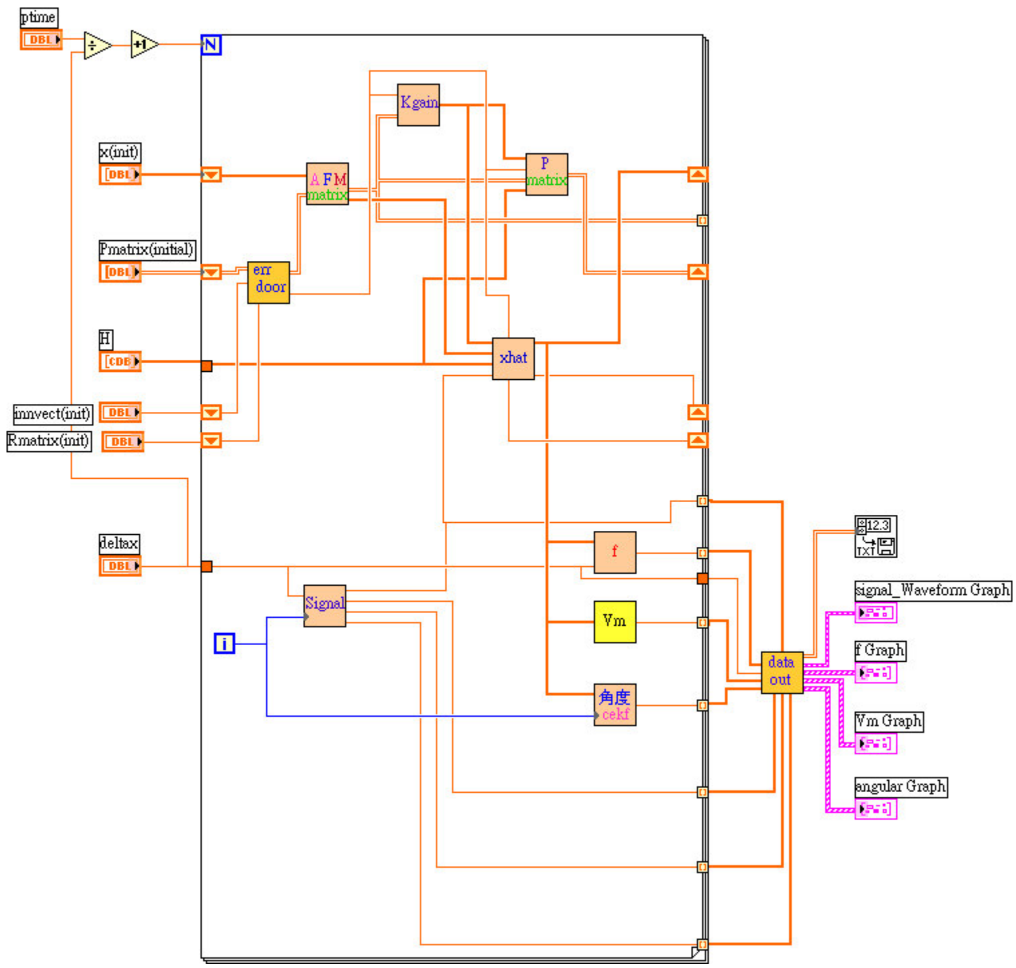

Figure 1. The program equation of robust complex extended Kalman filters.

larger setting time or not. If it is less than this value, then it has progressed to trace next time point. If it is larger than this value, then it has ended this tracking. Robust complex extended Kalman filter is by means of W_k of stage 5 which is substituted in Equation 6 to control the Kalman Gain value. Thus, it can restrain un-exact measurement value or the parameter's unusual change to the effect of total extrapolation procedure. When some unusual measurement occurs, it is presented that the measurement value y_k has a significant change. But the prediction of state variable has not detected the unusual measurement value and it has mistaken the calculation of measurement value function which is under normal condition. Thus, when the measurement value happens to distort, the absolute value of Innovation value will increase. This outcome will result in the value of exponential function to be reduced. Thus, it can assist to decrease the weight value. It can reduce the effect of distortion measurement value for extrapolation. Figure 1 shows the applied software LabVIEW edited equation of Robust Complex Extended Kalman filter.

NUMERICAL SIMULATION AND RESULTS

This paper has applied the program of robust complex extended Kalman filter on LabVIEW base. It has verified the practical measurement for three situations as follows. Firstly, it has given the sine wave by function generator. Secondly, it has given the voltage signal of laboratory grid. Thirdly, it has given the voltage signal of Sijhou secondary sub-station in Changhua County of Taiwan power company (TPC). The function generator supplies the sine wave form signal in the first condition. This signal can alter the magnitude of amplitude and frequency. This paper has proposed test signal frequency as 60 Hz and its amplitude as 1 V sine wave form signal. It has modulated parameter by the knob of function generator. The socket voltage signal measurement of micro computer laboratory is measured at National Formosa University in condition (2). The measurement of voltage value is approximately 110 V. We can get the maximum value which is 155.54 V after converting. The voltage signal measurement of Sijhou secondary sub-station is at Changhua County of Taiwan Power Company (TPC) in condition (3). Its measurement method is the same as condition (2). Now, different application results of signals measurement are depicted as follows.

Figure 2. The wave form of function generator by oscilloscope display.

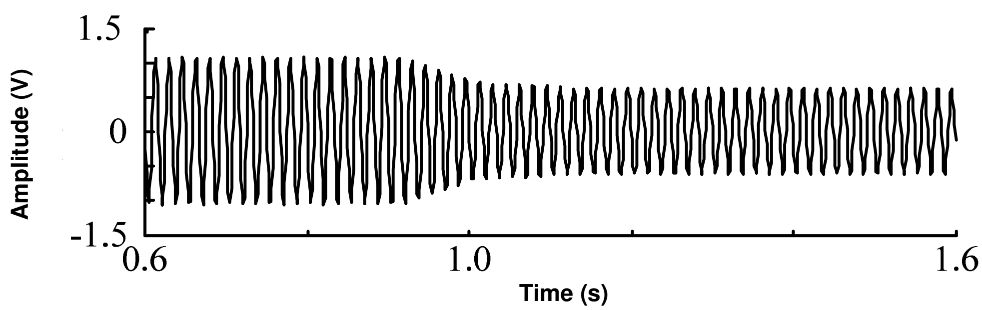

Figure 3. The signal wave form of function generator displayed from 0.6 to 1.6 s.

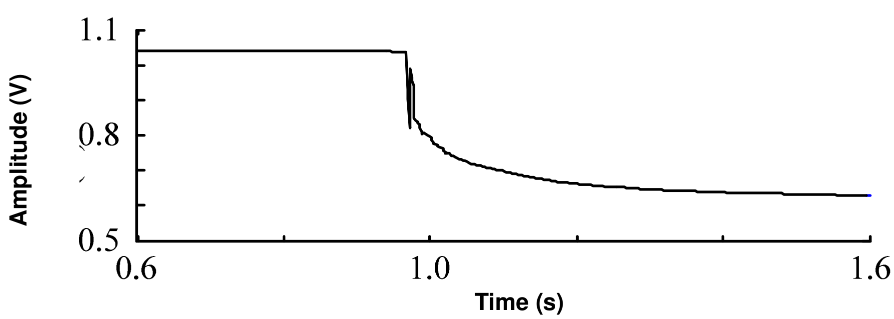

Figure 4. The amplitude extrapolation diagram of this proposed method.

Situation 1

The measurement that function generator supplies is the sine wave form signal.

Signal amplitude change

Figure 2 shows that function generator supplies the sine wave form. The frequency of this signal is 59.99 Hz and the amplitude is 1.05 V. Its amplitude is 0.625 V from 0.97 s to 1.1 s after variation. Figure 3 shows that function generator supplies the sine wave form from 0.6 to 1.6 s Figure 4 shows the amplitude extrapolation diagram of this paper's proposed method. The value of amplitude extrapolation is 1.041 V at 0.6 s before variation. Its relative error is 0.86%. The extrapolation value is 0.624 V at 1.8 s. Its relative error is 0.16%. Its response time of

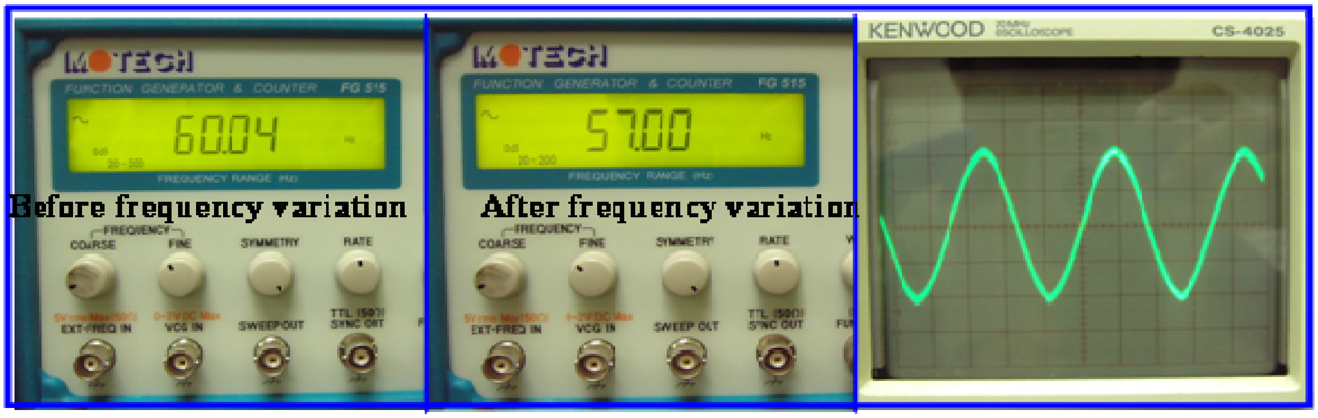

Figure 5. The wave form of function generator by oscilloscope display.

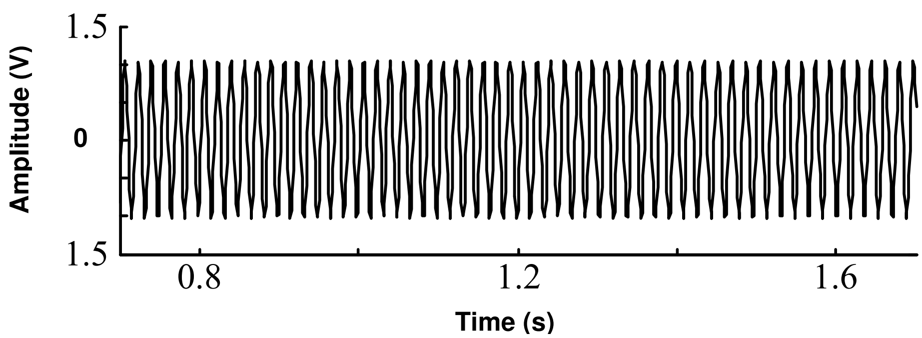

Figure 6. The signal wave form of function generator measured from 0.7 to 1.7 s.

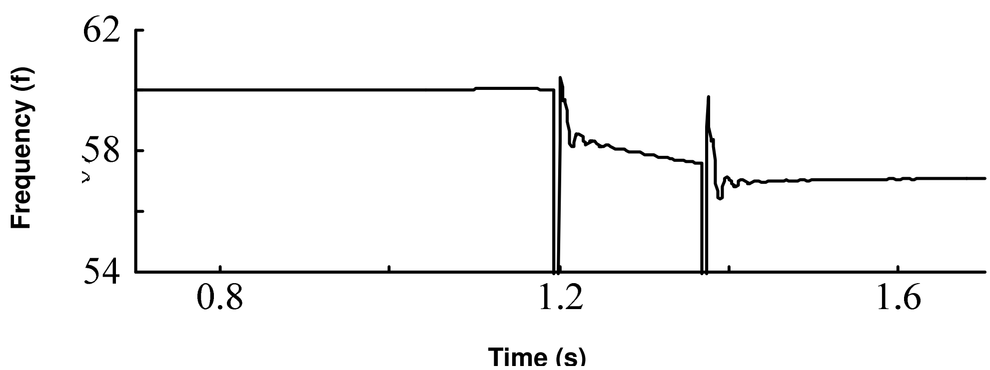

Figure 7. The frequency extrapolation diagram of this proposed method.

extrapolation is 0.7 s.

Signal frequency change

Figure 5 shows that function generator supplies the sine wave form. The frequency of this signal is 60.04 Hz and the amplitude is 1.05 V. Its frequency variation is from 1.19 to 1.40 s. Figure 6 shows that function generator supplies the sine wave form from 0.7 to 1.7 s. Figure 7 shows the frequency extrapolation diagram of this paper's proposed method. The frequency extrapolation happens to oscillate suddenly during frequency changes, then it will trace to the signal frequency. The frequency extrapolation value is 60.032 Hz at 1 s before frequency variation in Figure 7. Its value is closed to the value of

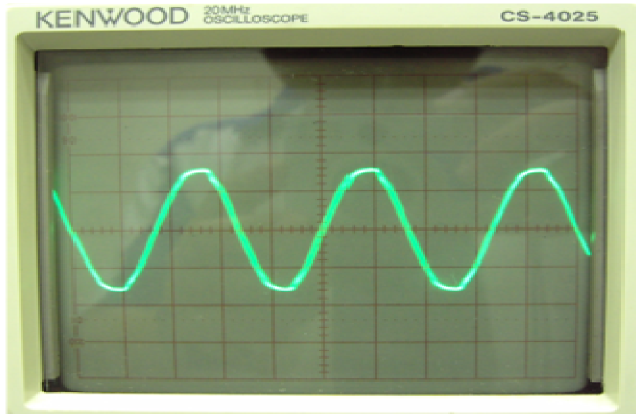

Figure 8. The grid wave form of laboratory.

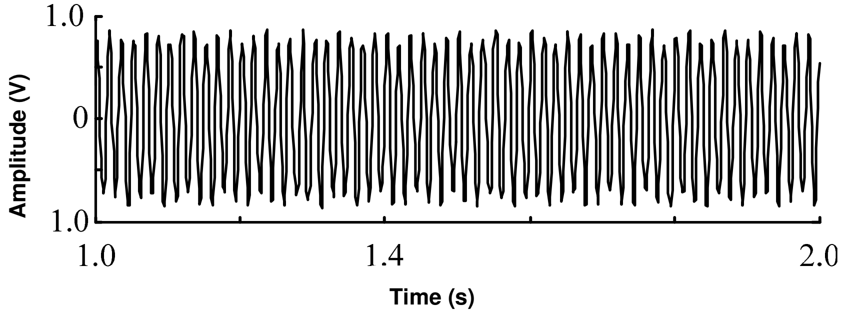

Figure 9. The grid wave form of laboratory from 1 to 2 s.

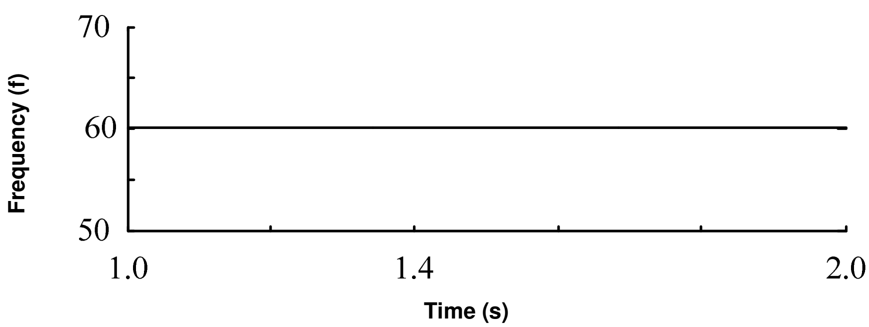

Figure 10. The frequency extrapolation diagram of this proposed method.

Figure 6. Figure 6 displays the value 60.04 Hz of function generator frequency. The relative error is 0.13% between Figures 7 and 6. After frequency variation, the frequency extrapolation value is 57.06 Hz at 1.6 s. The signal frequency of function generator is 57 Hz at 1.6 s. Therefore, there is a 0.06 Hz error at 1.6 s.

Situation 2

The grid voltage signal measurement at micro computer laboratory in National Formosa University. This condition measured the grid voltage signal of AC 110 V socket at micro computer laboratory in National Formosa University. Figure 8 shows the oscilloscope measured grid wave form by means of high voltage differential probe converting (× 200). Figure 9 shows the wave form of seizing grid signal by computer from 1 to 2 s. We can get the 0.8 V amplitude from observing the wave form of oscilloscope. The amplitude of practical grid is approximately 160 V by the scale calculation. The amplitude extrapolation value of this paper's proposed method is approximately 161.2 V. The relative error is 0.75% between measurement and extrapolation shown as Figure 10. We can get the 16.5 ms period from observing the wave form of oscilloscope. The frequency

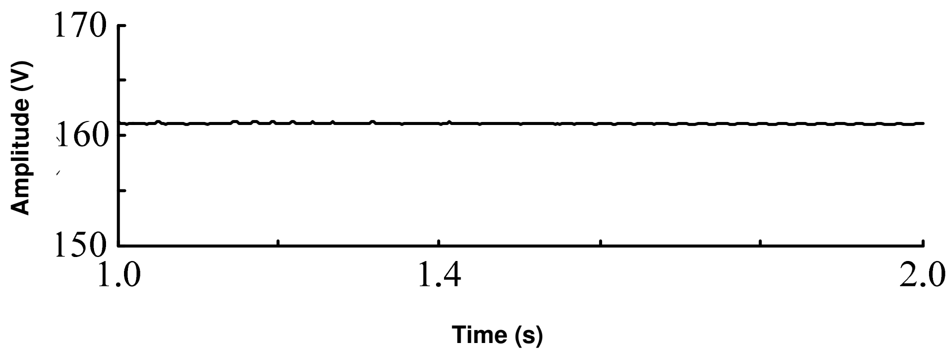

Figure 11. The amplitude extrapolation diagram of this proposed method.

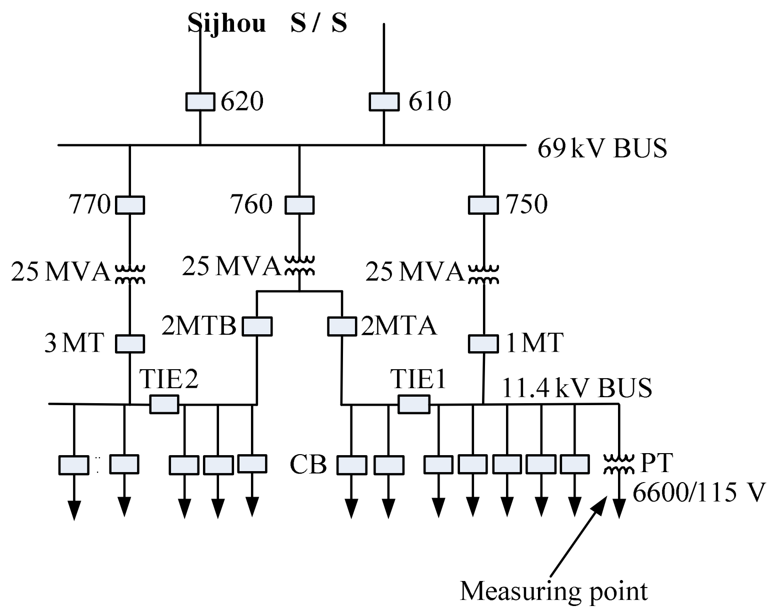

Figure 12. The single line diagram of Sijhou secondary sub-station.

value of converting is 60.06 Hz. The extrapolation frequency is 60.071 Hz. The relative error is 0.011 Hz between measurement and extrapolation shown as Figure 11.

Situation 3

The voltage signal measurement of Sijhou secondary sub-station at Changhua County of Taiwan Power Company (TPC). We take a practical measurement of Sijhou secondary sub-station at Changhua County of Taiwan Power Company (TPC). We measured the 11.4 kV BUS (Single Phase 66 KV) voltage signal at the substation by means of PT (6600/115 V) converting. The measured point is shown as Figure 12. Figure13 shows the measured wave form of power oscilloscope. Figures 14, 15 and 16 are the extrapolation diagrams of one phase frequency, amplitude and phase angle individual. The extrapolation value of frequency is 60.21 Hz. The extrapolation value of amplitude is 160.2 V. The voltage scale shown in oscilloscope is that, the amplitude is 160 V after converting. Both the extrapolation value and the oscilloscope display value are very similar. The extrapolation value of phase angle is approximately -129.5°.

Conclusions

It only takes the simulation of software verse signal parameter in past literature review. This paper proposes LabVIEW the software edited by means of the program of robust complex extended Kalman

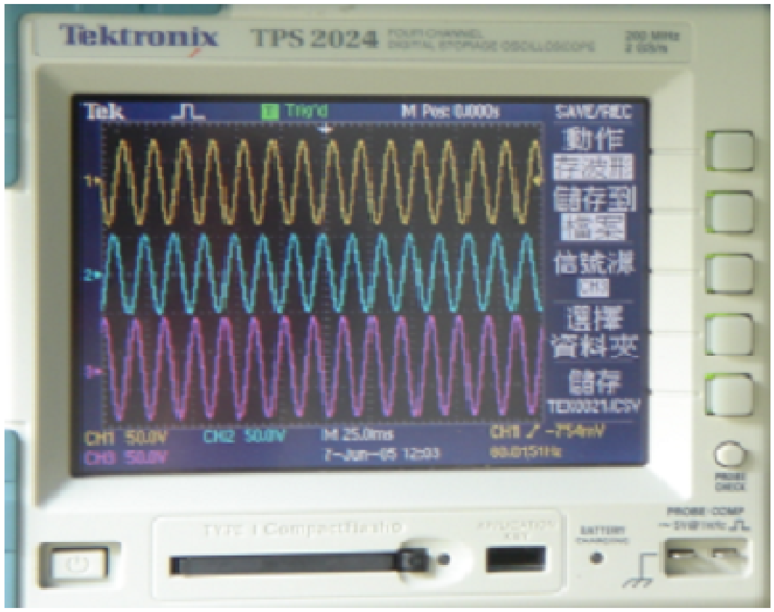

Figure 13. The measured wave form of power oscilloscope in Sijhou secondary sub-station.

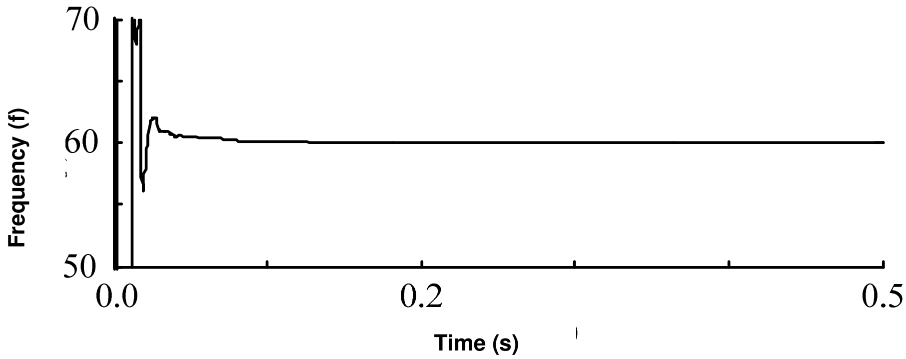

Figure 14. The frequency extrapolation diagram of this proposed method.

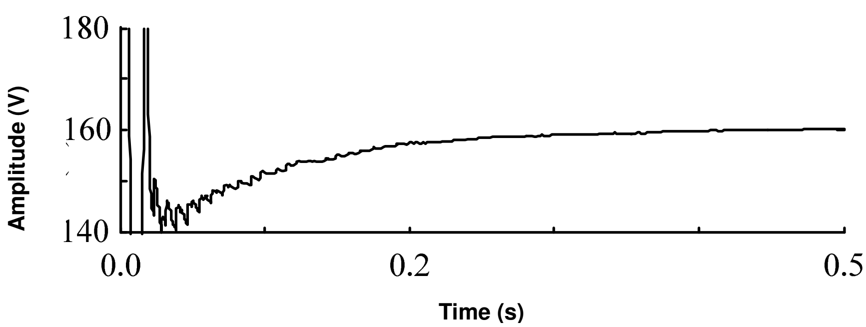

Figure 15. The amplitude extrapolation diagram of this proposed method.

filter. We can get state variable of system to trace the extrapolation parameters-amplitude, frequency and phase angle. Thus, we can accomplish to detect if the signal is in distortion or not. We can prove the feasibility of the structure that can trace the signal parameter by means of measuring the sine wave form of function

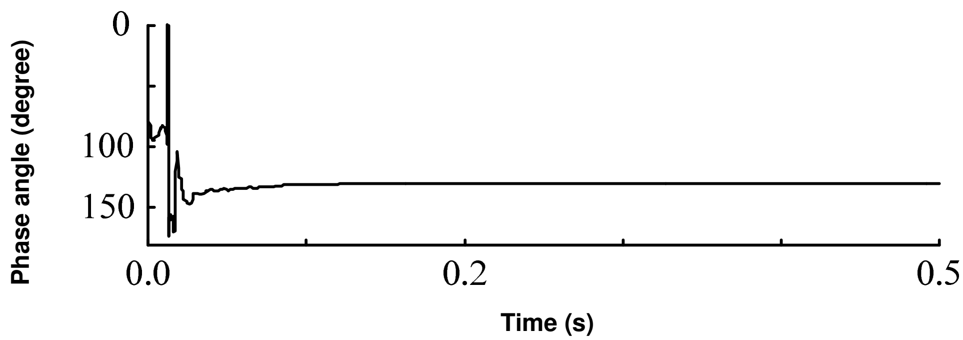

Figure 16. The phase angle extrapolation diagram of this proposed method.

generator through the AC 110 V power socket of micro computer laboratory in National Formosa University and the practical measuring Sijhou secondary sub-station at Changhua County of Taiwan power company (TPC).

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