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A Voltage-Frequency Central Difference Kalman Filter Detection Algorithm Based on d-q Coordinate Transformation

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Abstract: It is important to track and measure the amplitude and frequency of fundamental wave in AC grid accurately and rapidly. Especially on the conditions of variety interference signal. The traditionally method of filtration by software algorithm not only complex but also with low operation speed nor calculation accuracy. In this study, a nonlinear voltage-frequency detection mathematical model based on d-q coordinate transformation is presented, the Central Difference Kalman Filter (CDKF) algorithm is applied to the detection system. The simulation results show that the CDKF algorithm features high measuring precision and the calculating speed can significantly improved without external interference.

Key words: Voltage-frequency detection, CDKF, d-q coordinate transformation

INTRODUCTION

As a large number of renewable energy (photovoltaic, wind power, etc.) accessed into the electric power system, the proportion of unpredictable fluctuations in power source of system becomes more serious (Li and Zhong, 2006). The fluctuations of the output power which contains the transformation equipment and load, disturbance in power system, made the power grid voltage amplitude and frequency changed with time.

Testing and monitoring the frequency and amplitude of fundamental wave of the ac voltage accurately and rapidly plays a crucial role among the power grid, not only in the control system of power electronic circuit (Yang and Li, 2010), but also has an important significance in other control units of power supply system, as well as power quality monitoring and protection devices.

In measurement unit, the existence of all kinds of small electromagnetic signal, such as background noise, interfering the results of measurement by different degrees (Cui, 2007; Julier and Uhlmann, 2004). The adoption of the anti-interference measures hardwares would increase the measuring circuit devices. Nowadays, using appropriate software algorithm, without increasing the number of the hardware units, can achieve the purpose both of eliminating distractions and testing rapidly as well as accurately.

There are many filtering algorithm being used in testing of voltage amplitude and frequency, basically most of them belong to Kalman Filter (KF) algorithm (Cui, 2007; Rao, 2001). In some cases of the linear

observation model, the KF algorithm can make the optimal estimation to the state variables required, as a result of high precision and little error. But on contrary, if there are nonlinear components in the observation model, the observation equations needed to make Taylor series expansion for KF algorithm first, the second-order as well as higher order term could be neglected, then the linearized equation as the main observation model prepared for data calculation. Because of the high truncation errors produced by the approximation model, the precision of this kind estimation would be affected.

Extended Kalman Filter (EKF) algorithm also could be used to nonlinear observation model for processing (Dash *et al.*, 2000). But during the operation, it has to simplify the Jacobian matrix of measurement function and calculate the nonlinear state variables real-time, in the meantime, the hole speed of the measurement is lower. And the precision also needed to improve because the EKF algorithm can only achieve the first-order Taylor series in measuring process.

Unscented Kalman Filter (UKF) algorithm could be used to make the results of sampling nearby the estimated value of the state variables for the measurement (Crassidis and Markley, 2003; Julier and Uhlmann, 2004), meanwhile approximating estimate state distribution of random variables during the calculation process with the higher accuracy of result (Zhou *et al.*, 2007). Although, UKF algorithm uses actual nonlinear mode in calculation, but the speed of data processing is low and the real-time performance should be improved.

In this study, the Central Difference Kalman Filter (CDKF) is proposed for measuring voltage-frequency of

fundamental wave in AC grid (Yang and Li, 2010; Zhou and Mu, 2012). The approximation for posterior distribution of nonlinear state variables (mean and covariance) could be obtained by using central difference transformation. According to this core idea of the CDKF, compared to EKF algorithm, the nonlinear observation model of state variables and the Jacobian matrix of the measurement function would be get rid in calculating process. And at the actual conditions, the implementation of the CDKF is much simpler than UKF. No matter how complicated the nonlinearities of system model, the central difference transformation theory can approach the posterior of any nonlinear state variables with the second-order Taylor precision at least.

MATHEMATICAL MODELING FOR VOLTAGE-FREQUENCY DETECTION

Assuming that the AC voltage of power grid is three-phase balanced at the initial time of testing, with no harmonic components contained, as well as the initial voltage angle of phase A is 0, then the three-phase voltage phasor could be represented as:

$$\begin{pmatrix} u_a \\ u_b \\ u_c \end{pmatrix} = u_0 \begin{pmatrix} \cos(\omega_0 t) \\ \cos(\omega_0 t - \frac{2}{3}\pi) \\ \cos(\omega_0 t + \frac{2}{3}\pi) \end{pmatrix}$$

Among the expression above, the parameter u_0 is amplitude of steady-state voltage, the ω_0 is frequency of steady-state voltage, under this condition, the decoupled components of the voltage based on d-q transformation could be represented as Eq. 1 below:

$$\begin{pmatrix} u_d \\ u_q \end{pmatrix} = C_{32} \begin{pmatrix} u_a \\ u_b \\ u_c \end{pmatrix} \quad (1)$$

In Eq. 1, the C_{32} is a transformation matrix and the specific elements of this transformation matrix could be represented as:

$$\frac{2}{3} \begin{pmatrix} \cos \theta_0 & \cos(\theta_0 - \frac{2}{3}\pi) & \cos(\theta_0 + \frac{2}{3}\pi) \\ -\sin \theta_0 & -\sin(\theta_0 - \frac{2}{3}\pi) & -\sin(\theta_0 + \frac{2}{3}\pi) \end{pmatrix}$$

In the matrix elements, $\theta_0 = \omega_0 t + \delta_0$, δ_0 is the initial phase angle between the d axis voltage and phase A voltage. The result of the Eq. 1 could be simplified as:

$$\begin{pmatrix} u_{d0} \\ u_{q0} \end{pmatrix} = u_0 \begin{pmatrix} \cos \delta_0 \\ -\sin \delta_0 \end{pmatrix}$$

By the result above, during the steady-state time, the voltage of d axis u_{d0} and q axis u_{q0} should be dc components and with no fluctuation part. At any time while some disturbances come about in power grid (line fault, load changes, renewable energy power fluctuations, etc.), the variable quantities of the amplitude and frequency (Δu , $\Delta \omega$) would be produced in three-phase grid voltage as:

$$\begin{pmatrix} u_a' \\ u_b' \\ u_c' \end{pmatrix} = (u_0 + \Delta u) \begin{pmatrix} \cos((\omega_0 + \Delta \omega)t) \\ \cos((\omega_0 + \Delta \omega)t - \frac{2}{3}\pi) \\ \cos((\omega_0 + \Delta \omega)t + \frac{2}{3}\pi) \end{pmatrix}$$

At this time, the three-phase voltage of power grid which still balanced through as Eq. 1, then get the result as Eq. 2 below:

$$\begin{pmatrix} u_d' \\ u_q' \end{pmatrix} = C_{32} \begin{pmatrix} u_a' \\ u_b' \\ u_c' \end{pmatrix} = (u_0 + \Delta u) \begin{pmatrix} \cos(\delta_0 - \Delta \omega t) \\ -\sin(\delta_0 - \Delta \omega t) \end{pmatrix} \quad (2)$$

From the transformation result under the original steady-state frequency ω_0 , it can be confirmed that a certain amount of variation have arisen both in the quantities of state included amplitude and frequency of u_{d0} and u_{q0} , so with this understanding, the rotational frequency turns to $\omega' = \omega_0 + \Delta \omega$.

In many literatures, this results from Eq. 2 above are being used to next control parts directly, a certain extent errors would be generated in output inevitably because of linear distortion in this circumstance.

So, the dynamic voltage phasor quantity composed of amplitude u' , frequency ω' and corresponding variation amount of Δu as well as $\Delta \omega$ after disturbances must be calculated more accurately as Eq. 3-6 below:

$$u' = \sqrt{(u_d')^2 + (u_q')^2} = u + \Delta u \quad (3)$$

$$\Delta u = u' - u_0 \quad (4)$$

$$\frac{1}{u'} \frac{d}{dt} u_d' = \frac{-\sin(\delta_0 - \Delta \omega t) \Delta \omega}{-\sin(\delta_0 - \Delta \omega t)} = \Delta \omega \quad (5)$$

$$\omega' = \omega_0 + \Delta \omega \quad (6)$$

By means of the disposed as Eq. 3-6, the quantities and variations of voltage phasor can be obtained accurately.

APPLICATION OF CENTRAL DIFFERENCE KALMAN FILTER

The CDKF is a new filter algorithm for nonlinear model, any kinds of mean value and covariant component from nonlinear transformation could be estimated by CDKF. By means of Sterling interpolation formula, the nonlinear model could be expanded through the central difference form, without partial derivative of the evaluating a function and the results of state estimation would be unaffected by neither discontinuousness nor singular point of primitive function.

During the measurement of the amplitude and frequency in actual condition or operation, the measure system affected by the inevitable of disturbing quantity and background noise. The measured deviation would be came about directly in accordance with Eq. 3-6, in order to reduce the adverse effects, the interference must be removal by filtration and noise reduction

The original intention of adopting CDKF is that the quantities of state in next moment could be predicted precisely according the previous ones by the existence of various perturbations, meanwhile, in power grid, the amplitude and frequency of voltage obeys a Gaussian distribution, the condition of the application that changes of voltage come from fluctuation which in the form of mutation constitutionality of the CDKF.

Assume nonlinear model as Eq. 7:

$$\begin{aligned} x_{n+1} &= f(x_n, v_n) \\ y_n &= h(x_n, w_n) \end{aligned} \quad (7)$$

The f and h are state equation and measuring equation. x and y are quantities of state and measured value at a given time. v and w are disturbing quantities and background noise.

For example that the dimension of state vector is L in a certain nonlinear model. The Sigma points of CDKF are $2L+1$. In order that the Sigma points have the same structure of mean value variance high order central moment as the real state distribution, the Sigma points and correspondent multi-weights should be constructed as Eq. 8-11:

$$x_0 = \bar{x} \quad (8)$$

$$x_i = \bar{x} + h\sqrt{P_{x,i}}, i=1, 2, \dots, L \quad (9)$$

$$W_0 = \frac{(h^2 - L)}{h^2} \quad (10)$$

$$W_i = \frac{1}{2h^2}, i=1, 2, \dots, 2L \quad (11)$$

The specific algorithm of CDKF divided into 4 steps below:

Step 1: The generation of initial value:

$$\tilde{x}_0 = E(x_0) \quad (12)$$

$$P_0 = E((x_0 - \tilde{x}_0)(x_0 - \tilde{x}_0)^T) \quad (13)$$

Step 2: The construction of Sigma points:

$$\chi_{n-1} = (\tilde{x}_{n-1} \tilde{x}_{n-1} + h\sqrt{P_{n-1}} \tilde{x}_{n-1} - h\sqrt{P_{n-1}}) \quad (14)$$

Step 3: The time renewal:

$$\chi_{n|n-1} = f(\chi_{n-1}) \quad (15)$$

$$\tilde{x}_n = \sum W_i \chi_{i,n|n-1} \quad (16)$$

$$P_n = \sum W_i (\chi_{i,n|n-1} - \tilde{x}_n)(\chi_{i,n|n-1} - \tilde{x}_n)^T + P_w \quad (17)$$

$$y_{n|n-1} = h(\chi_{n|n-1}) \quad (18)$$

$$\tilde{y}_n = \sum W_i y_{i,n|n-1} \quad (19)$$

Step 4: The measurement renewal:

$$P_{\lambda_n y_n} = \sum W_i (\chi_{i,n|n-1} - \tilde{x}_n)(y_{i,n|n-1} - \tilde{y}_n)^T \quad (20)$$

$$P_{y_n y_n} = \sum W_i (y_{i,n|n-1} - \tilde{y}_n)(y_{i,n|n-1} - \tilde{y}_n)^T + P_v \quad (21)$$

$$K_k = P_{\lambda_n y_n} P_{y_n y_n}^{-1} \quad (22)$$

$$\tilde{x}_n = \tilde{x}_n + K_n (y_n - \tilde{y}_n) \quad (23)$$

$$P_n = P_n - K_n P_{y_n y_n} K_n^T \quad (24)$$

The P_w , P_v above are noise covariance in state procedure and measuring procedure.

According to specific computation steps above of CDKF, because of only need to put on the calculation results at this time for next calculation, the size of storage has more than is needed.

RESULTS AND ANALYSIS

According to Eq. 8, the equation states of amplitude and frequency could be build as Eq. 25:

$$\frac{1}{u'} \frac{d}{dt} \begin{pmatrix} u_d' \\ u_q' \end{pmatrix} = \begin{pmatrix} u_q' \\ -u_d' \end{pmatrix} \Delta\omega \quad (25)$$

Accession disturbing quantities v and background noise w in measuring circuit randomly, the measuring block diagram as shown in Fig.1.

In Fig. 1, the u_a^* , u_b^* , u_c^* are measurement of three-phase AC voltage, the u_d^* , u_q^* are the voltage of d axis and q axis after transformed as Eq. 2. v and w are disturbing quantities and background noise mentioned above.

The background of simulation is The IEEE 9 node example, the three-phase short circuit is set up as disturbances in 0.1sec and the short circuit would be cleared at 0.2sec, the short circuit point is set up at the balance bus. Simulation waveforms of u_d and u_q with UKF as shown in Fig. 2 and 3.

From the results as shown in Fig. 2 and 3, the rate of jitter in simulation waveforms without CDKF is huge, with lots of instantaneous variation components, the derivative calculation can not be proceeded as Eq. 25 for

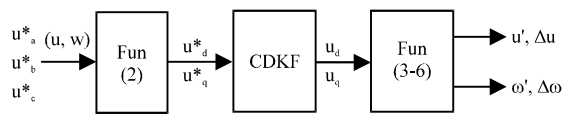


Fig. 1: Flow chart of CDKF detection algorithm

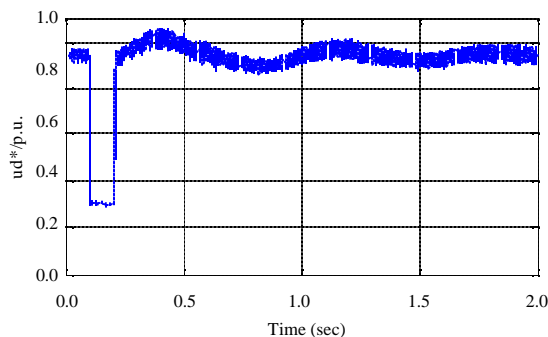


Fig. 2: Simulation waveforms of u_d with UKF

tracking the variation of frequency real-time. The waveforms of amplitude as shown in Fig. 4.

Contrastive analysis with CDKF algorithm adopted in measuring part as shown in Fig. 1. Simulation waveforms of u_d and u_q with CDKF as shown in Fig. 5 and 6.

From the results as shown in Fig.5 and Fig.6, in spite of interference existing, the waveforms of u_d and u_q with CDKF changing characteristic is more smooth than the results as shown in Fig. 2 and 3. According to Eq. 3-6, the amplitude and frequency could be calculated accuracy in time as shown in Fig. 7 and 8.

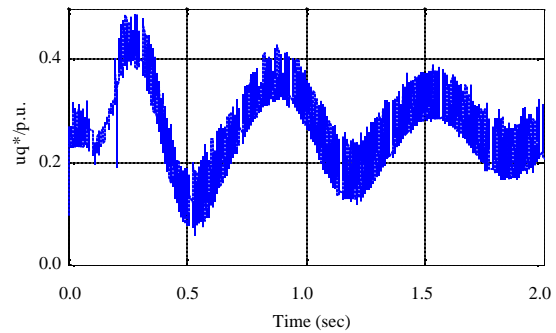


Fig. 3: Simulation waveforms of u_q with UKF

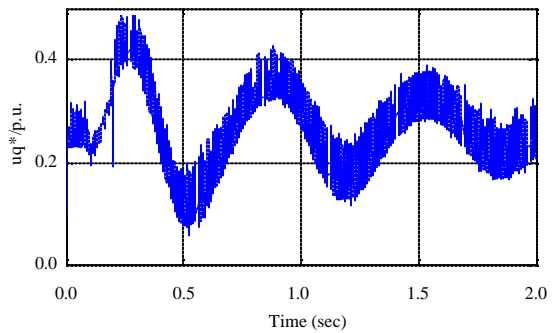


Fig. 4: Simulation amplitude of voltage with UKF

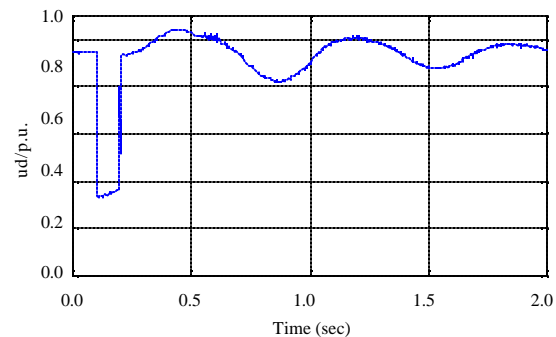


Fig. 5: Simulation waveforms of u_d with CDKF

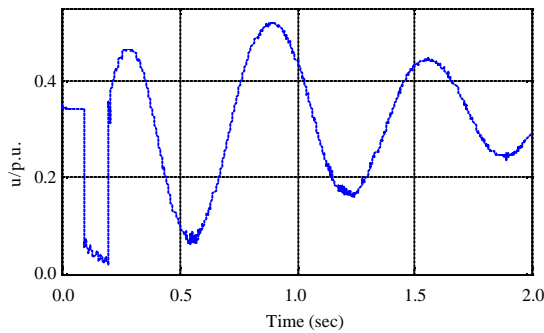


Fig. 6: Simulation waveforms of u_q with CDKF

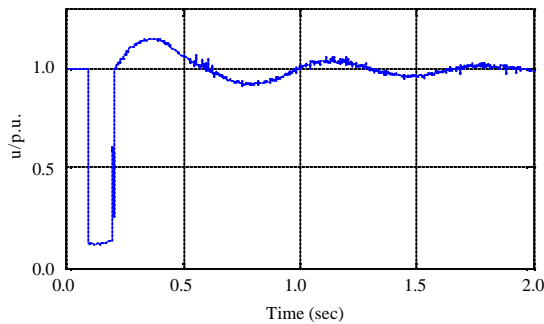


Fig. 7: Simulation waveforms of voltage with CDKF

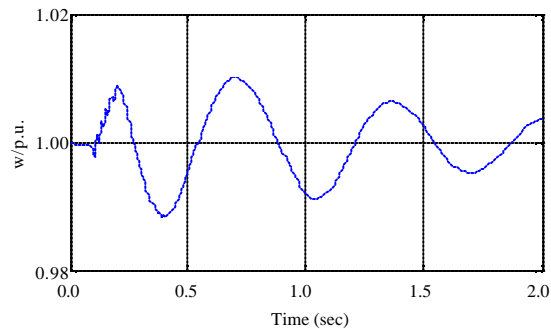


Fig. 8: Simulation waveforms of frequency with CDKF

Compared with simulation results without CDKF, the instantaneous value could be tracked by state variables u_d and u_q calculated.

CONCLUSION

Based on the analysis of a nonlinear voltage-frequency detection mathematical model in d-q coordinate transformation, the detailed movement as well as on the conditions of variety interference signal taken into consideration. Then the CDKF algorithm is applied to the detection system. The simulation results show that the

detection algorithm above can significantly improving its calculating speed and higher accuracy avoids external interference., the conclusions are listed follow:

Compared with the normal UKF, the fluctuation of State quantities could be reduced by CDKF and hole process is more observable.

The time of calculation by CDKF is shorter. Suitable for the application to the kind of power electronics equipments like VSI.

The pertinence of CDKF in other strong inertia system need to be further gone into research.

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