Calculation Method for Harmonic Impedance of System Side Based on Data Fusion

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Abstract: Starting from the existing Independent Component Analysis (ICA) method and Fluctuation Method, this paper explores the advantages and disadvantages of these two methods in calculating harmonic impedance. Combining the strengths of both methods, a data fusion-based harmonic impedance calculation method is proposed. The proposed method maintains high computational accuracy even in the presence of unstable background harmonics and correlated source signals on both sides of the Point of Common Coupling (PCC). The accuracy and effectiveness of the proposed method are verified through simulation experiments, providing theoretical guidance for subsequent harmonic mitigation efforts.

1 INTRODUCTION

With the increasing integration of nonlinear loads such as rectifiers, arc furnaces, variable frequency devices, and electrified railways, the distortion of system voltage and current waveforms caused by harmonic pollution has become a serious concern. To effectively allocate pollution responsibility and suppress harmonic pollution, accurately calculate the harmonic impedance of system side has become a pressing issue (Liu Yi., Wang Yang, Li Fengxiang.).

Fast independent component analysis (ICA) and Fluctuation Method are widely employed for assessing harmonic emission levels (Li Xiangqun, Du Wenlong, Meng Lingling). However, the former relies heavily on weak correlation between the system side and customer side, leading to significant measurement errors when there is a strong correlation between them. The latter requires stable background harmonics, and substantial measurement errors occur when the background harmonics fluctuate dramatically.

Therefore, in this paper, the concept of data fusion is introduced, and a data fusion-based method for calculating harmonic impedance is proposed. This method combines the characteristics of FastICA (Independent Component Analysis) and the Fluctuation Method method (Wang Shichmmmmmmmmmao, Li Yang, Wang Qianggang), achieving high computational accuracy even in scenarios with fluctuating background harmonics and strong correlation between the system side and customer side. In practical applications of Kalman filtering, the covariance matrices of input noise and measurement noise are often empirically determined, which introduces calculation errors. This paper presents a method for estimating the hyperparameters of the covariance matrices of input noise and measurement noise to accurately estimate them, thereby improving the accuracy of Kalman filtering in practical applications (Wang Qianggang, Xia Wei, Wang Jingcai). Finally, simulation analysis demonstrates that compared to FastICA and the Fluctuation method, the proposed method in this paper combines the advantages of both methods, expanding the applicable range and computational accuracy.

2 FASTICA ALGORITHM

2.1 Norton Equivalent Circuit

In harmonic analysis, the Norton equivalent circuit is commonly used as a theoretical model. The power grid is divided into two parts, the customer side and the system side, at the Point of Common Coupling (PCC). The Norton equivalent circuit is illustrated in Figure 1 (Wang Jingcai, 2015).

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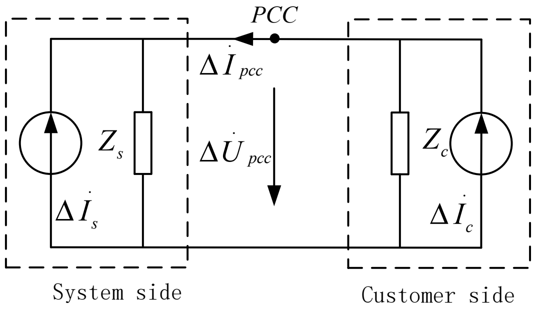

Figure 1: Harmonic Equivalent Model of System Side and customer side.

2.2 Fluctuation Method

This method starts from analyzing the fluctuation characteristics of the fluctuation magnitude at the point of common coupling (PCC). Based on the ratio of the fluctuation magnitude between the harmonic voltage and current at the PCC point, the harmonic impedance of the system is estimated.

The harmonic emission level of the user is estimated based on the measured values at the PCC point. The harmonic impedance on the system side depends on the short-circuit capacity of the system, which can be considered constant in a short period of time. The variation in the customer-side harmonic current can reflect the variation in the customer-side harmonic impedance. Therefore, when analyzing the fluctuations on the system side and the customer side, only the changes in the system-side harmonic current and the customer-side harmonic current need to be considered. Mathematically, this can be expressed as (Gong Hualin, 2010):

$$\Delta \dot{U}_{pcc} = \frac{Z_s Z_c}{Z_s + Z_c}(\Delta \dot{I}_c + \Delta \dot{I}_s) \tag{1}$$

$$\Delta \dot{I}_{pcc} = \frac{\Delta \dot{I}_c Z_c - \Delta \dot{I}_s Z_s}{Z_s + Z_c} \tag{2}$$

The harmonic voltage fluctuation characteristic at the point of common coupling (PCC), defined as KhVA, is the ratio of the fluctuation magnitude of the harmonic voltage at the PCC point to the fluctuation magnitude of the harmonic current on the common bus. Its value is given by:

$$K_{hVA} = \frac{\Delta \dot{U}_{pcc}}{\Delta \dot{I}_{pcc}} = \frac{\Delta \dot{I}_c + \Delta \dot{I}_s}{\Delta \dot{I}_c / Z_s - \Delta \dot{I}_s / Z_c} \tag{3}$$

When analyzing the fluctuations at the point of common coupling (PCC) caused by fluctuations on the system side or the customer side:

$$K_{hVA} = \frac{\Delta \dot{U}_{pcc}}{\Delta \dot{I}_{pcc}} = \begin{cases} Z_s, & \Delta \dot{I}_s = 0 \\ -Z_c, & \Delta \dot{I}_c = 0 \end{cases} \tag{4}$$

The geometric interpretation of KhVA is the slope of the harmonic voltage-current characteristic curve. As indicated by the above equation, the ratio of the harmonic current and harmonic voltage fluctuations at the PCC point can be used to estimate the harmonic impedance on both sides of the PCC point. Based on the sign of the harmonic voltage fluctuation characteristic at the PCC point, the obtained result can be identified as either the harmonic impedance on the system side or the harmonic impedance on the customer side. When the real part of the harmonic voltage fluctuation characteristic at the PCC point is positive, the result corresponds to the harmonic impedance on the system side. Conversely, when the real part of the harmonic voltage fluctuation characteristic at the PCC point is negative, the result corresponds to the negative value of the harmonic impedance on the customer side.

3 INDEPENDENT COMPONENT ANALYSIS (ICA)

Independent Component Analysis (ICA) is a novel blind source separation technique that has emerged in recent years. It separates mixed signals by exploiting the independence or weak correlation of the source signals. It primarily utilizes the independence between the fluctuation magnitudes of the customer-side harmonic sources and the system-side harmonic sources. In the absence of knowledge about the source signals, an appropriate separation matrix is obtained through iterative calculations. This matrix is then used to separate independent signal components from the measured data at the point of common coupling (PCC). These separated components exhibit a high degree of correlation with the source signals.

The basic steps of the ICA algorithm are illustrated in Figure 2 (Zhao Xi, 2015).

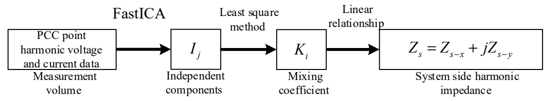

Figure 2: Basic steps of ICA algorithm.

4 DATA FUSION STRATEGY BASED ON KALMAN FILTERING

FastICA exhibits strong resistance to background harmonic disturbances but has high requirements for the mutual independence of signals. This limitation can result in situations where the separated source signals do not perfectly match the true source signals, leading to errors in calculating the harmonic impedance on the system side.

On the other hand, the fluctuation method is simple to operate and does not require mutual independence of the data, but it has poor resistance to background harmonic fluctuations, making it challenging to apply in practical situations. In order to overcome the limitations of FastICA and the fluctuation method, this paper proposes a data fusion strategy based on Kalman filtering for calculating harmonic impedance.

The proposed strategy applies the concept of data fusion to the calculation of harmonic impedance. It aims to overcome the limitations of FastICA and the fluctuation method. By employing Kalman filtering techniques, the strategy combines information from different sources to improve the accuracy of harmonic impedance estimation.

Considering the state-space model of a linear discrete dynamic system:

$$X(k) = AX(k-1) + \Gamma W(k-1) \quad (5)$$

$$Z(k) = HX(k) + V(k) \quad (6)$$

K represents discrete time; X(k) and Z(k) represent the state variable and measurement variable, respectively; W(k-1) and V(k) denote the input noise and measurement noise, respectively; **Γ** represents the noise driving matrix; A is the state transition matrix; H is the observation matrix.

Assuming that the input noise and measurement noise are mutually independent with zero means, their covariance matrices are denoted as Q and R, respectively. The statistical characteristics of the noise can be described as follows:

$$\begin{cases} E\{W(k)\} = 0 \\ E\{V(k)\} = 0 \\ E\{W(k)V^T(j)\} = 0 \\ Q(k)\delta_{kj} = E\{W(k)W^T(j)\} \\ R(k)\delta_{kj} = E\{V(k)V^T(j)\} \\ P(W) \sim (0,Q) \\ P(V) \sim (0,R) \end{cases} \quad (7)$$

When neglecting the noise errors, the prior prediction value can be obtained, and its mathematical expression is given by:

$$\hat{x}_k^- = A\hat{x}_{k-1} \quad (8)$$

$$\hat{x}_{kmea} = H^{-1}z_k \quad (9)$$

$\hat{x}_k^-$ represents the prior state prediction value at time k, and $\hat{x}_{kmea}$ represents the measurement prediction value.

The final prediction value of the Kalman filter at time k can be expressed as:

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H^{-1}\hat{x}_k^-) \quad (10)$$

K_k represents the Kalman gain, $K_k \in [0, H^{-1}]$.

The prediction error e_k and the prior error e_k^- can be expressed as:

$$e_k = x_k - \hat{x}_k \quad (11)$$

$$e_k^- = x_k - \hat{x}_k^- \quad (12)$$

When the variance of the error is minimized, the final prediction value is closest to the true value. The covariance matrix of the error, P_k, is given by:

$$P_k = E\left[e_k e_k^T\right] = E\left[(x_k - \hat{x}_k)(x_k - \hat{x}_k)^T\right] \quad (13)$$

Then

$$K_k = \frac{P_k^- H^T}{HP_k^- H^T + R} \quad (14)$$

To address the issue of increased error in Kalman filtering caused by using empirical values for Q and R, this paper proposes a hyperparameter estimation method for the covariance matrices of the input noise and measurement noise. This method aims to determine the covariance matrix Q of the input noise and the covariance matrix R of the measurement noise.

Assuming that the computational error e is given by:

$$e = Z_{s-j} - Z_{s-z} \quad (15)$$

$Z_{S\text{-}j}$ represents the computed value of the harmonic impedance on the system side, and $Z_{S\text{-}z}$ represents the true value of the harmonic impedance on the system side.

The variance of the error *e* is given by:

$$e = Z_{s-j} - Z_{s-z} \quad (16)$$

$Z_{S\text{-}j}$ represents the computed value of the harmonic impedance on the system side, and $Z_{S\text{-}z}$ represents the true value of the harmonic impedance on the system side. The variance of the error *e* is given by:

$$VAR(e) = VAR(Z_{s-j} - Z_{s-z}) \quad (17)$$

In the process of calculating the harmonic impedance, $Z_{S\text{-}z}$ is considered constant and can be treated as a constant. According to the variance propagation theorem:

$$VAR(e) = VAR(Z_{s-j} - Z_{s-z}) = VAR(Z_{s-j}) \quad (18)$$

Therefore, the values of the covariance matrix Q for input noise and the covariance matrix R for measurement noise can be determined based on the variances of the computed results obtained from FastICA and the fluctuation method.

In summary, Kalman filtering consists of three main parts: prediction, correction, and update. The computation process is shown in Figure 3, and the specific steps are as follows:

Step 1: Obtain the prior state prediction value $\hat{x}_k^-$, measurement prediction value $\hat{x}_{kmea}$, covariance matrix Q for input noise, and covariance matrix R for measurement noise. These values can be obtained using FastICA and the fluctuation method, where the prior state prediction value and measurement prediction value are computed results from FastICA and the fluctuation method, respectively.

Step 2: Calculate the prior error covariance matrix P_k^-, according to equation (13).

Step 3: Calculate the Kalman gain K_k using equation (14).

Step 4: Update the error covariance matrix P_k:

$$P_k = (I - K_k H) P_k^- \quad (19)$$

Step 5: Set k = k + 1 and repeat Step 2.

Step 6: Output the final prediction value.

The updated error covariance matrix is used to filter the signals at time k+1. In the subsequent iterations, the predicted values gradually approach the true values. The smaller the error between the computed results and the true values, the smaller the error generated by the Kalman filter.

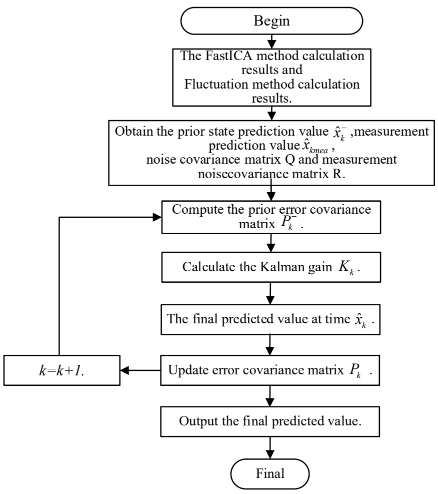

Figure 3: Kalman filter calculation flow chart.

5 CONCLUSION

In this study, a data fusion approach was introduced to combine the advantages of FastICA and the Fluctuation Method, resulting in a harmonic impedance calculation method based on data fusion. This method demonstrates high computational accuracy when dealing with intense background harmonic fluctuations and strong correlation between the system side and customer side. Furthermore, considering the empirical values commonly used for the covariance matrices of input and measurement noise in practical engineering applications of Kalman filtering, which can introduce calculation errors and affect convergence speed, a hyperparameter estimation method for the covariance matrices of input and measurement noise was proposed to accurately estimate these matrices.

Through simulation analysis and real-world cases, it was demonstrated that the proposed method, compared to FastICA and the Fluctuation Method, combines the strengths of both methods, thereby expanding the applicability range and improving computational accuracy.

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