An Improved Detection Algorithm of Three-phase Unbalanced Voltage Sag Detection Method for Improving Power Supply Reliability

C Peng¹², S L Hu¹² and X H Hao¹²

¹ School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu, China
² Center for System Reliability and Safety, University of Electronic Science and Technology of China, Chengdu, China

E-mail:201821040311@std.uestc.edu.cn

Abstract. With the popularization of high-power power electronic switching equipment and the technical update of electrical equipment, voltage sags have become a major problem affecting power quality, which seriously affects the reliability of power supply in power systems. In the case where the voltage sags failure cannot be avoided, rapid and accurate detection of the voltage sag has become a key technology for improving the reliability of the power supply of the power system. Based on the symmetrical component method, an improved detection algorithm for three-phase unbalanced voltage sag is proposed in this paper, which can significantly improve the detection speed and the reliability of power supply. The method firstly constructs the virtual orthogonal signal of the grid voltage and uses the symmetric component method to realize the fast and accurate extraction of the positive and negative sequence components of the grid voltage fundamental. In addition, an improved method for constructing virtual orthogonal signals is proposed in this paper, which effectively improves the accuracy of the constructed orthogonal signals. Finally, the feasibility and priority of the improved detection method have been verified by MATLAB/Simulink.

1. Introduction

With the rapid development of high technology in today's society, the proportion of user-sensitive equipment has increased significantly. Compared with traditional loads, these modern loads are very sensitive to power quality problems such as voltage sags and short-term interruptions. Power outages of sensitive loads caused by voltage sags become more and more [1]. Therefore, the requirements of modern power loads for power quality are becoming higher and higher, and the requirements for power supply reliability are becoming more and more strict. The reliability of power supply has become a current research hotspot [2-3].

Due to the effects of bad weather or short circuit faults, a large number of voltage sags occur every year in power grids in various regions, and voltage sags have developed into the most important power quality problem [4]. Although the voltage sag has not completely interrupted the power of the system and users, it cannot guarantee the continuous power supply for users. Therefore, it is necessary to quickly and accurately detect the voltage characteristic quantity to prevent the harm caused by the voltage sag and improve the power supply reliability of the power system.
Compared with single-phase voltage sag accidents, the damage caused by three-phase fault voltage sag is more serious, and there are relatively few studies on three-phase unbalanced voltage sag. The current literature [5] proposes a double dq transform detection method that can be used for three-phase unbalanced voltage sag. This method first performs a double dq transform and a single-phase dq transform without delay on the signal. After filtering by the pass filter, the positive sequence, negative sequence and zero sequence components of the voltage fundamental can be obtained, and then the characteristic value of the voltage sag is derived.

Because this detection method undergoes double dq transformation, the fundamental wave component is superimposed on the fundamental wave positive sequence component in the form of double frequency, and the fundamental wave positive sequence component needs to be obtained by filtering, so the voltage detection time is greatly extended, is not conducive to the fast requirements of Dynamic Voltage Restorer (DVR).

Literature [6] proposed a detection algorithm based on the least square method. This algorithm can separate the positive and negative sequence components of the fundamental wave without passing the filter when the three-phase unbalanced sag of the grid voltage occurs. The speed has increased, but this method does not consider the results of grid frequency detection and phase-locked detection, which are not very ideal.

In this paper, a fast detection method for three-phase unbalanced voltage sag is proposed based on the principle of symmetrical components in a rotating coordinate system. It can effectively deal with the accuracy and rapidity requirements of unbalanced voltage sag detection, and quickly extract the positive and negative sequence components of unbalanced voltage. Finally, the method is simulated and verified by MATLAB/Simulink, and the results show that the method is fast and practical.

2. Traditional power grid voltage imbalance detection method

According to the principle of the symmetric component method, the voltage of the three-phase unbalanced power grid can be decomposed into a positive sequence component, a negative sequence component and a zero sequence component. Based on the above assumptions, the three-phase asymmetric grid voltage can be described by the following formulas:

\[
U = U^+ + U^- + U^0 \tag{1}
\]

\[
U^+ = \begin{bmatrix}
u^+_a(t) \\
u^+_b(t) \\
u^+_c(t)
\end{bmatrix} = \begin{bmatrix}
U^+ \sin(\omega t + \theta) \\
U^+ \sin(\omega t + \theta - 2\pi/3) \\
U^+ \sin(\omega t + \theta + 2\pi/3)
\end{bmatrix} \tag{2}
\]

\[
U^- = \begin{bmatrix}
u^-_a(t) \\
u^-_b(t) \\
u^-_c(t)
\end{bmatrix} = \begin{bmatrix}
U^- \sin(\omega t + \xi) \\
U^- \sin(\omega t + \xi + 2\pi/3) \\
U^- \sin(\omega t + \xi - 2\pi/3)
\end{bmatrix} \tag{3}
\]

\[
U^0 = \begin{bmatrix}
u^0_a(t) \\
u^0_b(t) \\
u^0_c(t)
\end{bmatrix} = \begin{bmatrix}
U^0 \sin(\omega t + \phi) \\
U^0 \sin(\omega t + \phi) \\
U^0 \sin(\omega t + \phi)
\end{bmatrix} \tag{4}
\]

Where, \(U^+, \theta, U^-, \xi, U^0, \phi\) are the amplitude and initial phase of the positive, negative, and zero sequence components of the power grid.

Synchronous rotating coordinate transformation of the asymmetrical grid voltage signal shown in equation (1):

\[
U^+ = \begin{bmatrix}
u^+_a(t) \\
v^+_b(t) \\
v^+_c(t)
\end{bmatrix} = \begin{bmatrix}
U^+ \sin(\omega t + \theta) \\
U^+ \sin(\omega t + \theta - 2\pi/3) \\
U^+ \sin(\omega t + \theta + 2\pi/3)
\end{bmatrix} \tag{2}
\]

\[
U^- = \begin{bmatrix}
u^-_a(t) \\
v^-_b(t) \\
v^-_c(t)
\end{bmatrix} = \begin{bmatrix}
U^- \sin(\omega t + \xi) \\
U^- \sin(\omega t + \xi + 2\pi/3) \\
U^- \sin(\omega t + \xi - 2\pi/3)
\end{bmatrix} \tag{3}
\]

\[
U^0 = \begin{bmatrix}
u^0_a(t) \\
v^0_b(t) \\
v^0_c(t)
\end{bmatrix} = \begin{bmatrix}
U^0 \sin(\omega t + \phi) \\
U^0 \sin(\omega t + \phi) \\
U^0 \sin(\omega t + \phi)
\end{bmatrix} \tag{4}
\]

Where, \(U^+, \theta, U^-, \xi, U^0, \phi\) are the amplitude and initial phase of the positive, negative, and zero sequence components of the power grid.
where,

\[
T_{3s/2s}(ωt) = \begin{bmatrix}
\sin ωt & \sin \left( ωt - \frac{2π}{3} \right) & \sin \left( ωt + \frac{2π}{3} \right) \\
\cos ωt & \cos \left( ωt - \frac{2π}{3} \right) & \cos \left( ωt + \frac{2π}{3} \right)
\end{bmatrix}
\]

Therefore, the expression of equation (1) in the rotating coordinate system can be written as

\[
\begin{align*}
U_q &= U^+ \cos θ - U^- \cos (2ωt + \xi) \\
U_q &= U^+ \sin θ + U^- \sin (2ωt + \xi)
\end{align*}
\]

It can be seen that when the voltage of the power grid is unbalanced, it appears in the time domain as a DC component with a frequency-doubled AC component instead of a constant DC component after single synchronous coordinate transformation. In order to improve the accuracy of the output phase, it is necessary to design a low pass filter (LPF) to filter out the AC component of the double frequency [7]. However, the use of filters significantly slows down the phase lock speed.

**Figure 1.** Fast detection method for three-phase unbalanced voltage sag.

The fast detection method of asymmetrical power grid proposed in this paper is shown in Figure 1. First, considering that the three-phase asymmetrical grid voltage is the sum of three independent single-phase grid voltages. Next, the above three independent single-phase voltage signals are respectively constructed by virtual orthogonal signal, in order to obtain the orthogonal signals of each phase. To obtain the phasor expressions of the positive sequence component and the negative sequence component in the asymmetric grid voltage, and the symmetric component method can be used to perform positive sequence transformation and negative sequence transformation on the above phasor expression. Finally, in the asymmetric grid voltage formula, the time domain expression of the positive sequence component and the negative sequence component can be obtained by picking the α component from the above phasor expression. If harmonics, noise, frequency drift and other factors are not considered, the above ideas can achieve instantaneous phase-locking, so that it can significantly increase the synchronization speed of the power grid under asymmetric condition, the detailed derivation process is as follow.

**3. Fast construction method of voltage sequence component**
This paper is based on the classical symmetric component method to quickly extract the fundamental positive sequence voltage component. The process based on the symmetric component method in the form of phasors can be described by the following formula:

\[ U^+ = \tilde{T} \tilde{U} \]  

(7)

Where: \( \tilde{U} \) is the phasor of the virtual asymmetric grid voltage; \( U^+ \) is virtual positive sequence components; \( \tilde{T} \) is the positive sequence transformation matrix, expressed as

\[ \tilde{T} = \frac{1}{3} \begin{bmatrix} 1 & a & a^2 \\ a^2 & 1 & a \\ a & a^2 & 1 \end{bmatrix}, \quad a = e^{\frac{2\pi}{3}}, \quad a^2 = e^{\frac{2\pi}{3}} \]

The phasor expressions of the virtual asymmetrical grid voltage and its virtual positive sequence components can be described in the two-phase stationary coordinate system as

\[ U = U_a + j U_b \]

\[ U^+ = U_a^+ + j U_b^+ \]

(8)

(9)

Where:

\[ U_a = \begin{bmatrix} u_a(t) \\ u_b(t) \\ u_c(t) \end{bmatrix}, \quad U_b = \begin{bmatrix} u_a(t) \\ u_b(t) \\ u_c(t) \end{bmatrix}, \quad U_a^+ = \begin{bmatrix} u_a^+(t) \\ u_b^+(t) \\ u_c^+(t) \end{bmatrix}, \quad U_b^+ = \begin{bmatrix} u_a^+(t) \\ u_b^+(t) \\ u_c^+(t) \end{bmatrix} \]

The phase-locked operation of the single-phase system needs to construct a set of orthogonal signals required for synchronous rotation coordinate transformation \( (\alpha\beta/dq) \), one is collected in real time, and the other one needs to be constructed virtually by the single-phase grid voltage signal collected. The construction rules of the orthogonal signal group in this paper as follow: select the single-phase grid voltage signal collected in real time as the \( \alpha \)-axis component, and use the orthogonal component constructed virtually as the \( \beta \)-axis component. Among them, the construction method of virtual orthogonal components will be explained in detail later.

Therefore, according to the above construction rules, the positive sequence component of the three-phase unbalanced voltage can be obtained by combining the above equations and taking the real part

\[ U^+ = T_{\alpha a} U_a + T_{\alpha b} U_b \]

(10)

Where:

\[ T_{\alpha a} = \frac{1}{6} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}, \quad T_{\beta a} = \frac{\sqrt{3}}{6} \begin{bmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix} \]

The construction method of the negative sequence component is similar to the construction method of the positive sequence component. Due to paper limit, detailed derivation is no longer repeated, and the conclusion is directly given as follow:

\[ U^- = T_{\alpha a} U_a + T_{\alpha b} U_b \]

(11)
Where:

\[
T_{2a} = \frac{1}{6} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2 \\
\end{bmatrix},
T_{2b} = \frac{\sqrt{3}}{6} \begin{bmatrix}
0 & 1 & -1 \\
-1 & 0 & 1 \\
1 & -1 & 0 \\
\end{bmatrix}
\]

4. Open loop calculation method of voltage amplitude and phase

4.1. Typical amplitude phase detection method
Taking the positive sequence component as an example [8-9], the positive sequence component in the asymmetrical grid voltage can be quickly constructed according to equation (10), and the positive sequence component is substituted into equation (5) to perform synchronous rotation coordinate transformation, and we can obtain that:

\[
\begin{align*}
U_d &= U^* \cos \theta \\
U_q &= U^* \sin \theta
\end{align*}
\]

So the amplitude of the positive sequence component of the grid voltage is

\[
U^* = \sqrt{(U_d)^2 + (U_q)^2}
\]

If the initial phase \( \theta \in [0, 2\pi] \) of the positive-sequence voltage component is assumed, the synchronous phase of the grid voltage can be obtained according to equation (12):

\[
\sigma = \omega t + \theta = \omega t + \arctan \left( \frac{U_q}{U_d} \right) + \theta_{ex}
\]

Where:

\[
\theta_{ex} = \begin{cases} 
0, & U_d > 0, U_q > 0 \\
\pi, & U_d < 0 \\
2\pi, & U_d > 0, U_q < 0
\end{cases}
\]

4.2. Improved construction method of virtual orthogonal signal
In order to overcome the shortcomings of the high delay brought by the delay \( T/4 \) method and the inaccurate construction caused by the differentiation method [10-12], this paper proposes a short-time delay (STD) method, which is orthogonal signal construction method that can obtain orthogonal signals quickly and accurately.

The orthogonal component in equation (10) can be written as:

\[
\begin{align*}
u_{ua}(t) &= U_k \cos(\omega t + \phi_k) \\
u_{ub}(t) &= U_k \sin(\omega t + \phi_k)
\end{align*}
\]

Where: the value of \( k \) is a, b, c. \( U_k \) represents Amplitude

Supposing that one sampling period is \( T_s \), equation (15) can be rewritten as:

\[
\begin{align*}
u_{ua}(t) &= U_k \cos(\omega (t + T_s) + \phi_k) + U_m \cos(\omega t + \phi_m) \\
u_{ub}(t) &= U_k \sin(\omega (t + T_s) + \phi_k) - U_m \sin(\omega t + \phi_m)
\end{align*}
\]
Hence,

\[
\begin{align*}
    u_{ka}(t) &= u_{ka}(t+T_s)\cos(\omega T_s) + u_{qa}(t+T_s)\sin(\omega T_s) \\
    u_{kb}(t) &= u_{kb}(t+T_s)\cos(\omega T_s) - u_{qa}(t+T_s)\sin(\omega T_s)
\end{align*}
\]  \hspace{1cm} (17)

After simplification, the relationship between \(u_{ka}\) and \(u_{kb}\) after delaying \(T_s\) can be written as:

\[
    u_{kb}(t) = \frac{u_{ka}(t+T_s) - u_{ka}(t)\cos(\omega T_s)}{\sin(\omega T_s)} \hspace{1cm} (18)
\]

Considering that the above algorithm can only be implemented in discrete form, the virtual orthogonal signal constructed \(u_{kb}\) can be expressed at the \(k\)th sample

\[
    u_{kb}(k) = \frac{u_{ka}(k) - u_{ka}(k-1)\cos(\omega T_s)}{\sin(\omega T_s)} \hspace{1cm} (19)
\]

As shown in Figure 2, the accuracy of the quadrature signal constructed by the short-time delay method does not change with the sampling period \(T_s\), and the accuracy of the algorithm is relevant to the sampling rate of the discrete system.

![Figure 2](image_url)

**Figure 2.** The effect of different sampling frequencies on the construction of orthogonal signals. Sampling frequency is (a) 0.4kHz; (b) 1kHz.

### 5. Simulation analysis

In this paper, MATLAB/Simulink software is used to simulate the three-phase unbalanced voltage sag fault, and comparing the effects of the traditional detection method with the effects of the rapid detection method proposed. In order to observe the magnitude of the voltage sag intuitively, all value is expressed with the per unit in the figure.
Suppose that the three-phase unbalanced voltage sag fault occurs from 50ms to 150ms, the system sampling period $T_s$ is $10^{-3}$ms, and the fault waveform is shown in Figure 3.

![Figure 3. Three-phase unbalanced voltage sag waveform.](image)

In order to effectively filter out the double power frequency clutter (100Hz) in the three-phase unbalanced voltage sag detection, a 4th order Butterworth LPF with cut-off frequency which is 45Hz was designed in Traditional detection method. The STD method mentioned in this paper sets delay time which is 2ms to construct the virtual orthogonal component, and the detection results are shown in Figure 4.

![Figure 4. Comparison of different detection methods show as (a) Overall waveform comparison; (b) Start area waveform comparison; (c) End area waveform comparison.](image)

It can be seen from the simulation results that when the three-phase unbalanced voltage sag occurs in the power system, the dynamic response time of the traditional detection method is about 10ms, and the detection time of the fast detection method proposed in this paper is about 2.5ms, and the detection results follow the ideal detection waveform well. Experiment shows that the fast detection method
proposed in this paper greatly shortens the detection time of unbalanced voltage sag, and then improves the reliability of power supply.

6. Conclusions
Quick and accurate detection of the grid voltage is a basic requirement to ensure the reliability of power supply in the power system. This paper analyzed the shortcomings of the traditional closed-loop phaselocked method in the aspect of dynamic response speed and response to power grid voltage asymmetry; based on applying the symmetric component method and virtual orthogonal signal, this paper puts forward a calculation formula which can quickly and accurately separate the positive sequence component and the negative sequence component, and according to this, a fast detection algorithm for three-phase unbalanced voltage sag is proposed.

When the grid voltage releases three-phase unbalanced voltage sag, the method can quickly detect its positive sequence component and negative sequence component. When the frequency change is not considered, the dynamic response time of the new method is less than 3ms. Therefore, the rapid detection method proposed in this paper significantly improves the detection speed of the three-phase unbalanced voltage, ensures the real-time and accuracy of the dynamic voltage restorer, and can significantly improve the power supply quality problems caused by the three-phase unbalanced voltage sags.

References
[1] X Zhou, F H Wang, R H Huang, J Zhang and L Feng 2015 Assessment of voltage sags in substations based on power system and equipment sensitivity analysis Proceedings of the CSEE 35 1940-1946
[2] Mbarr J and Majumder R 2015 Integration of distributed generation in the volt/var management system for active distribution networks IEEE Transactions on Smart Grid 6 576-586
[3] G Weng, F T Huang and Y R Nan 2017 Optimize allocation of power quality monitoring sites with Distributed generators Transactions of China Electrotechnical Society 32 229-238
[4] S Tao, X N Xiao and X J Liu 2005 Study on distribution reliability considering voltage sags and acceptable indices Proceedings of the CSEE 25 63-69
[5] Liu Y C, C Huang, L Q Ou and W M Zhao 2007 Method for unbalanced voltage sags detection based on dq transform Proceedings of the CSU-EPSA 3 72-76
[6] X H Hao, S X Fang and W Chen 2010 Research and emulation of detection algorithm of dynamic voltage Restorer Technique and Method 29 72-74
[7] B C Wang, G C San and X Q Guo 2013 Grid synchronization and PLL for distributed power generation systems Proceedings of the CSEE 33 50-55
[8] L S Xiong, F Zhuo, X K Liu, M H Zhu and Y Chen 2015 Research on fast phase synchronization scheme for three-phase unbalanced power system Proceedings of the CSEE 35 5682-5691
[9] Kaura V and Blasko V 1997 Operation of phase loop system under distorted utility conditions IEEE Transactions on Industrial Application 33 58-63
[10] G L Zhao, B Z Liu, X N Xiao and H Y Xu 2004 Application of improved d-q transform without time delay in dynamic voltage disturbance identification Power System Technology 28 53-57
[11] J Zhou, X L Fu and S G Li 2019 Single phase voltage sag detection method based on derivation αβ-dq transformation combined with morphological filter Electrical Measurement & Instrumentation 8 12-23
[12] S Qu, C Huang, Y Q Jiang and Z X Zeng 2013 A new detection method of voltage sag applied in DVR Transactions of China Electrotechnical Society 28 234-239