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An Improved Method for Voltage Sag Detection Based on Weighted Least-Squares Estimation with Harmonic Models

***Abstract**. A rapid voltage sag detection method based on weighted least-squares estimation (WLSE) with harmonic models is proposed to satisfy the requirement of the dynamic voltage restorer. The covariance resetting technique is adopted to detect the voltage sag accurately and rapidly, even in condition the voltage contains considerable amount of harmonic components. The threshold of covariance resetting is larger than the steady state error between the sample and estimation of the voltage for the purpose of favorable covariance resetting only if the voltage sag occurs. The threshold of covariance resetting can be small because the steady state error will contain little harmonic components by the proposed WLSE method which have a positive impact on the detecting speed even if the depth of voltage sag is low. The algorithm has been tested under different conditions so as to verify its performance on voltage sag detection.*

***Streszczenie.** Zaproponowano metodę szybkiej detekcji zapadu napięcia bazująca na określaniu średniej ważonej najmniejszych kwadratów. Do detekcji zapadu wykorzystuje się technikę kowariancji co umożliwia szybką detekcję nawet przy znacznej zawartości harmonicznych. (**Ulepszona metoda detekcji zapadów napięcia bazująca na określaniu wartości ważonej najmniejszych kwadratów z uwzględnieniem harmonicznych**)*

Keywords: dynamic voltage restorer; voltage sag detection; harmonic models; weighted least-squares estimation.
Słowa kluczowe: zapady napięcia, dynamiczne odzyskiwanie wartości napięcia

Introduction

Voltage sag is defined as a dropping of root-mean-square(rms) voltage value from 0.9 pu to 0.1pu of nominal value for durations from 0.5 cycle to 1min [1], which can be caused by many reasons such as motor starting and short circuits. In generic situation, even if a short duration of voltage sag is detrimental to the stable operation of sensitive loads.

Dynamic voltage restorer (DVR) is an effective way to minimize the negative impact of voltage sag. Once the voltage sag is detected, the DVR will compensate the voltage of loads[2,4]. Therefore, quickly detection of voltage sag is the key issue for a DVR to function properly.

The symmetrical voltage sag detection methods, by means of transformation of the three-phase voltages to a rotating or a stationary reference, are widely used for its simplicity [5,6]. However, due to the harmonic components in supply voltage, analog or digital filters are required to suppress the harmonics. That is, there would be a tradeoff between precision of voltage sag detection and capability of harmonic suppressing. What is more, non-symmetrical voltage sags which are the majorities, will result in unacceptable inaccuracy by means of symmetrical detection method.

To solve this problem, several single-phase voltage sag detection methods, based on fourier transform, kalman filters and wavelets, have been proposed [7,8]. The rapidity of voltage sag detection based on Fourier transform depends on the length of window. The rms voltage will be refreshed rapidly when the window is sufficiently short, but at the same time the harmonic components will result in inaccuracy of the rms value. In [9], the sliding-window rms calculation method based on Fourier transform simultaneously caters for the rapidity and accuracy. However, if the voltage sag contains phase jump, the proposed method will be limited.

A rapid and accurate single-phase voltage sag detection method based on weighted least-squares estimation(WLSE) with harmonic models(HWLSE) is proposed in this paper. It is suitable for either symmetrical or non-symmetrical voltage sag detection. The proposed algorithm will get the estimation of fundamental and harmonic components accurately even if the supply voltage is distorted. The covariance resetting technique is adopted to detect the voltage sag rapidly. , the voltage sag detection will be delayed if the covariance is reset frequently when the supply voltage is steady. In such a case, the threshold of covariance resetting should be larger than the steady state error between the sample and estimation of supply voltage, which means that covariance will be resetted only if the voltage sag occurs. HWLSE algorithm is recommended, with regard to minimizing the threshold without missing covariance resetting when the depth of voltage sag is low. The experimental results verify the performance of the proposed method on voltage sag detection.

HWLSE Algorithm

A single-phase voltage with harmonic components Vs is defined as

$$V_s(t)=\sum_{n=1}^{N}V_n\cos(\omega_n t+\theta_n)=\sum_{n=1}^{N}\left(V_{dn}\cos\omega_n t-V_{qn}\sin\omega_n t\right) \quad (1)$$

where V_n is the amplitude, ω_n is a constant angular frequency, θ_n is the phase angle.

$$\begin{cases}V_{dn}=V_n\cos\theta_n\\ V_{qn}=V_n\sin\theta_n\end{cases}, \text{ n=1,2,3…N.} \quad (2)$$

Equation (1) can be expressed in terms of matrix, which is as follows

$$y(t_i)=H(t_i)x(t_i) \quad (3)$$

where

$$H(t_i)=\left[\cos(\omega_1 t_i)\quad -\sin(\omega_1 t_i)\quad ...\quad \cos(\omega_N t_i)\quad -\sin(\omega_N t_i)\right] \quad (4)$$

$$x(t_i)=\left[V_{d1}(t_i)\quad V_{q1}(t_i)\quad ...\quad V_{dN}(t_i)\quad V_{qN}(t_i)\right]^T \quad (5)$$

$$y(t_i)=V_s(t_i) \quad (6)$$

The cost function is chosen as

$$J\left[x(t_i)\right]=\sum_{j=0}^{i}\lambda^{i-j}\left(y(t_i)-H(t_i)\hat{x}(t_i)\right)^2 \quad (7)$$

where $\lambda\in(0,1)$ is the forgetting factor.

The solution $\hat{x}(t_i)=\left[\hat{x}_1(t_i)\quad ...\quad \hat{x}_N(t_i)\right]$ minimizes the cost function to achieving the optimum estimation, which $\hat{x}_n(t_i)$ is obtained by the following least-squares algorithm[10,11], which is shown as

$$r_n(t_i)=1+H_n(t_i)P_n(t_{i-1})H_n(t_i)^T \quad (8)$$

(9) $k_n(t_i) = P_n(t_{i-1}) H_n(t_i)^T r_n(t_i)^{-1}$

(10) $P_n(t_i) = \lambda^{-1}\left(P_n(t_{i-1}) - k_n(t_i) H_n(t_i) P_n(t_{i-1})\right)$

(11) $\hat{x}_n(t_i) = \hat{x}_n(t_{i-1}) + k_n(t_i)\left(y(t_i) - H(t_i)\hat{x}(t_{i-1})\right)$

where

(12) $H_n(t_i) = \left[\cos(\omega_n t_i) \quad -\sin(\omega_n t_i)\right]$,

(13) $x_n(t_i) = \left[V_{dn}(t_i) \quad V_{qn}(t_i)\right]$,

$\hat{x}_n(t_{-1}) = 0$, $P_n(t_{-1}) = \pi_{0n} I \in \mathbb{R}^{2\times 2}$ and $\pi_{0n} > 0$ is the initial covariance constant.

According to the solution $\hat{x}_1(t_i)$, the amplitude of estimated fundamental component of the single-phase voltage is described as

(14) $$\hat{V}_1 = \sqrt{\hat{V}_{d1}^2 + \hat{V}_{q1}^2}$$

Volatge Sag Detection

When a sudden change in the voltage has been recognized, the new solution $\hat{x}(t_i)$ will track the changed voltage.The tracking process maybe lasts several cycles, which is discrimental to the speed of voltage sag detection. However, if the covariance $P_n(t_{i-1})$ is reset with initial constant simultaneously, the tracking process will be faster, which is the so-called covariance resetting technique.

The steady state error between the sampled voltage and estimated voltage is defined as

(15) $$e(t_i) = y(t_i) - H(k_i)\hat{x}(t_i)$$

The covariance resetting technique is adopted only if $\left\|e(t_i)\right\|$ is larger than threshold ε , which avoid resetting frequently in normal condition. The threshold ε needs to be small, so that covariance resetting will not miss when the depth of voltage sag is low. Due to HWLSE algorithm, $\left\|e(t_i)\right\|$ can be small even if the supply voltage is distorted, for the reason that the algorithm not only estimates the fundamental component and also estimates the harmonic components. That is, the quality of the supply voltage has little impact on voltage sag detection based on HWLSE algorithm.

The covarience will be reset several times when a severe voltage sag occurs, which is due to the small threhsold. In such case, the tracking process will be slow. To ensure that the covariance will be reset only once when the sag occurs, the interval time of covariance resetting is set as half-cycle.

Experimental Results

The proposed voltage sage detection method is evaluated by using TMS320F2812 control chip, and the sampling frequency is 5kHz. Because in generic situation, the third, fifth and seventh harmonic components are large relatively, HWLSE algorithm only contains fundamental, third, fifth and seventh models for the purpose of reducing computational burden. The threshold ε is set as 0.15*V_1, and the initial value of $P_n(t_{-1})$ is given as

(16) $$\begin{cases} \pi_1 = 30 \\ \pi_{3,5,7} = 10 \end{cases}$$

The distorted single-phase voltage is supplied by the programmable AC source, which is given as

(17) $$\begin{aligned} V_s(t) = {} & 100\sin(\omega t) + 5\sin(3\omega t) \\ & + 5\sin(5\omega t) + 5\sin(7\omega t) \\ & + 2\sin(9\omega t) + 2\sin(11\omega t) \\ & + 2\sin(13\omega t) \end{aligned}$$

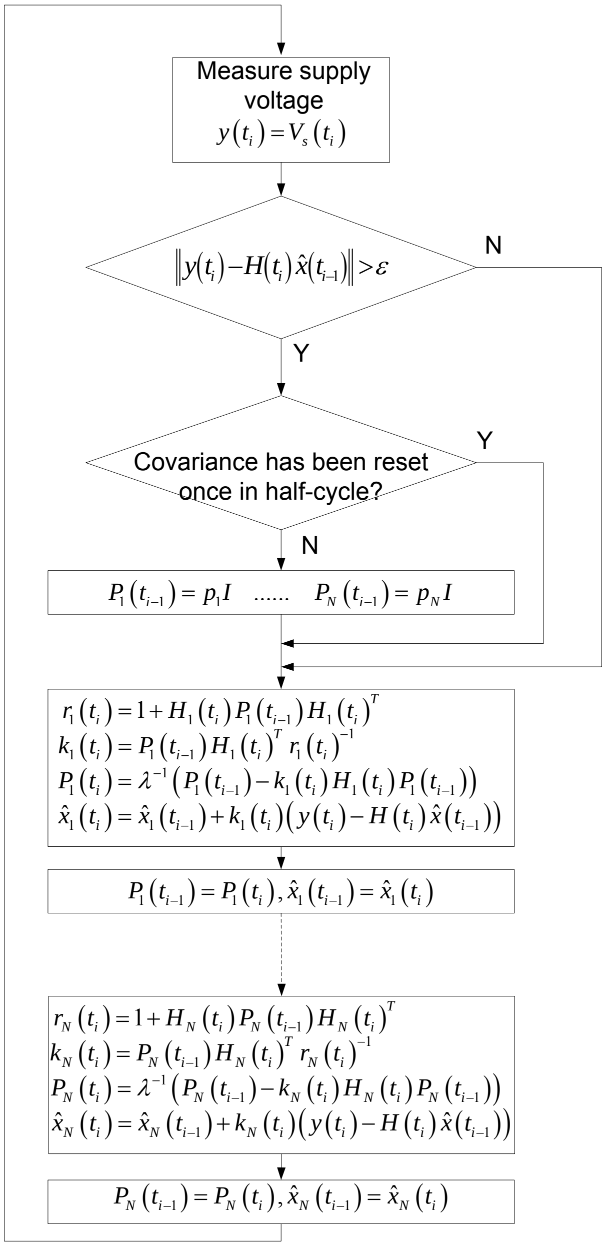


Fig.1 Flow Chart of the Proposed Algorithm

Fig.2(a) shows the distorted input single-phase voltage. Fig.2(b-e) shows the waveforms estimated by HWLSE algorithm for fundamental, third, fifth and seventh components. Fig.2(f) shows the steady state error between the sampled voltage and estimated voltage. It is possible to appreciate from Fig.2(f) that the error is relatively small, in such case, the threshold of covariance resetting can be reduced to enhance the speed of voltage sag detection even if the sag depth is low.

Beside harmonics, sag point on wave, depth of sag and phase jump can also affect the detection. Therefore, the proposed HWLSE algorithm should be evaluated under different test conditions to proving its high performance. Table.1 shows the different test conditions for voltage sag.

Table 1. Different test conditions for voltage sag

Point on wave[deg]	Depth of sag[%]	Phase jump[deg]
0	20	0
90	50	±30

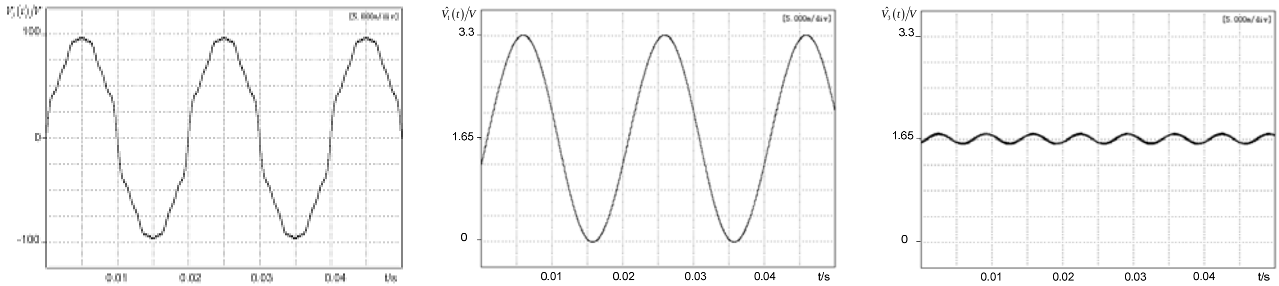
The sagged voltage is shown as：

$$\begin{aligned} V_s(t) = (1-\eta)\{&100\sin(\omega t+\phi)+5\sin(3\omega t+3\phi) \\ &+5\sin(5\omega t+5\phi)+5\sin(7\omega t+7\phi) \\ &+2\sin(9\omega t+9\phi)+2\sin(11\omega t+11\phi) \\ &+2\sin(13\omega t+13\phi)\} \end{aligned} \quad (18)$$

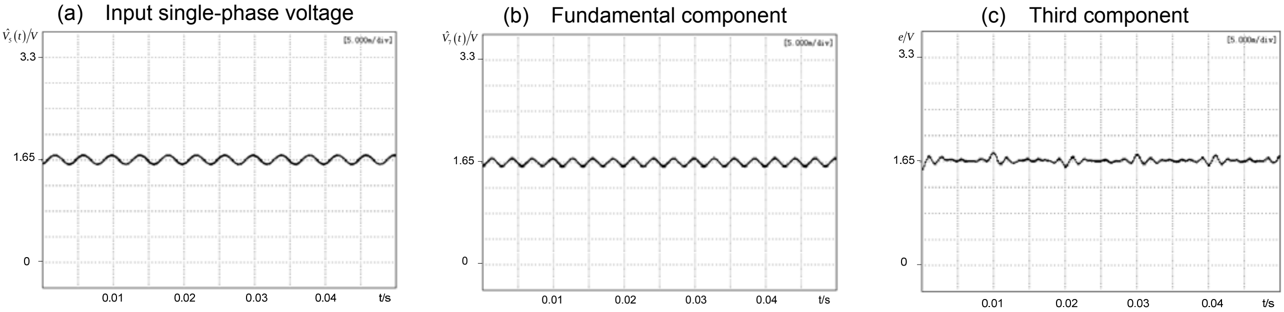
where η is the depth of sag and ϕ is the angle of phase jump.

The voltage sag occurs at 0.1s, which means that the point on wave is 0°. The voltage sag occurs at 0.105s, which means that the point on wave is 90°.

Fig.3(a-l) shows the transient process of amplitude of estimated fundamental component when different sag occurs. From Fig.3, it can be observed that the estimated amplitude fall to 0.9pu rapidly under these test conditions, however, the phase jump leads to different tracking process of the amplitude which will enhance the risk of misrecognition for voltage recovery. To tackle this problem, voltage recovery will not be recognized in half cycle, because in generic situation, voltage sag will last half cycle at least.

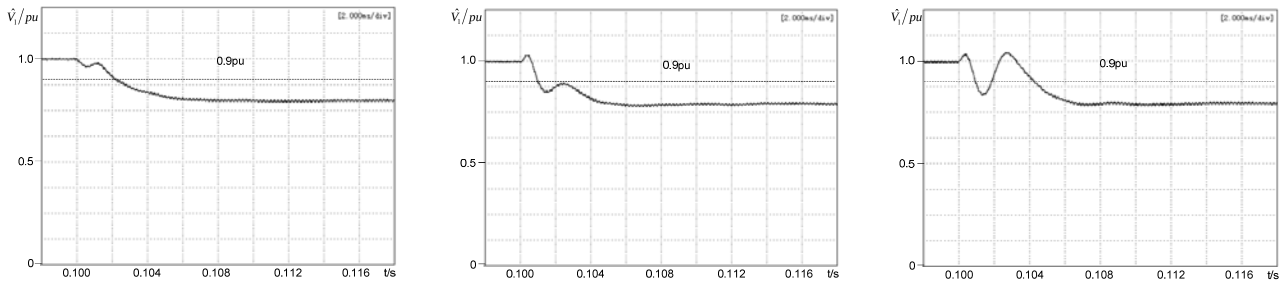


(a) Input single-phase voltage (b) Fundamental component (c) Third component



(d) Fifth component (e) Seventh component (f) Steady state error between the sampled voltage and estimated voltage

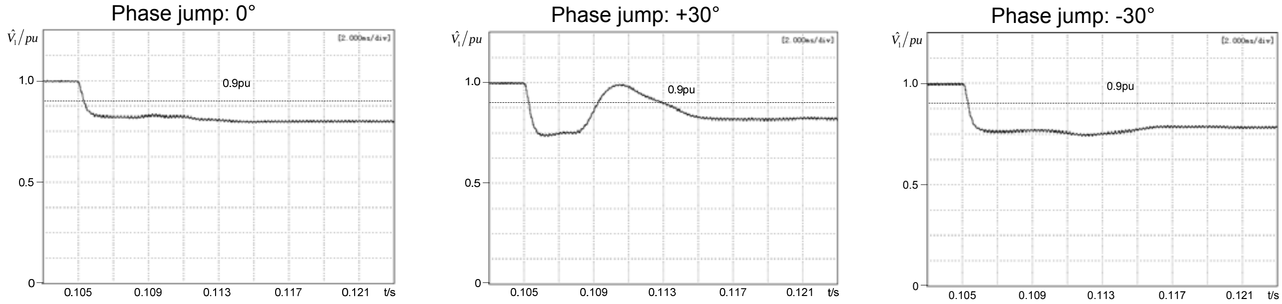
Fig.2 HWLSE experimental estimation of fundamental and harmonic components



(a) Depth of sag: 20% Point on wave: 0° Phase jump: 0°

(b) Depth of sag: 20% Point on wave: 0° Phase jump: +30°

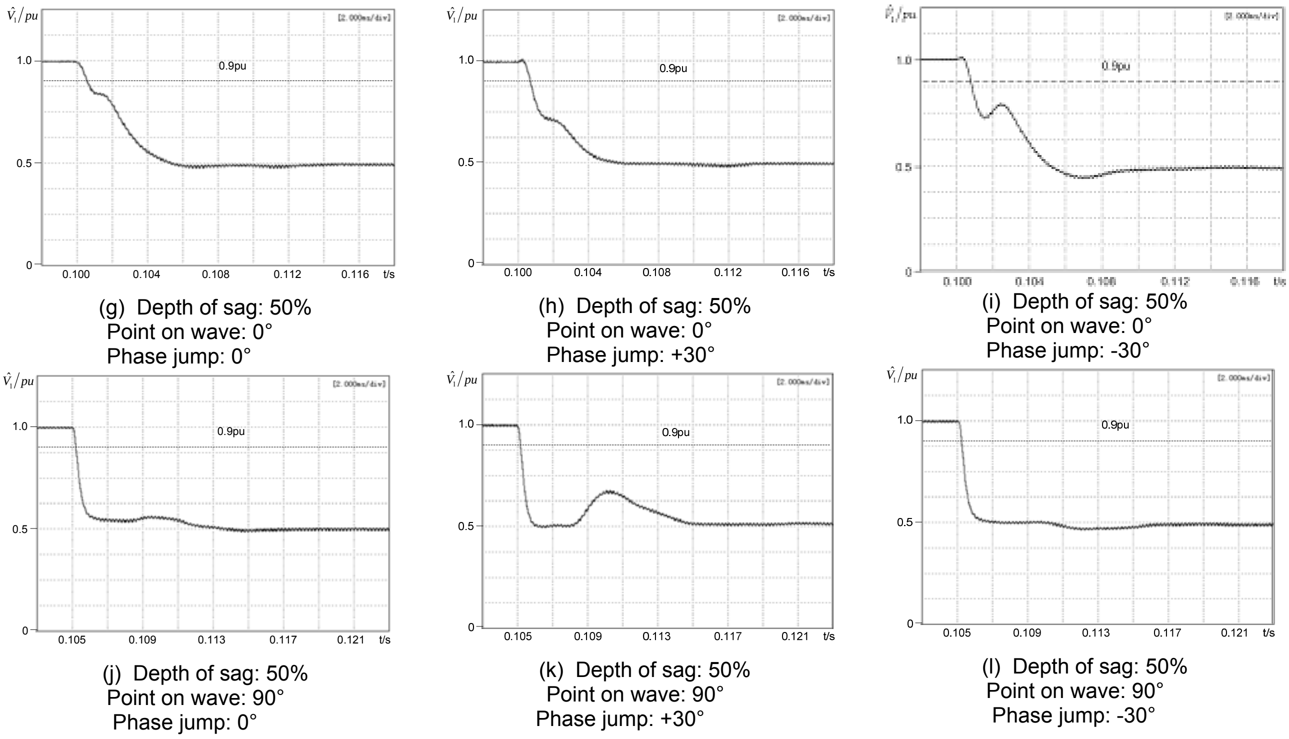
(c) Depth of sag: 20% Point on wave: 0° Phase jump: -30°



(d) Depth of sag: 20% Point on wave: 90° Phasejump:0°

(e) Depth of sag 20% Point on wave 90° Phase jump: +30°

(f) Depth of sag 20% Point on wave 90° Phase jump: -30°



(g) Depth of sag: 50%
Point on wave: 0°
Phase jump: 0°

(h) Depth of sag: 50%
Point on wave: 0°
Phase jump: +30°

(i) Depth of sag: 50%
Point on wave: 0°
Phase jump: -30°

(j) Depth of sag: 50%
Point on wave: 90°
Phase jump: 0°

(k) Depth of sag: 50%
Point on wave: 90°
Phase jump: +30°

(l) Depth of sag: 50%
Point on wave: 90°
Phase jump: -30°

Fig.3 Transient process of amplitude of estimated fundamental component when different sag occurs

The detecting time is the duration of estimated fundamental amplitude falling to 0.9pu of nominal value, and the stabilizing time is the duration of steady state error of estimated fundamental amplitude stabilizing within $\pm 3\%$ of nominal value.Table 2 shows the influence of different test conditions.

Table 2. Influence of different test conditions

Point on wave[deg]	Depth of sag[%]	Phase jump[deg]	Dectecting Time[ms]	Stabilizing Time[ms]
0	20	0	2.11	5.72
		+30	1.01	4.98
		-30	1.02	6.13
	50	0	0.56	6.21
		+30	0.62	5.32
		-30	0.65	9.52
90	20	0	0.36	7.15
		+30	0.28	9.56
		-30	0.31	9.65
	50	0	0.26	7.33
		+30	0.18	9.58
		-30	0.22	9.89

Conclusion

The proposed HWLSE algorithm offers excellent fundamental and harmonic components extracting ability even in condition the supply voltage is distorted. The covariance resetting technique is adopted to reduce the voltage sag detection time. The experimental results for different test conditions have been shown in this paper. The amplitude of estimated fundamental component falls to 0.9pu of nominal value in 0.2ms-2ms, and stabilizes in 5ms-10ms. Experimental results from a DSP-based system are included to support the theoretical analysis.

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