A Novel Detection Method for Voltage Sags

Kai Ding, K.W.E.Cheng, X.D.Xue, B.P. Divakar,
C.D.Xu, Y.B.Che, D.H.Wang, P.Dong

Power Electronics Research Center
Department of EE, The Hong Kong Polytechnic University

***Abstract*-- Determining the start and end of the voltage sag event is very important for sag analysis and mitigation. There are several detection methods for voltage sags in which sag voltages are usually expressed in the terms of RMS. The RMS method represents one cycle historical average value, not instantaneous value which may lead to long detection time when voltage sag has occurred. This paper will proposed a novel voltage sag detection method based on Miss Voltage Technique. Proper dead-band and hysteresis are used in the method. The actual instantaneous voltage is compared with certain percentage of desired grid voltage and certain percentage of the amplitude of the grid voltage. Through instantaneous value comparison, low instantaneous value of the grid is shielded which overcome the mishandling turnover of voltage sags. The approach is fully described, and the results are compared with other methods for marking the beginning and end of sag, such as RMS value evaluation method and Peak-value method and simulation result provides that the method is efficient and fast and can be used to determine the initiation and recovery of voltage sags accompanied by Missing Voltage Technique.**

***Index Terms*—Voltage Sag, RMS, Peak Value, Missing Voltage.**

I. Introduction

VOLTAGE sags are brief reductions in voltage, typically lasting from a cycle to a second or so, or tens of milliseconds to hundreds of milliseconds. Voltage swells are brief increases in voltage over the same time range.

Power systems have non-zero impedances, so every increase in current causes a corresponding reduction in voltage. Usually, these reductions are small enough that the voltage remains within normal tolerances. But when there is a large increase in current, or when the system impedance is high, the voltage can drop significantly. Voltage sags are the most common power disturbance. At a typical industrial site, it is not unusual to see several sags per year at the service entrance, and far more at equipment terminals. Voltage sags can arrive from the utility; however, in most cases, the majority of sags are generated inside a building. For example, in residential wiring, the most common cause of voltage sags is the starting current drawn by refrigerator and air conditioning motors. Sags do not generally disturb incandescent or fluorescent lighting, motors, or heaters. However, some electronic equipment lacks sufficient internal energy storage and, therefore, cannot ride through sags in the supply voltage. [1].

Some reasons for equipment fail when there are voltage sags on ac power systems are as follows.

1. Equipment fails because there isn't enough voltage.
2. Equipment fails because an undervoltage circuit trips.
3. Equipment fails because an unbalance relay trips
4. A quick-acting relay shuts the system down, typically in the EMO (Emergency Off).
5. A reset circuit may incorrectly trip at the end of the voltage sag

The costs associated with power outages at commercial facilities like banks, data centers, and customer service centers can be tremendous, ranging from thousands to millions of dollars for a single interruption. The costs to manufacturing facilities can be just as high, if not higher. And manufacturing facilities can be sensitive to a wider range of power quality disturbances than just outages that are counted in traditional reliability statistics. Voltage dips that last less than 100 milliseconds can have the same effect on an industrial process as an outage that lasts several minutes.

Determining the optimum supply system and electric system characteristics for industrial facilities requires an evaluation of many alternatives. Power quality can be improved by adding power conditioning for selected equipment or raising the bar for specifications and equipment design on either the utility or end-user side of the meter. But as you might imagine, all of these alternatives have different costs and associated benefits.

Power line conditions which can result in productivity losses vary from long term power outages to short duration voltage sags. However, voltage transients and momentary power interruptions, due to events such as lighting strikes, and line under-voltages(voltage sags) down to no less than 45-50% of nominal voltage , due to faults on the utility power system, account for the vast majority, 90-95%[2].

To face the problem, the existing standards and recommendations offer some guiding curves to verify the prescribed maximum magnitude and duration of lower and upper voltage limits for typical classes of loads. Fig.1

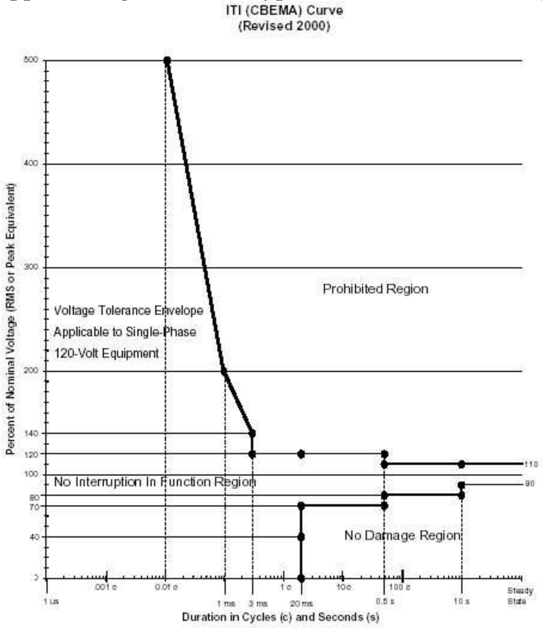


Fig.1 2000 Version of the IT Industry Tolerance Curves (update from original CBEMA curve).

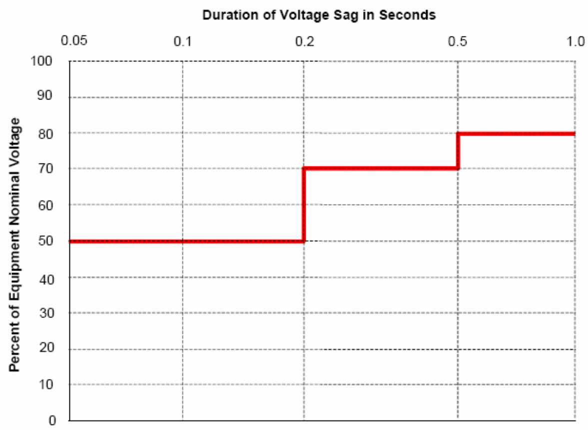


Fig.2. Required semiconductor equipment voltage sag ride-through capability curve

shows the 2000 Version of the IT Industry Tolerance Curves. The vertical axis is percent of nominal voltage. "Well-designed" equipment should be able to tolerate any power event that lies in the shaded area. Note that the curve includes sags, swells, and transient overvoltages.

As shown in Fig.2. The semiconductor industry developed a more recent specification (SEMI F47) for tools used in the semiconductor industry in an effort to achieve better ride through of equipment for commonly occurring voltage dips and therefore improving the overall process performance[3, 4]. It is basically the same as the ITI Curve but specifies an improved ride through requirement down to 50% retained voltage for the first 200 msec. Many short voltage dips are covered by this additional requirement. IEC 61000-4-11 and IEC 61000-4-34 provide similar voltage dip immunity standards.

The detection and evaluation of voltage sag is necessary when mitigating of sag is considered. Precise and fast and detection of the start and end of the voltage sags are key important. In this paper, several detection methods for voltage sags are given. A novel voltage sag detection method is proposed. The proposed method is compared with RMS method and Peak-value method. As shown in simulation results, the method can pick out the sag beginning and end faster than the other two.

II. Detection Methods

Voltage detection is important because it determines the dynamic performance of the voltage sag regulator. Precise and fast voltage detection is an essential part of the voltage sag compensator. Several voltage detection methods have been documented for use in various voltage compensation schemes. In this paper, RMS value evaluation method, Peak value method, and Missing voltage technique are introduced.

A. RMS Value Evaluation Method[5]

RMS values, continuously calculated for a moving window of the input voltage samples, provide a convenient measure of the magnitude evolution, because they express the energy content of the signal. Assuming the window contains N samples per cycle (or half cycle). The resulting RMS value at sampling instant k can be calculated by:

$$V_{rms}[k]=\sqrt{\frac{1}{N}\cdot\sum_{n=0}^{N-1}v^2[k-n]} \tag{1}$$

Suppose

$$S[k]=\sum_{n=0}^{N-1}v^2[k-n] \tag{2}$$

then

$$S[k-1]=\sum_{n=0}^{N-1}v^2[k-n-1] \tag{3}$$

from (2) (3) we get

$$S[k]-S[k-1]=\sum_{n=0}^{N-1}v^2[k-n]-\sum_{n=0}^{N-1}v^2[k-n-1] \tag{4}$$
$$=v^2[k]-v^2[k-N]$$

So

$$S[k]=v^2[k]-v^2[k-N]+S[k-1] \tag{5}$$

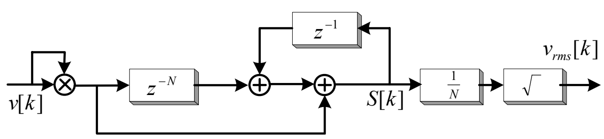


Fig.3 RMS value evaluation using a moving window

Fig.3 illustrates a z-domain representation for the voltage RMS magnitude evaluation using a moving window. The basic idea is to follow the voltage magnitude changes as close as possible during the disturbing event. The more RMS values are calculated, the closer the disturbing event is represented.

B. *Peak Value Evaluation Method*[6]

Assume that the input voltage $v_i(t)$ is given by

$$v_i(t) = V_P \sin(\omega t) \tag{6}$$

where V_P, is the peak value of the input voltage. If $v_i(t)$ is sent to a 90" phase shift circuit, then $v_i^{'}(t)$ is obtained as

$$\begin{aligned} v_i^{'}(t) &= V_P \sin(\omega t + 90^\circ) \\ &= V_P \cos(\omega t) \end{aligned} \tag{7}$$

The two signals, $v_i(t)$ and $v_i^{'}(t)$, are a pair of orthogonal functions. If they are sent to two separate multipliers and squared, the following two equations can be obtained:

$$v_{01}(t) = kV_P^2 \sin^2(\omega t) \tag{8}$$

$$v_{02}(t) = kV_P^2 \cos^2(\omega t) \tag{9}$$

where k is the multiplication factor of the multipliers. Due to the characteristic of orthogonal functions $v_{01}(t)$ and $v_{02}(t)$, it is easy to obtain the square of the input voltage peak value by adding (3) and (4):

$$\begin{aligned} v_{0a}(t) &= v_{01}(t) + v_{02}(t) \\ &= kV_P^2(\sin^2(\omega t) + \cos^2(\omega t)) \\ &= kV_P^2 \end{aligned} \tag{10}$$

In order to measure the peak value, the signal $v_{0a}(t)$ is fed to a square root circuit. Then the output of the square root circuit is

$$v_0(t) = k_1 V_P \tag{11}$$

where k_1, is the multiplication factor of the square root circuit. If the multiplication factors of the multiplier and the square root circuit are selected properly, the value of constant k_1, can be set as 1. The output voltage of the detector is equal to the peak value of the input voltage. Because the detector is based on the concept of an orthogonal function pair, it is called "orthogonal detector."

The process of measuring the peak value can be explained as follows[7]. The single-phase line-to-neutral voltage is measured, and the cosine value of the voltage is determined using a 90° phase shifter. Assuming a fixed value (50Hz) for the line frequency, the 90°-shifted value can be found by either an analog circuit or by digital signal processing. Both components of voltage are squared and summed to yield V_p^2. Obtaining the square root of V_p^2 results in the peak value of the detected voltage.

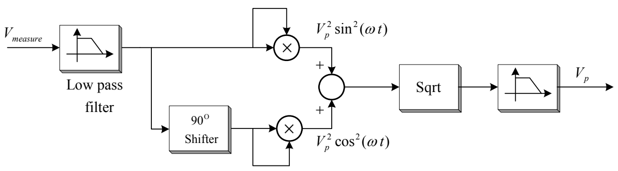


Fig.4 Voltage measurement using the peak detection method

C. *Missing Voltage Technique[8]*

The RMS value evaluation method is based on the averaging of previously sampled data for one cycle. Therefore, it represents one cycle historical average value, not momentary value. Due to the moving window retaining almost one cycle of "historical" information in the calculation, thus the duration of the sag is in error by almost one cycle if one examines only the RMS plot. Furthermore, the point on wave of initiation and recovery of the sag is not clear.

To avoid mis-representing the waveform, reference[8] proposed another approach, called the Missing Voltage Technique. The missing voltage is defined as the difference between the desired instantaneous voltage and the actual instantaneous value. The desired voltage is easily obtained by taking the pre-event voltage and extrapolating this out during the event, similar to the way a phase-locked loop (PLL) operates. A PLL is basically a control loop incorporating a voltage-controlled oscillator and phase sensitive detector in order to lock a given signal to stable reference frequency. We will call the desired voltage waveform the desired voltage or reference voltage and it will be locked in magnitude, frequency, and phase angle to the pre-event voltage waveform.

The missing voltage can be used to see the real time variation of the waveform form the ideal, and hence the actual severity of the sag. Furthermore, it gives a more accurate indication of the duration of the event.

III. NOVEL DETECTION METHOD

In the method of missing voltage technique, the missing voltage (MV) can be obtained by subtracting the actual instantaneous value from the desired instantaneous voltage. The start and end of voltage sags can be determined by MV. A detailed example will be given as follow for analysis.

A. *Problems When Using MV*

Assuming the normal grid voltage is 220VAC RMS, the amplitude of the grid phase voltage is 311V. Generally, there will be a voltage sag event when voltage drops to certain value. In this paper, we assumed that when the voltage depresses to a value lower than 80% of the desired value will lead to a voltage sag event. When the voltage is recovered back to more than 80%, we consider the voltage sag event is over and the grid turns to normal again.

Under the assumption mentioned above, when the instantaneous value of MV is equal or larger than 20% of the reference voltage, start of the voltage sag occurs. When the instantaneous value of MV is less than the 20% of the reference voltage, the gird goes back to normal. Because the MV is very small during the zero-crossing point, noise, sampling error and delay will affect the measurement value of MV which will cause mishandling of the voltage sag restorer.

Assuming $V_s(t)$ is the actual instantaneous value, $V_{ref}(t)$ is the desired instantaneous voltage. The voltage sag starting point can be determined by:

$$\left|V_{ref}(t_0) - V_s(t_0)\right| > 20\%\left|V_{ref}(t_0)\right| \quad (12)$$

During the low instantaneous value period, if the value of $V_s(t)$ approaches zero, although the grid voltage is normal, due to the sampling error, sampling delay, noise, there will be some problems when using (12).

Probelm1: when the grid is 100% normal, during the low instantaneous value period. For example, assuming at the point t_0, $V_{ref}(t_0) = 2$V,because of the disturbance, a detection value of 1.5V is possible, and then 25% voltage drop is recognized by the controller which will lead to mishandling. So during the low instantaneous value period, such kind of mishandling will be repeated.

When the gird is 100% normal, during the high instantaneous voltage period. For example, assuming at the point t_1, $V_{ref}(t_1) = 170$V, $V_s(t_1)$=170V. Although a lot disturbances may exist, but the detection error above 20% is rare. That means, obtaining a value of 136V when detecting the actual voltage value of 170V is almost impossible. So when the grid is 100% normal, the mishandling of voltage sag regulator during the high instantaneous voltage period is rare.

Problem II: Assuming the actual gird is 82% of the desired grid, during the high value period. For example, at the point t_1 $V_{ref}(t_1) = 170$V，$V_s(t_1)$=139.32V. The actual voltage is normal, but due to some disturbances, the detected value of $V_s(t_1)$ may be 134, the error is 5.32V which is possible when compared with 139.32V. So when the actual grid voltage approaches the critical value, mishandling is also possible.

In like manner, if the grid voltage is abnormal, the disturbances existing may also lead to incorrect switchover.

So it is necessary to add dead time and hysteresis band.

B. New Detection Method

Based on the inequality (12), in order to determine the start and end of a voltage sag event, fist we can add hysteresis band like this:

For example, when the grid is equal or smaller than 80% of desired grid, enable the voltage sag regulator. When the grid voltage is equal or bigger than 85% of the desired grid, disable the regulator, so adding hysteresis band may avoid wrong switchover at the critical value. But same as the problem I mentioned above, large error may appear during the low value period, although adding hysteresis band, incorrect switchover may also appear.

During the low instantaneous value period, the effect of voltage sags is smaller when compared with the sags at high value period. So screening the low voltage comparison may help solving the mishandling problems.

For example, when the grid voltage is satisfied

$$\left|V_s(t)\right| \le 85\%\left|V_{ref}(t)\right| - 5\% * AMP \quad (13)$$

where the AMP is the amplitude of the phase voltage 311V, form (13) we obtain

$$\left|V_s(t)\right| \le 85\%\left|V_{ref}(t)\right| - 15.5 \quad (14)$$

When the grid voltage satisfied the inequality (14), voltage sag event is started, and then during the low instantaneous value period, (0-15.55V), whatever, the grid voltage can not be equal or smaller than the value (85%Vref -15.55), so the low voltage value is shielded. If the grid voltage is 80%Vref, the grid voltage will be satisfied the inequality only when the instantaneous grid voltage reaches the peak value. That means, when the grid voltage drops to 80% V_{ref}, the detection of voltage sags is very sensitive near the peak value (90degree, or 270degree).

Now, assuming the grid voltage drops x%, θ is the detection angle when voltage drops x%, as shown in Fig.5, so from (14), yields

$$(100 - x)\% * 311 * \sin(\theta) \le 85\%\left|311\sin(\theta)\right| - 15.5 \quad \text{(x)} \quad (15)$$

from (15), obtains

$$\theta = ArcSin(\frac{5}{x - 15}) \quad (16)$$

Assuming MaxDelay is the max detection delay time. As shown in Fig.5, assuming the voltage drops more than 20% at the point M, due to the point M is shielded according the (15), until at the point N , the voltage sag event is not detected. So

$$MaxDelay = 2\theta = 2 * ArcSin(\frac{5}{x - 15}) \quad (17)$$

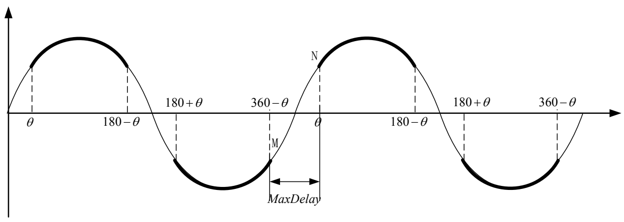


Fig.5. Available detection ranges for sag detection (thick line)

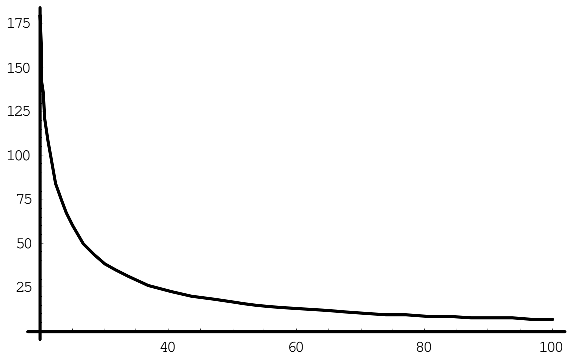


Fig.6. Max detection delay time when voltage drops x% ranges from 20% to 100%

As can seen from fig.6, the more the grid voltage drops, the less detection delay time. When the grid voltage drops 50%, the max delay time is about 16.4rad, about 0.045 period.

In like manner, gird voltage recovery discussion are as follows. When the grid voltage is satisfied

$$\left|V_s\right| \ge 75\%\left|V_{ref}\right| + 10\% AMP \quad (18)$$

we consider the voltage sag event is finished, the voltage sag regulator will be switchover to grid supply. Assuming the grid voltage drops x%, one obtains

$$V_s = (100 - x)\% V_{ref} \quad (19)$$

substitute (19) in (18), we get

$$(100 - x)\% * |V_{ref}| \geq 75\% |V_{ref}| + 10\% AMP \quad (20)$$

because

$$V_{ref} = Amp * Sin(wt) \quad (21)$$

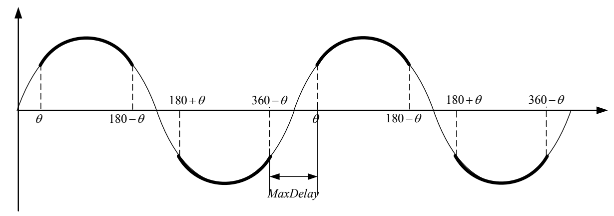


Fig.7. Available detection ranges for recovery detection(thick line)

so

$$(100 - x)\% * |Amp * Sin(wt)| \geq 75\% |Amp * Sin(wt)| + 10\% Amp \quad (22)$$

from (22) we get

$$|Sin(wt)| \geq \frac{10}{25 - x} \quad (23)$$

then, from (23)

$$\omega t = \theta \geq ArcSin(\frac{10}{25 - x}) \quad (24)$$

where $0 \leq \theta \leq \frac{\pi}{2}$

For example, as shown in the Fig.7, when the grid voltage is recovered back to 82% of the desired voltage, the value θ does not exist. So during this period, it whole power supply system remains pervious state. Only when the gird voltage recovered back to more than 85%, the θ exist. For example when the grid voltage goes back to 100%, the range of θ is

θ>=23.5782rad

the range is shown in Fig.7 (thick line), the value outside the rang is screened.

In sum, the above example employs the following method:

1) When the actual grid voltage satisfied:

$$|V_s| \leq 85\% |V_{ref}| - 15.5$$

voltage sag regulator is enable, the missing voltage is added to the actual grid voltage.

2) When the actual grid voltage satisfied:

$$75\% |V_{ref}| + 31.1 > |V_s| > 85\% |V_{ref}| - 15.5$$

holding the previous state

3) When the actual grid voltage satisfied:

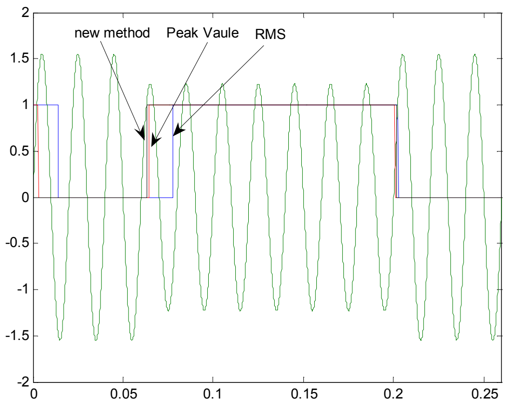
$$|V_s| \geq 75\% |V_{ref}| + 31.1$$

voltage sag regulator is disable, the power line supply voltage solely.

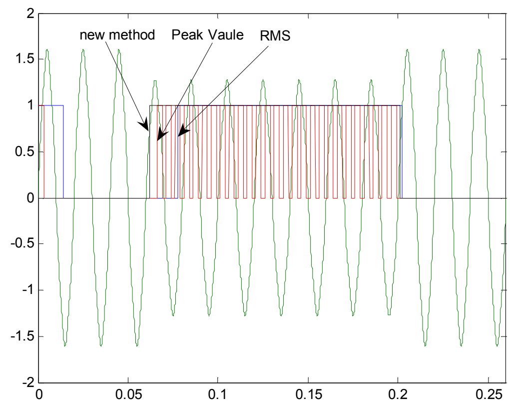
Of course, different value of percentage of the desired voltage and the amplitude will lead to different effects. The above mentioned parameters are employed in the example of this paper and the same parameters are also used in simulation.

IV. SIMULATION

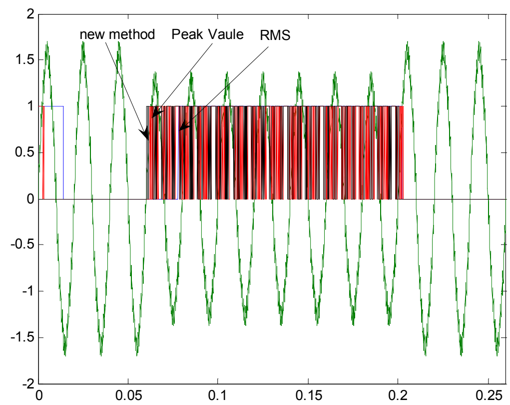
Simulations have been carried out to verify the proposed voltage sag detection method. The cases examined include those when the voltage is depressed to 79% of its nominal value. The sag event lasts for 0.14 s. As shown in Fig.8, three voltage sag waveforms aregiven, the first waveform as shown in Fig.8(a) drops at the end



(a)



(b)



(c)

Fig.8. Simulation results

of the third cycle, and last for 7 cycles. No harmonics in the waveform.

The second waveform is shown in Fig.8(b). The waveform is obtained by adding 250Hz harmonics with the amplitude 10V into the first voltage waveform.

The third waveform is shown in Fig.8(c).The waveform is obtained by adding 2500Hz harmonics with the amplitude of 20V into the second waveform.

Start and end of the voltage sag even can be determined through the proposed method. Similar, RMS method and Peak-value method also can be used to determine the start and end of voltage sag. The simulation comparisons of the three methods are also shown in Fig.8

As shown from the simulation results, the proposed method of this paper is the fastest one, the second is the peak value method, and the RMS method is relative slow. But from Fig.8(b), we can see that when adding some disturbances, mishandling switchover will be happened using the peak value method, the proposed method is still correct. But when adding the more harmonics to some extend, such as in the Fig.8(c), the mishandling switchover will also occur in both proposed method and peak value method, RMS method is based on the averaging of previously sampled data for one cycle, so RMS method can still determine the start and end of the voltage sag correctly, but slowly.

V. CONCLUSION

Obviously, the classical RMS calculation can be used to evaluate the magnitude and duration of the sag according to its definition. Also the RMS method avoid the need of dead-band or hysteresis. But the onecycle transition before reaching the nominal magnitude and the one-cycle rise to recovery due to the moving window used in the calculation make the classical method inadequacy to evaluate voltage sag in real-time. Monitoring the peak values of the supply is simple, but the draw back of the peak value method is that it can take up a half a cycle for the sag depth information to become available and the detection of the initiation and recovery of the sag has some difficulties when voltage disturbance occurs. Combined with Missing Voltage Technique, the proposed method is efficient for the evaluation of start time for voltage sags. The disadvantage of the method is that the possibility of noise affecting the detection results. The proposed method is fast and simple and no complex mathematics is required for implementation of the algorithm on a microprocessor.

REFERENCE

[1] "http://www.powerstandards.com/."

[2] D. M. Divan, "Dynamic Voltage Sag Correction," U. S. Patent 6 118 676, Sep. 2000.

[3] "http://www.f47testing.com/."

[4] SEMI F47-0200 Specification For Semiconductor Processing Equipment Voltage Sag Immunity.

[5] S. M. Deckmann and A. A. Ferrira, "About voltage sags and swells analysis," 2002.

[6] C. Hui-Yung, J. Hurng-Liahng, and H. Ching-Lien, "Transient response of a peak voltage detector for sinusoidal signals," *Industrial Electronics, IEEE Transactions on*, vol. 39, pp. 74-79, 1992.

[7] L. Dong-Myung, T. G. Habetler, R. G. Harley, J. Rostron, and T. Keister, "A voltage sag supporter utilizing a PWM-switched autotransformer," 2004.

[8] N. S. Tunaboylu, E. R. Collins, Jr., and P. R. Chaney, "Voltage disturbance evaluation using the missing voltage technique," in *International Conference on Harmonics And Quality of Power*, vol. 1, 1998, pp. 577-582.