Voltage dip detection with half cycle window RMS values and aggregation of short events

International Conference on Renewable Energies and Power Quality (ICREPQ'15)
La Coruña (Spain), 25th to 27th March, 2015
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.13, April 2015

Voltage Dip Detection with Half Cycle Window RMS Values and Aggregation of Short Events

Yun Qin, Gu Ye*, V.Cuk, J.F.G.Cobben

Department of Electrical Engineering
Technology University of Eindhoven
Campus of TU/e, 5612 AZ (Netherlands)
E-mail: **g.ye@tue.nl**

Abstract. This paper presents the results of the analysis on the 2 data window lengths adopted in instruments for the detection of voltage dips (sags). The first one is commonly applied which use one cycle window to calculate the RMS value of residual voltage, the other one uses half cycle window to calculate the RMS values. These two window lengths are compared analytically and based on a simulation in this paper. The short duration dips are emphasized as they lead to more differences. The different affective factors like residual voltage and phase angle jump are also discussed. A set of field measured dip data are analysed with these 2 methods and the results are given and compared.

Key words

Power quality (PQ), voltage dip, residual voltage, dip duration.

1. Introduction

Voltage dip is a power quality phenomenon which is described as: A sudden decrease of the voltage, between 90% and 1% of the designated voltage, followed by a quick recovery to the normal level. The decided time period lays between 10ms and 1 min. [1]

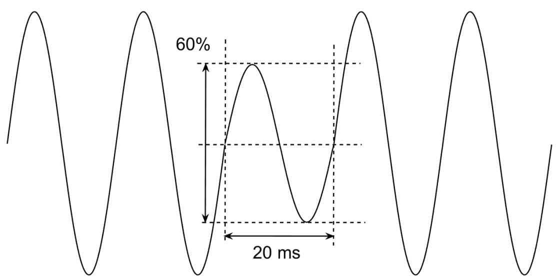

Fig. 1. A single phase 20ms 60% residual voltage dip.

Fig. 1 shows a single phase voltage dip. This dip event lasts for one cycle which is 20ms for a 50Hz electrical system and its residual voltage is 60% of normalized amplitude.

The measurement of dip parameters is essentially based on the voltage RMS measurement. There are two common ways to do the measurements: (1)sliding window RMS; (2)half cycle synchronization RMS. With one cycle window or half cycle window, the residual voltage and dip duration can be obtained. However, large detection differences can be brought if different RMS calculation methods are applied. Fig. 2(a) shows a 0% residual voltage and one cycle voltage dip, and Fig. 2(b) shows the results of two kinds of measurements (based on one cycle window). Both of the measured residual voltages are zero but the measured dip durations are quite different from the actual value (Instantaneous values). Taking the dip threshold voltage value as 90%, sliding window RMS will measure a duration about 158% of one cycle and synchronized RMS will measure a duration which is 150% of one cycle. In this example the difference is quite large considering the actual duration is only one cycle. [2]

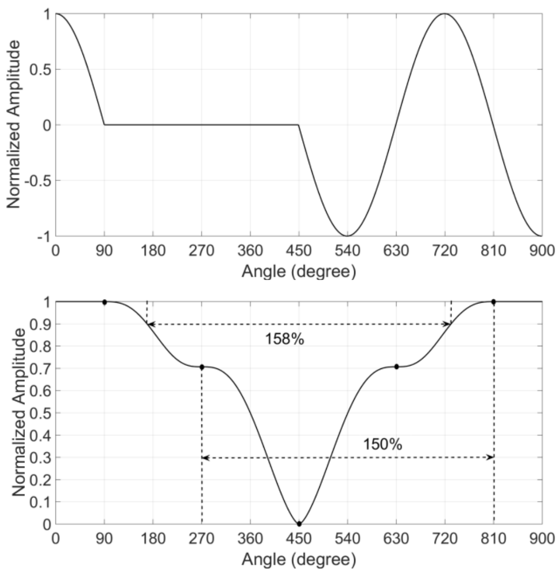

Fig. 2. Example of a one cycle duration and 0% residual voltage dip. (a) instantaneous voltages. (b) RMS values with sliding window (line) and half cycle synchronization (dots).

The shortest window to achieve accurate RMS values is half cycle for a sinusoidal shape signal. Based on this half cycle window measurement, sliding window RMS as well as half cycle synchronization RMS calculation can be both applied. So there're a total of four combinations of two algorithms with two data windows to detect a voltage dip:

1) One cycle window, sliding window RMS
2) Half cycle window, sliding window RMS
3) One cycle window, half cycle synchronization RMS
4) Half cycle window, half cycle synchronization RMS

2. Mathematical Analysis

The voltage here is considered as a cosine signal, so in the calculation, the cosine waveform is used. A voltage dip takes place at the phase angle $\boldsymbol{\varphi_i}$ and ends at phase angle $\boldsymbol{\varphi_f}$, there's a phase angle jump ($\Delta\boldsymbol{\varphi}$) during the dip event. Before dip takes place the waveform can be written as:

$$\mathrm{U} = \sqrt{2}U_i \cos(\theta + \varphi) \quad (1)$$

After dip takes place the waveform can be written as:

$$\mathrm{U} = \sqrt{2}U_f \cos(\theta + \varphi + \Delta\varphi) \quad (2)$$

After the dip event ends the voltage signal will get back to the waveform which existed before the dip, with a backwards phase angle jump.

A. One cycle window, sliding window RMS

The detected voltage RMS can be calculated based on equation (1) and (2) as:

$$U^2 = U_i^2 - \frac{U_i^2}{2\pi}[\alpha_i + sin\alpha_i \cos(\alpha_i + 2\varphi_i)] + \frac{U_f^2}{2\pi}[\alpha_i + sin\alpha_i \cos(\alpha_i + 2\varphi_i + 2\Delta\varphi)] \quad (3)$$

$$U^2 = U_f^2 - \frac{U_f^2}{2\pi}\left[\alpha_f + sin\alpha_f \cos\left(\alpha_f + 2\varphi_f + 2\Delta\varphi\right)\right] + \frac{U_i^2}{2\pi}\left[\alpha_f + sin\alpha_f \cos\left(\alpha_f + 2\varphi_f\right)\right] \quad (4)$$

Equations (3) and (4) and used to calculate the voltage RMS at the beginning and end of the dip event respectively.

The $\boldsymbol{\alpha}$ in these equations represents the phase delay. For example, if the dip threshold voltage is defined to be 90% of the normal voltage magnitude, phase delay is the angular duration before the instrument can detect a dip after the dip really happens. There're both phase delays before detecting the start of a dip ($\boldsymbol{\alpha_i}$) as well as detecting the end of a dip ($\boldsymbol{\alpha_f}$). Thus the measured dip duration has an unavoidable error, the measured angular duration can be calculated as:

$$\delta_m = \alpha_f - \alpha_i + \delta \quad (5)$$

The $\boldsymbol{\delta}$ represents the real dip angular duration. The relationship between phases angles ($\boldsymbol{\varphi_i}$ and $\boldsymbol{\varphi_f}$) follows:

$$\varphi_f = \varphi_i + \delta \quad (6)$$

B. Half cycle window, sliding window RMS

For half cycle window, the RMS value measuring duration becomes half a cycle, this leads to a different detected voltage RMS.

$$U^2 = U_i^2 - \frac{U_i^2}{\pi}[\alpha_i + sin\alpha_i \cos(\alpha_i + 2\varphi_i)] + \frac{U_f^2}{\pi}[\alpha_i + sin\alpha_i \cos(\alpha_i + 2\varphi_i + 2\Delta\varphi)] \quad (7)$$

$$U^2 = U_f^2 - \frac{U_f^2}{\pi}\left[\alpha_f + sin\alpha_f \cos\left(\alpha_f + 2\varphi_f + 2\Delta\varphi\right)\right] + \frac{U_i^2}{\pi}\left[\alpha_f + sin\alpha_f \cos\left(\alpha_f + 2\varphi_f\right)\right] \quad (8)$$

For the measurement of dip duration, equation (5) is still valid.

C. One cycle window, half cycle synchronization RMS

The RMS values calculated by half cycle synchronization method can be considered as one special example of sliding window method which has an updating step of half cycle. The sampling instants are those for which the instantaneous voltage assumes a value equals to zero. The conditions apply when:

$$\alpha_i + \varphi_i + \Delta\varphi = k_i\pi + \frac{\pi}{2} \quad (9)$$

$$\alpha_f + \varphi_f = k_f\pi + \frac{\pi}{2} \quad (10)$$

If we insert equations (9) and (10) into (3) and (4) respectively, the equations become:

$$U^2 = U_i^2 - \frac{U_i^2}{2\pi}\left[k_i\pi + \frac{\pi}{2} - \varphi_i - \Delta\varphi - sin(\varphi_i - \Delta\varphi)\cos(\varphi_i + \Delta\varphi)\right] + \frac{U_f^2}{2\pi}\left[k_i\pi + \frac{\pi}{2} - \varphi_i - \Delta\varphi - \frac{1}{2}\sin(2\varphi_i + 2\Delta\varphi)\right] \quad (11)$$

$$U^2 = U_f^2 - \frac{U_f^2}{2\pi}\left[k_f\pi + \frac{\pi}{2} - \varphi_f - \sin(\varphi_f + 2\Delta\varphi)\cos\varphi_f\right] + \frac{U_i^2}{2\pi}\left[k_f\pi + \frac{\pi}{2} - \varphi_f - \frac{1}{2}sin2\varphi_f\right] \quad (12)$$

The start and end of the dip event are detected after a delay phase angle corresponding to a delay index k, for which the functions (11) and (12) cross the dip threshold voltage $\boldsymbol{U_T}$, where k is the first integer number after the calculated voltage RMS passes through the magnitude threshold. Thus the measured angular duration can be calculated as:

$$\delta_m = (k_f - k_i)\pi \quad (13)$$

Where $\boldsymbol{k_i}$ and $\boldsymbol{k_f}$ represent starting phase delay index and ending phase delay index respectively.

D. Half cycle window, half cycle synchronization RMS

With half cycle window the equations (11) and (12) can be rewritten as:

$$U^2 = U_i^2 - \frac{U_i^2}{\pi}\Big[k_i\pi + \frac{\pi}{2} - \varphi_i - \Delta\varphi - sin(\varphi_i - \Delta\varphi)\cos(\varphi_i + \Delta\varphi)\Big] + \frac{U_f^2}{\pi}\Big[k_i\pi + \frac{\pi}{2} - \varphi_i - \Delta\varphi - \frac{1}{2}\sin(2\varphi_i + 2\Delta\varphi)\Big] \tag{14}$$

$$U^2 = U_f^2 - \frac{U_f^2}{\pi}\Big[k_f\pi + \frac{\pi}{2} - \varphi_f - \sin(\varphi_f + 2\Delta\varphi)\cos\varphi_f\Big] + \frac{U_i^2}{\pi}\Big[k_f\pi + \frac{\pi}{2} - \varphi_f - \frac{1}{2}sin2\varphi_f\Big] \tag{15}$$

To get the measured duration equation (13) is still valid.

3. Simulation Results

For long duration dips, all four measuring methods will obtain the actual residual voltage since the duration is much longer than one cycle. And the difference between measured duration $\boldsymbol{\delta_m}$ will not be so obvious because the actual angular duration $\boldsymbol{\delta}$ is much larger than the difference between initial phase delay $\boldsymbol{\alpha_i}$ and ending phase delay $\boldsymbol{\alpha_f}$. For this reason short dip events are mainly studied. In the simulations, events with one cycle dip duration are mainly considered. In the following sections two residual voltage 10% and 80% are chosen for study. Initial phase angle $\boldsymbol{\varphi}$ ranges from 0 to $\mathbf{2\pi}$ and phase angle jump $\Delta\boldsymbol{\varphi}$ are chosen to be $-\frac{\pi}{3}$ (red line), $-\frac{\pi}{6}$(pink line), 0(blue line), $\frac{\pi}{6}$(green line), $\frac{\pi}{3}$(black line).

A. 10% residual voltage

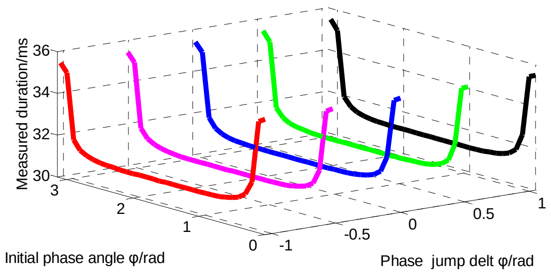

Fig. 3. One cycle window, dip duration measured with sliding window RMS for a 20ms dip with 10% residual voltage versus different initial phase angles and phase angle jumps.

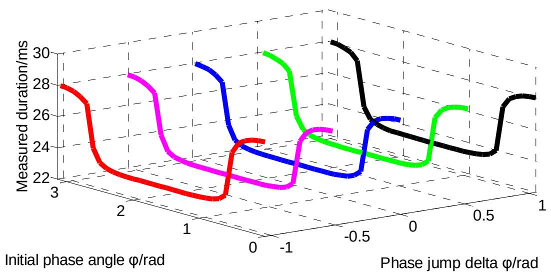

Fig. 4. Half cycle window, dip duration measured with sliding window RMS for a 20ms dip with 10% residual voltage versus different initial phase angles and phase angle jumps.

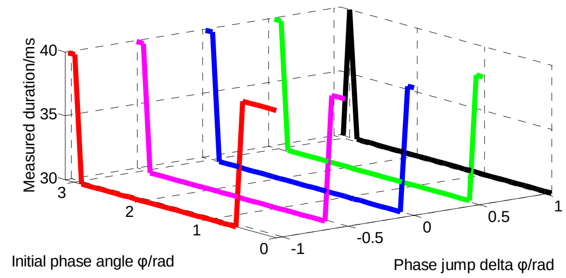

Fig. 5. One cycle window, dip duration measured with half cycle synchronization RMS for a 20ms dip with 10% residual voltage versus different initial phase angles and phase angle jumps.

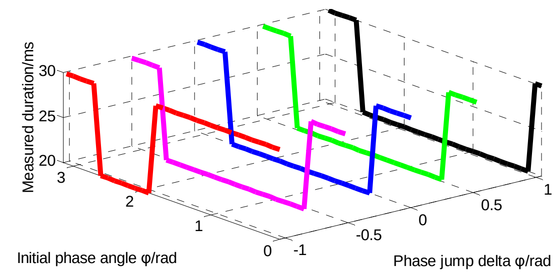

Fig. 6. Half cycle window, dip duration measured with half cycle synchronization RMS for a 20ms dip with 10% residual voltage versus different initial phase angles and phase angle jumps.

If we comparing Fig. 3 and Fig. 4 for sliding window measurement, Fig. 5 and Fig. 6 for half cycle synchronization measurement, it is noticable that half cycle window is more accurate than one cycle window when measuring the dip duration. For example, when it comes to synchronisation RMS calculations, using one cycle window (Fig. 5) leads to a result of approximately 30ms, while using half cycle windnow (Fig. 6) results in 20ms. The actual dip duration is 20ms so the conclusion is verified. It is important to notice that for a 10% residual voltage dip the phase angle jump doesn't have much influence on the duration measurement. This can be seen from the diagrams. For different phase angle jump $\Delta\boldsymbol{\varphi}$ there's almost no changes to the measured values.

B. 80% residual voltage

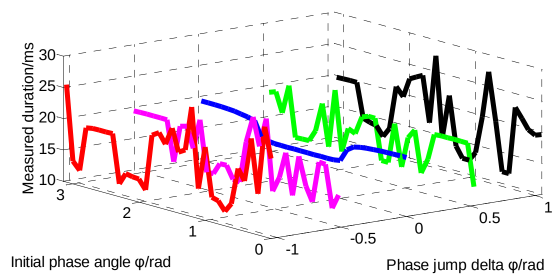

Fig. 7. One cycle window, dip duration measured with sliding window RMS for a 20ms dip with 80% residual voltage versus different initial phase angles and phase angle jumps.

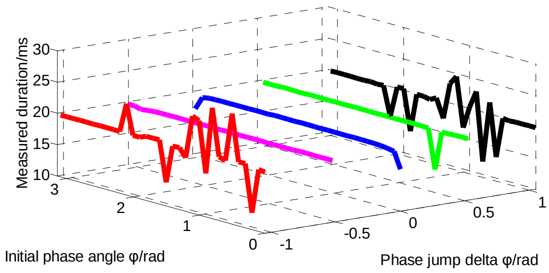

Fig. 8. Half cycle window, dip duration measured with sliding window RMS for a 20ms dip with 80% residual voltage versus different initial phase angles and phase angle jumps.

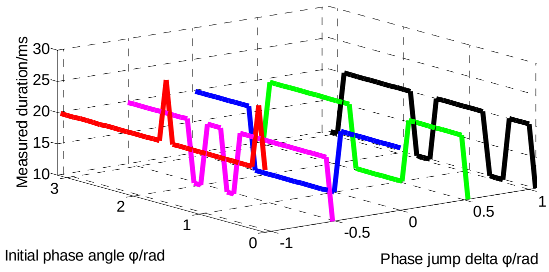

Fig. 9. One cycle window, dip duration measured with half cycle synchronization RMS for a 20ms dip with 80% residual voltage versus different initial phase angles and phase angle jumps.

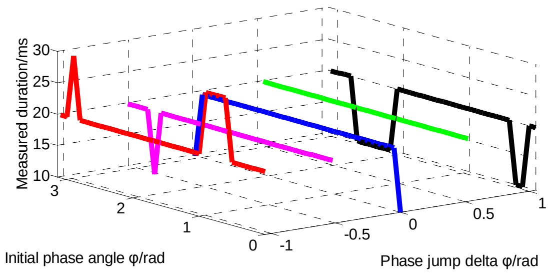

Fig. 10. Half cycle window, dip duration measured with half cycle synchronization RMS for a 20ms dip with 80% residual voltage versus different initial phase angles and phase angle jumps.

For one cycle window synchronization RMS measurement, when the residual voltage is 10% (Fig. 5), the changes of duration versus initial phase angle and phase angle jump are smaller than when the residual voltage is 80% (Fig. 9). The same conclusion can be drawn for half cycle window synchronized RMS but with a more accurate result. The different residual voltages will affect the measured results significantly with different phase angle jumps and initial phase angles. The lower the residual voltage is, the smaller the influence is. This conclusion holds for sliding window RMS measurement, comparing Fig. 3 and Fig. 7 for one cycle window as well as Fig. 4 and Fig. 8 for half cycle window.

If we compare Fig. 9 and Fig. 10 which represent one cycle window synchronized RMS and half cycle window synchronized RMS respectively at 80% residual voltage, then the conclusion that the half cycle window measurement is more accurate than one cycle window measurement is again proved. The half cycle window is mostly resulting in 20ms which is the actual value, however the one cycle window can obtain values 10ms or 30ms for a large chance which is obviously less accurate than half cycle window measurement. When comparing Fig. 5 and Fig. 6 (10% residual voltage), the same conclusion holds.

4. Field Measurement Data Analysis

A set of dip data are collected from 6 different substations in the Netherlands from 2010 to 2013, including voltage waveforms during dips. The residual voltages and durations of these dips are calculated using half cycle synchronization RMS method, with one cycle window and half cycle window respectively.

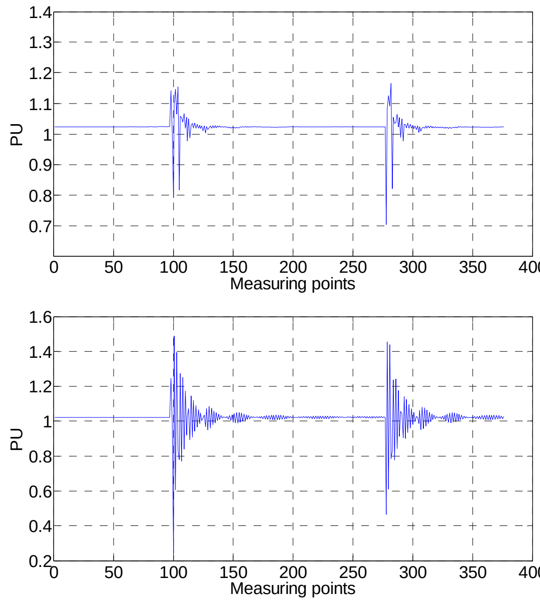

Fig. 11. Instantaneous voltage RMS of one phase of a dip event with one cycle window calculation (a) and half cycle window calculation (b)

Fig. 11 shows that one dip event may consist of 2 or more small dip events, these small dip events sometimes are not noticeable for one cycle window due to the small duration. Besides, when the network starts recovering from a dip event, the voltage magnitude may be very unstable, this also isn't easy to be detected by a one cycle window. More data are showing the similarities with Fig. 11. The dip event in Fig. 12 is also consisting of a lot of fluctuations, which brings detection difficulties. According to EN61000-4-30, 2008[3]: In three phase systems, a voltage dip begins when one phase RMS voltage falls below the dip threshold (here 90%) and ends when all three phase RMS voltages are equal or above the dip threshold plus a hysteresis voltage (here 2%). For dips which are similar to the ones shown in Fig. 11 and Fig. 12, this means many small events are contributing to a longer dip event. For this reason different duration aggregation algorithms are applied. In this paper a total of three approaches are introduced, they are:

1. Duration of superposition of all small events
2. Duration of the whole unstable period
3. Duration of the longest event

The introduction to these three methods is given below together with the results.

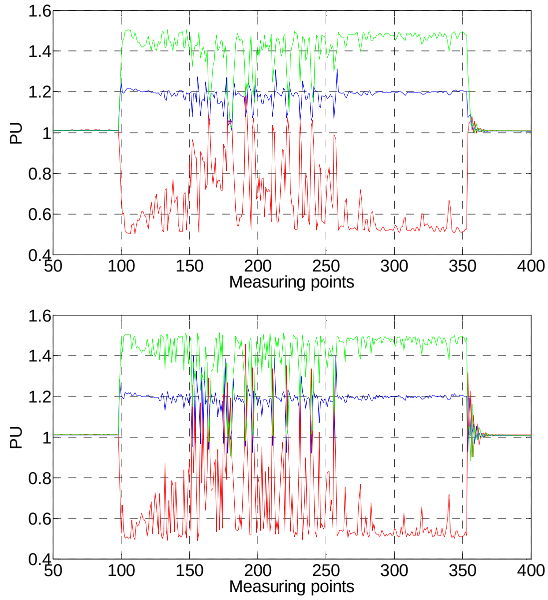

Fig. 12. Instantaneous voltage RMS of one dip event with one cycle window calculation (a) and half cycle window calculation (b)

A. *Duration of superposition of all small events*

As introduced before, many dip events consist of two or more small events and a number of fluctuations. In this paper a total of 175 dips are analyzed, among these, those with fluctuations or many small events or both of them occupy about 49%. To measure these dips' duration, one method is to obtain all the short events' durations and add them up. The results of this algorithm is shown below.

Table 1: One cycle window calculated values (superposition)

Residual Voltage(%)	Time(s)					
	$0.01 < \Delta t \leq 0.02$	$0.02 < \Delta t \leq 0.1$	$0.1 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 3$	$\Delta t > 3$
$90 > u \geq 85$	1	8	0	2	1	0
$85 > u \geq 70$	0	21	6	7	4	1
$70 > u \geq 40$	1	45	26	6	8	0
$40 > u \geq 10$	0	5	6	9	11	2
$10 > u \geq 0$	0	0	2	2	0	1

Table 2: Half cycle window calculated values (superposition)

Residual Voltage(%)	Time(s)					
	$0.01 < \Delta t \leq 0.02$	$0.02 < \Delta t \leq 0.1$	$0.1 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 3$	$\Delta t > 3$
$90 > u \geq 85$	0	2	0	2	1	0
$85 > u \geq 70$	1	7	2	9	4	3
$70 > u \geq 40$	10	21	31	6	8	1
$40 > u \geq 10$	2	13	23	11	9	2
$10 > u \geq 0$	0	0	2	2	2	1

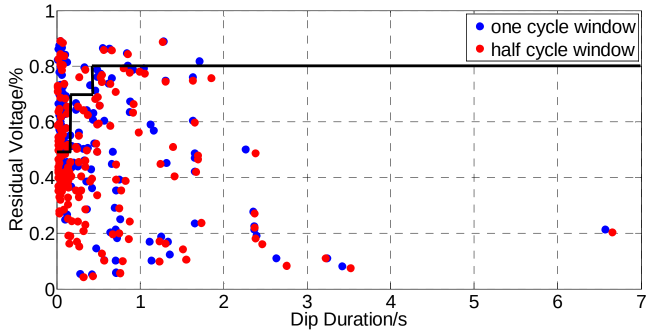

Fig. 13. Dip profile with SEMI F47-curve (superposition)

The differences between one cycle window and half cycle window RMS are obvious seen from Table 1 and 2 as well as Fig. 13. A total of 89 events under SEMI F47-curve are recorded with one cycle window calculation, however, with half cycle window calculation this number becomes 132. If we define the difference as in (16), the difference between the number of sever dips calculated with one cycle window and half cycle window goes up to 24.6%.

$$\text{Difference} = \frac{N_{half\ cycle} - N_{one\ cycle}}{N_{total}} \times 100\% \qquad (16)$$

B. *Duration of the whole unstable period*

Another algorithm to calculate the dip duration is to choose the first point at which one or more phases is below the dip threshold as the start point, and the last point when all three phases are again above the dip threshold plus a hysteresis as the end point. Using these two points we can calculate the total dip duration. The results of this method are shown below:

Table 3: One cycle window calculated values (the whole unstable period)

Residual Voltage(%)	Time(s)					
	$0.01 < \Delta t \leq 0.02$	$0.02 < \Delta t \leq 0.1$	$0.1 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 3$	$\Delta t > 3$
$90 > u \geq 85$	1	7	0	3	1	0
$85 > u \geq 70$	0	16	5	10	7	1
$70 > u \geq 40$	1	34	16	9	21	5
$40 > u \geq 10$	0	4	7	9	11	2
$10 > u \geq 0$	0	0	1	2	1	1

Table 4: Half cycle window calculated values (the whole unstable period)

Residual Voltage(%)	Time(s)					
	$0.01 < \Delta t \leq 0.02$	$0.02 < \Delta t \leq 0.1$	$0.1 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 3$	$\Delta t > 3$
$90 > u \geq 85$	0	2	0	2	1	0
$85 > u \geq 70$	0	8	1	7	7	3
$70 > u \geq 40$	9	7	29	8	18	6
$40 > u \geq 10$	2	10	14	13	16	5
$10 > u \geq 0$	0	0	1	2	3	1

In this case the differences between one cycle window measurement and half cycle window measurement are also obvious. A total of 104 events under SEMI F47-

curve are recorded with one cycle window calculation, with half cycle window calculation this number becomes 142. The difference in the number of sever dips is approximately 21.7%.

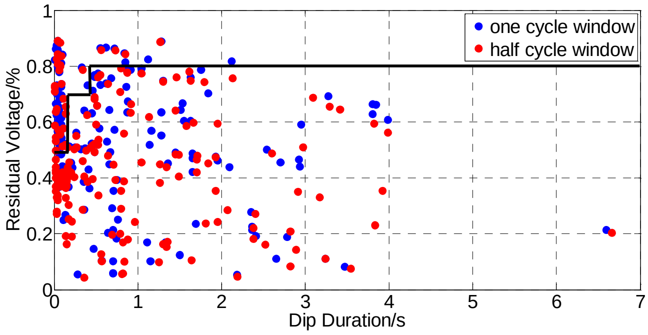

Fig. 14. Dip profile with SEMI F47-curve (the whole unstable period)

C. Duration of the longest event

The third algorithm to obtain the dip duration is to use the duration of the longest dip during the event. The results are shown below:

Table 5: One cycle window calculated values (longest event)

Residual Voltage(%)	Time(s)					
	$0.01 < \Delta t \leq 0.02$	$0.02 < \Delta t \leq 0.1$	$0.1 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 3$	$\Delta t > 3$
$90 > u \geq 85$	2	7	0	2	1	0
$85 > u \geq 70$	2	20	5	8	3	1
$70 > u \geq 40$	11	44	17	8	6	0
$40 > u \geq 10$	0	6	5	10	10	2
$10 > u \geq 0$	0	0	2	2	0	1

Table 6: Half cycle window calculated values (longest event)

Residual Voltage(%)	Time(s)					
	$0.01 < \Delta t \leq 0.02$	$0.02 < \Delta t \leq 0.1$	$0.1 < \Delta t \leq 0.5$	$0.5 < \Delta t \leq 1$	$1 < \Delta t \leq 3$	$\Delta t > 3$
$90 > u \geq 85$	0	2	0	2	1	0
$85 > u \geq 70$	0	8	1	10	3	4
$70 > u \geq 40$	16	22	24	6	7	2
$40 > u \geq 10$	2	23	13	12	8	2
$10 > u \geq 0$	0	0	2	2	2	1

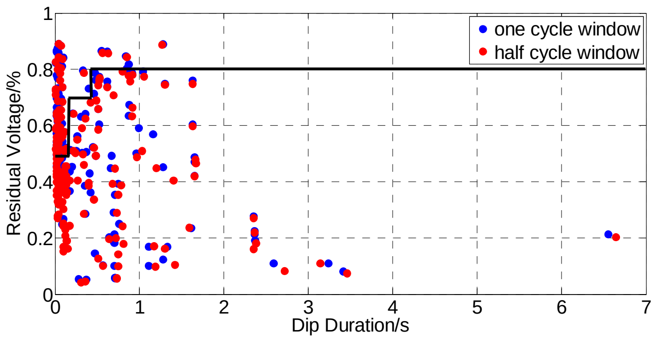

Fig. 15. Dip profile with SEMI F47-curve (longest event)

The differences between one cycle window measurement and half cycle window measurement for this algorithm are again obvious. A total of 87 events under SEMI F47-curve are recorded with one cycle window calculation, with half cycle window calculation this number becomes 129. The difference goes up to 24%.

Comparing the three algorithms, the duration of the whole unstable period method will obtain the most ‘influential’ dips. This is the worst case calculation. For very ‘sensitive’ customers this method may be suggested. When we use the duration of the longest event algorithm we don’t take fluctuations and multiple small events into consideration, which leads to the number of ‘influential’ dips is the least. This is the best case calculation. Duration of superposition of all small events lies between the above two algorithms, the results of this method are mostly close to actual dip durations.

5. Conclusions

At this moment, one cycle window is commonly applied in detecting voltage dips. However, this algorithm introduces an unavoidable error especially when measuring short dip events. The dips in real world usually consist of many fluctuations and small events, at the same time these fluctuations and small events are very short (less than one fundamental cycle). Such the one cycle window is not able to measure this type of dips. The residual voltage and dip duration obtained by half cycle window measurement for short dips still have errors but are much more accurate than one cycle window measurement.

Phase angle jumps and initial phase angles during the dip will influence the measured duration. The higher the residual voltage (swallow dips) is, the larger influence from above two aspects are. This holds for both one cycle window measurement and half cycle window measurement.

The 3 duration aggregation algorithms are applied to the dip data measured in the field. The differences between one cycle window and half cycle window for each algorithm are all significant. The difference of measured dips under SEMI-F47 curve between one cycle window and half cycle window goes up between 21.7% and 24.6%. This may influence the further immunity choices for customers.

References

[1] EN50160. (2010). Voltage Characteristics of Electricity Supplied by Public Distribution Systems.

[2] Gallo, D., Landi, C., Luiso, M., & Fiorucci, E. (2014). Survey on Voltage Dip Measurements in Standard Framework.

[3] EN61000-4-30. (2008). Testing and Measurement Techniques - Power Quality Measurement Methods.