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ACCURACY ANALYSIS OF VOLTAGE DIP MEASUREMENT

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Abstract – This paper analyzes accuracy of algorithms commonly adopted in instrument devoted to the detection and the characterization of voltage dips (also called sags). This analysis is particularly interesting because the results of dip measurements are utilized for calculation of severity levels and the site index assessment that are parameters adopted in determination of quality level of power supply, but also in developing planning and design criteria of new electrical power grid or for selecting equipment with proper intrinsic immunity. Anyway there is a certain degree of freedom left to instrument manufacturers (f.i. the choice of dip detection algorithm) and it can be found that different instruments significantly disagree in some actual measurements. The paper starts with an insight about dip phenomenon analyzing how accuracy impacts on severity index calculation. The results are applied, for accounting the systematic deviations in testing accuracy of commercial instrument, is presented. Then, experimental results derived form the accuracy testing in dip measurements of a commercial power quality instrument are shown.

Keywords Voltage dip; Power Quality Measurement; Accuracy analysis

1. INTRODUCTION

The Power Quality (PQ) phenomena that involve rms voltage variation such as long and short interruption, overvoltage and voltage dip (in UK English) or sag (in American English - the two terms are equivalent) are currently PQ issues with the greater economical impact. In fact, especially industrial customers highly suffer from regular production stoppages due to these phenomena [1]-[3].

Remarkable voltage reductions are caused by a short circuit or earth fault close to a substation that will force the voltage to a very low value in one or more phases. Smaller reductions are caused by the timely varying loads. Usually the reduction ends within a short time due to automatic switching actions, fault reparation or load stabilization.

These phenomena can be classified as voltage dips or interruption with respect to the event duration and the minimum voltage magnitude during the event. For the purpose of this paper we will refer to dip events as their durations is typically less than 0.1 s, so presenting greater measurement problems. Anyway obtained conclusions and described procedure can be extended to interruptions with minor changes. Many IEEE groups and task forces are working to develop a recommended practice for converting a suitably sampled voltage and current data set into specific power quality categories and describe specific attributes within each category. In particular, IEEE 1159.2 Working Group focuses on events such as dips and other non harmonic events between that delivered by power suppliers and that needed by equipment manufactures without technical digital definitions. The translation from sets of digital data to statistically comparable events would be used for purposes of comparing power suppliers, comparing susceptibility qualities of equipment, and evaluating performance versus specification or contract. Therefore a recognized set of digital definitions will benefit all the stakeholders of electrical energy market.

Anyway, instruments for dip measurement still present unresolved technical and theoretical issues related to performance assessment. So that, different implementations that fully meet definitions reported in standard ([1]-[9]) can still disagree significantly in some actual measurements. Mainly it happens, because standards do not include a well defined procedure for their performance characterization.

This paper starts with a discussion about parameters that characterize voltage dips, the use of these results in severity level calculation and site index assessment and accuracy requirement of measuring instrument devoted to this kind of event monitoring. Then systematic errors introduced by dip detection algorithms are analyzed presenting its analytical calculation. Significant case studies regarding dip measurement in ideal situations are presented. Finally, experimental results relating tests of accuracy in dip measurements by commercial power quality instruments are shown.

2. VOLTAGE DIP

2.1. Basic Definitions

EN 61000-4-30 [5] provides the first international definition and measurement method for the characterization of voltage dips (i.e. in terms of magnitude and duration). This standard is the fundamental reference for power quality monitoring instruments as it defines the methods for measurement and interpretation of results for power quality parameters in 50/60 Hz a.c. supply systems. Some basic definitions from [5] are recalled in the following.

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Supply voltage dips are reductions of the voltage magnitude at a point in the electrical system below a specified threshold chosen for the purpose of detecting and followed by voltage recovery after a short period of time (dip duration), from half a cycle to a few seconds. The lowest rms value measured during the event is called residual voltage.

The measured quantity for event detection could be either phase to ground voltage and/or phase to phase voltage with different detection capability [7]. Phase to phase voltages have wider detection capability, best results could be obtained with measurement on all six voltage amplitude (thee phase to ground and three phase to phase).

The dip threshold is a percentage of either U_{din} (declared input voltage) or the sliding voltage reference U_{sr} (voltage magnitude averaged over a specified time interval). Dip thresholds are typically in the range 85% to 90%. In the following analyses a thresholds of 90% will be adopted.

On single-phase systems a voltage dip begins when the rms voltage falls below the dip threshold and ends when the rms voltage is equal to or above the dip threshold plus the hysteresis voltage. The purpose of hysteresis voltage is to avoid counting multiple dips when the voltage magnitude oscillates around the threshold level. Typically, the hysteresis is equal to 1 or 2 % of U_{din}. In the following analyses an hysteresis of 2% will be adopted.

On polyphase systems a dip begins when the rms voltage of one or more channels is below the dip threshold and ends when the rms voltage on all measured channels is equal to or above the dip threshold plus the hysteresis voltage.

Typically, a voltage dip is characterized by a pair of data, residual voltage (U_{res}) and duration:

- the residual voltage is the lowest rms value measured on any channel during the dip;
- the duration is the time difference between the moment of beginning and of the end of the voltage dip. For polyphase measurements, the duration can be started on one channel and terminated on a different channel.

Voltage dip envelopes are not necessarily rectangular, so, for a given voltage dip, the measured duration depend on the selected dip threshold value. It is worthwhile underlining that phase shifts may occur during voltage dips.

Even if interest was focused on supply voltage dips, other similar PQ aspects should be accounted too as they directly impact on measurement parameters of voltage dips: fluctuation of the supply voltage, supply voltage interruptions, supply voltage swells. In addition, also others PQ phenomena have to be taken into account because they indirectly impacts on voltage dip measurement: fundamental frequency deviation, supply voltage unbalance, light flicker, voltage harmonics and interharmonics.

For this reason accuracy requirement of PQ measurement instrument have to be assured only when other PQ phenomena are within a specified range [5]. Maximum permissible error specifications for voltage dip are for residual voltage/voltage magnitude ±0.2 % of U_{din} and for duration ±1 cycle. It is worthwhile noting that [5] assumes as definition of accuracy: maximum expected deviation of a measured value from its actual value. This is not in agreement with [11] and in the following maximum permissible error will be preferred.

2.2. Site Index and Severity Indexes

Measurement results of a single dip event are used for troubleshooting and diagnostics. More often the calculation of single-event indices is an intermediate step in the calculation of site indices.

Site indices are used for compatibility assessment between sensitive equipment and the power supply and can be used as an aid in the choice of a voltage-dip mitigation method. They can also be used to provide information to local customers on the voltage quality e.g. for the follow-up of premium power contracts. Site indices are calculated from single–event indices, i.e. the residual voltage and the duration obtained for all voltage-dip events at one site during a certain period of time. At locations where seasonal variations in the number of dips can be expected, the monitor period should be an integer multiple of one year. For locations with a strong seasonal variation in the event frequency, a three to five-year monitoring period is recommended to incorporate year-to-year variations in the seasonal effects. Site indices can be calculated as the number of events more severe than a certain curve (i.e. the ITIC or the SEMI F47 curve) or below a certain residual voltage (SARFI indices as in IEEE Std 1564 draft 5) (see fig.1). The voltage dip severity is calculated from the residual voltage (in p.u.) and the duration of a voltage dip in combination with a reference curve.

It is recommended by [8] to use the SEMI curve as a reference, but the method works equally well with other curves. From the residual voltage, V_r, and the event duration, d, the event severity is calculated as follows:

$$S_e = \frac{1-V}{1-V_{curve}(d)} \tag{1}$$

where $V_{curve}(d)$ is the residual voltage of the reference curve for the same duration. For an event on the reference curve the severity equals one; for an event above the curve the index is less than one; for an event below the curve the index is greater than one. For events with the residual voltage above the dip threshold the severity is equal to zero. The longer the event duration and the lower the residual voltage, the higher the severity index. In Tab I some examples of calculation are reported.

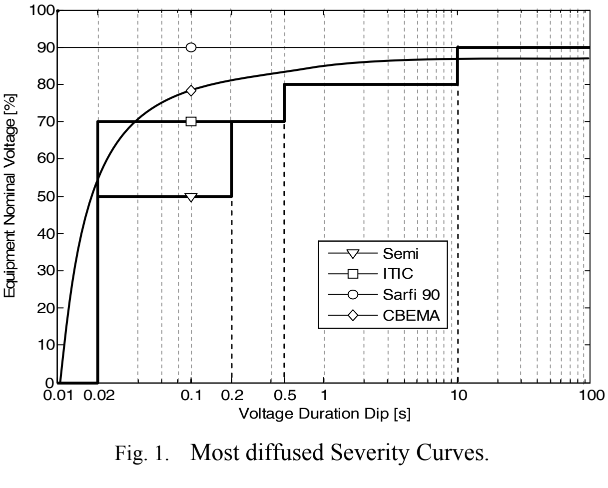

Fig. 1. Most diffused Severity Curves.

3. SYSTEMATIC DEVIATION IN VOLTAGE DIP MEASUREMENT

3.1. Rms Measurement

The measurement of dip parameters essentially lays on voltage rms measurement. According with [5], the basic rms measurement adopted for purpose is the value of the rms. voltage measured over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle (in the following simply called $U_{rms(1/2)}$). The $U_{rms(1/2)}$ values are measured on each channel. In this way, for polyphase systems, this technique will produce rms values at different time instants on different channels. These values are used not only for voltage dip measurements but also for voltage swell and interruption detection.

The synchronization to the fundamental zero crossing straightforwardly implies a systematic deviation in measurement of dip duration due to rounding that applies in detection of beginning and of the ending of the event. The authors of the standard are aware of this aspect and, in facts, accuracy specifications, reported in [5] about voltage dip, requires that the measurement results of best class instrument shall be within 1 cycle that is really poor accuracy for a time measurement. Moreover, it is possible to prove that, in a lot of practical dip events, systematic deviation much greater than 0.2% applies also for residual voltage measurements [12].

It is apparent that measurement results obtained by best instrument built in compliance with [5] cannot be used with severity curves reported in fig. 1 without unacceptable ambiguity especially due to maximum permissible error on measurement of dip duration (±1 cycle).

A minor impact is related with accuracy in residual amplitude measurement nevertheless the problem also applies. Moreover, obviously, this permissible error reflects also in calculation of severity index (1) with very remarkable effects especially for short events: it can make double the index of severity.

It is important to underline that this tolerance is systematic because it comes from detection algorithm that is imposed, in such a way that an instrument cannot perform better measurement in agreement with [5]. This makes the instrument IEC 61000-4-30 compliant useless for severity index and site index assessment.

Another important aspect to point out is related to the way to keep on performing rms measurements after the beginning of a voltage dip. During this event zero crossing are no more reliable reference because fundamental components even could miss at all or a phase shift may occur. This aspect is not clearly addressed by [5]

TABLE I. EXAPLE OF SEVERITY INDEX CALCULATIONS WITH SEMI F47

Residual voltage, U_r [pu]	Duration, T [s]			
	T≤0.02	0.02 < T ≤0.2	0.2<T ≤0.5	0. 5<T ≤10
0.0	1.0	2.0	3.3	5.0
0.1	0.9	1.8	3.0	4.5
0.2	0.8	1.6	2.7	4.0
0.4	0.6	1.2	2.0	3.0
0.6	0.4	0.8	1.3	2.0
0.8	0.2	0.4	0.7	1.0

Also different approaches for dip event characterization exist [8] and they adopt as the basic block of measurement, the rms voltage calculated over a full-cycle sliding window. In this way rms value is recomputed every sampling point. With this approach an increased resolution in residual voltage and duration parameters is expected [12]. On the other hand higher computational burden or specific synchronization hardware is required to keep the window length fitting actual fundamental period [13].

Anyway, actually, in rms measurement the difference between synchronized and nearly-synchronized measurements is expected to be small. In fact, it is possible to analytically calculate, under simplifying hypothesis, the normalized error that applies, when rms calculation is performed in a desynchronized condition. Considering a sinusoidal signal with a rms value *U*, with an estimated frequency *f*, and an actual frequency $f+\Delta f$, the maximum normalized error, $e_{n,Max}$, can be written as

$$e_{n,Max} = \sqrt{1 + \frac{\sin(2\pi\Delta f_n)}{2\pi(1+\Delta f_n)}} - 1 \qquad (2)$$

where normalized desynchronization Δf_n is introduced. Fig 3 reports $e_{n,Max}$, of (6) versus relative desynchronization, Δf_n. The value of $e_{n,Max}$ can be calculated, under small desynchronization hypothesis, adopting first order approximations,

$$e_{n,MAX} \cong \frac{1}{2}\frac{\Delta f_n}{1+\Delta f_n} = \frac{1}{2}\frac{\Delta f}{f+\Delta f} \qquad (3)$$

with this calculation absolute difference is less than 0.17% till relative desynchronization is less than 10%.

This surprisingly simple relation states that the relative error in rms voltage measurement is half of the relative error in frequency synchronization. The above-mentioned uncertainty requirements for residual voltage measurement (0.2%) thus translate into a 0.4% uncertainty requirement in frequency synchronization.

This result is in agreement with that contained in [8] obtained with a different approach. When digital signals are considered also uncertainty due to quantization of each sample in amplitude related to ADC finite number of bit and due to quantization in time related to sampling should be accounted [14]. Anyway, the preeminent part of uncertainty for most of situations is related to accuracy of synchronization and it can be calculated with (8). In the following both synchronized and desynchronized techniques will be accounted.

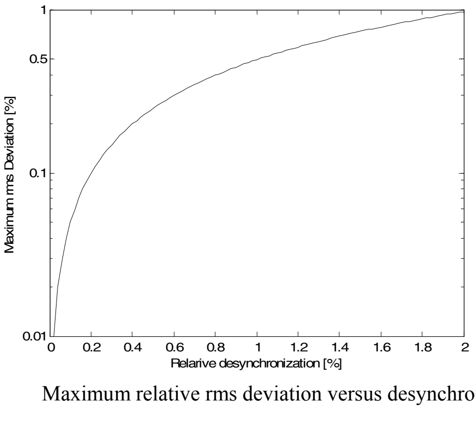

Fig. 2. Maximum relative rms deviation versus desynchronization.

3.2. *Duration Measurement*

A not trivial question about dip characterization is measurement of the event duration. In fact, event beginning and ending are ideally time instants but for their measurement reference is made to rms value that is an integral value thus defined over a time interval.

It is worthwhile analytically calculating, even under simplified hypothesis, delay phase angle, α, between the beginning and the detection of the event.

Let consider a sinusoidal signal, with, U_i the relative rms amplitude before that the event applies, U_r is the relative amplitude after beginning of the event (the residual amplitude) that is considered constant until detection applies, ΔU_n the relative detection threshold, φ the phase angle at which the event starts, and α the delay phase angle after which the event is detected performing a continuous rms calculation with a sliding window of one period. With some mathematical manipulation, [16], the relation among parameters can be written as:

$$2\pi\frac{U_i^2-\Delta U_n^2}{U_i^2-U_r^2}=\alpha-\sin(\alpha)\cos(\alpha+2\varphi) \qquad (4)$$

This is an implicit function that can be only numerically inverted. It is worthwhile underlining that relation (4) can be used also for sudden amplitude increasing but in this case the delay in detection of event is equal to $2\pi-\alpha$.

For sake of clarity, in following detection delay is expressed in relative term that is a percentage of the fundamental period:

$$d=\alpha\frac{100}{2\pi} \qquad (5)$$

This result can be easily associated to time interval multiplying for fundamental time period.

Fig. 3 reports the detection delays obtained by (4) and (5) versus the starting phase angle, φ, for different values of the residual amplitude, A_r adopting initial amplitude equal to 1 and a detection threshold equal to 90 %. It is evident that phase angle affects the detection delay for a value that does not overcome the 25% of the period. Bigger impact comes from residual voltage values. The worst case applies obviously when residual voltage is equal to detection threshold (A_r =0.9). This case is not reported in Fig. 5 as the relative delay is obviously 100% whatever the phase angle is.

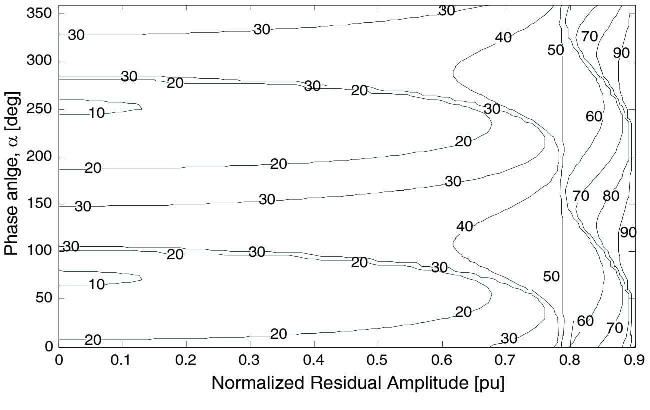

Fig. 3. Normalized detection delay versus phase angle for different values of the residual voltage adopting the detection threshold equal to 0.9.

Minimum delay is about 10%. It applies when the beginning of the dip is exactly half of the detection delay angle before of the value of 90° for instantaneous phase angle. In this condition the effect of the dip is the most remarkable because the amplitude reduction affects the values around the peek of sinusoidal. Nevertheless, adopting (4) the minimum delay could be even lower reaching nearly zero value.

This condition corresponds to the situation in which the initial amplitude, A_i, was only slightly higher than detection threshold so that the amplitude reduction is immediately detected. Best conditions for an accurate evaluation of event duration are those corresponding to an amplitude reduction around 79 % followed by a return to rated conditions: in these cases the delay in detection of beginning of the event are nearly equal to the delay in detection of ending and these systematic effects nearly compensate each other.

Starting from the detection delays obtained with (4) for a rms calculation with sliding window, the delays for a synchronized rms calculation, α_s, can be calculated by

$$\alpha_s = ceil\left(\frac{\alpha+\varphi}{\pi}\right)\cdot\pi-\varphi \qquad (6)$$

where *ceil*, the function that rounds to the nearest integer towards infinity, was introduced. In this situation, the detection always applies with a greater delay because, after deceasing of rms value below detection threshold (α delay), an additional delay have to be accounted because the detection can take place only when instantaneous phase angle ($\theta+\varphi$) reaches the next integer multiple of π (*ceil* function) corresponding to the next zero crossing. Also this delay can be normalized with (5).

Fig. 4 reports the synchronized detection delays obtained by (6) in the same condition of fig. 3. The phase angle affects the detection delay for a maximum value that is 50% of period. This additional delay can be reached whatever residual amplitude is accounted. The worst case reaches the values of nearly 150 %. It applies when residual voltage is equal to detection threshold (A_r =0.9) and event begins immediately after the zero crossing. Also in this situation α_s values can be used for calculating delays for detection of a sudden amplitude increasing. In this case, the (6) become:

$$\alpha_s=ceil\left(\frac{2\pi-\alpha-\varphi}{\pi}\right)\cdot\pi+\varphi . \qquad (7)$$

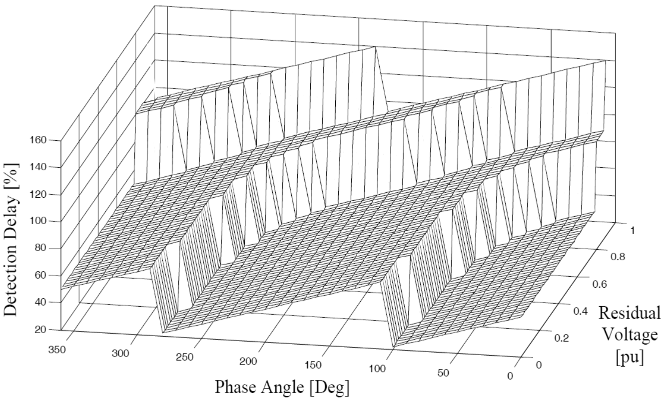

Fig. 4. Quantized detection delay versus phase angle for different values of the residual voltage adopting the detection threshold equal to 0.9

Minimum delay is about 20%. It applies when the detection of the dip is immediately before the zero crossing. Nevertheless, also for synchronized rms calculation, the minimum delay could be even lower reaching nearly zero value if the initial amplitude, A_i, was only slightly higher than detection threshold so that the amplitude reduction is immediately detected.

The results obtained in both Fig. 3 and Fig. 4, point out a great concern in adopting severity curves as those reported in Fig. 1. In fact, for a given voltage dip, the measured duration is highly dependent on the phase angle at which the event starts. So, the same event (e.g. the rms amplitude suddenly become zero for one cycle than it return to nominal value) can be measured with a completely different duration according to the phase angle at which it applies due to delays in detection of its beginning and its ending and the measured values can range from 12 ms to 32 ms.

4. NUMERICAL CASE STUDY

In order to apply the obtained results, two numerical case studies are presented.

Let consider a voltage dip characterized by a 70% of residual voltage for exactly 2 cycles and with initial phase angle equal to zero (see fig. 5a where x axis reports time expressed as a percentage of the fundamental period). The depicted signal is what a power quality calibrator presents as output when 2 cycle 70% dip with 0 initial phase angle is required.

Nevertheless, even with an ideal measurement of voltage rms (see fig. 5b)), this event has a different duration. Performing rms calculation with a sliding window (solid line in 5b) event duration is estimated as 241 %, considering rms values each half cycle synchronized with fundamental zero crossing (dots in 5b) the time duration is 250 %.

No method detects 2 cycle event. This means that in accuracy assessment of dip detection instrument, adopting calibrator settings as reference values produces unfair deviations that should be corrected before accuracy calculation in order to find out real performances. Of course this deviation depends on dip depth and starting phase angle. Tab. II reports the results of application of formulas from (4) to (7). The parameters of first two rows correspond to the situation of first case study and the results are in agreement with delays found with the numerical simulation: the difference between delay in detection of ending and beginning of the event correspond to found deviation. This means that formulas (4)-(7) can be utilized to correct systematic deviation from calibrator settings before calculation of instrument accuracy.

A little more complex situation is considered in case study 2: at initial phase of 90 degree the amplitude at first decreases to 80% for one cycle, then becomes 0% for another cycle. Finally, the value of restored voltage is 95% (see fig. 6). Once again actual event duration is 2 cycle but sliding method detects a duration of 246% and synchronized method a duration of 250%. The parameters of last two rows correspond to the situation of second case study and also in this more complex case the results are in agreement with delays found with the numerical simulation.

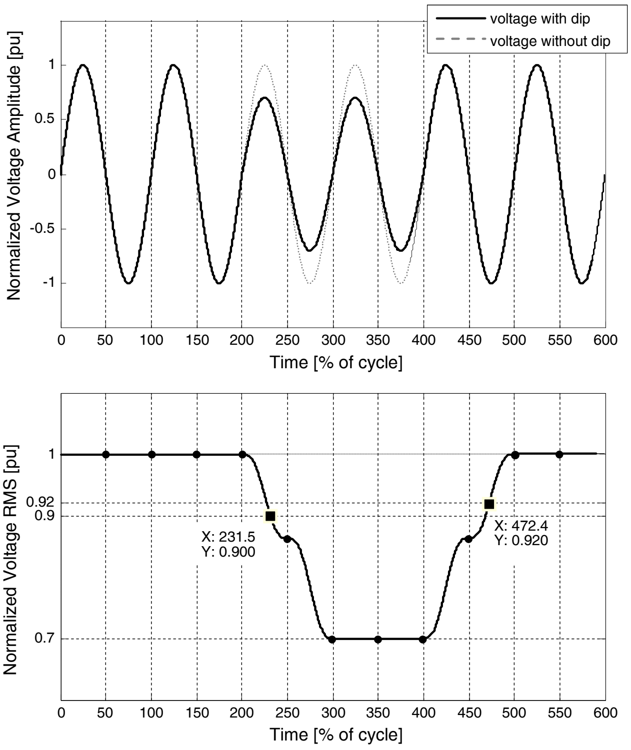

Fig. 5. Case study 1 voltage dip a) istantaneous voltages; b) rms values calculated with sliding window (line) and half cycle syncronization (dots).

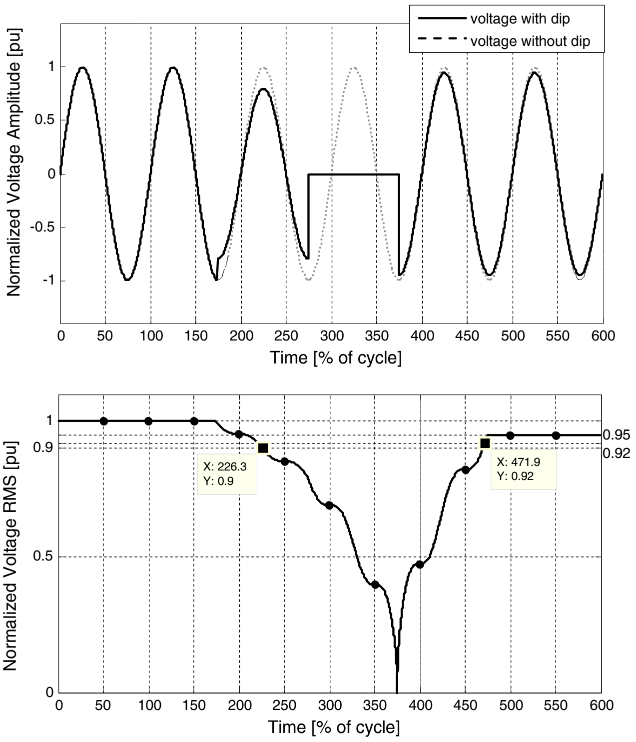

Fig. 6. Case study 2 voltage dip a) istantaneous voltages; b) rms values calculated with sliding window (line) and half cycle syncronization (dots).

TABLE II. EXAMPLE OF TIME DELAY CALCULATION

φ [deg]	Ui [%]	Ur [%]	ΔUn [%]	d [%]	ds [%]
0	100	70	90	31.47	50
0	70	100	92	72.42	100
90	100	80	90	51.39	75
90	0	95	92	96.85	125

TABLE III. EXPERIMENTAL RESULTS

Residual voltage [%]	Phase [deg]	Duration [ms]	Duration (corr.) [ms]	Measured [ms]	Deviation [%]
0.5	0	30.00	40.00	38.00	-5
0.5	45	30.00	40.00	32.20	-20
0.5	90	30.00	40.00	40.00	0
0.5	135	30.00	40.00	30.00	-25
0.25	0	20.00	30.00	21.00	-30
0.25	45	20.00	30.00	26.60	-11
0.25	90	20.00	20.00	20.00	0
0.25	135	20.00	20.00	20.00	0
0.12	0	20.00	10.00	20.00	100
0.12	45	20.00	20.00	20.00	0
0.12	90	20.00	10.00	10.00	0
0.12	135	20.00	10.00	16.40	64
0.5	0	250.00	260.00	254.60	-2
0.5	45	250.00	260.00	260.00	0
0.5	90	250.00	260.00	257.80	-1
0.5	135	250.00	260.00	250.00	-4

It worthwhile underlining that proposed approach for the calculation of systematic delays cannot be directly applied in field measurement because some of parameters of (4) are unknown at measurement time and they could be only estimated which leads to a not reliable application. Anyway, these results can be very useful in performance assessment of instruments for dip monitoring [15]-[17]. In fact, during these tests, rms voltage before and during test is known with negligible uncertainty, and formula (4)-(7) can be used in calculating what is the expected value of dip duration from an ideal meter including the systematic deviations due to rms calculation and threshold utilization.

5. EXPERIMENTAL RESULTS

In this section some experimental results, about testing a commercial instrument for power quality analysis, are reported. Fluke 6100A as power quality calibrator and Fluke 1760 as power quality instrument have been used.

In Table III results of 16 experimental tests are reported. Events waveforms are similar to that depicted in Fig.5a, but residual voltage, phase and duration are those indicated in the first three columns of Table III. The fourth column shows dip duration corrected with formulas (6)-(7) because considered instrument performs dip analysis in agreement with [5]. The fifth column shows duration values measured by instrument under test, and the sixth the deviation with respect to duration corrected values. It worthwhile underline that instrument under test performs measurement in agreement with [5] this means that results are always integer multiple of half cycle (10 ms as 50 Hz system was accounted). Nevertheless, the instrument repeating the same test more than once not always presents the same result. So, reported measured values are the average of 100 test repetition and therefore are not integer multiple of 10 ms.

As it is obvious, for long dip events, the systematic delays introduced by measurement algorithm produce negligible effects and deviations are under 4%. Worst cases manifest when there are low depths and short durations: errors are even 100%. Another relevant consideration is that there are lowest errors when phase angle is 90° in agreement with minimum values of fig. 4.

6. CONCLUSION

This paper analyzed accuracy of algorithms commonly adopted in instrument devoted to the detection and the characterization of voltage dips (also called sags). The paper started with an insight about dip phenomenon analyzing how accuracy impacts on severity index calculation. Then, analytical formulas are derived: some related to maximum relative rms deviation versus frequency desynchronization; some other related the delay phase angle after which the event is detected. The results were applied for accounting systematic deviations in testing accuracy of commercial instrument is presented. Then, some experimental results, derived form the accuracy testing in dip measurements of a commercial power quality instrument, are shown.

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