New synthetic Power Quality Indexes and associated Measurement Procedures

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Abstract- In recent years, particular attention has been focused about problems regarding Power Quality. In 1995, IEEE technical committee defines some fundamental indexes capable of quantifying the quality of the power generation and transmission. In authors' opinion, the list of the proposed indexes [1] seems to be inadequate to exhaustively detect voltage or current disturbances at all. In this paper, the authors propose for new indexes and a respective original procedure for measuring and evaluating voltage sags, according to the standards definitions.

I. Introduction

The changes about production and utilization of electrical power has driven many researchers to interest in Power Quality phenomena. In particular non-linear loads with power electronic components, that generate harmonics on power lines, have increased, such as devices more sensible to power supply distortion. This means that a power supply without interruptions is not enough; Power Quality also regards the voltage and current waveforms, voltage dips, swells, interruptions, harmonic distortion. In order to quantify the electric power good quality, various quality indexes have been defined. IEEE Std.1159-1995 [1] has been published to properly address users in the monitoring and the data analysis of electromagnetic phenomena causing power quality problems. To this aim, a wide set of indexes for Power Quality phenomena have been defined, in order to facilitate data exchange and comparison within the power quality community. In the following table [1] the categories and typical characteristics of power system electromagnetic phenomena are illustrated.

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	< 50 ns	
1.1.2 Microsecond	1 µs rise	50 ns-1 ms	
1.1.3 Millisecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3-50 ms	0-4 pu
1.2.2 Medium frequency	5-500 kHz	20 µs	0-8 pu
1.2.3 High frequency	0.5-5 MHz	5 µs	0-4 pu
2.0 Short duration variations			
2.1 Instantaneous			
2.1.1 Sag		0.5-30 cycles	0.1-0.9 pu
2.1.2 Swell		0.5-30 cycles	1.1-1.8 pu
2.2 Momentary			
2.2.1 Interruption		0.5 cycles-3 s	< 0.1 pu
2.2.2 Sag		30 cycles-3 s	0.1-0.9 pu
2.2.3 Swell		30 cycles-3 s	1.1-1.2 pu
2.3 Temporary			
2.3.1 Interruption		3 s-1 min	< 0.1 pu
2.3.2 Sag		3 s-1 min	0.1-0.9 pu
2.3.3 Swell		3 s-1 min	1.1-1.2 pu
3.0 Long duration variations			
3.1 Interruption, sustained		> 1 min	0.0 pu
3.2 Undervoltages		> 1 min	0.8-0.9 pu
3.3 Overvoltages		> 1 min	1.1-1.2 pu
4.0 Voltage imbalance		steady state	0.5-2%
5.0 Waveform distortion			
5.1 DC offset		steady state	0-0.1 %
5.2 Harmonics	0-100th H	steady state	0-20%
5.3 Interharmonics	0-6 kHz	steady state	0-2%
5.4 Notching		steady state	
5.5 Noise	broad-band	steady state	0-1%
6.0 Voltage fluctuations	< 25 Hz	intermittent	0.1-7%
7.0 Power freq. variations		< 10 s	

Table 1. IEEE 1159-1995 , Tab. 2 page 12

In this paper, the authors focused their attention about a particular type of power quality disturbance, i.e. the sag (or dip). The sag is a short duration voltage decrease, generally incoming when the loads of a Power System become quickly variable [2].

II. Sags phenomena

Voltage sags are usually associated with system faults (typical fault clearing times range from 3 to 30 cycles, depending on the fault current magnitude and the type of overcurrent detection and interruption), but can also be caused by switching of heavy loads or starting of large motors. In fact, an induction motor will draw six to ten times its full load current during starting and this lagging current causes a voltage drop across the impedance of the system. If the current magnitude is large relative to the system available fault current, the resulting voltage sag can be significant [1].

The most prevalent problem associated with interruptions, sags, and swells is equipment shutdown. In many industries with critical process loads, even instantaneous short duration phenomena can cause process shut-downs requiring hours to restart. In these facilities, the effect on the process is the same for a short duration variation as for long duration phenomena. Monitoring is important because it is often difficult to determine from the observable effects on customer equipment which electromagnetic phenomena caused the disruption.

Voltage sags account for deviations of the voltage or current waveforms from their ideal values; their duration is typically within the range from 1/2 cycle to 1 min. The presence of sags can be identified through RMS voltage measurements. In particular, a sag has occurred if the RMS voltage of the waveform assumes value lower than 90% of its nominal value (see IEEE 1159-1995 , Tab. 4 pag. 46). Occurrences of RMS voltage lower than 90% of its nominal value, the duration of which is longer than 1 min, are classified as undervoltages.

As suggested in [3] and [4], the basic measurement time interval to correctly evaluate the fundamental quantities (supply voltage, harmonics, interharmonics and unbalance) shall be a 10-cycle time interval for 50 Hz power system. As an example, a typical sag detected by a power analyzer in the presence of heavy loads switching is illustrated in Figure 1. Voltage sags are generally acknowledged to be a common power quality event.

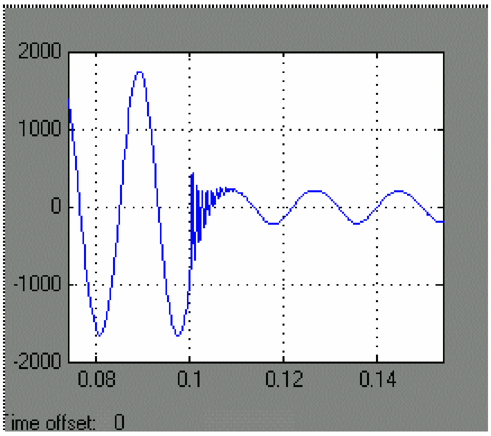

Figure 1. Example of detected sag when the switching of heavy loads occurs.

The standard characterise voltage sags in terms of its features, depth and duration. At this aim, these characteristics are firstly evaluated by means of a RMS measurement on one-cycle and subsequently updated each 1/100 cycle. The worst drawback of the approach proposed by the standard consists of considering voltage sags as disturbance with rectangular time evolution. Unfortunately, the depth often varies during the sags, and an analysis limited to depth and duration can hide more useful information.

III. Indices definition and their significance

To attain more precise identification of the beginning and end of the voltage sag using simple thresholds (see [3] and [5]), it may be useful to calculate one-cycle r.m.s values, and subsequently to update its value more frequently than every half-cycle. For example, it may be useful to update the one-cycle r.m.s. value 100 times each cycle, as specified in [3].

The thresholds of 0.9 p.u. is used to accommodate the rms variation performance indices. Once voltage samples are stored (a voltage sag has been detected) a signal process is necessary to extract the following indices:

$$WSF = V_{p\,min} n_p / \left(\sqrt{2} \cdot V_{rms}\right); \quad (1)$$

$$SQ = {}^{V_{p\,min}}\!\!\Big/\!{}_{\sqrt{2} \cdot V_{sag}}; \quad (2)$$

$$SI = \frac{\Delta T}{T_{meas}} \cdot \frac{V_{sag}}{V_{rms}}; \quad (3)$$

$$ITSR = \frac{\sum NI}{\sum Nt}; \quad (4)$$

Where $V_{p\,min}$ stands for the lowest peak voltage value during the sag event, n_p a term expressing the ratio between the time $V_{p\,min}$ occurs and the time any peak value in the sag event, and V_{sag} is the RMS voltage value during ΔT . V_{rms} is the first one cycle RMS value evaluated out of the disturbance during the measurement time T_{meas}.

To correctly monitor sag phenomenon, data storage has to start when 1/100 cycle RMS value is $0.1 V_{nom} \le V_{\frac{1}{100}cycle\_RMS} \le 0.9 V_{nom}$ and stops when it is out of this interval (where V_{nom} is the theoretical 1 cycle RMS value for a single-phase power line, and it is assumed to be the RMS value on the first cycle detected).

The acronyms used in the expressions above are here explained: *WSF* is the Worst Sag Factor, *SQ* is the Sag Quality, *SI* represents the Sag Incidence, and *ITSR* is the Instantaneous to Total Sag Ratio.

Finally, the ΔT value, i.e. the effective duration of disturbance, is determined in the subsequent processing stage.

In (1) $V_{p\min} / \sqrt{2}$ may be considered as the RMS value we'd observe the voltage sag event if it consisted of a pure sinusoidal waveform with a peak value $V_{p\min}$. The first two indices has to be coordinated with (3) to measure the importance of the lowest peak voltage value into the calculation of the total incidence of sag.

The Sag Quality (see (2)) is a number between 0 and 1, and may be valued as the capability of sag event in not introducing harmonic distortion and in not implying the visible annoying effect called flicker. This is produced by a periodical amplitude modulation of the voltage sinusoidal waveform with a frequency of 0.5–25 Hz, sufficient in duration to produce a visual observation of the luminance fluctuations in an incandescent lamp [6].

The last index has been introduced for distributed measurement systems; *NI* is the number of monitored reference nodes where instantaneous voltage variations (0.5-30 cycles) have been noticed and *Nt* is the total number of monitored reference nodes from the section of the considered system (in more than one year), and reporting any duration sag.

IV. Measurement algorithm

The implemented measurement station detects the first fundamental zero crossing and starts to sample (100 kS/s, that is to say, at 50 Hz fundamental, 2 kS/period) the voltage input waveform. A simple counter is initialized to zero (cont = 0) and after the first fundamental cycle the relative RMS calculation is performed on the last N samples, where $N = \frac{sampling\_rate}{f_{fund}}$ (the value N is 2000 for a 100 kS/s sampling rate and with the fundamental frequency f_{fund} of 50 Hz). The nominal value V_{nom} is used as a reference to define the threshold individuating sag event: if the RMS voltage is out of the interval $\left(0.1 \cdot V_{nom}, 0.9 \cdot V_{nom}\right)$ no sag is detected, else the counter is increased (cont = cont +1), and the last 2000 samples are stored to be processed afterwards. Each 1/100 cycle the 1 cycle RMS is updated and another comparison with the threshold is made.

That is to say, our algorithm performs a sliding window of 0,02 seconds to calculate the one cycle

RMS value (every $\frac{1}{100}\cdot\frac{sampling\_rate}{f_{fund}}$ samples), according to the following formula:

$$V_{RMS}(k)=\sqrt{\frac{1}{N}\cdot\sum_{i=1}^{N}\left(V(k-i+1)\right)^2}$$

When the event is no more persistent, if count is different from zero, the entire time interval to which the storage data are referred, is:

$$\Delta T=\frac{1}{f_{fund}}+(cont-1)\cdot\frac{1}{100}\cdot\frac{sample\_rate}{f_{fund}}\cdot\frac{1}{sample-rate}=0.02+\frac{(cont-1)\cdot 20}{10^5},$$

but monitoring system goes on saving voltage samples until the total observation period is T_{meas}.
We know from Table 1 the detected event may belong to one of the following case

- case A: ΔT is less than $t_1=30\cdot f_{fund}$;
- case B: ΔT is between t_1 and $t_2=3$ s;
- case C: ΔT is greater than t_2, but less than 1 minute long.

This is why we choose to set the observation time to 61 seconds. In data processing step the exact beginning and stop of the event is detected, just by the comparison of a voltage sample with its corresponding sample in the previous cycle of fundamental frequency (see [7]). When the difference between the latter and the former is higher than 0.1 pu, the event is starting. This is to extract the four indices proposed.

V. Measurement Station

In order to assess the performance of the proposed method and quality indexes, a suitable measurement station has been set up. Signals acquisition was performed through *(i)* a high resolution VXI digitizer characterised by 16 channels and a 16 bits A/D, with maximum sample rate of 200 kS/s and record length of 64 kS for each channel; *(ii)* a high speed waveform digitizer, characterized by a 12 bits A/D converter and a maximum sample rate of 10 MS/s. The VXI backplane is then connected to a Personal Computer via a standard interface. The software to manage the measurement process, acquire signal samples and process data has been realized in LabVIEW^{TM} software, by means of VISA commands[8].
The high resolution acquisition board is used to acquire, at a sampling rate of 100 kS/s, the voltage waveform during normal conditions. When the zero crossing with positive slope is recognized, the board starts to collect 2000 samples, calculates V_{RMS} and compares it with the nominal voltage value. Then the digitizer carries on the acquisition, while the software updates the RMS voltage and executes the comparison each 1/100 cycle (i.e. each 20 samples).
When a sag occurs, the collection of signal samples is executed by the second digitizer that is characterized by a faster sample rate. Once acquired all data regarding the sag event, the software itself executes the algorithm to calculate the proposed indexes.
In Figure 2 the front panel of the realized virtual instrument is shown.

Sample rate [kS/s] 100
Full scale [V] 1000
Nominal Voltage [V] 220
Sample per period 2000
V RMS [V] 219,2
Measurement time [s] 12,23
Signal frequency [Hz] 49,987
Sag threshold [V] 200,0
C:\PQindexes.xls
RMS update [n samples] 20
Cont 41
Sag Duration [s] 0,100
Vp min [V] 42,4
Sag occurrence
Worst Sag Factor 0,011
Sag goodness 0,741
Sag incidence 0,075
ITSR 0,000

Figure 2. Front panel of the realized virtual instrument.

In the panel the waveform graph of the phase voltage (line-neutral measurement), V_{RMS}, and signal frequency, for each phase, are displayed. When a sag occurrence is detected, the estimate of the four proposed indexes immediately starts; indexes value is continuously updated and displayed on the front panel. However, during a sag, the data collection is saved on a file, whose path has been previously selected, such as successive data processing is possible.

VI. Conclusions

In this paper, four new indexes to evaluate the power quality related to sags phenomena have been presented. The authors also proposed the measurement algorithm to evaluate the indexes, in which give advice to update the one-cycle voltage r.m.s. value 100 times each cycle, in order to have more precise identification of the beginning and end of the voltage sag, using simple thresholds. Finally the measurement station, based on VXI technology, monitoring the voltage parameters and evaluating the indexes value has been presented.

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