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Evaluation of a new Power Quality index, based in Higher Order Statistics

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Abstract.

The present works deals with the presentation and test of a novel Power Quality index, based in Higher-Order cumulants. Synthetics are used for test different start point, amplitude and length for the most common Power Grid disturbances (DIP, Oscillatory Transient, Harmonic Temporal Distortion and Impulsive Transient), obtaining a high accuracy (over 99% in some disturbances). Then real signals are used for confirm synthetics results. Finally, the Power Quality index presented, is confirmed with real signals as a good tool for detect imperfections in the power waveform.

Key words

Higher-Order Statistics, Power Quality, Detection, Index, Automatic.

1. Introduction

Power generation scenario, and moreover power consumption scenario is changing in developed countries. This change in caused by the development of the new generation technologies and new types of loads.

New generation technologies makes more environment respectable the power grid, but it makes more difficult to the system to control the power flow [1] and stablish the energy price [3] , due to in some of those technologies, the original power source can't be controlled, and generation must be support with fast reaction power plants, e.g. a combined cycled, based in a gas turbine.

Advanced in the charged side has changed the consumption paradigm, in the beginning only pure sinusoidal consumption are found (active or reactive power), but now almost all domestically loads are electronics loads (which do not take current in a pure sinusoidal way, if they do not have a perfect filter) and even can be found very high loads, as the electrics and pluggable hybrid cars. [5] [6] . This is the reason of the efforts in develop high quality filter for keep the signal pure sinusoidal [7] . In addition, Power Quality (PQ) must be evaluated in every point of the power grid, with the objective of detect and correct as soon as possible consequences of a disturbance in a high connection level grid. In this line, researchers worldwide has been working in this line, for photovoltaics plants [8] [9] , advanced harmonic detection [10] [11] , or using advanced techniques as Higher-Order Statistics (HOS) [12] [13] .

This last research line inspires the actual work. In base to HOS, some fast computation time domain PQ indexes have been developed. Then, they have been tested in a wide synthetics signal conditions. Finally, results are confirmed with real signals.

2. HOS and PQ index

Second Order Statistics has the ability to understand the power of the signal, in addition to the averaged amplitude. However, some features of the signal are indistinguishable in a secondary order analysis, e.g. symmetry. With the objective of obtain an analysis tool, with the capacities beyond Second Order ones, Higher-Order statistics, via Higher-Order cumulants, are used in this work.

Higher-order cumulants are being used extensively to deduce newly statistical features from the data of non-Gaussian measurement time-series [12] [14] [15] .

For the cumulants calculation, let's consider a $\{x(\mathrm{t})\}$ rth-order stationary real value random process, the rth-order cumulant is defined as the joint rth-order cumulant of the random variables $x(\mathrm{t})$, $x(\mathrm{t}+\tau_1)$,..., $x(\mathrm{t}+\tau_{r-1})$. This compacted notation is expressed in Eq. (1)

$$C_{r,x}\left(\tau_1,\tau_2,...,\tau_{r-1}\right)= \\ Cum\left[x(t),x(t+\tau_1),...,x(t+\tau_{r-1})\right] \quad (1)$$

Where $\tau_1, \tau_2, ..., \tau_{r-1}$ are time shifts, always multiple of the sampling period T_s , and usually $\tau_n = n \cdot T_s$. Cumulants, defined in Eq. are estimated using the Leonov-Shiryaev formula, in particular, 2 nd-, 3 rd- and 4 th-order cumulants, for a zero-mean time-series (central cumulants) x(t) can be estimated via [16] :

$$\begin{aligned}
&C_{2,x}(\tau) = E\{x(t)\cdot x(t+\tau)\} \\
&C_{3,x}(\tau_1,\tau_2) = E\{x(t)\cdot x(t+\tau_1)\cdot x(t+\tau_2)\} \\
&C_{4,x}(\tau_1,\tau_2,\tau_3) = \\
&E\{x(t)\cdot x(t+\tau_1)\cdot x(t+\tau_2)\cdot x(t+\tau_3)\} \\
&-C_{2,x}(\tau_1)\cdot C_{2,x}(\tau_2-\tau_3) \\
&-C_{2,x}(\tau_2)\cdot C_{2,x}(\tau_3-\tau_1) \\
&-C_{2,x}(\tau_3)\cdot C_{2,x}(\tau_1-\tau_2)
\end{aligned} \quad (2)$$

Where $E\{\ \}$ is the expected value operator. These are a measurement of the original time series and time shifted version, if not time shift is considered, $\tau_1 = \tau_2 = \tau_3 = 0$, calculations over the original time series are done. That change the Eq. (2) into the minima computational complex expression, shown in Eq. (3):

$$\begin{aligned}
&\gamma_{2,x} = E\{x^2(t)\} = C_{2,x}(0) \\
&\gamma_{3,x} = E\{x^3(t)\} = C_{3,x}(0,0) \\
&\gamma_{4,x} = E\{x^4(t)\} - 3(\gamma_{2,x})^2 = C_{4,x}(0,0,0)
\end{aligned} \quad (3)$$

These equations consist in an indirect measurement of the variance, skewness and the kurtosis, the base for the PQ index considered. Symmetrical distributed data show a skewness zero (but not *vice-versa*) and Gaussian distributed data show a kurtosis zero (but not *vice-versa*). Standardized quantities are defined as $\gamma_{4,x}/(\gamma_{2,x})^2$ for kurtosis and $\gamma_{3,x}/(\gamma_{2,x})^{3/2}$ for skewness.

The base of the power signal is a sinusoidal waveform, which change with time. However, a constant output for the HOS-analysis is desired, in healthy conditions, in order to determinate system properties. For that an analysis window over the power signal is taken, with a length which make the signal statistically equal, no matter the time taken. This length is a complete number of cycles of the base sinusoid of the power signal. Statistical distribution of signal points will be the same, and consequently, all moments will be the same [16] . So a window, with a length exactly a complete number of cycles of the base frequency of the power signal, in this work one cycle has been selected, is taken and swept along the signal. For each position, cumulants are calculated.

Once established the calculation kernel and the calculation procedure, the PQ index is presented.

For each point, a set of three cumulants values is obtained. Up to this point, a classification in base to them, considering all values has been done [9] [12] [13] [16] [17] .

Now a PQ index which is calculate with the combined information of all three HOS cumulants is presented, in order to find a simple and powerful evaluation method for the Power Quality.

The best way to take any value variation is to subtract the normal condition value to any HOS cumulants, and then the absolute value is calculated for each one. This allow to detect any variation, no matter if it were an increment or a decrement. Three normalized HOS values are added, and result is our PQ index. Eq. (4) show this calculation. Any variation of HOS properties will affect or PQ index.

$$PQi = |Var(x) - 0.5| + |Skew(x)| + |Kur(x) + 1.5| \quad (4)$$

PQ index is calculated in each analysis window and the maximum returned the signal analysed is taken as the signal PQ index.

This index has been tested in synthetic and real conditions, in order to show their properties. First a high number of synthetic conditions has been considered.

3. PQ index value study

Most common power grid disturbances have been considered, and a wide range of conditions has been tested, in order to show the response of the PQ index.

In all studied situations, a base 50 Hz unitary amplitude sinusoidal waveform has been used as a power waveform, with a Sampling frequency of 8000 Hz, and a 1% of additive noise. In all studied situations, the initial point is swept, in order to observe all possibilities.

First disturbance under test is Sag or DIP, a sudden amplitude reduction in the power wave. The reduction observed, in relation with the normal amplitude is called depth. Depths from 0.1 to 0.9 and duration from one cycle (0.02s) to 4 cycles (0.08 s) have been considered. In Fig 1 the experience is shown.

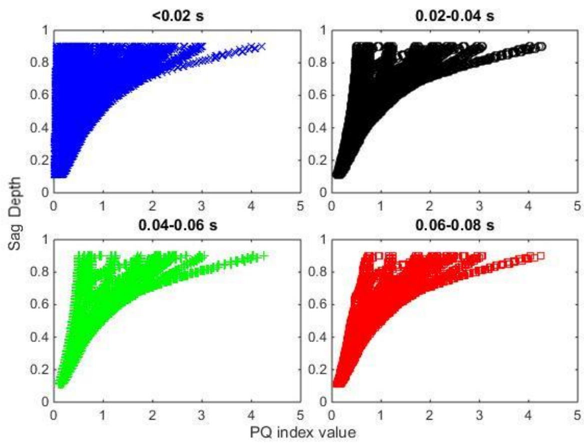

Figure 1: PQ index value for different durations and Depths of Sag

Each graph corresponds to a range of durations, vertical axis shows the depth (Amplitude reduction), and horizontal axis the PQ index value.

As depth increases, PQ index show a higher value. For any disturbance duration, their value shows a similar behaviour, with a similar minimum value and increasing the maximum value as duration increases. Durations longer than a cycle, returns different than zero PQ index for Sags with a greater depth than 0.2.

Other common disturbance in the power system is the oscillatory transient, a sudden start high frequency oscillation with an exponential amplitude decay. Some total durations (from start to total dissipation), and different initial amplitude conditions has been considered, with three different oscillation frequencies. In Fig. 2 this experience is shown.

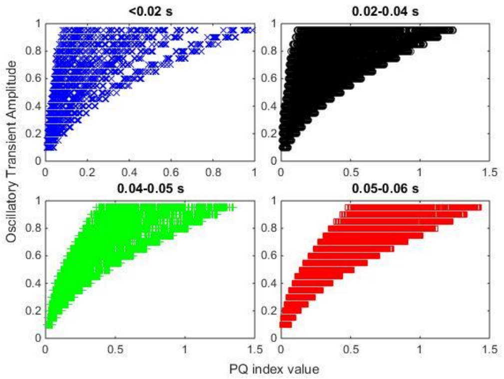

Figure 2: PQ index value for different durations and initial amplitudes of oscillatory transient

Now a similar shape can be observed in all of them. Higher transient initial amplitude involves a higher PQ index.

Longer transients show a higher minimum value of PQ index for the same amplitude, so as longer they are, better the detection is.

Main amplitude is observed in this kind of disturbances in the first oscillation, due to the exponential decay. Frequencies of 400 Hz and higher are used, so straight oscillation results.

A similar disturbance, where the amplitude appears suddenly and keeps constant until it disappears, is the Harmonic temporal distortion. Same conditions used in Oscillatory Transients are used, but the exponential decay, and the result is shown in Fig. 3

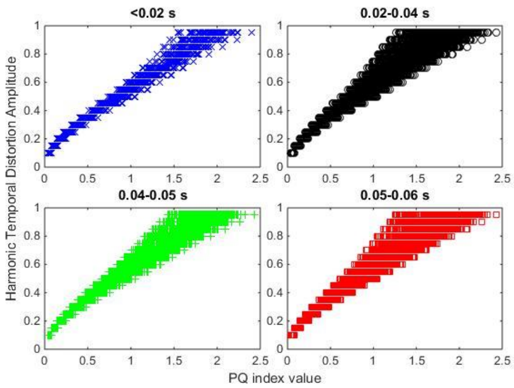

Figure 3: PQ index value for different durations and amplitudes of temporally harmonic distortion

Higher values are observed, due to the constant amplitude of the signal introduced (in contrast to the previous exponential decay). In contrast to the oscillatory transient, no low PQ index value in any harmonic temporal distortion, is observed.

Impulsive transient is another disturbance very common in the power system. It is an instantaneous change of value, with a fast value recover. Different impulse amplitude and different impulse width have been considered. Result of this experience is shown in Fig. 4.

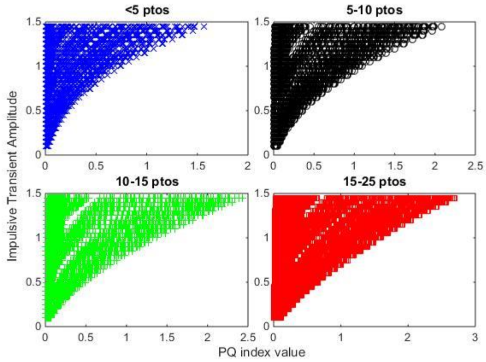

Figure 4: PQ index value for different durations and amplitudes of impulsive transients

Same behaviour can be seen for all disturbance durations, but with different maxima values, higher as impulse width increases. Pulses studied has a width from 1 to 25 points, and a 50 Hz cycle, with a Sampling frequency of 8000 Hz has a width of 160 points. Position has great importance.

All disturbances show a higher PQ index as they are more important (higher amplitude, higher duration, higher depth …). However, all of them start in low PQ index values. When disturbances have low impact, PQ index show a low value. This allows to select a threshold for the PQ index, in order to detect defective signals. But before, in Fig. 5, the effect of the Noise Level in a healthy signal is study.

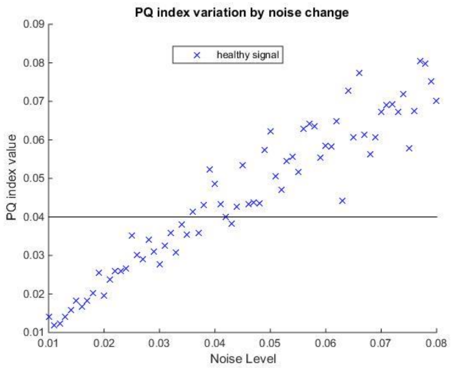

Figure 5: PQ index value for Sinusoidal unitary amplitude signal in different Noise conditions.

A contamination of a 1% is considered in the actual experience, higher than the observed in the Power Grid, It returns a PQ index values lower than 0.02. As Noise is increased, signal variance is increased, and signal shape is modified, so kurtosis is changed. As it still symmetrical, skewness keeps zero. Those changes increase the PQ index value as can be seen in the graph.

If a threshold of 0.04, for the PQ index is taken, a Nosie contamination over 3.5% is needed for obtain it in a healthy signal. This contamination level is very high for a power distribution line. Indeed it would detect these

abnormal conditions. But lower threshold can be selected if lower nose resistant is considered.
With this threshold, considering the simulations, a calculation of accuracy in detection is done over the simulations, and it is show in table I.

Disturbance	Simulations	Accuracy
Sag	121905	99.80 %
Oscillatory transient	43200	85.07 %
Harmonic temporal distortion	43200	99.99 %
Impulsive transient	53334	63.30 %

Table I: Accuracy of detection using PQ index for simulated data

As indicated before, impulsive transient and oscillatory transient, are disturbances with an active signal very straight, in contrast to the sag and the harmonic temporal distortion. That makes that the position of the disturbance start has an important effect over the HOS cumulant values of the signal. It makes more difficult to detect those type of disturbances using PQ index, based on HOS cumulants, when they appears alone. If the response of the PQ index is studies for Oscillatory transients, for different start points, the Fig. 6 is obtained

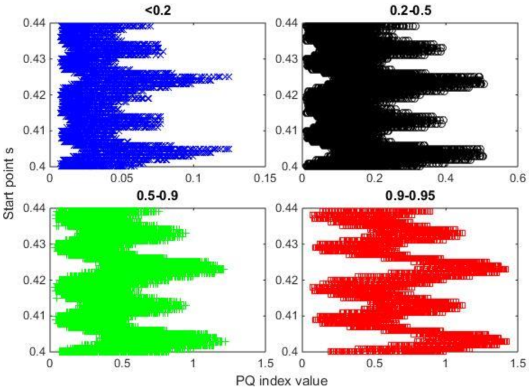

Figure 6: PQ index value for different amplitudes and start point of Oscillatory Transients.

A 50 Hz cycle has 0.02 length, so two cycles has been considered. A sine type signal has been used, so in the first half cycle has the positive part, and in the second half, the negative one. When the base waveform is in the positive semi cycle (start seconds 0.4-0.41, 0.42-0.43), maxima PQ index values are observed, higher as the start second are nearer to the wave maximum (0.405 and 0.425 seconds). Lower PQ index values are observed in the negative semi cycle, and minima PQ index values are observed when start points are slightly after to the sinus zero cross (0.4, 0.41, 0.42, 0.43, and 0.44).
Now the changes of the PQ index depending the start point will be examined in the Impulsive transients, in Fig. 7.

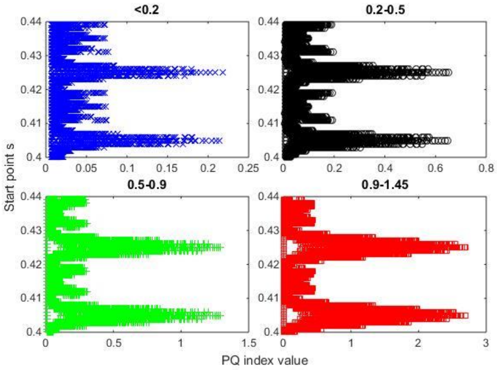

Figure 7: PQ index value for different amplitudes and start point of Impulsive Transients.

In this figure can be seen the cause of the difference in the accuracy in the detection of Impulsive Transient and Oscillatory transient. Impulsive transients show a higher PQ index value when they appears in the positive semi cycle, and moreover near to the maximum value to the sinusoidal waveform. However, even in the higher amplitudes situations, low PQ index values appears. In addition when other start points are considered, even the sinusoidal extreme value in the negative semi cycle, PQ index are much lower.
In real situations, a perfect disturbance, without any other coupled effect it is not very common. That makes easier to detect all of them, due to each couple disturbance affect HOS cumulants values, and in the same way, the PQ index.
In the next section, Real signal will be studied, using the PQ index.

4. Real signals

Now, some real signals, obtained from the Power System of our Research Lab, using a 1000:1 differential probe, will be analysed, in order to show the real capacities of this PQ index. First a normal situation signal will be studied. This signal is shown in Fig.8

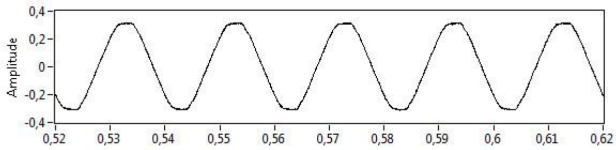

Figure 8: Normal situation real signal.

As can be seen in the figure, even in normal situation, in the analysis point, a permanent distortion of the power signal is observed and a non-pure sinusoidal is received. This distortion, non-studied as a disturbance, create a change in the variance and kurtosis, and in the same way, in the PQ index. This signal has a PQ index of 0.03. This proves that PQ index detects not only punctual disturbances, it can mark wave imperfections too. This wave can be seen clearly as a non-sinusoidal, but if it were more distorted, PQ index will mark it as defective, due to it is not a perfect Power Waveform.
Following the same structure, a Sag is shown in Fig. 9.

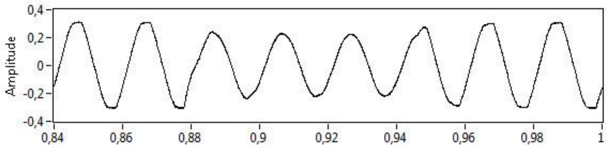

Figure 9: Real Sag disturbance.

This is a 25% depth sag. A slight deformation of the waveform can be observed during the disturbance. A PQ index of 0.77 is taken. That is a higher value than the observed by the simulated sags for similar depths. This is caused by coupled disturbances, in this situations, the wave deformation.
A very depth sag was detected in the power system, it can be observed in Fig.10

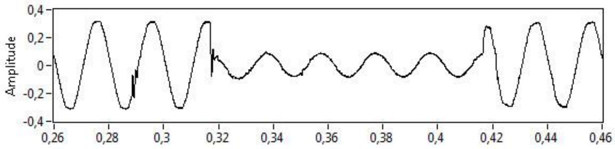

Figure 10: Real depth Sag disturbance.

It has a 68% depth, and sudden start and end (in the crest of the cycle) are observed, join to an oscillatory transient at sag start, and another one just previous cycle. Now the PQ index value is 8.14, much higher than the previously observed, due to all conditions analysed.
Now real oscillatory transients will be examined in Fig. 11.

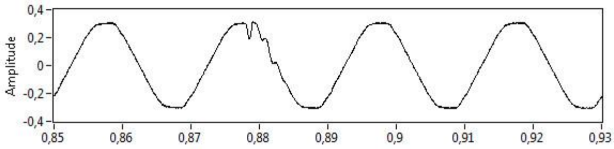

Figure 11: Real Oscillatory transient.

This real oscillatory transient only takes a quarter of cycle length, and an initial amplitude of 40 % of the power wave. Now the PQ index value is 0.09, in the range of the ones seen in the simulations.

In Fig. 12 it is shown a special situation detected, an oscillatory transient is cyclically introduced in the power system, with a deformation during few cycles.

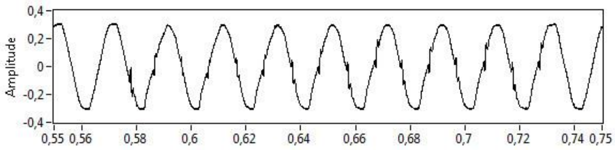

Figure 12: Real multiple Oscillatory transient.

The multi oscillatory transient effect create a wave deformation which change the PQ index value to 0.34, even when each individual oscillatory transient show a very low length and amplitude.
As next example, a harmonic deformation of the power waveform is studied is Fig. 13.

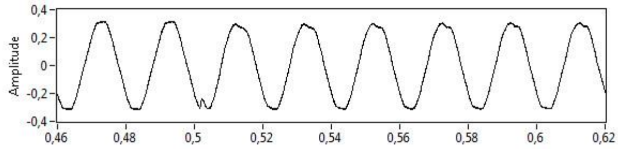

Figure 13: Real harmonic temporal distortion.

Harmonic temporal distortion of the power wave usually start after another disturbance, in this situation after a small impulsive transient. In the figure can be seen how the main wave changes its shape. This deformation keeps few cycles and then disappears. This signals creates a PQ index value of 0.22.

And last but not least, an impulsive transient situation is studied in Fig 14.

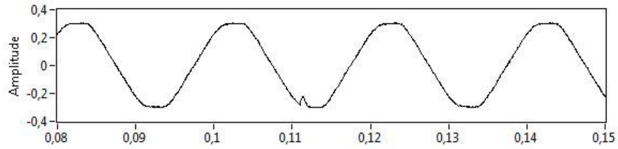

Figure 14: Real Impulsive Transient.

In the figure can be seen an impulse, with a 24 % of the Power Wave amplitude, and a short length. A PQ index of 0.07 is observed here. Even with this small distortion, in the worst phase of the signal for the detection, analysis procedure has detected the imperfection.

5. Conclusion

An easy to calculate and implement PQ index has been developed, based in HOS cumulants.
One of the most common and most regulated disturbances, sag, has returned an almost perfect detection, for depths from 10% to 90% and length. In addition, Harmonic Temporal Distortion, can be detected in the same way with a very high accuracy. Disturbances which implies a lower change in the signal statistical features, up to fourth order, as Oscillatory Transient and Impulsive Transient, changes the PQ index value depending the start position in the power waveform.
Examining some real signals, PQ index vales higher than the ones observed in the simulations are taken. Coupled disturbances are present in almost all real disturbances, and that increases the PQ index value.
With all previous considerations, a PQ index for detection anomalies in the Power Signal has been created. Threshold taken allows to make an auto detection of most of the disturbances in the Power Grid and detects any imperfection in the Power Signal, which affects to power, shape or signal symmetry.

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