Detection and characterization of amplitude defects using Spectral Kurtosis

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Abstract- This paper describes a new procedure for analyze amplitude defects, based on Spectral Kurtosis (SK). It extracts the kurtosis of each frequency component, which is related to the amplitude evolution. The proposed procedure allows the identification and characterization of frequencies with constant or very variable amplitude. An amplitude defect involves a step in the amplitude level, and that affect to frequencies around 50 Hz, which originally are not present, and could be detected by the SK. Some theoretical situations and a real one will be analyzed in order to proof the great capacities of the SK in the analysis of this kind of defect.

I. Introduction

Changes in the electrical power generation paradigm have taking place nowadays. These changes are related to a migration from big power plants based in controlled energy processes, as coil, petrol or nuclear energy, to small power generation system, based in uncontrollable processes, as wind, solar energy or ocean waves. These changes have an important impact in the Power Quality (PQ).

Traditional power plants are based in big synchronous generators, with constant rotation frequency, which gives a perfect waveform at their output. In addition this type of generators could change the amount of reactive power generated or consumed, adjusting to the needs of the power grid, stabilizing it in this way.

New small power generation systems are usually based in asynchronous generators, or even synchronous generator, but without constant rotation frequency. Additional power electronics are required for ensure the correct connection of these systems to the power grid. While these power electronics could control the voltage level, the frequency and other parameters; the operation could introduce distortions (non-desirable phenomena) in the power waveform, as harmonics and transients. Moreover this type of generation could not control the reactive power as well as traditional synchronous generators.

However this changes search a pollution reduction, using power sources which involve less noxious emission, so a mix of these types could get a stable and cleaner energy system. But in these conditions the PQ must be measured, in order to ensure that delicate loads are no feed with low quality energy.

In this work a frequency domain procedure is proposed for the PQ assessment. Generally, only FFT is used in the frequency domain. It returns the amplitude or power for each frequency compound of the data under test. The SK analysis is used. This procedure returns the kurtosis for each frequency, which is related with its amplitude variations. This technique can be considered novel in this context, but it has been applied in other situations with excellent results [1] [2]. In [3] advantages of Higher Order Statistics as kurtosis, compared with Second Order Statistics, are proved.

II. Spectral Kurtosis

There is not a rigorous procedure for the SK calculation. In this paper, the procedure used in former works by the J.J. G. De la Rosa *et al.* has been used [1]. This calculation requires pre-processing the data. The time domain register is divided in realizations or segments overlapped a 50 %. This means the second half of a realization is the first half of the next realization. Then the FFT of each realization is calculated and saved in a matrix, every new FFT in a new row. With data presented in this way the formula (1) could be applied.

$$\hat{G}_{2,X}^{N,M}(m) = \frac{M}{M-1}\left[\frac{(M+1)\sum_{i=1}^{M}\left|X_N^i(m)\right|^4}{\left(\sum_{i=1}^{M}\left|X_N^i(m)\right|^2\right)^2} - 2\right] \tag{1}$$

where **X** is the FFT matrix, in which the upper index "i" means the row (realization) and the "(m)" index means the column (frequency). *M* realizations with *N* points have been considered. The final SK vector will have the same points as the FFT vector, this means *N/2*. More realizations are involved in the calculation, more precise is this procedure. However the computational load increases with the size and the number of realizations, so a correct size and number of points must be indicated for the realizations for a suitable resolution and precision, but with an acceptable computational load. In this case 1,000 realizations of 0.1 s each one, using a Sampling frequency of 20,000 Hz will be used for all analysis. This means a SK vector of 1,000 points and a maxima frequency of 10,000 Hz.

III. Amplitude defect

The power system could be altered by many different types of anomalies; one of them is the amplitude defect. This kind of defect consists in a change of the level of the amplitude of the power signal. There are three types of amplitude defects. If amplitude increases over the normal one, the defect is called swell. When the amplitude reduces the defect is called sag, unless it gets to zero, in that situation the signal disappears completely and the defect is called interruption. However, the difference between the power signal's amplitude and the ideal value must be higher than 10% to consider the amplitude variation as a defect. Any change in the amplitude level which go beyond the limit will not be consider as an amplitude defect, it depends on the duration of the disturbance. An amplitude defect has duration upper than half cycle and lower than few minutes. If the length is extremely short the defect is a transient, and if it is excessive long, it is consider as a permanent change of amplitude level. If there is an interruption, it can be consider as a short or a long interruption, the maxima extension of a short interruption is 3 minutes, in other case it is a long interruption. The level of the defect will be named by the deviation in relation with the normal operation amplitude.

These kinds of defects are usually detected by amplitude level or signal power meters, which can characterize the deep of the defect very well, but anything about the properties of the transition. Usually in the transition there are some coupled defects and the level or power meters are too slow to characterize them. A group of amplitude defects will be analyzed in order to evaluate the capacities of the SK to characterize the events happens during the transitions between normal and defective status. If a synthetic is analyzed, 1% of random Gaussian noise will be added in order to avoid perfect conditions in the analysis.
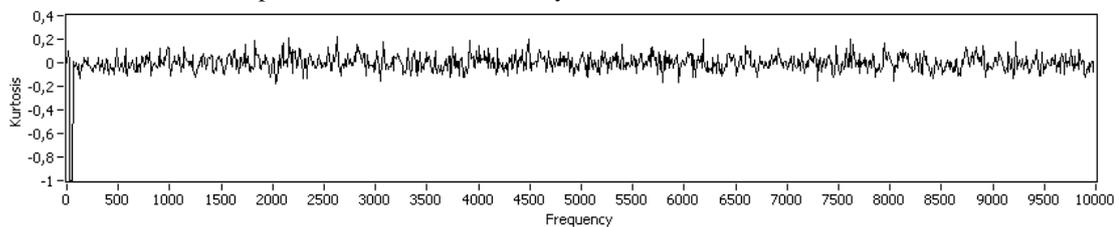

Figure 1. Healthy signal's SK.

Some amplitude defects will be analyzed, but the Fig.1 is not the result of one of them. It shows the aspect of the SK when there is not any anomaly in the power signal. This is an important figure to understand all subsequent analysis, because any difference between them and this graph is an indication of anomaly behaviour. First thing to say about Fig. 1 is about its axis. It is an SK representation, so the information is given for different frequencies values. That is the reason because the X axis shows frequency. As it is a kurtosis representation, the Y axis shows kurtosis value.

In the graph could be observed the same behaviour for almost all the frequencies, this is a kurtosis value around zero, with a maxima deviation of 0.2. Zero value is related to a Gaussian process, in this case these really low values means process very near to Gaussian behaviour. 50 Hz frequency and its nearby contour do not follow this trend. This range of frequencies shows a kurtosis value completely different of the rest of the spectrum. The value indicated is -1 in spite of 0 as previous seen. It is related to a frequency which keeps its amplitude constant along the time.

In this paper electrical signals are analyzed. In this kind of signals, in normal operation conditions, there is only one frequency present, the frequency of the power system. In Europe this frequency is 50 Hz, for that reason in this paper that frequency has been used. In relation with the previous paragraph only the system frequency are indicated as different, because all other frequencies are the Gaussian noise added.

When a healthy signal is analyzed the SK takes the aspect view in the Fig. 1. As said before the SK has been calculated in base to a frequency spectra matrix. If signal analyzed is healthy, another second is acquired and frequency spectra related to the oldest second are removed from the spectra matrix. In this way the matrix always has same dimension, but its data is related to the last signal in the Power Grid. In a defective situation, last second acquired is marked as defective and all spectra related to it is deleted from the spectra matrix. In this way

the matrix has only healthy data and the hollow will be refill by the spectral data of following second. In addition the defect has been located in time and could be saved for a subsequent analysis.

Hereinafter, some amplitude defects will be analyzed. Different conditions of this kind of defect will help to understand how SK can help in the detection and characterization of them. As first simulation a 10 % sag will be analyzed, with duration of 0.1 s. Fig. 2 represents on its left side the area of the analyzed signal affected by the defect. On its right side is shown a detail of the SK, only the range 0-300 Hz.
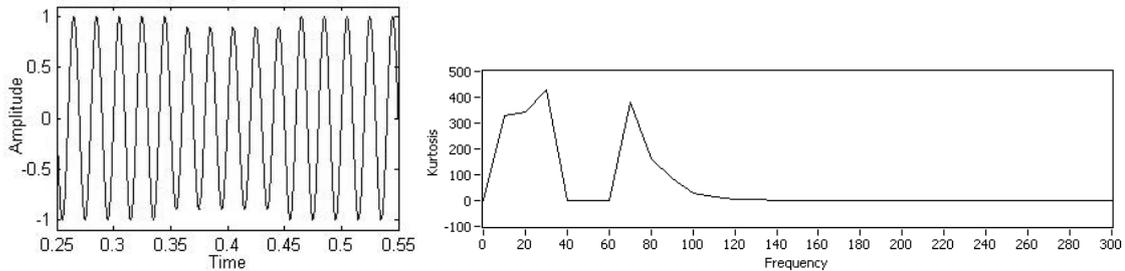

Figure 2. Waveform and SK of sag 10 % 0.1 s.

On the left side of Fig. 2 only complete defect have been plotted (all the others cycles are perfect sinusoids). In this representation the properties of the sag (deep, duration and suddenness of the change of level) can be perfectly observed.

In relation with the graph on the right in Fig. 2, rest of the SK has not been represent because is exactly the same as the perfect signal situation, seen in Fig. 1. However, now the response for non-affected frequencies looks as perfect zero value due to scale of the kurtosis axis. Difference with the healthy SK is in frequencies less than 140 Hz. In that range kurtosis values have been increased enormously, except for the 50 Hz frequency. Although the defect increases the kurtosis, strict constant value of the power signal keeps the -1 value for the kurtosis on the 50 Hz frequency. 50 Hz frequency has not been altered, but the surroundings frequencies are in a different situation. They have not anything which keeps their value low, and quick change of value for 50 Hz affect them, increasing their kurtosis.

In the next example the symmetrical situation will be examined. A swell defect with an increment of 10 % and 0.1 s will be analyzed.
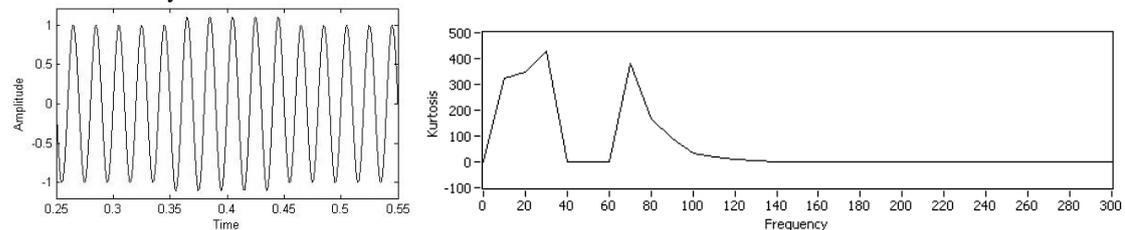

Figure 3. Waveform and SK of swell 10 % 0.1 s.

On the left side of Fig. 3 can be seen the temporally increment of the voltage. This is the opposite defect as the previous one. The SK response for this signal is exactly the same as the obtained for the sag analyzed previously. This is because SK measure variability patterns, and both analysis implies the same variation of amplitude during the same duration, although a sag defect has a reduction and a swell defect is an increment of the voltage level.

So the response for an amplitude defect is the same, no matter if it is an increment or a reduction of amplitude. In this way the SK cannot difference these two types of amplitude defects, but in fact detect an amplitude defect.

Next situation to be analyzed will be deeper sag, in particular with 40 % of deep and with the same duration, 0.1 s.
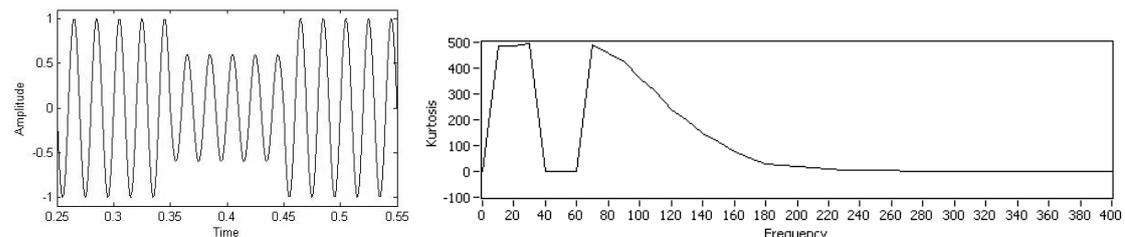

Figure 4. Waveform and SK of sag 40 % 0.1 s.

In Fig. 4 the difference between this and previously defects is easy to see. Now, it is deeper and the defect is more obvious. During the defect there is less amplitude and the transitions are sharper. Frequency scale in the

SK is now wider. The alteration in kurtosis level takes now from 0 to 270 Hz, so using a spam of 300 Hz could not be clear the representation. In addition, kurtosis values are higher for all the frequencies altered by the defect, but the pattern is the same. This is 50 Hz unaltered and surroundings frequencies with an elevated kurtosis, and zero response for any other frequency. Now the defect is more important, and in the same way the response of the SK is higher too.

The extreme situation of reduction of amplitude is an interruption. Following the same structure an interruption of 0.1 s will be analyzed as the next simulation.
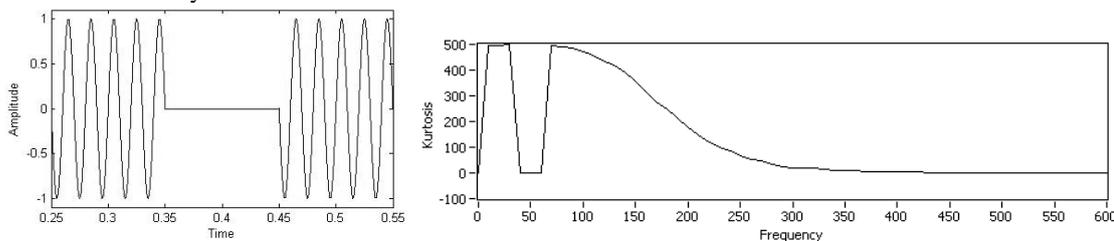

Figure 5. Waveform and SK of interruption, 0.1 s.

Now the waveform disappears completely during the defect, Fig. 5 shows that. This might seem as an exaggerate situation, but it occurs. If there is a fail, the protections cut the power and the interruption starts, but some protections have a system to re-establish the power after an indicated time. There are a maximum number of re-connections followed, after which the system keeps disconnected. In the SK representation, spam has been increased, because of the defect affects to more frequencies, from 0 to 430 Hz. This graph follows the same trend as seen in previous simulations. As expected in relation with the previous analysis, kurtosis values are higher, due to in this situation change of amplitude is more important. In fact, in any amplitude defect which involves a reduction of amplitude, the reduction of amplitude could not be higher.

Just this point the same pattern has been used, same duration and sudden change of level without coupled defect. With the information collected right now, the response to any amplitude defect is the same, changing the spectral spam and the maxima kurtosis value, depend of the deep of the defect. Hereinafter other possibilities will be studied. Now the same interruption as previous will be simulated, but at the start of the defect a 1,000 Hz oscillation will be considerate.
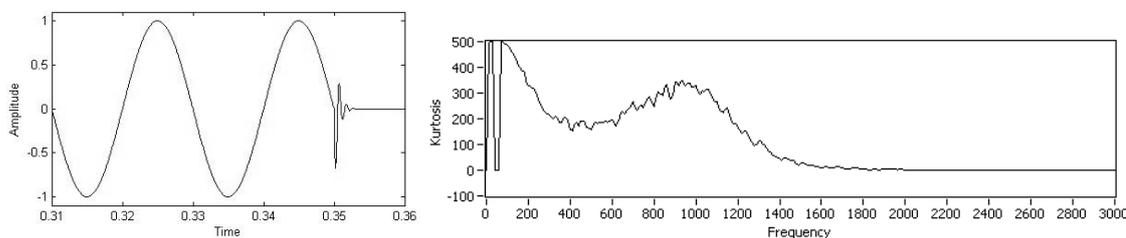

Figure 6. Waveform and SK of interruption, 0.1 s with a 1,000 Hz transient at start.

In Fig. 6 has been represented only the start of the interruption, in order to be able to see the transient. If same scale as in previous graphs was applied to this one, transient would be almost impossible to see, it only would look as a small blot at the start of the interruption. This situation can seem strange, but a real system cannot change the state as fast as seen in previous simulations, and sometimes a transient occurs at the start of the defect. Although there are only few oscillations at high frequency, the response of the system is totally different. Centred in the oscillation frequency, 1,000 Hz, there is an area of high kurtosis. This increment of kurtosis value is related to the sudden appearance and disappearance of a frequency. That frequency has not any amplitude during all the simulation, except the noise, and in a moment it presents a value. That sudden and temporally change increase its kurtosis. As that frequency appears suddenly, surrounding frequencies are affected too.

In detection of compound defects is when SK shows its capacities in the field of amplitude defects. If amplitude or power analysis has been done, this transient cannot be seen, but the SK can detect and characterize it in frequency perfectly.

In order to show the capacities of characterization of SK against compound defects, the same defect analyzed in this simulation will be considered in the next one, but another transient will be added at the end of the interruption. Now a 500 Hz oscillation will be introduced.

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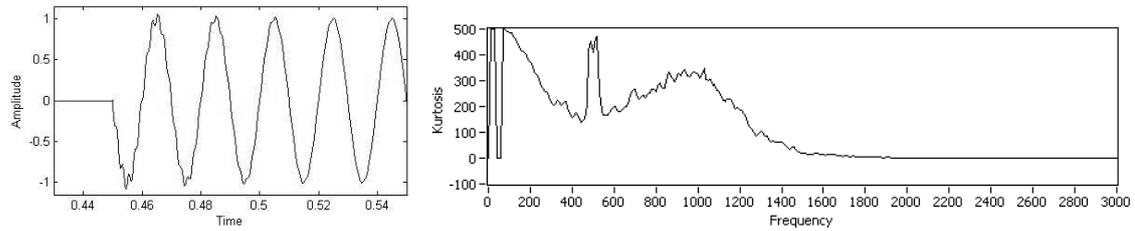July 18-19, 2013, Barcelona, Spain

Figure 7. Waveform and SK of interruption, 0.1s with a 1,000 Hz transient at start and 500 Hz transient at end.

In Fig. 7 has been represented the end of the transient. As said before start of the transient is the same as seen in the Fig. 6. In this simulation when the power returns, the waveform is no perfect. Is the same situation as the defect at the start of the transient, if a real system changed extremely fast between states, it could appear a transient state. The spectral representation has the same spam as in the previous simulation. As the actual defect includes the previous one, the response related to the start transient is present in the SK graph. However, comparing the SK representation of Fig 7 and Fig 6 there is a difference, a peak over 500 Hz. This is the frequency introduced in the oscillations at the end of the interruption. Once again the SK has detected and characterized in frequency the defects, although they are coupled. Final transient has less amplitude and more duration. This situation makes a less alteration to surroundings frequencies.

Analysis capacities in relation with coupled defects of SK have been proved. Next simulation will be a very deep sag, a 90 % of amplitude reduction, with a deformation of the waveform. This will be done coupling a frequency of 300 Hz with constant amplitude during the interruption.
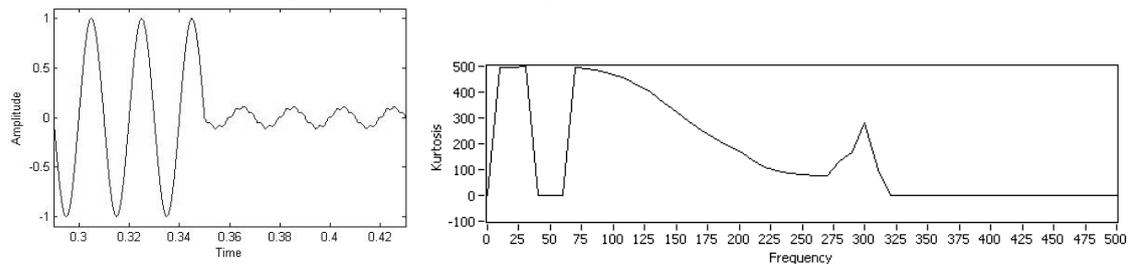

Figure 8. Waveform and SK of sag 90 % 0.1 s, with a frequency of 300 Hz coupled.

In Fig. 8 is shown the start of the defect. There, the deformation of the waveform during the defect can be perfectly seen. This situation occurs when there is a power failure in a line, and from another line the 50 Hz signal is induced to the analyzed line. This gives a distorted 50 Hz frequency signal. This signal has not coupled the previous defects, only sag and oscillations indicated. The response around 50 Hz is the one related to sag defect. The difference with normal sag is in the 300 Hz frequency, there is a peak related to the oscillations during the sag. Although the amplitude of the oscillations is constant during the sag defect, and the response for a constant amplitude is -1, that is only for constant amplitude for all the analysis time, and it only exists while the defect is present, in addition it has two sudden changes of level, one appearing at the beginning of the sag and other disappearing at its end.

As final analysis a real life signal will be analyzed. This signal has been acquired from a plug in the lab we work, as a consequence of a continuous monitoring of the Power Grid. The base signal has different amplitude in relation with the synthetics, it is 0.32. With this last analysis, the application of SK to real conditions in amplitude defects evaluation will be examine, in order to avoid ideal conditions and introduce non controlled events. This signal is sag defect with a 30 % of deep and duration of 0.05 s.
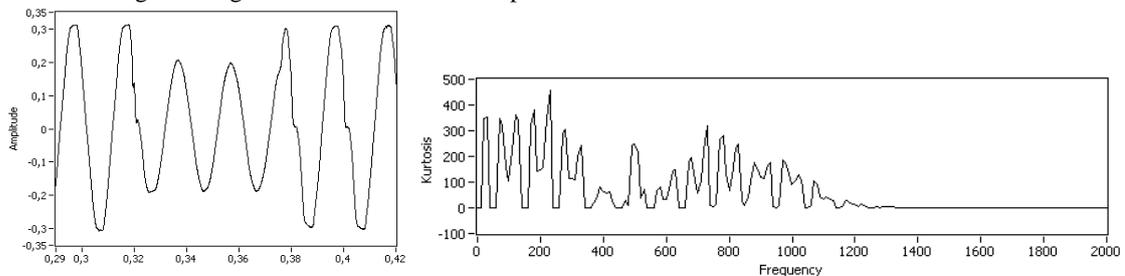

Figure 9. Waveform and SK of real sag 30 % 0.05 s.

Fig. 9 plots a real defect; it is sag with a 30 % of reduction of amplitude and duration of 0.05 s. Just at the start of the sag there is an oscillatory transient with own frequency slightly lower than of 750 Hz. Represented signal looks strange in relation with previously represented ones. This is a real signal and the waveform has coupled

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noise from real system and acquisition process. Base signal is not as perfect as simulated ones due to real conditions, but all the peculiarities of this process can be observed in the graph. Just this point all analysis done showed regions of high kurtosis around the 50 Hz, without change its value due to its constant amplitude during all the analysis. But the base signal in this analysis is not perfect, as the used in the simulations, it has harmonic distortion coupled. This means frequencies multiple of the main one are present with constant amplitude all the time. This new situation creates a -1 response for the kurtosis value for all those frequencies. The harmonic contents of this signal are odd order ones just 1150 Hz or order 23. But, although even order harmonic have not constant amplitude, they have a low variation rate, and it is shown in the reduction of kurtosis for all the frequencies related to them.

If reduction of kurtosis related to the base frequency and harmonics are not take in consideration, in the SK graph there are three interesting things, first one in the low frequency (0-450 Hz) a region, second one over 500 Hz a peak and third one from 550 to 1200 other region, all of them with high kurtosis level. This sequence is the same as seen in the Fig. 7. Low frequency area is related to the amplitude defect, as seen in all previous defects. The narrow peak is related to long oscillatory transient. This occurs after the sag, the signal keeps distorted by the 500 Hz frequency during few cycles. Last region altered is related to a short oscillatory transient, which is located at the start of the amplitude defect, with duration lower than two transient's oscillations with an own frequency of 750 Hz.

This last analysis shows how in a real application all the considerations extracted from synthetics are completely applicable. In addition new properties of SK have been discovered in the analysis of the real signal.

IV. Conclusions

In the current power system scenario the PQ measurements are necessary. In that context SK has been tested to detect and characterize amplitude defects. In a first step this analysis technique can detect any amplitude defect, giving an important response even with a low change in the amplitude of the base waveform. In a second step the SK shows important capacities in detection of compound defects. Amplitude defects usually not come alone; there are some distortion effects together. If there is a high speed oscillatory transient during transitions or a long time distortion in the signal, they will be detected and characterize by the SK. Finally the presence of harmonics can be perfectly locked due to the response of -1 kurtosis of any frequency with constant amplitude.

In order to show this is not only a theory, a real defect has been analyzed. In its analysis the same response as in the synthetics cases has been obtained.

SK has proof its properties as analyzer and characterizer tool in theoretical and real conditions along this work for amplitude defects.

Acknowledgment

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