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Detection and characterization of oscillatory transient using Spectral Kurtosis

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Abstract-This paper describes a new procedure for analyze oscillatory transient, based in the Spectral Kurtosis (SK). It gives the kurtosis of each frequency component, and it is related to the amplitude evolution. With all this information any frequency which amplitude keeps constant or suddenly change will be identified. This second case is the oscillatory transient, in which a specific frequency appears. SK detects and characterizes that frequency univoquely. 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.

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

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*. As 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. Oscillatory Transient

The Power Grid could be altered by many different types of anomalies, one of them in the oscillatory transient. This kind of defects consists in a high frequency oscillation around the healthy power signal, which starts suddenly and its amplitude decreases in an exponential way. Total duration of an oscillatory transient is usually lower than a cycle of the base power signal. Due to its short duration, analysis techniques based in averaged methods, which compute a cycle or half cycle, such as some power analyzers could not detect them, or only detect this anomaly as a small deviation of normal operation, but without any characterization of its properties. A group of oscillatory transients will be analyzed in order to prove that SK can detect and characterize this kind of defects. When a synthetic will be analyzed, 1% of random Gaussian noise will be added in order to avoid perfect conditions in the analysis.

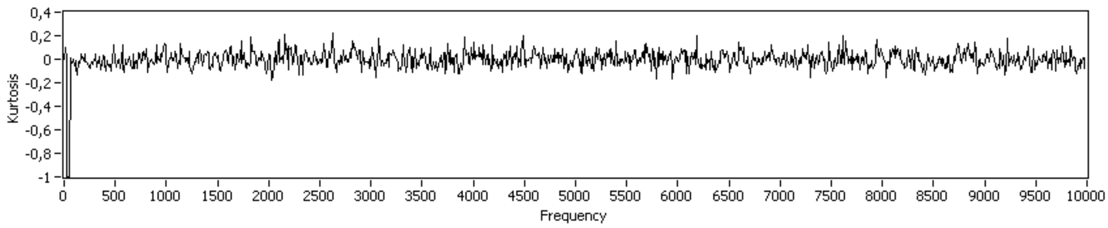

Figure 1. Healthy signal's SK.

Some oscillatory transients 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 oscillatory transients will be analyzed. Different conditions of this kind of defect will help to understand how SK can help in the detection and characterization of this kind of defect. As first situation, a 2,000 Hz transient is going to be analyzed, with initial amplitude of 20 % of power signal amplitude and a quarter of power signal cycle as duration until its complete extinction. Fig. 2 represents, on the left side, the only defective cycle of the analyzed signal and in the right side a detail of SK from 0 to 3,000 Hz.

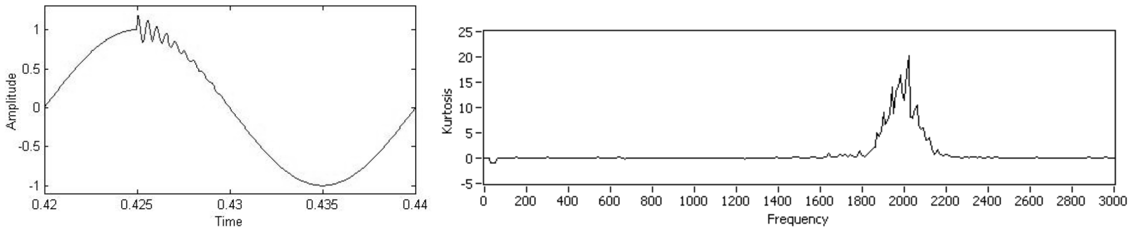

Figure 2. Waveform and SK of oscillatory transient with 2,000 Hz, ¼ cycle duration and 20% amplitude.

On the left side of the Fig. 2 only the defective cycle has been plotted because all the others are perfect sinusoids. In this representation the oscillatory transient and its properties (origin, amplitude, frequency and duration) can be perfectly observed.
In relation with the right graph in the Fig. 2, rest of the SK has not been represented because is exactly the same as the perfect signal situation, seen in Fig. 1. The difference with the healthy situation is in the frequency interval of 1,800-2,200 Hz where a peak is present. It shows its maximum value in 2,000 Hz, which is the oscillation frequency of the defect. Out of that peak the response is the same as the healthy situation, zero kurtosis for all the frequencies, except 50 Hz and surroundings, in which there are the -1 peak.
This first example shows how the SK can detect and characterize an oscillatory transient. As second example almost the same situation will be generated, but the initial amplitude will be incremented, which will be 50% instead of 20%. With all these the defect will have 2,000 Hz of own frequency, ¼ cycle of the power waveform as duration and an initial amplitude of 50% of the power signal amplitude.

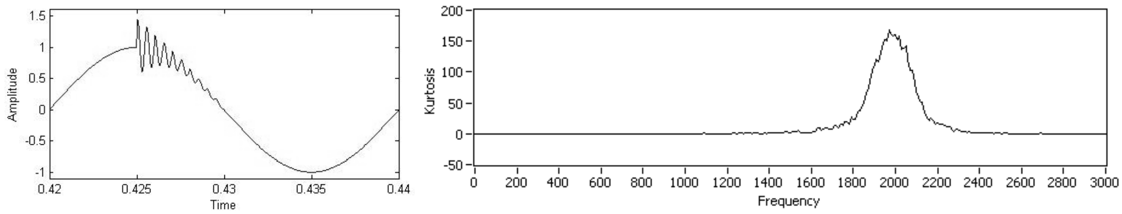

Figure 3. Waveform and SK of oscillatory transient with 2,000 Hz, ¼ cycle duration and 50% amplitude.

In the Fig. 3 can be observed the signal analyzed. The difference of amplitude is easy to see between this and the previous simulation. This difference makes this second defect more important than the first one, with more impact over the system, which makes it easier to detect because it change more the properties of this. As a consequence of this greater presence of the defect, the peak observed in the SK graph reach higher values. As the frequency of the transient is the same, this peak is centred in the same frequency. However, as consequence to beginning of defect is more abrupt than in the previous simulation, more surroundings frequencies have been altered, so the area with kurtosis over zero is wider. Now the vertical axis of the graph takes higher vales than in the previous analysis, and for that reason it is impossible to see the -1 peak at the beginning of the SK graph, but it is there.
Increasing the amplitude of the defect the response of the SK had been greater. In the next simulation the amplitude will be returned to 20% to normal amplitude, but the duration of the defect will be increased to half cycle instead a quarter of cycle of the base power signal. The own oscillation frequency will be the same as previous, 2,000 Hz.

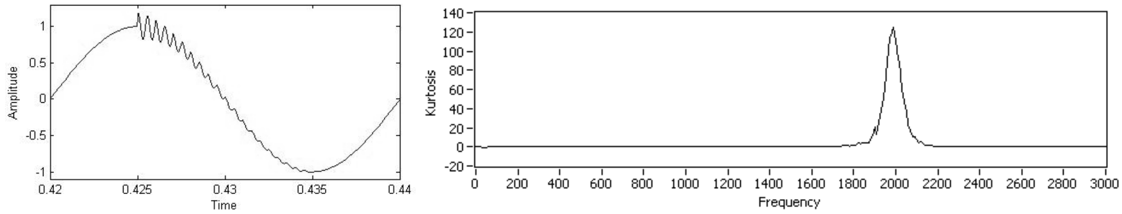

Figure 4. Waveform and SK of oscillatory transient with 2,000 Hz, 1/2 cycle duration and 20% amplitude.

As has been said before this defect is double length in relation with previous ones, and that can be observed in Fig. 4. As oscillations reduce their amplitudes in an exponential way, half of the oscillations show very low

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amplitude. Even in these conditions, as the defect is present more time, higher alterations in normal operations conditions took place in the system. In fact those changes can be detected by the SK and the response is much bigger. Since the initial amplitude is the same as the first defect analyzed, the peak shows the same spectral wide as that situation. However, the effect over the system is higher, because the oscillation transient is present more time, for that reason the SK arrives to greater values. In this scale of the SK graph, the 50 Hz peak can be subtly seen.

Up to now, only one transient has been introduced in a healthy environment. Next simulation will include more than one transient in order to study the impact to that situation for a SK analysis. Following the same structure the defect introduced will be the same as the introduced in the first simulation, but in this case two of them will be introduced, in two consecutive cycles.

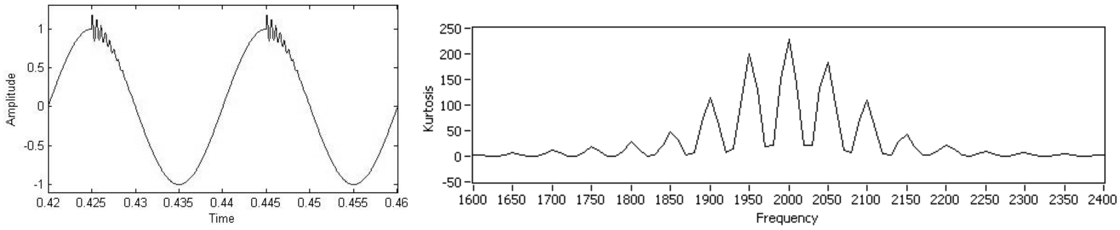

Figure 5. Waveform and SK of two oscillatory transients with 2,000 Hz, ¼ cycle duration and 20% amplitude.

Both representations of Fig. 5 are a little different than previous ones. That is because the defect introduced in this simulation involve two cycles, so both need to be represented. SK graph is also different. The result of this simulation need to be examined in detail, thus a bigger zoom has been done over the kurtosis, representing only the frequencies between 1600 Hz and 2400Hz. Up to this point the SK response have been soft regions centred in the oscillation frequency, but in this simulation there are some thin peaks. The higher one is over the oscillation frequency and the others reduce their height as they move away from the 2,000 Hz, either to higher or lower frequencies. In the first simulation the maximum value reached by the SK was around 20. Nevertheless in this case only with two transients equal as it, the maximum value is over 200, a higher value than a situation with a bigger or a longer transient.

Besides the high kurtosis value, the SK graph shows a special shape, as indicate above. These defects are separated exactly by 0.02 s, the period of a 50 Hz waveform. This is the same situation as modulate in amplitude the defect with a 50 Hz signal. As a consequence of that amplitude modulation, there are spectral alterations. In this kind of modulation spectral pulses appear separate from the modulated frequency either to higher or lower values a distance indicated for the modulating frequency. That is the situation showed in the SK graph, the higher peak is over the frequency of 2,000 Hz, the one related with the transient. The rest of the peaks have lower amplitude, lower and lower according to their frequency are farther than 2,000 Hz. That means alterations of those frequencies, which increase their variability, and as a result increase their kurtosis. Higher alteration was made in 2,000 Hz, the most important compound in this defect. As other compounds have lower amplitude, the effect over the variability of them is lower too. In fact, the amplitude and the variability of the compounds are lower according to the frequency are farther from 2,000 Hz.

Following simulation considers a different situation. In this case some frequencies have been introduced at the same time, specifically 2,000, 3,000 and 4,000 Hz have been introduced at the same point as oscillatory transient. Others characteristics of the transient are the same as previous, in relation with the power signal 20% of the amplitude and a quarter of cycle of the duration.

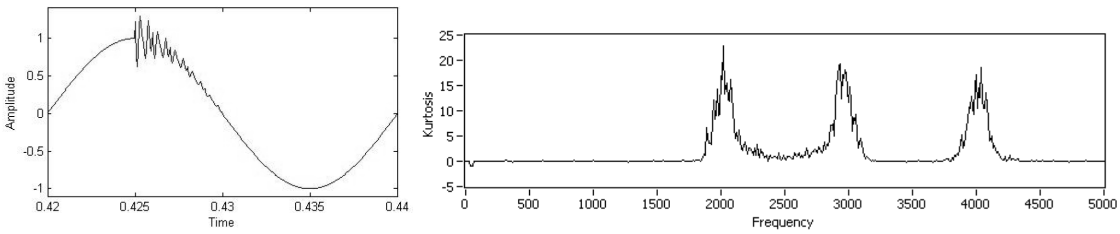

Figure 6. Waveform and SK of oscillatory transient with 2,000 Hz, 3,000 Hz and 4,000 Hz, ¼ cycle duration and 20% amplitude.

In a first seen of signal showed in Fig. 6 could look as chaotic oscillations around the power signal. It may be consider as a defect with high noise level, but we know that is not the situation. It is a compound defect which includes some frequencies. However, in the SK graph the frequencies involved in the defect are perfectly detectable. In relation with the amplitude of each peak, it is the same as the first defect studied, because each frequency appears in this simulation with the same properties as in that case. This result is possible because the spectral decomposition difference the frequencies, even when they are completely overlapped.

Next situation will be a transient, with the same properties as the first case, but a high noise level will be introduced during the defect. So the simulation would has a quarter of cycle in relation with the power signal of duration, and a 20 % of its amplitude, and the base sinusoid generated for create the transient, with 2,000 Hz of frequency, has coupled a normally distributed noise.

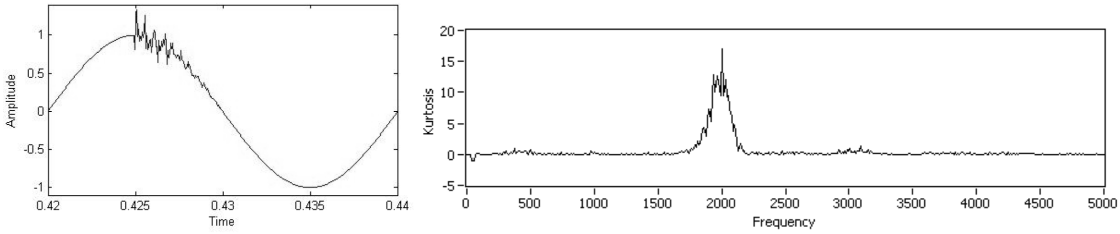

Figure 7. Waveform and SK of oscillatory transient with 2,000 Hz, ¼ cycle duration and 20% amplitude and normally distributed noise.

Transient showed in Fig. 7 could remember the showed in the Fig. 6, but it is completely different. Now random normally distributed noise is the cause of the alteration of the sinusoidal shape, instead of a composition of frequencies as in the previous simulation. However, SK can detect perfectly the oscillation frequency, in spite of the high level of noise. However, the base line of the SK graph is a little different. The sudden presence of high level of noise, which involves all frequencies, generates an increment in the kurtosis of all the frequencies, changing the constant zero value into random peaks with a value slightly over cero. That changes the aspect from flat to rough surface.

Sometimes oscillatory transients occur with higher amplitude and a lower duration. Next simulation represents this situation. Now, a defect with initial amplitude of 50% of the power signal amplitude and duration of 7.5% of a cycle of the base signal will be analyze. The oscillation frequency will be the same as previous, 2,000 Hz.

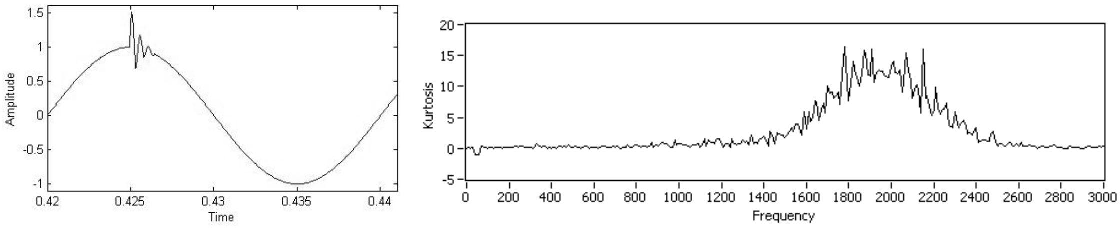

Figure 8. Waveform and SK of oscillatory transient with 2,000 Hz, 7.5% cycle duration and 20% amplitude.

Now the situation is a little different. In Fig. 8 transient observed is not as previous, it is closer to a pulse than an oscillation due to its short duration and high amplitude. Those conditions create a sudden change in the waveform level, at the start of the defect. In the SK graph the response is a little different. Although the region with kurtosis altered has the maximum value over the oscillation frequency, 2,000 Hz, it is wider. Frequencies involves in this analysis are from 1,400 Hz to 2,600 Hz, instead of the range 1,800-2,220 Hz seen in the first defect. The sudden start with high value of this defect is the responsible of the new pattern in the SK graph. Sudden changes involve nearby frequencies, and in this simulation start and end are very hasty.

As conclusion, a real signal will be analyzed as example of real application of the present work. It has been acquired in a power plug in our lab, as a result of a continuous monitoring of the Power Grid. The base signal has the same frequency as the simulated ones, but it has not the same amplitude. Now the base signal has amplitude of 0.32. In the simulations, the characteristics of the transients are the start point, however, now this is a real defect so the characteristics can't be known a priori.

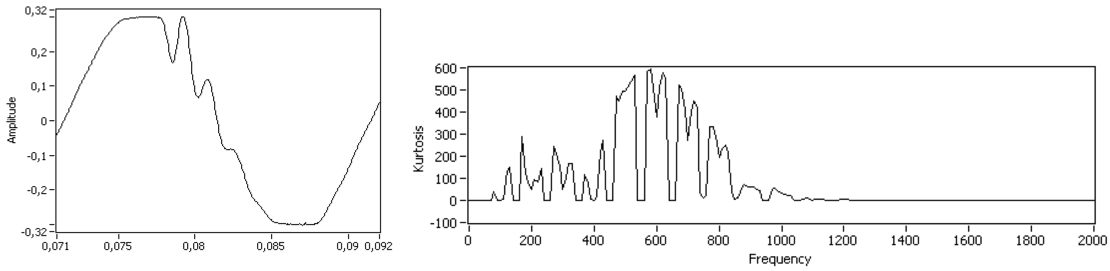

Figure 9. Waveform and SK of real oscillatory transient with 600 Hz, ¼ cycle duration and 30% amplitude.

In simulated cases the signal showed has not coupled the noise, but in the Fig. 9 the real signal has noises from the Power Grid and from the acquisition procedure coupled, so the waveform looks rougher. There are bigger oscillations because the own frequency of the defect is slower than previous defects analyzed, so any oscillation

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takes more time. In relation with the amplitude, it is a little higher than in almost all simulated cases, a 30 % in relation with the amplitude of the base signal. The oscillation frequency of this defect is 600 Hz, and the time extension is a quarter of a cycle of the power signal, all the parameters measured over the power signal.
Due to real conditions, sinusoid is not perfect, it has harmonics. A harmonic is a multiple of the base frequency, and this signal has all the odd multiples of 50 Hz just 1150 Hz with constant amplitude, due to the -1 response in all of them. In addition the even harmonics present a reduction of the kurtosis value, so their amplitude is less variable than the surroundings frequencies. Now the SK will be analyzed without take in consideration the harmonic contents. The region with highest kurtosis is around 600 Hz, the oscillation frequency of the defect. The defect analyzed in this situation creates a region of high kurtosis, but inside that region the frequencies related with the harmonics present reduced value.
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 is necessary. In that context SK has been tested to detect and characterize oscillatory transients. In a first step this analysis technique can distinguish between frequencies which present constant amplitude along the time, noise and frequencies with sudden changes of levels. Then the simulations confirm the SK as a good tool for detection and characterization for oscillatory transients. It returns a different answer for any situation studied. The SK detect events composed by some frequencies, consecutive oscillatory transients in consecutive power cycles and give a response related to de initial amplitude and the duration to the transient.
In order to show this is not only a theory, a real transient 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 oscillatory transients.

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