IDENTIFICATION OF ELECTROMAGNETIC DISTURBANCES IN MODERN POWER SYSTEMS

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Abstract – the paper presents a method for temporary disturbances identification and analysis. In the infield standards the analysis of the voltage dips and swells is made using the same method that is the calculus of the r.m.s voltage on a cycle updated every half of cycle. This method brings the disadvantages of more calculus then needed. Thus, the authors propose a new methodology for the identification and analysis of the mentioned short duration disturbances. The originality of the method consists in the distinction between the identification and the analysis stages. In this way less time is needed to find if any disturbance occurred and extra calculus is eliminated.

Keywords: voltage dip, voltage swell, time domain analysis, modern power systems

1. INTRODUCTION

The modern power systems have a dynamic operating state that most of the time is harmonic polluted and unbalance. In this electromagnetic environment appear temporary disturbances like voltage dips and voltage swells that accentuate the real state negative effects.

Voltage dips and swells are the consequences of transient events, thus they have a transitory character and impress to the power system a temporary operating state.

The voltage dips sources are represented by faults localized in the production, transport, distribution and electrical energy use installations and they affect all consumers connected to the supply power network at that moment. These faults can be the consequences of natural phenomenon (atmospheric discharge, storm, snow, frost etc.) or of other nature (advanced wear, bad quality of equipment materials, high level of pollution, wrong maneuvers etc.).

The main causes localized in the supplier's side are faults due to the breakdown of equipments isolations, switching or atmospheric overvoltages etc. Voltage dips can also appear because of voltage losses produced in a network before protections disconnect a defected element.

A user can himself produce voltage dips in its own installations even if there is no disturbance from the supply network. These voltage dips are produced due to the following causes: faults in the internal network, working of installations that have a high current at start or handling of installations with fluctuating load.

Voltage dips determine negative effects especially on electronic equipments that are very sensitive to the magnitude variations of the supply voltage, thus in some situations a simple voltage dip can cause the stopping of devices that have electronic commands.

Voltage swells are of interest especially in the field of selection and coordination of conductors' isolation. As a result, the main objective is to reduce the deteriorations determined by dielectric stresses and to raise the working safety of electric equipments.

Voltage swells are caused typically by three phenomenons [1]:

- Atmospheric (lighting): appear generally due to atmospheric electric discharge in installations and are characterized as being single-pole (amplitudes of thousands of kV), strongly damped and very short duration (μs). Their shape depends on the type of installation earthing, particularly of the electric parameters of this installation;
- Switching: they are alternative voltage swells that appear generally because of a switching operation or a fault, and they are characterized as being strongly damped (magnitude is 1.5 – 3 times the magnitude of line-to-line voltage) and short duration (between μs to ½ cycle - 10 ms). These voltage swells can be with steep front (in case of circuit breakers) or slow front (in the case of capacitors or electric machines working in open-circuit);
- Temporary: they are caused by switching activities (i.e. disconnection an important load), faults (phase-to-ground faults) and also by non-linear phenomenon (harmonics and ferro-resonance). These voltage swells have the shape of poorly damped oscillations with relatively large duration.

Besides the voltage swells determined by atmospheric causes or maneuvers in the transport and distribution networks, there can appear also voltage swells injected by users. They can be induced by ignition of discharge lamps, arc furnace operation or welding equipment, operating equipment with static switching, high power engine start etc.

Voltage swells from power networks, that have a random character, are not dangerous to the people, but they can affect the sensitive equipments, which even if are not damaged, suffer an early ageing.

Considering the aspects described in the former paragraphs, it can be understood the necessity of voltage dips and swells identification and analysis in a quick and

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efficient manner, in order to limit their effects as soon as possible after the occurrence of the event.

The paper continues with a section that contains the description of the standard methodology for voltage dip and swell analysis. On the other hand, the methods proposed in the specialty literature are also briefly described. The next five sections present the methodology used for the identification and analysis of voltage dips and swells, followed by some examples, which underline the utility of the proposed method. The paper ends with a section of conclusions.

2. BACKGROUND

The disturbances identification is the process that finalizes with the finding of the electric signals' characteristic parameters, which correspond to the influence of the electromagnetic disturbances on the functioning of the power systems.

A voltage dip is defined to be the decrease with ΔU_i (Fig. 1 and 2) of the r.m.s. value of voltage in any power network's node, for a time interval t_i, in which the voltage is always lower than the nominal value U_n. Voltage dips can affect only a phase, two phases or all phases at the same time [2].

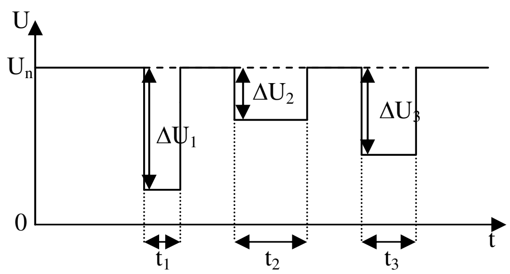

Fig. 1. Examples of voltage dips. R.m.s. voltages

A voltage dip is characterized with the help of three quantities: amplitude, duration and occurrence frequency. The amplitude is defined as the difference between the r.m.s. value of the nominal voltage and the minimum r.m.s. value of the voltage during the voltage dip. The amplitude, ΔU_i, can take values between 0.1 and 0.95 from the nominal supply voltage, U_n. The duration of a voltage dip represents the time interval t_i (Fig. 1, i = 1...3) and can have values between 0.01 and 60 s. In Fig. 2 is illustrated a voltage dip, considering the harmonic pollution, and using instantaneous values.

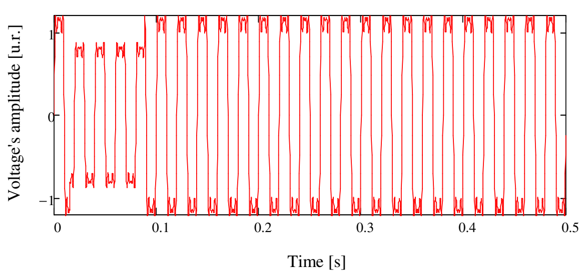

Fig. 2. Voltage dip. Instantaneous values

In 10% from the observed events, voltage dips don't have a shape that can be properly characterized using only the amplitude and the duration. From the practice point of view, a general characterization by using the two quality indices: amplitude and maximum duration on the three phases of the three phase power system can be accepted [3, 4, 5, 6].

In power systems appear situations of voltage swells (Fig. 3) when the voltage value suffers a sudden increase of very short duration (from several tens of μs to one ms) and very high amplitude (several times the nominal value) followed by recovery of the voltage's value to the initial level [7].

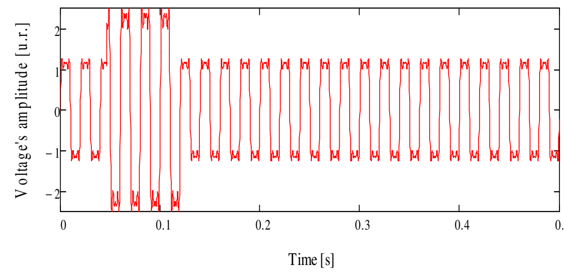

Fig. 3. Voltage swell. Instantaneous values

As in the case of voltage dips, the voltage swells characteristics depend on the causing source as follows: atmospheric phenomena determine voltage swells with amplitude as much as thousands of kV, short duration and steep front; switching processes cause voltage swells strongly cushioned, amplitude 1.5 to 3 times the nominal voltage and short duration; a load switching determine long duration and amplitude oscillation close to the amplitude of the nominal voltage. The main negative effect of voltage swells is the ageing of electric equipments isolations.

Under present infield standards [8], the measured value for voltage dips and swells (further on in order to simplify the exposure will use the term disturbance when referring to voltage swells and dips) is the r.m.s. value for a cycle, denoted in [8] with $U_{rms(1/2)}$, on each phase of an three phase power system. This value is used to determine the characteristics, but also to identify the disturbance's occurrence.

The disturbance is detected when the measured value $U_{rms(1/2)}$ falls below (exceeds) a threshold value to the supply voltage, U_{din}, which was declared before the occurrence of the disturbance or to the U_{sr}, the r.m.s. voltage measured some time before the detection started.

In single-phase systems, a disturbance begins when the voltage $U_{rms(1/2)}$ goes out of range (0.9 and 1.1 of the reference voltage), and ends when the measured voltage is between the limits plus (minus) the hysteresis voltage (in general, it is 2% of the supply voltage).

In multi-phase systems a disturbance begins when the voltage $U_{rms(1/2)}$ on at least one phase goes out the threshold interval and ends when the voltage on all phases is between the defined limits. In [8] is specified that the opening thresholds voltage and the hysteresis voltage are chosen by the user as needed.

In previous paragraphs the reference voltage is the voltage that the disturbances are related with. The user can choose this voltage as having a fixed value, namely the supply voltage, or a value range. According to [8],

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this voltage is calculated using a first order filter with a time constant of 1 minute. The filter is characterized by the following mathematical relationship:

$$U_{sr}(n) = 0,9967 \cdot U_{sr}(n-1) + 0,0033 \cdot U_{(10)rms}; \qquad (1)$$

where $U_{sr}(n)$ is the reference voltage used in the current analysis window, $U_{sr}(n-1)$ – the previous value of the reference voltage and $U_{(10)rms}$ – the most recent value measured as r.m.s. voltage on an interval of 10 cycles.

At the start of disturbance detection, voltage reference value is set, and then updated every 10 periods.

In the infield literature [9 – 18] several analytical methods (wavelet transform, S transform etc.) and artificial intelligence techniques (artificial neural networks, expert systems) are proposed for the voltage dips and voltage swells identification. In [9 – 15, 16] the authors apply the wavelet transform with the aim of solving different aspects concerning the transients' issue that appear in the distribution networks. Thus in [9, 10] the discrete wavelet transform with Daubechies mother wavelet is used for the identification of voltage sags, voltage swells, outages and transients. The multi-resolution analysis is used to create models for the circuit elements so as to use an equivalent scheme for the calculus of the circuit during transients operating states in [14]. Morlet wavelet is applied in [15] in order to perform the multi-resolution analysis for the detection of transients contained by the electric signals. In [17] the S transform is the base of a pattern recognition technique for the detection, classification and quantification of power quality disturbance waveforms. An expert system dedicated for the classification and analysis of power system events (voltage dips or voltage swells) in presented in [18].

As it was former presented, the standard identification and analysis of the disturbances is made by determining the r.m.s value of voltage even if the disturbances appeared or not. Thus extra calculus is performed and more memory is needed. On the other hand the use of the wavelet transform implies many calculations in order to detect properly the exact moment the disturbances occured. These disadvantages were eliminated in the proposed algorithm that is described in the next sections.

3. ALGORITHM ANALYSIS

The proposed algorithm dedicated for identification and analysis of temporary disturbances is based on time domain analysis, and supposes two steps. Firstly the signal is processed in order to find out if any sudden changes occurred in the string values of the digital electric signal. The result dictates if the 2nd step must or not be performed. If so, the analysis is continued and the signals' parameters that characterize the disturbances are determined: start time, end time and signal's amplitude during the event. According to these quantities disturbance's duration and amplitude are gotten. The first characteristic is calculated by making the difference between the end and start moments, while the amplitude is the difference between the reference value and minimum r.m.s. voltage in the case of voltage dips and the difference between the maximum r.m.s. value and the reference value during voltage swells. Fig. 4 illustrates the principle of the proposed algorithm.

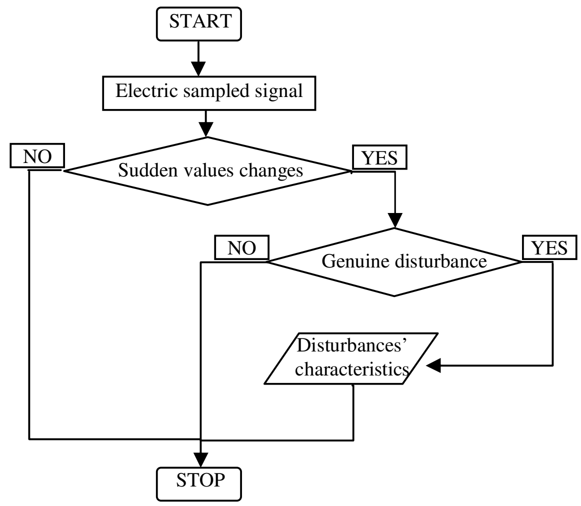

Fig.4. The principle diagram of the proposed algorithm

The 1st algorithm's step is realized using the „edge detection", and applying the convolution between the analyzed signal and Morlet function.

4. TIME DOMAIN IDENTIFICATION

The disturbances are characterized by the appearance of a sudden change (increase in the case of voltage swells and drop in the case of voltage dips) of the voltage r.m.s. value and consequently of the instantaneous values. In this case the usage of time domain analysis is the most understanding approach. Thus the edge detection method is used, and the mathematical relationships are:

$$P(k) = \left| \sum_{n=0}^{M-1} u(n) \cdot f_{tr}(k,n) \right| \qquad (2)$$

$$f_{tr}(k,n) = f\left(\frac{n-k}{2}\right) \qquad (3)$$

where $P(k)$ is the string values that contains information about the sudden changes appearance, $u(n)$ – the string values of the sampled electric signal, $f(n)$ – the used function (named the "identification function"), $f_{tr}(n)$ is a translation of the identification function, M represents the number of the electric signal samples and $k = 0 \ldots M-1$.

In order to find the proper identification function, several functions that are used in the case of wavelet transform: Morlet, Shannon, Mexican Hat and 2nd Gauss derivative, were studied. These functions were chosen because their properties make them proper for the identification of transients. The functions' mathematical description is presented in table 1 [19, 20, 21, 22, 23].

The graphical representations of the identification functions are illustrated in the next imagines.

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Table 1. Identification functions

Identification functions	Mathematical relationship Time variation
Morlet	$f(t)=c(\sigma)\cdot\pi^{\frac{-1}{4}}\cdot e^{\frac{-1}{2}t^2}\cdot\left(e^{i\sigma\cdot t}-k(\sigma)\right)$ $c(\sigma)=\left(1+e^{-\sigma^2}-2e^{-\frac{3}{4}\sigma^2}\right)^{-\frac{1}{2}}$ $k(\sigma)=e^{-\frac{1}{2}\sigma^2}$, $\sigma=6$
Shannon	$f(t)=\frac{\sin\left(\frac{\pi\cdot t}{2}\right)}{\frac{\pi\cdot t}{2}}\cdot\cos\left(\frac{3\cdot\pi\cdot t}{2}\right)$
Mexican Hat	$f(t)=\frac{2}{\sqrt{3\sigma}\cdot{}^{\frac{1}{4}}}\cdot\left(1-\frac{t^2}{\sigma^2}\right)\cdot e^{\frac{-t^2}{2\sigma^2}}$, $\sigma=0.4$
2nd Gauss derivative	$f(t)=\left(1-t^2\right)\cdot e^{\frac{-t^2}{2}}$

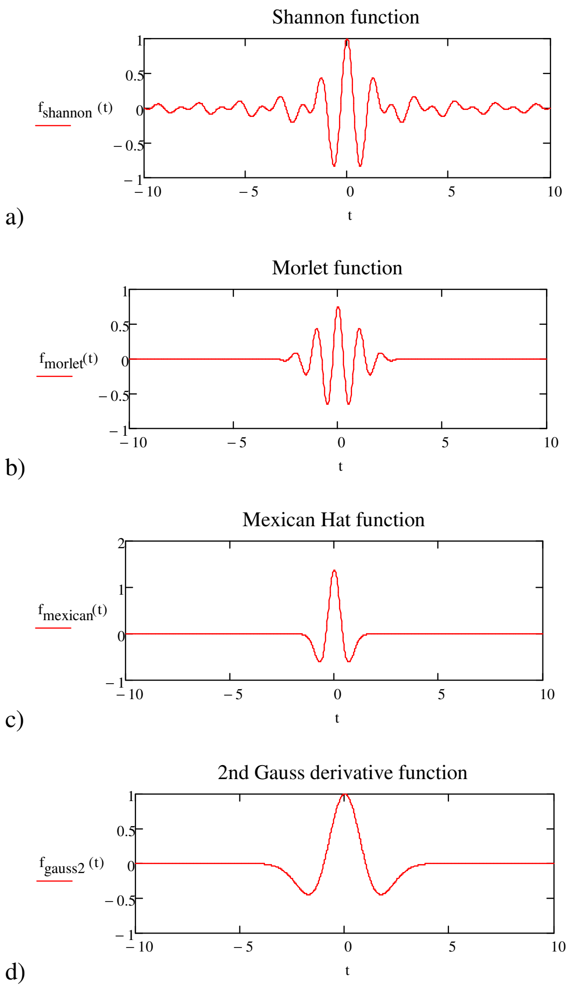

Fig. 5. Identification functions time variation

With the intention to compare the identification functions and to underline the choosing of Morlet function, the digital signal from Fig. 2 was analyzed and the results are presented in the graphics from Fig. 6.

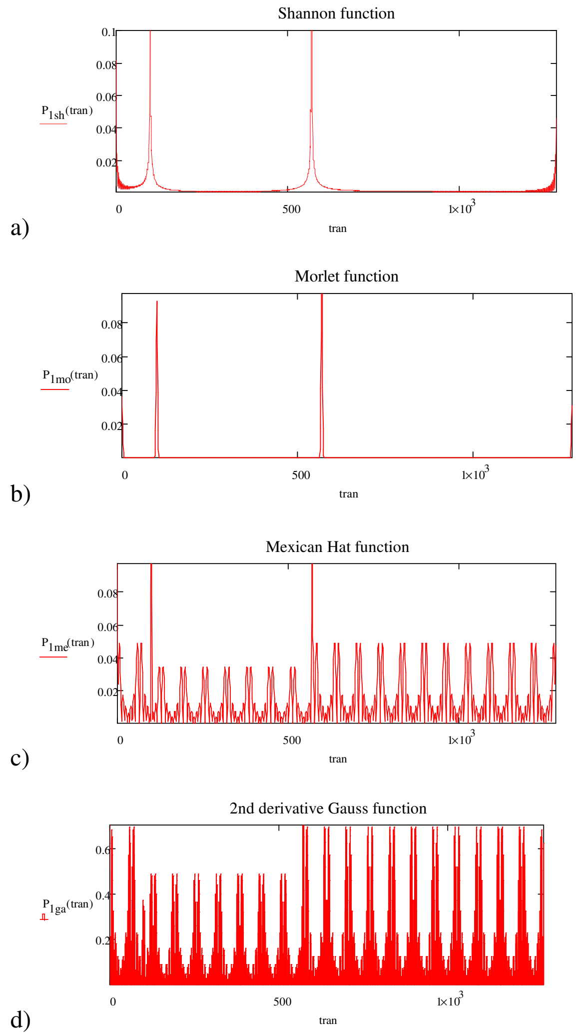

Fig. 6. Analysis of digital signal containing a voltage dip

The graphics show that in the cases of Shannon and Morlet functions the results indicate properly the moments when the signal's values suffer a sudden change; while in the case of the other functions the obtained data is quite difficult to process as to determine the exact moments.

By analyzing the resulted data from several signals analysis, the selected identification function was the Morlet function. This function is a complex one, but it can be used to process real signals, on which the convolution operation projects them to modulus-phase form. The phase plot is particularly suited for the detection of singularities. In the identification the real part of the function was used, and the parameter σ was set to 6. This value was obtained after several calculations with other σ values.

5. ANALYSIS

At the 1st step, after determining if a sudden change occurred in the signal structure, to find out the

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disturbance type (voltage dip, voltage swell or a simple insignificant change), the r.m.s. voltage is determined on a cycle that surrounds the transition point. The obtained value is compared with the reference value, which is chosen at the beginning of the analysis, and depends on the voltage r.m.s. value before the event start. As the real operating state of the power network is considered, namely the presence of harmonics disturbances and the unbalanced steady state.

The 2nd step supposes the analysis that is made on the digital signal as to determine the specific parameters of the voltage dip or swell. The analysis is performed on 10 time cycles (about 20 ms). This method is similar to the one proposed in [8], the difference is that the r.m.s. value is actualized every quarter of cycle ($U_{rms(1/4)}$), thus a more appropriate shape is obtained.

The start time is considered when the disturbance graphic intersects the level corresponding to the 90 % or 110 % and ends when the graphic grows more than 90.2% or drops below the threshold of 109.2 % (is taken account the hysteresis voltage). Fig. 8, 9, 10 and 11 illustrate the described procedure that is the moment when the graphic crosses the limits levels. All moments are found depending on the zero moment (the 1st signal sample) of the digital signal.

The identification and analysis were implemented as a virtual instrument (VI) using the graphical G programming language. First several VIs for the single-phase analysis were developed and then these ones were used to build a complex VI that makes the identification and analysis for three-phase electric signals.

The algorithm was verified on several digital waveforms containing voltage dips and voltage swells virtually created. Thus the disturbances characteristics could be easy controlled and compared with the obtained results.

6. EXAMPLES

Several complex waveforms were studied as to verify the algorithm, but in the paper only four representative examples are illustrated: a typical voltage dip, a typical voltage swell, a very short duration voltage swell and a variation of the voltage r.m.s. values that is not a disturbance. The temporary disturbances were included in the structure of non-sinusoidal unbalanced three-phase signals. In order to simplify the examples presentation, only the single-phase analysis is described. Consequently, the support waveform is a single-phase non-sinusoidal electric signal. In Fig. 7 is presented the base waveform containing the typical voltage dip. Table 2 contains the disturbances instantaneous characteristics included in the examples.

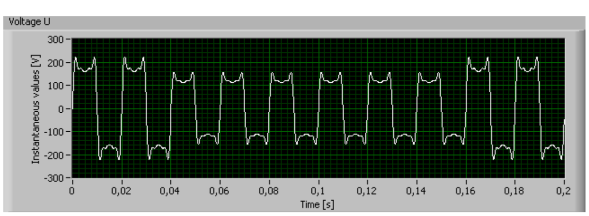

Fig. 7. Non-sinusoidal electric signal containing a voltage dip

Table 2. The instantaneous characteristics of the temporary disturbances

Example \ Instantaneous characteristics	t_0 [s]	d [s]	A [%]
1	0.04	0.12	70
2	0.04	0.12	170
3	0.14	0.002	1500
4	0.1	0.08	95

t_0 [s] – start moment
d [s] – time duration
A [%] – minimum amplitude % (comparing the reference value) of the digital signal during the temporary disturbance

Fig. 8 contains the variation in time of the r.m.s. values for the first example. It also includes the explanation of the way the start and end moments are determined. It can be observed that the disturbance is a usual voltage dip.

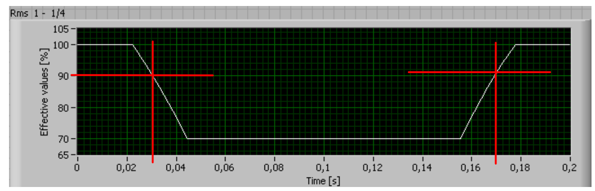

Fig. 8. Variation in time of the r.m.s. values for the 1st example

Fig.s 9 and 10 illustrate the r.m.s. values of the waveform in the case of a typical and a very short duration voltage swell, respectively. The way the voltage swells' characteristics are determined can be seen in the corresponding figures.

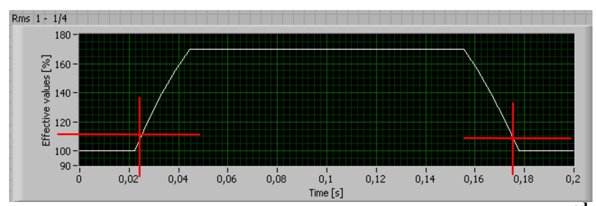

Fig. 9. Variation in time of the r.m.s. values for the 2nd example

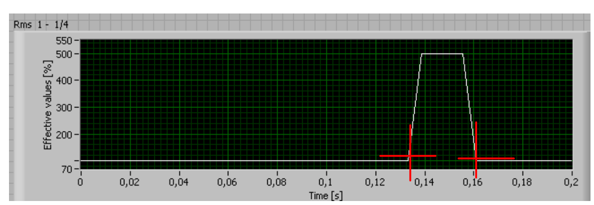

Fig. 10. Variation in time of the r.m.s. values for the 3rd example

The 4th example, whose variation in time of signal is illustrated in Fig. 11, underlines the thresholds that define the disturbances definition intervals and the fact that the algorithm and the developed virtual instruments work properly.

Table 3 contains a comparison between the results obtained using the standard method (that was also implemented as a virtual instrument) and the proposed one. The results show that both methods determine

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properly the disturbances amplitude. Differences appear in the disturbances durations case, because of the way the r.m.s. values are updated, namely in the standard method case the r.m.s. value is updated every half of cycle, while in the case of the proposed method every quarter of cycle. This fact also brings an advantage for the proposed method that is a closer to reality disturbance shape.

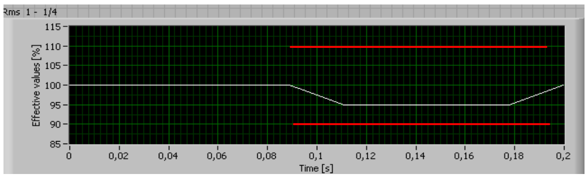

Fig. 11. Voltage r.m.s. values time variation. Example 4

Table 3. Comparison between the obtained results and the standard method

Standard method			Proposed method		
t_0 [s]	d [s]	A [%]	t_0 [s]	d [s]	A [%]
Example 1					
0.03	0.13	70	0.03	0.125	70
Example 2					
0.03	0.13	170	0.025	0.135	170
Example 3					
0.13	0.02	498	0.125	0.02	500
Example 4					
-	-	-	-	-	-

t_0 [s] – start moment
d [s] – time duration
A [%] – minimum amplitude % (comparing the reference value) of the digital signal during the temporary disturbance

7. CONCLUSION

The papers presents a method for voltage dips and voltage swells identification in single and three-phases power networks. Consequently, further on the situation of the temporary disturbances identification is explained by describing the aspects from infield standards and the characteristics of real electric signals which contain voltage dips and voltage swells.

The method offers the same precision as the wavelet transform, but it has the advantage of using less calculations. On the other hand, comparing it with the method proposed in standards the proposed method is quicker (less calculation is performed).

The presented examples show that both the standard and the proposed method gives accurate results concerning the amplitude of the disturbances, but more exact is the proposed method when determining the start and end moment, that is the duration and the disturbances' shape.

The proposed method offers more advantages comparing the standard method:

- Less calculus – disturbance is first identified and then the characteristics are determine;
- The exact moment of disturbance start and end are precisely determined;
- The disturbance shape is more close to the reality.

Future research can be made in order to include more disturbances in the algorithm and to decrease the time needed for calculus (develop more advanced virtual instruments).

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