A Wavelet-Based Algorithm for Disturbances Detection Using Oscillographic Data

F. B. Costa, K. M. Silva, K. M. C. Dantas, B. A. Souza and N. S. D. Brito

Abstract— **This paper presents a discrete wavelet transform approach to disturbance detection by the analysis of electromagnetic transients in transmission lines using oscillographic data. The detection is carried out by the analysis of the detail coefficients energy of the phase currents. The performance of the method was evaluated for actual oscillographic data and excellent results were obtained.**

Index Terms— **Disturbance detection, transmission lines, wavelet transform.**

I. Introduction

Electromagnetic transients in power systems are characterized by high frequency components during a short period of time. These signals superpose both voltage and current waveforms in a variety of disturbances such as faults, capacitor bank switching transients and lighting strikes. As a consequence, excessive currents or over voltages may appear in power system, reducing its reliability.

The wavelet transform (WT) has been widely used to analyze non-stationary phenomena, such as electromagnetic transients, due to its ability to analyze a localized area of a signal, revealing discontinuities and related frequency spectrum [1], [2].

The aim of this paper is to introduce a method for disturbance detection at wavelet domain by the analysis of electromagnetic transients in transmission lines, using actual oscillographic data. The detection is carried out by the analysis of the wavelet coefficients energy related to phase currents. Disturbances produced by faults, capacitor switching and transmission line energization and deenergization are taken into account. The performance of the method was evaluated for actual oscillographic data and excellent results were obtained.

Software based on the proposed method has been used by Hydro Electric Company of São Francisco (CHESF), an utility company of Brazil, with a satisfactory performance.

II. WT and Filter Banks

The WT is a powerful time-frequency method to analyze a signal within different frequency ranges, by means of dilating and translating of a single function named *mother wavelet* [3].

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The discrete wavelet transform (DWT) is normally implemented by Mallat's algorithm [4]. Its formulation is related to filter bank theory, since it uses the high-pass $h(k)$ and the low-pass $g(k)$ filters to divide the frequency-band of the input signal into high- and low-frequency components. This operation may be repeated recursively, feeding the down-sampled low-pass filter output into another identical filter pair, decomposing the signal into approximation $c(k)$ and detail $d(k)$ coefficients for various scales of resolution. In this way, the DWT may be computed through a filter bank framework: in each scale, $h(k)$ and $g(k)$ filter the input signal of this scale, yielding new approximation and detail coefficients, respectively. So, this process divides the frequency spectrum of the original signal into octave bands [3]. This filter bank framework is depicted in Fig. 1. The down-pointing arrows denote a decimation by two and the boxes denote a convolution by $h(k)$ or $g(k)$.

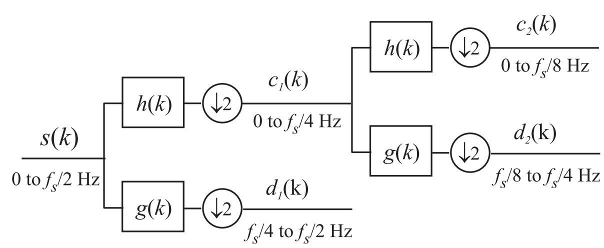


Fig. 1. DWT filter bank framework.

The coefficients of the filters pair are associated with the selected mother wavelet. Daubechies wavelet family is the most used for analysis of power system transients [5]. In this paper, the Daubechies 4 (db4) wavelet was used as the mother wavelet, due to its good time resolution that provides an accurate detection of the fast transients [6].

III. Energy of the Detail Coefficients

In order to compute the wavelet coefficients energy, named *detail-spectrum-energy (DSE)*, at scale j, a moving data window goes through the detail coefficients shifting one coefficient at a time, viz

$$\mathcal{E}_w(k) = \sum_{n=k}^{k+N_w/2^j} d_j^2(n), \tag{1}$$

where N_w is the window length (number of samples contained in one cycle of the fundamental frequency of the original signal), $k = \{1, 2, \ldots, (N_s - N_w)/2^j\}$ and N_s is the total number of samples of the original signal.

Fig. 2 depicts the windowing process to obtain the DSE, at scale 1, for a faulted current (Fig. 2(a)). The detail coefficients (Fig. 2(b)) are obtained after applying one stage of the DWT in the original signal and the DSE (Fig. 2(c)) is obtained by (1). According to windowing process, the sample related to the beginning of the disturbance is anticipated from the actual sample on original signal by $N_w/2^j$ samples.

IV. Detection of Power System Transients

The most common sources of transients in power systems are atmospheric phenomena and switching of power system apparatus. In this way, transient phenomena are present in faults, voltage sags, capacitor switching transients and transmission line energization and deenergization.

The transient phenomena analyzed in this paper and their respective detail coefficients analysis are discussed in the following.

A. Capacitor Switching

Fig. 3 depicts a typical actual transient current waveform related to a capacitor switching, that was obtained from a transmission line. This kind of transient occurs for a very short duration, usually less than one cycle, and the electrical circuit is quickly restored to original operation [7]. The detail coefficients of the current depicted in Fig. 3 are shown in Fig. 4 for different levels of resolution.

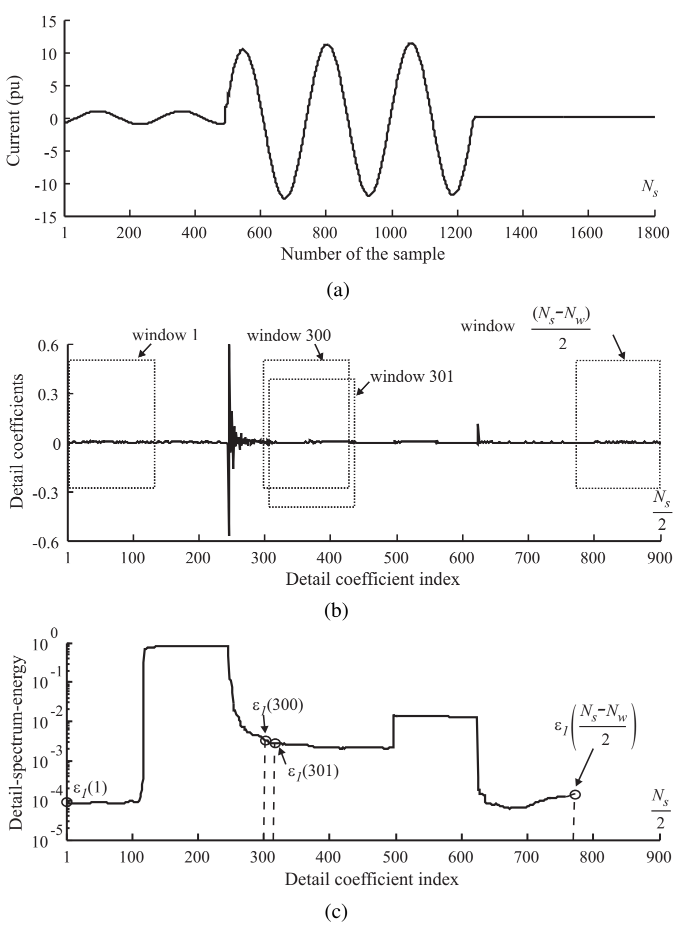


Fig. 2. Windowing: (a) original signal; (b) detail coefficients; (c) DSE

According to *multiresolution decomposition* theory, at scales with high resolution, the wavelet is most localized in time and oscillates rapidly within a very short period of time. In these scales, the wavelet is must suitable to detect fast and short changes on the signal (Fig. 4(a)). Whereas, at scales with low resolution, the dilated wavelet version becomes less localized in time and less oscillatory. In these scales, the wavelet is more suitable to detect low frequency components (Fig. 4(d)).

The higher detail coefficients are related to transient phenomena (Fig. 4). At first scale, these coefficients can be used for disturbance detection and for beginning and end time identification [8].

B. Transmission Lines Energization and Deenergization

Transmission lines energization is a typical switching operation accomplished by circuit-breakers and may cause several transients in power systems.

Fig. 5 depicts a typical actual current waveform due to a transmission line energization. Theirs related detail coefficients are depicted in Fig. 6. According to these figures, the major value of the detail coefficients indicates the circuit-breaker operation and it can be used for disturbance detection.

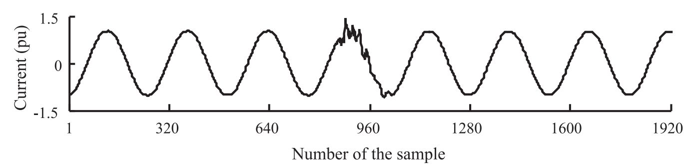


Fig. 3. Normalized current waveform of a capacitor energizing transient.

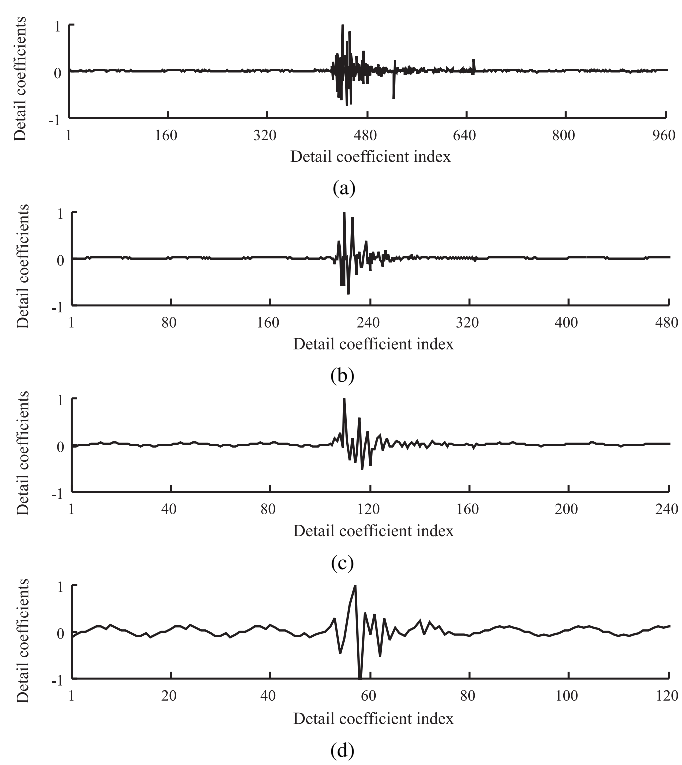


Fig. 4. Detail coefficients: (a) scale 1; (b) scale 2; (c) scale 3; (d) scale 4.

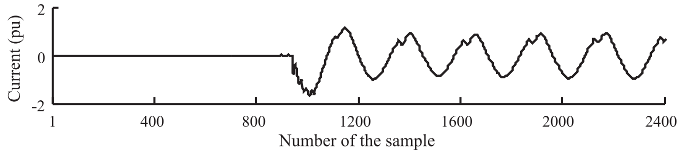


Fig. 5. Normalized current waveform of a transmission line energization transient.

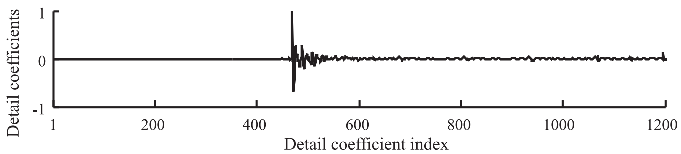


Fig. 6. Detail coefficients at scale 1.

In the same way, transmission line deenergization transients are switching operation accomplished by circuit-breakers, that interrupt the power flow through the transmission line.

Fig. 7 depicts a typical actual current waveform due to a transmission line deenergization. Theirs related detail coefficients are depicted in Fig. 8. It can be observed that the major value of the detail coefficients indicates the disturbance and circuit-breaker operation.

C. Faults

The current and voltage signals obtained from a transmission line when a fault occurs have high frequency components, that are quickly dumped [9]. These components are present around the beginning and end time of the fault and they are appropriately detected at first wavelet scale.

Fig. 9 depicts the voltage and current at the faulted phase, for an actual single-phase-to-ground fault. The related detail coefficients, at first scale, are shown in Fig. 10.

D. Voltage Sags

Voltage sags are related to power quality problems. They are characterized by rms voltage reduction (between 0.1 and 0.9 pu) from steady-state normal system operation, during a period of time from 0.5 to 30 cycles [10].

A fault on a transmission line generates sags and swells at voltage signals. Sags occur on the faulted phases during a fault until the protection system acts to clear the fault. On the other hand, swells are not as common as sags, but they may occur at phases that are not involved on the fault, specially during a single-phase-to-ground fault [10].

A very common occurrence of voltage sag is related to faults on other transmission lines from the same power system. In these case, the transmission lines will experiment a sag until the protection system acts to clear the fault.

Voltage sags can also be related to switching of large inductive loads due to inrush currents, but this kind of occurrence is less common than those aforementioned.

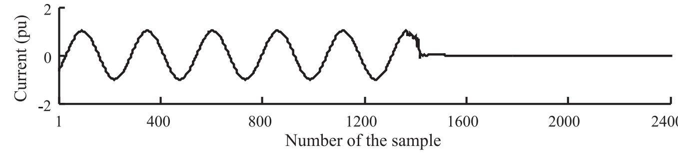


Fig. 7. Normalized current waveform of a transmission line de-energization transient.

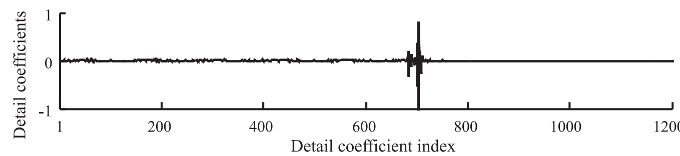
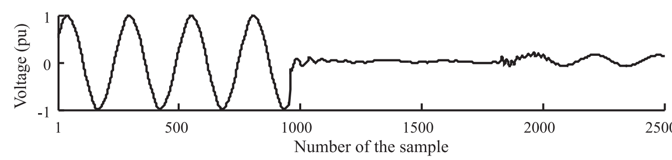


Fig. 8. Detail coefficients at scale 1.

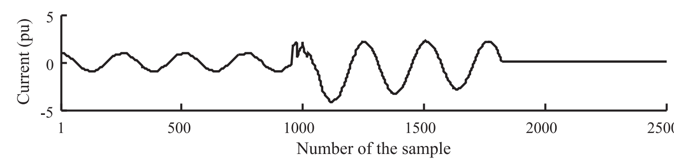
In this paper, voltage sags related to faults on a parallel transmission line are analyzed.

Fig. 11 depicts an actual voltage sag. The detail coefficients for voltage and current are shown in Fig 12.

A common event associated with transmission line voltage sag is the transient phenomena at currents and voltages waveforms. Therefore, the first scale may be suitable to detect these fast electromagnetic transients.

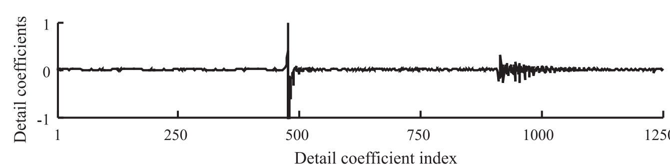


(a)

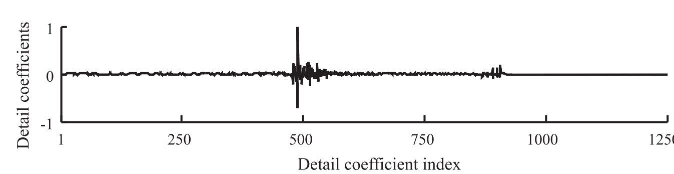


(b)

Fig. 9. Normalized waveform of an actual fault: (a) voltage; (b) current.



(a)



(b)

Fig. 10. Detail coefficients at scale 1: (a) voltage; (b) current.

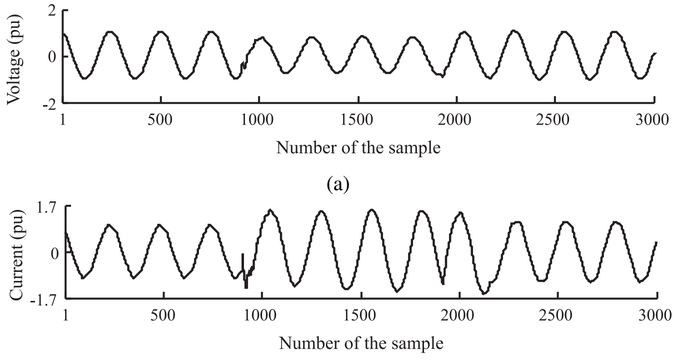


Fig. 11. Normalized waveforms of an actual voltage sag: (a) voltage; (b) current.

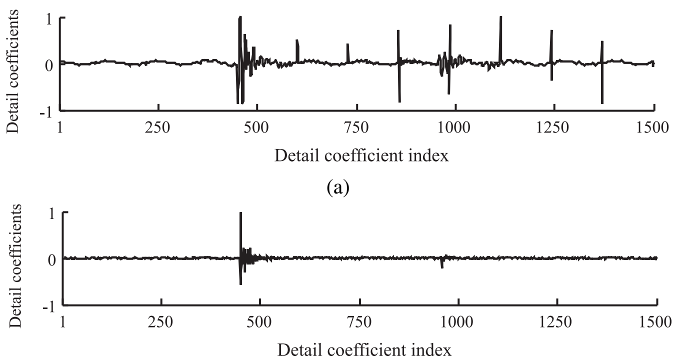


Fig. 12. Detail coefficients at scale 1 for phase A: (a) voltage; (b) current.

V. Proposed Method

It is proposed a method for detection of disturbances in transmission lines by the analysis of electromagnetic transients using actual oscillographic data. The detection is carried out by the analysis of the DSE of the phase currents. In other to develop the method, exhaustive studies related to DSE were accomplished and it was observed that:

1) The first wavelet scale is most appropriated for disturbance detection.
2) DSE of the currents provides a pattern that may be used for transients detection.
3) For oscillographic data without disturbance (e.g. Fig. 13) the DSE may range between thresholds E_1 and E_2 (Fig. 14), which are discussed in Section VI.
4) For oscillographic data with disturbance, the following statements can be derived from the DSE illustrated at Fig. 15, which is related to the current waveforms depicted in Section IV.
    a) The energy values related to steady-state normal system operation, usually, range between thresholds E_1 and E_2.
    b) In records due to transmission line energizations, deenergizations and faults (e.g. Figs. 15(b), 15(c) and 15(d)), the energy may reach values below E_1.
    c) There is a sharp variation corresponding to the transients beginning time.
    d) The energy values are greater than E_2 during the transient phenomena.

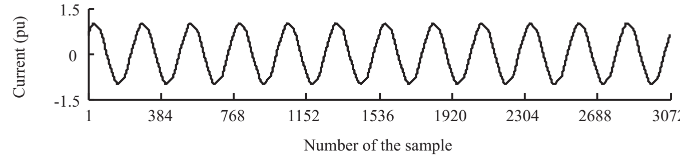


Fig. 13. Normalized current waveform of an actual oscillographic data without disturbance.

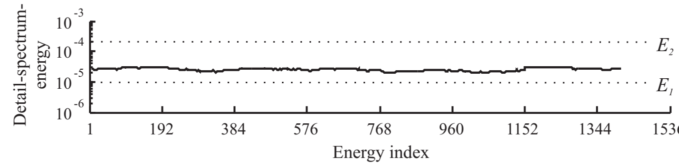


Fig. 14. DSE of the current, at scale 1, without disturbance.

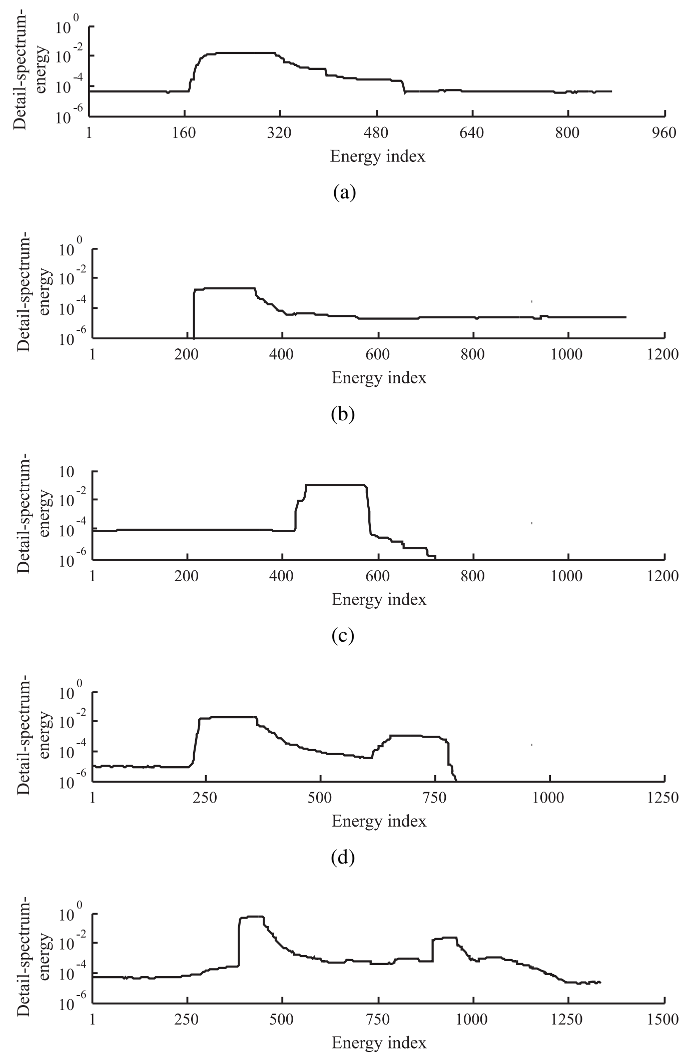


Fig. 15. DSE of the current, at scale 1, related to: (a) capacitor switching; (b) transmission line energization; (c) transmission line deenergization; (d) fault; (e) voltage sag.

Fig. 16 is used to introduce the method. It depicts the DSE curve related to a capacitor switching and the parameters used to disturbances detection, which are described in the following:

1) E_1 and E_2: used to delimit the region in which the energy values are related to steady-state normal system operation.
2) E_{max}: maximum energy value during disturbance time.
3) ΔE: energy variation in five consecutive energy points.
4) E_{pos}: mean energy at one cycle of the fundamental frequency, computed after disturbance.
5) k_1: sample related to the beginning time of the disturbance.
6) k_2: sample related to the end time of the disturbance.
7) $\Delta k = k_2 - k_1$: delimit the time of the disturbance.

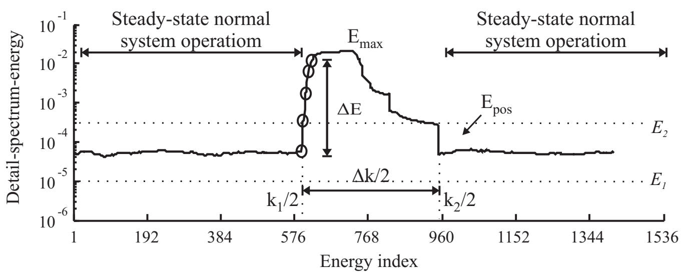


Fig. 16. Parameters at DSE curve for disturbance detection.

The major energy variation of DSE (ΔE_{max}) is related to the beginning time of the disturbance. This is the main characteristic used by the proposed method for detection. For each sample k, ΔE is computed considering five consecutive points of the DSE curve:

$$\Delta E = max\{\mathcal{E}_1(k), \mathcal{E}_1(k+1), \ldots, \mathcal{E}_1(k+4)\} - \mathcal{E}_1(k), \quad (2)$$

where: $\mathcal{E}_1(k)$ is the energy value at sample k; $max\{.\}$ returns the maximum energy value among related samples.

A. Summary of the Proposed Method

The following algorithm is carried out for disturbance detection:

1) Normalize the phase currents (I_A, I_B, I_C) of the oscillographic record.
2) Apply the DWT for each phase current to get the detail coefficients at scale 1.
3) Calculate the DSE of the phase currents ($\mathcal{E}_A$, $\mathcal{E}_B$ and $\mathcal{E}_C$), according to (1).
4) If $E_{max} < E_2$, so the oscillographic record do not correspond to a disturbance (analysis ended).
5) Otherwise, get $k = 1$.
   a) From the k, identify some $\Delta E(k) \geqslant \Delta E_{min}$ at the energies $\mathcal{E}_A(k)$, $\mathcal{E}_B(k)$ and $\mathcal{E}_C(k)$.
   b) If $\Delta E(k) \geqslant \Delta E_{min}$ was obtained.
      i) Get $k_1 = k$.
      ii) From the k_1, identify the set of energy samples with main value less than E_2, getting E_{pos}, k_2 and $\Delta k = k_2 - k_1$.
      iii) if $\Delta k \geqslant \Delta k_{min}$, so the disturbance was detected (analysis ended).
      iv) Otherwise, get $k = k_2$ and go to step 5a.
   c) Otherwise, the oscillographic record do not correspond to a disturbance (analysis ended).

ΔE_{min} is the minimum energy variation to disturbance detection and Δk_{min} is the number of samples in 2 cycles.

VI. Proposed Method Implementation

The method was based on the actual oscillographic records presented in Tab. I, which ware obtained from transmission lines with different voltage rates (138, 220 and 500 kV) and different sampling rates (1.2, 2.4 and 15.36 kHz).

TABLE I
TYPE AND AMOUNT OF AVAILABLE ACTUAL OSCILLOGRAPHIC RECORDS FOR DETECTION RULES ELABORATION.

Oscillographic record	Amount of available records
Without disturbance	40
transients due to capacitor switching	33
energization of transmission line	25
deenergization of transmission line	20
fault	33
sag	50

Fig. 17 depicts the histograms with minimum and maximum energy values, related to available oscillographic records without disturbance (Tab. I).

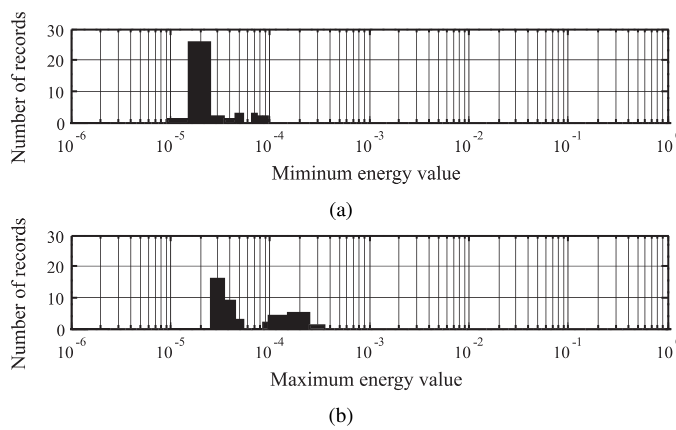


Fig. 17. Energy histogram for the oscillographic records without disturbance: (a) minimum values; (b) maximum values.

According to Fig. 17, the smaller energy value is 1.10^{-5} (Fig. 17(a)) and the bigger energy value is 3.10^{-4} (Fig. 17(b)). Therefore, $E_1 = 1.10^{-5}$ and $E_2 = 3.10^{-4}$.

Fig. 18 depicts the histograms with ΔE_{max} of the transients due to capacitor switching, fault and sag (Tab. I).

For each oscillographic record, it was observed that ΔE_{max} corresponds to beginning of the disturbance. According to Fig. 18, for transients due to capacitor switching, ΔE_{max} ranges from 1.10^{-3} to 1.10^{-1}; for faults, it is bigger than 8.10^{-2} and for sags, ΔE_{max} ranges from 4.10^{-4} to 6.

Similar energy histograms for transmission line energization and deenergization was available, and it was stabilized $\Delta E_{min} = 1.10^{-4}$.

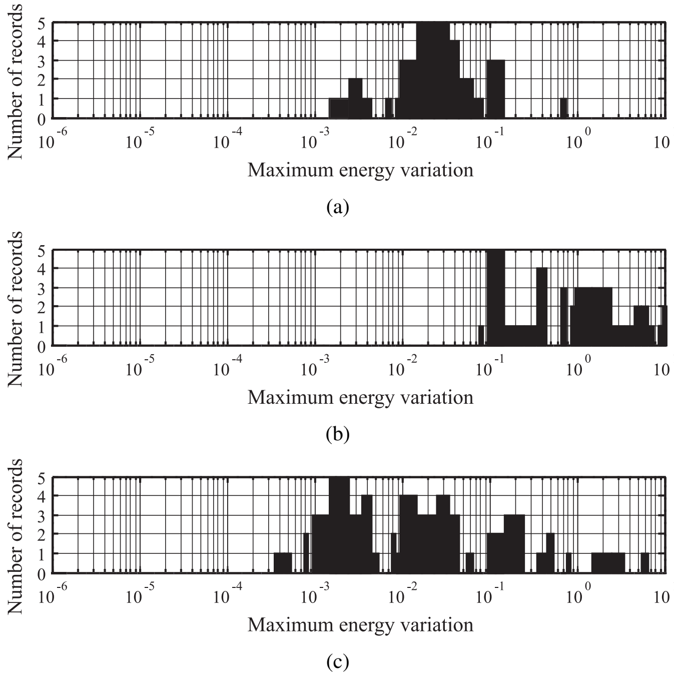


Fig. 18. Histogram of the maximum energy variation for the oscillographic records with: (a) transients due to capacitor switching; (b) fault; (c) sag.

VII. Proposed Method Performance Evaluation

The proposed method was evaluated for 772 actual oscillographic records (Tab. II) from different transmission lines of CHESF, with different voltage rates (138, 220 and 500 kV) and different sampling rates (1.2, 2.4 and 15.36 kHz). It was obtained a success rate of 97.40%.

TABLE II
Performance of the method.

Diagnostic: Real	Diagnostic: Desired	Amount of records	Right diagnostic
Without disturbance	Without disturbance	233	233
Energization	With transients	85	85
Deenergization	With transients	60	59
Fault	With transients	63	63
Sag	With transients	284	270
Transients due to capacitor switching	With transients	47	42
		772	**752**

Conclusion

A novel method for transmission lines disturbance detection by the analysis of electromagnetic transients using oscillographic data was presented. The method was evaluated with actual data and the obtained results reveal that it is independent of the voltage rate of the transmission lines.

As a byproduct, the method provides the beginning and end time of the disturbances, but due to energies windowing process, the obtained beginning time is backward of the actual value for about one cycle of fundamental frequency.

Some problems was observed in few oscillographic data, in which the transient signals are very dumped. In these cases, the DSE curve can not present a sharp energy variation needed to disturbance detection.

A software based on the proposed method was installed at oscillographic network, of an utility company of Brazil and excellent results have been obtained.

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