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A new method to characterize power quality disturbances resulting from expulsion and current-limiting fuse operation

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Abstract
This paper presents a new method for the characterization and diagnosis of electrical disturbances caused by fuses operation in the electrical distribution systems. A set of descriptors is proposed in order to quantify the typical features of the distortions caused by operation of expulsion and current limiting fuses. A multivariate statistical analysis is performed to select the descriptors with the best profiles qualifiers and the optimal decision thresholds are selected to classify the disturbances using machine learning algorithms. Voltage and current signals of the fuses operation are obtained from the ATP-EMTP simulation, as well as some real signals, to be all used in the validation of the new proposed algorithm, obtaining optimal performance and efficiency results. The algorithm was implemented in Matlab and the computational requirements are minimal.

Keywords: Electromagnetic disturbances; expulsion fuse; current-limiting fuse; descriptors; Multivariate Analysis of Variance (MANOVA).

Nuevo método para la caracterización de perturbaciones de la calidad de la potencia producto de la operación de fusibles de expulsión y limitadores de corriente

Resumen
Este trabajo presenta un nuevo método para la caracterización y el diagnóstico de perturbaciones eléctricas causas por la operación de fusibles en los sistemas de distribución de energía eléctrica. Se propone un conjunto de descriptores con el propósito de cuantificar las características propias de las distorsiones originadas por la operación de fusibles de expulsión y limitadores de corriente. Para seleccionar los descriptores con los mejores perfiles clasificatorios se realiza un análisis estadístico multivariable y a través de algoritmos de aprendizaje automático se seleccionan los umbrales de decisión óptimos para los mismos. A partir de la simulación en ATP-EMTP se obtienen señales de tensión y corriente de la operación de fusibles, así como algunos registros de eventos reales, para en conjunto ser utilizados en la validación del nuevo algoritmo propuesto, obteniéndose un óptimo desempeño y eficacia en los resultados. El algoritmo fue implementado en Matlab y los requerimientos computacionales son mínimos.

Palabras clave: perturbaciones electromagnéticas; fusible de expulsión; fusible limitador de corriente; descriptores; análisis multivariante de la varianza MANOVA.

1. Introduction

Power quality concept represents a great interest to both customers and the electrical utilities. The study of different types of electrical disturbances and the associated causes has been the basis for recent research, which aims to prevent, control, or mitigate such disturbances. Therefore, studies related to the generation of new tools to diagnose electric power quality are currently very important. The purpose of these tools is to improve power quality and reliability of electricity services.

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The fuse is one of the most used protective devices in any electrical system due to its simplicity and performance characteristics, in addition to its low cost compared to other protective devices. The fuse operation is reflected by distortions of voltage and current waveforms that are recorded by power quality monitors. From these recorded signals it is possible to extract valuable and useful knowledge for the management and maintenance of electrical distribution systems. Through an analysis of the diagnosis and characterization of electrical disturbances, important results are obtained to provide better electric service and improve power quality indices.

A comparative analysis of the effects of expulsion and current-limiting fuse (CLF) operation is presented in [1]. Some conclusions are, that CLFs improve power quality and reduce the duration of the voltage sags, although they generate overvoltage for customers near the fault location. Furthermore, the expulsion fuse presents longer voltage sag duration and a smaller transient recovery voltage (TRV).

In [2], a characterization of electrical disturbances caused by the operation of current-limiting fuses is presented. This paper is the first contribution made by the authors on the subject of characterizing power quality disturbances resulting from the fuses operation, specifically for CLFs.

Now, this present study aims to develop a unique methodology to identify the electrical disturbances caused by expulsion fuses and CLFs. A first step is to propose a set of descriptors from the waveform characteristics caused by the fuse operation. Second, a multivariate statistical analysis determines the set of relevant descriptors, which in turn identify the type of electrical disturbance. Finally, the decision rules and the algorithm are proposed.

The second section of this paper presents the overview of the expulsion fuse and CLFs. The third section presents the fuse modeling methods. The models were verified by comparing simulation results. Section IV shows the formulation of the descriptors, the statistical analysis and selection decision rules, as well as the design and validation of the algorithm. Conclusions are given at the end of this paper.

2. The fuse overview

The fuse is a simple and reliable safety device, which has great advantages compared to other protective devices due to its ease of implementation. Fuses are current sensitive devices, with characteristics of operation inverse time [3]. They are constituted by a conductive element which has a reduced cross section, usually surrounded by an arc extinguisher and heatsink, encapsulated in a cartridge (a cylindrical shape) and provided with respective terminals.

The fuse element is within the cartridge, which is formed by a wire or metal strips with a reduced section and is calibrated according to its current capacity. In this metal section a high current density is produced, which, in turn, causes the element fusion and the opening of the connected circuit [4]. In the case of low voltage and currents, the fuse elements are manufactured using a lead-based alloy and in the case of higher currents, a tape based alloy of copper or aluminum [1].

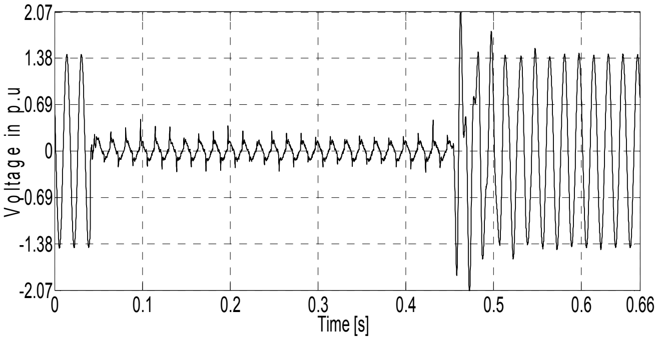

Figure 1. Voltage distortion caused by expulsion fuse.
Source: The authors.

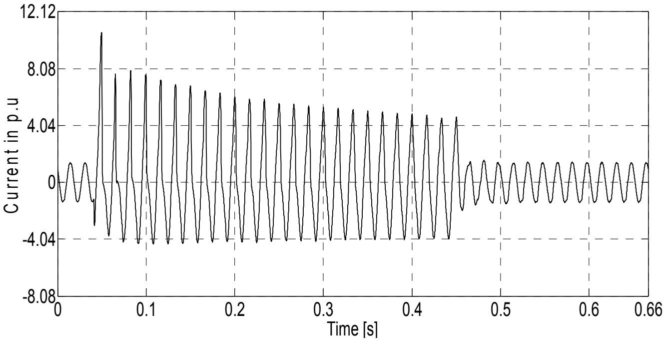

Figure 2. Current distortion caused by expulsion fuse.
Source: The authors.

2.1. *Expulsion fuse characteristics*

Expulsion fuses use high-pressure gas generated by compressed tablets of boric acid in order to extinguish the arc. Fuse element is located between two contacts, one mobile and one fixed. In [5], various physical characteristics of the expulsion fuse are presented. Expulsion fuses commonly have long operation times ranging from half a cycle to times exceeding minutes [1], according to Fig. 1 and Fig. 2.

The waveforms show voltage sags and long periods of overcurrent. This involves the flow of large amounts of energy (I^2t) through the electric circuit, thereby exposing the sensitive equipment to high currents [1]. Unlike current limiting fuses, the factor I^2t is much lower for an expulsion fuse, due to its rapid action.

2.2. *Current-limiting fuse characteristics*

The current-limiting fuse is a fast-acting device, with interruption time of the fault current in less than a half-cycle time by introducing a high resistance in the circuit. Fig. 3 shows the voltage distortion by current-limiting fuse.

The fuse element has a greater length than in the expulsion fuse and is located within silica sand to focus the arc. Pressure is incremented along the fuse element and produces a momentary increase in resistance, limiting fault current [4]. In addition, the operation time is reduced to a value that is considered in the first half cycle of the current waveform [3].

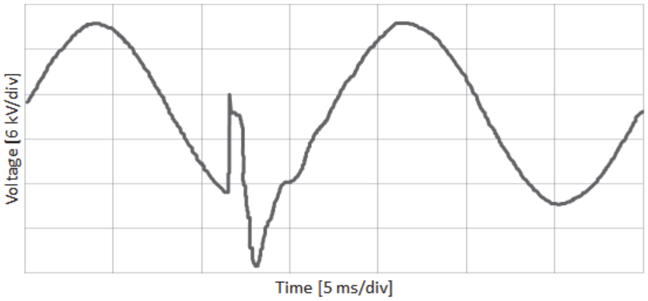

Figure 3. Voltage distortion caused by current-limiting fuse.
Source: The authors.

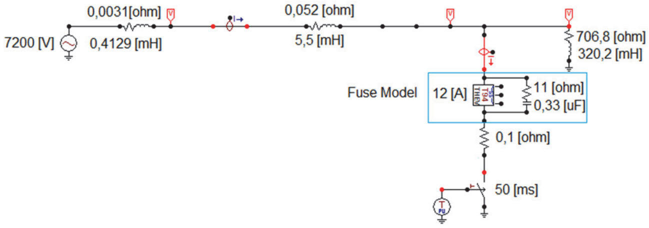

Figure 4. Model of the fuse operation.
Source: The authors.

3. Fuse modeling and simulation of its operation

In order to study the effects of the expulsion and current-limiting fuse operation in an electrical network, the devices were modeled using the inverse time characteristics (expulsion and current-limiting fuse) in the fuse model, implemented in ATP-EMTP, Fig. 4.

3.1. Expulsion fuse modeling

The expulsion fuse was modeled as an ideal switch whose opening time is determined by the inverse time curve and the zero-crossing time of the instantaneous current, Fig. 4.

The model meets the basic requirements of an expulsion fuse. These requirements are:

- ✓ Overcurrent detection.
- ✓ Operating time depending of the overcurrent magnitude.
- ✓ Current interruption with zero-crossing time.
- ✓ Open the protected feeder.

Fuse models were programmed on the “MODELS” package and were implemented in ATP-EMPT using the *Type-94 Thevenin model* [6]. Simulations were performed on two test circuits and a set of voltage sags was obtained for the characterization of disturbances and some testing of the proposed algorithm. A system of 13 nodes [8] and one of 34 nodes [9] are the test feeders used in the simulations. Different types of faults were obtained, including single line-to-ground, double line-to line and three line faults, recorded voltage and current waveforms.

3.2. Current-limiting fuse modeling

Two principal parameters were taken into account in its modeling. One is the fuse’s melt I^2t and the other is the fuse’s non-linear resistance characteristic after melting open. The implemented model was taken from a current-limiting fuse of 8.3 kV, 20 A. According to [1], the current-limiting fuse was modeled as a nonlinear resistance.

This model was implemented on ATPDraw and simulated on two test circuits, Fig. 4, whose records were obtained for the characterization of the disturbances and for future tests of the methodology. Two radial test feeders, of 34 and 13 nodes, were used in the simulations [8], [9].

4. Methodology and implementation

The following subsections describe relevant aspects of each of the steps set for the development and elaboration of the proposed methodology for the characterization of the electrical disturbances by expulsion and current-limiting fuses.

Initially the proposed descriptors are described according to their waveform characteristics. The implementation of descriptors is performed using functions programmed in MATLAB. Subsequently, the multivariate statistical analysis is presented. The aim of this step is to determine the degree of relevance of each of the descriptors and the selection of decision rules, based on machine learning techniques for the design of the proposed methodology. Validation is performed using the different types of previously identified disturbances. Lastly, the proposed algorithm is applied to a set of actual and synthetic recorded data.

4.1. Formulation of descriptors

Descriptors formulation is made based on the waveforms of electrical disturbances, as well as features identified in [2]. Some of these features are, the event duration, slopes of instantaneous and RMS overcurrent, ratio between fault and pre-fault currents, zero-crossing in overcurrent opening, disturbance waveform in the instantaneous and RMS values sequence, and percentages of variation in voltage and current rms. A number of descriptors that measure these and other features are postulated in this article. These descriptors are described below.

4.1.1. Disturbance time delta (ΔTP)

The ΔTP is defined as the difference between the endpoint (n_{final}) and starting point ($n_{inicial}$) of the disturbance, in respect to the total number of samples per cycle (n).

$$\Delta TP = \frac{n_{final}-n_{initial}}{n_{cycle}} \tag{1}$$

The start and end points of the disturbance were determined using a segmentation tool developed in [13]. This algorithm identifies changes in the magnitude and frequency of the signal and estimates segments according to the detected variations in these parameters. Its operation is formed with the use of tensor analysis and wavelet transforms (decomposition with family Bior 3.9). The proposed algorithm combines the advantages of both techniques and has become a highly efficient tool for signal segmentation.

4.1.2. Ratios of voltage and currents (RVI)

The expected behavior for the waveforms of the voltage and current signals when operating a fuse is a relative increase and decrease in the effective signals during a disturbance. During the disturbance, it can be seen that the current always increases while the voltage tends to decrease. The RVI descriptor quantified this characteristic behavior, identifying the phases involved in network fault. RVI is a descriptor of the binary type, which defines whether a perturbation of this type of behavior in the voltage and current signals results in the operating of a fuse. This descriptor, unlike others, is calculated using the RMS sequences of voltage and current of one phase, and the expected result is the value *1*, which indicates the increasing of the current while the voltage decreases during the event and the value zero for otherwise. The calculation method is presented below.

$$\begin{aligned} \%vTe &= \frac{V_{rms\_Fault}}{V_{Rms\_Prefault}} * 100 \\ \%vCe &= \frac{C_{rms\_Fault}}{C_{Rms\_Prefault}} * 100 \end{aligned} \tag{2}$$

$$RVI = \begin{cases} 1, & if\ \ \%vTe < 100\ and\ \ \%vCe > 100 \\ 0, & other\ cases \end{cases}$$

Values $\%vTe$ and $\%vCe$ correspond to the percentages of variation of RMS sequence voltage and current respectively. The set of RMS values taken into account are those that correspond to the values located between 15% of the measurements following the start point of the disturbance and 15% of the measurements before the end of the event. It is calculated by comparing the voltage and current signals with a replica signal RMS, built from an analysis of pre-faults waveforms.

4.1.3. Nearest zero-crossing (NZC)

When a disturbance occurs, it is important to identify the time at which the disturbance is cleared. For this, the zero crossing before the opening of fault is taken as a reference point.

NZC descriptor is formulated in order to estimate the proximity between the point of fault clearing and the nearest zero crossing. Consequently, it is determined that the interruption was presented in a different value of current than the wave normal crossing zero (distinguishing feature between a current-limiting fuse and fuse expulsion).

In summary, NZC descriptor computes the number of samples between the end point of the disturbance and the zero crossing closest to this point, as shown in Fig. 5.

$$\begin{aligned} +NZC &= \frac{\#n_{cross_0}}{n_{cycle}} \\ -NZC &= \frac{n_{cycle-(\#n_{cross_0}+1)}}{n_{cycle}} \end{aligned} \tag{3}$$

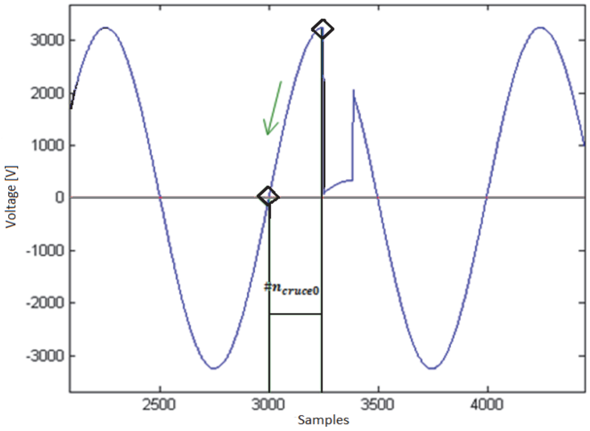

Figure 5. The Nearest Zero-Crossing.
Source: The authors.

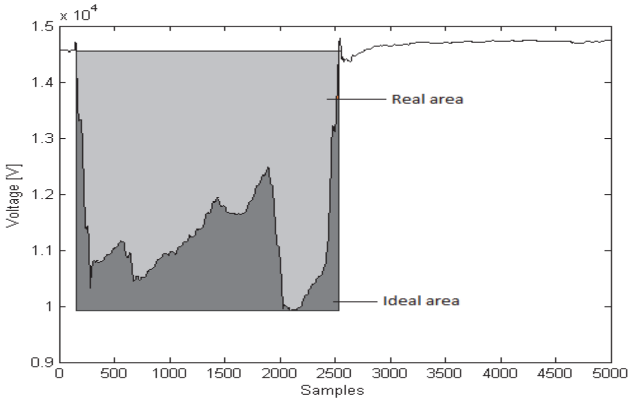

Figure 6. Rectangular shape coefficient
Source: The authors

4.1.4. Rectangular shape coefficient (RSC)

The RMS voltage sequences of the voltage sags show rectangular waveforms generally. The shape coefficient is used to quantify whether the sequence of the effective values of stress during evolution follows a rectangular hole.

If the disturbance corresponds to the operation of an expulsion fuse, then RSC will have values close to unity, and values close to zero in the opposite case.

The descriptor is quantified by comparing the areas, i.e. the area under the curve of the perturbation is calculated and is compared with the area under the curve of a perfect rectangle, using E.q. 4. Ideal rectangle consists of the start and end points of the disturbance and the lowest value of RMS voltage during this period of time, as illustrated in Fig. 6.

$$RSC = \frac{Area_{ideal} - Area_{real}}{Area_{ideal}} \tag{4}$$

4.1.5. Current rise and fall time

ePI^{+} and ePI descriptors measure the speed at which the RMS current grows and decays during the duration of the disturbance.

Table 1.
Complementary descriptors.

Descriptor	**Definition**
$iTSC$	Instant triangular shape coefficient
ΔTP	Disturbance time delta
iPI^{+}	Up slope of instant overcurrent
iPI^{-}	Slope down of instant overcurrent
$\%iVF$	Instant voltage fall percentage
i_{RATIO}	Instant currents ratio
$I2t$	Dissipated energy
iRSC	Instant rectangular shape coefficient
$\pm FOIA$	Fuse operation insertion angle
NZC	The nearest zero-crossing
$IZ0$	Increase of zero-sequence impedance
$IZ-$	Increase of negative-sequence impedance

Source: The authors

$$\frac{dI}{dt}=\frac{I_{peak}-I_{start/end}}{t_{peak}-t_{start/end}} \qquad (5)$$

These descriptors extract important information about the transient state of the disturbance and identify the fuse operation among other disturbances of long duration. The slopes (rise and fall) of the electrical current determine the behavior during casting of the fuse element and the resulting bow.

4.1.6. Others descriptors proposed in [2]

Table 1 presents a summary from [2] of some proposed descriptors, compiled by the authors of this work. This set of descriptors is primarily used for the characterizing of the disturbances caused by current-limiting fuses.

4.2. Multivariate analysis of variance-MANOVA

According to the descriptors mentioned above, a multivariate statistical analysis is performed to establish the level of effectiveness of the descriptors and the degree of relevance of each of in the identification of events caused by the fuse operation. Eighty electrical signals from voltage and current (obtained by simulation and of real records) are analyzed. These waveforms have been previously identified and classified into three classes of causes: current limiting fuse operation, expulsion fuse operation and capacitor bank energization.

Multivariable analysis verified the existence of groups or classes in the data, i.e. the degree of influence of each feature event, allowing for the knowledge of the importance of each descriptor to the origin of the event (limiting fuse, expulsion fuse, energizing capacitor banks).

Parameter R^2 -corrected (see Table 2, third column) indicates the degree of influence of the cause of the event on each one of the exposed descriptors. R^2 values (corrected close to the unit) indicated greater relevance regarding the origin of a disturbance. Descriptors were selected which had the greatest degree of influence; these were those that had R^2-corrected ≥ 0.5 values.

Table 2.
Descriptors and their relevance according to a statistical analysis.

Descriptor	**Definition**	R^2
ΔTP	Disturbance time delta	0.800
NZC	The nearest zero-crossing	0.643
RVI	Ratios of voltage and currents	0.873
RSC	Rectangular shape coefficient	0.581
$iTSC$	Instant triangular-shaped coefficient	0.639
iRSC	Instant rectangular-shaped coefficient	0.586

Source: The authors

Table 3.
Extracted rule set using CN2 induction algorithm.

Rule	Cause Assignation
If RVI=1 AND ΔTP >0.643 AND NZC≤0.036 AND 0.76≤RSC≤3.02	Cause= Expulsion fuse
IF RVI=1 AND ΔTP ≤ 0.5313 AND NZC>0.047 AND 0.402<iTSC≤1 OR 1.721<iRSC≤338	Cause= Current-limiting fuse

Source: The authors

According to this analysis, ΔTP, *NZC*, R*VI*, *RSC, iTSC* and *iRSC* descriptors were selected as the relevant descriptors for electromagnetic disturbances characterization by expulsion and current-limiting fuses.

4.3. Selection of the rules decision thresholds

Selection of thresholds and decision rules seek to find appropriate values for the descriptors for the classification task. These values allow the classification of the disturbance cause and avoid overlap in the disturbances groups. Data mining was used to obtain these thresholds, this being a pattern and regularity recognition technique used with large databases.

The CN2 algorithm was used, which is an automated learning technique based on an iterative algorithm searching for IF- THEN rules [11]. Every iteration looks for a set of descriptors covering a large number of examples in a specific class, and only some from another classes. Therefore, this could be used to make a reliable prediction of the class containing the covered examples. Table 3 shows the decision rules and thresholds.

4.4. Methodology design

According the results obtained and presented in Table 3 and in order to obtain a complete analysis tool, these results, together with those obtained in [2], are consolidated to create a methodology that allows for the identification of the disturbances caused by the operation of current-limiting and expulsion fuses, Fig. 7.

The process of automatic identification is presented in Fig. 7, in which the input signals are voltages and currents (per phase). These signals are acquired from power quality

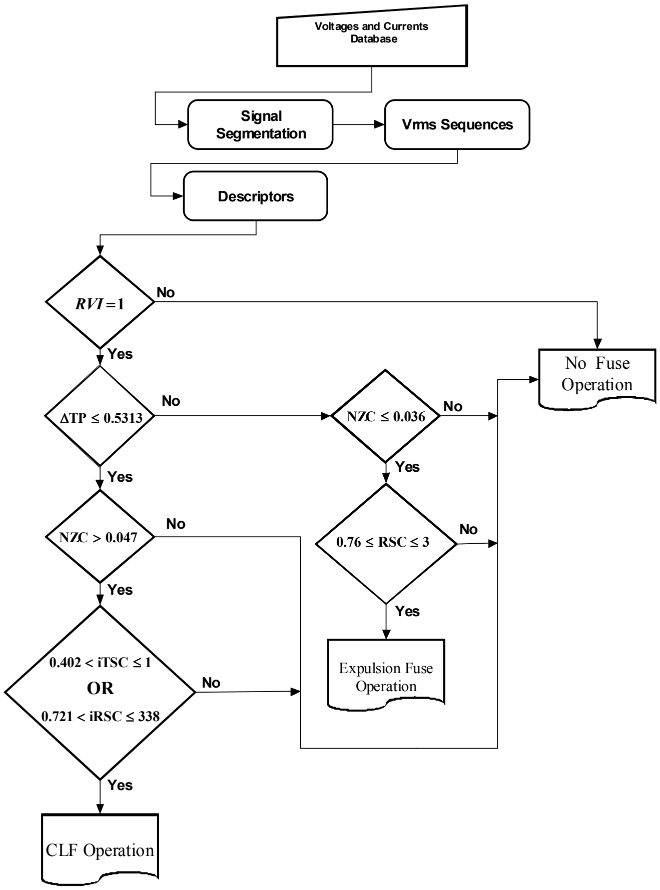

Figure 7. Proposed methodology for identifying disturbances related to expulsion and current-limiting fuse operation.
Source: The authors.

monitors. From these signals, the descriptors are calculated as priorities, where their values are evaluated in the rules decision.

The proposed algorithm has several steps, including a step for loading the signals records, segmentation of the signals, calculating RMS sequences, calculating of the proposed descriptors and evaluation of the decision rules and finally diagnosis of the fuse operation.

5. Testing

Evaluation and validation of the proposed methodology are performed on a set of 50 electrical registers, formed by 15 disturbances caused by expulsion fuse, 20 current-limiting fuses and 15 disturbances by other causes. These registers are comprised of real data, as well as disturbances obtained by simulation, which are used only in the validation stage, differing from those used in the MANOVA stage analysis. The results are shown in Table 4.

The true positives rate (*TPR*) is the efficiency with which the algorithm correctly classifies the disturbance, according to the cause (expulsion fuse, current limiting fuse or no fuse). For example, as shown in Table 4 with the disturbances by fuse operation, the *RTP* indicates that correctly classified disturbances make up 86 % of the entire set of events.

Table 4.
Confusion matrix with the results obtained from test case.

CAUSE	Expulsion Fuse	CLF Fuse	No Fuse	Total
True Positives (TP)	11	17	15	43
False negatives (FN)	4	3	0	7
False positives (FP)	0	0	9	9
True negatives (TN)	35	30	26	-----
True Positive Rate (TPR)	0.73	0.85	1	**0.86**
False Positive Rate (FPR)	0	0	0.25	**0.071**

Source: The authors

The false positives rate (*FPR*) indicates the degree of confusion of the methodology for assessing the cause of a disturbance.

Some results and operational details regarding the methodology are presented. Three different types of disturbance are presented: events caused by current-limiting fuse operations (synthetic and actual signals), events caused by expulsion fuse operations (synthetic and actual signals) and events caused by capacitor bank energizing (synthetic signals).

5.1. A case of expulsion fuse operation

The next record was taken from a real substation's database, regarding a disturbance caused by expulsion fuse operation. Voltage and current waveforms are presented in Fig. 8.

According to Table 5, it was concluded that the disturbance was caused by expulsion fuse operation because of its *RVI* descriptor value was 1, which means that there are voltage increases and current decreases during the disturbance. Moreover, its duration was 11.6 cycles ($\Delta TP = 11.6$) and its fault time was close to a zero-cross ($NZC \approx 0$). Also, effective signal

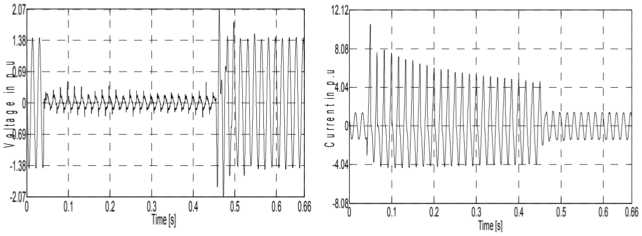

Figure 8. Disturbance caused by expulsion fuse operation.
Source: The authors.

Table 5.
Descriptor for a disturbance caused by expulsion fuse operation.

Descriptor	Value
RVI	1
ΔTP	11.6
NZC	0.07
RSC	1.4

Source: The authors

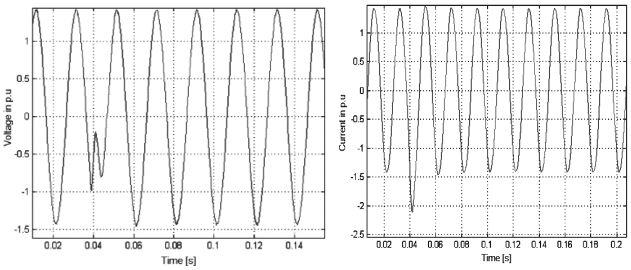

Figure 9. Disturbance caused by current-limiting fuse operation.
Source: The authors.

Table 6.
Descriptor for a disturbance caused by current-limiting fuse.

Descriptor	Value
RVI	1
ΔTP	0.3906
iTSC	0.9596
iRSC	1.9469
NZC	0.1719

Source: The authors

disturbance waveforms were rectangular-shaped (voltage) because *RSC* were close to the unit (*RSC* = 1.4).

5.2. *A case of current-limiting fuse operation*

A real case of current-limiting fuse record was taken from a real substation's database. Voltage and current waveforms are presented in Fig. 9.

According to Table 6, its *RVI* descriptor value was 1, which means that its voltage increases and current decreases during the disturbance, therefore, there are losses of load. Moreover, its duration was around two fifth part of a cycle *(ΔTP = 0.3906)* and its fault time was not close to a zero-cross (*NZC* > 0). Also, instantaneous signal disturbance waveforms were triangular-shaped (current) because *iTSC* were close to the unit (*iTSC = 0.9596*). Rectangular-shaped (voltage) is significant (*iRSC = 1.9469*). It was concluded that the disturbance was caused by current-limiting fuse operation.

5.3. *A case of capacitor bank energizing*

The methodology was tested using a simulated record of capacitor bank energizing [15]. The methodology ruled out that a fuse operation was the cause due to the descriptors values (see Table 7). Voltage and current waveforms are presented in Fig. 10.

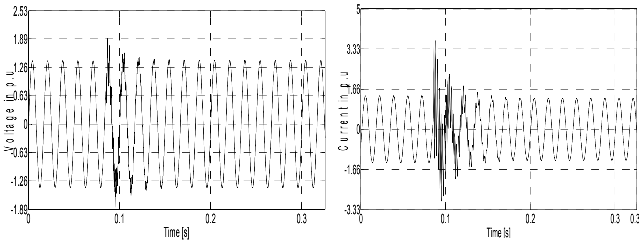

Figure 10. Disturbance caused by capacitor bank energizing.
Source: The authors.

Table 7.
Descriptor for a disturbance caused by capacitor bank energizing.

Descriptor	Value
RVI	0
ΔTP	9.3125
NZC	0.2813
RSC	0.032

Source: The authors

This case was ruled out at the beginning of the methodology because the RVI descriptor value was zero, which means that there was no loss of load recorded.

6. Conclusions

The proposed methodology is a useful and reliable option for electrical utilities that want to improve the power quality optimization of their resources. The methodology has descriptors, which were selected as relevant from the characterization of electrical disturbances caused by expulsion and current limiting fuses operation.

The combination of multivariate statistical analysis and machine learning techniques are presented as support for other studies in different areas, in order to generate methodologies for the formulation of features (descriptors) of a certain event or a failure state.

The effectiveness of the results depends on the quality of the signals to be analyzed. Features such as sampling rate, the distance that was taken from the recording point of the disturbance source and the signals with noise are elements can lead to errors in the descriptors.

This study presents an innovative tool that can be integrated with other automatic methodologies and can also be used to realize the characterization, assessment, and mitigation of electrical disturbances that affect the power quality.

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