Characterising Power Quality Disturbances Resulting from Expulsion Fuse Operation

N. Ortiz S, J. Blanco S., G. Ordoñez P., J.F. Petit and V. Barrera N.

Abstract— **This paper presents easily implementable tools for the characterization and diagnosis of electrical disturbances caused by fuses operation. This paper describes a methodology where the use of some descriptors allows identifying electrical disturbances associated with the expulsion fuses operation. This paper aims to provide new tools in order to assess power quality, characterize and extract information from the current and voltage records that were obtained by monitoring electrical distribution systems. MATLAB was used to validate this methodology, by receiving voltage and current records of simulated events in ATP-EMTP and also, real events as input.**

***Index Terms*— Electromagnetic disturbances, expulsion fuse, descriptors, variance multi-variant analysis (MANOVA).**

I. Introduction

In recent years, a great interest in the way electromagnetic disturbances affect power quality has emerged. 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. In turn, the study of different electromagnetic disturbances and the resulting economic impact are issues of interest to electrical utilities.

According to the regulatory framework, the electrical utilities must continuously monitor electrical systems in order to check power quality by generating various indices. For this reason, studies related to the generation of new tools created to diagnosis electric power quality are currently very important. The purpose of these tools is to improve power quality and reliability of electricity services.

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.

Precisely, such records may become 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.

Expanding on the work [1], focused on the characterization of electrical disturbances caused by the operation of current-limiting fuses, the present study aims to develop a methodology to identify the electrical disturbances caused by expulsion fuses.

A set of descriptors is proposed obtained from the waveform characteristics caused by the expulsion fuse operation and by multivariate statistical analysis. This analysis determines the set of relevant descriptors, which in turn identify the type of electrical disturbance.

The second section of this paper presents the overview of expulsion fuse. The third section presents the expulsion fuse modeling method. 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.

II. Expulsion 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.

The fuses are current sensitive devices, with characteristics of operation inverse time [2]. 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 is produced a high current density, which in turn causes the element fusion and the opening of the connected circuit [3]. 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 [4].

The focus of this paper is fuses expulsion and was created as a complementary work to [1], where the operation of current-limiting fuses was characterized.

The expulsion fuse uses high pressure gas generated by compressed tablets of boric acid in order to extinguish the arc.

The 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

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commonly have long operation times ranging from half a cycle to times exceeding minutes [3], according to Figures 1 and 2.

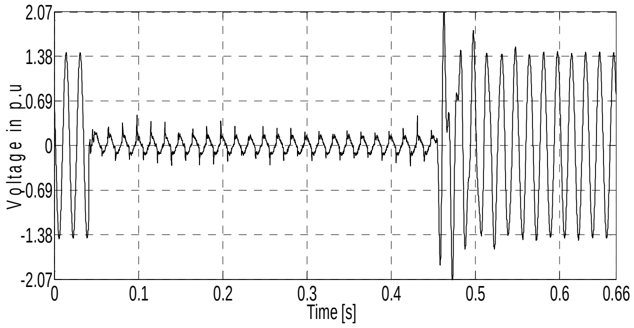

Figure 1. Voltage distortion caused by expulsion fuse.

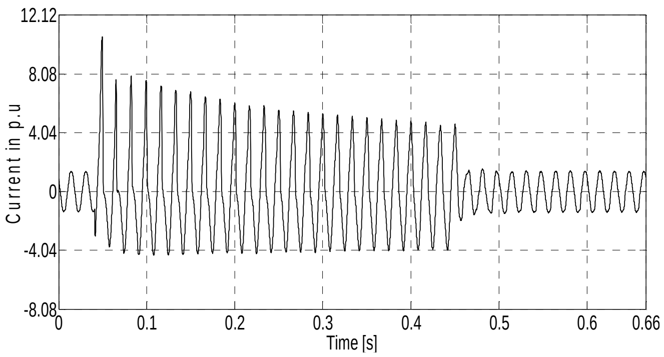

Figure 2. Current distortion caused by expulsion fuse.

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 [4]. Unlike current limiting fuses, the factor I^2t is much lower for an expulsion fuse, due to its rapid action.

III. Fuse Modeling and Simulation of its Operation

In order to study the effects of the expulsion fuse operation in an electrical network, the device was modeled using the inverse time characteristic. The 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.

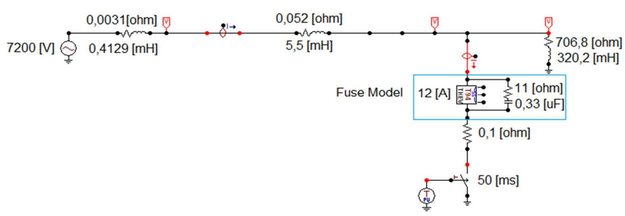

Figure 3.Model of expulsion fuse.

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.
- ✓ Overcurrent detection.
- ✓ Open the protected feeder.

The model was programmed in MODELS and implemented in ATP-EMPT. The model used was *Type-94Thevenin*, [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.

IV. 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 electrical disturbances by expulsion 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. The validation is performed using the different types of previously identified disturbances. Lastly, the algorithm proposed is applied a database with real disturbances.

A. *Descriptors formulation*

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 rms overcurrent, ratio between fault and pre-fault currents, zero-crossing in overcurrent opening, form disturbance in the 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. Below, these descriptors are described.

A.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).

$$\Delta TP = \frac{n_{final} - n_{inicial}}{n_{cycle}} \qquad (1)$$

The start and end points of the disturbance were determined using a segmentation tool developed in [13]. The tool 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.

A.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.

$$\%vTe = \frac{V_{rms\_Fault}}{V_{Rms\_Prefault}} * 100$$

$$\%vCe = \frac{C_{rms\_Fault}}{C_{Rms\_Prefault}} * 100 \qquad (2)$$

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

Where the values $\%vTe$ y $\%vCe$ 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.

A.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.

The *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 Figure 4.

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$$+NZC = \frac{\#n_{cross_0}}{n_{cycle}}$$

$$-NZC = \frac{n_{cycle}-(\#n_{cross_0}+1)}{n_{cycle}} \qquad (3)$$

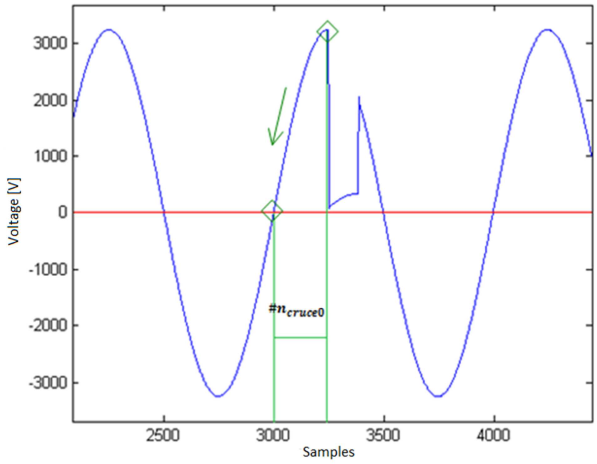


Figure 4. The Nearest Zero-Crossing

A.4 Rectangular shape coefficient (RSC)

The RMS voltage sequences of 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.

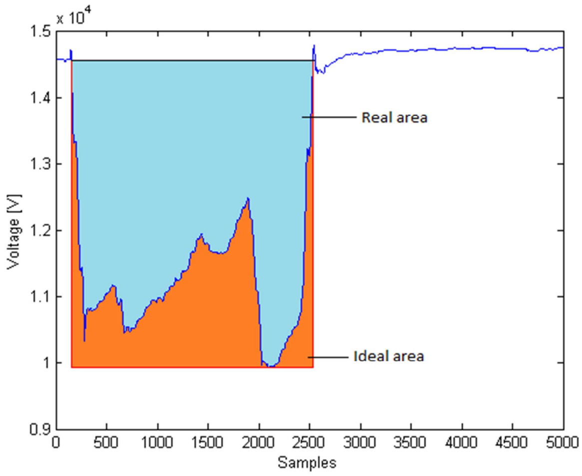


Figure 5. Rectangular shape coefficient

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 equation 4. The 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 Figure 5.

$$RSC = \frac{Area_{ideal} - Area_{real}}{Area_{ideal}} \qquad (4)$$

A.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.

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

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 of the rise and fall of the electrical current estimate the behavior during casting times the fuse element and bow on its operation.

B. 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. A total of 80 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). Thus, the expulsion fuse operation is considered as an independent variable, while the formulated descriptors are the dependent variables.

Parameter R^2 -corrected (see Table I, third column) as a result of this analysis indicated 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, being those having R^2-corrected $\geq$ 0.5values.

TABLE I
PROPOSED 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
ePI^+	Up slope of effective overcurrent	0,054
ePI^-	Slope down of effective overcurrent	0,052
RVI	Ratios of voltage and currents	0,873
RSC	Rectangular shape coefficient	0,581

According to this parameter, ΔTP, NZC, RVI and RSC descriptors were selected as relevant descriptors for electromagnetic disturbance characterization by expulsion fuses.

C. Selection of Decision Thresholds

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

The CN2 algorithm was used, being 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.

Consequently, and also in order to avoid fake data from CN2, the heuristic of Laplacian mean error estimate was used [11].

TABLE II
EXTRACTED RULE SET USING CN2 INDUCTION ALGORITHM.

RULE	*CAUSE ASSIGNATION*
IF VI=1 AND ΔTP >0,643 AND NZC≤0,036 AND 0,76≤RSC≤3,02	*CAUSE=EXPULSION FUSE*

D. Methodology Design

According the results obtained and presented in Table II, an algorithm is proposed for identifying disturbance caused by the expulsion fuse operation, which is shown in Figure 5.
Additionally, in order to obtain a complete analysis tool, these results together with those obtained in [1], are consolidate to create a methodology that allows for the identification of the disturbances caused by the operation of current-limiting and expulsion fuses.

The process of automatic identification and analysis is presented in Figure 6, where the input signals are the rms voltage and current (per phase). These signals are acquired from power quality monitors. From these signals, the descriptors are calculated as priorities, where their values are evaluated in the rules decision. The results may be: Expulsion fuse or no fuse operation.

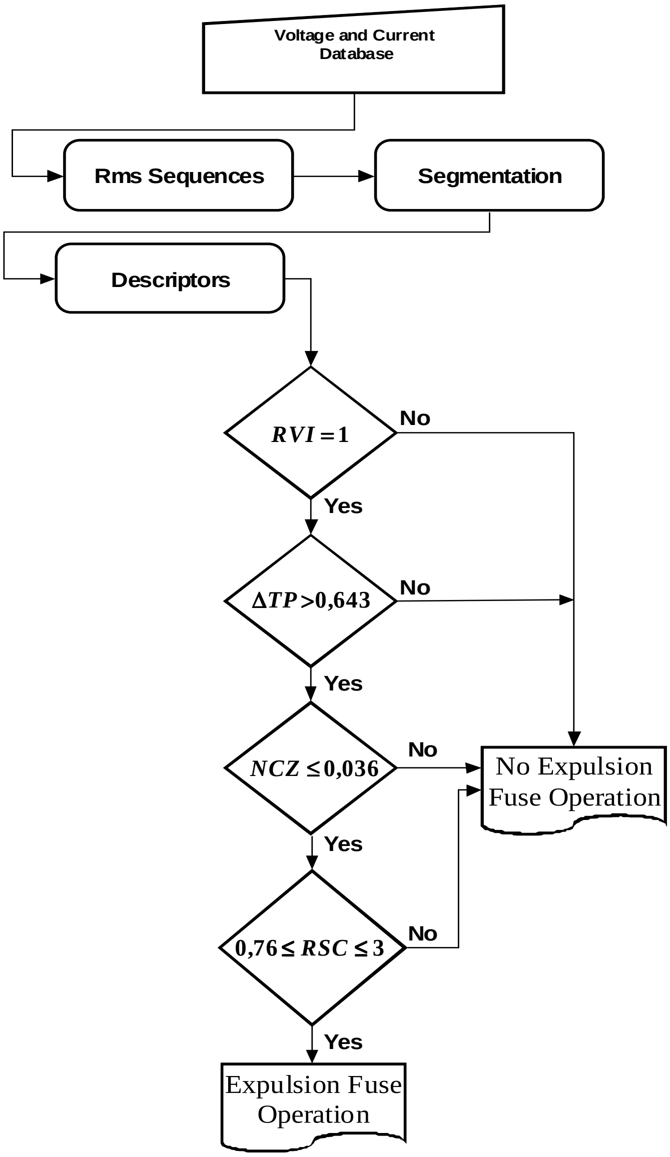


Figure 6. Methodology for identifying disturbances related to expulsion fuse operation.

E. Test case

The evaluation and validation of the methodology are performed on a set of 45 electrical registers, formed by 15 disturbances caused by expulsion fuse, 15 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 analysis MANOVA stage. The results are shown in the Table III.

TABLE III. CONFUSION MATRIX WITH THE RESULTS OBTAINED FROM TEST CASE

CAUSE	Expulsion Fuse	No Expulsión Fuse	Total
True Positives (TP)	11	15	23
False negatives (FN)	4	0	9
False positives (FP)	0	9	9
True negatives (TN)	15	6	-----
True Positive Rate (TPR)	0,73	1	0,865
False Positive Rate (FPR)	0	0,6	0,8

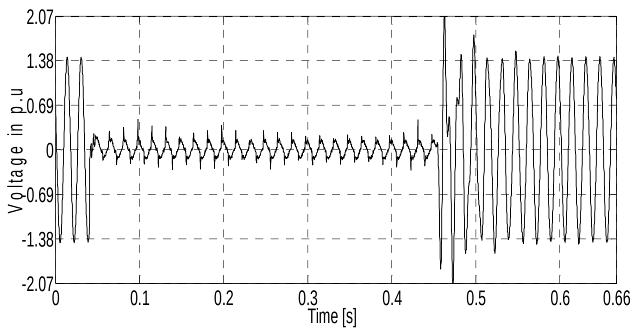
The true positives rate (*TPR*) is the efficiency with which the algorithm correctly classifies the disturbance, according to the cause (expulsion fuse, the current limiting fuse or no fuse) For example, as shown in Table III with the disturbances expulsion fuse, the *RTP* indicates that correctly classified disturbances make up 86,5 % of the entire set of events.
The false positives rate (*FPR*) indicates the degree of confusion of the methodology for assessing the cause of a disturbance. Thus, in the case of disturbances caused when the limiting fuses is zero, and it is interpreted that the algorithm is not assigning this cause to different events that are not.

F. Results analysis

Some results and operational details regarding the methodology are presented. Three different types of disturbance are presented: those that caused by current-limiting fuse operation (simulated record), those caused by expulsion fuse operation (real record) and those caused by capacitor bank energizing (simulated record).

F.1 Expulsion fuse operation

The next record was taken from a real substation's database, regarding a disturbance caused by expulsion fuse operation.
According to Table IV, 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 *(*Δ*TP*=11,6*)* and its fault time was close to a zero-cross (*NZC*≈0). Also, effective signal disturbance waveforms were rectangular-shaped (voltage) because *RSC* were close to the unit (*RSC*=1,4).



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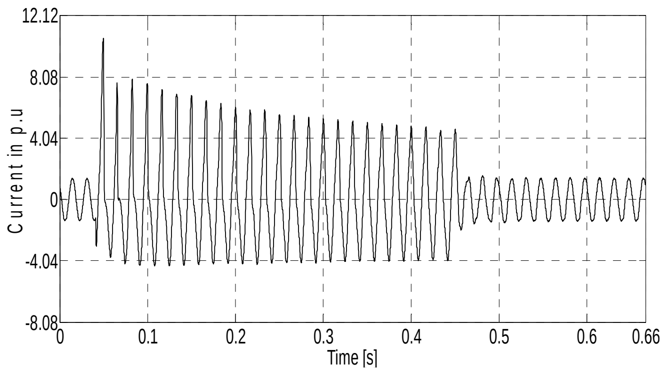


b)

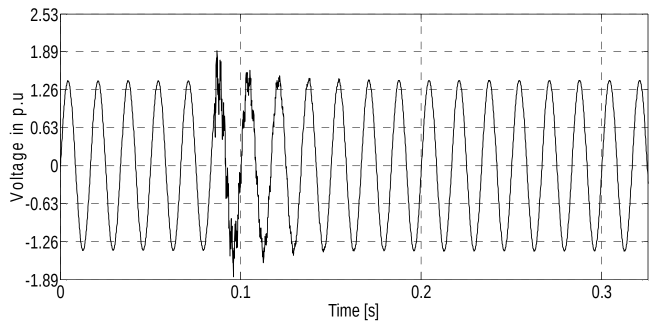
Figure 7. Disturbance caused by expulsion fuse operation. a) Voltage [p.u] b) Current [p.u]

TABLE IV
DESCRIPTOR FOR A DISTURBANCE CAUSED BY EXPULSION FUSE OPERATION

DESCRIPTOR	*VALUE*
RVI	*1*
ΔTP	*11,6*
NZC	*0,07*
RSC	*1,4*

F.2 Capacitor energizing

The methodology was tested using a simulated record of capacitor bank energizing [15]. The methodology ruled out that an expulsion fuse operation was the cause, due to a value zero for *RVI* and also for *RSC* (see Table V).



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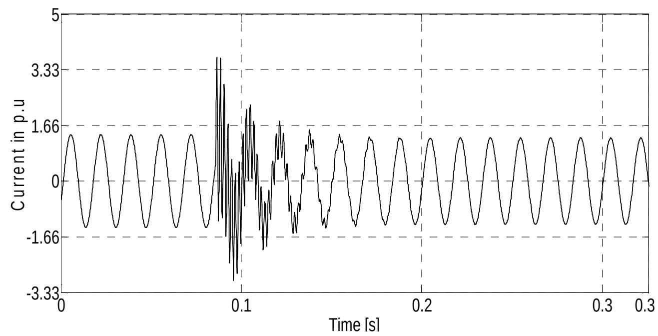

b)

Figure 8. Disturbance caused by capacitor bank energizing. a) Voltage [kV] b) Current [A]

TABLE V
DESCRIPTOR FOR A DISTURBANCE CAUSED BY CAPACITOR BANK ENERGIZING

DESCRIPTOR	*VALUE*
RVI	*0*
ΔTP	9,3125
NZC	*0,2813*
RSC	*0,032*

V. 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 proposed has descriptors which were selected as relevant on 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.

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

VI. ACKNOWLEDGEMENTS

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