Characterising power quality disturbances resulting from current limiting fuse operation

Caracterización de Perturbaciones Eléctricas Causadas por la Operación de Fusibles Limitadores de Corriente

N. Ortiz S[1], J. Blanco S[2], G. OrdoñezP[3], V. Barrera N[4]

***Abstract*— This article presents novel and easily implemented tools for characterising electrical disturbances originated by fuse operations. A methodology is described that (with the use of some descriptors) led to identifying electrical disturbances of this kind. The algorithm's decision thresholds were estimated using machine learning techniques. This work was aimedat providing new tools for assessing power quality, characterising and extracting information from voltage and current records obtained from monitoring distribution systems. MATLAB was used for validating this methodology, receiving voltage and current records of simulated events in ATP-EMTP and also real events as input.**

***Keywords*—Electromagnetic disturbances, current limiting fuses, descriptor, variance multi-variant analysis (MANOVA)**

***Resumen*— Este artículo presenta nuevas herramientas de fácil implementación para la caracterización de perturbaciones eléctricas originadas por la operación de fusibles. Se describe una metodología que, mediante el uso de algunos descriptores, permite la identificación de esta clase de perturbaciones eléctricas. Los umbrales de decisión del algoritmo son estimados mediante técnicas de aprendizaje automático. Este trabajo tiene como objetivo proporcionar nuevas herramientas para evaluar la calidad de energía, caracterizando y extrayendo información de los registros de tensión y corriente obtenidos a través de la monitorización en los sistemas eléctricos de distribución. La validación de la metodología se realiza en MATLAB tomando como señales de entrada algunos registros de tensión y corriente obtenidos por simulación en ATP-EMTP y utilizando también algunos registros de eventos reales.**

***Palabras Claves*— Perturbaciones electromagnéticas, fusibles limitadores de corriente, descriptores, análisis multivariante de la varianza (MANOVA).**

[1]N. Ortiz S is student in electrical engineering from the Industrial University of Santander (UIS) Colombia. He belongs to the Research Group on Electric Power Systems GISEL. Email: itan_leon@hotmail.com

[2]J. Blanco S received the B.Sc. degree in electrical engineering from the Universidad Industrial de Santander (UIS), Bucaramanga, Colombia, in 2009. Currently, he is pursuing master studies in electrical engineering at Universidad Industrial de Santander. Email: jablas_19@hotmail.com

[3]G. Ordoñez P received the B.Sc. degree in electrical engineering from the Universidad Industrial de Santander (UIS), Bucaramanga, Colombia, in 1985. He received his PhD in Industrial Engineering from the Universidad PontificiaComillas, Madrid, Spain, in 1993. Currently, he is Titular Professor of the School of Electrical Engineering at the Universidad Industrial de Santander (UIS-Colombia). E-mail: gaby@uis.edu.co.

[4]V. Barrera N received the B.Sc. and M.Sc. degrees in electrical engineering from the Universidad Industrial de Santander (UIS), Bucaramanga Colombia, in 2003 and 2006, respectively. Barrera is with (IIiA) Institute of Informatics and Applications of the University of Girona (UdG), Catalonia. He is PhD student in UdG and member of C4.112 CIGRE working group "Guidelines for Power Quality Monitoring". Email: victor.barrera@udg.edu, http://eia.udg.edu/~vbarrera

1. INTRODUCTION

The power quality concept was introduced in the electric power sector, there has been great interest in studying electrical disturbances affecting service quality. There is great current interest in studying electromagnetic disturbances affecting power quality. Recent investigations have studied different types of disturbance and their associated causes for improving power quality.

Electromagnetic disturbances and their consequent economic impact have prioritised their analysis by the electricity sector, having special interest for utilities. The actual regulatory framework states that these companies have to implement monitoring equipment in power systems to record electromagnetic disturbances and are required to report power quality-related indicators. Progress must thus be made in this kind of research.

Electromagnetic disturbance-related research is interested in identifying the localisation of and causes associated with a specific event. These causes are often related to internal network anomalies or external faults.

Protective device use and coordination are thus used to prevent severe damage to an electrical grid due to such anomalies or faults; they operate in a characteristic way, according to the type of protection and pertinent operating principle. Fuse protection is one of the most widely used in power systems due to its operation simplicity, protection features and low cost compared to other protection devices.

Some phenomena have an impact on power qualityduring fuse operationwhich is reflected in voltage and current waveform distortions which can be recorded by monitoring equipment. There has been increasing interest in their study because of this, and the continuing emergence of equipment which is increasingly sensitive to such phenomena. Major developments in voltage sag and swell characterisation have been documented in the literature by such authors as Bollen (Bollen and Zhang, 2000; Bollen and Zhang, 1999), but few publications have been related to short-term perturbation analysis, such as current-limiting fuse operation.

Kojovic and Williamshave highlighted the effects of operating current limiting fuses by researching and testingvoltage and current wave distortion during fuse operation in the presence of faults (Kojovic*et al.*, 1997; Kojovic*et al.*, 2002; Kojovic*et al.*, 1998). Allen and Chopra's study (2010) is worth mentioning because they identified and quantified the characteristics of current-limiting fuse operation in voltage and current waves recorded downstream of the measuring point.

To continue this line of study and summarising the results presented in the aforementionedpublications, this paper develops and proposes a methodology based on characterisingwaveform perturbations.

2. FUSE OVERVIEW

A fuse is a simple and reliable safety device which has great advantages compared to other protective devices due to its ease of application and the ability to protect people and equipment. It is a current sensitive device consisting of a conductor element having a small cross-section which is usually surrounded by an arc-extinguisher and a heat sink encased in a cartridge (usually cylindrical) and equipped with terminal connections.

The fuse element is contained inside a cartridge, normally consisting of a wire or metal strip with a reduced section and is calibrated according to its current capacity. There is high current density in this metallic section for a given value and for a preset time, producing the melting of the element and the opening of the circuit which it is protecting. A lead-based alloy is usedfor fuse elements in the case of low voltages and currents, and a tape-based copper or aluminium alloy in the case of higher currents.

Its main function as a protective device is to interrupt a circuit when there are high currents, especially concerning overload and/or short circuits, andthe ability to withstand the transient recovery voltage that occurs subsequent to a fault being cleared.

Most fuses are specified according to their current, voltage rating and interrupting capacity. Nominal current indicates the current that can flow through the device without melting it or exceeding the temperature limit. Nominal voltage specifies the maximum voltage that can be applied to a fuse's terminals and interrupting capacity defines the maximum short circuit current that a fuse can safely interrupt. If a fault current is much greater than a fuse's breaking capacity, then an explosion may occur when operating, due to high pressure and electromagnetic stress. According to its breaking capacity, installation location and cost, it is possible to select the type of fuse in relation to electrical system requirements.

This work considers current-limiting fuses. A current-limiting fuse is a fast-acting device, having less than a half-cycle fault current interruption time introducing high resistance intoa circuit. Some distortions in voltage and current waveforms are shown in Figures 1 and 2.

The fusible element, whose length is greater than the expulsion fuse and is located within silica sand to focus the arc (Angelopoulos, 1991), raises pressure along the fuse element and produces a momentary increase in resistance, limiting fault current, thus reducing operation time to a value considered in the first half cycle of the current wave (Wright and Newbery, 2004, pp. 38).

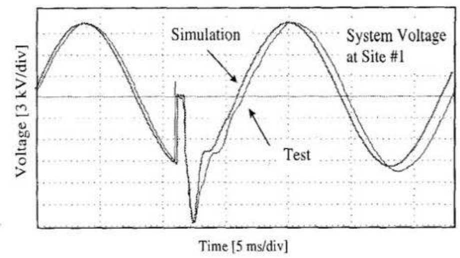


Figure 1. Voltage distortion caused by current-limiting fuse operation (Kojovic*et al*., 1998).

3. FUSE MODELLING AND SIMULATING ITS OPERATION

A current-limiting fuse was modelled as a nonlinear resistance according to Kojovic and Williams (Kojovic*et al.*, 1998). The two main parameters taken into account in its modelling were the fuse's melting point I^2t and the fuse's non-linear resistance characteristics after melting open. The implemented model was taken from a 8.3 [kV], 20 [A]current-limiting fuse.

This model was implemented in ATPDraw and simulated on two test circuits whose records were obtained for characterising the disturbances and for future tests of the methodology. A 34-node system and a 13-node system (Kersting and Dugan, 2000) were used in the simulations.

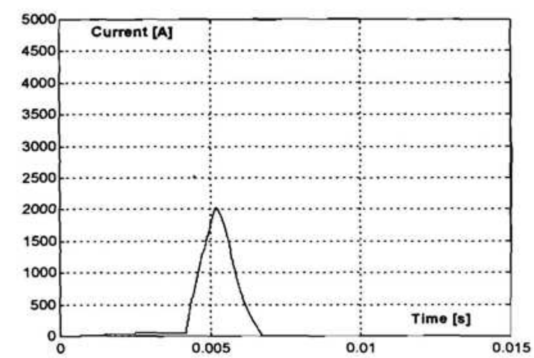


Figure 2. Current peak for operation of the current-limiting fuse (Kojovicand S. Hassler, 1997).

4. METHODOLOGY AND IMPLEMENTATION

The following sections describe relevant aspects of each stage in developing and elaborating the methodology. According to waveform disturbance types, analysed in MATLAB, different descriptors were proposed and explained. These waveforms corresponded to simulated events in ATP-EMTP, as mentioned in section 3.

Applying a multivariable statistical analysis for obtaining the relevance factor for every descriptor and selecting its decision threshold according to automatic learning methodologies is presented later on, as well as the methodological design and some tests on different disturbances previously identified for its validation.

A. *Descriptor formulation*

Descriptor formulation was based on disturbance waveforms, taking the characteristics identified in (Allen *et al.*, 2010) as a starting point, i.e. event duration, disturbance starting and finishing angles, overcurrent slope rise and slope fall and fault / pre-fault current ratio. A group of descriptors was proposed for measuring these characteristics.

A.1 Instant triangular shape coefficient (iTSC)

This descriptor was defined as instant current signal triangular form coefficient. It was proposed to estimate whether current waveform during a disturbance had a triangular form. It was originally proposed by Blanco and Jagua(2009, pp. 39) for RMS values. If current is different to current-limiting fuse operational value, then *iTSC* will report small values close to zero, because the electrical current pattern is different to that of a triangle.

Instant current length is compared to the length of one side of a reference triangle to quantify this categorisation; the vertex is equal instant current pre-fault, post-fault and maximum or minimum value recorded during a disturbance (Figure 3). In other words, it measures the degree to which overcurrent value sequence pattern resembles the reference triangle's sides. The following factors were estimatedfor calculating*iTSC*:

A.1.1 Similarity coefficients (CC and *CS):CS*was the difference between the side having a positive slope and current length was calculated from the pre-fault point (i_0) to the sample containing maximum instantaneous overcurrent (i_{max}). *CC*was the difference between the triangle's side having a negative slope and current length was between i_{max} to post-fault current (i_1).
The mathematical expression for current length was:

$$\ell_{s,c} = \sum_{i=2}^{n-1} \left(\sqrt{((1/n)^2 + (i(n_{i+1}) - i(n_i))^2)} \right) \quad (1)$$

where*n* was the total number of samples recorded during each current.

$$CS = \left| \frac{\ell c_p - \ell_s}{\ell c_p} \right| CC = \left| \frac{\ell c_n - \ell_c}{\ell c_n} \right| \quad (2)$$

whereℓc_p and ℓc_nwere the reference triangle's positive and negative slope sides.

*A.1.2.Limitation coefficient (LC):*This coefficient examined the percentage of currents points appearing outside the reference triangle. This percentage referred to the total number of samples in a record (n).

$$LC = \frac{n_{out-\Delta}}{n} \quad (3)$$

$n_{out-\Delta}$was the number of samples where instant current value appeared outside the reference triangle.

The *instantaneous triangular shape coefficient* was mathematically defined with these coefficients:

$$iTSC = 1 - (CC + CS + LC) \quad (4)$$

Hence, it would be expected that the $iTSC$ descriptor had values close to one for current-limiting fuses. The same analysis was performed for disturbances present during the negative semi-cycle taking the event sequence'sabsolute value.

A.2 Increased zero-sequence impedance (IZO) and increased negative-sequence impedance (IZ)

Descriptors IZ0 and *IZ*$^-$were used to calculate the degree of load unbalance. A variation of this kind of impedance is typical on the load output due to operating protection devices, i.e. fuses.
IZ0 and *IZ*$^-$ were defined as the difference between zero sequence impedance integrals before and after a disturbance.

$$IZ0 = Z0_{pos-fault} - Z0_{pre-fault} \quad (5)$$

$$Z0_{pre,pos-fault} = \sum \frac{Z_0(t)}{Z_{pre,pos-fault}} \quad (6)$$

$Z0_{pre,post-fault}$wascalculated during two cycles before and after a disturbance and was the sum of the magnitudes of zero sequence impedances ($Z_0(t)$) in p.u of the pre-fault and post-fault fault at each instant of time.
With this result the load output could be identified after a fault, thereby becoming a fuse operation indicator.

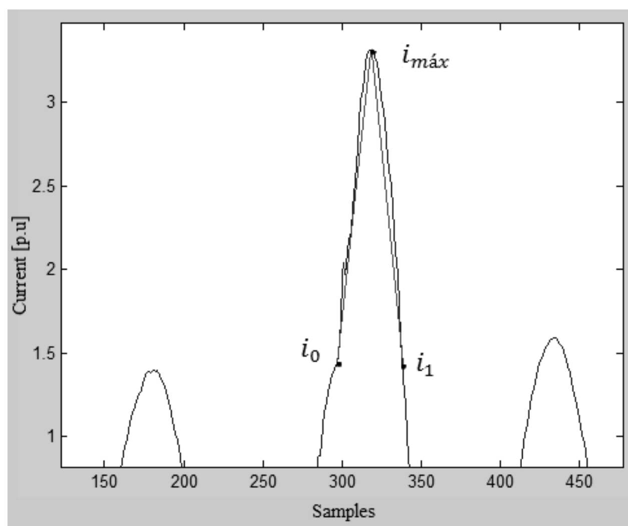


Figure 3.Triangular shapedcurrent peak

A.3 *Disturbance time delta* (ΔTP)

Descriptor ΔTP was defined as the number of samples between the disturbance's final and initial points, divided by the total number of samples per cycle.

$$\Delta TP = \frac{n_{final} - n_{initial}}{n_{cycle}} \quad (7)$$

To determine the initial and final points of an event, decomposition was executed by wavelet transform coefficients (WTCs) according to Vega (2007); such decomposition was done by the Bior 3.9 family.

The detail coefficients vector (CD) was then analysed. This vector presented points on the signal where sudden changes appeared. Sample selection was performed, taking into account points of the CD vector exceeding the mean value of 3 standard deviations.

$$Up = |CD| + 3 * \sigma(CD) \quad (8)$$

This is represented in Figure 5 as the horizontal line, where Figure 4 is the original signal. The initial point was defined as the sample corresponding to the first intercepted peak by the Upline, observed from left to right and the final point was defined as the sample corresponding to the first interception between the Upline and the first peak, but observed from right to left.

A.4 Instant current upslope and downslope (iPI^{+}andiPI^{-}):

Descriptors iPI^{+}andiPI^{-} estimated the ratio of instant current growth and decay during disturbance time and were defined as the slope of linear regression calculated for current values between i_0 - i_{max} foriPI^{+} and i_{max} - i_1 foriPI^{-}.

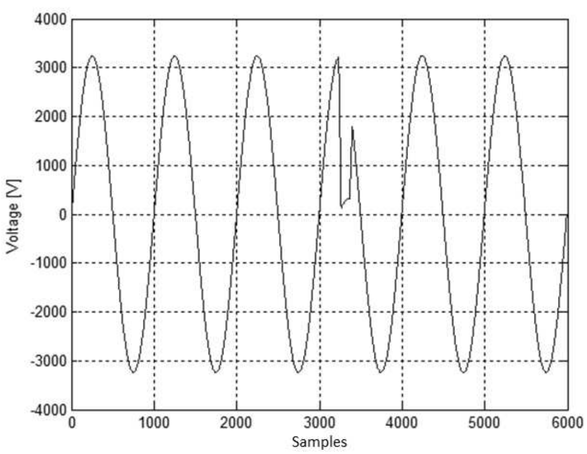


Figure 4. The time domain signal

Important information about the transient state of the event could be extracted with these descriptors and fuse operation with other short-duration faults could be ruled out. Electrical current upslopes and downslopes were estimations of fuse behaviour during melting and arcing time during operation.

A.5 Instant voltage fall percentage (%iVF)

Instant voltage fall percentage refers to the degree of voltage reduction during aparticular disturbance.

$$\%iVF = 1 - \left(\frac{v(n)_{disturbance}}{v(n)_{replica}}\right)_{mean} \quad (9)$$

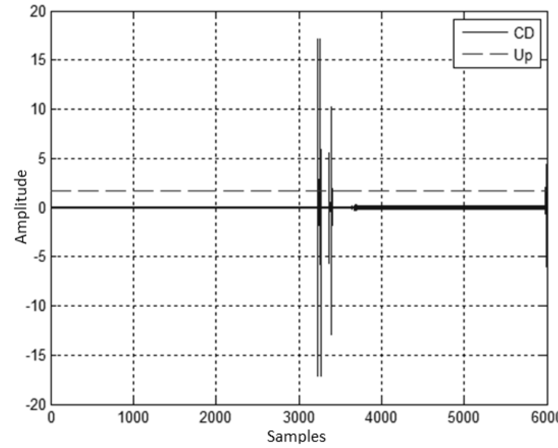


Figure 5. Detail coefficients by wavelet transform Bior 3.9

An identical voltage signal was constructed to that of the original pre-fault datafor such calculation and the mean value of the ratio between both voltages was calculatedwith the samples corresponding to the disturbance.

Consequently, events having 40% to 60%reduced instant voltage corresponding to fuse operationstatistical values could be identified with this descriptor.

A.6 Current ratio (I_{RATIO})

This descriptor determines the overcurrent values reached during the first disturbance which compared to other values reached by the current-limiting fuse offers orientation regarding fuse operation identification. It is defined as:

$$I_{RATIO} = \frac{i_{fault}}{i_{pre-fault}} \quad (10)$$

wherei_{fault} and $i_{pre-fault}$were such current'speak values.

So $I_{RATIO}$was the ratio between the peak current attained during the disturbance and pre-fault peak current.

A.7 Dissipated energy (I2t)

The *I2t*descriptor was used to estimate the amount of energy dissipated by afusewas defined as the integral of the fault current squared and estimated during the event time.

$$I2t = \int_0^t i^2 dt = \sum i^2(n) \quad (11)$$

This descriptor differentiated the disturbances caused by expulsion fuses and those caused by current-limiting fuses. Expulsion fuses dissipate energy over 10,000 [A^2s] and current limiting ones dissipate below this amount (Kojovic*et al.*, 1998).

A.8 Instant rectangular shape coefficient (iRSC)

TheiRSC descriptor is proposed as an estimator for calculating voltage signals' disturbance shape, which is normally presented as a rectangular shape.

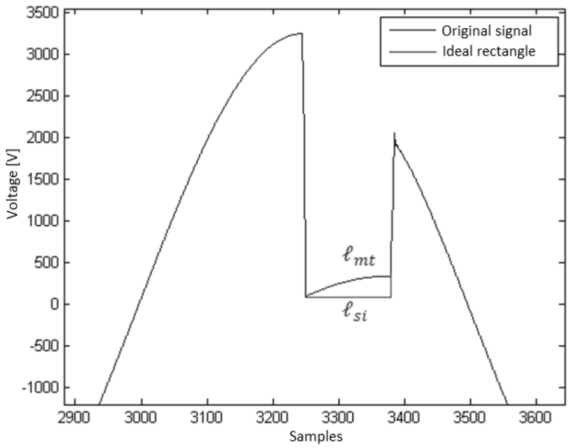


Figure 6. Real voltage notch ℓ_{mt} and ideal voltage notch ℓ_{si}

This descriptor was intended to obtain the rectangular tendency regarding voltage values during fuse operation.

It was calculated by comparing the lengths of the rectangle's base (taking an ideal square as reference) formed by initial and final samples' values concerning the disturbance and the least absolute value recorded during such event. The least absolute value was considered due to the probability that disturbance could occur on a positive or negative semi-cycle. Reference rectangle base length was defined as:

$$\ell_{\text{si}} = n - 1 \quad (12)$$

ℓ_{si}: $Maximum\ length\ of\ the\ ideal\ signal$
n: $total\ samples\ number\ during\ the\ disturbance$

The length of the instant values on the voltage notch was defined as:

$$\ell_{mt} = \sum_{i=2}^{n-1} \sqrt{((1/n)^2 + (v(n_{i+1}) - v(n_i))^2)} \quad (13)$$

ℓ_{mt}: $Voltage\ notch\ length$

With these lengths, the instant rectangular shape coefficient could be mathematically defined as:

$$iRSC = \frac{\ell_{mt} - \ell_{si}}{\ell_{si}} \quad (14)$$

A.9 ±fuse operation insertion angle (FOIA)

This descriptor represented voltage signal phase angle when fuse operation began. This descriptor was proposed for voltage waveforms and not for current waveforms because current signals are more likely to be distorted by high frequency components producing unwanted zeros.

The operation angle was measured from the zero-cross prior to the disturbance until the instant value when an event began.

The insertion point of the fault in a signal must be identified to calculate the descriptor, determining whether it occurred on a positive or negative semi-cycle and estimating the angle.

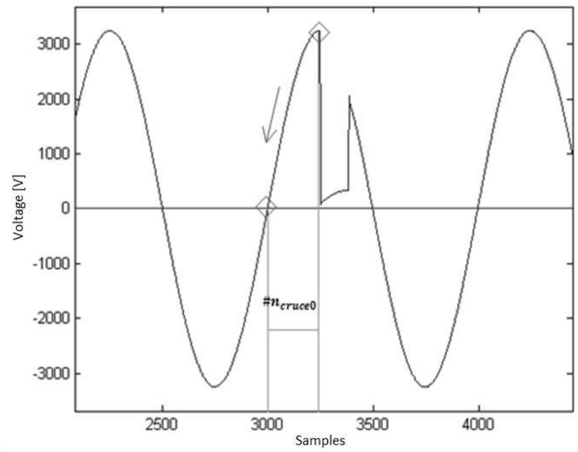


Figure 7. Fuse operation angle voltage

The number of samples between the two reference points was then determined. The number of samples was counted from the initial fault point, counting backwards until a sign change was detected, thereby indicating a zero-cross.

According to the initial event's semi-cycle, the descriptor value was:

$$+FOIA = \frac{(\#n_{cross_0}) * 360}{n_{cycle}} \quad (15)$$

$$-FOIA = \frac{\left(\frac{n_{cycle}}{2} - (\#n_{cross_0} + 1)\right) * 360}{n_{cycle}} \quad (16)$$

n_{cycle}: $Number\ of\ samples\ during\ a\ cycle$

A.10 the nearest zero-crossing (NZC)

After a disturbance has appeared, it is important to identify the instant when it disappears due to fault clearing, taking semi-cycles' final instants (zero-crosses)as reference points.

The *NZC*descriptor estimated fault clearing point proximity to the nearest zero-cross. It would thus have been determined whether the disturbance was present regarding a different current value than normal waveformzero-crossing, this being the main characteristic of current-limiting fuses'fast action.

The*NZC* descriptor calculated the number of samples between disturbance final point and the zero-cross nearest to that point. A similar procedure to that presented in section A.9 was followed, the difference being that in this descriptor the number of samples between the zero-crosses before and after the final point of the event were recorded. The descriptor value was the least of the two distances divided by the total number of samples per cycle.

B. *Multivariate analysis of variance (MANOVA)*

A multivariable statistical analysis was performed after applying a set of 79 current and voltage signals (obtained by simulation and real electrical systemrecords) to establish the previously described descriptors' effectiveness and the degree of relevance of each in identifying current and voltage events caused by fuse operation. These signals were identified and classified into three classes (according to the type of cause):

capacitor bank energising, current-limiting fuse operation and expulsion fuse.

Multivariable analysis verified the existence of groups or classes in the data,i.e. it sought whether there were clouds corresponding to fuse-related disturbances (current-limiters and expulsion) and capacitors in the descriptors (variables) space. Significant descriptors were thus identified by applying MANOVA.

MANOVA's purpose was to explore how independent variables affected dependent variables' behaviour (Barker and Barker, 1984), i.e. the degree of influence regarding the event in each characteristic revealing the importance of each descriptor regarding an event's origin (limiting fuse, expulsion fuse, capacitor bank energising).

For example, current-limiting fuse operation was considered as an independent variable and the descriptors so formulated were dependent variables.

ParameterR^2-*corrected* (see Table 1, 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^2values (corrected close to the unit) indicatedgreater relevance regarding the origin of a disturbance. Descriptors were selected which had the greatest degree of influence, those having R^2-*corrected* $\geq$ 0.5values.

According to this criteria, descriptors *iTSC*, ΔTP, iRSCand*NZC*were selected as relevant descriptors for electromagnetic disturbance characterisation based on current-limiting fuses.

Table 1 presents a list of the descriptors explained in this section and their corresponding R^2index.

Table 1. Proposed descriptors and their relevance according to a statistical analysis

Descriptor	Definition	R^2
$iTSC$	Instant triangular-shaped coefficient	0.639
ΔTP	Disturbance time delta	0.727
iPI^+	Instant overcurrent upslope	0.002
iPI^-	Instant overcurrent downslope	0.023
$\%iVF$	Instant voltage fall percentage	0.046
i_{RATIO}	Instant current ratio	0.036
$I2t$	Dissipated energy	0.035
iRSC	Instant rectangular-shaped coefficient	0.586
$\pm FOIA$	Fuse operation insertion angle	0.123
NZC	The nearest zero-crossing	0.717
$IZ0$	Increased zero-sequence impedance	0.100
IZ-	Increased negative-sequence impedance	0.046

C. *Selecting the decision thresholds*

Selecting decision thresholds was the search forsuitable values so that descriptors could distinguish between different causes and prevent overlapping disturbance grouping according to cause. 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 (Clark and Boswell, 1991).Every iteration looks for a set of descriptors covering a large number of examples in a specific class and just some from another classes so this could be used to make a reliable prediction of the class containing the covered examples.

Consequently, and in order to avoid fake data from CN2, the heuristic of Laplacian estimate of mean error was used (Peter and Robin. 1991).

Table 2 presents the selection rules obtained.

Table 2. Extracted rule set using cn2 induction algorithm

Rule	Cause assignation
If ΔTP $\leq$ 0.5313 and (1.721<iRSC$\leq$338 or 0.402<iTSC$\leq$1) and NZC>0.047	Cause=current-limiting fuse
If ΔTP >9.918 and NZC$\leq$0.047 and (iRSC$\leq$0 or iTSC$\leq$-65.662)	Cause=expulsion fuse
If 0.813<ΔTP<9.918 and NZC>0.047and (0<iRSC$\leq$13.17 and -65.66<iTSC$\leq$0.402)	Cause=capacitor bank energising

Table 2 shows that some of the obtained decision rules implied causes which were not studied by this article;such rules would have allowed the discrimination of current-limiting disturbances from other causes. Some descriptors were identified which could be useful in studying these events.

D. *Methodology design*

Figure 8 presents the automatic identification of electrical disturbances caused by current-limiting fuse operation. Monitoring voltage and current were the input. Selected descriptors were then calculated and the results were used to evaluate case decision.

E. *Test cases and result analysis*

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

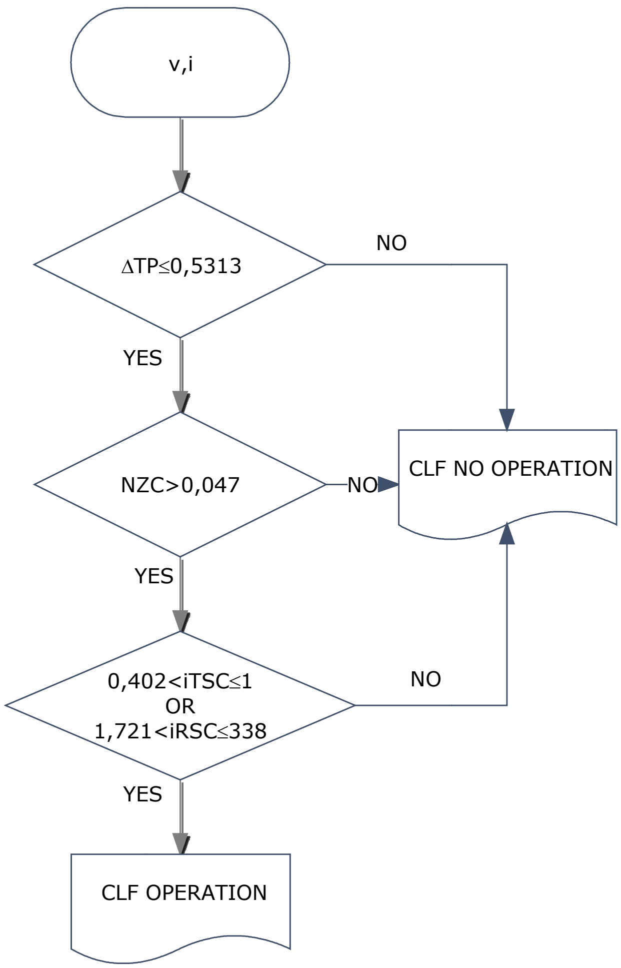
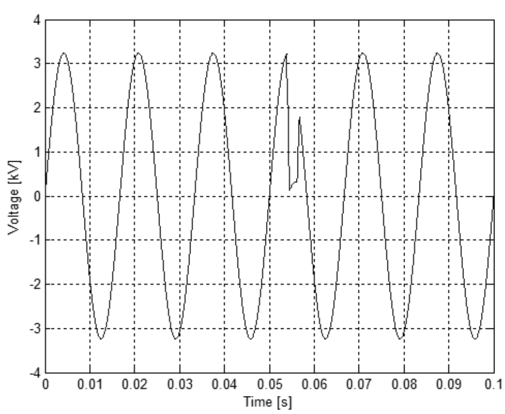


Figure 8. Framework for identifying disturbances related to current-limiting fuse operation

E.1 *Current-limiting fuse operation*



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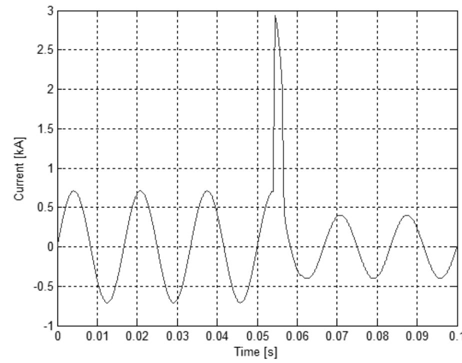


b)

Figure 9. Disturbance caused by current-limiting fuse operation a) voltage [kV]. b) current [kA].

Table 3. Descriptors for a disturbance caused by current-limiting fuse operation

DESCRIPTOR	VALUE
ΔTP	0.1663
iTSC	0.9571
iRSC	26.9974
NZC	0.1964

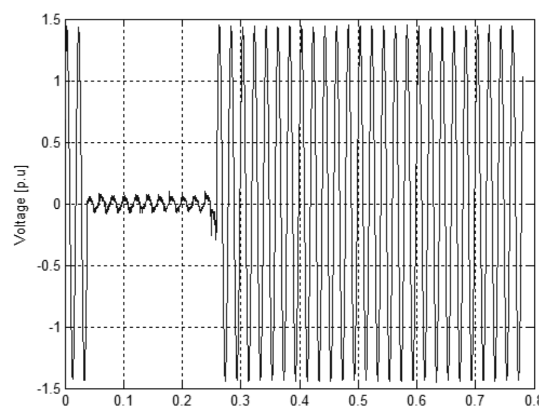
Table 3 presents descriptor values for a disturbance caused by a current-limiting fuse simulated in ATPDraw. ΔTP was less than 0.5313 and it could be considered as a possible source of a disturbance, given that ΔTP=0.1663 indicated that it represented a short disturbance.

The fault clearance was different from zero regardingone instant, the overcurrent peak was triangular-shaped (iTSC close to the unit) and the event was present in the voltage waveform as a rectangular-shaped notch (iRSC between threshold values).

So, according to the proposed methodology, this record was classified as a disturbance caused by current-limiting fuse operation.

E.2 Expulsion fuse operation

The next record was taken from a real substation'sdatabase regarding a disturbance caused by expulsion fuse operation.



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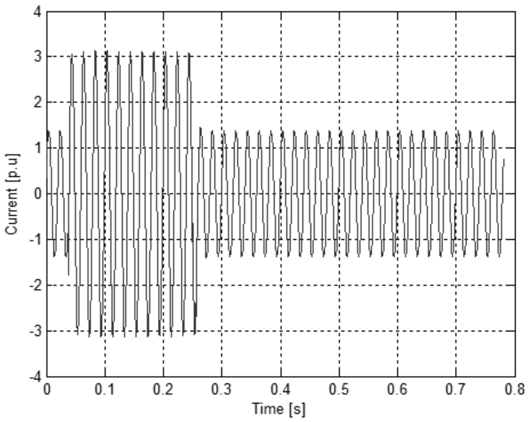


b)

Figure 10. Disturbance caused by expulsion fuseoperation a)voltage [p.u] b) current [p.u]

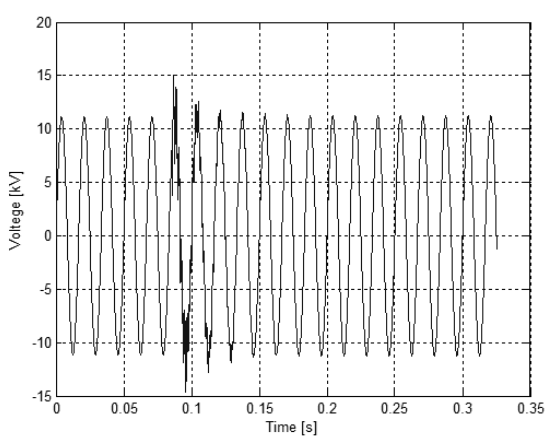
Table 4. Descriptors for a disturbance caused by expulsion fuse operation

DESCRIPTOR	VALUE
ΔTP	11.0625
iTSC	-46.5032
iRSC	-0.9894
NZC	0.0781

According to Table 4, it was concluded that the disturbance was not caused by current-limiting fuse operation (Figure 8) because its duration was a semi-cycle (ΔTP way over the unit). Also, instant signal disturbance waveforms were not triangular-shaped (current) or rectangular-shaped (voltage) because iTSC and iRSCwere less than zero and fault time was close to a zero-cross (*NZC*≈0).

E.3 Capacitor energising.

The methodology was tested by using a simulated record (Santos *et al.*, 2001) of capacitor bank energising.
The methodology ruled out that the cause was a current-limiting fuse, due to the high ΔTP value (see Table 5).



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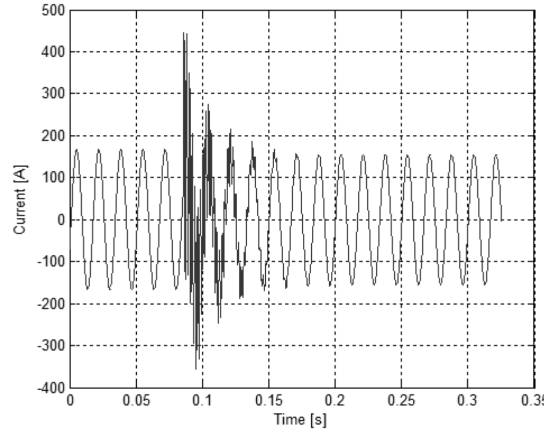

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Figure 11.Capacitor bank energising a)voltage [kV]. b) current [A].

Table 5. Descriptors of a disturbance caused by capacitor bank energising

DESCRIPTOR	VALUE
ΔTP	9.3125
iTSC	-38.41782
iRSC	544.1908
NZC	0.2813

5. CONCLUSIONS

A methodology has been proposed for the automatic detection of events caused by operating current-limiting fuses.
The characterisation of events caused by current-limiting fuses was based on the selection of a set of descriptors for quantifying relevant disturbancecharacteristics. Combining statistical tools with previous analysis of input registers led to developing descriptors which were evaluated to obtain their effectiveness. Thresholds decisions were estimated by using data mining techniques. This methodology was validated with a set of real and simulated events.

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