CLASSIFICATION OF SHORT DURATION FAULTS (VOLTAGE SAGS) IN TRANSMISSION AND DISTRIBUTION POWER SYSTEMS

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Abstract:

Two techniques for voltage sags characterisation and classification have been integrated. The objective is to assist monitoring systems in order to improve automatic recognition of faults. The abstraction of significant information (temporal and phasorial) is proposed to model faults based on simple descriptors instead of trying to obtain analytical models. A classification of such fault based on phasorial analysis is compared with the results obtained using a learning algorithm that allows an automated and unsupervised classification. Voltage sags waveforms are gathered in a 25kV substation. The goal is to locate the origin of such fault registered in the substation (transmission or distribution).

Keywords: Monitoring, abstraction, classification, power quality, phasorial analysis.

1. Introduction

Nowadays, the electricity dependence of industries, commerce and services has provoked the regulation of power quality. The objective is to reduce damages or misbehaviours to consumer devices and/or processes. Basically, four parameters are used to measure and characterise the supplied voltage waveform (sine wave of 50 /60 Hz): frequency, amplitude, shape and symmetry. However, from generators to customers, these parameters can suffer alterations that affect quality. The origin of such alterations can be the electrical facility operation, external agents or due to the operation of specific loads. This alteration of the sinusoidal wave is usually transmitted to the electrical system [1] and the responsibility of possible damages caused to customers is usually assigned to distribution companies. Consequently these are interested in monitoring their power sytems.

From monitoring point of view, power systems are complex systems basically due to three main points:

- They are distributed systems: Generation and consumption are interconnected through a highly meshed system of lines and transformation stations. This causes that events happened somewhere in the network are propagated through it.
- Power systems are hierarchically controlled and supervised. It is performed automatically in order to isolate damaged lines and to distribute the adequate amount of electricity to every client.
- They are highly coupled systems: Anytime and anywhere management and control of multiple generators and transmission systems are done to continuously supply the amount of energy to be consumed by every client an assuring the quality of this electricity. Consequently the system configuration changes continuously. Additionally, the system is operated by protective actuators, which automatically isolate damaged lines in case of detected faults.

This work is focused in monitoring faults registered in distribution (close to customer) in order to infer information related with the origin and location of the fault (fault diagnosis). Model based techniques can not be applied because the difficulties (the system is continuously being reconfigured) of having an accurate model (distributed parameters model). Therefore signal and knowledge based approaches have to be applied.

Two methodologies have been integrated in this paper in order to characterise a type of short duration faults (voltage sags): one of them is based on phasorial analysis (widely extended in the power systems community) whether the second is based on a classification (machine learning) of temporal descriptors extracted from the waveform. Fault classification is proposed as the first step to perform an on line diagnosis. Classification is necessary to define fault patterns to be recognised and used to infer the origin of such fault using a case based methodology ([2],[3]). Automatic classification of faults in power systems has not been widely treated and correct classification rates for the actual events are not as high as classification results used in areas such as pattern recognition, speech recognition, and so on ([15],[16]).

In next section the voltage sag characterisation based on symmetrical components is presented. In section 3, unsupervised classification based on temporal descriptors is described, and also this section is dedicated to conclude correspondences between phasorial and temporal based classifications. Finally some conclusions of the related work are given in section 4.

2. Voltage sag characterisation based on symmetrical components

The magnitude of the voltage sag is defined as the minimum rms value obtained during the event and its duration is the time interval between the instant when rms voltage crosses the voltage sag threshold (usually 90% of normal voltage) and the instant when it returns to normal level. All existing standard documents on voltage sags characterize voltage sag through one magnitude (remaining voltage or voltage drop) and one value for the duration ([4],[5],[6]). There are obvious limitations to this method as one e.g. neglects the phase-angle jump ([5],[7]) and the post-fault voltage sag [8].

The existing method of characterisation uses the lowest of the three voltages and the longest duration. An example of a three-phase unbalanced voltage sag is shown in Figure 1.

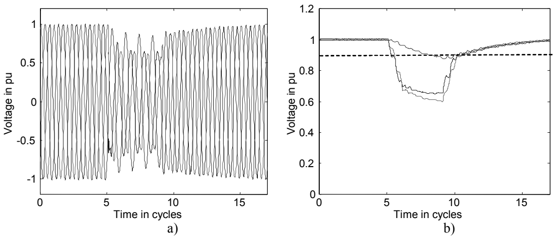


Figure 1 a) Three-phase unbalanced voltage sag. b) rms voltage.

2.1 Voltage sag characterisation approaches

Voltage sag characterisation is often part of the voltage characteristics / power quality in general. Using the lowest of the three voltages to characterize the voltage sag will result in erroneous results for both single-phase and three-phase equipment. An alternative technique proposed in [5], which enables a characterisation through one complex voltage, without significant loss of information. The method is based on the decomposition of the voltage phasors in symmetrical components [9]. The three (complex) phase voltages in an unbalanced (not all three phases have the same magnitude or 120º between them) system can be completely described through three component voltages, known as symmetrical components. Positive-sequence voltage $\vec{V}_1$, negative-sequence voltage $\vec{V}_2$ and zero-sequence voltage $\vec{Vo}$ are calculated from the complex phase voltages $\vec{V}_a$, $\vec{V}_b$ and $\vec{V}_c$ as follows:

$$\begin{bmatrix} \vec{V}_0 \\ \vec{V}_1 \\ \vec{V}_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} \vec{V}_a \\ \vec{V}_b \\ \vec{V}_c \end{bmatrix} \tag{1}$$

Where

$$a = -\tfrac{1}{2} + \tfrac{1}{2} j\sqrt{3}$$

An additional characteristic is introduced to enable exact reconstruction of the three complex voltages. The demonstration and formulation of this method can be consulted in [5].

From the voltage magnitude and the voltage phase angle for the three phases, a voltage sag type is obtained, and two additional characteristics: *characteristic voltage* (absolute value of the complex phasor indicating the severity of the sag) [1] and *PN Factor* (defined as the relation between the positive and negative-sequence source impedance). All three characteristics are complex voltages as a function of time. The magnitude of the characteristic voltage is the main characteristic [5].

2.2 Voltage sag types based on symmetrical components

The voltage sag type indicates which phases are involved in the event. The seven basic types are given in Figure 2. Balanced voltage sag (voltage sag type A) is due to an equal drop in the values of voltage in the three-phases. Unbalanced voltage sag (types C and D) is due to a drop but not all the three phases are equally involved. The C-types are voltage drops between two phases: type Ca is a voltage drop between phases b and c, type Cb between phases a and c, and type Cc between phases a and b. The D-types are voltage drops in one phase: type Da is a voltage drop in phase a, type Db in phase b, and type Dc in phase c.

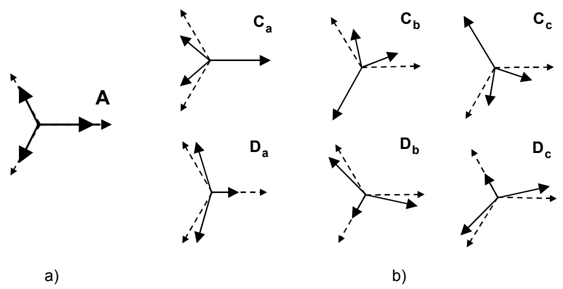


Figure 2. a) Three-phase balance voltage sag, b) six types of three-phase unbalanced voltage sags.

The characteristic voltage is the main indicator of the severity of the event. The absolute value (magnitude) of the characteristic voltage is comparable to the rms voltage for single-phase measurements and should be used to determine duration and retained voltage from three-phase measurements. The characteristic voltage is defined in such a way that it does not change when propagating through a transformer.

The PN-factor is defined from the positive-sequence and negative-sequence voltages to provide a complete set of characteristics next to characteristic voltage and zero-sequence voltage. The PN-factor indicates the unbalance of the event. For voltage sags due to single-phase and phase-to-phase faults the PN-factor is equal or somewhat less than the pre-event positive-sequence voltage. The difference is due to the dynamic effects of the load. Like the characteristic voltage the PN-factor is defined in such a way that it does not change when propagating through a transformer.

The voltage sag type is found from the angle between positive-sequence voltage $\vec{V}_1$ and negative-sequence voltage $\vec{V}_2$. The classification method is described in more detail in literature [5].

$$k = \text{round}\left(\frac{\text{angle}\left(\overline{V}_2, 1 - \overline{V}_1\right)}{60^{\circ}}\right) \tag{2}$$

where,

k=0: type Ca k=1: type Dc k=2: type Cb

k=3: type Da k=4: type Cc k=5: type Db

Knowing the voltage sag type, the negative-sequence voltage can be calculated back to the corresponding value for prototype voltage sag:

$$\vec{V}_2' = \vec{V}_2 e^{-jk60^{\circ}} \tag{3}$$

where, k is obtained according to (2) and the negative sequence voltage of the measured voltage sag. Characteristic voltage $\vec{V}$ and PN-factor $\vec{F}$ are obtained from:

$$\begin{aligned} \vec{V} &= \vec{V}_1 - \vec{V}_2' \\ \vec{F} &= \vec{V}_1 + \vec{V}_2' \end{aligned} \tag{4}$$

The voltage magnitude is defined as the absolute value of the characteristic voltage. The voltage phase angle as the argument of the characteristic voltage. The voltage sag type and the PN Factor are used as additional characteristics to classify registered voltage sags from a real plant (Sections 2.3 and 2.4).

2.3 Application in a 25kV-Electrical substation

Spanish Electrical Facility (Endesa Distribution SL) has measured voltage sags in a 25kV distribution substation during a period of six months. From the recorded, 52 voltage sags are chosen to apply this method. They were separated in two subgroups according to the origin of the fault (transmission/distribution) and the previous algorithm was applied to them. The different types of three-phase voltage sag obtained are summarized in table 1.

	A	Ca	Cb	Cc	Da	Db	Dc
Transmission	6	3	5	5	7	8	2
Distribution	3	0	1	0	1	10	1

Table 1: Results of measured voltage sags classification

In this particular 25kV distribution substation system the 35% of voltage sag occurred are type Db, it aims to conclude that the phase b is the most affected.

2.4 Characteristic voltage and PNfactor as a fault location criteria

The decision to work with those phasorial descriptors fallows the idea proposed in the overview of voltage sag characterisation done in [5]. Where, it was found that the PN-factor is very close to unit in transmission systems and less than unity in distribution systems, due to the effect of induction motor load. In this application loads differs from such assumed in [5], instead of this kind of load are residential customers.

Experimentally the fallowing thresholds have been selected, after exploring the set of 52 registers. This phasorial analysis allows to distinguish between transmission and distribution, using the module of the characteristic voltage and PN-factor.

For transmission voltage sags: Unbalanced voltage sags with either *characteristic voltage* higher than (0.8) or absolute value the *PN-factor* lower than (0.9). Balanced voltage sags with *characteristic voltage* higher than (0.8).

For distribution voltage sags: Unbalanced voltage sags with either *characteristic voltage* lower than (0.8) or absolute value the *PN-factor* higher than (0.9). Balanced voltage sags with *characteristic voltage* lower than (0.8.).

Voltage sags	Vchar>0.8	Vchar<0.8	PNf>0.9	PNf<0.9
Transmission & Balanced	5	1	0	6
Transmission & Unbalanced	17	13	26	4
Distribution & Balanced	0	3	0	3
Distribution & Unbalanced	1	12	12	1

Table 2: Records of measured voltage sags

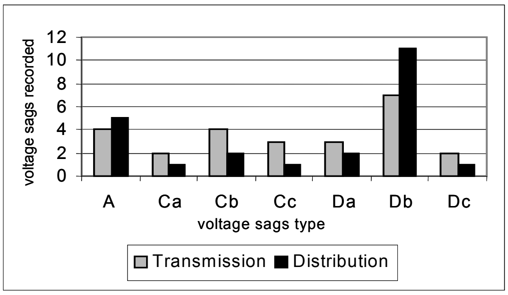


Figure 3: Voltage sags type versus Voltage sags recorded

As a result, 80% of the unbalanced sags and 90% balanced voltage sags were correctly classified. In the figure 3, the voltage sags type predominant is Db for distribution and transmission systems in such cases the classification uncertainty is maximum.

3. Voltage sag characterisation based on temporal descriptors.

This voltage sag characterisation is based on temporal descriptors of signals in conjunction with a "Learning Algorithm for Multivariate Data Analysis – LAMDA [11]", used as classification system. This algorithm is settled in order to obtain clusters of similar faults.

3.1 Learning Algorithm for Multivariate Data Analysis – LAMDA classifier.

Classification methods based on hybrid connectives combine both the pure numeric and the pure symbolic classification algorithms, taking profit of fuzzy logic and hybrid connectives ([10],[11]). LAMDA (Learning Algorithm for Multivariate Data Analysis) is proposed as a classification technique to obtain fault models [12]based on temporal descriptors. The following paragraphs resumes the classification principle used in LAMDA.

One object (X_i) has a number of characteristics called "descriptors". These descriptors are used to describe the object. Every object is assigned to a "class" in the classification process. Class (c_i) is defined as the universe of descriptors, which characterize one set objects (Figure 4). MAD (Marginal Adequacy Degree) concept is a term related to how similar is one object descriptor to the same descriptor of a given class, and GAD (Global Adequacy Degree) is defined as the pertinence grade of one object to a given class ([13],[14]) as in fuzzy membership functions ($m_{ci}(x)$).

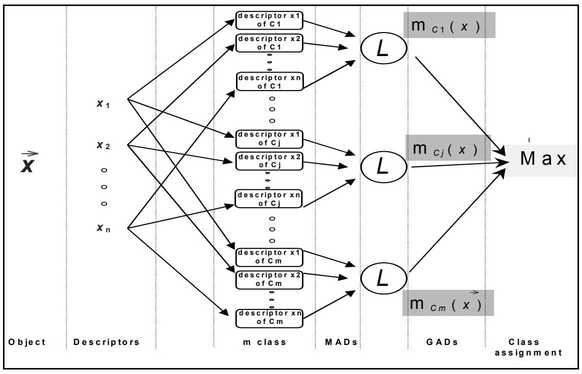


Figure 4. Basic LAMDA recognition methodology

Classification, in LAMDA, is performed according to similarity criteria computed in two stages. First MAD to each existing class is computed for each descriptor of an object. Second, these partial results are aggregated to get a GAD of an individual to a class. The former implementation of LAMDA included a possibility function to estimate the descriptors distribution [11] based on a "fuzzification" of the binomial probability function computed as (5):

$$MAD_{c,d} = \rho_{c,d}^{X_{i,d}} \; (1-\rho_{c,d})^{(1-X_{i,d})} \qquad (5)$$

Where

$\rho_{c,d} =$ Learning parameter (Ro) for class ***c*** and descriptor ***d***

$X_{i,d} =$ Descriptor ***d*** of individual ***i***

Other implementation, when the volume of the observed data is larger and close to Gaussian or semi-Gaussian distribution [11] is computed with the following marginal adequacy (6). In this work, MAD has been computed according to (6).

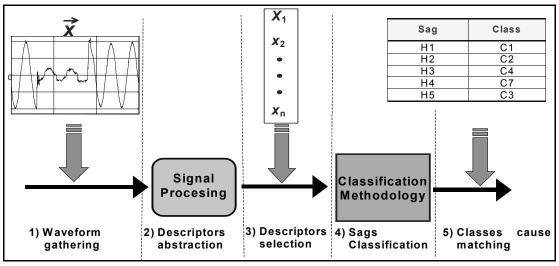
$$MAD_{c,d} = e^{-\frac{1}{2}\left(\frac{X_{i,d}-\rho_{c,d}}{0.15}\right)^2} \qquad (6)$$

GAD computation is performed as an interpolation between a t-norm and a t-conorm by means of the β parameter such that β = 1 represents the intersection and β = 0 means the union.

$$GAD = \beta T(MAD) + (1-\beta) S(MAD) \qquad (7)$$

3.2 Characterisation of voltage sags based on temporal descriptors.

Four steps compose the general methodology developed to perform the voltage characterisation based on temporal descriptors: waveform gathering, processing data, descriptors selection and sag classification (Figure 5).



Sag	Class
H1	C1
H2	C2
H3	C4
H4	C7
H5	C3

Figure 5. Functional steps for the identification process

Sag waveforms were associated with supplementary information related to causes and fault location (transmission /distribution). According to LAMDA these waveforms must be considered as objects characterised by a set of descriptors or descriptors. Two types of temporal descriptors have been selected: three phase and single-phase descriptors.

Three-phase descriptors (Figure 6):

i. *Three-phase sag magnitude (h3φ):* Defined as the maximum reduction of voltage in three-phase power system during the sag.

ii. *Three-phase sag duration (d3φ):* Defined, as the maximum time during the rms voltage in a three-phase power system, is lower to 0.9 p.u.

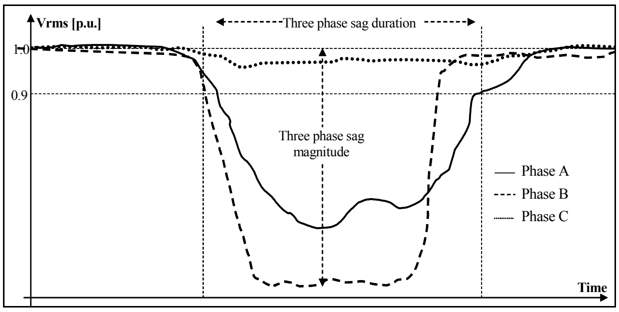


Figure 6: Three-phase voltage sags descriptors

Single-phase descriptors (Figure 7):

i. *Single-phase sag magnitude (h1φ):* Maximum voltage reduction of voltage in every single phase of the power system.

ii. *Single-phase sag duration (d1φ):* Maximum time during the rms voltage is lower to 0.9 p.u. in every single phase of the power system .

iii. *Single-phase minimum stage duration (msd1φ):* Time during the rms voltage remains in an α width band over the minimum voltage value. In this case α was selected as 2%.

iv. *Single-phase voltage fall slope (vfs1φ):* Slope at the first part of the single-phase voltage sag. It is computed using the voltage magnitude difference between 0.9 and the α width band over the minimum voltage value.

v. *Single-phase voltage recovery slope (vrs1φ):* Slope in the last part of single-phase voltage sag. It is computed in the same way as the single-phase voltage fall slope is.

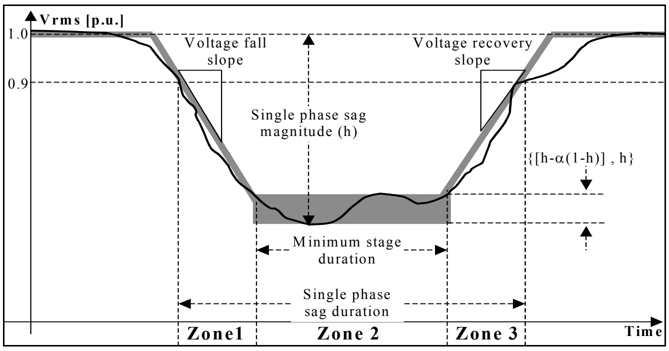


Figure 7: Single-phase voltage sags descriptors

The temporal evolution of voltage sag presents three different zones according to different temporal fault stages (Figure 7).

i. Zone 1: It defines the starting stage of the fault, which produces the voltage sag. The selected descriptors are: Three-phase voltage sag magnitude, all single-phase voltage sag magnitudes, and voltage fall slope in each phase.
ii. Zone 2: In this zone the fault is usually stabilized, and the protective relaying system is not causing any breaker trip to insolate the possible fault. The selected descriptors are: Three-phase voltage sag magnitude and duration, all single-phase voltage sag magnitude, all single-phase sag duration, and minimum stage duration for each phase.
iii. Zone 3: In this zone, the protective relaying system opens the breaker to insolate the fault, as a consequence the voltage come back to its normal value (1.0 p.u. aprox.). The selected descriptors are: Three-phase voltage sag magnitude, all single-phase voltage sag magnitude and voltage recovery slope for each phase.

Voltage sag classification obtained for zone 1 is directly related to fault type (single-phase to ground, three phase, and double-phase) and the possible electrical distance from the fault location to the place of voltage sag measurement. For zone 2, the resulting groups should be related to the protective system relaying operation (It also depends on the location of these devices). Finally, zone 3 allows distinguishing among different types of loads (motors, transformers, etc) and faults. It provides information related to the utility customers.

3.3 Classification results and analysis

This analysis considers the individual behaviour of the classification for every zone (individual analysis) and the behaviour of groups of sags according to the conjunction of the three zones (transversal analysis).

i. Individual (or zone) analysis

According to the classification performed in the first zone five different classes can be distinguished. The class 1 and 2, only appears in the data corresponding to the transmission system. The classes 3 and 5 are present in both, transmission and distribution power systems. The class 4, only appears in data corresponding to the distribution system. In the classification performed using data in zone 2, six classes appear. Resulting that classes 1, 2, 3 and 5 appear for data corresponding to both distribution and transmission system. The class 4 only appears once and corresponds to the transmission system. The class 6 appears twice and corresponds to distribution systems. Finally, in the last zone (zone 3) five classes appear and the following results are observed: The class 1 only appears in transmission system. The class 2 does not contain any data. The classes 3, 4 and 5 appears for data corresponding to both, transmission and distribution system. Table 3 summarises these results.

Voltage	Zone 1		Zone 2		Zone 3	
	Yes	Not	Yes	Not	Yes	Not
Transmission System	**1**(18.5%) **2**(22.2%) **3**(18.5%) **5**(9.26 %)	4	**1**(13%) **4**(1.85%) **2**(37%) **5**(3.7%) **3**(13%)	6	**1**(27.8%) **5**(1.85%) **3**(16.7%) **4**(20.4%)	
Distribution system	**3**(1.85%) **5**(9.26%) **4**(20.4%)	1 2	**1**(13%) **5**(5.56%) **2**(1.85) **6**(3.7%) **3**(7.41%)	4	**3**(24.1%) **4**(5.56%) **5**(1.85%)	1

Table 3: Resulting classes in the individual analysis for voltage sags in transmission and distribution systems

The presence or not for each individual class for data in transmission or distribution system and its percentage rate are also determined. The total amount of data of voltage sags corresponds to 38 (70.37%) voltage sags caused by faults in transmission systems and 16 (29.62 %) voltage sags caused by faults in distribution systems, all of these measured in a distribution substation.

ii. Transversal (or sag) analysis

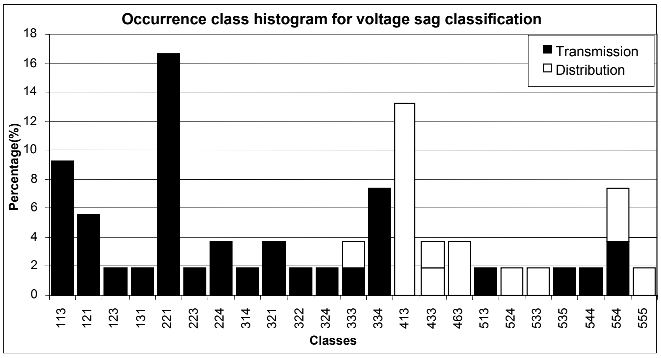


Figure 8: Transversal classification of voltage sags

This analysis considers the whole perturbation (sag) as a sequence of classes (obtained from every individual zone) e.g. class "123" means class 1 in the first zone, class 2 in the second zone and class 3 in the third one. Figure 8 resumes the results obtained divided in transmission and distribution faults and the same results are presented numerically in table 4.

Voltage level \ Presence	Yes				Not			
Transmission system	113 121 123 131 221	223 224 314 321	322 324 333 334	513 535 544 554	413 433	463 524	533 555	
Distribution System	333 413	433 463	524 533	554 555	113 121 123 131	221 223 224 314	321 322 324 334	513 535 544

Table 4: Transversal analysis for voltage sags in transmission and distribution systems

3.4 Concluding correspondences between phasorial and temporal based classifications

A comparison between type of sags defined by the phasorial analysis and the transversal analysis given by the classifier is represented in the Figure 9 and Figure 10 histograms.

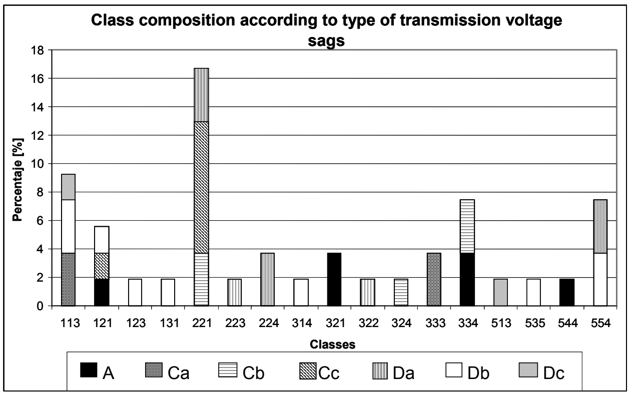


Figure 9: Class composition according to type of transmission voltage sags

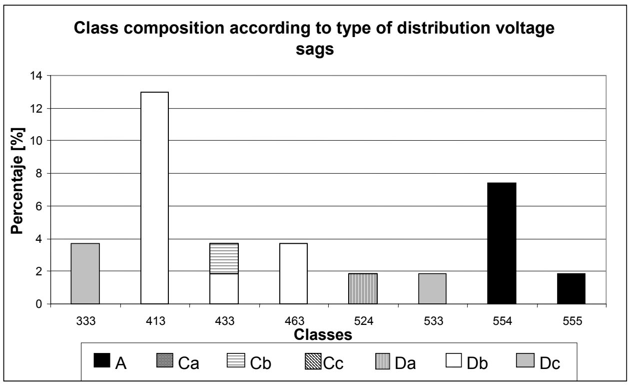


Figure 10: Class composition according to type of distribution voltage sags

These pictures show that the type voltage obtained from phasorial analysis in both transmission and distribution systems are strongly related to a specific class given by LAMDA. Type Cc is not present in distribution systems and is directly related with transmission class 221. A few percentages of voltage sags classes are related to more than one type of sag. In these cases, is not possible to identify a characteristic behaviour of the system, associated to this kind of fault. A type of voltage sag could be a part of different classes. It shows the behaviour of the power system, due of the possibility of different severity grades of the same kind of fault.

4. Conclusions

A fuzzy classification tool has been used to relate voltage sags records to its possible location (transmission or distribution system). Using the proposed classification approach, some classes strongly related to one real situation defined by the facility's experts have been determined. Determination of possible location of new voltage sag has been performed, addressing the restoration plan and prevent some types of events in the future.

The obtained information helps companies in network operation to maintain the continuity indexes. It is due to the improvement on the response in applying restoration strategies to recover the faulted system. To planning purpose, the information obtained by means of this analysis, will be useful to network companies to locate the zones influenced by voltage sags. It addresses the location of new sag sensitive equipment.

The proposed methods presented in this paper to analyse and locate the faults, are using off-line. It is possible to be implemented fault location online by using in protection relays, by means of speeding the calculation.

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References

[1] M.H.J. Bollen, Understanding Power Quality problems" IEEE Press. New York, 2000

[2] Meléndez J., Colomer, J, Macaya, D. "Case based reasoning methodology for supervision". Proc. of the European Control Conference (ECC2001), pp: 1600-1605, Oporto (Portugal), 2001.

[3] Meléndez J, Colomer J, De la Rosa, J.Ll, "Expert Supervision Based on Cases". Proceedings of IEEE-ETFA'01, Nice (France), Sept, 2001c

[4] N. Kagan. "Influence of RMS variation measurement protocols on electrical system performance indices for voltage sags and swells" Proceedings. Ninth International Conference on, Vol. III, pp. 790 - 795, 2000.

[5] Arrillaga, J.; Bollen, M.H.J.; Watson, N.R, "Power quality following deregulation", Proceedings of the IEEE , Volume: 88 Issue: 2, Page(s): 246 -261, Feb. 2000.

[6] Electromagnetic Compatibility (EMC), Part 4. Testing and measurement protocols. Section 11. Voltage dips, short interruptions and voltage variations immunity tests. IEC document 61000-4-11.

[7] M.H.J.Bollen, P. Wang, N. Jenkins, Analysis and consequences of the phase jump associated with a voltage sag, Power System Computation Conference, Dresden, Germany, August 1996.

[8] M.H.J. Bollen, The influence of motor reacceleration on voltage sags, IEEE Transactions on Industry Applications, vol.31, 1995, p.667-674.

[9] J. J. Grainger, W. D. Stevenson, Power Systems Analysis, McGraw-Hill, México (1998), pp. 441-497.

[10] K. Moore, et al: "Using neural nets to analyse qualitative data". A Marketing Research, vol. 7, nº. 1, p. 35-39, Winter 1995.

[11] J. Aguilar-Martin and R. López de Mántaras: "The process of classification and learning the meaning of linguistic descriptors of concepts". Approximate Reasoning in Decision Analysis. p. 165-175. North Holland, 1982.

[12] N. Piera,: Connectius de lògiques no estandard com a operadors d'agregació en classificació multivariable i reconeixement de formes. N. Piera. Doctorate dissertation in the Universitat Politècnica de Catalunya, 1987.

[13] J.C Aguado,: "A Mixed Qualitative-Quantitative Self-Learning Classification Technique Applied to Situation Assessment in Industrial Process Control". Ph. D. Thesis Universitat Politècnica de Catalunya, 1998.

[14] J.C Aguado, et al: "Comparison of structure and capabilities between a non-standard classification technique and the radial basis function neural networks". Proceedings of the 13th European Simulation Multiconference (ICQFN 99), Vol. II, pp. 442-448, Warsaw, Poland, 1999.

[15] L.I. Eguiluz, M Manana; J.C. Lavandero, Disturbance classification based on the geometrical properties of signal phase-space representation. Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on, Volume: 3, 2000.

[16] M. Kezunovic, Automated analysis of voltage sags, their causes and impacts. Power Engineering Society Summer Meeting, 2001, Volume: 2, 2001