Automatic Management of Voltage Sags Recorded in a 25kV Substation

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Abstract

This paper describes an application specially designed to manage and analyse information related to voltage sags registered in a 25kV substation. The purpose of the application is to assist substation managers in the identification and location of faults in the network. The application is conceived to integrate and to exploit complementary information registered during faulty operation.

Key words

Sags, network operation, power monitoring, waveform analysis.

1. Introduction

Today's power quality monitoring instruments capture a wide variety of power quality events ranging in frequencies from DC to a few mega hertz. Typical measured quantities are instantaneous voltages and current waveforms, fundamental frequency, power factor among of them. Thanks to the advances in data storage and software technologies, power quality phenomena manifested in voltage and current can be continuously measured and recorded resulting in a tremendous amount of data. On the other hand, protective systems based on digital relays are capable to report trips. Both registers are provoked by the presence of perturbations in the network, resulting in complementary information gathered by equipment far away from each other. In this work power monitors have been considered located in the transformers of a substation (HV/MV) whereas protective systems considered are those that are capable to send event information to operation centre. In order to distinguish between the origins of information related to register of events, in this paper the following convention has been adopted:

- *Event*, designs fault attributes registered by power monitor instruments. Events associated with sags usually are duration, voltage drop, time stamp, etc (Fig. 2). According to power monitoring equipment events can also be associated with a register of its waveform (See Fig. 1).
- *Incidence*, information related to protective system operation gathered by relays (or manually) and transmitted to control centre where they are stored in data bases (Fig. 3).

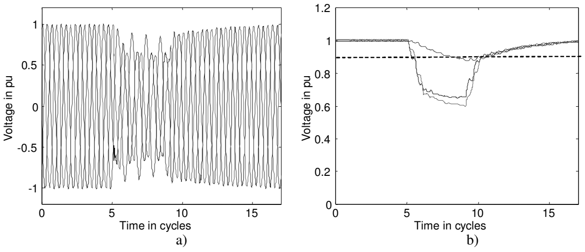
An application especially designed to manage and analyse information related to voltage sags have been developed. The purpose is to assist substation management in the identification and location of faults in the network facilitating the knowledge management in decision making. Consequently, the application is conceived to integrate and to exploit this complementary information registered during the occurrence of faults (events, waveforms and incidences).

The power monitoring system used for this application is conformed by the software SMS-1500 (System Manager Standalone) and the Circuit Monitor CM-3000. A Circuit Monitor is a multifunction, digital instrumentation, data acquisition and control device. Events and waveforms, used in the development of this application, have been registered by two CM-3000 installed in the secondary winding of two 132/25kV transformers located in a 25kV substation (ENDESA) installed in SALT (Girona-Spain). These two equipments allow monitoring 9 feeders (MV/LV) and at same time to register faults occurred in HV. Thus, both events (propagated from where faults occur to monitoring systems, through transformers and lines) and incidences (generated by the operation of protective elements sent to the control centre) have been used in the project.

The paper is structured as follows: Section 2 gives some definitions and problem description related to sags management. Section 3 shows main steps in the application structure, in Section 4 the conciliation of events and incidences is explained. Section 5 is dedicated to the analysis of the waveforms performed in the application while section 6 is focused in the developed methods for diagnosing sags exploiting the data base. Section 7 exposes the obtained results. Finally, Section 8 ends the paper with further work and concluding remarks.

2. Sags: Events, waveforms and incidences associated.

Standard definition of sags ([1],[2]) is based on the minimum r.m.s. value obtained during the event and its duration is the time interval between the instant when r.m.s. voltage crosses the voltage sag threshold (usually 90% of normal voltage) and the instant when it returns to normal level (a three-phase unbalanced voltage sag is shown in Fig. 1).



a) b)

Fig. 1. a) Example of a three-phase unbalanced voltage sag. B) r.m.s. voltage.

In three-phase systems the existing methods to characterise voltage sag use the lowest of three-phase voltages and the longest duration among of them. In this work sag duration (See Fig. 2) is defined from the instant when the first phase falls down (under 0.9 p.u.) until the instant when the last phase goes up (over 0.9 p.u.). This definition has been used to characterize both single and three phase sags.

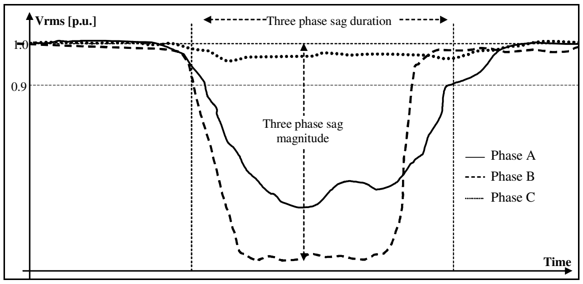


Fig. 2. Event attributes in a three-phase voltage sag: duration and magnitude

Events (waveforms) and incidences are usually registered in data bases far away from each other. Typically, power quality monitoring systems are installed in substation; consequently events are stored in such equipments and downloaded periodically. On the other hand, registers of incidences generated by protective systems distributed in the electric network are registered in the control centre in a centralised data base (See Fig. 3). In presence of sags, power quality equipment registers the events and waveforms and simultaneously acting protective systems (only when faults are large enough to trip) sends information of actuation to the network control centre. Similar information can be registered manually when repair or maintenance works are executed.

Main problem to associate both registers (events and incidences), that occur at the same time (fault time), is due to the different synchronization of local clocks and the fact that management centre can store a huge number of incidences (see Section 4). A second drawback of the actual system is that different registers (incidences, events, waveforms) are only accessible from particular applications making difficult the use of existing information from a single access point. Additionally, the possibility of processing waveform for extracting additional attributes must be computed externally.

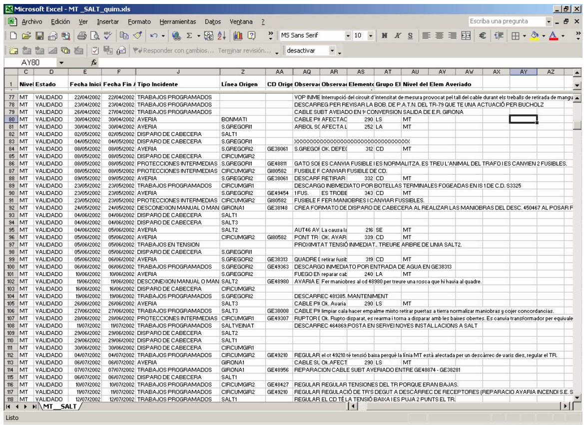


Fig. 3. Example of incidence data base

The application here described, solves this questions providing an integrate view of sags, by associating events, waveforms and incidences in the same data base. Waveforms are processed to obtain additional information and offering an integrated and interactive visualisation framework.

3. Application structure

The application is composed by three differentiated parts: The database, the management module and the visualization module, described in the following paragraphs (See Fig. 4).

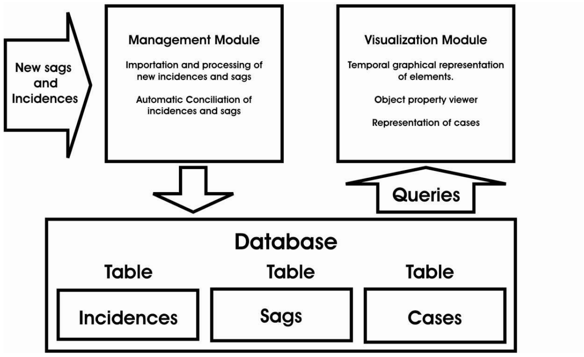


Fig. 4. Block Diagram of the application

The database contains all the registered information of the events (sags) and incidences. This database is provided by the electrical company and has been composed by collecting the information provided by the power monitor (substation) and the control centre register of incidences.

It is also included in the database a table containing the distribution lines feed by each transformer in the substation. If at any time the network structure changes, it can be registered in some way. This knowledge of the structure, allows improving the conciliation mechanisms discarding failures not physically associated to a line or transformer.

The database has been developed in Microsoft Access.

The management module is used to perform modifications to the database and the integration of all existing information related to a single occurrence in a common structure. Some features of this module includes:

- Importing data: waveforms in COMTRADE format are converted to data base registers and images. Incidences from external data base can be incorporated.
- Waveform analysis and processing. A Matlab based algorithm embedded in the application that extracts attributes related to duration and magnitude of r.m.s.. value for both single and three phase sags. See section 5.
- The implementation of the conciliation algorithm that associates events and incidences. It will be explained in section 4.
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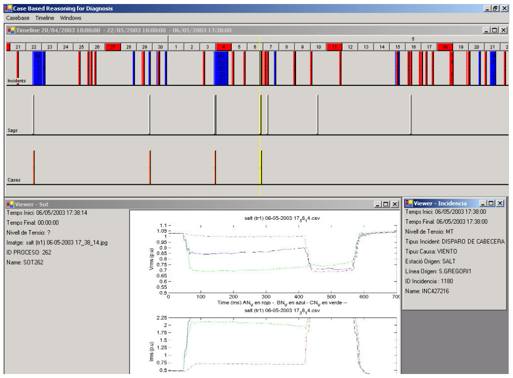


Temps Inici: 06/05/2003 17:38:14
Temps Final: 00:00:00
Nivell de Tensio: ?
Imatge: salt (tr1) 06-05-2003 17_38_14.jpg
ID PROCESO: 262
Name: SOT262

Temps Inici: 06/05/2003 17:38:00
Temps Final: 06/05/2003 17:38:00
Nivell de Tensio: MT
Tipus Incident: DISPARO DE CABECERA
Tipus Causa: VIENTO
Estació Origen: SALT
Línea Origen: S.GREGORI1
ID Incidencia : 1180
Name: INC427216

Fig. 5. Visualization module

The visualization module is used to make a better presentation of the whole information included in the database. It has been designed as a timeline divided in three different axes where incidents, sags and cases (associations among events and incidences) are graphically represented. The viewer has the capability to interact and show attributes corresponding to these objects.

In Fig. 5 this interfaces is depicted. Incidences are represented in the first row and events in the second one. They are placed according to time stamp. Third row indicates events associated with incidences in the event assigned time stamp. On the bottom, a graphic representation of the waveform (r.m.s. value) is enclosed with incidence (on the bottom-right) and event attributes (on the bottom-left).

The visualization module has been implemented using three custom classes developed exclusively for this application: Incidence, Sag and Case Class.

All the objects generated from these classes obtain their property values from the registers of the associated tables (Incidences, Sags and Cases tables) in the database. Queries in the database are made each time the visualization module objects are represented, one for each kind of object (See Fig. 6).

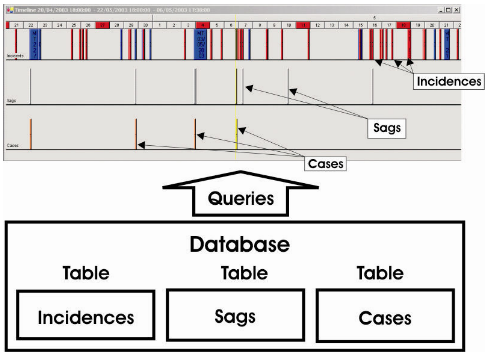


Fig. 6. Incidences, sags and cases generated from the database

The Incidence class has particular properties like the initial time of the incident, the final time, the tension level associated to this incident, origin of the fault, and reports about the cause or actors.

The Sag class has the same properties except the final time property because due its short duration it is not necessary to consider that the sag has duration. It is then considered a punctual event.

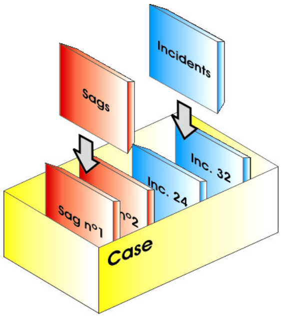


Fig. 7. The Case Class. Incidences, Sags could be stored in the object collection of the case class.

The Case class is understood as a container of the other classes in the form of an object collection (See Fig. 7). The case class may contain several incidences and sags inside it. Each time a new object is inserted in the collection, the initial and final time properties of the Case class vary according to the duration of the object introduced. The power of the Case class resides on the fact that any kind of object can be introduced in its collection, preserving all the information about the introduced object properties, and in particular its temporal duration.

If at any time a new class is created or modified, the new generated objects could also be introduced in already existing cases. This feature provides flexibility to the maintenance of the case base and expandability for the future.

The visualization module has been developed in Visual Basic .NET for its facility for graphical user interface development and object management.

Other additional modules have been developed in order to provide extended functionality to the application. These are external to the application and takes profit of processed waveforms in order to analyse system performances and extract diagnosis from previous situations.

A classification tool (LAMDA) has been used to analyse sags origin and location. The implementation of distance criteria based in the Manhattan distance function and the Dynamic Time Warping algorithm (See Section 6).These two modules will be also useful to retrieve similar cases and improve diagnostics.

4. Conciliation of Events and Incidences

The stochastic nature of sags ([3]) makes feasible the assumption that sags are not concurrent (in time). Consequently, the registers of events and incidences can easily be associated according to their time stamp. In practice this is not always possible due to several drawbacks inherent in the utility installations and procedures:

- Inexistence of a unique temporal reference: Every Registering equipment has its own clock that is synchronized once a month by modem. Although the system tries to compensate the delays, a variation (seconds or sometimes minutes) among clocks is always introduced.
- Different operation of protective system: when protective systems are automatically tripped in presence of a fault, time stamp is correctly registered. On the other hand when operation is manual, usually provoked by (i.e., switches or sectionalizers) a programmed work or maintenance needs instead of a fault, incidences are registered with large and variable time delay (minutes) with respect to the event generation.

Notice that in the first case delay can be both positive and negative, whereas in the second situation usually is positive. In order to cope with this drawback a conciliation algorithm has been developed to associate events and incidences. The algorithm basically takes into account the existence if incidences in a time interval (Δt) centred at the time stamp of every registered event (Ej.ti) and some constraints related with the system configuration and the origin of the perturbation. Thus, for every registered event (Ej) the goal is to find incidences (Ii with i:1..N) that match the following condition (for a ninitially narrow Δt).

$$|Ej.ti - Ii.ti| < \Delta t$$

With:

Ej.ti: time stamp associated o the beginning of the event number j.

Ii.ti: time stamp associated o the beginning of the incidence number i.

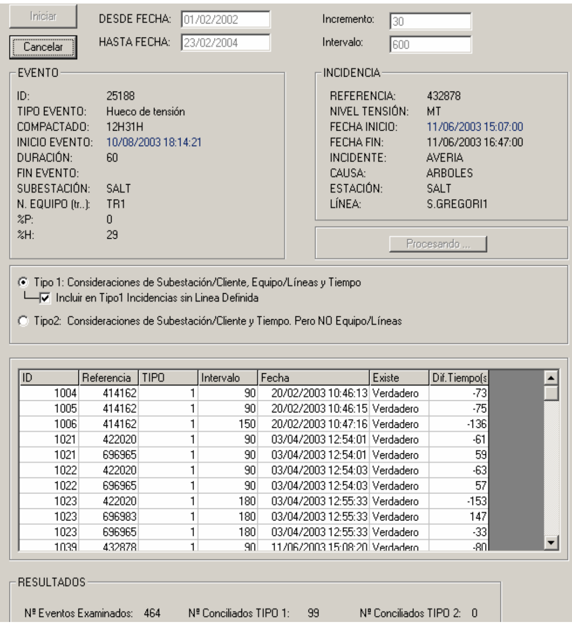
Firstly, from the possible set of incidences that keeps inside this condition only distribution (and clients) faults are considered. For this subset, it is possible to verify if the affected line corresponds to a line feed by the transformer where the power monitor that gathered the event Ej is connected. In such case the match is performed. Otherwise, the algorithm considers the occurrence located in transmission. Thus, if any inside the temporal window, these would be observed from different power monitors in the substation and matching performed also with other events.

In case that temporal window is too narrow to observe any incidence inside the interval, matching results empty. Then, the algorithm increases this temporal window (typically Δt++) and previous casuistic is applied until a maximum window is reached.

Several casuistries are given according the nature and location (HV/MV/LV) of faults:

- *Event –incidence (desirable and expected conciliation)*
- *Event without incidences associate*: when origin of faults is located in points where information is not always available (Red Electrica, generation, short circuits in consumers, etc.) or when sags do not trip protective systems.
- *Incidence without events associated*: when sags are produced by programmed discharges in transformation centres, sags occurred in distribution lines different from which the transformer where installed, trip of intermediate protections in consumers (fuses) , and similar.
- *Events associated with multiple incidences*: It can occur in both transmission and distribution. In such situations, time stamp associated with all these incidences must coincide exactly.

The application has been run with two power monitors connected to transformers feeding four lines each. The Δt parameter has been fixed to 30 sec. A conciliation example is shown in the application window of Fig. 8.



DESDE FECHA: 01/02/2002
HASTA FECHA: 23/02/2004
Incremento: 30
Intervalo: 600

EVENTO
ID: 25188
TIPO EVENTO: Hueco de tensión
COMPACTADO: 12H31H
INICIO EVENTO: 10/08/2003 18:14:21
DURACIÓN: 60
FIN EVENTO:
SUBESTACIÓN: SALT
N. EQUIPO (tr..): TR1
%P: 0
%H: 29

INCIDENCIA
REFERENCIA: 432878
NIVEL TENSIÓN: MT
FECHA INICIO: 11/06/2003 15:07:00
FECHA FIN: 11/06/2003 16:47:00
INCIDENTE: AVERIA
CAUSA: ARBOLES
ESTACIÓN: SALT
LÍNEA: S.GREGORI1

● Tipo 1: Consideraciones de Subestación/Cliente, Equipo/Líneas y Tiempo
☑ Incluir en Tipo1 Incidencias sin Linea Definida
○ Tipo2: Consideraciones de Subestación/Cliente y Tiempo. Pero NO Equipo/Líneas

ID	Referencia	TIPO	Intervalo	Fecha	Existe	Dif.Tiempo(s
1004	414162	1	90	20/02/2003 10:46:13	Verdadero	-73
1005	414162	1	90	20/02/2003 10:46:15	Verdadero	-75
1006	414162	1	150	20/02/2003 10:47:16	Verdadero	-136
1021	422020	1	90	03/04/2003 12:54:01	Verdadero	-61
1021	696965	1	90	03/04/2003 12:54:01	Verdadero	59
1022	422020	1	90	03/04/2003 12:54:03	Verdadero	-63
1022	696965	1	90	03/04/2003 12:54:03	Verdadero	57
1023	422020	1	180	03/04/2003 12:55:33	Verdadero	-153
1023	696983	1	180	03/04/2003 12:55:33	Verdadero	147
1023	696965	1	180	03/04/2003 12:55:33	Verdadero	-33
1039	432878	1	90	11/06/2003 15:08:20	Verdadero	-80

RESULTADOS
Nº Eventos Examinados: 464
Nº Conciliados TIPO 1: 99
Nº Conciliados TIPO 2: 0

Fig. 8. Conciliation window in the management module.

5. Waveform analysis

This section explains the analysis of the waveforms registers that the application executes for every new register. Fist, format of data registers is briefly described, later on all the information abstracted from the register by the algorithm is explained and finally the report file is described.

A. *Waveform format*

Waveforms registered by the Circuit Monitor equipments are stored by the SMS software in the COMTRADE format (IEEE C37.111-1191, Standard Common Format for Transient Data Exchange for Power Systems). Data is converted to '*.csv' (comma separated values) format and processed in order to extract significant attributes. Files are named with the name of the transformer where the CM-3000 is installed and the date when sag is occurred, i.e. TR1 15-03-2003 19_11_58.csv, this name is useful for the conciliation between events and incidences.

A waveform register contains: 6400 samples registered every 0.15625 ms (data is available for the three phases including at least two cycles pre-event voltages), line-voltages (Vab, Vbc and Vca), phase-voltages (Va, Vb and Vc) and phase-currents (Ia, Ib and Ic).

B. *Information abstracted from the waveform*

Among the information abstracted with the purpose to characterise the sags we distinguish between temporal and phasorial attributes.

First group are temporal attributes those are summarized as follows: three-phase temporal attributes (see Fig. 2), divided in three-phase sag magnitude and three-phase sag duration. Single-phase temporal attributes (see Fig. 9); divided in single-phase sag magnitude, single-phase sag duration, voltage fall slope and voltage recovery slope. For more detail consult ([4],[5]).

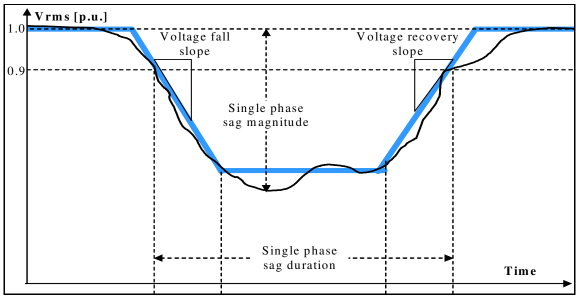


Fig. 9. Three-phase voltage sags attributes

Second group are phasorial attributes, those are the voltage sags types and characteristic voltage. The voltage sag type indicates which phases are involved in the event. The seven basic types are given in Fig. 10. Balanced voltage sag (type A) is due to an equal drop in the values of voltage in the three-phases. Unbalanced voltage sags (types C and D) depend on the phases 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. Once voltage sag type is defined another information can be abstracted , it is known as *characteristic voltage;* the characteristic voltage is comparable to the rms voltage for single-phase measurements and should be used to compare global shape of sags. The demonstration and formulation of this method can be consulted in [2].

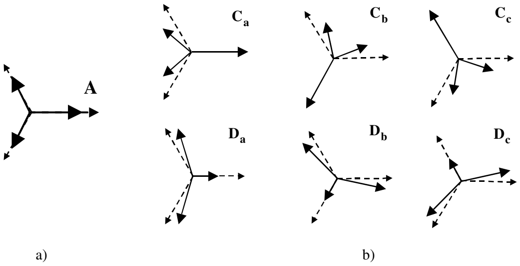


Fig. 10. a) Three-phase balance voltage sag, b) six types of three-phase unbalanced voltage sags.

In order to abstract above information the following steps are computed:

- To obtain the r.m.s. voltage values per each phase, 1 cycle window has been used.
- To determine voltage fall slope and voltage recovery slope per each phase.

- To determine three-phase sag magnitude and three sag duration, according to definition in section 2.
- To define the voltage sag type. This point considers signal processing methods as FFT (Fast Fourier Transform) and symmetrical components analysis. This step is more explained in [2].

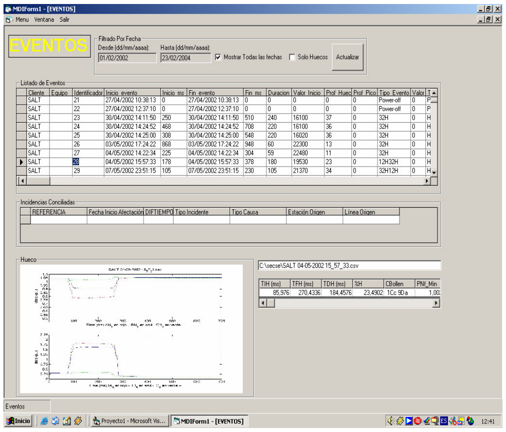
The algorithm has been developed in Matlab and embedded into the application as standalone executable file.

A. *Reporting waveform analysis*

As analysis waveform report, two new files are created, one with (*.csv) format that contains temporal and phasorial attributes, this file is updated every new sag register, see Table 1. The second file contains the waveform charts of voltages and currents in R.M.S. values. Both are integrated in the data base and interfaced by the application Fig. 11 shows.

	Three-phase temporal Attributes		Single-phase temporal Attributes						
			Phase 1				Phase 2	Phase 3	Type
Sag name	Magnitude %H	Duration (ms)	Magnitude %H	Duration (ms)	Fall slope	Recovery slope			
………………….									
TR1 19-03-2003..	11.898	51.273	0	0	0	0	…………	…………	A
TR3 20-03-2003..	37.47	100.983	37.47	100.983	0.335	2.253	…………	…………	Da
TR1 17-04-2003..	35.875	87.539	17.497	35.016	0.4	0.749	…………	…………	A
TR1 19-04-2003..	22.903	148.504	19.681	147.254	0.295	0.101	…………	…………	Dc
TR3 23-04-2003..	32.061	144.44	32.061	142.564	0.5	0.743	…………	…………	Da
………………….									
TR3 08-06-2003..	14.802	58.464	0	0	0	0	…………	…………	A
TR1 09-06-2003..	13.406	33.14	0	0	0	0	…………	…………	A
TR3 21-06-2003..	14.486	68.781	14.486	68.781	0.091	0.552	…………	…………	Dc
TR1 22-03-2003..	11.076	28.138	0	0	0	0	…………	…………	Cb
TR1 22-03-2003..	10.72	6.878	0	0	0	0	…………	…………	Ca
………………….									

Table 1 Analysis waveform report file.



Filtrado Por Fecha

Desde (dd/mm/aaaa): 01/02/2002

Hasta (dd/mm/aaaa): 23/02/2004

☑ Mostrar Todas las fechas ☐ Solo Huecos

Listado de Eventos

Cliente	Equipo	Identificador	Inicio_evento	Inicio_ms	Fin_evento	Fin_ms	Duracion	Valor_Inicio	Prof_Huec	Prof_Pico	Tipo_Evento	Valor	T
SALT		21	27/04/2002 10:38:13	0	27/04/2002 10:38:13	0	0	0	0	0	Power-off	0	P
SALT		22	27/04/2002 12:37:10	0	27/04/2002 12:37:10	0	0	0	0	0	Power-off	0	P
SALT		23	30/04/2002 14:11:50	250	30/04/2002 14:11:50	510	240	16100	37	0	32H	0	H
SALT		24	30/04/2002 14:24:52	468	30/04/2002 14:24:52	708	220	16100	36	0	32H	0	H
SALT		25	30/04/2002 14:25:00	308	30/04/2002 14:25:00	548	220	16020	36	0	32H	0	H
SALT		26	03/05/2002 17:24:22	868	03/05/2002 17:24:22	948	60	22300	13	0	32H	0	H
SALT		27	04/05/2002 14:22:34	225	04/05/2002 14:22:34	304	59	22480	11	0	32H	0	H
SALT		28	04/05/2002 15:57:33	178	04/05/2002 15:57:33	378	180	19530	23	0	12H32H	0	H
SALT		29	07/05/2002 23:51:15	105	07/05/2002 23:51:15	230	105	21370	34	0	32H12H	0	H

Incidencias Conciliadas

REFERENCIA	Fecha Inicio Afectación	DIFTIEMPO	Tipo Incidente	Tipo Causa	Estación Origen	Línea Origen

Hueco

C:\secse\SALT 04-05-2002 15_57_33.csv

TIH (ms)	TFH (ms)	TDH (ms)	%H	CBollen	PNf_Min
85,976	270,4336	184,4576	23,4902	1Cc 9Da	1,00

Fig. 11. Processed waveforms in the management module

6. Application exploitation

The database stored about 1233 registers of incidences and 1404 registers which 922 of them were sags. All these register where recorded from 1/2/2002 until 26/2/2004.

In Table **2** is it possible to see percentages of the different types of incidents. The most important in number are main breaker trips and programmed maintenances.

Type of incidence	Number	%
Main breaker trip	736	59,7
Programmed maintenance	256	20,8
Malfunction	68	5,5
Work under tension	65	5,3
Unknown cause	61	4,9
Faults due to intermediate protections	25	2,0
Manual disconnections	22	1,8
Total	1233	

Table 2 Percentages of the different type of incidences.

After applying the conciliation algorithm using a maximum time window of 600 seconds, 532 conciliations were performed; involving 66 incidences and 322 sags. 189 of the them were conciliated using information related to transformer and lines and 133 without it.

Information abstracted from sag waveform (temporal and phasorial descriptors) has been used for diagnosis purpose as it is explain in the next subsections. The aim is to infer information related with the location (transmission or distribution) of the fault (fault diagnosis). Two methodologies have been applied to get this aim, one is based on a *classification* (machine learning) whether the second apply metrics based on *similarit*y for sag comparison.

A. *Classification of voltage sag*

A classification is performed based on temporal attributes of voltage sag. For classification purpose a Learning Algorithm for Multivariate Data Analysis-LAMDA ([6],[7]), working on unsupervised training strategy is used. This fuzzy classification tool has been used to relate sags to their possible location (transmission or distribution). Using this approach some classes (set of registers with the same features) strongly related to one real situation defined by the facility's experts have been determined. This is profitable during the restoration plan and prevents some types on event in the future. For more detail consult ([5]).

B. *Voltage sag similarity*

The goal is to compare sags in order to retrieve the most similar voltage sags from a set of registers. Next step is to use the diagnostic (transmission or distribution) associated to the most similar sag retrieved. Two metrics have been applied, one using Manhattan distance to the temporal attributes and the second measuring distance between characteristic voltages waveforms by using Dynamic Time Warping.

Most of algorithms that operate with time series of data use the Euclidean distance or some variation. However, Euclidean distance could produce an incorrect measure of similarity because it is very sensitive to small distortions in the time axis. A method that tries to solve this inconvenience is Dynamic Time Warping (DTW), this technique uses dynamic programming ([8],[9]) to align time series with a given template so that the total distance measure is minimised, main idea is depicted in Fig. 12. For more detail consult ([4]).

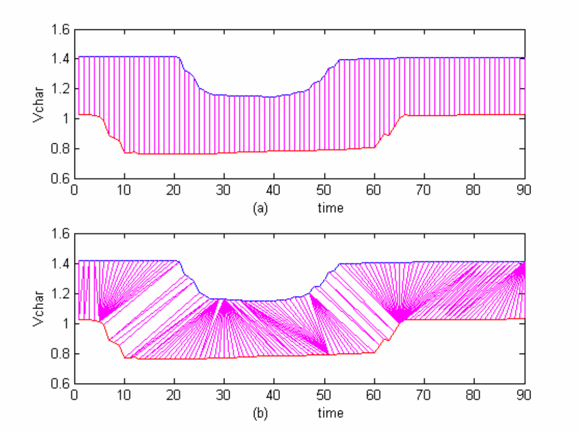


Fig. 12. Two similar characteristic voltage sag . a) The Euclidean distance b) DTW

7. Conclusions and future work

The application described in this paper has been built with the aim to integrate two complementary registers of events affecting a 25kV substation such provided by power quality monitors and registers of operations performed by protective devices.

The work has been restricted only to low duration under-voltage events (voltage sags). The available sags registers come from power monitoring equipment and trip data bases.

The proposed methods for diagnosis purpose 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

In this work similarity criteria of sag were performed. This is the first step to build a diagnostic systems based on the reuse of past experiences (diagnosed sags) according to the Case Based Reasoning (CBR) methodology. Cases are registers containing a description of a problem, “sag symptoms”, and its solution, “sag diagnostic”. The aim is to reuse these cases for solving new problems by analogy. In presence of a new problem, the basic procedure consist of Retrieving analogue cases (sags), according to their description (attributes), and reusing their solutions (diagnostic), future work will be focused in finishing and integrate this diagnostic methodology in to the application for an efficient diagnosis.

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