AUTOMATED DIGITAL FAULT RECORDING ANALYSIS SYSTEM

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ABSTRACT

This paper presents the development, implementation, simulation results and field tests of an automated digital fault recording analysis system. The proposed system, which is based on measurements provided by intelligent electronic devices (IEDs) installed at the substation level and/or along the electrical networks, is capable of evaluating the behaviour of protection systems, the performance of the networks under faults and power quality events. It consists of five software modules and a human-machine interface responsible for: reading voltage and current signals stored in COMTRADE sets of files [1], [2]; filtering the direct current (DC) decaying component of the current signals; estimating the phasor quantities and identifying the transition instants of these signals; estimating the network's state; and presenting the results. The system is installed in "Companhia Paranaense de Energia" , one of the largest Brazilian G,T&D utility [3], and it is under evaluation.

INTRODUCTION

Electrical networks are subject to faults caused by a variety of situations, such as: bad weather, equipment failures and accidents. These occurrences result in decreased service reliability and power quality problems.

In the past, power system operators and engineers, responsible for assessing contingencies, had little data to produce a complete and detailed analysis of the problems in their electrical networks. Moreover, there was a lack of information to predict or determine the level of maintenance required for their assets.

The application of digital technology, with regards to monitoring, supervision, protection, measurement and control of electrical systems, has become increasingly available to system operators and engineers. This technology is capable of providing a considerable amount of information and the ability to fully operate the system. Thus, it is essential to correctly process all this information in order to improve system reliability, efficiency and power quality to consumers.

However, it is important to point out that manually processing all this information may be a time consuming task for operators and engineers [4], particularly when processing distribution system information, since the number of occurrences may produce large amounts of data. Thus, an automated digital fault recording analysis system, capable of automatically processing all recorded data during power system occurrences, may allow operators and engineers to improve their situational awareness and to better adapt to emergency situations, which means, to improve actions to restore power, to minimize failures in the protection systems, optimize protection settings, investigate power quality problems and optimize assets utilization.

Power system occurrences

Power system occurrences fall into two basic and interrelated categories: power quality and short-circuit occurrences. While power quality occurrences are transient or steady-state disturbances in voltage and/or current waveforms, that may or may not be related to short-circuit events and can be classified according to the nature of the waveforms distortions, as in [5, 6], short-circuit occurrences are abnormal current variations caused bad weather, equipment failures, accidents, etc., that eventually result in power quality problems.

Automatic analysis of power quality and short-circuit occurrences has been subject of research interest from many authors. For instance, references [7, 8] present methods for automatic classification of power quality disturbances, based on the modified S-transform, wavelets transform and support vector machines, and reference [9] presents a method based on the wavelets transform for short-circuit event classification.

Automatic power occurrences analysis

As described in reference [5], automatic analysis of power system occurrences is usually based on the block diagram depicted in Fig. 1. The analysis consists of automatically reading and processing information provided by IEDs, sensors and other equipment installed along the electrical networks, in order to determine their status, to anticipate future problems, and to enable effective actions.

Since the main pieces of information are voltage and current samples stored in COMTRADE sets of files, the analysis consists of: reading the voltage and current samples; determining the transition instants of these signals, as depicted in Fig. 2; and extracting the features of each signal segment in order to proceed with the event classification.

Additional processing may be used to interpret other available pieces of information, such as: circuit-breakers, reclosers and sectionalizers status; recorded event data of the IEDs, which describes the behaviour of the protection and automation systems during the disturbances; etc.

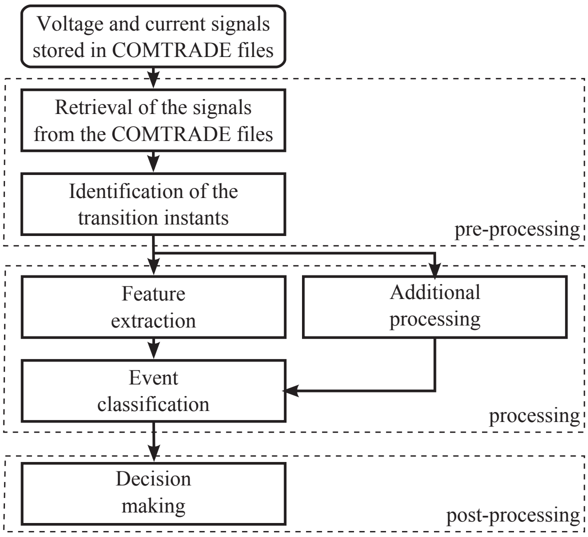

Figure 1: Block diagram of the power system analysis.

The Event Classification step provides valuable information which may help system operators and engineers to define the best strategies for electricity restoration, management of their networks assets, optimization of the protection settings and/or minimization of protection systems failures, etc.

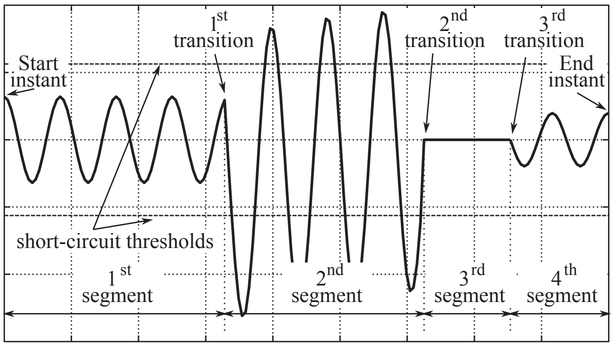

Figure 2: Example of a current waveform during a fault.

DESCRIPTION OF THE PROPOSED SYSTEM

The automated digital fault recording analysis system, proposed in this paper, is based on analog and digital signals stored in COMTRADE sets of files. This system is composed of five software modules and a human-machine interface (HMI) coded in ANSI C/C++ and Visual Basic, as depicted in Fig. 3.

COMTRADE Reader

This software module is responsible for extracting the phase voltages (v_{an}, v_{bn}, and v_{cn}) and line currents (i_a, i_b, and i_c) samples written in the COMTRADE sets of files, and storing them in the system's relational database. This software module makes the rest of the system independent of the data exchange format, in such a way that future modifications in the COMTRADE standard will not imply in major software upgrades.

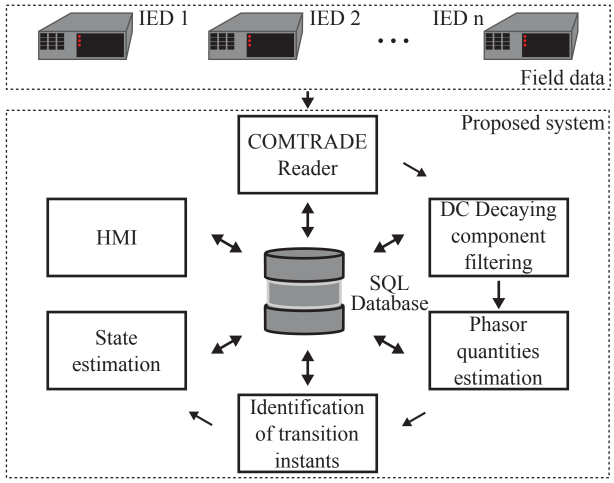

Figure 3: System structure.

Direct current decaying component filtering

A typical first-order power system current signal can be described as:

$$i(t) = I_0 \cdot e^{-\alpha \cdot t} + I_1 \cdot \cos(w_1 \cdot t + \varphi_1) \quad (1)$$

Where:

$i(t)$ → Current signal;

I_0 → Magnitude of the direct current decaying component;

I_1 → Magnitude of the fundamental component;

w_1 → Angular frequency of the fundamental component;

φ_1 → Phase difference of the fundamental component.

In order to eliminate the direct current (DC) decaying component present in the line current signals, this software module implements the digital filter detailed in [10]. This filter is based on the following difference equation:

$$x_k = G \cdot \{a \cdot i_k - i_{k-m}\} \quad (2)$$

Where:

x_k → Output of the difference equation;

i_k → kth current sample;

m → Integer number (digital data window size);

G and a → Real constants.

The real constants are calculated considering two conditions: the digital filter must completely eliminate the DC decaying component, and it must provide unitary gain to the fundamental component.

$$a = e^{\alpha \cdot m \cdot T} \quad (3)$$

$$G = \left\{ a^2 - 2 \cdot a \cdot \cos\left(\frac{2 \cdot \pi}{N} \cdot m\right) + 1 \right\}^{-0.5} \quad (4)$$

Where:
α → Inverse of the power system time constant;
T → Fundamental period;
N → Number of samples per cycle of the fundamental.

Phasor quantities estimation

This software module is responsible for estimating the phasor quantities of phase voltages and line currents, with the use of the respective samples stored in the system's database. Since the previous software module is capable of removing the DC decaying component, present in the current signals, it is possible to use the Discrete Fourier Transform (DFT) method, as follows.

$$\dot{X}_k = \frac{2}{N} \cdot \sum_{l=0}^{N-1} \left\{ x_{k+l-N+1} \cdot \left[\cos\left(\frac{2\pi}{N} \cdot l \right) + j \cdot \sin\left(\frac{2\pi}{N} \cdot l \right) \right] \right\} \quad (5)$$

Where:
$\dot{X}_k$ → k[th] phasor quantity;

This software module estimates the phasor quantities of all samples, considering all voltage and current samples stored in the database.

Identification of the transition instants

The software module for the identification of the transition instants is based on the probability density function (PDF) digital filter (p_k), as in (6).

$$p_k = e^{\frac{(X_k - M_k)^2}{(V_k)^{ep}}} \quad (6)$$

The average value (M_k) of the phasor magnitude is:

$$M_k = (1 - l_m) \cdot X_k + l_m \cdot M_{k-1} \quad (7)$$

And the variance value (V_k) of the phasor magnitude is:

$$V_k = (1 - l_v) \cdot (X_k - M_k)^2 + l_v \cdot V_{k-1} \quad (8)$$

Where:
X_k → Magnitude of $\dot{X}_k$;
l_m → Forgetting factor of the average value;
l_v → Forgetting factor of the variance value;
ep → Exponent of the probability density function.

The block diagram depicted in Fig. 4 illustrates the procedure for the identification of the transition instants. This procedure, which is applied to all phase voltages and line currents from a specific event stored in the database, starts with the normalization of the samples' array under analysis. After the normalization step, it follows the calculation of the phasor quantity and magnitude, the average, variance and probability density of the k^{th} normalized sample, as described in (5-8). The next step is to check whether there are two cycles between consecutive transition instants (this step is necessary since the PDF is based ont the DFT, which uses a data window of one cycle).

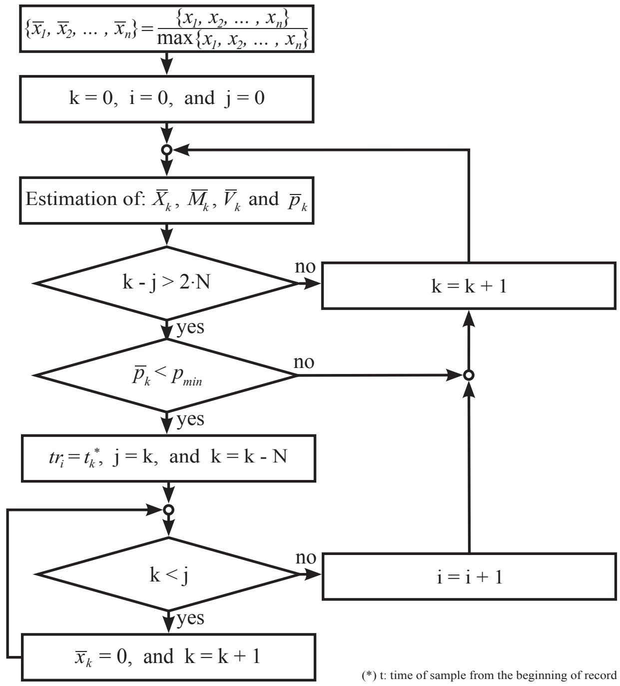

Figure 4: Identification of the transition instants - Block diagram

Then, the procedure compares the probability density of the k^{th} normalized sample to a predetermined value (p_{min}). When a new transition instant is found (tr_i), the array is modified to prevent the influence of the samples from the newly found segment in the estimation of the following transition instants. This procedure is completed when the last sample is evaluated.

State estimation

The software module for the state estimation starts with building a single and coherent timeline of the event under evaluation, using the transition instants found in all phase voltages and line currents signals. In order to build such a timeline it is necessary to merge proximate transition instants and to define common segments.
After constructing the timeline, the state estimation module evaluates the magnitude of the current signals, in each common segment between transitions, in order to determine whether there is a fault or not. If so, the software module determines the fault type and the phases involved, as illustrated in the block diagram depicted in Fig. 5.
The fault classification and identification of the faulted phases is based on the evaluation of the relations among the phase differences and magnitudes of the sequence components of the line currents. Where:

$$\begin{bmatrix} \dot{I}_0 \\ \dot{I}_1 \\ \dot{I}_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1\angle -120^\circ & 1\angle 120^\circ \\ 1 & 1\angle 120^\circ & 1\angle -120^\circ \end{bmatrix}^{-1} \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} \quad (9)$$

And I_0, I_1, and I_2 are the magnitudes of the sequence components.

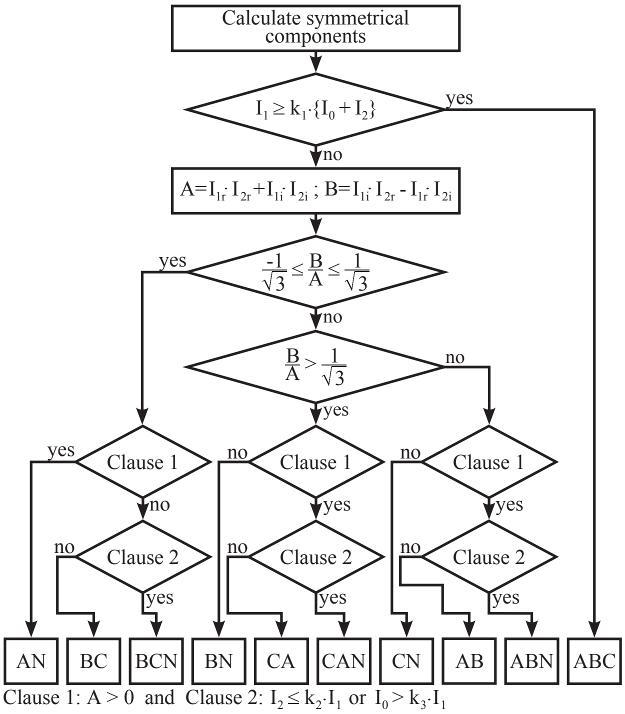

Figure 5: Fault classification and identification of the faulted phases.

System interface

The human-machine interface (HMI) was coded in Visual Basic, and is responsible for accessing large amounts of results stored in the database, providing actionable information.

FIELD TESTS AND RESULTS

The system is installed in COPEL and performed, automatically, three hundred and twenty one evaluations of short-circuit events in distribution feeders of five different distribution substations.

Table I presents the percentage of faults ([%]), according to the fault type, the average value of the fault current (μ_i) and also the average value for the extinction time of the short-circuit current (Δt), provided by the proposed system.

It is important to point out that this table presents only a small part of all the results that the system can provide to operators and engineers.

Table I: Details of the results

Fault type	[%]	μ_i [A]	Δt [ms]
LG	68.2	1691	30
LL	4	2261	25
LLG	27.2	1176	32
LLL	0.6	548	147

CONCLUSIONS

This paper presented the development, implementation, simulation results and field tests of an automated digital fault recording analysis system, which is based on measurements provided by intelligent electronic devices (IEDs) installed at the substation level and/or along the electrical networks.

This system is capable of evaluating the behaviour of protection systems, the performance of the networks under faults and power quality events, and was installed in COPEL, one of the largest Brazilian G,T&D utility.

The paper also presented preliminary field tests and results, which were achieved with the pilot installation. These results have been used primarily to revise the configuration of the IEDs, with respect the COMTRADE settings.

The system is still under evaluation and future modifications may be included in the final version of the system.

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