Proceedings of the 5th WSEAS Int. Conf. on Power Systems and Electromagnetic Compatibility, Corfu, Greece, August 23-25, 2005 (pp274-279)

Diagnostics of Electric Power Equipment by Discriminating Signals Coming from Different Sources

CIPRIANO BARTOLETTI, STEFANO RICCI, GIANCARLO SACERDOTI
Electrical Engineering Department
University of Rome "La Sapienza"
Via Eudossiana 18, Rome 00184
ITALY

GIUSEPPE FAZIO
Electronic Engineering Department
University of Rome "Tor Vergata"
Tor Vergata, Rome 00133
ITALY

FRANCESCO MUZI
Electrical Engineering Department
University of L'Aquila,
Monteluco di Roio, L'Aquila 67100
ITALY

Abstract: - The proposed diagnostic method is based on signal processing procedures applied to information coming from the structure under investigation and generated by both natural and designed stimuli which may also be different in nature. The discrimination of signals acquired by each sensor and coming contemporarily from different sources allows to identify various anomalies in the different parts of the structure. An effective mathematical procedure is proposed with an aim to distinguish the contribution of each source from the entire information collected. After a preliminary calibration performed using designed stimulation, the diagnostic system is applied to apparatuses under normal operating conditions through the following steps: data acquisition by means of sensors and transducers; processing and discrimination of the acquired data using specific analysis software; comparisons of the processed information so as to isolate common characteristics and consequently identify significant diagnostic parameters; data post-processing to recognize a number of belonging classes so as to define the state of the different parts of the structure. The method was applied with slight changes to diagnose a number of different electromechanical structures such as power transformers, circuit breakers, railway components, joints and terminations of MV and HV cables.

Key-Words: - Diagnostics of electromechanical systems, Signal processing and recognition techniques, Electrical distribution systems

1 Introduction

The proposed diagnostic method for complex jointed structures depends on a number of factors, such as the type and configuration of the structure, the nature of the used stimuli, the type and arrangement of the acquisition system, the mathematical procedures and software implemented to process the acquired signals [10]. The main electromechanical structures examined are the following:

1) Power transformers, consisting of windings, magnetic core (yokes and legs), and insulation elements (oil and insulating bushings) [9].

2) HV-circuit-breakers, consisting of many different parts, such as contacts, mechanisms, springs, bearings, shock absorbers, etc. [8].

3) Railway components (pantographs current collectors, contact lines, wheels, etc.) [11].

4) Joints and terminations of MV and HV cables, arranged with insulations, conductors, shields, armoring, protective covering, etc. [5], [6].

The diagnostic process allows the state characterization of a complex structure (or apparatus) divisible into a number of subsystems (or parts); the number of parts can be increased as the diagnostic system resolution improves. The signal discrimination procedure (suggested by prof. Sacerdoti) requires a stimulation of the internal sources of the structure, whose reactions are properly acquired and processed. The signals emitted by the sources (usually corresponding to resonant oscillators) are defined by spectrum and decay time. Signals generated by the oscillators are acquired using an appropriate number of sensors depending mainly on the number of the parts of the structure to be investigated. Sensors sensitivity and placement must be accurately chosen. Stimuli applied to the structure can be natural or properly designed. Natural stimuli can be subdivided into environmental stimuli (for instance external temperature) or operating stimuli (for instance the supply voltage of the apparatus). Different shapes can be chosen for the designed stimuli, such as pulses, steps, ramps, sinusoids, etc.

The diagnostic process requires the following actions:

1) Definition of the different source-sensor transfer functions and calibration of the diagnostic system. These procedures are performed on apparatuses not in operation (usually in a laboratory) and require accurately designed stimuli.

2) Discrimination of the signals emitted by the different sources using proper software to process sample data coming from all the sensors. This procedure is usually performed directly in the field on apparatuses under normal operating conditions and subject to natural stimulation. In particular conditions also designed stimulation may be used.

3) Characterization of the signals linked to the different sources by means of a set of parameters representing the object state (state vector).

4) Definition of the state-vector space on the basis of the previous acquired experience to define the conditions of a part of the structure (placed in a defined environment) using labels such as: good, warning state, bad.

The diagnostic process allows the identification of the object state when the characteristics of the object parts do not reveal changes during time intervals less than the time employed in the information acquisition process; in addition, also the characteristics of the channels connecting sources and sensors must remain in the same state found at the time of the previous calibration procedure. At times structure configuration can suddenly change during the monitoring phase, as with circuit breakers during open/close operations. The diagnosis can however be performed also in this situation, supposing the apparatus to be bi-stable (or, more generally, multi-stable). Of course, these cases require more complex mathematical models. This aspect will be better explained in section 4.

If the transmission channels can be randomly influenced by unpredicted, even minimal stimuli the proposed method might give wrong results. In these cases, methods based on chaos-theory procedures may be more appropriate. Finally, as concerns the state parameters of the object, it is very important to know the limits of the change range in advance, usually through a proper previous experimentation.

2 The proposed diagnostic method

The method is described and commented in the following by referring to the block diagram in Fig.1.

Block 1 concerns the known stimuli applied to the apparatus. They can be distinguished into three types:

a) Operating stimuli.
b) Environmental stimuli.
c) Designed stimuli.

Block 2 concerns the primary transfer channels transmitting the signals generated by the external sources to the sensors. These channels can be:

a) Linear.
b) Non linear, passive.
c) Non linear, active with amplification.

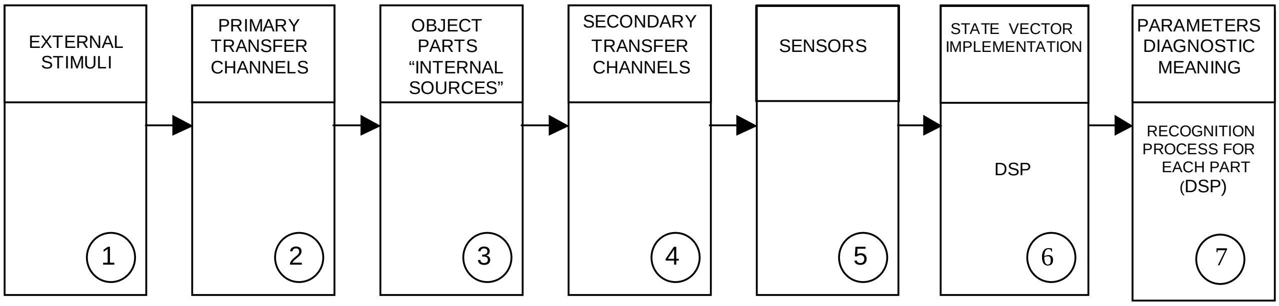

Fig.1. Block diagram of the proposed diagnostic process.

Block 3 involves the various parts of the object that through internal, properly stimulated sources transmit signals to the sensors.

Block 4 concerns the secondary transfer channels linking local sources to sensors. These channels as well are classified into three types:

a) Linear.
b) Non linear, passive.
c) Non linear, active.

Block 5 takes into account the sensors which acquire signals containing information linked to the jointed structure behavior. Sensors can be subdivided into three types:

a) Regular passive.
b) Regular with trigger.
c) Chaotic.

The characteristics of sensors depend on the properties of the signals, which in their turn can be of different nature:

– Vibro-acoustic.
– Electromagnetic.
– Optical (high frequency electromagnetic waves).
– Chemical.
– etc.

Block 6 examines the hardware devices and software procedures used for the Digital Signal Processing (DSP). Starting from the acquired signals (often in sampled form), this diagnostic phase allows to extract the parameter set necessary for the construction of the state vector that characterizes the state of the different parts of the jointed structure under examination.

Block 7 involves the subsequent operation performed by the DSP consisting of a comparison of the state vector obtained during the previous operation and the stored set of state vectors concerning all the possible states that the structure may assume. The aim is to identify and classify the condition of each part of the object.

3. Discrimination of the contributions coming from different sources

The method can be applied to jointed structures having multiple transmission channels (source/sensor). Transmission channels are supposed linear and modeled with electrical networks with lumped or distributed parameters. The structure is supposed to contain N sources whose signals are contemporarily received and acquired by N sensors. In addition, the following symbols are adopted:

- k, the sequential number of the source $(1 < k < N)$;
- i, the sequential number of the sensor $(1 < i < N)$;
- g, the number of parameters describing the emitted signal.

An $s_k(\omega)$ harmonic of the signal generated by the k source is identified by the $A_k(\omega)$ amplitude, ω frequency and $\varphi_k(\omega)$ phase:

$$\dot{s}_k(\omega) = A_k(\omega)\cdot\left[\sin\varphi_k(\omega) + j\cdot\cos\varphi_k(\omega)\right] \qquad (1)$$

Fig. 2 shows the different c_{k1} transfer channels that link all the S_k sources to sensor 1. Similar links send the contribution of all sources to each other sensor as a comprehensive signal. This circumstance is valid for each harmonic of the signal.

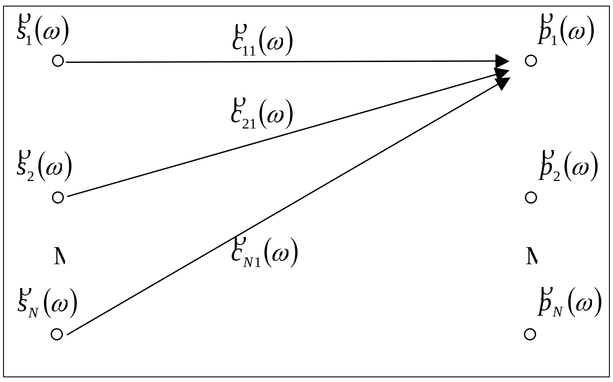

Fig. 2. Transfer channels linking all the sources to the first sensor.

As Fig. 2 shows, if $g=2$ the transfer function from the source k to the sensor i for each frequency can be written using complex numbers as follows:

$$\vec{c}_{ki}(\omega) = |c_{ki}(\omega)| \cdot [\sin\varphi_{ki}(\omega) + j \cdot \cos\varphi_{ki}(\omega)] \qquad (2)$$

On the other hand, the $\vec{s}_k(\omega)$ source vector can be written in the following form:

$$|s_k(\omega)| \qquad (3)$$

The single harmonic of ω frequency received by the *i-th* sensor and caused by only the k source is:

$$|c_{ki}(\omega)| \cdot |s_k(\omega)| \qquad (4)$$

The complete harmonic of ω frequency received by the *i-th* sensor corresponds to the sum of all the contributions having the same frequency from all the sources:

$$|p_i(\omega)| = \sum_{k=1}^{N} |c_{ki}(\omega)| \cdot |s_k(\omega)| \qquad (5)$$

From the knowledge of the $\vec{p}_i(\omega)$ vector-set, with $1<i<N$, it is possible to obtain the complete set of the signals emitted by each source (that is, magnitude and phase for each frequency). In other words, from the measured $\vec{p}_i(\omega)$ values (magnitude and phase) with $i = 1, 2, \dots N$ the values of $\varphi_1 \dots \varphi_N$ and $A_1(\omega) \dots A_N(\omega)$ can be calculated.

As already said, for the proposed model to be valid it is necessary that the characteristics of the transfer channels should be the same as in the previous off-line characterization and both apparatus and channels could be considered as linear. Since a transmission source/sensor channel consists of a number of parallel channels, the transmission link is linear when each channel is linear.

If the system does not degenerate, two sensors allow the discrimination of signals coming from two sources. The procedure is less accurate when the two sources are very close; this difficulty can however be overcome using, for example, signals of different nature. In the case of $g=2$, the complex operator assumes the form of an impedance (with real and imaginary components).

When the signal is characterized by more than two parameters ($g>2$), the direct use of complex numbers become inadequate and a vector notation containing the N requested information for each signal must be used. In this case, the N relations (5) are converted into a system of linear equations of N degree with complex coefficients, which can be solved by discriminating frequency by frequency. In the linear system, $\vec{p}_i(\omega)$ are the known quantities while the $\vec{s}_k(\omega)$, with $k=1,2,\dots N$, are the unknown items.

4 Algorithms and software codes

The implemented software performs the following procedures:

1) Acquisition and storage of signals detected by sensors. This procedure was implemented in a LabView environment.
2) Signal analysis. This procedure, also implemented in a LabView environment, allows to identify a number of important signal characteristics. The implemented software can contemporarily manage signals from different sensors. In order to reduce computation time, only the “useful” part of the signal is selected by means of triggers properly activated immediately before the signal useful for diagnostic purposes is generated.
3) Selection of the main parameters suitable for the subsequent diagnosis. This procedure, also implemented in a LabView environment, uses data coming from the previous analysis.
4) Association of the previous parameters with a state of each part of the structure. This procedure was implemented in *c* language.

The analysis phase can be performed by means of a number of software codes, either commercial or from the open source world. Among these, the most powerful and complete are: LabVIEW of National Instruments, now in its 7.1 version, and MATLAB of MathWorks, now in its 7.0.1 version. The former allows a very efficient management of the signal acquisition procedure, whereas the latter supplies further analysis tools. If also the signal acquisition procedure must be performed, the MATLAB code requires the toolbox Instrument Control. In any case, both software codes are programmable by the user to implement original data analysis algorithms.

In connection with the examined cases, analyzed objects do not always remain in the same state for periods greater than the time requested for the monitoring phase. This is the case of circuit breakers, where signals are usually acquired only during open/close operations (fast transients) [8]. In these conditions, the Fourier transform, being basically aimed at analyzing steady, periodic phenomena, does not usually allow satisfactory analyses. For fast aperiodic phenomena time-dependant transforms, e.g. the so called time-frequency transforms, may prove of greater usefulness [7]. From this point of view, both the STFT (Short Time Fourier Transform) and wavelet transform appeared to be particularly useful [8]. Without considering the mathematical difference between the two above analysis procedures, it can be briefly observed that STFT does not discriminate events happening in less than Δt (or $\Delta\omega$ in the frequency domain). This means that there exists indetermination margins which involves the condition to have both resolutions $\frac{\Delta t}{t}$ and $\frac{\Delta\omega}{\omega}$ variable. This observation justifies the use of wavelet analyses in all those applications that require to process slow and fast phenomena at the same time with the same indetermination. Actually, wavelet transform allows a flexible management of the observed analysis indetermination [1], [3], [8].

5 Sensors and acquisition hardware

As regards mechanical structures, usually speech recognition techniques are adopted because signals (aimed at diagnostics) are mainly of acoustic-vibration nature [4], [8], [9].

The main types of sensor adopted in the performed applications are the following:

1) Endevco Sensors 751-10, characterized by a ±500 *g* range and a frequency response within 1 and 15,000 Hz (these sensors were mainly adopted on applications dealing with transformers and railway components).
2) Shadow SH-2001 piezoelectric audio pickups (especially used for transformers and circuit breakers).
3) A number of PAC sensors having frequency responses up to 100 KHz and remarkable sensitivity (these sensors were found to be particularly useful in the acquisition of signals generated by partial discharges in cable joints, insulators, etc.).
4) Shure Microphones mod. SM81 (this model returned good results in the acquisition of signals coming from rubbings of train pantograph current collectors).
5) Other sensor types to acquire quantities of different nature, such as temperature, humidity, electromagnetic signals, strain gage, etc.

As concerns the acquisition hardware, the evolution in electronics allows the implementation of procedures either off-line or on-line. Regarding the acquisition signal, the actual limits of A/D converters reach resolutions of 24 bit with a sample rate of 7KSPS, since for the analysis of fast phenomena chips reaching up to 1/2 Giga SPS are now commercially available.

In the implementation of advanced acquisition systems such as those above mentioned, a number of design difficulties often arise. Actually, analyses requiring high resolutions in the acquired information (16 or more bits) usually exhibit the following problems (also noticed in the field experimentations):

1. Noise and the related techniques to be adopted for its suppression.
2. Changes of the characteristics of the electronic components connected to temperature and aging.
3. Consequences due to the necessity to load the equivalent Thevenin generator (for the signal under analysis) under 2^n with an aim not to modify the behavior of upstream circuits significantly.

As concerns signal conditioning, some applications require ad hoc devices to be built taking into account both the operating conditions and the used transducers [2]; on the other hand, this process often does not meet industrial standardization procedures. In addition, when signals are very fast (for instance those acquired during open-close circuit breaker operations) the distributed parameters of the structures become important and must be taken into account.

To perform signal analysis, other than the general-purpose processors (PC), there exist dedicated systems for Digital Signal Processing (DSP), which even with lower working frequency allow higher throughputs reducing instruction decoding time. Actually, the systems for H/W loop control allow:

- To perform complex functions such as cross-correlation using only two program rows.
- To use more busses to access directly to two distinct tables.
- To extensively use the indexed addressing, such as the parallel computation systems applied to latest generation DSP.

It may be useful to mention the main operating solutions adopted in the performed experimental activities:

- Realization of specific conditioning circuits for the different sensors used, which, among other things, allow both DC supply of the sensors (accelerometers) and signal amplification. In particular conditions, it was even necessary to isolate each sensor and to implement a filtering process for the different signals.
- Use of a simple PC (desktop, portable or notebook depending on the application) to acquire and process signals, equipped both with commercial acquisition cards (usually

manufactured by National Instrument) and a number of different busses (ISA, PCI, PCMCIA).

6 Conclusions

Signals generated by sources stimulated by both natural and designed stimuli and located on the single parts of a jointed structure, are transmitted to sensors through source-sensor transmission channels whose characteristics depend on to the type of the structure and the assembly of its parts. The proposed diagnostic method can be applied when the characteristics of the transmission channels do not change after their preliminary identification. As a matter of fact, channel characteristics are defined through a first off-line experimental procedure performed using properly designed stimulation. In the applications carried out by the authors but also by other researchers the stability of the transmission channels was usually ascertained, for instance for transformers and electromechanical structures in general. The transmission channel set may involve one or more connecting networks. Signals associated to a single stimulus usually follow preferential transmission channels, which are different inside each distinct part of the joined structure. The transmission times are usually different, and the observed delays can often help in the definition of the state of a structure; for instance the delays noticed during open/close operations of circuit breakers proved to be very useful. In the case examined vibrations were detected after the activation of triggers properly coordinated with the performed circuit breaker operations. To increase the observation resolution of the diagnostic system, that is, to detect a greater number of parts of the joined structure, an increase in the number of the significant parameters is usually required. The diagnostic process was implemented by adopting knowledge-based procedures. Actually, also statistical processes may be used, but in this case a relevant number of tests must be done as concerns the behavior of the different parts subjected to a known stimulation performed by means of either natural or designed stimuli. If statistical data is abundant and a great knowledge of the involved phenomena is reached, also subsequent knowledge-based procedures could be applied, usually obtaining more reliable results.

References:

[1] J.C. Van den Berg, *Wavelets in Physics*, Cambridge University Press, Cambridge, 1999.

[2] Russel M. Merserau, Mark J.T. Smith, *Digital Filtering*; Georgia Institute of Technology, 1994.

[3] G. Strang, T. Nguyen, *Wavelets and Filter Banks*, Wellesley-Cambridge Press, Wellesley, Massachusetts, 1996.

[4] G. Fazio, L. Lezzerini, G. Sacerdoti, M. Caporaletti, D. Sacerdoti, R. Visco, *Supervision of airport areas by techniques of acoustic survey and analysis*, Bird Strike Committee Europe, BSCE22/WP-66 Conference, Vienna, August 1994.

[5] S. Cara, V. Di Luozzo, V. Di Pierri, G. Fazio, M. Pompili, G. Sacerdoti, D. Sacerdoti, *Diagnosi acustica degli accessori per cavi MT*, Annual meeting AEI, 1997, pp.95-100 (in Italian).

[6] C. Bartoletti, G. Fazio, D. Sacerdoti, G. Sacerdoti, P. Saulli, *Measurements on non-homogeneous insulations in MV electric devices: methods and apparatus*, XV IMEKO Conference, June 13-18 1999.

[7] G. Fazio, V. Lauropoli, F. Muzi, G. Sacerdoti, *Variable-window algorithm for ultra-high-speed distance protection*, IEEE Transactions on Power Delivery, Vol.18 April 2003 pp.412-419.

[8] G. Fazio, F. Muzi, S. Ricci, G. Sacerdoti, *Circuit-breaker diagnostics based on continuous wavelet transform*, IEEE PowerTech International Conference, Bologna, June 23-26, 2003.

[9] C. Bartoletti, M. Desiderio, D. Di Carlo, G. Fazio, F. Muzi, G. Sacerdoti, F. Salvatori, *Vibro-acoustic techniques to diagnosi power transformers*, IEEE Transactions on Power Delivery vol. 19, January 2004 pp. 221-229

[10] C. Bartoletti, G. Fazio, M. Marinelli, F. Muzi, G. Sacerdoti, *Electromagnetic and acoustic emissions to diagnose complex electrical and mechanical structures*, IEEE Power Engineering Society, General Meeting, Denver, Colorado USA, June 6-10, 2004.

[11] M. Cerullo, G. Fazio, M. Fabbri, F. Muzi, G. Sacerdoti, *Acoustic Signal Processing to Diagnose Transiting Electric-Trains*, IEEE Transactions on Intelligent Transportation Systems, Vol. 6, No. 2 June 2005.