Visual predictive maintenance tool based on SOM projection techniques

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This paper presents a portable condition monitoring system named MAPREX, which was developed as a result of the cooperation between the University of Oviedo and Aceralia inside of a research project funded by the ECSC Steel RTD program. The system integrates powerful monitoring and data visualization techniques based on the Self Organizing Map (SOM) algorithm. This paper describes in details the system architecture and performances, visualization techniques implemented and an example displaying real data from a 6,000 kW DC motor of a hot strip mill rolling stand.

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■ INTRODUCTION

This paper presents a portable condition monitoring system named MAPREX, which was developed as a result of the cooperation between the University of Oviedo and Aceralia inside of a research project funded by the ECSC Steel RTD program. The system integrates powerful monitoring and data visualization techniques based on the Self Organizing Map (SOM) algorithm. The architecture of the system is described in details as well as the visualization methods implemented.

■ THE VISUALIZATION APPROACH

In complex industrial processes and particularly in steel processes, there is usually a lack of models that provide a comprehensive description of the process behaviour. All the information available is often present in quite heterogeneous ways, much the same as sparse pieces of knowledge, which had to be put together and related. In a typical steel rolling process, there are several sources of knowledge :

- *Sensor data* : Data from multiple sensors are often systematically recorded in huge databases, being available for subsequent processing in the mill computer. Data from sensors clearly convey a lot of information about the underlying process behaviour, which is implicitly embedded in the geometry of the data.
- *Partial models* : When looking for a model to represent a new process, it usually happens that there are models that describe well parts of that process, while there is a lack of models that accurately describe the full process behaviour.
- *Rule based knowledge* : Often, most of the knowledge is in hands of the staff that deals everyday with the process and in many cases that staff does not have a deep mathematical background to materialize that wealth of knowledge about the process in mathematical models. The knowledge is often present in terms of a bunch of rules (often fuzzy), which have proved to be useful along years.
- *Cases* : Finally, another source of knowledge comes from cases. These are sets of data from key situations, such as breakdowns or others, aroused formerly, which underwent an investigation process. These datasets, in consequence, may convey a lot of associated knowledge that can be used for better understanding of the process.

Outil visuel de maintenance prédictive fondé sur des techniques de projection SOM

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Introduction

Cet article présente un système portable de maintenance conditionnelle dénommé MAPREX, développé en partenariat entre l'Université d'Oviedo et la société Aceralia, dans le cadre d'un projet de recherche financé par le programme de RDT « Acier » de la CECA. Le système intègre de puissantes techniques de surveillance et d'affichage de données, basées sur l'algorithme SOM (Self Organizing Map).

Dans le cas des processus industriels complexes, on observe fréquemment un manque de modèles permettant de décrire le comportement du processus. Dans le développement d'un système de surveillance, la phase de compréhension du processus demande normalement beaucoup de temps et de ressources, ainsi que des outils puissants pour afficher les données d'une façon efficace et trouver ainsi des règles permettant de construire un modèle représentatif. Le système portable décrit dans cet article utilise une version continue du SOM pour projeter un vecteur dimensionnel de haut niveau, représentatif des données du processus (typiquement obtenu dans une phase préalable d'extraction de caractéristiques), sur un espace de visualisation bidimensionnel, V, dans lequel les nombreuses conditions du processus sont représentées par différentes zones de l'espace.

Espace de visualisation

L'espace de visualisation constitue un cadre unifié de représentation de processus, dans lequel on peut représenter les variables du processus ainsi que des jeux de conditions précédentes (obtenues avec le processus en fonctionnement dans des conditions connues). Ceci permet d'obtenir une représentation graphique des conditions de travail en termes de régions, d'une façon similaire à la représentation de densités de population, de courbes de hauteur ou de taux de pluie dans des chartes cartographiques.

Description du système

Le système MAPREX est installé sur un PC portable ordinaire qui comprend le processeur, des unités de disque, un écran LCD et tous les dispositifs auxiliaires habituels, dans une seule boîte de $40 \times 35 \times 25$ cm³. Il inclut également plusieurs ports PCI pour cartes d'acquisition de données. L'architecture du système comprend quatre modules principaux :

• Un module d'acquisition de données (DAQ), dont la fonction est la saisie périodique de blocs de données, avec une fréquence d'échantillonnage programmable et une mémoire tampon prédéfinie, à travers les canaux pré-configurés des cartes d'acquisition.

• Un module d'extraction de caractéristiques (FX) totalement configurable, qui permet le calcul et l'affichage d'un jeu de caractéristiques pour chaque variable mesurée et chaque mémoire tampon. Le système utilise deux méthodes d'extraction de caractéristiques :

a) caractéristiques statiques, obtenues en calculant la moyenne des valeurs contenues dans la mémoire tampon pour les variables dont la forme d'onde n'est pas significative,

b) caractéristiques spectrales, qui représentent l'énergie contenue dans des bandes spectrales prédéfinies, dont il est possible de configurer les fréquences centrales et les largeurs de bande pour chaque caractéristique.

• Un module SOM, qui permet de modéliser les jeux de caractéristiques obtenues préalablement avec le module (FX) en utilisant un algorithme SOM. Cet algorithme définit une charte non linéaire sans-pic à partir de l'espace de caractéristiques sur un espace de visualisation bidimensionnel (V), permettant d'afficher l'information du processus de façon efficace. Ce module offre de multiples possibilités d'affichage :

a trajectoire de statut, constituée par la projection de chaque vecteur du processus ayant une nouvelle signature dans (V), ce qui définit une trajectoire montrant l'évolution du statut du processus ,

b) chartes de caractéristiques, qui affichent dans l'espace de visualisation la valeur de chaque caractéristique du processus par des chartes de couleurs, permettant de relier les conditions actuelles du processus avec leurs régions correspondantes dans l'espace,

c chartes d'activation, qui permettent d'identifier les régions de l'espace de visualisation correspondant aux états précédents (connus) du processus,

d) chartes de corrélations locales, qui montrent les interdépendances locales entre deux caractéristiques quelconques du processus.

• Un module de résiduels, qui utilise des chartes avec les couleurs correspondantes pour afficher l'évolution des vecteurs résiduels, définis comme la différence entre le vecteur actuel de caractéristiques du processus et l'estimation du même vecteur fournie par le modèle SOM. Les vecteurs résiduels fournissent de l'information sur les possibles déviations par rapport au comportement espéré du processus et permettent d'afficher la présence de conditions anormales dans le processus ainsi que les variables concernées.

Résultats

L'article présente également un exemple d'application du système pour la visualisation de plusieurs variables d'un moteur CC (6 000 kW) de grandes dimensions en service sur un train à bandes. Dans l'exemple, trois variables sont suivies : courant de champ, courrant du rotor, et voltage du rotor. Le système est configuré pour l'extraction des caractéristiques de ces trois variables ainsi que celles des énergies des harmoniques du courant du rotor à 300 et 600 Hz, qui sont étroitement liées aux ondulations d'ondes provoquées par le redresseur à double pont qui alimente le moteur. Le modèle SOM a été entraîné avec les données saisies sur le moteur et les chartes produites avec ces variables (ces chartes sont incluses dans l'article), identifiant les différents états du moteur : fonctionnement en charge, fonctionnement à vide, régénération, arrêt. Ceci permet de comprendre et de superviser les modes de fonctionnement du moteur à chaque instant.

Conclusions

MAPREX est un système intelligent portable, de grande versatilité, qui présente une alternative à la plupart des systèmes portables commerciaux de surveillance conditionnelle. MAPREX permet la saisie de données par multiples canaux, la surveillance FFT, le suivi des énergies dans des bandes de fréquences prédéfinies et une visualisation avancée en deux dimensions, fondée sur la technique SOM, des conditions du processus. Le système permet aux techniciens de configurer in situ tous les paramètres (sélection de mesures, étape d'extraction de caractéristiques, etc.) en fonction des conditions de l'installation et des besoins de production. Grâce à sa portabilité, le système peut être utilisé là où il est nécessaire, de la même façon qu'un oscilloscope, en fonction des besoins de la maintenance à chaque moment, ce qui évite la nécessité d'installer un grand nombre de systèmes de surveillances conditionnelles fixes.

Such different types of knowledge about the process are virtually impossible to merge in an automated fashion and need human intervention in the loop of process analysis. The process understanding stage in the development of any supervision system usually takes a lot of time and resources and requires powerful tools, which allow visualizing the data in an efficient manner in order to find rules or regularities that allow building a sensible model.

Visualization techniques have been recently used for extremely complex problems such as gene expression analysis in the field of Genomic, or document organization and retrieval in information technologies. The human being usually thinks visually. We often say "to see something" or use visual metaphors such as "to see something clear" or "to get a perspective of something" to represent cognitive processes. The visualization approach seeks to take advantage of the extremely powerful visual reasoning and pattern recognition abilities of the humans by producing 2D-3D visualizations of high dimensional process data without loosing significant information about the process, which permits the human to reason and infer conclusions through these visualizations.

One way to achieve that is the dimension reduction approach (DR). The DR approach consists of generating a (typically non-linear) mapping from the multi-dimensional process data space (P) onto a low dimensional (2D, 3D) visualization space (V) in such a way that no significant information about the process data geometry is lost. Such a mapping results in an one to one correspondence between a low dimensional manifold living in the high dimensional space (P) that adapts its shape to the process data, and a low dimensional space, called the visualization space (V), used for representation purposes, on which all process data are to be projected.

In this way, the process evolution, which leads to a trajectory of a point in the high dimensional process data space (P), is mapped on (V), leading to a 2D trajectory that can be visualized and tracked. This allows converting the problem of supervision and condition monitoring into a matter of tracking the regions in (V) that the 2 D trajectory reaches at every moment. Some representative techniques of this paradigm, which have been used in the literature for process analysis and supervision, are principal component analysis (PCA) projections, multidimensional scaling (MDS), and Self Organizing Maps (SOM), among others.

The visualization space (V) provides a unified framework for process representation in which process variables, as well as sets of previous states where the process was performing under known conditions, can be represented and this allows to describe the working condition in a graphical way, in terms of regions, in the same way as cartographic maps allow to represent population densities, mountain elevations or rain fall indices.

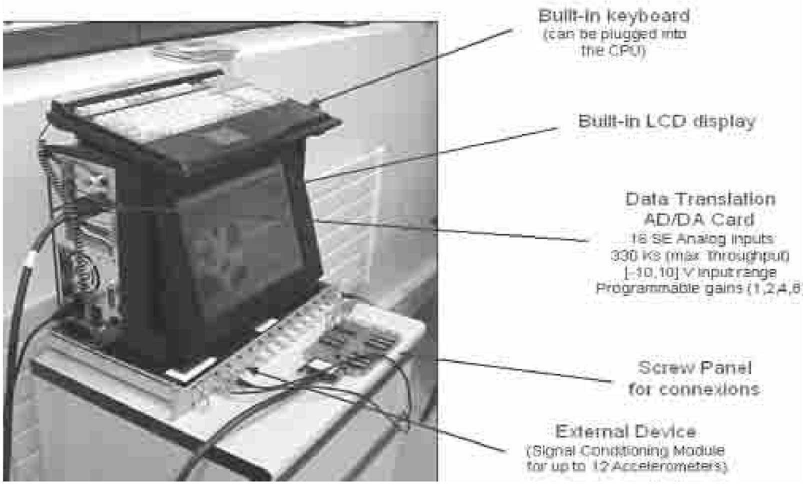

Fig. 1 – Picture of the MAPREX system.

Fig. 1 – Vue du système MAPREX.

■ SYSTEM DESCRIPTION

Hardware description

The idea of visualization described in the previous section was carried out on a portable system meant for analysis and supervision of a wide variety of steel processes. The system, called MAPREX, was developed as a result of the cooperation of the University of Oviedo and Arcelor-Aceralia Corporacion Siderurgica in a research project funded by the ECSC Steel RTD program.

MAPREX *(fig. 1)* consists of a commercial portable PC, which integrates the motherboard, disk units, an LCD monitor and all the typical auxiliary devices, in a single box of $40 \times 35 \times 25$ cm^3, including several PCI ports for data acquisition boards.

Functional description

MAPREX is structured in four functional blocks, which are shown in *figure 2 :*

- A data acquisition module (DAQ) designed for data acquisition board management and raw data storage.
- A feature extraction module (FX), which obtains an appropriate feature set for unique characterization of the process working state.
- A SOM visualization module, which uses a SOM map to model and visualize the process data (features), as well as to visualize on line the 2D state projections.
- A residuals module, which allows the detection and visualization on line of any deviations of the process from those states learnt from the training data.

These four blocks are next described in details.

Data acquisition module (DAQ)

MAPREX has a data acquisition (DAQ) module that manages everything concerning the acquisition of data and allows the configuration of different parameters such as :

- sampling period,
- timings for captures,
- buffer lengths, etc

This module uses the DT-Open Layers standard from Data Translation Inc being able to manage a wide range of Data Translation AD/DA cards.

The module periodically captures blocks of data (each block composed by one buffer per channel) at the selected sampling rate (f_s) and predefined length (N) from a number of previously configured channels of the acquisition board, for further processing by the next modules.

Feature extraction module (FX)

The feature extraction module (FX), allows the obtaining of a set of characteristics from each measured variable and buffer. It is fully configurable.

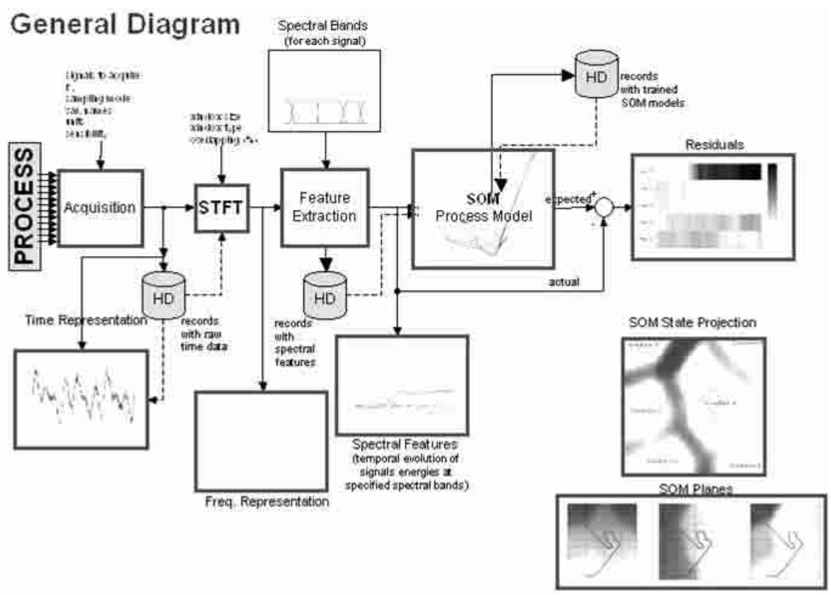

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Fig. 2 – MAPREX functional block diagram.

Fig. 2 – Diagramme de blocs fonctionnels de MAPREX.

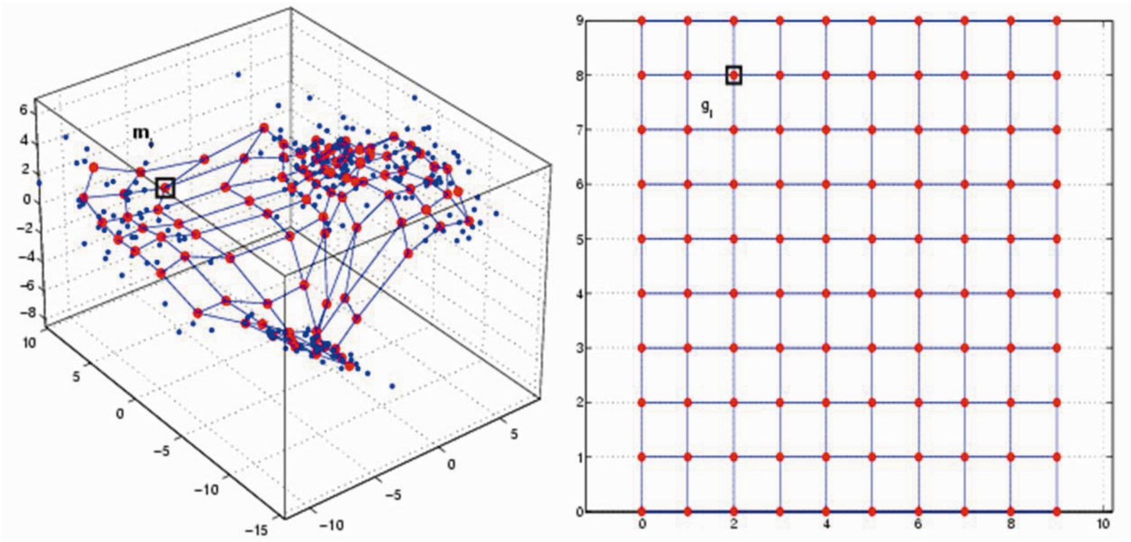

Fig. 3 – SOM mapping : On the left, the process data space, (P). On the right, the visualization space, (V).

Fig. 3 – Cartographie SOM : À gauche, l'espace de données du processus, (P). A droite, l'espace de visualisation (V).

The characteristics of the variables can be extracted in three ways :

a) Static features, which are obtained by taking the mean value along the buffer for those variables in which the wave shape is not significant (typically pressures, temperatures, and so on).

b) Stationary spectral features (fixed frequency bands). This feature allows MAPREX to extract characteristics by computing the energy content in predefined spectral bands of the variables considered. Centre frequencies and bandwidths can be configured for each characteristic.

c) Non-stationary spectral features (variable frequency bands). Additionally, variable centre frequencies (typically intended for applications involving mechanical vibrations) can be set in MAPREX by relating the centre frequency to another variable. This allows, as an example, to obtain the power content in a 5 Hz band around a frequency that is twice the rotating speed of a motor.

When properly chosen, all the characteristics computed in the k-th block of buffers form a feature or characteristics vector that can be considered the signature or firm of the process and which mathematical expression is of type :

$$f(k) = [f_1(k), f_2(k) \ldots, f_n(k)]^T$$

These characteristics vector will be used for further visualization and analysis in the SOM module.

SOM module

As previously mentioned, the characteristics vectors f(k) obtained in the FX module, under a proper choice of features, are supposed to contain significant information of the process status. These vectors, obtained from a wide variety of process status, are stored in the system and used for further processing.

The stored characteristics vectors that represent different previous process states can be retrieved to train a Self Organizing Map using the batch version of the SOM training algorithm:

$$c(k) = \arg\min_i \|f(k) - m_i(t)\|, \; k = 1, 2, \ldots, N$$

$$m_i(t+1) = \Sigma_k \, h_{c(k)i} \, . \, f(k) \, / \, \Sigma_k \, h_{c(k)i}$$

where m_i represent the coordinates of the (i-th) SOM unit in the process data space of the SOM nodes (units), c(k) represents the index of the best matching unit, $m_{c(k)}$, and $h_{c(k)i}$ is a neighbourhood function defining a proximity measure of node i to node c(k) in the visualization space V.

After the training process, the SOM defines a non-linear smooth mapping from the multidimensional space of process data characteristics (P) on the two dimensions visualization space, (V) allowing displaying the current status of the process defined by its signature. *Figure 3* shows a graphical example of the correspondence between both spaces.

The SOM module allows several visualizations :

a) *State trajectory* : The online projection of each new signature vector of the process on (V) defines a trajectory, which shows the evolution of the process state.

b) *Characteristics maps* : Each point in (V) has a corresponding point in the feature space ; this allows the display of the value of each feature (e.g. temperature, or 25 Hz power content of an acceleration measurement), using color maps that give a clue of the current condition that the process is reaching.

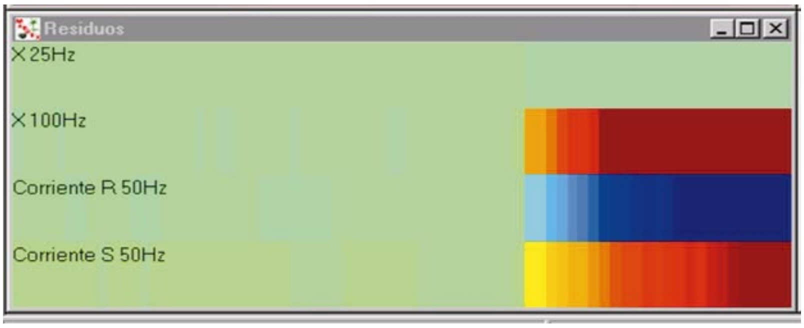

Fig. 4 – Residuals map of 4 variables of a process.

Fig. 4 – Charte de résiduels de 4 variables d'un processus.

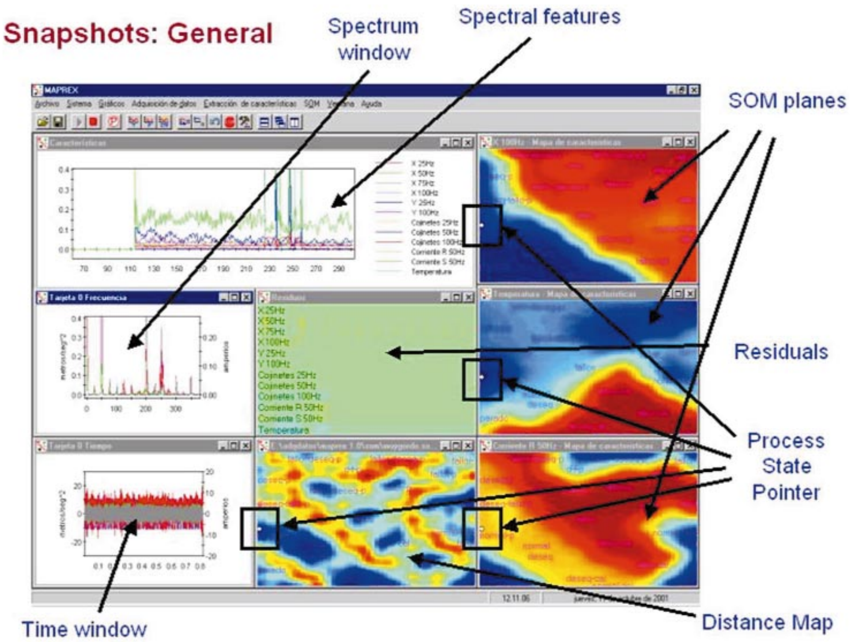

Fig. 5 – Different MAPREX on-line visualizations.

Fig. 5 – Différents affichages on-line de MAPREX.

c) *Activation maps* : Regions corresponding to previous (known) process states can be shown in the visualization space using an algorithm developed by the authors, allowing to label regions in (V) corresponding to known conditions (case-based knowledge).

d) *Distance maps* : This kind of map gives a representation of the inter-neural distances and shows how the SOM divides the visualization space (V) in a set of clusters that correspond to different stable process conditions.

e) *Correlation maps* : Two variables or features of the process could be directly correlated for some working points and inversely correlated for other states. This is impossible to see by using the traditional methods, based on the (global) correlation matrix. MAPREX is able to compute a local version of the correlation matrix on each point of the image in the process space (P), describing the second order properties in the neighbourhood of the given point, and show the individual correlations r_{ij} in (V). This leads to the so-called correlation maps, which show up the local correlations existing between two given features in the neighbourhood of each process working point, building indeed a map of process correlations.

Examples of the different types of maps are given in *figures 4 and 5* and commented upon later on in this paper.

Residuals module

The SOM is actually a geometrical model of the process data (feature vectors), which allows describing each feature vector by means of an estimation according to the model.

Residuals vectors are defined as the difference between the actual feature vector of the process and its best estimation according to the SOM model.

$$r(k) = f(k) - m_{best}(k)$$

When a process condition is properly modeled by the SOM, the residuals for that condition become close to zero. However if a novel condition or fault appears, which was not present in the training data, some residuals become significantly non-zero. Moreover, variables with non-zero residuals can be considered as suspicious for being involved in the apparition of the new condition or fault.

In the same way as the feature vectors and their projections on the visualization space, the residuals vectors (r (k)) are computed each time a new buffer of data is acquired. The residual vectors are composed by a set of scalar residuals corresponding to each of the features that compose the characteristics vector and their mathematical expression is of the type :

$$R(k) = [r_1(k)\ r_2(k) \ldots r_n(k)]^T$$

An efficient visualization of the residual vector, as it is implemented in MAPREX, is done by computing the matrix :

$$R = [r(k-n+1)\ r(k-n+2) \ldots r(k-1)\ r(k)]$$

and then visualizing it by means of an image whose pixels are the elements of R and using a colour code. The chosen code uses colour scale that goes from dark blue, which represents highly negative values, to dark red, corresponding to high positive values, the light green being the colour that represents residual values near to zero, which should be the normal situation when everything goes according to the expected behaviour. In this way, we can obtain a representation where the x-axis represents time, the y-axis represents the features whose residuals are computed, and any colour different from green represents positive (red tones) or negative (blue tones) deviations from the expected values for the corresponding feature or variable.

This visualization allows displaying the presence of an abnormal process condition and even the variables involved on it by looking at the colour of their residuals. *Figure 4* is an example of a residual map of four variables, corresponding to an induction motor that starts having phase current unbalance. It can be seen as at a given moment phase (S) current starts increasing and phase (R) current decreasing. This causes an unbalance in the motor that is represented by an abnormal increase of the 100 Hz harmonic.

Finally, *figure 5* shows a typical screen of the MAPREX system during normal operation where are displayed at the same time several on line visualizations of the process state, such as: the instantaneous spectrum, the evolution of the selected features, a pointer describing the projected state trajectory over several SOM maps (distance map, SOM maps, activation maps, etc). The screens are refreshed on line at a rate of about some six frames per second.

■ RESULTS

As an example of the type of results that can be currently obtained from MAPREX, next are shown the results obtained after applying this system to the visualization of three electrical variables : armature voltage (V_a), field current (i_f) and armature current (i_a), of a large (6,000 kW) DC motor used in a hot strip mill finishing stand.

MAPREX was connected to the motor signals during a period that includes different motor working conditions like: stopped, running under no load and running under rolling load among others.

Figure 6 is a screen of MAPREX showing the evolution along time of those three signals as well as two more characteristics extracted by MAPREX STFT module that represent the energies of the armature current (Ia) harmonics at 300 and 600 Hz. These two harmonics are present in the system as a consequence of the half reversing configuration of the rectifier used to feed the motor and they give information about the rectifier working conditions.

In *figure 6*, motor stopped conditions are represented by the motor armature voltage (V) at zero level, motor running under no load represented by situations where (V) is high (700 volts) while the armature current (Ia) remains near to zero, motor running conditions when values of (V) and (Ia) are simultaneously high and motor regenerating (pumping energy back to the electric network) during the short periods at the end of a rolling period when (V) is high and (Ia) goes to negative values. 300 Hz armature current harmonic is a consequence of the six-pulse reversing rectifier hence that its value is high during regeneration, while 600 Hz harmonic, inherent to the twelve-pulse forward rectifier, increases during rolling conditions. Regions where values of 300 and 600 Hz harmonics are high simultaneously, while the motor is running under no load conditions, are created by the rectifier working alternatively in forward and reverse situations when trying to keep constant the motor speed. This is usually caused by mechanical problems like misalignment of the motor tachometer, backlash or unbalance of spindles, etc.

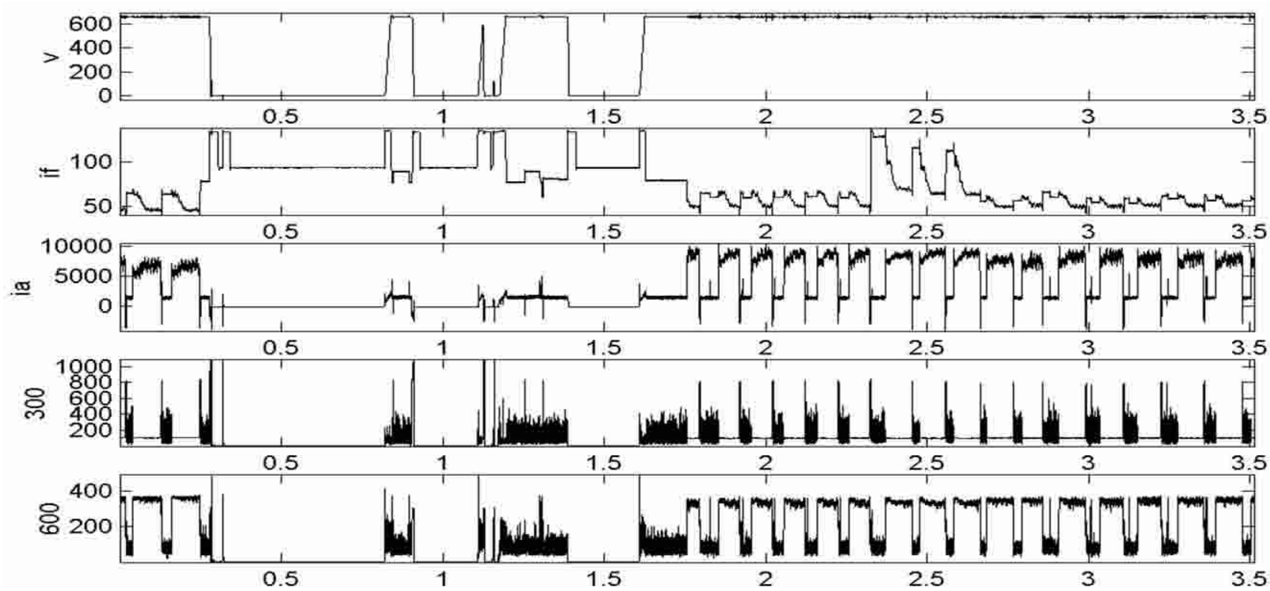

Fig. 6 – Five features taken from a 6,000 kW, DC motor.

Fig. 6 – Cinq caractéristiques saisies d'un moteur CC de 6 000 kW.

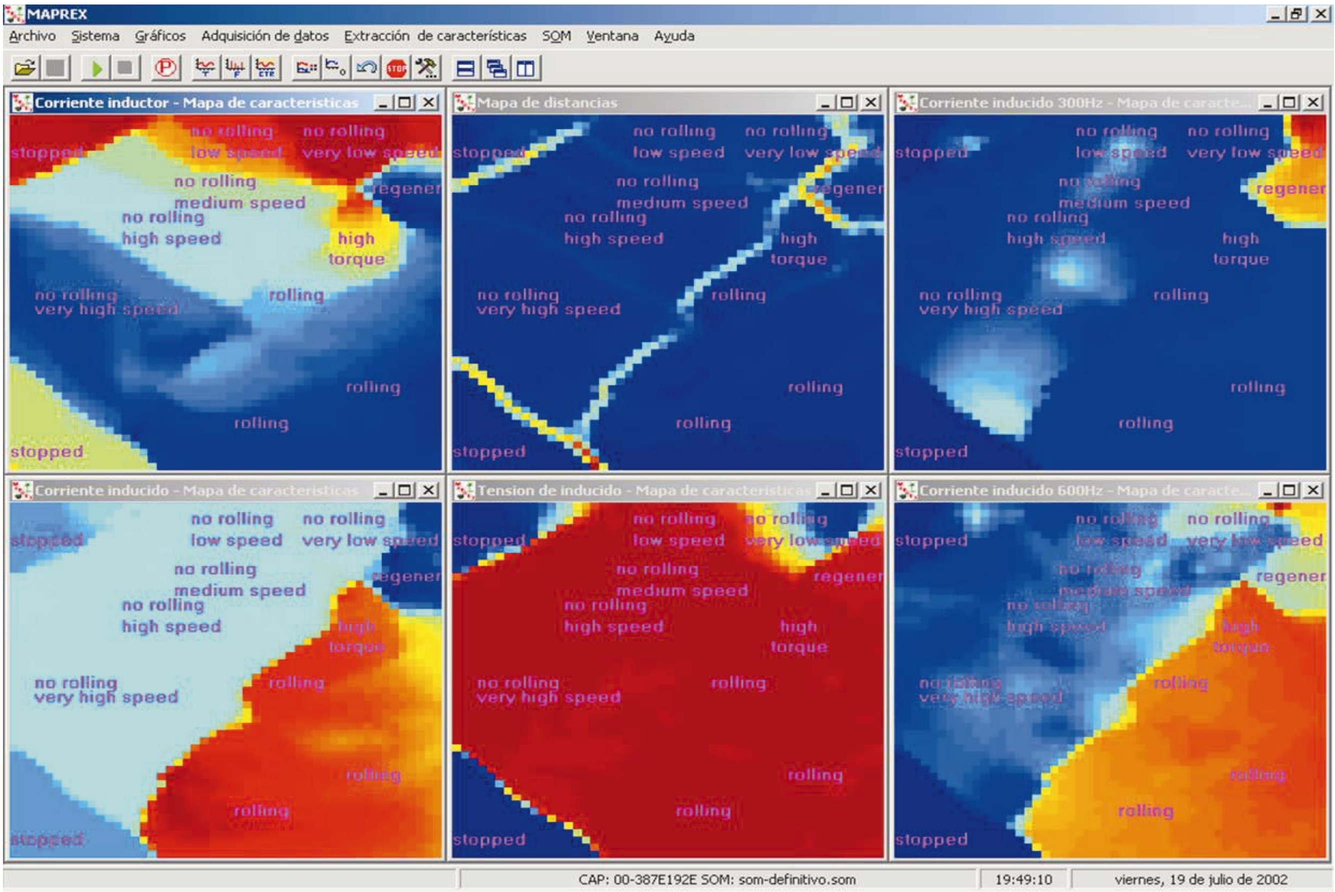

Fig. 7 – SOM maps obtained by MAPREX from data of a 6,000 kW DC motor.

Fig. 7 – Cartographie SOM, obtenue par MAPREX, des données d'un moteur CC de 6 000 kW.

Data captured of the three variables read, representing different motor working conditions, plus the two variables extracted by the STFT module, were used to train the SOM. The result was a set of maps generated by the SOM for each one of these variables. *Figure 7* shows the distance map (top centre) and the characteristics maps for the five variables considered. The distance map shows clearly identified five clusters or regions that correspond to different motor conditions : motor stopped with the breaker open, motor stopped with breaker closed, motor running under no load conditions, motor running under rolling load and motor regenerating. Different sub-clusters are also identified inside of each region, which correspond to different values of the variables.

Identification of each one of these regions with each motor condition is quite easy using basic motor regulation knowledge, like used previously to explain curves of *figure 6*. Motor running under rolling load conditions will correspond in the maps to areas of simultaneous high values (reddish colour) of the armature current (Ia), 600 Hz harmonic and armature voltage (V), condition that is present in the bottom right corner region of the characteristics maps of these variables, so that clusters represent, for all the maps, the rolling condition. Motor regenerating will be represented in the maps by areas where the 300 Hz harmonics is high (reddish colour) and armature current negative (deep blue colour), conditions that are present at the top-right corner of the characteristics maps. Motor stopped with its breaker open will be represented by regions where the armature voltage (V) and field current (If) are low simultaneously, which happens in the bottom left corner. Similar reasoning will permit to identify the rest of the clusters and sub-clusters. The degree of identification will depend only on the expert knowledge of the user.

As it can be seen the identification procedure is made easier by the fact that the SOM places the same process condition in the same position in all the maps. Labelling of all the clusters is also very easy : put the mouse pointer on the selected region of any map, do a double click and write the text for that cluster. The same label will appear automatically in the same region of all maps.

Figure 7 shows an example of the aspect of the SOM maps once the identification of the different clusters is completed.

For this example the SOM was trained using only normal working motor conditions, but it can be also trained with different fault or alarm conditions or any other condition for which there is enough information available. The SOM will create specific regions in the maps for each one of these conditions.

Once the SOM is trained, the system can be taken to the plant and connected to the variables selected for its on line monitoring. A live pointer that represents the current process condition will appear in same position in each one of the different SOM maps. This pointer position is refreshed some six times per second. Looking at the current pointer position and reading the label of that region, or looking at its colour, it is possible to have a quick idea of the current status of the variables displayed.

■ CONCLUSIONS

MAPREX is a highly versatile portable system that represents an alternative to most of the commercial portable condition monitoring systems, which are typically meant for data logging, FFT monitoring and alarm threshold setting, and in most cases only allow a reduced number of signals to be analyzed simultaneously.

This system allows the technical staff to configure in situ the whole setup (measurement selection, feature extraction stage, etc.) according to the actual conditions of the plant and the production requirements. It can also be used just there where it is needed, in the same fashion as an oscilloscope, depending on the requirements of the plant maintenance, thus avoiding the need of installing many fixed condition monitoring system.

The fact that it can be configured in plant, the easy procedure implemented to label the different map regions (which allow the incorporation of the user's expert knowledge and perceptual information) and its flexibility in the variable and feature selection, permits an instantaneous prototyping of supervisory systems. Also, the modular approach followed during the development of the prototype for the math and acquisition modules makes easy the incorporation of new features.

MAPREX system is not yet fully achieved and some of the original work still has to be done. Current work is focused on the integration of a database in the system and remote access using a TCP/IP protocol. A new interesting feature, currently in progress, is the integration of a fuzzy inference system (FIS), which will permit the integration of prior knowledge based on rules.

The FIS could be applied to residuals, features, or SOM codebooks to provide specific diagnostics. This feature is especially interesting in the case of SOM codebooks, which will allow the generation of the so called "fuzzy maps" that represent the regions in the visualization space where a rule or set of rules are valid.

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