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A PATTERN RECOGNITION APPROACH TO CONDITION-BASED PLANT MAINTENANCE

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1.INTRODUCTION

The maintenance optimization comes to the balance between the cost of failures and maintenance expenses. However, if the latter can be easily assessed, the former is rather vague. Usually to show qualitative optimum the cost of failures is drawn as a decreasing function of a maintenance volume [1] whereas the maintenance expenses increase at least linearly (considering the preventive maintenance only). The sum of these functions gives of course a minimum. Such presentation of the cost of failures function suggests that it is proportional to the failure probability function which (in authors' opinion) from a quantitative point of view is impossible to find. Nevertheless, this diagram shows two ways to expenditures minimization by maintenance costs and/or a failure probability decrease. In accordance with G.Zwingelstein [1] the condition- based maintenance is "the only way of significantly decreasing the probability of major failures" by the early determination of the necessity for preventive restoration actions. This sort of plant maintenance "is initiated as a result of a pre-determined type of criteria which measure equipment degradation" [1], then one can conclude that the plant reliability and safety improvement depends on the quality of the chosen criteria. In this paper authors propose to enrich the existing and widely used integral and threshold criteria by the differential ones using the pattern recognition techniques. The simple logical system to condition monitoring and surveillance is proposed and exemplified.

2. CONDITION-BASED SURVEILLANCE SYSTEM CONCEPT

The simplest conditions for the nuclear reactor restoration actions or/and reactor stop consist in checking whether some pre- determined parameter overcome some pre-determined threshold. For example, Fig.1 [2] shows the power fluctuations σ_W/W -the relative average power standard deviations- of the IBR-2 Dubna (Russia) reactor during an operation time period from the end of 1987 to the beginning of 1991. Because of the abrupt σ_W/W increase i.e. almost 1% a month (marked by the arrow in Fig.1), the action was undertaken that led to the σ_W/W stabilization on the 8% level. However, because of significant σ_W/W in time fluctuations and the closeness of the reactor stop threshold, the threshold criterion is insufficient anymore. The more accurate criterion is necessary to monitor early failures, degradation trends and their possible sources. Early restoration actions could increase, in turn, the reactor resource cycle.

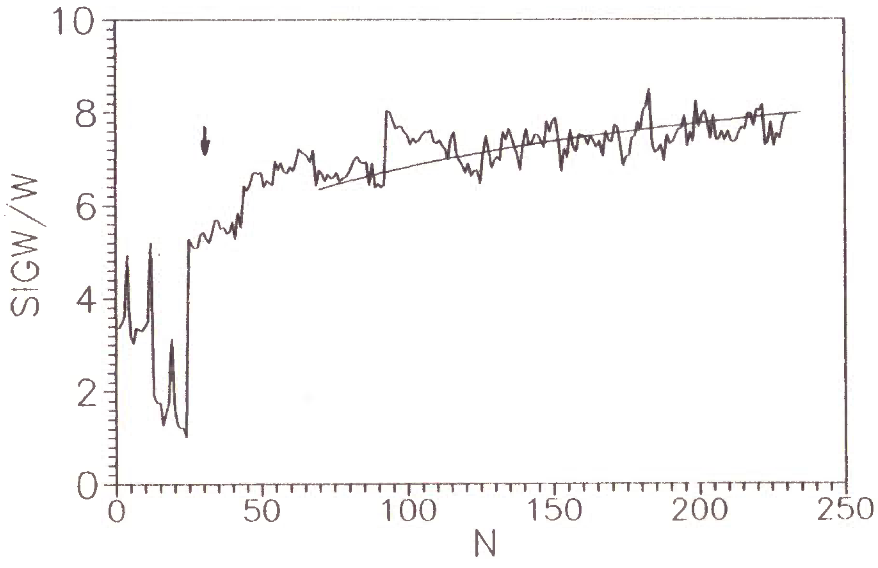

Fig.1 The power fluctuations σ_W/W during the IBR-2 reactor operation period from the end of 1987 to the beginning of 1992. The interpolated degradation is shown.

The differential characteristics as the power spectral densities (PSD) or the power time series are more sensitive to the reactor operation changes than their respective integrals [3]. The changes in e.g. subsequent PSD form (may not be followed by the changes of their respective integrals) can reflect the abnormal reactor operation [3], incipient degradation [2] and even help to find the source of failures. However, in contrast with the clear threshold conditions, the set of subsequent spectra must be conditioned in a quite different manner. One out of the possible approaches to this problem consists in the comparison of the subsequent spectra with a base of specified number of spectra which corresponds in turn to the normal reactor operation using the set of discriminants. The discriminants are defined so that they describe different features of the signal behavior [4]. Then, the membership of a subsequent spectra in the base could determine the normal reactor operation. However, the only information that the subsequent spectra is not the base member is insufficient to undertake the restoration actions. Let us suppose that one can determine the source of a deviation unessential for the normal reactor operation. What should be done then? The new spectra must not be neglected but has to be included in the new updated base as a member. The degradation processes like aging requiring the continuous base update contribute to its expansion and compactness loss. The new discriminants must be introduced to prevent the membership mistakes and an accuracy loss.

Inadequacy of such an approach to the condition- based maintenance mainly results from considering the reactor to be a stable system. The useful information about its dynamic behavior i.e. the reactor operation past and degradation trends are neglected. In Fig.2 the flowchart of the proposed "dynamic" surveillance system is depicted. Let us X_{Mi} be the principal transient reactor operation characteristics e.g. the power fluctuations represented by its PSD, and $\{\sigma_{Mi}\}$ be a set of X_{Mi} integrals recorded e.g. the average and maximum power standard deviations. Simultaneously with X_{Mi} and σ_{Mi} the secondary reactor characteristics X_{Ki} $\{K=1,\ldots,N\}$ reflecting the separate reactor piece of equipment or the subprocesses behavior (e.g. the vibrations of rotating machinery, pumps, coolant flow noises etc.) and their

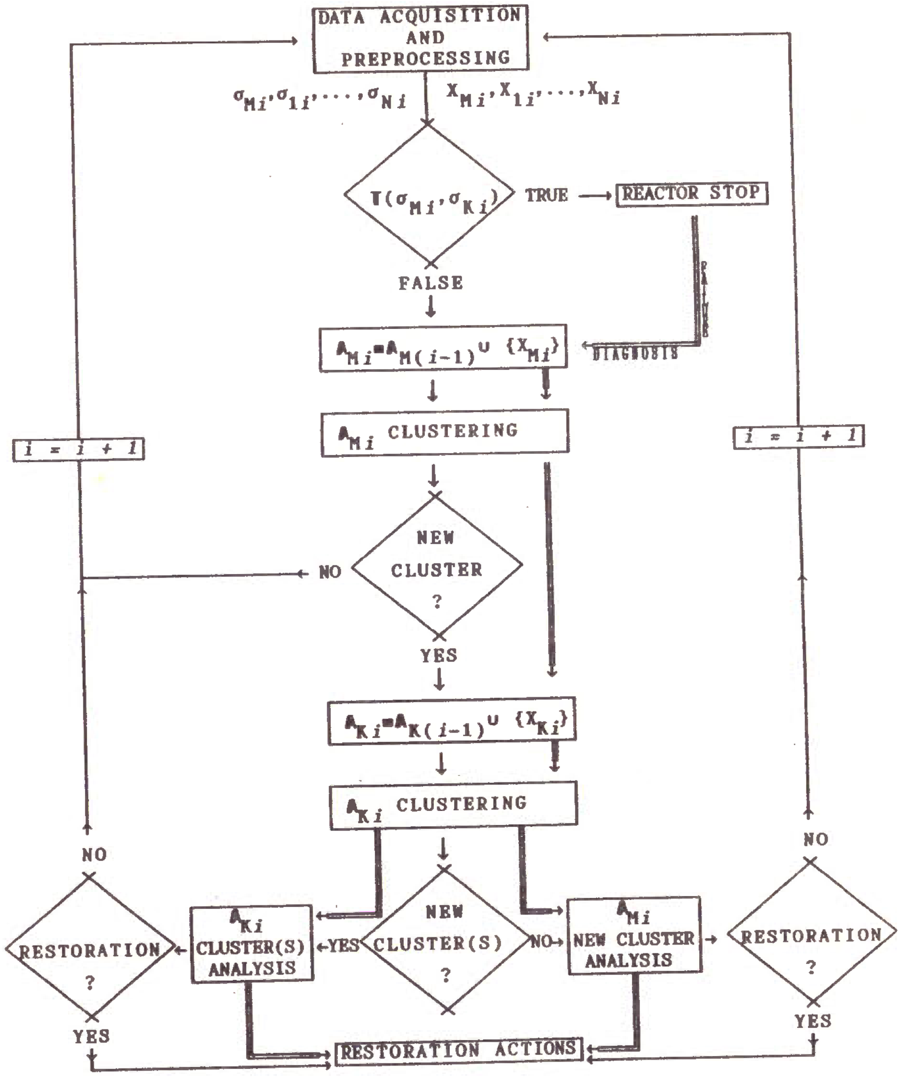

Fig.2 The flowchart of the surveillance system proposed.

integrals σ_{Ki} are collected. If $\mathbf{T}\{\sigma_{Mi},\sigma_{Ki}\}\equiv$TRUE, where $\mathbf{T}$ is the set of pre-determined threshold stop conditions implied, the reactor stops and then the flowchart is followed along the failure diagnosis path. Otherwise, the subsequent X_{Mi} and X_{Ki} are added to the respective sets $\mathbf{A}_{M(i-1)}\equiv\{X_{Ml}, l=1,\dots,i-1\}$ and $\mathbf{A}_{K(i-1)}\equiv\{X_{Kl}, l=1,\dots,i-1\}$ of X-es recorded earlier. The updated set $\mathbf{A}_{Mi}$ undergoes clustering by means of the techniques presented in [5] and [6]. If a new cluster appears the flowchart is followed, otherwise the subsequent $X_{M(i+1)}$ and $X_{K(i+1)}$ are measured and preprocessed. A new cluster appearance signals a change in the reactor operation [3]. To find the source of an anomaly, the sets of secondary reactor characteristics $\mathbf{A}_{Ki}$ undergoes clustering separately. A new cluster appearance for one or a few of them points to the supposed anomaly sources. The decision to undertake restoration actions or not, with or without the reactor stop, depends on the source of anomaly and the results of estimation of its actual and predicted (if possible) influence on the main reactor operation parameters. If the clusters structures of each of $\mathbf{A}_{Ki}$ sets remains unchanged, the other reasons of abnormal reactor operation than those pre-determined by the choice of the set of secondary reactor characteristics recording, can be expected. In this case the process of cluster analysis and trends separation for the single $\mathbf{A}_{Mi}$ set, like as in [2], can help one in decision making. If the restoration actions are not necessary yet, the flowchart cycle is repeated. However, in contrast with the member-of-base approach the new updated cluster structure preserves the information about the reactor operation past and trends, that allow one to observe and signal its change in the next surveillance cycle. In the next section the application of this draft approach to the condition- based maintenance is exemplified.

3. THE APPLICATION

The system based on the logic briefly described above is used and developed for the IBR-2 pulsed reactor (Dubna Russia) long term surveillance. The IBR-2 reactor is used as a pulsed neutron source for performing the physical investigations on the neutron beams. The pulse energy (reactivity) is considered as the principal reactor operation characteristics, and its fluctuations analysis as the most valuable factor in the reactor safety control [7,8]. The power fluctuations are measured by means of the vacuum and ionization fission chambers placed mainly in the center of the reactor core and on the neutron beam. They are transformed into the power spectral density (PSD) computed for the assumed and constant control period [2]. Simultaneously with the principal reactor characteristic, several [6] secondary ones are measured. Two of them, namely, the moving reflectors vibrations (the main (OPO) and the additional (DPO) one), are still taken into account to the reactor surveillance. They are considered as the main rotating machinery characteristics influencing the reactor power fluctuation directly. In the nearest future the next five will be included i.e. desynchronization of the OPO/DPO angle, coolant temperature on the reactor core input and output and coolant flow rates in A and B loops of the cooling system. The moving reflectors vibrations are detected using capacity sensors, and then transformed into the respective spectral densities. The integrals like as the average and maximum standard deviations for the power fluctuations and moving reflector vibrations are computed and displayed. The regime of the long term IBR-2 reactor operation is periodical one i.e. in the single cycle it works non- stop two weeks then waits one weak with zero power.

The system proposed by the authors is rather aimed to the long term surveillance than to the transient (in-time) one. The operation changes from one reactor cycle to the another are traced. The subsequent integrals and differential characteristics are collected during a single reactor cycle and then the flowchart depicted in Fig.2 is followed. Such an approach contributes to the increase of the system accuracy and to avoidance of the point-to-cluster membership ambiguity.

As is pointed at the beginning of the previous section, the IBR-2 reactor has been operating for the last two years (see Fig.1) on the 8±0.5% average power standard deviation operation level, close to the 10% threshold level meaning the reactor stop condition. The only useful information about the trends in reactor operation must be derived directly from its differential characteristics. In Fig.3 the cluster membership time diagrams are presented both for the power (A_{Mi}) and moving reflectors OPO and DPO (A_{1i},A_{2i}) spectral densities sets. Fig.3 shows to which clusters the subsequent reactor characteristics fall during the last two years operation period. The correct coincidence between the power diagram changes and OPO and/or DPO ones (the

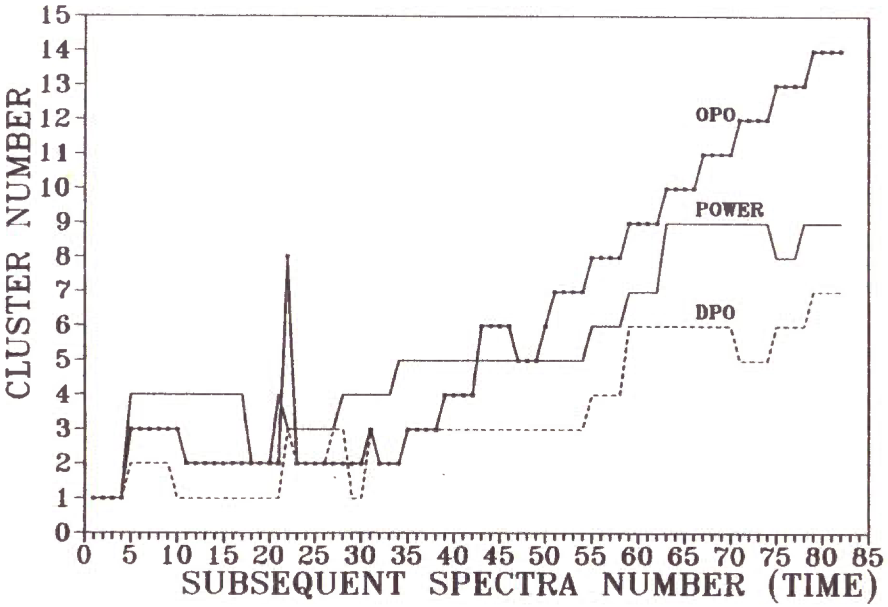

Fig.3 The cluster membership time diagrams for the power PSDs and OPO/DPO moving reflectors spectral densities. It shows to which clusters the subsequent reactor characteristics fall during the last two years reactor operation period. The coincidence between the power diagram changes and OPO and/or DPO ones can be observed.

appearance of a new clusters in power diagram is accompanied by the new clusters appearance for OPO and DPO cluster diagrams) can be observed. Therefore, following the flowchart presented in Fig.2 after a subsequent reactor cycle the mechanical deviations of moving reflectors turn out to be the main reason of the reactor operation changes. The decision about restoration actions can be elaborated by means of the degradation tendency control and the estimation of its influence on the main reactor characteristics. In Fig.4 the maps of the power, OPO and DPO subsequent spectral densities are presented. They are used for the detailed reactor operation control and decision making process. The mechanical deviations of the moving reflectors are still estimated as unessential for reactor operation because this anomalous effect initiates the fluctuations of reactivity on a 10^{-6} Δk/k level. Up to now it does not require immediate intervention. However, the bonds loose both for the jacket and supporting device of the moving reflectors are kept under a strict control.

The only anomaly in the power cluster time diagram (Fig.3) not accompanied with the new cluster(s) appearance in the respective OPO and DPO diagrams is placed in the (18,20) spectra number interval (cluster no.2). In accordance with Fig.2 the analysis of only PSD cluster structure was carried out. It can be done using the method presented in [2] i.e. splitting the full PSD frequency interval [0,2.5]Hz or [1.256] frequency channels, into three

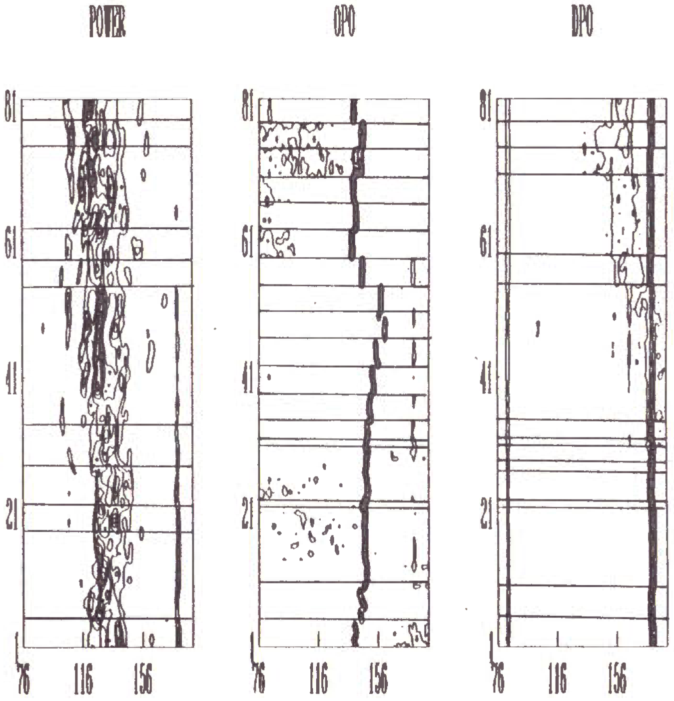

Fig.4 The power PSDs and moving reflector spectral densities topological maps for the last two years reactor operation period. The X and Y axis show the number of a subsequent spectral density (time) and the frequency channel number, respectively. The new clusters appearance and the cluster number memberships changes are marked by the solid lines. One can observe both the degradation tendencies for this three types of data and their mutual interactions. The processes responsible for the cluster to cluster transitions and operation trends changes are apparent too.

frequency windows. The spectral densities in each of them reflects the main sources of power fluctuations. The lowest frequency window [0.01,0.78]Hz (or [1,80] frequency channel number interval) corresponds to the cooling flow noises. The clustering process carried out for this PSDs frequency window revealed the new, well separated cluster in the (18,20) spectra number interval, responsible for the cluster no.2 appearance in the power time diagram shown in Fig.3. The more detailed analysis of the cooling flow loop pointed to by the surveillance system as the source of disturbance, detected some incorrectnesses in the pumps work which contributes to the higher coolant flow rate. The power time diagram in Fig.3 shows that just after restoration actions (the reactor stop was not necessary) the previous operation regime was attained.

4.CONCLUSIONS

The condition- based maintenance is a very important factor to the plant maintenance optimization. It can contribute to the considerable failure probability decrease so that safety and reliability are improved. The pattern recognition elements introduced to the surveillance system, and simultaneous control of the most important reactor differential characteristics enable one not only to detect the failures in the very beginning stage but to point to the probable source of them as well. The clustering techniques and the way of their application let one to control additionally the reactor operation trends and degradation processes taking place both inside the reactor core and its external equipment [2]. An increase in number of the differential reactor characteristics measured and recorded should contribute additionally to the system reliability improvement. However, the clustering results should be then analyzed using simple artificial intelligence methods. Apart from the experimental IBR-2 reactor, the proposed system is tested on the WWR power plant data in collaboration with the Institute for Nuclear Research in Rez (Czecho-Slovakia).

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