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PATTERN RECOGNITION APPLICATION FOR SURVEILLANCE OF ABNORMAL CONDITIONS IN A NUCLEAR REACTOR

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1. INTRODUCTION

Early diagnostics of various disturbances and changes taking place inside or close to the reactor core gives the opportunity to avoid abnormal reactor operation and accidental situations. Reliability of a diagnostics system depends on the proper choice both of the parameters being measured which yield the digital image of a reactor and the methods for its analysis. Their sensitivity on the reactor operation changes determines the quality of the system.

Earlier investigation of random processes [1,2,3] taking place in the IBR-2 reactor core, show that the character of spectral densities of energy pulse fluctuations (PSD) is tightly coupled with the current reactor state. The combination of PSD and spectral densities of the main sources of reactivity fluctuations e.g. the moving reflectors vibrations (RSD), can be treated as an instant reactor noise image. Then the set of subsequent instances represents the history of the reactor states for a given time period. Each of instances can be treated as a point in the N-dimensional Euclidean space. As is shown earlier by Tou and Gonzales [4] and Bargiel et al. [5], an ensemble of subsequent points reveals the clusters structure. Assuming that each cluster includes points which correspond to similar reactor operation conditions, the abnormal (anomalous) system behavior can be defined as an abrupt change in the position of an instant cluster center, a change in its shape or an initiation of a new cluster. The reason of an abnormal behavior can be investigated by comparing the PSD clusters with that obtained for other measured parameters.

The clustering methods and methods for clusters analysis should yield correct detection of anomalies as early as possible. The clustering algorithm ISODATA used by Tou and Gonzalez [4], Bargiel et al. [5] and Weiss [6] has several deficiencies which obliged one to look for a better method. It gives adequate results rather for static than dynamic systems and needs several parameters which must be fitted to various reactor operation conditions. Considering the "rigid" clusters structure and difficulties to investigate it, the new cluster initiation may be delayed. Moreover, the ISODATA algorithm for more sophisticated cluster forms, gives wrong results

(Weiss[6] and Gowda and Krishna[7]). In the following chapter, the hardware and software systems for diagnostics of the abnormal reactor operation are described briefly. The hierarchical clustering method presented first by Gowda and Krishna[7] and impoved by Dzwinel and Pepyolyshev, and other pattern recognition methods of clusters analysis have been applied.
In the next chapters the system application for the IBR-2 reactor diagnostics is presented and conclusions are reported.

2. HARDWARE AND SOFTWARE SYSTEMS

The monitoring system presented in Fig.1 has been developed at the periodical fast pulsed reactor IBR-2 (Dubna). The system is oriented to the reactor core diagnostics and moving reflectors (PO) control. Concurrently with power fluctuations, three (or five) signals connected with the characters of PO mechanical vibrations are registered. The signals are detected by the fission chambers placed in the center of the reactor core and on the neutron beam, and other sensors. Two minicomputers SM 1300.01 equipped with CAMAC-standard and IBM PC-386, connected by the PS-232c, are used to perform data storage and preprocessing. The fluctuations of the parameters being measured (e.g. power pulsed energy, positions of moving reflectors, etc.) are passed with FFT transformation into the corresponding spectral densities. Each of them is treated as a point in the 257-dimensional Euclidean space. The space dimension is determined by the recorded number of the spectral densities descrete values. The current data being sent by SM-1300.05 and the data basis which includes the host of images registered well before, constitutes the main input for the software part of the system. It is presented in Fig.2 and consists of two main programs called MNN and PRR, respectively. In the data preprocessing block the current data validity are checked. If they are correct, then they are saved in the data base and added to the host of images. For the updated set of subsequent spectral densities the most informative frequencies (features) are selected. Then the Euclidean distances (stored in an array) between N dimensional point (spectral densities) are updated. In the following step the clustering procedures are invoked. The mutual nearest neighborhood (MNN) algorithm is exploited, slightly modified in comparison with that proposed by Gowda and Krishna[7]. Unlike ISODATA algorithm, one parameter, namely the cut-off radius R_{cut}, is fitted only (number of neighbors in the original MNN method). If the point to point distance is

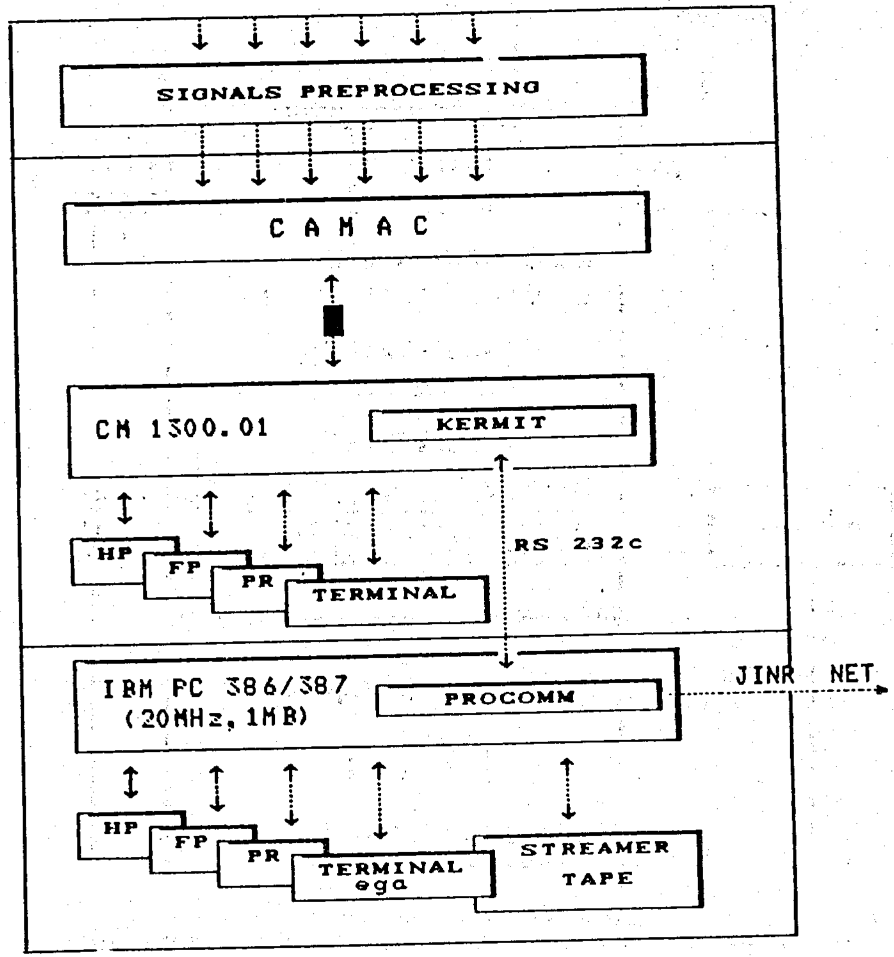

Fig. 1. The hardware system for: signal preprocessing, data storage, communication and data processing (HD - hard disks, FD - floppy disks, PR - line printer, TERM - terminal.

larger than R_{cut}, then they are placed reliably in different clusters. The cut-off radius may be chosen once only (e.g. on the project stage of the system) and can be modified, if necessary. The MNN algorithm signals that a new cluster appears. It recognizes the clusters having sophisticated structures e.g. spherical, branched, "bridged" and others. Because, the MNN algorithm is hierarchical, it enables one to observe the agglomerative process from start to finish. The computational efficiency of the MNN method allows real time reactor control. However, to obtain a more reliable system, several clustering

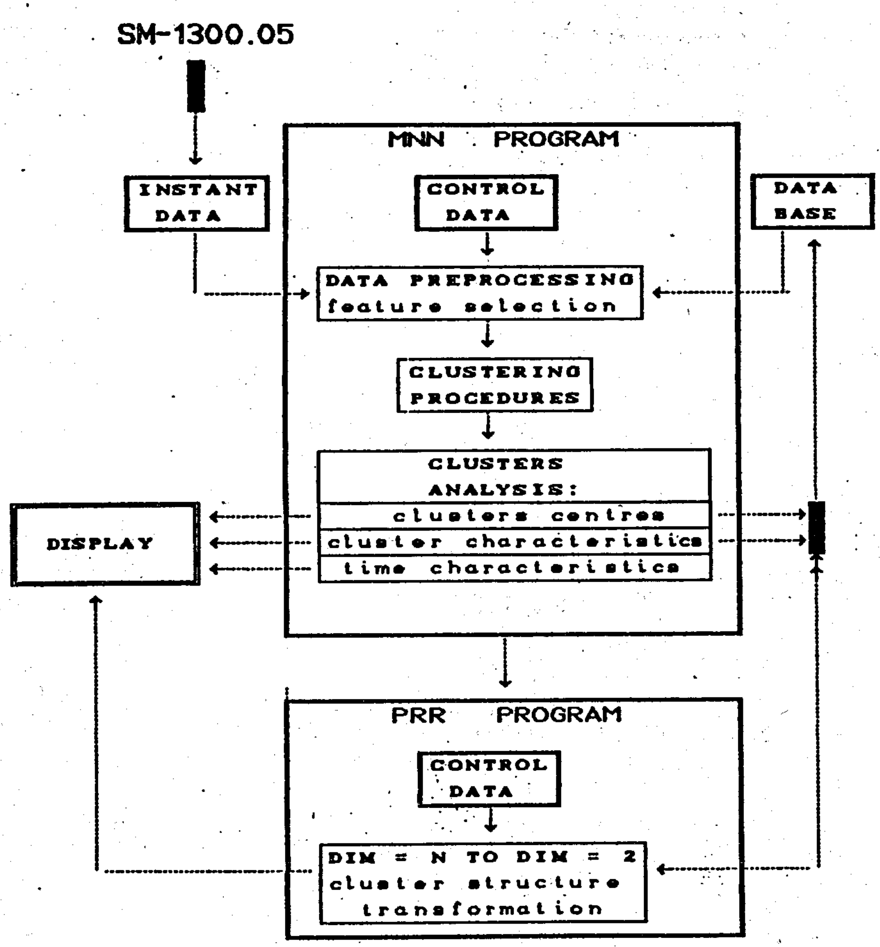

Fig. 2. The pattern recognition software system for the reactor diagnostics.

algorithms should be applied. That is why the ISODATA algorithm can be invoked optionally for comparison purposes and static structure investigations. The cluster analysis results i.e. clusters centers, compactness, distances between clusters, time characteristics and other are displayed and stored.

The anomalous effects may be manifested by either abrupt or continuous clusters shapes changes. As it is impossible to observe such changes directly, and the cluster analysis gives poor information about clusters shapes, another method appears to be necessary. The PRR program represents the bulk of data transformation from 257 - dimensional space to two (or three) -

dimensional one. In order to preserve the original clusters structure, two algorithms have been elaborated[8]. The first one is based on the Niemann technique[9] and the second on the simulated annealing method. For the comparison and analysis purposes, a classical Karhunen-Loeve transformation[9] is implemented too, and may be optionally invoked. A two-dimensional pattern can be observed on display. It considerably enriches information about the N dimensional clusters structure. The PRR and MNN programs supplement each other, although they can be used independently too. They are written in FORTRAN 77 and have the OLYMPUS[10] structure. The system has been developed on IBM PC 386 (387, 20MHz, 1MB) clone and computations are performed using both NDP386 and RMF FORTRAN compilers. In the next chapter some results of the system application to the IBR-2 reactor are reported.

3. THE SYSTEM APPLICATION

The IBR-2 reactor operates in the 2MW average power regime. The frequency of reactor pulses, and the sodium flow rate are equal to: 5/sec and 90^3/hour, respectively. The basic reactor work time period from October 1987 to January 1990 (with a new version of the main moving reflector) is considered and measurements transformed into appropriate spectral densities are treated as the host of images of subsequent reactor states. The power spectral densities (PSD) and the spectral densities of the moving reflectors vibrations (RSD) (i.e. the main (OPO) and the additional ones (DPO)) and the spectral densities of angle fluctuations between them, have been collected and processed. The frequency interval (0.01-2.5) Hz is sampled in 257 points. In Fig. 3 subsequent PSD's are shown. In accordance with Bargiel et al.[5] two main frequency subintervals can be extracted. They correspond to the main sources of power fluctuations i.e. the moving reflectors vibrations (0.57-2.2) Hz and cooling flow noises (0.01-0.38) Hz[3]. In dependence on the sort of fluctuations investigated, either the whole frequency interval or an optional "window" may be processed. The former is considered here.

After a first stage of processing, the PSD's are distributed into clusters and the cluster analysis is done. Up to now six clusters have been obtained. The substructure of the fourth cluster (see Fig. 4) is revealed using a PRR program. The clustering procedures fail to extract it because of the fact that two subclusters are joined and create a "crescent roll" cluster shape (see Fig. 4). The analysis of RSD shows

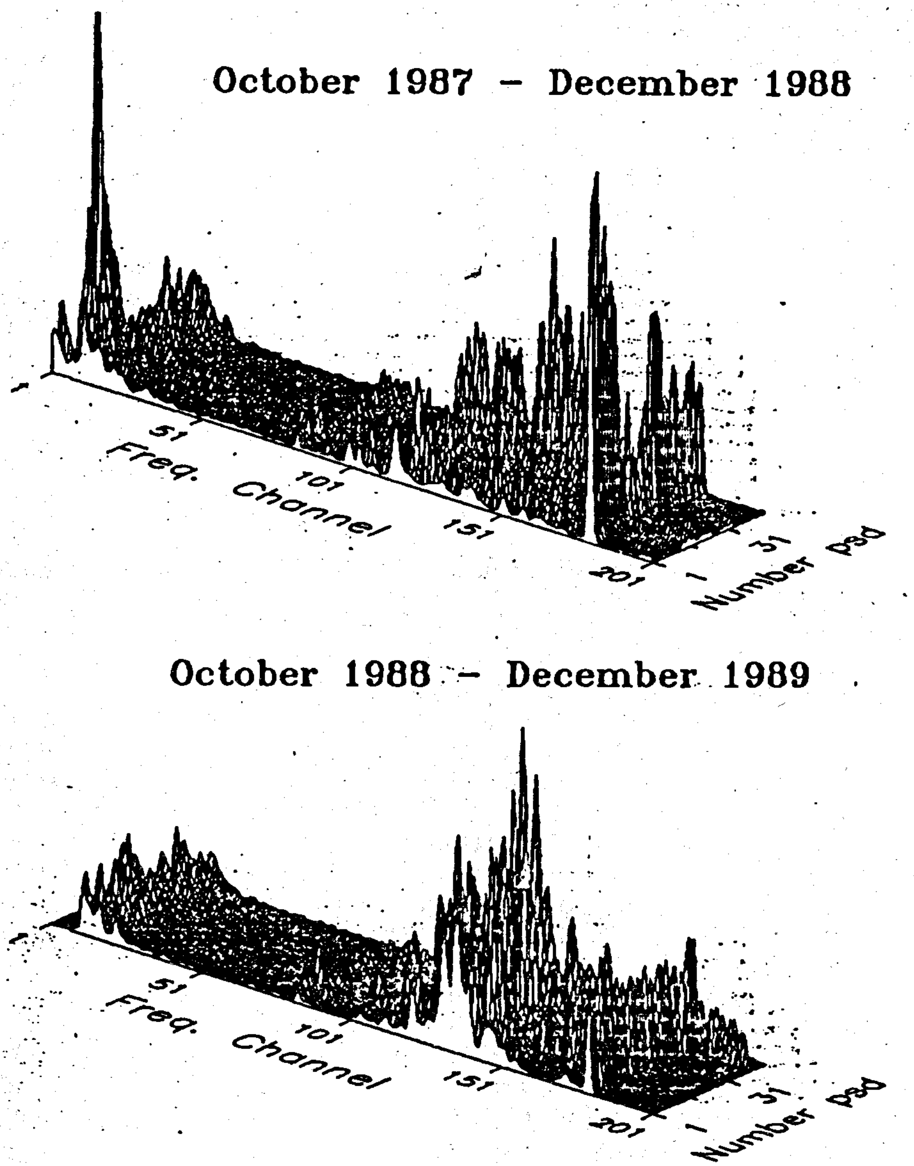

Fig. 3. The subsequent PSD noise images of IBR-2 reactor.

that the first four clusters formation and the substructure of the fourth one are due to OPO and DPO vibrations, respectively. These clusters represent a normal reactor operation. However,

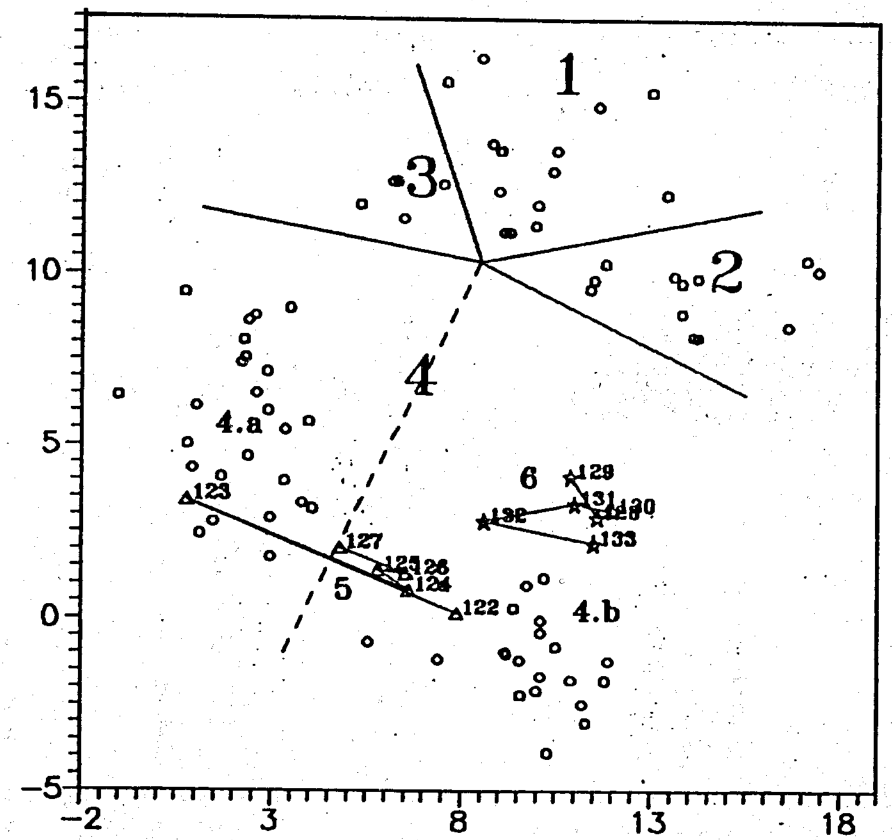

Fig. 4. The clusters structure which is obtained using the Niemann transformation of the N-dimensional Euclidean space into a two dimensional one.

as is shown in Fig. 5 considerable changes in the fourth cluster center position are observed. In Fig. 6 a time characteristic is shown, which indicates the clusters (1,2,..., M - where M is the number of clusters) each of subsequent PSD´s belongs to. The new clusters initiation is apparent. The fifth one (which is not seen in Fig. 4), signals some changes in the reactor state. However, the sixth one which is extracted both by the clustering procedures and the Niemann algorithm (see Fig. 4) corresponds to some new operation conditions. Since the formation of these two clusters is not correlated with RSD changes, they can be treated as anomalous and require further extra study. Additionally, the coefficients η_M^2 and η_S^2 are calculated. They are defined as follows:

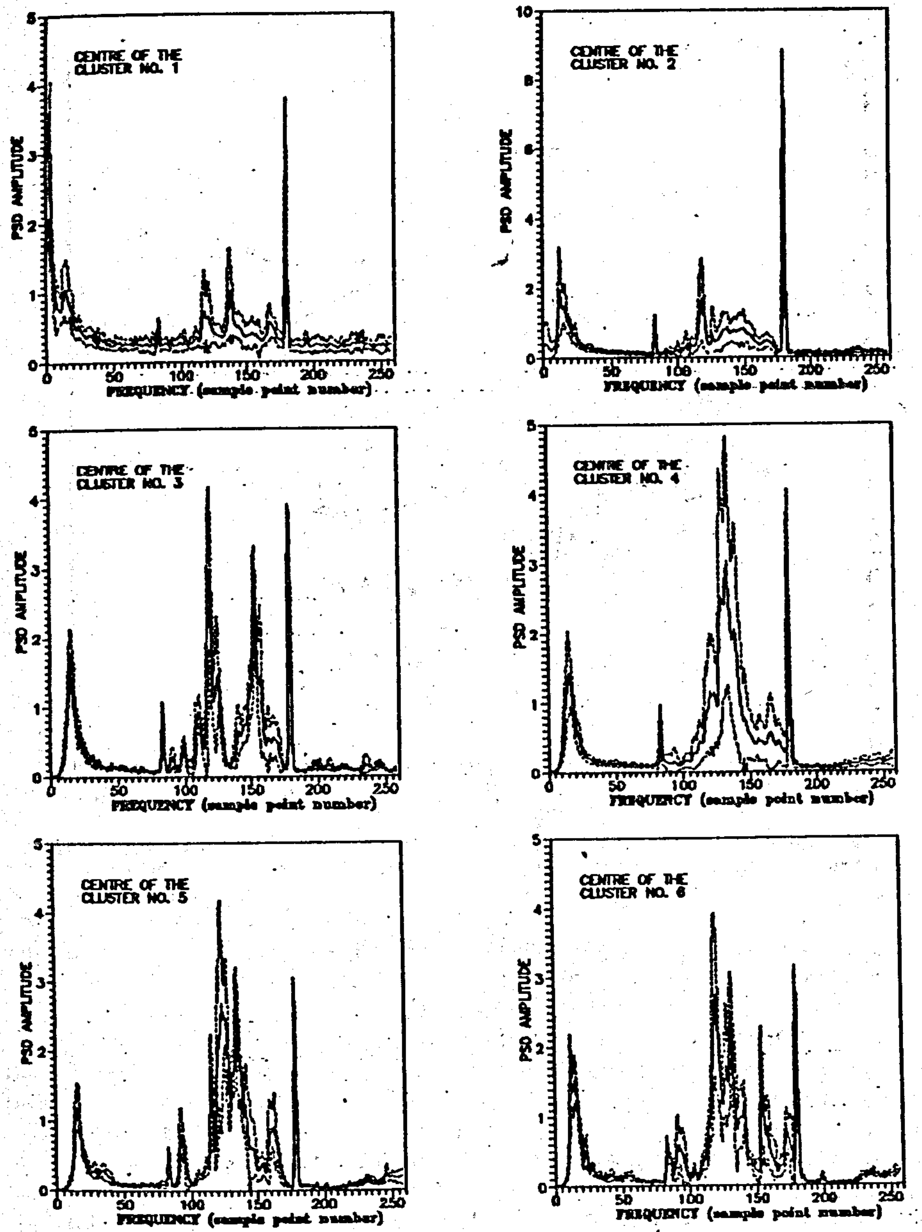

Fig. 5. The clusters centers (solid lines) computed as mean spectral densities which belong to the same cluster. The (+-) dispersion is shown (dashed lines).

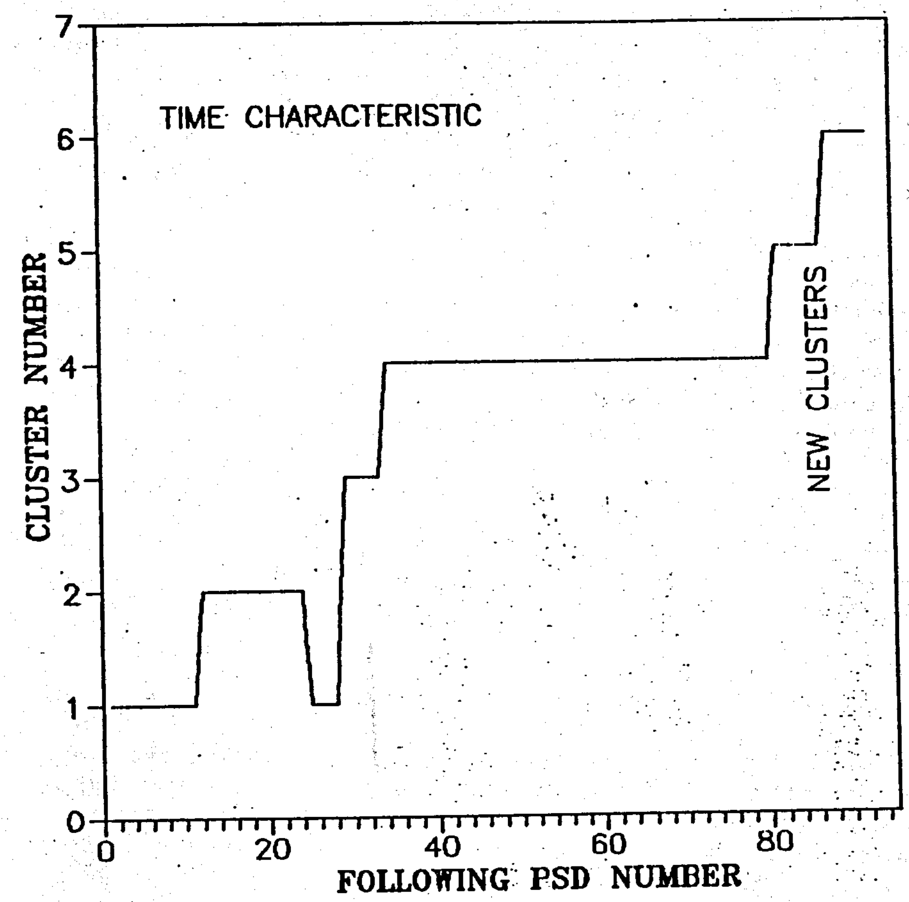

Fig. 6. The time characteristic which shows the clusters (1, 2, ... M, where M number of clusters) each of subsequent PSD's belongs to. The new clusters initiation is apparent.

$$\eta_M^2 = (\sigma_{opo}^2 + \sigma_{dpo}^2 + \sigma_{fi}^2)/\sigma_Q^2$$

$$\eta_s^2 = \sigma_s^2/\sigma_Q^2 ,$$

where σ_i^2 are dispersions of PSD (Q), RSD (opo, dpo, fi) and "sodium noises" (S), where:

$$\sigma_i = \int_o^{f_{crit}} S_i(f) \cdot \gamma_i^2(f) \cdot df, \quad i = (opo, dpo, fi, S, Q)$$

f - frequency, $f_{crit} = f_o/2$, $f_o = 5Hz$ - sample frequency, S(f) - spectral density, $\gamma_i(f)$ - gamma coherency function between the i-th process and Q. The η^2 coefficients represent mechanical (M) and "sodium noises" (S) contributions to the power fluctuations dispersion. As is shown earlier by Pepyolyshev/2/, $\eta_S^2 \sim 20\%$ and $\eta_M^2 \sim 60\%$ for the normal reactor operation. However, in the last measurements η_M^2 decreases considerably, although η_S^2 remains unchanged. The anomalous clusters formation and η^2 changes show that some unrecognized power noise factor is detected. The investigations were being carried out to find it. It is most likely that the anomalous effect corresponds to mechanical vibrations of not only OPO and DPO moving reflectors, but of the whole construction as well. However, the derived contributions of anomalous effects to the power fluctuations are minute. According to estimated external reactivity (K) fluctuations, which cause them, they do not exceed $2 \cdot 10^{-6}$ $\Delta K/K$. The σ_Q/Q, σ_{opo} and σ_{dpo} estimates show that the reactor exploitation characteristics are not influenced. Nevertheless, tendencies to changes in the clusters character are continually controlled.

4. CONCLUSIONS

Using the system presented above for the IBR-2 reactor, one may see that the method developed is rather effective for early diagnostics of various disturbances and changes taking place inside or close to the reactor core. Anomalous effects, initiating accidental reactivity disturbances on a 10^{-7}-10^{-6} $\Delta K/K$ level, are apparent. The pattern recognition algorithms here i.e. a mutual nearest neighborhood algorithm and clusters visualization methods, supplement each other and constitute a useful tool for reactor diagnostics. To obtain a more reliable system a greater number of parameters should be measured and several various clustering methods should be concurrently used. The full automated reactor control is not accomplished yet. Up to now the process of data acquisition and clustering has been automated only. The clustering results described earlier are displayed, however, their interpretation depends entirely on the human factor. In future the diagnostics system should evolve an automated experts system.

The presented software system is fitted to rather modest computational power, although noting stands on the way to use it in a relatively large data set processing. The computational time necessary for the full processing of three hundreds of 257-dimensional vectors on IBM PC-386 is equal to 10 minutes and increases as nlong (where n is the space dimension or the number of points). The method developed, can be used for monitoring the conditions of nuclear reactors of different types and other complex systems, where the data can be represented as set of packets of discrete values (N-dimensional points).

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