

IDENTIFICATION OF IRIS REACTOR TRANSIENTS WITH SELF-ORGANIZED MAPS

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Artificial Neural Networks (ANN) are powerful tools that can be used to solve many of the Nuclear Engineering (NE) surveillance and diagnostic needs, in special those of the next generation of nuclear energy systems. IRIS, the International Reactor Innovative and Secure, is an Integrated Primary System Reactor (IPSR) with innovative features that can meet many of the requirements set forth in the Generation IV Roadmap Study coordinated by the US Department of Energy (DOE). The IPSR concepts are characterized by the inclusion of the entire primary system within a single pressure vessel, including the steam generators and pressurizer. This paper presents a possible solution for the transients classification and identification that can be used to develop tools to help the safe operation of IRIS. The approach studied in this paper is based on self-organized maps (SOM). The initial results have shown that the use of SOM is quite promising in the identification of initiating transients of the IRIS reactor.

KEYWORDS: artificial neural networks, surveillance and diagnosis, IRIS Reactor

I. Introduction

Nuclear engineers are working on the development of new reactors concepts that can fulfill requirements such as those defined by the Generation IV International Forum (GIF) for the Nuclear Energy supply systems of the future [1]. IRIS is an international cooperation effort to design a nuclear energy system capable of meeting many of these requirements. Westinghouse started the conceptual design of this new reactor to answer a DOE request under the NERI program. IRIS takes full advantage of its integral configuration to implement a safety by design approach [2] to meet challenging safety goals. Even with the principle of "safety by design" and the complementary "safety features" provided in the design, further analysis and creative tools have to be considered to demonstrate that its "paramount safety" stands up among the other recent reactor concepts. In recognizing this aspect, every possible source of "safety vulnerability" has to be addressed and adequately coped with [3]. One of the most critical aspect connected with this concern is related to human factors and, certainly, any effective solution to work with human factors involves information and knowledge. Safety by design and the safety barriers recommended by the principle of defense in depth can eliminate some and attenuate many of the consequences of human factors in the operations, but to really cope with this vulnerability, one must recognize that safe operation will require the use of the most modern tools to provide "good information" for the operation team.

This paper presents a promising solution for transient classification and identification, that can be used to develop operator supporting tools to help the safe operation of IRIS.

The approach is based on self-organized maps (SOM) operating on-line with the reactor. This kind of representation can allow to the operator to watch how a given transient is evolving with respect to its severity, as the time path of the activated units is migrating towards the border of a new class of transients.

The central idea is the identification and classification of a specific transient behavior in its early stage, allowing to the operator to be concentrated in other tasks and able to react as necessary. A reasonable set of transient simulations, described in terms of the time history of nine key process variables, was used to test the proposed SOM approach. Although the project is in an exploratory phase to dimension the amount of efforts, preliminary results obtained have shown that the use of this technique served its purpose in identifying different operational transients of the IRIS reactor.

II. IRIS Description

IRIS is a modular, integral, light water cooled, medium power (335 MWe/module) reactor which addresses the requirements of proliferation resistance, enhanced safety, improved economics and waste reduction. The technical characteristics of IRIS are discussed in detail in references [4-9]. Its "safety by design" approach, where accidents are "designed out" to the maximum extent possible, instead of engineering how to cope with their consequences is presented in [2].

The 6.78m outside diameter by 21.4m in height IRIS integral vessel houses the reactor core, its support structures, upper internals, eight steam generators, internal shields, pressurizer and heaters, and eight reactor coolant pumps

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(Fig.1). Hot coolant rising from the reactor core to the top of the vessel is pumped into the steam generators annulus. The integral vessel configuration is essential to the safety by design approach as shown in [9] and thus it is key to satisfy the enhanced safety requirement.

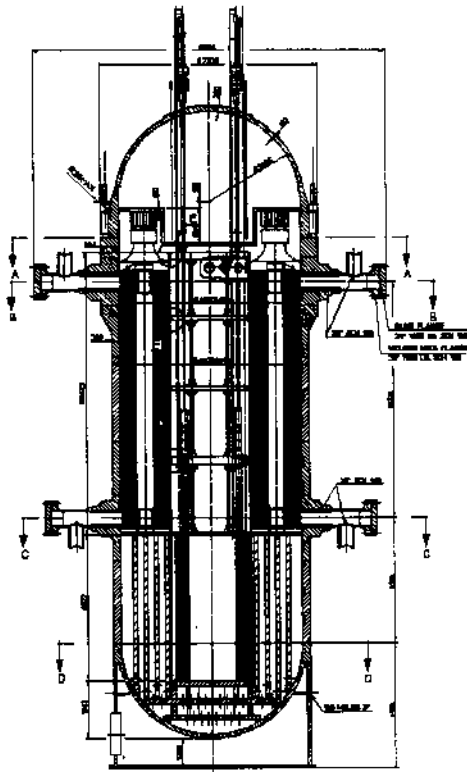


Fig.1 IRIS: Integrated Primary Systems.

II. Self-organized Maps

Self-Organized Maps are artificial neural networks with a single layer where the units are placed in a 1-D or 2-D grid. In the 2-D SOM, the units are placed in a square or hexagonal lattice (Fig.2). The training of the SOM is based on the competitive learning concept: units compete with each other to be activated when a specific pattern is presented and the result is that just a single unit is really active at a given moment. The original idea of the competitive learning -winner takes all- was proposed in 1958 by Rosenblatt [10] but the most general model was developed in the 80's by Teuvo Kohonen [11].

The principle of the topographical maps formation, as formulated by Kohonen is: *the spatial location of an output unit in a topographical map corresponds to a domain or peculiar feature extracted from the input space*. This concept reproduces one of the features of the brain: *the organization of the sensorial inputs in the higher planes, represented by topographical maps*. The units in this grid are assigned to specific features of the input, producing topographical maps related to specific classes of patterns, i.e., the spatial

locations of the units are indicative of the statistical features of the input patterns. These indications can be seen as a non-linear generalization of the Principal Component Analysis (PCA).

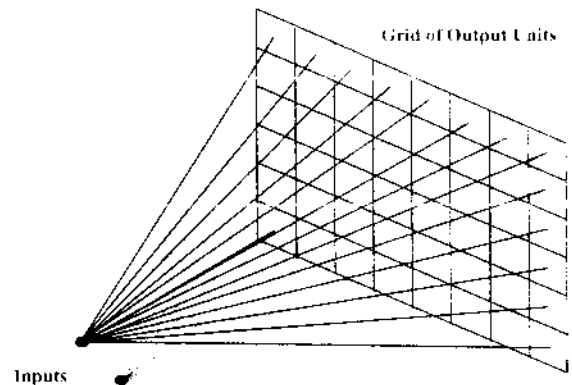


Fig.2 2-D SOM.

In the SOM there are not any known or desired output. The objective of the network is to search similarities among patterns and to promote the classification of the input data into groups, in a non-supervised learning method. An incoming pattern triggers a competition among the units and the winner weights are updated to become more close to the input pattern. These maps are such that, patterns close to that which have previously activated one unit, will either activate the same unit or one of its neighbors. The winner unit is the one whose weights vector is the closest to the input pattern, based on a Euclidean distance. There are lateral communications between the units in the grid, which obey a *neighborhood function*, usually represented by a Gaussian like function:

$$V_{ij}(n) = \exp\left[-\frac{\|r_j - r_i\|^2}{2\sigma^2(n)}\right] \quad (1)$$

where j^* indicates the winner unit; $\|r_j - r_i\|$ is the Euclidean distance between the unit j and the winner unit. $\sigma(n)$ defines the width of the neighborhood, which starts as wide as possible and decreases with increasing n , i.e., with training:

$$\sigma(n) = \sigma \cdot \exp\left(-\frac{n}{\tau_\sigma}\right) \quad (2)$$

The weights are updated according with:

$$w_j(n+1) = w_j(n) + \eta(n)[x(n) - w_j(n)] \quad (3)$$

where $x(n)$ is the input vector. The learning rate, η , varies as a function of the distance between the unit j and the winner unit (by the V function) and as function of the time (n):

$$\eta(n) = \eta \cdot \exp\left(-\frac{n}{\tau_\eta}\right) V_{j^*}(n) \quad (4)$$

SOM is an excellent tool for the exploratory phase of data analysis. It projects the input space into prototypes of lower dimensionality, i.e., into 1-D or 2-D regular-in-shape grids that can be used to explore the data features. "Visualization" is the first step in the pattern classification, and it is completely done by SOM in a unsupervised mode. In this step only qualitative features of the input data can be obtained. "Selection" is the "extraction" of the characteristics. The next step is "classification," when the selected characteristics of the input data are assigned to individual classes. It is known that, in the pattern classification phase, the performance is improved if the "selection" is followed by a supervised classification, i.e., it is convenient the use of an "adaptive pattern classifier." In this work we have used the learning vector quantization (LVQ) scheme proposed by Gersho and Gray, 1992 [12]. This scheme considers that the SOM results in approximations of the Voronoi vectors. After the convergence phase, each cell is assigned to a specific class according to its response, in terms of distance, to a specific input. The classification is effected in the supervised training phase as follows:

- ✓ consider that $\{w_i\}$ represents the set of Voronoi vectors and that $\{x_i\}$ is the set of input vectors;
- ✓ find the Voronoi vector, w_c , closest to the input x_i ;
- ✓ compare the Voronoi vector associated class, \check{c}_{wc} with the input class, \check{c}_{xi} and update the weights:

if $\check{c}_{wc} \neq \check{c}_{xi}$ then

$$w_i(n+1) = w_i(n) + \alpha(n)[x_i - w_i(n)] \quad (5)$$

if $\check{c}_{wc} = \check{c}_{xi}$ then

$$w_i(n+1) = w_i(n) - \alpha(n)[x_i - w_i(n)] \quad (6)$$

the remaining vectors are not updated, i.e., they remain as they were at the end of the SOM unsupervised training.

III. Transient Data and the System Concept

As any nuclear reactor, IRIS can be subjected to different kinds of transients. In this paper only few of them are considered: positive and negative step load changes; ramp load variations; spurious SCRAM; inadvertent relief valve opening; and an artificially large step of 50% of full power. Together with these transients, the training data set contains several steady state conditions patterns from 30% to 105% of full power.

The response of the reactor systems to each one of these transients depends on the control system, which is being developed. At this early stage of development, when the control architecture and parameters are not optimized, simplified models are good enough to provide basic data to

characterize IRIS behavior. Reference [13] describes the simplified tools that produced the data used in this paper and also presents results for many transients. Fig.3 illustrates the pressure response for a negative power step of 10% from full power.

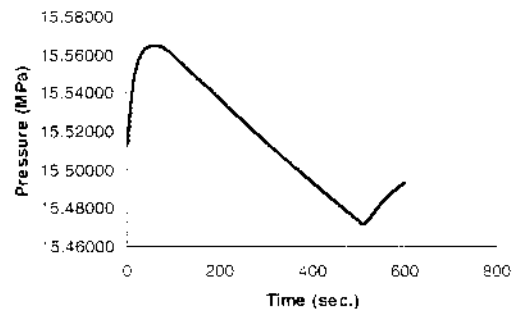


Fig.3 Step Load of -10%; Pressure Response IRIS.

The Transient Identification System (TIS) was conceived considering that few variables can characterize a single transient. For instance one can consider the reactor and the secondary system power; the temperature at different points; and the pressurizer pressure, temperature and water level. The central idea is to provide a system, based on self-organized maps, able to identify which kind of transient is happening in its early beginning. The system will have a buffer to collect data for few seconds of the main variables, which will be the input for the SOM. It is expected that TIS' screen will light a single cell, previously assigned to a kind of transient that is in course. The diagram of Fig.4 defines the basic idea of TIS. In a next step the system will be improved with a new screen with a continuous boundary for each transient class. In this final version the location of the lighted cell will represent the status of the reactor plant, i.e., if the plant is in a specific power level at steady state; or if it is being submitted to a slow transient; or if it is undergoing a fast transient; or in the beginning of any kind of abnormal event.

Although we have tested two different-size buffers with different acquisition times, the data used in the paper was limited only to the results for a twenty-seconds buffer, containing data of the first two minutes of each transient beginning. Nine variables were selected: 1) reactor power, 2) SG's power, 3) core outlet temperature, 4) riser mean temperature, 5) SG mean temperature, 6) downcomer temperature, 7) primary system pressure, 8) pressurizer temperature, and 9) pressurizer water level. It was used a sampling interval of 2 seconds (0.5 Hz) during 120 seconds for each transient. Fig.5 illustrates, for two variables, a "six-period" buffer sequence for 30 different transients used in initial tests. These transients are defined in Table 1.

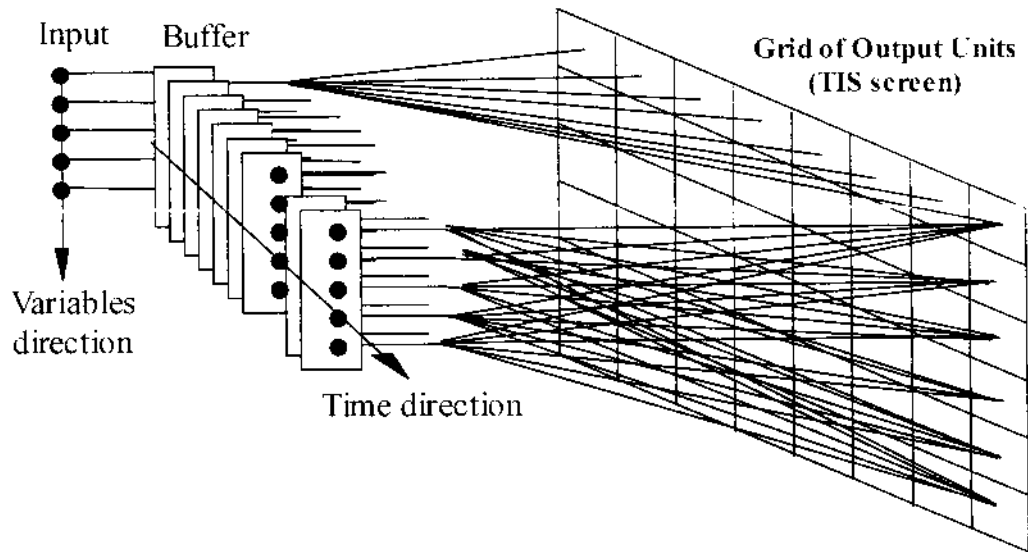


Fig.4 Transient Identification System based on SOM.

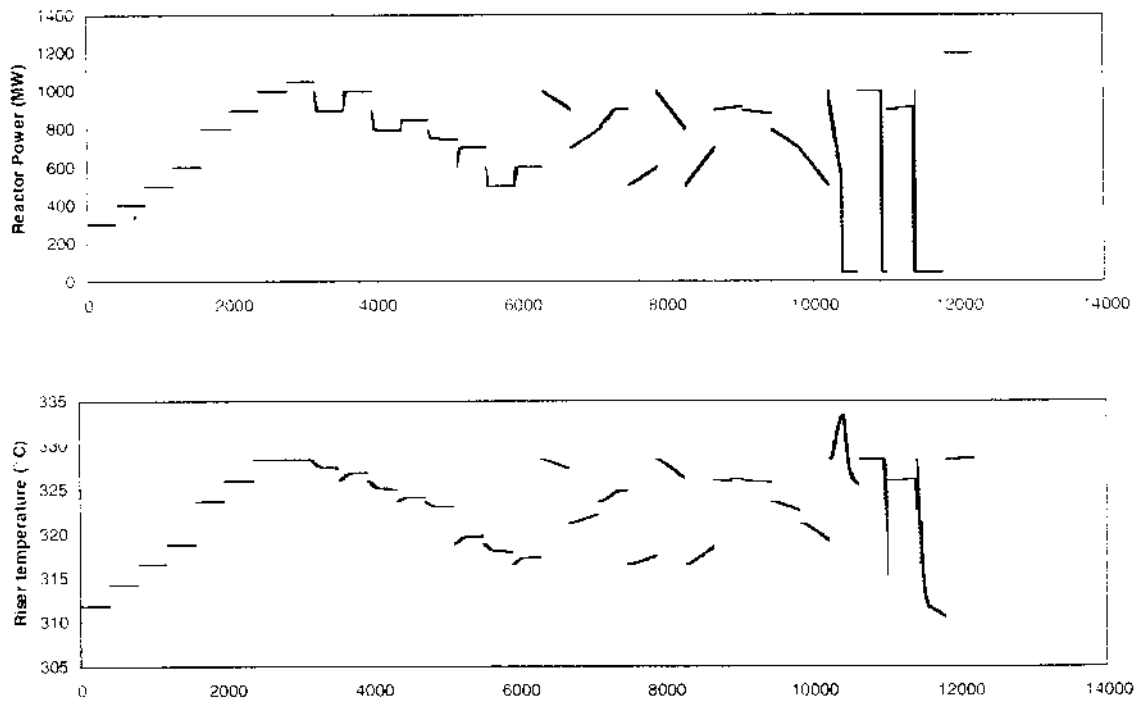


Fig.5 Six seconds of variables behavior for the 42 transient patterns.

Table 1 -- Transient list.

Transients			
1	30% Steady state	17	100% Ramp -5%/min
2	40% Steady state	18	70% Ramp +5%/min
3	50% Steady state	19	80% Ramp +10%/min
4	60% Steady state	20	50% Ramp -5%/min
5	80% Steady state	21	100% Ramp -10%/min
6	90% Steady state	22	50% Ramp -10%/min
7	100% Steady state	23	90% Ramp -1%/min
8	105% Steady state	24	90% Ramp -1%/min
9	100% → Step -10%	25	80% Ramp -5%/min
10	90% → Step +10%	26	70% Ramp -10%/min
11	90% → Step +10%		
12	80% → Step +5%		Not normal
13	80% → Step -5%	27	100% → Step -50%
14	60% → Step +10%	28	Safety Valve Opening
15	60% → Step -10%	29	90% Small LOCA
16	50% → Step +10%	30	100% SCRAM

As a very initial approach, the data was normalized only with respect to each variable value, although a pattern normalization may be necessary to improve the classification performance, considering each buffer content; *this approach will be taken in a future step of the present work.*

To test the SOM capability, a network with a 10x10 square array was selected and trained in the unsupervised mode for 2000 époques¹. The objective of this test was to verify TIS ability to make clear distinction between three kinds of operating conditions: steady-state, ramp transients and step transients. After this initial training the sensibility of each cell of the SOM was tested and assigned to the "most closest transient class", defining the Voronoi vectors. This "most closest class" refers to the shortest Euclidean distance of the cell to the input; *the shortest distance to a specific class assigns the class name of the input to the cell class.* After associating each cell to a class, TIS was submitted to the supervised vector quantization process for new 500 époques. Fig.6 illustrates

the TIS screen showing the sensibility of each cell to a specific transient class, considering the three classes: 1- Steady state, 2- Ramp, and 3- Steps.

After training TIS was tested in the *monitoring mode* showing what cell lights when a specific transient is presented. In this test, each transient was presented as a set of 52x9x10 data (52 buffer contents of 9 variables by ten acquisition periods). Each acquisition period was 2 seconds, what means a total of 104 seconds for each transient. The total number of patterns (full buffers) was 1352.

Fig.7 illustrates the sequence of cells lighted for few examples. The steady-state conditions -from 30% to 105% of full power- are represented by *blue-cells*. Observe that the slow ramp transients are characterized by the *continuous*

alternation of the lighted cell and the step transients are represented by almost straight "jumps".

Two important features were observed: *sometimes one cell lights for more than one transient class, and many cells never lights at all.* These features can be associated with the sensitivity analysis method based only on the Euclidean distance; *the Voronoi vectors produced in this way may be the root cause.* To investigate this problem a new method to the sensitivity analysis was devised: *the cells class association was done in terms of "frequency of activation", i.e., the cell is assigned to the class that most frequently lights it.* Fig.8 show the results for a 20x20 network.

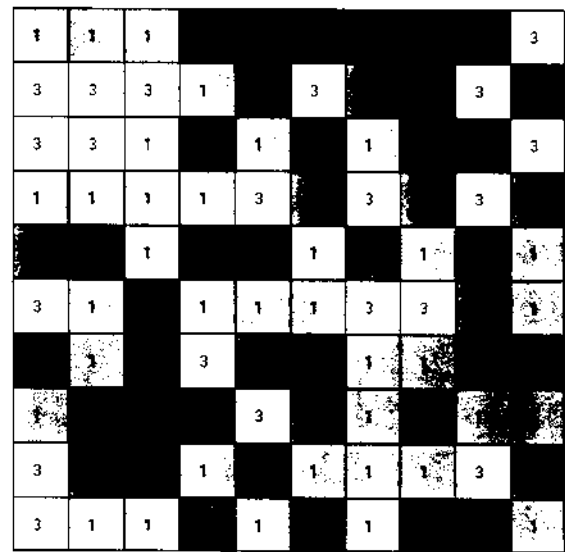


Fig.6 TIS screen: Class sensibility for the first test.

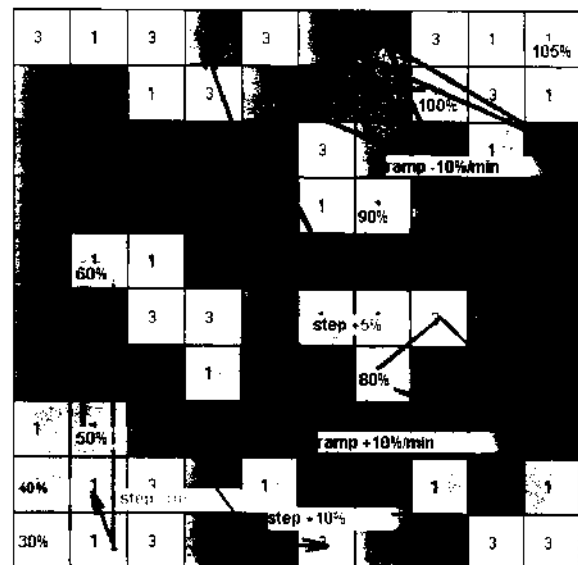


Fig.7 TIS screen: Monitoring mode.

¹Epoque means "a single presentation of the complete training set."

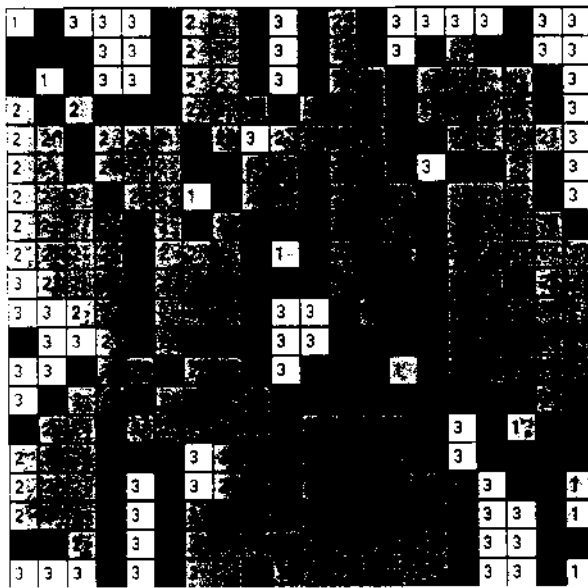


Fig.8 20x20 TIS screen: Sensitivity by frequency.

In respect to the "never lighted cells," the "blue-cells" with a "0" class association in Fig.8, they did not "win" for any input pattern of the training set. Although these cells can respond to new patterns, they were not associated with any one of the first three classes. It is interesting to note that these cells have occurred almost always as a separation layer between cell classes. Fig.9 shows the class association based on the sensitivity-by-distance; where every cell is associated with one of the three classes.

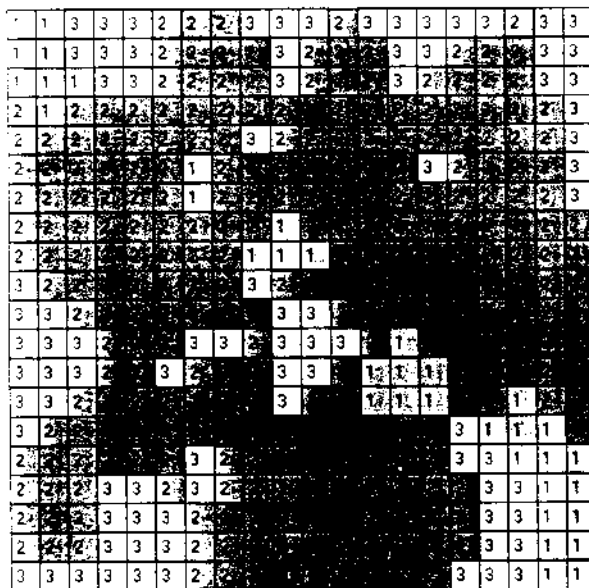


Fig.9 20x20 TIS screen: Sensitivity by Distance.

Results for few transients supervised by TIS after its training and quantization in the "sensitivity-by-frequency approach" are illustrated in Fig.10. All of the steady-state patterns of Table 1 were analyzed and the corresponding cells associated with each one of them are presented in Fig.10, showing its alignment in a diagonal pattern. Also the sequence of cells lighted in the first 104 seconds of the negative 10% power step from full power (Table 1, N.9) is represented by the brown line at left. The ramp up transient from 50% of power at a rate of 5%/min (Table 1, N.20) is represented by the light-blue line at right, also for the first 104 seconds of the transient, which corresponds to the early beginning of a transient.

Although Fig.10 presents few results, every transient was analyzed showing that: a) each cell assignment to a specific class was correct; the initial phase of each transient followed trajectories within its correspondent class region; and, b) the step transients, characterized by "almost straight" trajectories within the "map," can be differentiated from the ramp transients not only because of its different colored regions, but also because ramp transients follow very sinuous lines, in a continuous alternation from cell to cell.

Patterns not present in the training set also were tested. One of these tests was the steady power operation at the level of 70%. It was observed that a "blue-cell," i.e., a cell without a previous class association was lighted when this pattern was presented (see bottom of Fig.10). Although "not-previously-classified," this cell is within a "class-two" region (see Fig.9) and out of the "diagonal region of the steady-state cells," what confirm the initial doubt and means that a more extensive training, in terms of the patterns training set, may be needed. The case at hand seems to indicate that we need a finer training set in terms of different power level steady-states.

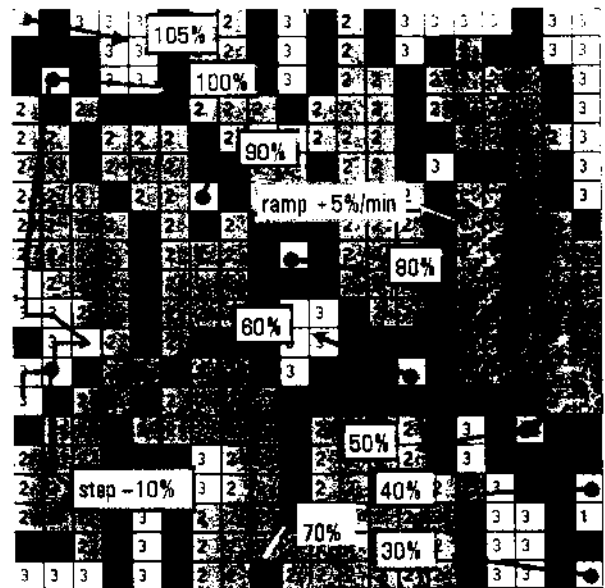


Fig.10 TIS screen: Typical response to different patterns.

The results above showed that this unexpected behavior was not observed when the sensitivity analysis method based on the Euclidean distance and that the Voronoi vectors produced in this way can be used without any doubt. A new training with the complete set of data of Table 1 was performed, now considering four classes of data: 1) steady-state, 2) ramp transients, 3) steps, and 4) abnormal transients. The transient classification process had generate the topographic map showed in Fig.11. Fig.12 illustrates the TIS behavior when subjected to many different transients.

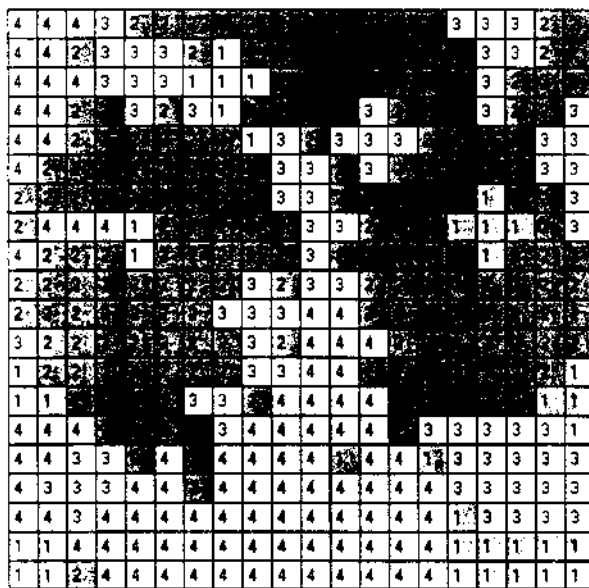


Fig.11 20x20 TIS screen: Sensitivity by Distance.

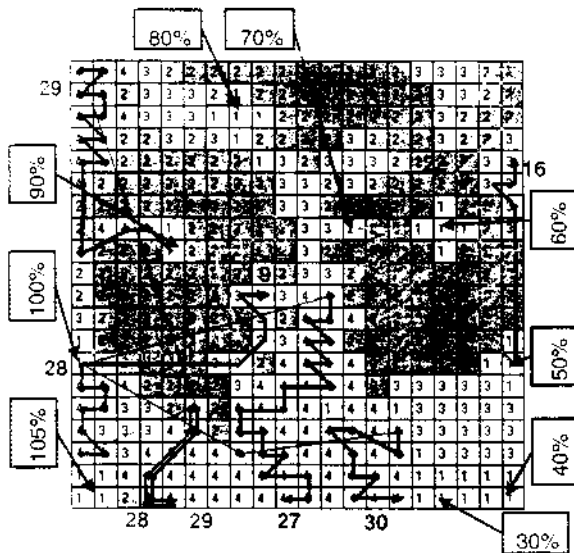


Fig.12 TIS screen: Transient response.

The steady-state conditions of Table 1 were illustrated in Fig.12 by "white-cells" with the percentage of power

indicated in the blue-boxes. The 70% of power condition, not present in the training set, was represented in a yellow cell. Although this condition was internally represented in a previously class-2 cell (defined by ramp transient data), its position was coherent with all other steady-state conditions. This fact indicates that the ramp transients may represent only a sequence of quasi-steady-state conditions. Now the positioning of the steady-state conditions was in a round counter-clockwise array.

Once again the behavior of ramp transients was characterized by the frequent alternation of cells lighting while the step transients was represented by almost straight jumps. Most of the abnormal transients were characterized by the initial alternation of cells followed by an abrupt jump to a distant region; the exceptions were the SCRAM (transient N. 30) and the 50% Step (N. 27). It was evident that these jumps represent the abrupt power change due the sudden power mismatch in the early beginning of the transients.

The most remarkable observation is that TIS may be able identify a transient type in its early beginning.

IV. Conclusion

Although the work is in an exploratory phase, the preliminary results reached up to now shows that a TIS concept based on SOM, looks very promising. Its capability in identifying different kinds of transients, specially normal from abnormal transients, was demonstrated. Also the tests performed were sufficient to show the different behavior of ramp and step transients identified by TIS.

It was possible to observe that the behavior of a reactor under operational transients is characterized by relatively slow processes. This observation can indicate the convenience of using a minimum number of classes to TIS architecture: two classes to separate normal from not normal events may be a good solution.

This initial work tried to evaluate the potential of the concept and to uncover the main problems to be solved. As an example, it was observed that most of the time of quicker transients, as steps and abnormal transients, contains information identical as that of ramp transients, when the reactor is approaching a steady-state condition, this fact can produce erroneous cells class association. A possibility to deal with this problem is to provide training only during the very short periods necessary to identify the transient class.

Two different grid sizes were tested but it is too early to conclude anything about the grid size: it is expected that greater the size, greater the number of unused cells. It also can be expected that hexagonal grids may improve TIS effectiveness. It is also important to analyze the effect of "buffer content normalization," a task considered important to improve SOM performance. Different sets of variables also must be tested. Another important step will be the development of an algorithm to associate the irregular map to a regular regions transition map.

Nomenclature

ANN - Artificial Neural Network
DOE - US Department of Energy
GIF - Generation IV International Forum
I-NERI - International Nuclear Energy Research Initiative
IPSR - Integrated Primary System Reactor
IRIS - International Reactor Innovative and Secure
LVQ - Learning vector quantization
NE - Nuclear Engineering
PCA - Principal Component Analysis
SCRAM - "Safety Control Rod Axe Man": the sudden shutting down of a nuclear reactor
SG - Steam Generator
SOM - Self-Organized-Map
TIS - Transient Identification System.

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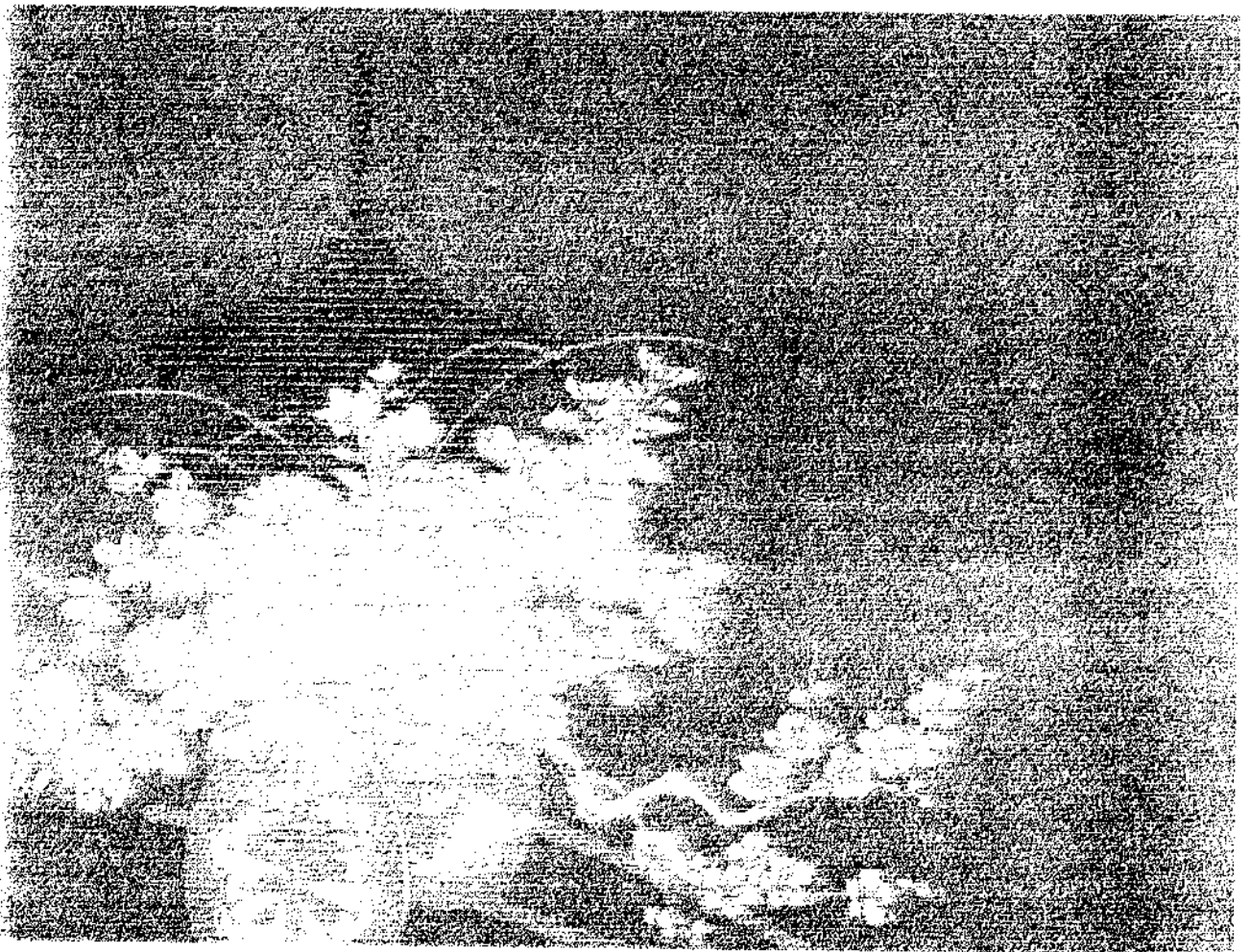


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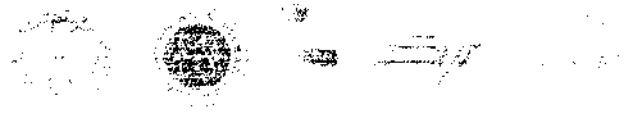
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GENES4/ANP2003 PROGRAM

16A. IRIS Design

(11:20-13:00) at Room 2B

Chairs: Shigeru Urata (Kansai EPC, Japan)
Antonio Barroso (CNEN, Brazil)

1130 IRIS Economics

K. Miller (British Nuclear Fuels plc, UK)

1136 Enabling 48 Month Maintenance Intervals for IRIS

R. Boroughs, J. Wilson, W. Eberly, G. Boles, R. Emrath
(Tennessee Valley Authority, USA)

1144 A Plant Control System Development Approach for IRIS

R.T. Wood, C. R. Brittain, J. A. March-Leuba (Oak Ridge
National Laboratory, USA), L.E. Conway, L. Oriani
(Westinghouse, USA)

1140 Sizes for Secondary Plant Components for Modularized Iris Balance of Plant Design

M. R. Williamson, L. W. Townsend (Univ. of Tennessee,
USA)

16B. IRIS Safety

(14:00-15:40) at Room 2B

Chairs: Takashi Sawada (Mitsubishi Heavy Industries,
Japan)
Carlo Lombardi (Politecnico de Milano, Italy)

1146 IRIS Pre-Application Licensing

M. D. Carelli, C.L. Kling (Westinghouse, USA)

1078 Preliminary Level-1 Probabilistic Risk Assessment of the IRIS Plant in a Conceptual and Preliminary Design Phase

Y. Mizuno, L. Oriani, L. E. Conway, H. Ninokata (TTT, Japan)

1142 Use of PRA Techniques to Optimize the Design of the IRIS Nuclear Power Plant

M. D. Muhlheim, J. W. Cletcher, II (Oak Ridge National
Laboratory, USA)

1131 Development of a Coupled Containment-Reactor Coolant System Methodology for the Analysis of IRIS Small Break LOCA

A. Manfredini, F. Oriolo, S. Paci, D. Grgić, T. Bajs (Pisa Univ.,
Italy), L. Oriani (Politecnico de Milano, Italy)

17. Internal CRDM and IRIS Development

(16:00-18:30) at Room 2B

Chairs: Hisashi Ninokata (TTT, Japan)

Mario Carelli (Westinghouse, USA)

1028 Hydraulically Driven Control Rod Concept for Integral Reactors: Fluid Dynamic Simulation and Preliminary Test

M.E. Ricotti, E. Colombo, M. Passoni, C. Rizzo, M.D.
(Politecnico di Milano, Italy), Carelli (Westinghouse, USA), C.
Lombardi (Politecnico di Milano, Italy)

1233 Development of Internal CRD for Next Generation BWR

T. Narabayashi, T. Yamamoto, M. Sato, N. Kobayashi, T.
Kameda, T. Tokumasu, S. Kawano, T. Hagiwara (Toshiba,
Japan), M. Mori, S. Ohmori (TEPCO, Japan), T. Terai, H.
Madarame, Y. Morimoto (Univ. of Tokyo, Japan)

1232 In-vessel Type Control Rod Drive Mechanisms for Integral-type Reactors

T. Ishida (JAERI, Japan), S. Imayoshi (Shinsei Giken, Japan),
T. Kanagawa (Mitsubishi Heavy Industries, Japan)

1153 Selection of an Appropriate Turbulence Modeling in a CFD code for an Ultra-long Life Core for the "IRIS" Reactor

E. Baglietto, H. Ninokata (TTT, Japan)

1185 Identification of Iris Reactor Transients Using Self-Organized Maps

B. D. B. Filho (Instituto de Pesquisas Energéticas e Nucleares,
Brasil), A. C. de O. Barroso (Comissão Nacional de Energia
Nuclear, Brasil)

1016 Robust Techniques for Monitoring and Fault Diagnosis of Helical Coil Steam Generators

B.R. Upadhyaya, K. Zhao (Univ. of Tennessee, USA), R.T.
Wood (Oak Ridge National Laboratory, USA)

WEDNESDAY SEPTEMBER 17, 2003

Session chair's breakfast

(07:00-07:40) at Kyoto Tokyu Hotel, Gion room

"Business Climate" plenary

(8:30-9:50) at Buzz Hall

Chair: Regis Matzie (Westinghouse, USA)

"A Vendor's Perspective on the Business Climate for
Advanced Nuclear Power Plants", Regis Matzie
(Westinghouse, USA)

"The Promise of New Nuclear", Dan Keuter (Entergy, USA)

"ACR Program Status", Ken Hedges (AECL, Canada)

"Development of APWR and Next Generation Plant", Yutaka
Nakahara (Mitsubishi Heavy Industries, Ltd., Japan)

"Business Environment of Nuclear Power Industry in Korea",
Yoon Young Lee (Doosan Heavy Industry Co., Korea)

Coffee service

(09:40-10:40, 15:00-16:00) at "Café Saveur"

3. Advanced PWR design and development (10:00-12:05) at Buzz Hall

Chairs: Susumu Ueda (JAPC, Japan)

Larry Conway (Westinghouse, USA)

1064 Design and Licensing Experiences of the Advanced Power Reactor 1400 Development

S. J. Cho, D. W. Jerng, E. J. Lee, J. H. Na (Korea Hydro &
Nuclear Power Co., Korea)

1063 Constructibility Assessment of APR1400

S. J. Cho, Y. C. Kang, J. G. Lee, W. S. Lim (Korea Hydro &
Nuclear Power Co., Korea)

1099 Core and fuel design of APWR

K. Seki, T. Tanaka (Kansai Electric Power Co., Japan), S.
Ueda (JAPC, Japan)