Military Technical College
Kobry El-Kobbah,
Cairo, Egypt

7th International Conference
on Electrical Engineering
ICEENG 2010

Neurofuzzy Computing aided Fault Diagnosis of Nuclear Power Reactors

By

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Abstract:

Nuclear Power Reactors (NPRs) are large in scale and complex, so the information from local fields is excessive, and therefore plant operators cannot properly process it. When a plant malfunction occurs, there are data influxes, so the cause of the malfunction cannot be easily and promptly identified. A typical NPR may have around 2,000 alarms in the Main Control Room (MCR) in addition to the display of analog data [1--4]. During plant transients, mode changes and component trips, hundreds of alarms may be activated in a short time. Hence, to increase the plant safety, this article proposes the operator support systems based on neurofuzzy assisted alarming and diagnosis system. Throughout this framework the neurofuzzy fault diagnosis system is employed to fault diagnosis of nuclear reactors. To overcome the weak points of both linguistic and neuro learning based approaches an integration between the neural networks and fuzzy logic has been applied by which the integrated system will inherit the strengths of both approaches.

Keywords:

Neurofuzzy computing, fault diagnosis, nuclear power reactors

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1. Introduction:

A fault diagnosis system is a kind of operator support system. The objective of a fault diagnosis system is to make the task of accident diagnosis easier, to reduce human mistakes, and to ease the workload of operators by quickly suggesting likely faults based on the highest probability of their occurrence. During the first few minutes after an accident occurrence, operators in a MCR must perform highly mentally workloaded activities. The operators may be overworked and disorder may result. Information overload and stress may severely affect the operator's decision-making ability just when it is required. In such situations, using a fault diagnosis system will be very helpful in that it will enhance operator's decision-making ability and reduce their workload. Recently many advanced intelligence systems have been developed using information and digital technologies [5-9].

In this paper, the feasibility study of the neurofuzzy diagnosis system (NFDS) on the recognition of multiple alarms in NPRs has been introduced. When a plant disturbance occurs, sensors outputs or instruments may trigger firing of alarms and form a different alarm pattern that represents a different fault. This proposed technique is applied on two hierarchical levels; the first one is the global fault diagnosis system as in subsection 3.1 and detailed fault diagnosis on a central critical node as in subsection 3.2. Throughout this framework the alarm and fault patterns of Angra II and Kori II reactors have been employed. The diagnosis of faults is approached from a pattern matching perspective in that an input pattern is constructed from multiple alarm symptoms and that symptom pattern is matched to an appropriate output pattern that corresponds to the fault occurred. The first layer of the system is fuzzy system where the rules are applied to check whether the input pattern is known else it acknowledges unknown alarm pattern. The second layer is multi-layer neural Network. The implemented neural layout contains an input layer, which consists of 12 alarm input nodes, a hidden layer, which consists of 7 nodes, and an output layer, which consists of 9-class fault identification nodes [10-14], as explained in Kori II cooling pump case of study.

The rest of the paper is organized as follows; in section (2), the plant safety and fault diagnosis have been introduced. Section 3 presents the proposed neurofuzzy fault diagnosis technique in global and detailed levels. In section (4), Results of the NFDS learning is presented. Finally in section (5) the conclusion is drawn.

2. Safety, Alarming and Fault Diagnosis of NPR:

The main control room (MCR) operators in a NPR have a supervisory role in terms of information gathering, planning, and decision making. During abnormal conditions or situations in which an accident has occurred, the operator's task is to comprehend a malfunction in real time by analyzing alarms, values or trends of multiple instruments,

and so on. For a correct and prompt diagnosis of plant status, operators should perform diagnostic tasks by observing instruments that clearly show the current state. In a NPR, there are many instruments that indicate the status of the plant. While an analysis of all instruments is the best way to ensure a correct diagnosis, the number of instruments makes it impossible for operators to look at each one individually. If there are no operator support systems, which include alarms that serve as major information sources for detecting process deviations, operators have to consider too many instruments and a diagnosis will take too long. A slow reaction on the part of the operator could result in accidents and could have serious consequences, so it is imperative that operator support systems are effective. Alarms help operators to make quick diagnoses by reducing the number of instruments that must be considered. Even though alarms help the operators' situation awareness, there are too many of them; a typical MCR in a NPR has more than a thousand of alarms. In emergency situations such as a loss of coolant accident (LOCA) or a steam generator tube rupture (SGTR), hundreds of lights turn on or off within the first minute. Since having many alarms that turn on and off repeatedly may cause operator confusion, an operator support system can be useful for accident management [15—16]. Throughout this study some essential recommendations have been proposed. Moreover, an intensive research on AI techniques for present nuclear reactors is presented, figure 1.

The following attributes are essential factors for the future reactor designs:
- The reactor should be passively safe.
- The transparency of the safety of the plant to both the public and the regulators.
- The design should be acceptable in terms of safety.
- The plant should be simple to operate, upgrade and maintain.
- The plant design must be simple in assembly and disassembly.
- Online capability to refuel and to perform maintenance
- The system should ensure minimal environmental impact.
- The design should use a simple fuel cycle to have high fuel burn up.
- The reactor could be site assembled and transported to the definite sites quickly.

If any one of the reactor's parts has a fault or failure, transducers transfer a fault or failure signal to the neurofuzzy alarming network which is considered as an alarm signal generator. This process is called alarm processing stage. The objectives of the alarm processing system are; to reduce the number of alarms presented, to recognize alarms so that they could be grouped in relation to a single cause, to order the alarms within a group, and to display suitable alarm messages. Alarming signals and messages are transferred to neurofuzzy diagnosis network to analyze alarm signal and to identify a primary causal alarm, and can diagnose possible failure modes and failed systems. This

process is called diagnosis stage. Throughout this paper an integrated alarming and fault diagnosis system based on neurofuzzy approach is presented.

Figure 1: A typical core and cooling cycle of a pressurized water reactor

2 Reactor's Safety based on Artificial Intelligence:

AI-based diagnostic systems have been extensively studied to support nuclear reactors operators during abnormal conditions. The main tasks of a diagnostic system are alarm detection and fault diagnosis. A fault represents a deviation with respect to the expected system behavior. Alarm signals are elaborated on real time case of study. Fault detection consists in the generation of symptoms from the fault indicators and the evaluation of the time of detection. Fault detection determines, from a set of symptoms, the kind and the location of the primary fault and relates it to a physical component whose behavior is not consistent. Even if it is clear that diagnosis is a strategic necessity, very few real applications are yet in use.

AI based Classification or pattern recognition approach is the way to deal with fault diagnosis. It is based on process data or expert knowledge about the nuclear reactor and its misbehavior. Relevant symptoms are identified to be representative of each type of failure. The relationships between symptoms and faults are obtained by supervised learning when faults are known a priori, for instance by an expert: in this case the system decision is tuned to correspond to the right answer from a training set of known examples. The diagnostic system is a classifier that must then recognize, in real time, the actual situation represented by a new symptom vector and associate it to one of the known faults. The classifier may also have some on-line learning capacity to deal with unknown faults.

In this framework neurofuzzy techniques have emerged as a mean to deal with 'grey-box' models with good numerical accuracy and reasonable interpretability. Recurrent topologies for neurofuzzy systems have been attentively studied. This research work proposes a recurrent neurofuzzy network that allows the construction of a 'global' non-linear multi-step ahead prediction model by the fuzzy conjunction of 'local' dynamic models, which are, in turn, linear auto regressive models. Recurrent neurofuzzy networks have also been successfully used for the diagnosis of global and detailed fault diagnosis of nuclear reactors.

3. *The proposed Neurofuzzy Approach:*

In diagnostic applications, faults are characterized by their symptoms, which can evolve with time, performing a trajectory in the observed variable space. Neurofuzzy systems for diagnosis are pattern. The design of the Neurofuzzy Fault Diagnosis System (NFDS) is shown in figure (2). The overall NPR has tight alarming and fault diagnosis system. This system has multi-level alarm and fault diagnosis techniques. Every part of the plant has its own diagnosis system. The overall Plant has a global alarming and fault diagnosis system, which links all individual subsystems. As the control system of the plant can be tested by NFDS to define the fault if found, also all parts of the plant can be tested by a pattern recognition NFDS technique.
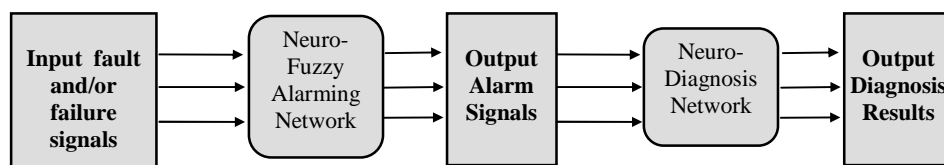

Figure 2: Neurofuzzy fault diagnosis system (NFDS)

3.1. *Fault Diagnosis of Angra II:*

This first Case of study, Angra Nuclear Power Plant, is Brazil's sole nuclear power plant. It is located at the Central Nuclear Almirante Álvaro Alberto (CNAAA) on the Itaorna Beach in Angra dos Reis, Rio de Janeiro, Brazil. It consists of two Pressurized water reactors, Angra I, with a net output of 657 MWe, first connected to the power grid in 1985 and Angra II, with a net output of 1,350 MWe, connected in 2000. The list of alarming signals of both primary and secondary loops (a1, a2, ….a17) and the system faults (f1, f2, … f17) of Angera II are indicated in table 1. In [17] the authors employed the individual alarms to detect the fault based on fuzzy quantization vectors. The presented research work applies the fuzzy rules to the temporal behavioral analysis where several central nodes (p_1, p_2, p_3, … p_i) are selected to observe the most important parameters like neuron density (n_1, n_2, n_3, … n_i), temperature (c_1, c_2, c_3, … c_i)), pressure (s_1, s_2, s_3, … s_i), flow rate (r_1, r_2, r_3, … r_i) and level (l_1, l_2, l_3, … l_i) of a nuclear power reactor, see figure 3.

Alarms	Definition	Faults	Definition
a1	Nuclear power	f1	Normal state (no fault)
a2	Cold leg temperature	f2	External power blackout
a3	Hot leg temperature	f3	Feed-water isolation without SCRAM
a4	Core output temperature	f4	Main feed-water rupture without SCRAM
a5	Primary loop pressure	f5	Main steam isolation without SCRAM
a6	Subcooling margin	f6	Steam generator's tubes rupture
a7	Primary loop coolant flux	f7	Reactor trip
a8	Core coolant flux	f8	External power blackout without SCRAM
a9	Pressurizer level	f9	Feed-water isolation
a10	Thermal power	f10	Main feed-water isolation without SCRAM
a11	Radioactivity of the secondary loop	f11	Main steam isolation
a12	Steam generator feed-water flux	f12	Main steam rupture
a13	Steam flux	f13	Turbine trip without SCRAM
a14	Steam pressure	f14	Loss of coolant in the primary loop
a15	Steam generator level (narrow range)	f15	Main feed-water rupture
a16	Steam generator level (wide range)	f16	Main feed-water isolation
a17	Primary coolant leakage flux	f17	Reactor and turbine trip

Table 1: Alarms and fault of Angra II reactor

One should consider that not all these parameters are essential at all nodes. The distribution map of these parameters over the critical points is considered and the relation among these parameter spaces over the time is analyzed, see figure 3. The logic fuzzy rules could be formulated as;

Figure 3: Pressurized water reactor with 17 critical point

IF   *(Neuro Conition$_1$ Logic Operator Neuro Conition$_2$ ..... Neuro Condition$_i$)*

　　　THEN *Action.*
　　　　ELSE IF *(Neuro Conition$_1$ Logic Operator Neuro Conition$_2$ .....)*
　　　　　THEN *Action.*
　　　ELSE *Action*
　END IF

Where neuro condition$_i$ is the neural based fault detection of parameter value (n_i, c_i, s_i, r_i, l_i)) at p_i critical nodes and the logic operator are AND, OR NOT , … The redundancy in fault diagnosis leads to more robustness. A case of study explaining the neural condition is presented in subsection 3.2 on the Kori II cooling pump faults detection.
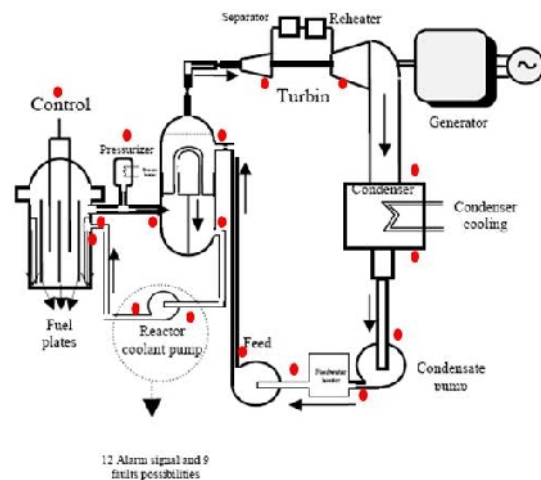
3.2. Fault Diagnosis of Kori II cooling pump:

In subsection 3.1 a global fault diagnosis system is introduced to study the fault detection on selected critical nodes on the reactor while this subsection introduces more detailed on the neurofuzzy fault diagnosis in a certain node, it is the cooling pump. One of the most important parts of the NPR is the RCP. This part of reactor has 12 alarming signal (a1, a2, a3, ..., a12) and the possibility of faults are 9 (f1, f2, f3, ... f9). The design of the NFDS used is shown in figure (4.a, 4.b) whereas it consists of two major phases the first one is the fuzzy system and the second one is neural network. The neural network consists of 12 input nodes, 7 hidden nodes, 9 output nodes. The definition of the faults and their corresponding alarms are shown in table (2.a, 2.b).
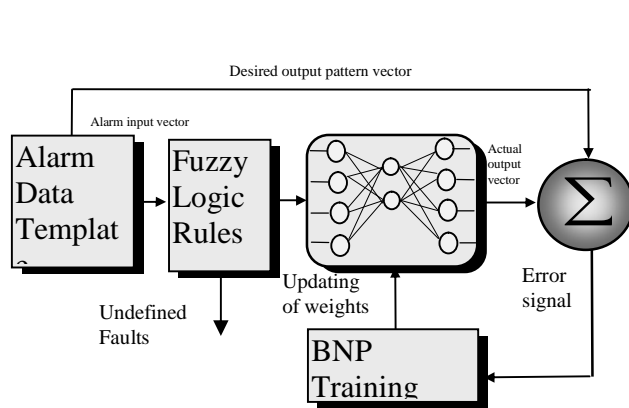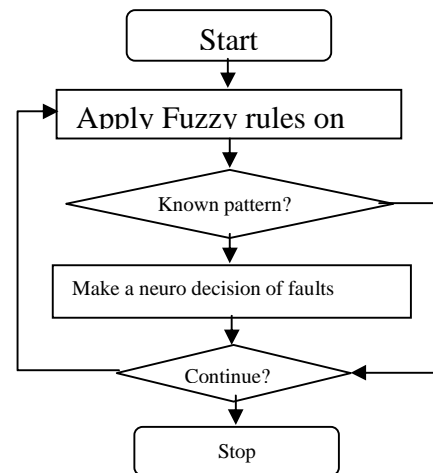

Figure (4.a) The NFDS learning diagram   Figure (4.b) Structure of the implemented Neural Network

As the error back propagation training algorithm EBPTA is running, weights of the NFDS are changing till the allowed root mean square error RMS reaches its recommended value learning, then learning stops. After learning process is considered we can obtain the diagnosis of any fault can be caused by any alarms pattern, see [9] for more details.

4. Results of the NFDS Training:

The outputs comparison of both reference training patterns and the output of the NFDS show that they are typical so the network is well trained and it can easily detect any possible system faults.

6. Conclusions:

In this paper, the feasibility study of the NFDS in fault diagnosis of NPRs is presented.

The neurofuzzy approach has more powerful advantages (e.g., Short knowledge acquisition time, low development cost, fast running time, robustness to noisy alarm signals, and general mapping capabilities) over the conventional alarm processing methods. Results show that once the network has been fully trained with various alarm patterns, it can identify with a good accuracy the faults well. Although untrained or incomplete/sensor-failed alarm patterns are given, the network can diagnose a fault properly. In addition, multiple faults can be easily diagnosed using a given alarm pattern. The network also has the capability of identifying the time-varying fault behavior. In conclusion, the neurofuzzy approach is almost appropriate for pattern recognition problems in environments where plant actual data are abundant and noisy. Moreover, the neurofuzzy based systems can run very fast if hardware implementations are becoming available. This makes the systems, especially well suited for real-time applications such as alarm processing and fault diagnosis in NPR.

Alarm signal	Description
a1	Seal injection filter differential pressure high
a2	Charging pump flow low
a3	Seal injection flow low
a4	No. 1 Seal differential pressure low
a5	No. 1 Seal leak off flow low
a6	Standpipe level low
a7	Standpipe level high
a8	No. 1 Seal leak off flow high
a9	Thermal barrier flow low
a10	Thermal barrier temperature high
a11	Bearing flow low
a12	Bearing temperature high

Table (2.a) Alarming signals definition

Fault signal	Description
f1	Seal injection filter blockage
f2	Charging pump failure
f3	Seal injection water high temperature
f4	Reactor coolant system pressure less than 400 psig
f5	No. 1 Seal damaged
f6	Volume control tank back pressure high
f7	No. 2 Seal failure
f8	Insufficient component cooling water flow to RCP
f9	Motor Bearing damaged

Table (2.b) Fault signals definition

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