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Nuclear Reactor Core Dynamics Control Using Neural Networks

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Abstract: Stable power processes are never guaranteed. An assortment of unstable behaviors wrecks power apparatus, including mechanical vibration, malfunctioning control apparatus, unstable fluid flow, unstable boiling of liquids, or combinations thereof. A necessary condition for stable reactor power is that the reactor distortion accompanying a temperature rise decreases the reactivity, thus slowing any further rise in power. Nuclear Reactor may changes with time for the number of reasons: Nuclear Fuel Shuffling, Fuel burn up, Control rod motion, coolant flow Perturbations. Our paper involves coolant flow perturbations control using Artificial Neural networks. ANNs have been widely used for various tasks, such as pattern classification, time series prediction, nonlinear control, and function approximation neural networks are intrinsically parallel and non-algorithmic methods; these features of neural networks make real-time processing of data and information feasible. Neural networks, have been trying to fill the gap for which traditional techniques have, so far failed to offer a reasonable solution.

Keywords: **Reactor core dynamics, Coolant Flow Perturbations, Neural Network.**

I. INTRODUCTION

Good understanding and prediction of the nuclear reactor dynamics are essential parts of correct system simulation for overall nuclear power plant performance and safety during transients. A Nuclear Power Plant is a nuclear system and a mechanical system. It is also a heat-transfer system, tied in with controls, boilers, turbines, human operators and a multiplicity of other complicating factors. The possibilities for instability are myriad. The mechanical oscillation was coupled with the nuclear power oscillation in an unstable combination. Water-moderated reactors, the type most commonly used for the generation of power, might be susceptible to catastrophic nuclear power oscillations, if the pressure of the water in the reactor suddenly decreased, creating vapor bubbles in the core.[1]

A. Reactor Kinetics:

Reactor kinetics refers to the manipulation of parameters that affect *k* (reactivity) and to the subsequent **direct response** of the reactor system. Examples are:

- Absorber rods or shim movements to compensate for fuel burn up.
- Safety scram rods to rapidly shutdown the chain reaction.
- Control rods to provide real-time control to keep *k* = 1 or to maneuver up and down in power.

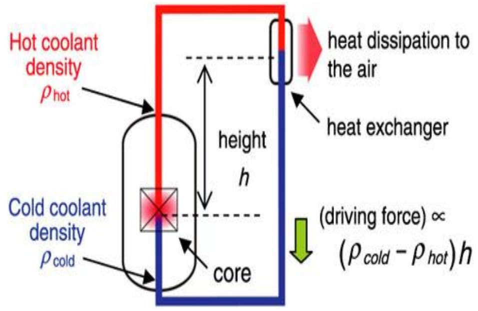

Fig1. Natural circulation in the heat transport systems

B. Reactor Dynamics

Reactor dynamics refers to the more **indirect feedback mechanisms** due to power level effects [6] and other overall system effects such as:

- Temperature feedback.
- Void feedback.
- Pump speed control (affects water density and temperature).

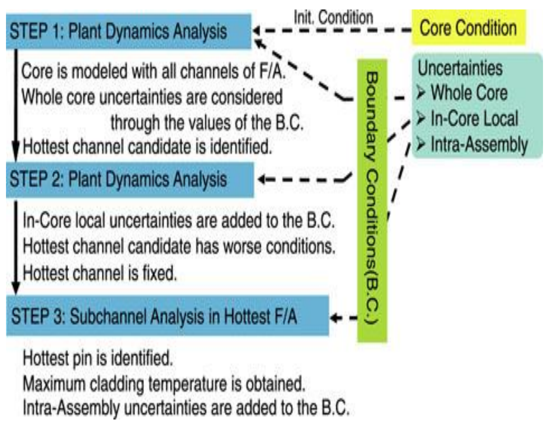

Fig 2. Plant Dynamics

The transient response of the reactor to the above direct and indirect changes in basic parameters is highly dependent on the design details of the reactor. Sample issues are:

- Where the control rods should be placed for maximum effectiveness?
- Will the power go up or down if a void is introduced into the reactor?
- Will the power go up or down if core temperature goes up?
- How often should the reactor be refueled?

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In this paper, the term reactor dynamics refers to changes in reactivity or any of the kinetics parameters that occur on timescales on the order of hours to years. [6]

C. Reactor Coolant Recirculation System

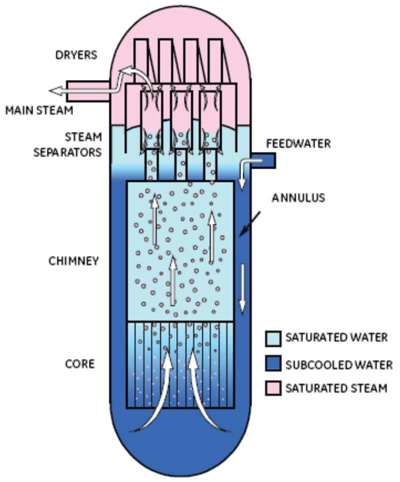

Fig 3. Reactor Coolant Recirculation System

Nuclear power reactors generate electricity by directly boiling the light water in a reactor pressure vessel to make steam that is delivered to a turbine generator. After driving a turbine, the steam is converted into water with a condenser and pumped into the reactor vessel with feed water pumps. A part of the water is sent into the reactor vessel after being pressurized with recirculation pumps installed outside of the vessel and fed into the reactor core from the bottom part of the reactor vessel with jet pumps. Inside reactor pressure vessel (RPV), feed water enters through nozzles high on the vessel, well above the top of the nuclear fuel assemblies (these nuclear fuel assemblies constitute the "core") but below the water level. The feed water is pumped into the RPV from the condensers located underneath the low pressure turbines and after going through feed water heaters that raise its temperature using extraction steam from various turbine stages. The feed water enters into the down corner region and combines with water exiting the water separators. The feed water sub cools the saturated water from the steam separators. This water now flows down the down corner region, which is separated from the core by a tall shroud. The water then goes through either jet pumps or reactor internal pumps that provide additional pumping power (hydraulic head). The water now makes a 180 degree turn and moves up through the lower core plate into the nuclear core where the fuel elements heat the water. When the flow moves out of the core through the upper core plate, about 12–15% of the volume of the flow is saturated steam.

II. COOLANT FLOW PERTUBURATIONS

The Nuclear reactor's core is surrounded by a shroud. The cooling water enters into this "jacket-like" space between the shroud and the wall of the reactor (Figure 4). The water travels down the outside of the core and then rises up inside it. As it rises, the fuel rods heat it until it starts to boil. As the steam bubbles form, the water "swells" (its steam-to-water ratio rises). The goal of the control system is to keep the fuel rods always covered in order to protect against their overheating and melting. Normally, the levels and the steam/water ratios within the core are not measured. The water level outside the shroud is measured, but does not reflect the level inside once the water level drops below the suction of the jet disperser. Consequently, this level measurement is meaningful only during normal operation, and is useless during emergencies caused by loss of cooling.

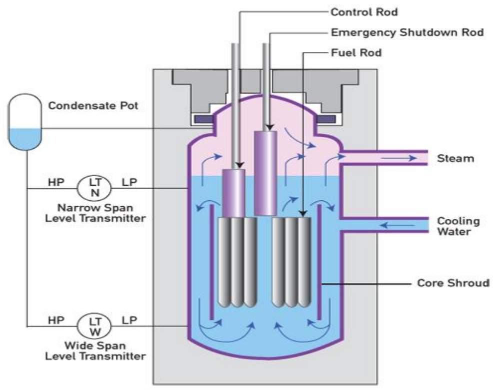

Fig 4. Coolant Flow Perturbations

The level outside the shroud is usually measured over two ranges, a narrow (LT-N) one and a wide (LT-W) one. The narrow span LT-N is more sensitive and is a better indicator of the surface level while LT-W detects the total hydrostatic head in the reactor (the collapsed level). They both usually are the d/p types, provided with condensate-filled wet legs. The condensate pots are un insulated, and drain back into the reactor through a sloped connecting pipe. In old plants, these transmitters (or d/p indicators) are often located in the control room through long, water-filled lead lines connecting them to the reactor. This is a terrible idea because these long lead lines often cause gas blockage, leaks or oscillation, but 40 years ago they were in use by some.[8] These level transmitters are inverse-acting (the reference leg is the high-pressure side), and therefore, a maximum level produces a zero-differential reading, while a zero level causes a maximum output signal. The measurement also assumes that the wet leg is full with condensate at ambient temperature. During an accident, neither of these assumptions is guaranteed. In fact, they are likely to be wrong, because once the level in the reactor drops below the low-pressure tap of LT-N, the reading is meaningless (zero). Also, if the water in the reactor is boiling, these d/p cells detect the hydrostatic head (mass of water), not the level. The more bubbles form (swelling), the lower the density. Therefore, the lower level is reported by the d/p cell. Inversely, as the rate of steam formation drops (shrink phase), the density increases, and the level reading rises. In other words, when the surface of the boiling water rises (swell condition) the level reading drops, and when the boiling rate and, therefore, the level drops, the measurement

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rises. The level shrinks or swells whenever the loading of the reactor changes because during that time, the rate of water entering is different from the rate of steam leaving [4].Swelling occurs when the steam pressure drops (the steaming rate increases), and shrinking occurs when the steaming rate is reduced (the steam pressure rises), and bubbles collapse. Therefore, the d/p cell outputs can be converted into indications of the surface level only if the density is separately determined. This correction was/is inaccurate or nonexistent. Therefore, these level measurements are unreliable or useless. Because of this, the level control loop cannot be closed (cannot be placed in automatic) and is often under manual control, which is unacceptable.

A. Detecting Level Correctly Outside the Core

In order to accurately measure the level outside the core, several pressure detectors (P1 to PX on the left of Figure 5), should be installed at equal distance (A) from each other. The smaller the distance A is, the higher will be the precision of measurement. If we define ΔP as the pressure difference between any two adjacent sensors, when ΔP is zero, there is no water at that level—this is the case between P2 and P3 in Figure 2—and if ΔP equals A(SG), that means that there is no steam at that elevation. (SG is the specific gravity at the actual temperature.) By this method, both the level of the boiling surface (Ls) and the pressure at that elevation (Ps) can be determined.

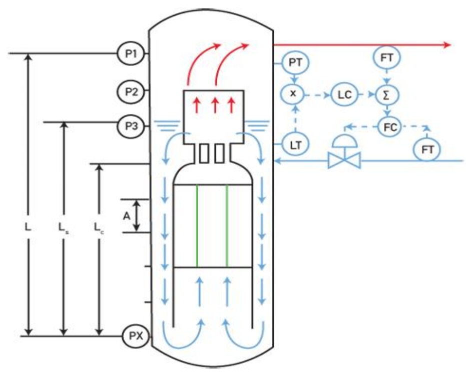

Fig 5. Reactor Core Steam/Water measurements

The various combinations of these measurements can be used to obtain the following information:

- Steam/water ratio (S/W) at any elevation is S/W = ΔP/A(SG).
- Collapsed total water level is Lc = ΔPs/(PX – P1).
- Total S/W in the whole reactor S/Wr = (PX – P1)/L(SG).
- Steam/water ratio of the boiling column of water from up to the elevation Ls is S/Ws = (PX – Ps)/Ls(SG).

Provide both the d/p cells and the pressure detectors with battery backup and with wireless output signal backup, so that if either the regular power supply fails, or the regular output signal wires are damaged, the level information will still be available and can be read not only in the control room, but anywhere. As to the method of detecting the in-core water level, use probes designed to measure the temperature at the different elevations in the core (Figure 2). The temperatures at the different elevations reflect the steam/water ratio, because water is a better heat conductor than steam, and therefore, the probe temperature will rise as the proportion of steam bubbles rise. During transient conditions, the coolant density effect runs counter to the desired net inherent reactivity response. However, as the coolant loop cools in response to the resultant lowered heat generation, the long term contribution of the coolant density feedback is negative reactivity. The Coolant density reactivity provides a detrimental contribution to prompt inherent power control but becomes an important beneficial effect as power stabilizes in the long-term.

B. Nominal ranges:

The main circulating pumps have the capacity of 5,500–12,000 m³/h and are powered by 6 kV electric motors. The normal coolant flow is 8000 m³/h per pump; this is throttled down by control valves to 6000–7000 m³/h when the reactor power is below 500 MWt. Each pump has a flow control valve and a backflow preventing check valve on the outlet, and shutoff valves on both inlet and outlet.[2] Each of the pressure channels in the core has its own flow control valve so that the temperature distribution in the reactor core can be optimized.

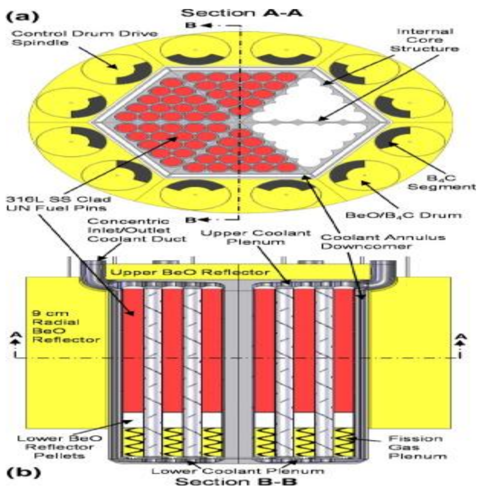

Fig 6. Internal Core Structure

The nominal coolant flow through the reactor is 46,000–48,000 m³/h. The nominal temperature of the cooling water at the inlet of the reactor is about 265–270 °C (509–518 °F) and the outlet temperature 284 °C (543.2 °F), at pressure of 6.9 MPa (in the drum separator)[2].The pressure and the inlet temperature determine the height at which the boiling begins in the reactor; if the coolant temperature is not sufficiently below its boiling point at the system pressure, the boiling starts at the very bottom part of the reactor instead of its higher parts; the positive void coefficient of the reactor makes the reactor very sensitive to the feed water temperature. If the coolant temperature is too close to its boiling point, cavitations can occur in the pumps and their operation can become erratic or even stop entirely. The feed water temperature is dependent on the steam production; the steam phase portion is led to the turbines and condensers and returns significantly cooler (155–165 °C (311–329 °F)) than the water returning directly from the steam separator (284 °C). At low reactor power, therefore, the inlet temperature may become dangerously high. The water is kept below the saturation temperature to prevent film boiling and the associated drop in heat transfer rate. The reactor is tripped in case of too high or low water level in the steam separators (with two selectable low-level thresholds), high steam pressure, low feed water flow, or loss of two main coolant pumps on either side. These trips can be manually disabled. The level of water in the steam separators, the percentage of steam in the reactor pressure tubes, the level at which the water begins to boil in the reactor core, the neutron flux and power distribution in the reactor, and the feed water flow through the core have to be carefully controlled. The level of water in the steam separator is mainly controlled by the feed water supply, with the deaerator tanks serving as a water reservoir. The maximum allowed heat-up rate of the reactor and the coolant is 10 °C (50 °F)/h; the maximum cool-down rate is 30 °C (86 °F)/h.

III. NEURAL NETWORKS

Signal validation and process monitoring problems require the prediction of one or more process variables in a system. The prediction of system state variables is performed traditionally using either physical or empirical models .Empirical models require knowledge of all variables having significant effect on the signal to be modeled .The model characterizes a critical signal as a function of a set of other measurements which is modeled. Model-based prediction assumes a fixed structure for characterizing steady-state or dynamic relationships among process variables [3].The generation of an accurate model requires an effort which is proportional to the size and complexity of the system. An alternative new method, neural network distributed parallel processing, offers several advantages in signal validation when compared to the traditional model-based techniques. A Neural Network (NN) is a massively parallel distributed processor made up of simple processing units, which has a natural propensity for storing experiential knowledge and making it available for use. The knowledge is acquired by the networks from its environment through a learning process which is basically responsible to adapt the synaptic weights to the stimulus received by the environment. [3]

A. Neural Approach in Coolant circulation loop

Neural networks are Multi-Input Multi-Output (MIMO) function approximators, which can be used to learn an un-known functional dependence between inputs and outputs using test data. Consider an example 3-input 2-output linear neural network. The dynamics of Nuclear reactor core are captured by Recurrent Neural Networks.[5]The training process determined through a back propagation algorithm which minimizes a quadratic error between the desired and network outputs. The gradient descent method with momentum weight/bias learning rule has been used to train considered ANNs. It is a developed algorithm of the basic back propagation algorithm A net input (Vj) to a neuron in a hidden layer k is calculated by this formula

$$\mathbf{V_j = {}^{n}\Sigma_{i=1} (W_{ji}\, \theta_i + \theta_j)}$$

Where n is the number of k-1 layer neurons for a general type of feed-forward ANNs and the number of all of the previous layer neurons for a cascade type of feed-forward ANNs. Weights are noted by Wji; and the threshold offset by ├j [11].

The steam void due to reactor coolant boiling has a negative-reactivity effect, which can suppress a power rise even if a positive reactivity is added. The reactor power can be controlled by two methods: reactor-coolant recirculation-flow control and control rod operation. The heat generated in fuel rods is transferred to the reactor coolant. The magnitude of heat transferred according to the temperature difference between the heat transfer surface and the coolant has been obtained first. Since the heat transfer decreases in the transition film-boiling region in which the boiling becomes violent that could cause a burnout of fuel cladding tube, the heat transfer in the nucleate-boiling region is utilized in the reactor. Therefore, the reactor operation limits are imposed on reactors not to approach to the transition film-boiling region during normal operation and abnormal operational transients. Core flow is controlled by changing the dual speed recirculation pumps from one discrete speed to another and by throttling a variable position flow control valve [7].The recirculation flow control system for all product lines allows individual or ganged control of each flow control device. Safety Relief Valves are used for pressure control and reactor core insulation cooling. Main Reactor coolant system flow depends on reactor coolant pump speed and steam generator primary differential pressure. Consider the following Alarm Signal and the fault signal. Neural networks provide us easier solution to find out the faults.[9]

Alarm signal	**Description**
a1	Water Inflow
a2	Coolant Pump Pressure
a3	Maximum Temperature
a4	Minimum Temperature
a5	Precipitation
a6	Snow melt

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a7	Steam Water ratio
a8	Threshold Level
a9	Heat up rate

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	Tripping due to maximum or minimum water level
f9	Insufficient component cooling water flow to RCP

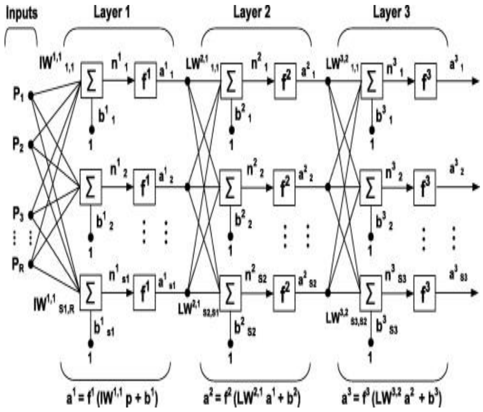

Fig 7. Neural Approach

Input → Hidden Layer (12) → Output Layer (10)

IV. RESULTS

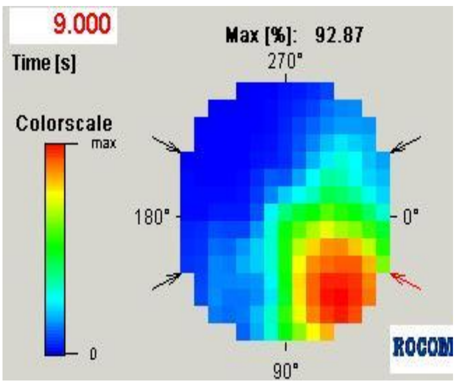

Fig 8. Perturbation in Core Inlet Plane [10]

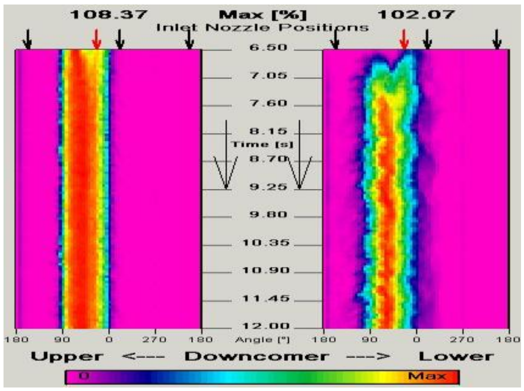

Fig 9. Time record of the perturbation at the sensors in the down comer

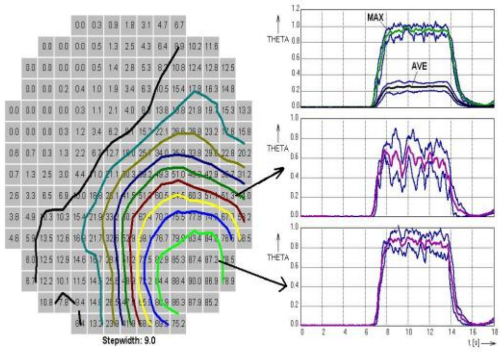

Fig 10. Plateau averaged distribution of the perturbation in the core inlet plane (left) and time evolution of the perturbation at different positions in the core inlet plane including confidence intervals [13]

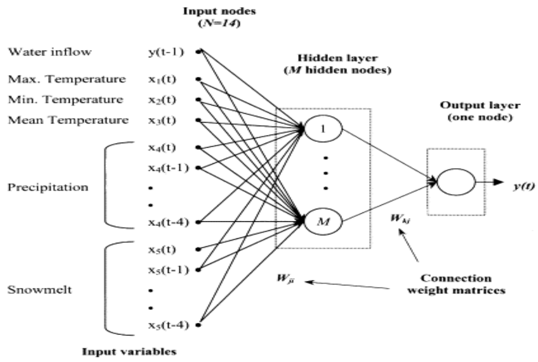

Fig 11. Neural Network in Reactor Core Operations [12]

V. CONCLUSION

Flow distribution in the primary circuit of pressurized water reactors is an important issue connected to different operational problems. For instance, the quasi-steady flow with macroscopic oscillating swirls inside the reactor pressure vessel can cause temperature fluctuations and therefore is of importance to long-term thermal fatigue. The flow distribution at the core inlet is influenced by the flow field in the reactor pressure vessel and the flow distribution between the loops. An asymmetric loop flow distribution is possible for example due to the pump

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operation uncertainties during power operation or due to the total pump failure during accident scenarios. Neural networks can capture complex dynamics of the system yielding satisfactory predictions. ANN software is to obtain fast estimation tool which allows large explorations of core safety parameters. This software is very useful in reactor core designing and in-core fuel management or loading pattern optimization.

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