A Nuclear Reactor Simulator for Teaching Purposes

The nuclear power reactor furnishes an excellent illustration of many of the principles and problems involved in the field of nuclear engineering. The design and operation of a portable electronic reactor simulator suitable for teaching purposes are discussed.

Perhaps the most interest-provoking situation in which controlled nuclear reactions are used in an engineering application is in the nuclear power reactor. This application is a good one for teaching purposes, because it illustrates several types and complexities of nuclear measurement. The larger problem of correlating these measurements with measurements of temperature, flow, etc., and using this information to control the reactor is also worth considerable study.

The nuclear power reactor is part of an integrated system in which a nuclear reactor serves as a source of power, say in a steam-electric generating station. The problem has several interesting facets, that of reactor control, that of the control of the steam-electric part of the system, and the over-all problem of determining the dynamic performance of the integrated complex. Fig. 1 shows a block diagram of a possible simplified arrangement of such a system.

Using the appropriate unclassified literature and reasonable engineering approximations, a set of equations can be written to represent the flow of energy and information in the system. Two items are of primary concern: nuclear kinetics in the reactor itself, and heat transfer in the reactor and the heat exchanger. In addition, since most reactors are designed so that the reactivity is a function of temperature, the interrelationship of the two must be established.

Investigation shows that because of this relationship between reactivity and temperature, the system has many of the characteristics of a feedback amplifier. It can thus be treated analytically by the well-developed techniques that are available for the analysis of feedback amplifiers and automatic control systems. In most cases of interest, the reactor kinetic equations are nonlinear, hence the additional interesting problem of treating nonlinear differential equations is introduced.

Several useful approaches to the problem are available. One of these involves linearization of the equations, and a subsequent application of the linear theory of feedback systems, such as the Bode diagram type analysis, to investigate system stability. This approach is interesting not only because it leads to useful results in this situation, but also because it is so widely applicable to problems in the automatic control of large systems.

The effect of the nonlinearity may also be treated, and appropriate unclassified publications are available. Again the method of treating the problem may be much more generally applicable than to this specific situation.

ANALOGUE COMPUTERS

As an alternative or as a supplement to the analytical approach, it may be desirable to use an analogue computer or reactor simulator to study system performance. The use of the simulator allows the nonlinearity of the system to be treated with facility. The simulator also allows easy and rapid variation of system parameters, and exhibits the changes in system performance which result therefrom.

An important advantage of an analogue computer is that as one observes solutions developing on the recorder, an intuitive "feel" for system performance is developed. This may be much more difficult to achieve from a purely analytical treatment.

The simulator which is used to treat the reactor power plant study can be either very elaborate or fairly simple. Although the simpler types have less precision, they have the advantages of compactness, portability, and low cost. They serve admirably as demonstration units for teaching purposes.

PORTABLE UNIT

A PORTABLE REACTOR SIMULATOR has been constructed at the University of Michigan which is of sufficient accuracy for teaching purposes. The equations simulated are, using the notation of Bell and Straus: \[ dN/dt = (k_{eff}/k)N - (\beta/\lambda)N + e^{\lambda t} \sum_{i} \lambda_{i} C_{i} + (T - T_{0})K_{1} N + S \] \[ dC_{i}/dt = -\lambda_{i} C_{i} + (e^{-\lambda t}/\lambda)\beta_{i} N \] \[ Q = M \frac{dT}{dt} + W(T - T_{c}) \]

Here, in addition to the symbols defined by Bell and Straus:

- \( T \) = temperature of the lumped reactor
- \( T_{0} \) = reference temperature of reactor
- \( T_{c} \) = average coolant temperature
- \( K_{1} \) = temperature coefficient of reactivity
- \( Q \) = reactor heat output, directly proportional to \( N \)
- \( M \) = thermal capacity of reactor fuel elements
- \( W \) = heat transfer coefficient from reactor to coolant

The basic circuit used to simulate the reactor proper is essentially that of Bell and Straus. This circuit is an
analogue of the one group, namely thermal, point reactor equations. Five neutron delay groups are included.\(^8\)

In addition, the effect of temperature rise in the reactor core caused by increased power level is also simulated. The position of the control rods, or \(\delta \kappa_{eff}\), the coolant flow rate, the "source" magnitude and the temperature coefficient of reactivity \(K_1\) are under the control of the operator from the front panel.

A block diagram of the circuit is shown in Fig. 2. A push-pull high gain d-c amplifier \(A\) is connected as an integrator with feedback capacitor \(C_1\). The output voltages of \(+N\) and \(-N\) are proportional to the time integral of the input current \(\Sigma i\), while the input voltage remains substantially constant. The panel voltmeter \(V_1\) indicates the neutron flux \(N\) at any instant. A current source \(i_g\) simulates the production of prompt neutrons, the rate being determined by the setting of the \(\delta \kappa_{eff}\) control and the level of \(N\).

Current sources \(i_{1}...i_{6}\) represent the delayed neutrons, and the time constants of the delay networks, \(\Delta_1...\Delta_6\), are set equal to the mean lives of their precursors. The time constants are fixed at the values: 0.62, 2.20, 6.52, 31.6, and 80.2 seconds. The delay fraction of each source is adjustable individually. The total delay fraction or percent of delayed neutrons represents about 0.75 per cent of the total neutron production under steady-state conditions. There is a primary fixed source \(i_0\) which is independent of level \(N\), but which is manually adjustable. A current \(K_1NT\) is also added to the integrator input representing the effect of temperature on reactivity.

The loss due to neutron absorption and diffusion out of the reactor core region is given by \(i_d\). This current is proportional to the level \(N\). The sum \(\Sigma i\) of all currents including the negative current: \(i_d\) denotes the excess neutron production and determines the rate of change of reactivity. When \(\Sigma i = 0\), for example, the reactor neutron population is constant.

A current proportional to the \(+N\) voltage is fed to a capacitor \(C\). This represents the heat input to the reactor, and \(C\) represents its thermal capacity. A control simulating the coolant flow rate, determines the current flow rate out of capacitor \(C\), and represents the rate of removal of heat from the reactor by the coolant. It is assumed that heat loss by radiation and conduction is small compared to that removed by the coolant. The voltage \(V_1\) on this capacitor represents the mean reactor temperature and is indicated by the panel voltmeter \(V_1\).

As mentioned previously, the effect of temperature variation on the reactor is obtained by feeding an additional source of neutrons \(K_1NT\) to the integrator input. \(K_1\) is the temperature coefficient of reactivity, and is negative in practical controlled reactors. Thus, the current contribu-

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Footnotes:
- Full text of a paper presented at the Nuclear Engineering and Science Congress, Cleveland, Ohio, December 12-15, 1955, and recommended for publication by the AIEE Committee on Nucleonics.
- L. Orr, W. Kerr, and H. J. Gomberg are with the University of Michigan, Ann Arbor, Mich.
- The authors gratefully acknowledge the interest and financial assistance of the Dow Chemical Company in the construction of this simulator.
tion is actually negative. Because this contribution is proportional to the product of flux level $N$ and temperature $T$, an electronic multiplier $M$ is used to obtain the required product. The output of the current generator $K_1$ in the diagram is the required current, and is added to the integrator input. The magnitude of temperature coefficient of reactivity $K_t$ is under the control of the operator.

The circuits used to accomplish the desired result are grouped into two sections. The first section contains the prompt and delayed neutron sources, the source balance control, the $\delta k_{\text{eff}}$ control, the electronic integrator, and the $N$ meter. The circuitry associated with this section is quite similar to the original Bell and Straus' circuit, except that the $\delta k_{\text{eff}}$ control is equipped with a vernier adjustment.

The second section contains the temperature circuit, coolant flow rate control, $T$ meter, the $N$ voltage converter, electronic multiplier, and the $K_1$ control.

**TEMPERATURE CIRCUIT**

A simplified version of the temperature circuit (Fig. 3) shows the coolant flow rate control and $T$ meter. The current $i_1$ represents the heat generated in the reactor, and this

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**Fig. 3 (left).** Temperature circuit and coolant flow rate control

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**Fig. 4 (above).** $N$ voltage converter and electronic multiplier

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**Fig. 5 (left).** $N$ voltage converter response

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**Fig. 6 (above).** Multiplier response
flows into capacitor $C_{100}$ representing the thermal capacity of the reactor. This current is proportional to the voltage difference between the $+N$ voltage and the capacitor voltage, which is always small compared to $+N$. The current $i_2$ flowing out of $C_{100}$ through $R_{102}$ and $R_{104}$ represents the heat removed by the coolant, and this is proportional to the capacitor voltage. The capacitor voltage represents the mean reactor temperature and is indicated by the meter $T$. Spatial variation of temperature throughout the volume of the reactor is not represented in this simulator, since a lumped reactor is simulated.

When the net capacitor current $i_1 - i_2$ is zero, the mean reactor temperature remains constant. Changing the setting of the coolant flow rate control $R_{104}$ varies the current $i_2$, representing a change in the coolant flow rate. The temperature changes, thus changing reactivity until a new stable operating power level is established.

To give a suitable output to the electronic multiplier, an adjusted $T$ voltage is required. This is furnished by the tap on $R_{106}$. For the temperature corresponding to the stable shutdown value, this control is adjusted to give an adjusted $T$ voltage of $-8.0$ volts.

**THE $N$ VOLTAGE CONVERTER**

The $N$ voltage converter is a 330-kc Hartley oscillator. This is shown at the left side of Fig. 4. The $N$ voltage is decoupled, and used as the $B+$ supply voltage to the oscillator. The circuit constants and bias values are so arranged that the amplitude of the oscillator output is approximately proportional to the $N$ voltage over a fairly wide range of values, as indicated by the curve in Fig. 5. This converted $N$ voltage is used to feed the input of the electronic multiplier.

**ELECTRONIC MULTIPLIER**

The product $NT$ is required for simulating the effect of temperature upon reactivity. The circuit performs this function by generating a source of "negative" neutrons proportional to $K_1NT$ as described previously. Since $K_1$ is generally negative in actual reactors, the current $K_1NT$ is bled off from the integrator input, as indicated in Fig. 2.

The circuit performing the multiplication is accurate to several per cent over the range of useful operation. Although perhaps not adequate for accurate computation, it is satisfactory for demonstration purposes. It is based on the principle that certain variable gain tubes have a transconductance versus grid voltage curve closely approximating a straight line. The 6SK7, operated at a fixed screen voltage of 100 volts, gives an almost straight-line relationship between transconductance and control grid voltage in the region of control grid voltages from $-8$ to $-2$ volts. The circuit in Fig. 4 shows the method of obtaining zero gain at $e_v = -8$ volts by adding the neutralizing resistor $R_{117}$.

The converted $N$ voltage is fed to the grid of the 6SK7 through $C_{109}$, while the adjusted $T$ voltage, which is the grid bias, is fed in through $R_{115}$. The plate load is a resonant tank tuned to oscillator frequency, and the output is taken from the 6SK7 plate. This output is zero for $e_v = -8$ volts, and for other values is proportional to product $NT$.

The multiplier output is rectified, and fed to a d-c amplifier and inverter stage having as its output a current proportional to $K_1NT$. The multiplier response is indicated in Fig. 6 for three values of $N$ voltage. The output current is negative for a negative setting of $K_1$, which is the normal mode of operation, and this current is drawn from the integrator input as described previously.

**REFERENCES**