Simulation of Reactor and Turbine Power Transients in CANDU 6 Nuclear Power Plants

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ABSTRACT

As a part of developing engineering simulator for CANDU 6 nuclear power plants, present paper gives the tentative simulation results of reactor and turbine power transients including reactor-follow-turbine operation. One point kinetics equations are used for neutron dynamics, iodine and xenon loads. To calculate time-dependent high and low pressure turbine powers and grid frequency deviation, simple first order differential equations are used. In addition, control logics (reactor regulating system, demand power routine, and unit power regulator) used in the plant's process computers have been referenced.

1. Introduction

CANDU reactors have the capability of operating in a mode where the plants automatically respond to the daily variations in the electricity demand imposed by electrical grid. CANDU plants can also operate to continuously respond to and correct for variations in the electrical grid frequency[1]. The overall plant control scheme in the operation of CANDU 6 power plant has two different modes, normal and alternate. In the normal control mode, the turbine electrical power is controlled by Unit Power Regulator(UPR) and the Boiler Pressure Control program(BPC) is required to maintain boiler pressure by varying the reactor power setpoint for Reactor Regulating System(RRS). On the other hand, in the alternate control mode, the reactor power is controlled by RRS and BPC maintains boiler pressure by varying the turbine load setpoint[2,3]. This is the normal operation currently done in the CANDU power plants in Korea.

As a part of the IAE's project for the development of an engineering simulator for CANDU 6 power plants, we have been developing a simplified simulation model including overall plant contol. The various simulation results of reactor and turbine power transients including the load following operation in CANDU 6 nuclear power plant are presented in this paper.

Focus is put on the normal mode plant operation where the load following capability can be realized. To this purpose, firstly, one point kinetics equations have been used for reactor power and xenon loads, and secondly, some differential equations for turbines and valve dynamics have been used. In addition, control logics(reactor regulating system, demand power routine, and unit power regulator) used in plant's process computers have been referenced[4] although they may have many limitations.

2. Governing Equations

2.1 Reactor Dynamic Model

Neutron Flux - One Point Kinetics

A one point kinetics model with 6 delayed neutron groups has been used for the simulation of reactor power as following[5,6]:

$$\frac{dn}{dt} = \frac{(\rho_t - \beta)\, n}{l^*} + \sum_{i=1}^{6} \lambda_i C_i \tag{1}$$

$$\frac{dC_i}{dt} = \frac{\beta_i\, n}{l^*} - \lambda_i C_i \qquad , \ i = 1, \ ...., \ 6 \tag{2}$$

where

$$\beta = \sum_{i=1}^{6} \beta_i \tag{3}$$

$$\rho_t = \rho_c + \rho_{Xe} \tag{4}$$

where n, ρ, λ, C, β, and l^* are the reactor neutron flux normalized to unity at full power, reactivity, the inverse delayed neutron time constants, the normalized delayed neutron concentration, the effective delayed neutron fraction, and the mean neutron lifetime, respectively. The subscripts t, c, and Xe in Eq.(4) denote the total, conrol mechanism, and Xenon, respectively.

Xenon Load

In addition, by assuming that the total reactor power is proportional to flux, and making use of the fact that steady state full power xenon reactivity is ~ 28 mK, the rescaled point model iodine and xenon rate equations from Ref.6 in reactivity units(mK) are given by

$$\frac{d\rho_I}{dt} = 33.987\, n - 0.1053\, \rho_I \tag{5}$$

$$\frac{d\rho_X}{dt} = 3.11546\, n + 0.1053\, \rho_I - 0.0756\, \rho_X - 1.2495\, n\, \rho_X \tag{6}$$

where ρ_I and ρ_X are iodine and xenon reactivities in mK.

The primary reactivity control mechanism in CANDU 6 is light water liquid zone controllers(LZC). The reactor bulk power control is normally done by regulating the 14 zonal liquid levels using control valves, according to which the reactivity changes. Therefore the model for those valves should be established.

Zone Control Valve Dynamics

The actual dynamics of zone control valve can be approximated by a second order differential equation with respect to valve position s_z with given damping coefficient ζ and undamped natural frequency W_{nz} as following[7]:

$$\frac{d^2 s_z}{dt^2} + 2\zeta w_{nz} \frac{ds_z}{dt} = w_{nz}^2 (s_z^* - s_z) \tag{7}$$

where ζ, w_{nz}, and s_z^* are the damping coefficient of zone control valves, the undamped natural frequency of zone control valves, and the demanded zone control valve position (defined in section 3.1), respectively.

The primary assumption is that 14 zone controllers are considered as single mechanism where average level is imposed.

The resulting rate of change of zone liquid level L_z can be approximated by

$$\frac{dL_z}{dt} = \frac{k_z}{k_{lz}} \left(\frac{s_z^2 - 0.5}{0.5} \right\} \tag{8}$$

where k_z is the maximum rate of reactivity change due to zones with a value of 1.0 x 10^{-4} K/sec and k_{lz} is the constant relating zone reactivity with zone level of 7.1 x 10^{-3} K.

2.2 Turbine-Generator Dynamic Model

To construct a turbine-generator dynamic model, it is assumed that a fraction of the high pressure stage turbine output is assumed constant with a value of RHP = 0.41 at all power levels. The high pressure stage turbine power is proportional to the steam flow at the governor valve, and is lagged to the transport time τ_{HP} = 0.5 seconds. Therefore, the rate of change of normalized high pressure turbine power is given by[7]

$$\frac{dP_{HP}}{dt} = \frac{RHP\frac{w_{tbn}}{w_{tbn100}} - P_{HP}}{\tau_{HP}} \qquad (9)$$

where w_{tbn} and w_{tbn100} are steam flow rate to turbine at any turbine power and that at 100 %FP, respectively.

The low pressure turbine is a function of high pressure stage turbine power, and is also lagged to the transport time τ_{LP} = 3.3 seconds.

$$\frac{dP_{LP}}{dt} = \frac{P_{HP}\frac{1 - RHP}{RHP} - P_{LP}}{\tau_{LP}} \qquad (10)$$

The total mechanical power is the sum of the high pressure stage power P_{HP} and low pressure stage power P_{LP}.

Under normal conditions, all of the mechanical power delivered to the turbine will be converted to electrical power by the generator. However, when the generator is disconnected from the grid, or a portion of the grid is separated from the rest grid(grid island case), the mechanical power and the electrical power will be out of balance and the balance of the power will go to changing the speed of the turbine and generator. This will affect the governor, which will react to try to maintain the synchnonous speed of the turbine-generator. Thus, under normal conditions, the generator electrical power P_E is equal to P_M. Whereas, under abnormal conditions the electrical power will be an independent variable, a specified function of time. This power imbalance acts to accelerate the turbine-generator away from its 60 Hz nominal speed (1800 RPM). The resulting rate of change of frequncy deviation can be given by

$$\frac{d\delta_f}{dt} = -\frac{D_E}{2C_t} + \frac{W_1}{2C_t}(P_M - P_E) \qquad (11)$$

where δ_f, D_E, C_t, and W_1 are deviation from synchronous frequency, generator damping coefficient, turbine inertia constant, and synchronous frequency, respectively.

3. Control of Reactor and Turbine Power

3.1 Control of Reactor Power

The reactivity control in CANDU 6 is done by light water liquid zone controllers(LZC), adjusters and mechanical control absorbers(MCA). The reactor bulk power control is preliminarily done by regulating 14 zonal lquid levels. The adjusters are normally fully inserted into the core and MCA's are fully withdrawn. RRS determines the banks to be used and their speeds of motion according to the liquid zone level and percentage power error as shown in Fig.1. The mechanical control absorbers are not only used for reactivity control at normal control mode but also when stepback signal is initiated[2].

The unit control computers sample reactor flux, as measured by incore detectors and out-of-core ion chambers, every half second. Zone control valves are operated by the computer control signals to make these measurements agree with demanded power. The valves are manipulated in unison to control bulk power and differentially to control flux tilts[2]. Only the combined action to control bulk power will be simulated here.

Liquid Zone Controller

The demanded zone control valve position s_z^* used in Eq.(7) should be calculated from the demand power routine(DPR) in process computer as follows [3]:

$$s_z^* = \frac{E_p - E_{PC}}{E_{PO} - E_{PC}} \tag{12}$$

where E_P is the effective power error, E_{PC} and E_{PO} are the reactor power errors at which valve is fully closed and open, whose values are -0.05 and 0.02, respectively. The effective power error E_P used in Eq.(12) is given by DPR as a sum of power error and power rate of change for use in digital proportional and differential (PD) control as following[3]:

$$E_P = k_b(\log_{10} n^n - P_{DLOG}) + k_r\left(\frac{\log_{10} n^n - \log_{10} n^{n-1}}{\tau_s}\right) \tag{13}$$

where superscript n denotes the sampling time index and P_{DLOG} is the demanded reactor power at current time which is calculated by DPR.

Adjusters and MCA's

Adjusters and mechanical control absorbers are controlled by using the control logic as shown in Fig.1.[2] The calculated velocity of their motions given zone level L_z and effective power error E_P can be calculated from Fig.1 hence their positions.

3.2 Control of Turbine Power (Unit Power Regulation)

Unit power regulation program in CANDU 6 process computer is used for maneuvering turbine load setpoint(LS) towards the turbine target load(TL) at a rate that can be calculated as the maximum permissible on the basis of high pressure cylinder outer metal temperature or may be provided by operator. The actual load(LA) is continuously adjusted to the target load to compensate for disturbances. The pulse time in a sampling time of 2 second to lower or raise the governor valve position is calculated from the process computer as following [3]:

$$Z_1 = \frac{LS - \frac{L100\, f_d}{D} - LA}{K_1} \tag{14}$$

where f_d is the percent frequency deviation, K_1 is the maximum speed of motor drive, $L100$ is the 100% full power load, and D is the governor droop[1]. The digital control schematic of governor valve by UPR is shown in Fig.2.

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[1] percentage change in frequency to cause a change from full load to no load.

3.3 Description of Load Following Operation

In the normal operation of the plant as shown in Fig.2, the unit power regulator in the plant control program calculates the pulse time Z1 from Eq.(14) for the given turbine target load in every 2 seconds. If Z1 is greater than zero, the raise contact is closed for |z1| seconds to raise the governor valve position, and if less than zero, the lower contact is closed for |Z1| seconds to lower the position as depicted in Fig.3. In parallel to the turbine load maneuvering, boiler pressure control program calculates the reactor power setpoint (given by the sum of turbine power, measured reactor power, pressure error gain, integral term to be used for bumpless transfer of control modes, and constant depending on boiler pressure times warmup/cooldown rate). The calculated reactor power setpoint is sent to the demand power routine which generates the control signal to be used in reactor regulating system. In this paper, we considered only the turbine power term for setpoint to separate reactor power transient behavoir following turbine power.

4. Results and Discussion

Fig.4 shows a neutronic power transient during setback from 100 %FP to 20 %FP at a rate of 1 %FP/sec with accompanying variation of average zone level and MCA position. In this particular case, the average liquid zone level reaches its upper limit of 70 % where the neutron power is only 33 %FP which is above the end point of 20 %FP. Therefore, pertaining to the RRS control logic, the neutron power control is transferred from LZC to MCA, which, normally fully withdrawn, is slightly inserted to further decrease the neutron power. When the power goes below the end point, the MCA is stuck, and the LZC is drained to compensate for the ready inserted negative reactivity due to LZC, MCA and small amount of Xenon which has built up in the mean time. In this case, the power undershoot is about 3 %FP.

Stepback from 100 %FP to 60 %FP is also simulated and the result is shown in Fig.5. The initial average zone level is assumed 65 %, the reason why this level is used is to see the effect of Xenon buildup after zone level draining. The procedure for this partial stepback is as following: When the stepback signal is generated, MCA starts to drop by the gravity force. When the projected reactor power ($P_p = P_n + K(P_n - P_{n-1})$) goes below the end power, the clutch contact is closed, and then the negative reactivity due to MCA and Xenon is compensated for by draining zone level. However, when the zone level reaches its lower limit, the adjuster rods starts to be withdrawn at about 270 seconds after stepback signal initiation to supply with positive reactivity. Fig.6 shows the variation of reactivities due to reactivity mechanisms and Xenon. The negative reactivity due to MCA's(inserted for stepback) and Xenon is slowly compensated for by positive reactivity insertion by reactivity control mechanisms other than MCA's - zone controller level draining to lower limit of 20% within 300 seconds and later due to withdrawal of the adjuster bank #1 according to the control logic depicted in Fig.1.

Fig.7 shows the normal mode unloading of turbine from 100% to 60% load level at a rate of 1%/sec and accompanying reactor power variation and turbine shaft rate of revolution. In this simulation, the reactor power set point is equal to turbine power since the boiler pressure error term has not been considered. The reactor power is delayed about 8 seconds.

5. Conclusions

Tentative results from the simulation of reactor and turbine power controls in a CANDU 6 nuclear power plant are presented. One point kinetics equations are used for reactor model considering xenon loads. High and low pressure turbine dynamics are accounted for by using the first order differential equations. Control programs are tested using these models.

Simulated reactor power transients are setback and stepback. Workability of programs for reactor power and turbine power controls in load following simulations are also tested for future application to more complicated reactor and turbine dynamic models.

References

1. Pressurized Heavy Water Reactors for Korea, KEARI-AECL, 1993
2. Overall Plant Control, AECL.
3. KEPCO, Preliminary Safety Analysis Report for Wolsung 3&4.
4. CANDU 6 Control Program, private communication.
5. J.J. Duderstadt, Nuclear Reactor Theory, John-Wiley & Sons, 1976.
6. Nuclear Theory-Rev.1, Nuclear Training Department, Point Lepreau Generating Station.
7. A.W. Yang, PHW Simulation Program Description, 1977.

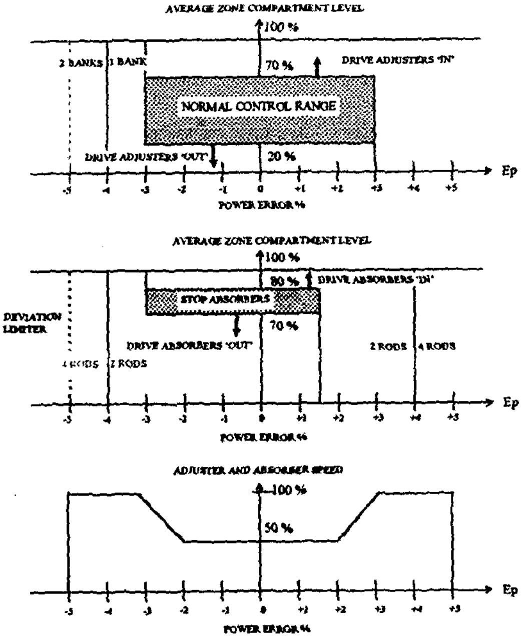

Fig. 1 Reactivity unit control diagram.

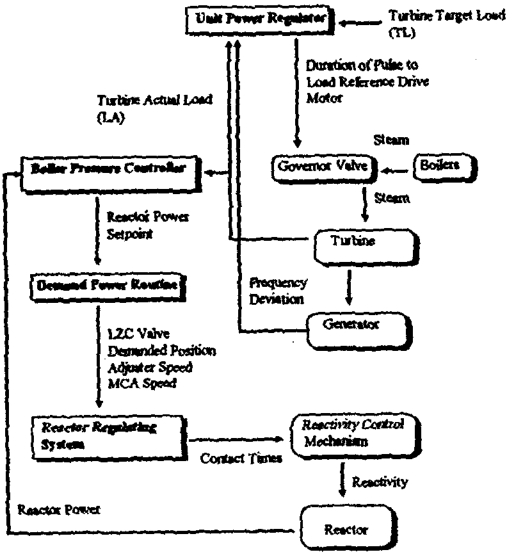

Fig. 2. Signal flow block diagram for reactor-follow-turbine operation in CANDU 6.

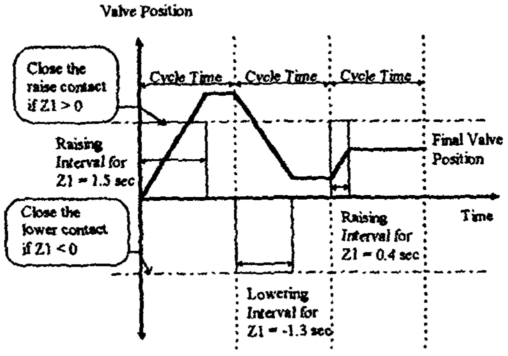

Fig. 3. Digital control of governer valve by UPR (if Z1>0, close the raise contact of the positioner for |Z1| sec; if Z1<0, close lower contact for |Z1| sec).

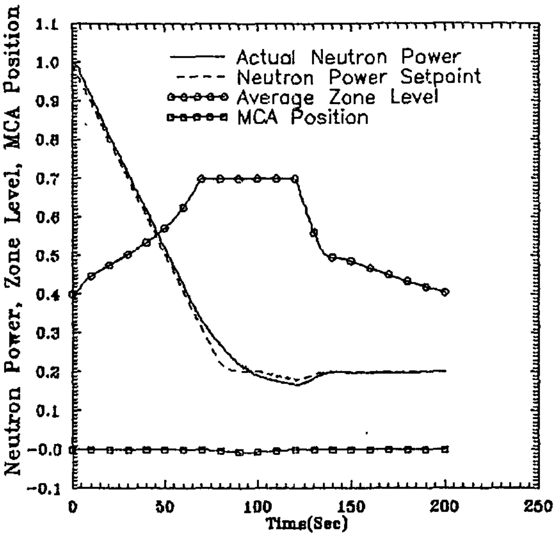

Fig. 4. Neutronic power transient during setback from 100 %FP to 20 %FP at a rate 1 %/sec with accompanying variation average zone level and MCA position (initial zone level = 40 %).

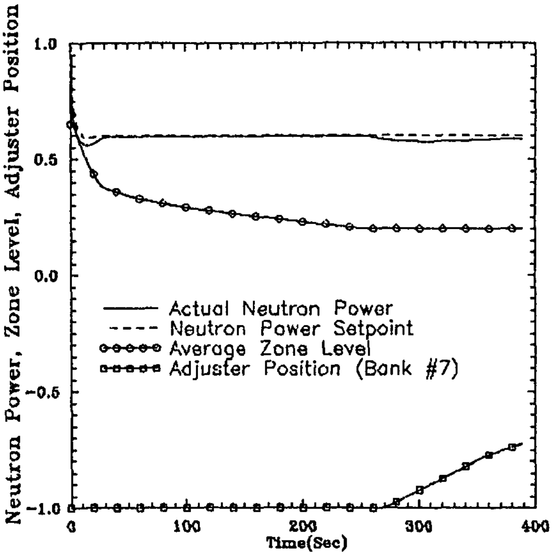

Fig. 5. Neutronic power transient during stepback from 100 %FP to 60 %FP with accompanying variation of MCA position, average zone level, and MCA and adjuster position (initial zone level = 65 %).

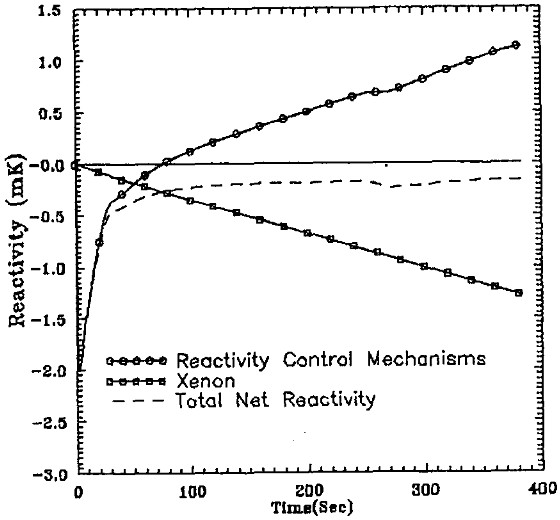

Fig. 6. Variation of reactivities due to reactivity control mechanisms and Xenon in the case of Fig.5.

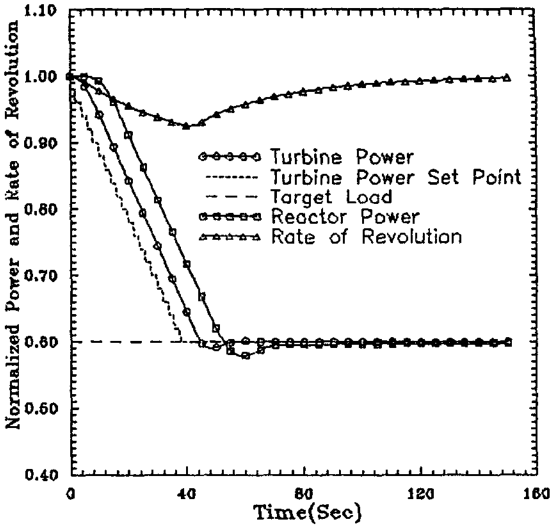

Fig. 7. Normal mode unloading of turbine from 100% to 60% at a rate of 1%/sec with accompanying variations of reactor power and turbine rate of revolution.