DYNAMIC MODELLING FOR CONTROL OF A NEW GENERATION NUCLEAR POWER STATION

Olis Rubin*, John Pritchard**

** Control System Specialist, PBMR (Pty) Ltd*
*** Group Leader, Control and Functional Analysis Group, PBMR (Pty) Ltd*

Abstract: The PBMR company is developing a new generation power plant that uses a high-temperature gas-cooled nuclear reactor. The gas from the reactor is used directly to drive the turbo machines in a closed-circuit Brayton cycle. The plant is simulated by a complex thermo-hydraulic model that is used extensively in the controller design phase. This paper describes a simplified model of the plant that was developed to further assist with the design of the power control loop.

Keywords: Dynamic Modelling, Control.

1. INTRODUCTION

The PBMR power plant is designed as a Generation IV Nuclear power station that includes a high-temperature gas-cooled reactor, with the fuel material being designed in the form of pebbles. The high-temperature source allows the implementation of a heat engine with high efficiency. The hot gas from the reactor directly drives a power turbine and electrical generator, in a closed loop Brayton cycle gas circuit as shown in Figure 1, that utilizes the latest turbo and materials technology.

2. PLANT DESCRIPTION

Helium gas at a high pressure passes through the nuclear reactor (core) where it is heated to a very high temperature. This gas is firstly passed through a high-pressure turbine (HPT) that drives a high-pressure compressor, and then through a low-pressure turbine (LPT) that drives a low-pressure compressor, and finally through a power turbine (PT) that drives the generator. After the power turbine it passes through the low-pressure side of a Recuperator to heat the gas that flows into the reactor. After being cooled by a pre-cooler, it passes through the low-pressure compressor (LPC), an intercooler, and the high-pressure compressor (HPC). It is then heated by the recuperator, before flowing back to the reactor. The following energy interchanges occur. Nuclear energy is produced by the reactor, and used to heat the gas. Thermodynamic energy is converted into mechanical energy by the power turbine. Thermal energy is removed by water in the pre-cooler and intercooler. Thermal energy is converted into mechanical energy by the high-pressure turbine, to drive the high-pressure compressor, and by the low-pressure turbine, to drive the low-pressure compressor. The recuperator exchanges heat between two gas streams.

3. CONTROL ASPECTS

The plant supplies electricity to the national grid. This can include fairly rapid ramping up and down of the power in accordance with demands from the control centre, as well as rapid steps in power to counteract severe grid disturbances. Conventional thermal and nuclear power stations use steam turbines, where power can be directly controlled by an upstream valve that regulates the flow through the turbine. The PBMR plant is quite different. The control of the hot gas upstream of the turbine presents severe material problems. It is thus necessary to use control valves and controllers that differ significantly from the well-established technology used with conventional plant.

The primary mechanism is to control the power generated by the turbine by changing the total mass of helium that is circulating within the plant, and therefore through the turbine. Helium is extracted by venting gas from the exit of the high-pressure compressor into storage tanks, and injected into the inlet of the low-pressure compressor. This process exploits the internal pressures within the plant, the flow being controlled by means of valves, shown in Figure 1. Another control mechanism is to reduce the output of the power turbine by means of a bypass valve (see Figure 1) that diverts gas at the outlet of the high-pressure compressor, to return directly back to the input of the low-pressure compressor.

The controller includes a feedback loop that manipulates these valves to correct for deviations of the grid power from the setpoint. The design of the loop is based on the response of the plant to control actions. The frequency response is used to determine its phase margin and loop gain. The system is then extensively tested by simulation before implementation on the hardware.

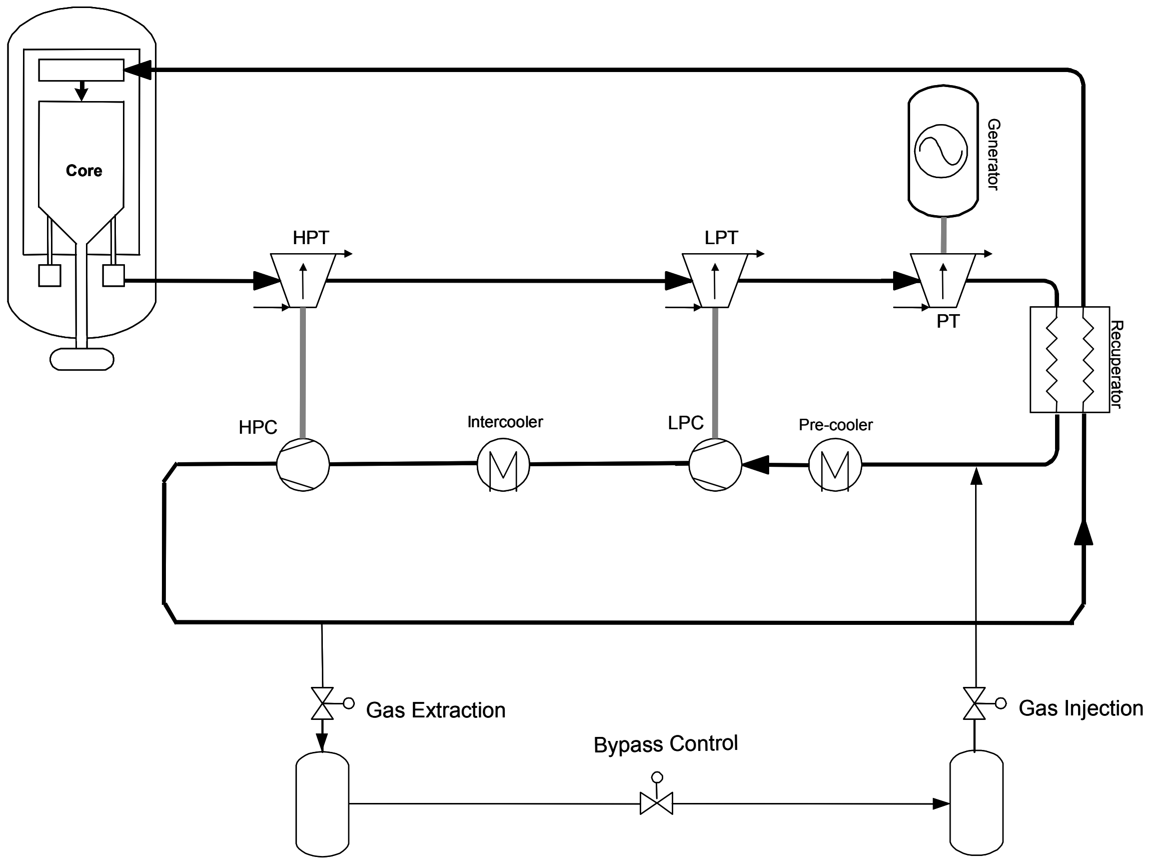

Fig. 1. Simplified schematic drawing of the main power system of the PBMR

4. MODELLING REQUIREMENTS

A plant of this complexity requires many computer models for the various elements. There are very detailed finite element models, computational fluid dynamics, and other models that minutely describe its neutronic and thermo-hydraulic behaviour. There is also an overall model based on Flownex® (Rousseau and van Ravenswaay, 2003) that includes a simulation of the reactor neutronics as well as thermo-hydraulic simulation of the overall plant. This model consists of literally thousands of elements such as pipes, heat exchangers, valves, as well as the turbo machines. The thermo-hydraulic model is operated with Simulink®, to include the overall control system.

The state of the thermo-hydraulic model is determined at any instant by a numerical solver that iteratively finds the temperatures and pressures at the various elements which satisfy the basic equations of mass, momentum and energy conservation. The engineer is thus presented with a solution, but does not necessarily gain insight into the internal functioning of the plant.

For example, consider the change in output of the power turbine about an operating point, in response to a step change of helium injection. The time response of the thermo-hydraulic model is shown in Figure 2 (curve labelled flownet). The long-term power ramps up proportionally to the increasing mass of helium. This can be confirmed by finding the steady state output power for different quantities of helium in the plant. Figure 2 also shows that the first effect of helium injection is to reduce the output power of the plant, taking well over a minute before there is a net increase in output. The understanding of such behaviour is obscured by the complexity of the thermo-hydraulic model.

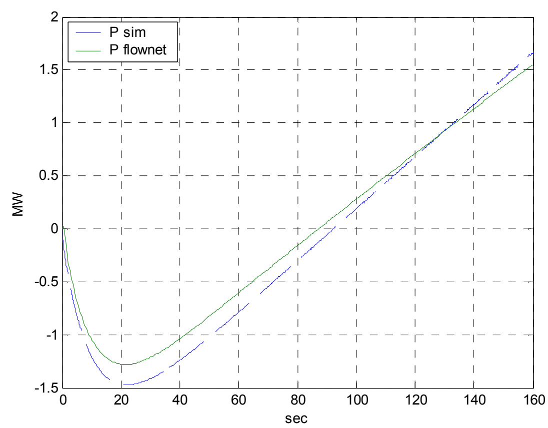

Fig. 2. A comparison between the Flownet results and simulation by the linear model

The frequency response of the plant can be found by fitting a linear transfer function model to the time response shown in Figure 2, giving:

$$P(s) = 0.019(-94.1s+1) / s(8.2s+1) \quad (1)$$

This mechanistic approach gives little insight into the physical significance of the above poles and zeros.

There is thus a need for a simplified model of the plant that gives more insight and understanding into the behaviour of the plant.

5. BASIS OF THE SIMPLIFIED MODEL

The elements in the thermo-hydraulic model contain gas, whose state (pressure, temperature, and velocity) varies throughout the system. The state description was drastically reduced by putting all these gas storage elements into five equivalent tanks.

Tank H is the largest, and includes the volume of the reactor, the gas path between the high-pressure compressor and the reactor, and the pipes between the reactor and the high-pressure turbine. It also includes the gas within the high-pressure compressor:

P_h = pressure in tank H

Tank L is between the power turbine and the low-pressure compressor, which includes the volume of the recuperator low-pressure side, and that of the pre-cooler. It also includes the gas within the turbine:

P_l = pressure in tank L

Tank M is between the two compressors, and includes the volume of the intercooler, and the gas within the low-pressure compressor:

P_m = pressure in tank M

Tanks M1 and M2 are much smaller, being downstream of the high-pressure and low-pressure turbines. They are included in the model to facilitate computation of conditions at these points:

P_{m1} = pressure in tank M1
P_{m2} = pressure in tank M2

This state description could be further reduced by eliminating the independence of temperature as a state. Firstly, the reactor core materials have a large heat capacitance, and also act as a temperature regulator. When considering relatively fast transients, the gas in tank H can be approximated as being at a fixed temperature. Similarly, the pre-cooler and intercooler allow the gas in tanks L and M to be approximated as being at a fixed temperature. The temperatures of the gas in tanks M1 and M2 are predominantly determined by their upstream turbines, and can be calculated from other state variables. The simplified model is not intended to give answers to all aspects of plant operation. For example, it does not consider energy conversion or efficiency. However, it gives surprisingly accurate results for the designer in the operating frequency band of the power controller.

The simplified model is implemented using Simulink as shown in Figure 3, where the gas flow can be traced through the above five tanks. Start with helium injection into tank L at the input (1):

HeIn = the mass flow rate of helium

This is added to the mass flow rate (Q_t) that comes from tank M2, through the power turbine and into tank L. Gas also flows at a mass flow rate (Q_{lc}) out of the tank L, through the low-pressure compressor and into tank M.

The state variable (P_l) is generated by an integrator:

$$dP_l / dt = (HeIn + Q_t - Q_{lc}) / C_{lp} \quad (2)$$

C_{lp} = the capacitance of the tank.
See (Buckley, 1964).

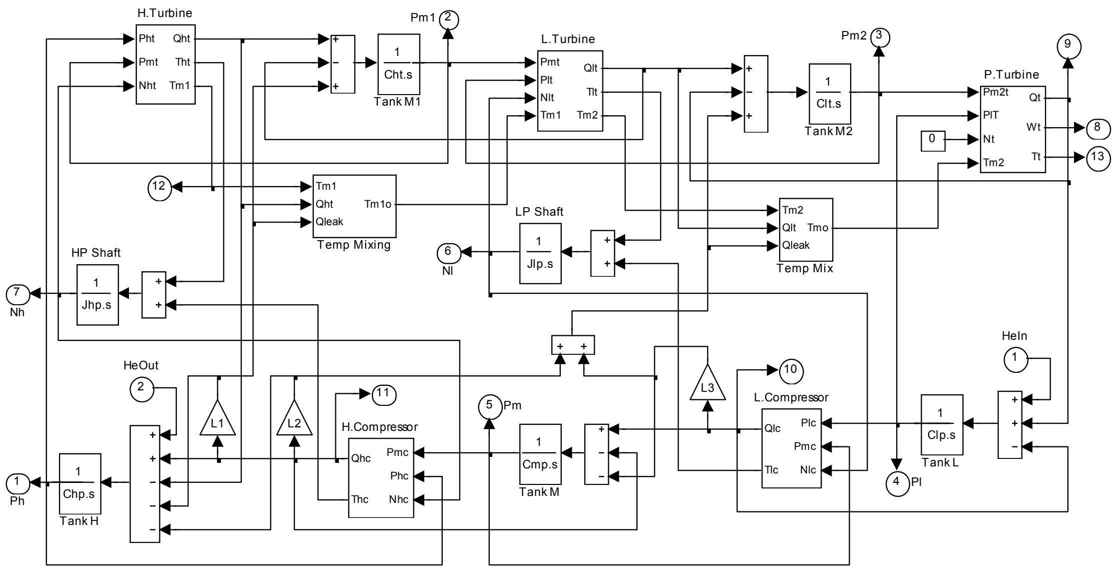

Fig. 3. A block diagram of the linearized model

The mass flow (Q_{lc}) is determined by the algebraic operation labelled "L Compressor", as a function of:

P_l = the inlet pressure to the compressor
P_m = the outlet pressure
N_{lc} = the shaft speed of the compressor

Q_{hc} is then the mass flow rate out of tank M, through the high-pressure compressor, and into tank H, while Q_{ht} is the mass flow rate out of tank H, through the high-pressure turbine, and into tank M1. Helium can also be extracted from tank H at the input (2), and the model can include leakage through the paths L_1 and L_2. Q_{lt} then flows out of tank M1, through the low-pressure turbine and into tank M2, and Q_t flows flows out of tank M2, through the power turbine and back to tank L. These mass flows are determined by the blocks "H Compressor, H Turbine, L Turbine, P Turbine" as functions of the corresponding inlet and outlet pressures, and the shaft speeds. The tank pressures (P_m, P_h, P_{m1}, P_{m2}) are then given by integrals of the net inflows, similar to equation (2).

The shaft torques are also determined by the above Turbine and Compressor blocks. Newton's laws of motion are then used to generate the shaft speeds of the turbo machines, which are also state variables, for example the acceleration of the high-pressure machine is given by:

$$dN_h / dt = (T_{ht} - Tl_{hc}) / J_{hp} \tag{3}$$

T_{ht} = the torque produced by the high-pressure turbine
Tl_{hc} = the torque to drive the high-pressure compressor
J_{hp} = the moment of inertia of the combined turbo-compressor

The shaft speed (N_l) of the low-pressure machine is similarly found from T_{lt} and T_{lc}. The power turbine is assumed to remain synchronized to the grid.

6. LINEARIZATION

The primary objective of linearizing the model was to calculate its frequency response. The elements within the plant were linearized, as this gave insight into the modes of motion as well as the global response. Linearization was achieved by considering relatively small motion about a fixed operating condition.

For example, the shaft output power (W) from the turbine is given by the enthalpy calculation:

$$W = Q.C_p.(T_1 - T_2) \tag{4}$$

Q = mass flow rate through the turbo machine (kg/s)
T_1 = the inlet temperature (^oK)
T_2 = the outlet temperature (^oK)
C_p = the specific heat of the gas at constant pressure ($J/(kg.^oK)$)

In the non-linear equation (4), T_1, T_2, Q and W described the actual values of the variables. Considering relatively small motions of these variables about their nominal values, T_{o1}, T_{o2}, Q_o and W_o, (4) can be linearized to give equation (5) where the symbols T_1, T_2, Q and W now describe deviations from the nominal values. This notation will be used throughout – non-linear equations are in terms of actual variables while their linearized equivalents are in terms of deviations from nominal values. Assuming that C_p remains constant, (4) is linearized to give:

$$W = C_{WQ}.Q + C_{WT}.(T_1 - T_2) \tag{5}$$

$$W = C_{WQ}.Q + C_{WT}.(1-C_{TT}).T_1 - C_{WT}.C_{Tr}.K_{r1}.P_1 - C_{WT}.C_{Tr}.K_{r2}.P_2$$

$$C_{WQ} = W_o/Q_o$$

$$C_{WT} = Q_o.C_p$$

The operation of a turbine is dependent on its inlet-outlet pressure ratio:

P_{rt} = pressure ratio for turbine = $P_1 / P_2 > 1$
P_1 = the inlet pressure (bars)
P_2 = the outlet pressure (bars)

Small changes in the pressure ratio due to changes from the steady state pressures are then given by:

$$P_{rt} = K_{r1}.P_1 + K_{r2}.P_2$$

$$K_{r1} = \partial P_{rt} / \partial P_1 = 1 / P_{02}$$

$$K_{r2} = \partial P_{rt} / \partial P_2 = -P_{01} / P_{02}^2$$

The steady state behaviour of the axial turbines and compressors can be described by operating maps, such as those shown in Figure 4, where:

Q' = normalized mass flow rate through the turbo machine
N = the shaft speed of the machine (rev/s)
η_t = isentropic efficiency for turbine
$\eta_t = (T_2/T_1 - 1) / (P_{rt}^{-g} - 1)$

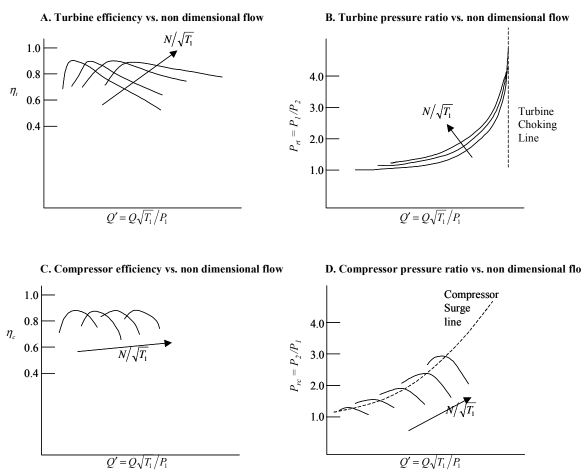

Fig. 4. Illustrations of the turbo machine maps

$\gamma = C_p/C_v$

C_v = the specific heat of the gas at constant volume (in J/(kg K))

$g = (\gamma-1)/\gamma$

The gas transit time through these turbo machines is so small that their transient responses can be approximated by the above maps.

The turbine pressure ratio map can be linearized for relatively small motion about an operating condition:

$P_{rt} = \mathbf{C_{rQ}}.Q' + \mathbf{C_{rN}}.N'$ = change in pressure ratio due to changes in mass flow and speed

$\mathbf{C_{rQ}} = \partial P_{rt} / \partial Q'$ = slope of pressure ratio map

$\mathbf{C_{rN}} = \partial P_{rt} / \partial N'$ = gradient of the N' contours

This equation can be expanded further:

$$P_{rt} = \mathbf{C_{rQ}}.[C_{QQ}.Q + C_{QP}.P_1 + C_{QT}.T_1] + \mathbf{C_{rN}}.[C_{NN}.N + C_{NT}.T_1]$$

Many of these partial derivatives are determined analytically:

$C_{QQ} = \partial Q' / \partial Q = Q_o'/Q_o$

$C_{QP} = \partial Q' / \partial P_1 = - Q_o'/P_{o1}$

$C_{QT} = \partial Q' / \partial T_1 = Q_o'/2.T_{o1}$

$C_{NN} = \partial N' / \partial N = N_o'/N_o$

$C_{NT} = \partial N' / \partial T_1 = - N_o'/2.T_{o1}$

Whence:

$$P_{rt} = C_{rQ}.Q + C_{rP}.P_1 + C_{rT}.T_1 + C_{rN}.N \quad (6)$$

$C_{rQ} = \mathbf{C_{rQ}}.C_{QQ}$

$C_{rP} = \mathbf{C_{rQ}}.C_{QP}$

$C_{rT} = \mathbf{C_{rQ}}.C_{QT} + \mathbf{C_{rN}}.C_{NT}$

$C_{rN} = \mathbf{C_{rN}}.C_{NN}$

Small motions in the mass flow rate can then be found by solving equation (6):

$C_{rQ}.Q = P_{rt} - C_{rP}.P_1 - C_{rT}.T_1 - C_{rN}.N$

$C_{rQ}.Q = (K_{r1} - C_{rP}).P_1 - K_{r2}.P_2 - C_{rT}.T_1 - C_{rN}.N$

For the low-pressure turbine, this can be written as a linear equation that models small motions about a nominal operating condition on the turbine map shown in the top right pane of Figure 4:

$$Q = Klt(1,1).P_1 - Klt(1,2).P_2 + Klt(1,3).N - Klt(1,4).T_1 \quad (7)$$

$Klt(1,1) = (K_{r1} - C_{rP}) / C_{rQ}$

$Klt(1,2) = K_{r2} / C_{rQ}$

$Klt(1,3) = C_{rN} / C_{rQ}$

$Klt(1,4) = C_{rT}$

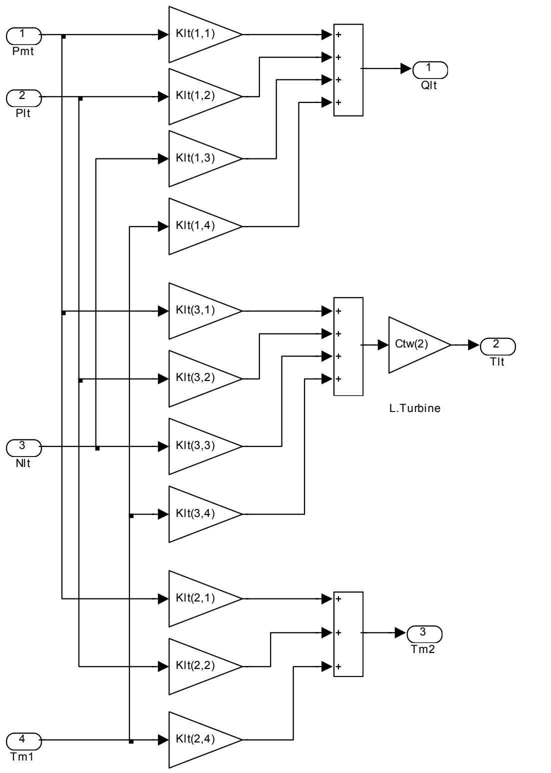

Fig. 5. The structure of the low-pressure turbine map

The efficiency of the turbo-machines is nearly constant for small transients:

$$\eta_t = (T_2/T_1 - 1) / (P_{rt}^{-g} - 1)$$

This relationship can then be linearized in terms of the turbine outlet temperature:

$$T_2 = C_{TT}.T_1 + C_{Tr}.P_{rt} = C_{TT}.T_1 + C_{Tr}.K_{r1}.P_1 + C_{Tr}.K_{r2}.P_2$$

$$C_{TT} = \partial T_2 / \partial T_1 = \eta_t (P_{rt}^{-g} - 1) + 1$$

$$C_{Tr} = \partial T_2 / \partial P_{rt} = -g . \eta_t . T_{o1} . P_{rt}^{-1-g}$$

For the low-pressure turbine, this gives an equation of the form:

$$T_2 = Klt(2,1).P_1 + Klt(2,2).P_2 + Klt(2,4).T_1 \quad (8)$$

Equations (5), (7) and (8) give the torque produced by the turbine:

$$T_{m2} = W / (2 \pi N)$$

$$T_{m2} = K(3,1).P_1 + K(3,2).P_2 + K(3,3).N + K(3,4).T_1 \quad (9)$$

Equations (7) to (9) define the Simulink model of the low-pressure turbine, as shown in Figure 5.

7. MODEL PERFORMANCE

The response of the linearized model (Figure 3) to a step change in helium injection is shown in Figure 2 (curve labelled Sim) to compare well with that of the thermo-hydraulic model.

The corresponding changes in the pressures around the system are shown in Figure 6, and also compare well with the thermo-hydraulic model. Note that this plot shows changes in pressure from their nominal values, where the nominal pressure (P_{oh}) of tank H is much higher than that (P_{ol}) of tank L. Tank L pumps up much faster than the other tanks, so that the pressure drop across the power turbine reduces and lowers its output power. This can be seen from Figure 3, since helium is injected directly into tank L, which then charges up tank M. Tank H then charges up relatively slowly, because it has a large capacity. All these arguments help provide more insight into the control of the plant.

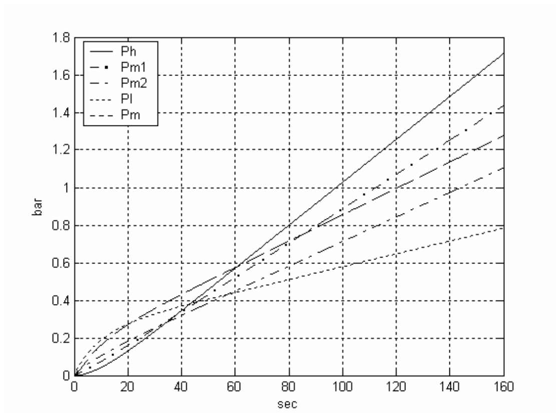

Fig. 6. The simulated changes in pressure at the various tanks

The linear model shown in Figure 3 corresponds to the following transfer function, where some faster poles and zeros have been neglected:

$$P(s) = -0.28(s-0.012)(s+0.677)/s(s+0.0969)(s+0.953) \quad (10)$$

The effect of the nonminimum phase zero (s-0.012) appears in the middle decade of the frequency response, plotted in Figure 7. It flattens the gain slope while increasing the phase lag, which severely limits the achievable bandwidth of a power control loop around P(s). In practice, the plant is run with some gas bypass around the compressors (from tank H to tank L). The transfer function for bypass changes does not have a nonminimum phase zero:

$$P_B(s) = 0.25/(s+0.0969)$$

It is then possible to design a higher bandwidth loop around the combined response $P(s)+ K.P_B(s)$ to helium injection plus a proportional reduction in bypass flow. It is important to consider the robustness of this loop, since the relative bypass gain (K) is affected by uncertainties associated with the control valves.

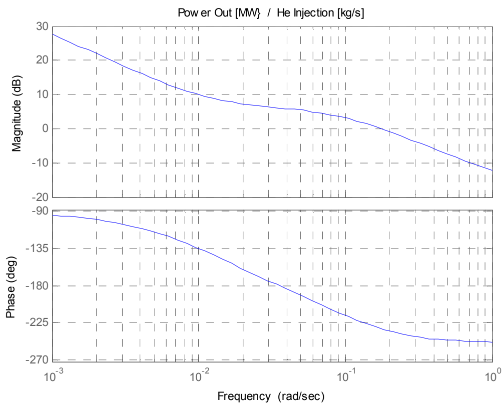

Fig. 7. A Bode plot of the transfer function from helium injection to electrical output power

The simplified model gave another spinoff. It can also be used to give "quick look" answers for studies where excessive time was taken by the thermo-hydraulic simulation, for example to find integrated control errors over long time periods.

8. CONCLUSION

The PBMR plant uses a closed cycle gas circuit that is simulated by a complex thermo-hydraulic model. The design of the controller relies heavily on this simulation.

A simplified model of the plant was developed that gave further insight into plant behaviour. It also gave supporting frequency response data, which was necessary for the design of the power control loop.

REFERENCES

Rousseau, P.G., J.P. van Ravenswaay (2003). Thermal-Flow Comparison of Three- and Single Shaft Closed Loop Brayton Cycle Configurations for HTGR Power Conversion. *Proceedings of ICAPP '03*, May 2003, Paper 3292.

Buckley, P.S. (1964). *Techniques of Process Control*, chapters 14-15. Wiley, New York.