MDRAP - A MATLAB-Based Detector Response Analysis Package

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ABSTRACT

An analysis program has been developed, in the MATLAB environment, for determining in-core flux detector dynamic response characteristics from a combined knowledge of the local detector flux and measured detector output. Critical to the program is an accurate estimate of the local detector flux. The estimated local detector flux is input to a detailed model of the detector and its electronic compensators; the model output is compared with the recorded signal. The model of the detector is then iteratively adjusted to minimize the mean square error between the output of the model and the recorded signal. The process is completely automated, requiring no manual input by the code user. The program has been used on both Pt-clad and vanadium detectors for the Point Lepreau Nuclear Generating Station for various power rundown tests. This paper describes the code and presents results from the analysis of Pt-clad detectors with data from the 1997 shutdown system (SDS1) Trip Test at Pt. Lepreau.

1. Introduction

The dynamic response of in-core flux detectors (ICFDs) is characterized by an immediate or prompt response and a delayed response. The delayed response is assumed to be linear and can be adequately represented by a sum of first-order lags, each characterized by an amplitude and a time-constant. The amplitude is the fraction of the total steady-state response at equilibrium resulting from the particular lag. The time-constant determines the rate of change of the delayed component. The total delayed response is the sum of the amplitudes of all the lags. Since the total fractional response is unity, the prompt fraction is one minus the delayed fraction.

In the analysis of the 1995 shutdown system 1 (SDS1) Trip Test at Point Lepreau, discrepancies were noticed between the Reactor Fueling Simulation Program (RFSP) [1] simulated detector readings and measured values for SDS1 and Reactor Regulating System (RRS) detectors. The detectors for both systems are straight individually replaceable (SIR) Pt-clad Inconel ICFDs. Analysis was performed to determine if the observed discrepancies could be attributed to a change in prompt fraction of the detectors. For the analysis it was assumed that any changes in detector dynamics were due solely to changes in the amplitudes and not in the time constants of the detector lag terms. This approach has been used because of the non uniqueness of coefficients when both time constants and amplitudes are optimized simultaneously.

The program MDRAP (MATLAB-Based Detector Response Analysis Package) was developed to calculate the prompt fraction that would account for the observed detector readings. The methodology cannot be used to determine the cause of the change in dynamics but merely to calculate detector delayed amplitudes which account for the observed response.

2. Background

At the time of installation in 1992, the SIR detectors were known to produce a signal that on average was about 89% prompt, with the remaining 11% subject to delays. These are referred to as design values. Knowledge of the prompt fractions of Pt-clad detectors is important, especially when they are used in the regional overpower (ROP) protection system which activates the shutdown system when local flux levels exceed specified levels. The ROP is installed in both shutdown systems, SDS1 and SDS2, each of which contain several detectors located throughout the core. Either shutdown system can shut the reactor down independently. The orientation of the SDS1 and SDS2 assemblies (tubes containing detectors) is different. SDS1 assemblies are oriented vertically whereas SDS2 assemblies are horizontal. The detectors within each shutdown system are distributed among three channels. Any detector reading exceeding its trip setpoint will trip its channel. Two or more channels of a shutdown system tripping will trip the reactor.

When Pt-clad detectors are used in the ROP, a multiplier is applied to the prompt part of the dynamic signal, which decreases with time in a way that approximately reflects the signal delays i.e. the detector signal is "compensated". This compensation is designed to ensure that the compensated detector signal is greater than the power to fuel at all times. The signals for both RRS and ROP detectors pass through amplifiers and compensators before reaching the data logger. For the simulated detector readings to closely match values measured at site, it is necessary that the parameters used for both the detectors and the electronics be close to their actual values, and also that the RFSP model reflects reality.

Experimental measurements of the dynamic signals for Pt-clad detectors (in Bruce B and the NRU reactor) indicate a degree of variability in the magnitude of the delays from detector to detector, and also as a function of time for a given detector. The main factor contributing to varying response is the continued exposure of the detectors to the high neutron flux present in the core. This exposure results in transmutation of the nuclides comprising the detectors because of neutron capture.

Simulation of the 1992 SDS1 Trip Test at Point Lepreau, after installation of the detectors, showed good agreement between simulated detector response and measurements. Small discrepancies were attributed to expected variations in individual detector responses from the average behaviour. Though RRS, SDS1 and SDS2 detectors were examined, no apparent trends showing consistently different behaviour for detectors in the 3 different systems were apparent. However, in the analysis of the 1995 SDS1 Trip Test at Point Lepreau, noticeable discrepancies were apparent between the RFSP-simulated detector response and measurements. A clear pattern emerged that showed RRS and SDS1 detectors were responding faster than design values, whereas SDS2 detectors were responding according to design values.

3. Methodology

The program MDRAP was developed for the analysis of the 1995 Trip Test at Point Lepreau. The methodology implemented in MDRAP consists of using as input an RFSP simulation of the flux at the detector location. To obtain a simulated output (reading), the flux is passed through an accurate model of the detector, the dynamic compensator (in the case of ROP detectors) and the electronic circuitry leading to the device that records the detector signal (data logger). The amplitudes of the detector delays are treated as variable parameters that are varied iteratively until the difference between the simulated signal and the measured signal for that detector is minimized. The 2 signals are compared at discrete instants in time for tens of thousands of seconds following the trip. It is always preferable to have as long a span of data as possible, the only practical considerations being the resulting reduction in processing speed and the creation of arrays which exceed the physical memory (RAM) of the computer.

The quantity to be minimized is called the cost. The cost is derived from a cost function. The cost function for the detector D(t) used in the implementation of MDRAP documented in this paper is

$$D(t) = S(a_i, t) - C(t) \tag{1}$$

D(t) is the difference between the simulated and measured signals for a given detector. S and C are the simulated and measured signals respectively. The dependence of S on the delay amplitudes a_i is shown explicitly.

The cost that produces a least-squares minimization of the cost function given by Equation (1) is

$$\min \sum_{j} (S_j(a_i) - C_j)^2 \qquad (2)$$

S_j and C_j are the site measured fluxes and the calculated fluxes respectively at the j^{th} instant in time. MDRAP uses a least-squares optimization algorithm to find delay amplitudes (a_i) that result in a minimization of the cost.

Implicit in the definition of the cost is a power dependence. This power dependence results in a bias that favours the minimization of the discrepancy at high powers. Likewise, a bias also results if the points are equally spaced in time. This bias is less apparent but favours the calculation of the amplitudes of long-lived delays. For the longer delays, there are more points spanning the range between the start of the growth (immediately after the trip) and end of decay (two to three time constants) of the long-delay terms. These two biases work in opposite directions, but the exact effect of the combination is difficult to determine. In addition to the two biases, the very short time interval in the second or so after the trip, when the drop in both the flux and the detector readings is highest, is critical to the accuracy of the computed delays and must be covered adequately. As a means of overcoming these problems, comparison times were equally spaced logarithmically.

MATLAB [2] was chosen as the environment in which to model the detector system and to perform the minimization of the cost function (optimization). MATLAB is an interactive environment for technical computing, combining computation, visualization and high-level programming. The graphical interface of Simulink [3], a MATLAB toolbox, allows the simulation of very complex dynamic linear and nonlinear systems. In Simulink, dynamics can be defined in the s domain (continuous frequency), the z domain (discrete frequency), time domain (state-space representation), or as hybrid systems (mixed continuous and discrete). To facilitate model definition, Simulink adds a new class of windows called block-diagram windows. In these windows, models are created and edited principally by mouse-driven commands. After a model has been defined, it can be analyzed and run by choosing options from the Simulink menus, by entering commands in MATLAB's command window or through program control. The final results of the simulation can be made available in the MATLAB workspace when a simulation is complete. Tremendous computational power can be achieved by combining Simulink models with toolboxes such as the Optimization Toolbox [4] used by MDRAP. Using MATLAB, modelling of the detector signals, and variation of the delay amplitudes is done under program control and is completely automated so that no manual iteration is required on the part of the user. Delay amplitudes and hence prompt fractions for all detectors can be computed in a single run.

4. Detector Modelling

It is customary to represent the relationship between the input and output for each of the delays in the Laplace frequency, or s domain.

The detector output D(s) resulting from an input X(s) is

$$D(s) = (1 - \sum_i a_i) * X(s) + \sum_i \frac{a_i}{\tau_i s + 1} * X(s) \qquad (3)$$

where a_i and τ_i are the amplitudes and time constants of the lag terms and $1 - \sum_i a_i$ is the detector prompt fraction.

Though the frequency domain representation was used initially in the development of MDRAP, the need to account for non-equilibrium conditions for the delays at the time of trip made this representation somewhat cumbersome. A state-space representation which is the time-domain equivalent of a transfer function was found to be more intuitive.

The time-domain equivalent of the transfer function

$$Q_i(s) = \frac{X(s)}{\tau_i s + 1} \qquad (4)$$

is

$$\frac{dq_i(t)}{dt} = \frac{x(t) - q_i(t)}{\tau_i} \qquad (5)$$

with $q_i(0)$ as the initial condition.

The MATLAB state-space representation uses the following format:

$$\frac{dz(t)}{dt} = Az(t) + Bx(t)$$

$$q(t) = Cz(t) + Dx(t) \qquad (6)$$

where x(t) is the input, and q(t) is the output. In state-space notation, the following values of the coefficients implement Equation (5)

$A = -1/\tau_i \qquad B = 1/\tau_i \qquad C = 1 \qquad D = 0$

The time-domain equivalent of Equation (3) is

$$d(t) = (1 - \sum_i a_i) * x(t) + \sum_i a_i * q_i(t) \qquad (7)$$

It can be seen that the detector response d(t) given by Equation (7) is obtained by integration. The reference time of the integration is the instant of the trip and corresponds to t = 0.

For the accurate computation of delay amplitudes, data suitable for analysis by MDRAP must span at least twice the time constant of the longest-lived delay. In-core flux detectors have delays with time constants of several thousand seconds. The electronics through which the detector signal passes have extremely short delays, typically between 5 and 100 ms. The large range of variation in these delays means that in order to achieve a high level of accuracy in the simulated output, integration time-steps of milliseconds are required to simulate the first few seconds after a trip occurs, when there is a rapid variation in the flux. If the same integration time step were used throughout the entire period, the time required for simulation would be unacceptably long. Therefore two models are necessary: a very detailed model that includes the electronics for the first 5 seconds, and a less detailed model that excludes the electronics for the remainder of the simulation, where the drop in flux is more gradual. The initial conditions for the integrators in the second model are obtained from the first simulation. Figure 1 shows the Simulink model which includes electronics and is used to simulate detector readings for the first 5 seconds. Figure 2 shows the Simulink model which does not include electronics. The models assume that the Pt-clad detectors are characterized by 6 delays. Table 1 lists the design time constants and amplitudes for the delays. Table 2 lists the observed variation in amplitudes for new detectors.

5. Data Pre-Processing

Data suitable for optimization must typically span a period of several hours before and after a trip. Because the drop in flux is very rapid after a trip occurs, the time interval between data samples must be small. If the same small sample period was used for the entire range, it would result in excessively large data files. As a result, data is usually broken into 2 files. One file spans the interval from a few minutes before the trip to a few minutes after the trip and is sampled at a very high rate, typically tens of milliseconds. The other file generally has sample times of the order of minutes and covers the entire data range, with overlap in the vicinity of the trip.

The first pre-processor in MDRAP is a text parser that combines data from two or more ASCII data files and creates an array containing all the data in MATLAB binary format. Ordering of data in the array is the same as the order in which the files appear in the function call. The second pre-processor uses a trip marker signal in the array to calculate the time of trip, sorts the array in order of increasing time, and removes duplicate data.

The data in the array can now be divided into 2 segments, one before the trip occurs and one after the trip occurs. The pre-trip readings are used to calculate the initial conditions for the delays, whereas post-trip readings are used to calculate the optimal delay amplitudes. The initial conditions of the integrators $q_i(0)$ are obtained from flux variations before the trip. Early versions of MDRAP used a value of 0 for all $q_i(0)$. In the transfer function representation this assumes the delays have reached equilibrium. For a particular delay, equilibrium is reached when the output from the delay settles asymptotically to some constant value and no longer varies with time. In most planned trips, the assumption of equilibrium conditions is not correct since there is usually power manoeuvring before the trip. As a result, in most cases only the shorter-lived delays reach equilibrium.

The computation of the initial conditions is an important aspect of MDRAP and is handled by means of a pre-trip interface. The interface requires a source of pre-trip flux. The best flux source is obtained from an RFSP simulation of the pre-trip conditions. Such a simulation would entail detailed modelling of the device movements and fuelling conditions before the trip. For the analysis of the 1997 trip at Point Lepreau, no such pre-trip simulation was performed. The only means of inferring the pre-trip flux was to use reverse filtering (deconvolution) on the Pt-clad detector readings before the trip occurred. The prompt fraction used for the deconvolution came from the analysis of the 1995 Trip Test. In that analysis a prompt fraction was estimated not through the computation of individual amplitudes, but by using one constant multiplier for all amplitudes. All delays were thus assumed to have changed by the same factor. A short time span of about 200 s for the detector readings dictated such an approach. Though not as precise as the present computation of delay amplitudes, it was felt accurate enough to be used for purposes of estimating initial conditions. Figure 3 shows the Simulink Pt-clad model used for deconvolution. Because the output Y for a linear model described by a matrix H for an input X is given by

$$Y = H * X \qquad (8)$$

Deconvolution can be used to achieve the opposite, namely to obtain the input from the output using

$$X = H^{-1} * Y \qquad (9)$$

Using values of k (prompt fraction multiplier) for each detector obtained from the 1995 analysis, the system in Figure 3 was linearized using MATLAB's linmod function to obtain H. Matrix inversion was used to obtain H^{-1}. The X obtained through the application of Equation (9) is the pre-trip flux. The magnitude of the variation rather than the actual value is what determines the amplitude of the delay at the time of trip. Since the state-space and transfer function representations are equivalent, use of one over the other is a matter of preference. For this application, the transfer function representation is more convenient. Assuming a initial amplitude of 1, if equilibrium were reached, the output from the delay would also be one. The ratio of the simulated output from the delay to the equilibrium output at the instant just before the trip is $q_i(0)$, the initial condition for the i^{th} delay necessary to solve Equation (6). One value is calculated for each delay. Figure 4 shows Simulink models used for each of the delays.

6. Optimization

The optimization consists of finding the values of the variables that result in a minimum of the cost given by Equation (2). In addition to the amplitudes a_i, two other variables are optimized. One is the DC offset that is the normalized detector reading when the flux is zero (days after the trip). The other is the timing difference between the time of trip in the RFSP simulations and the time of trip as recorded by the data logger. This is referred to as a time-shift.

The variation of the terms to be optimized is handled by the MATLAB function CONSTR.M, which finds the constrained minimum of a function of several variables. The following syntax is used; X=CONSTR('FUN',X0,OPTIONS,VLB,VUB). CONSTR.M starts at X0 (vector of initial guesses for X) and finds a constrained minimum to the function that is described in FUN.M. The function 'FUN' should return 2 arguments: a scalar value of the function to be minimized, F, and a matrix of constraints, G. If there are no constraints, G must be defined as an empty vector. VLB and VUB are vectors defining the lower and upper bounds for X (a_1, a_2, a_3, a_4, a_5, a_6, time-shift, DC offset). Defining the upper and lower limits for the solution is necessary because it is possible, in certain instances, for the optimized amplitudes to be physically meaningless, such as, for example, optimal values greater than one. The vectors VLB and VUB are chosen sensibly so as not to affect the final solution.

7. Results from MDRAP analysis of 1997 SDS1 Trip Test at Point Lepreau

Figure 5 shows a typical RFSP-simulated local post-trip detector flux, the simulated detector reading using design values, and the detector reading measured at site for the 1997 Trip Test.. Table 3 lists MDRAP optimized values for the 16 RRS detectors analyzed with data from the same test. For purposes of comparison, the prompt fractions for the same detectors calculated from the 1995 Trip Test at Point Lepreau are shown in Table 4. This 1995 analysis was performed with an early version of MDRAP, which assumed delays had reached equilibrium at the instant of the trip. In addition, deficiencies in the 1995 data did not permit individual delay amplitudes to be computed. Despite the differences between the 2 analyses, the average prompt fraction for the 16 detectors analyzed is the same and is approximately 5% higher than the design value of 88.9 %.

A version of MDRAP, based on methodology identical to that described in this paper but with the appropriate detector models, has been used for the analysis of vanadium detectors.

Based on the increased detector prompt fractions calculated with MDRAP, a recommendation would be for a redesign of the dynamic compensator for ROP detectors which would result in detector responses closer to design safety requirements. Adjusting each dynamic compensator individually is in principle feasible; however, applying this in the field would represent a sizable quality assurance problem. From this point of view, it is preferable that the redesign of the dynamic compensator be based on average values and variations or uncertainties in these values.

8. Conclusions

Using detailed modelling and high-speed measurements of detector readings, MDRAP is able to calculate the amplitude of delayed coefficients of in-core flux detectors. This capability permits the determination of the prompt fraction, which is an essential parameter in predicting detector dynamic response.

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REFERENCES

[1] B. Rouben "Overview of Current RFSP-code Capabilities for CANDU Core Analysis", AECL-11047, 1996 January.

[2] The MathWorks Inc., "MATLAB - High Performance Computation and Visualization Software", Version 5.2, 1997 December.

[3] The MathWorks Inc., "Simulink - Dynamic System Simulation Software", Version 2.2, 1997 November.

[4] The MathWorks Inc., "Optimization Toolbox", Version 1.5.2, 1997 September.

Figure 1 - Model for Pt-clad detector system, including the electronics.

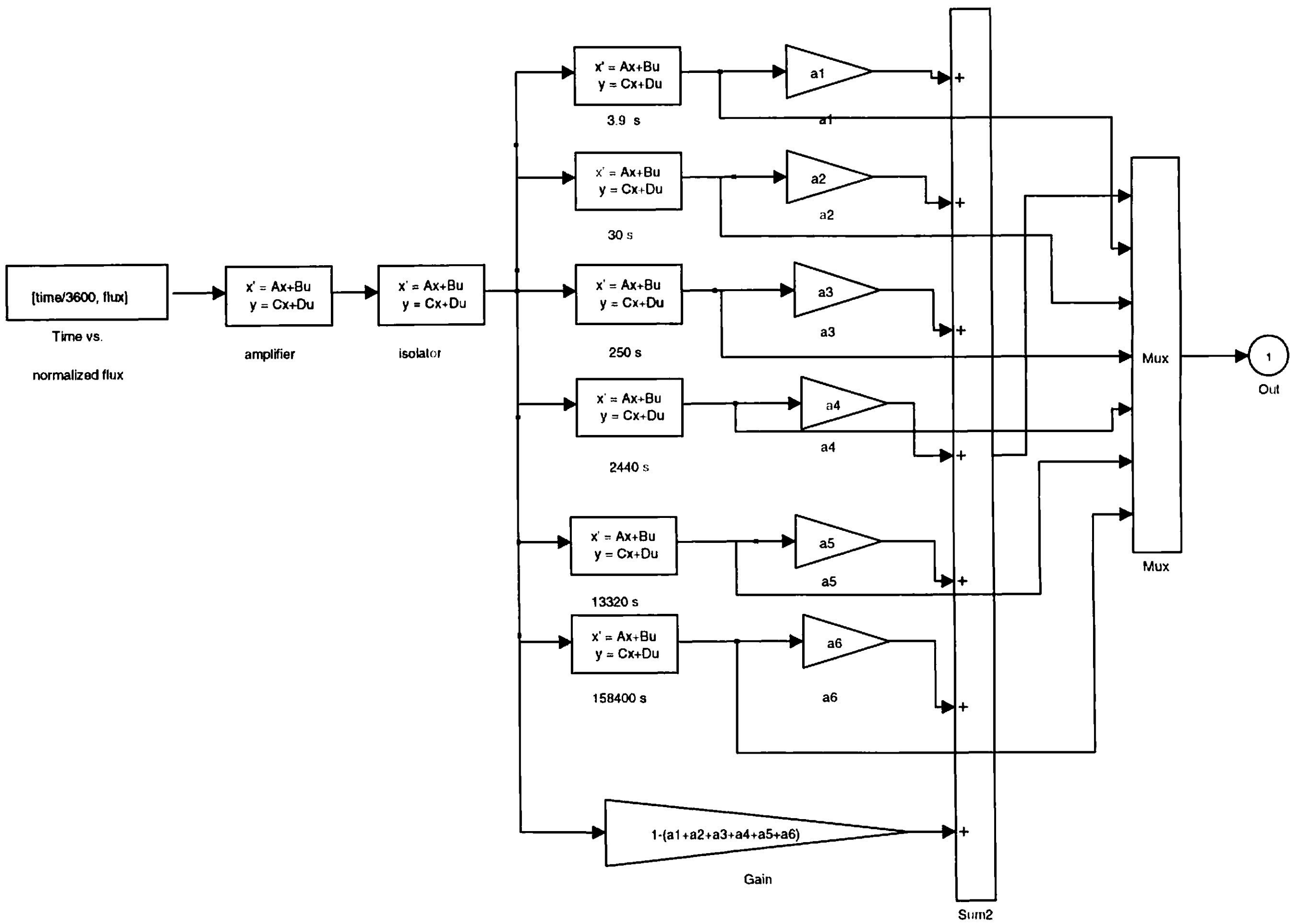

Figure 2 - Detailed model for Pt-clad detector system, excluding the electronics.

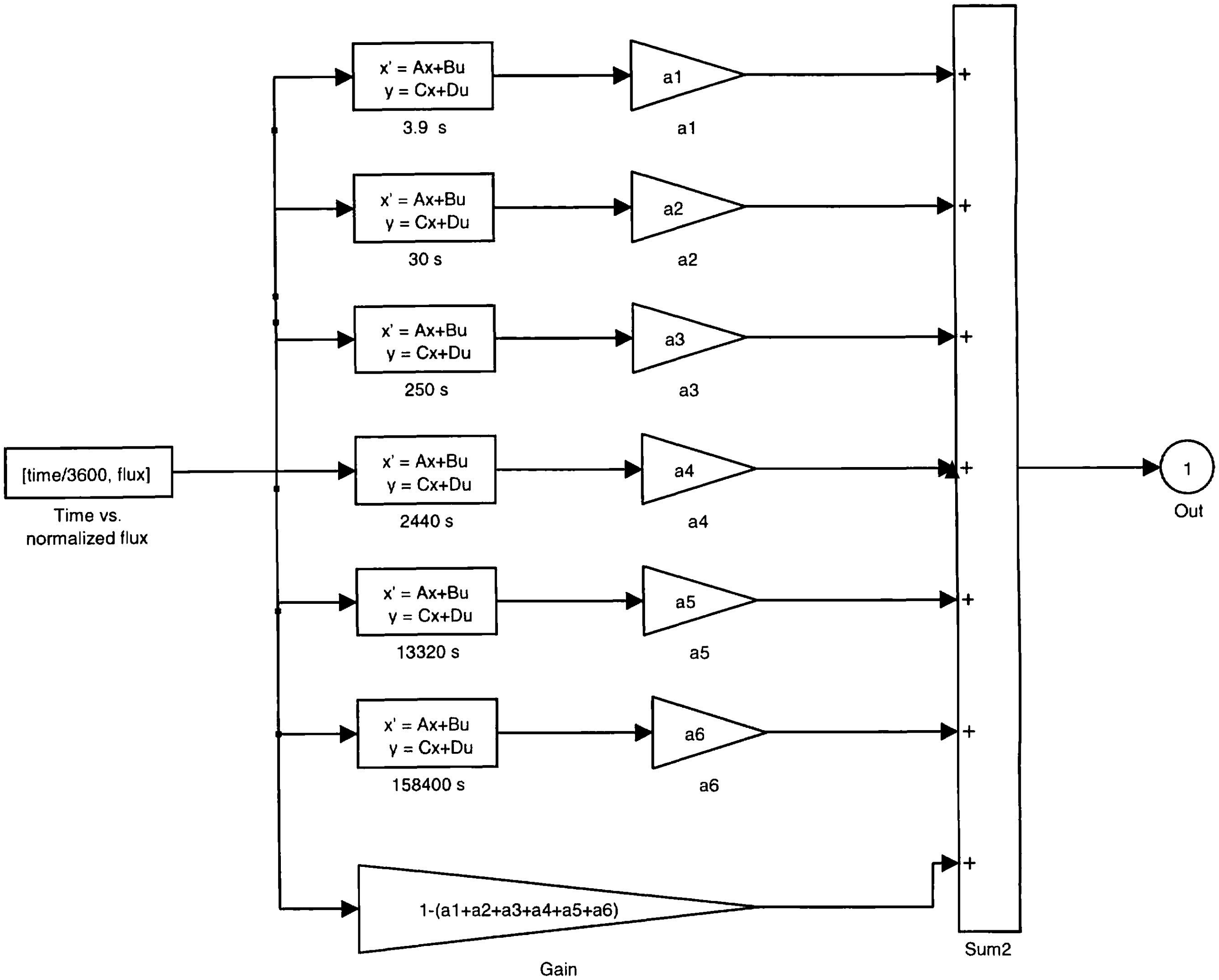

Figure 3 - Simulink model of Pt-clad detectors used to estimate pre-trip flux variation.

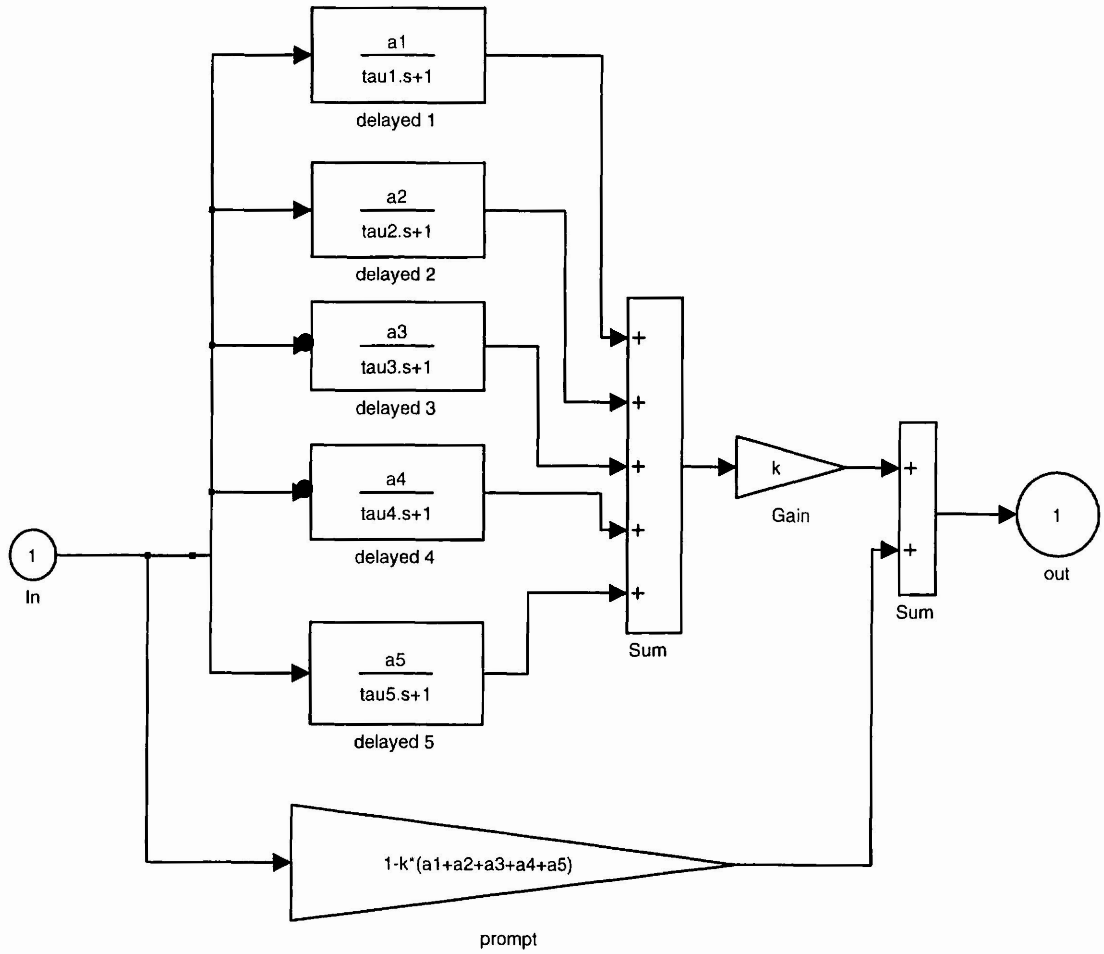

Figure 4 - Simulink models used to calculate delay initial conditions.

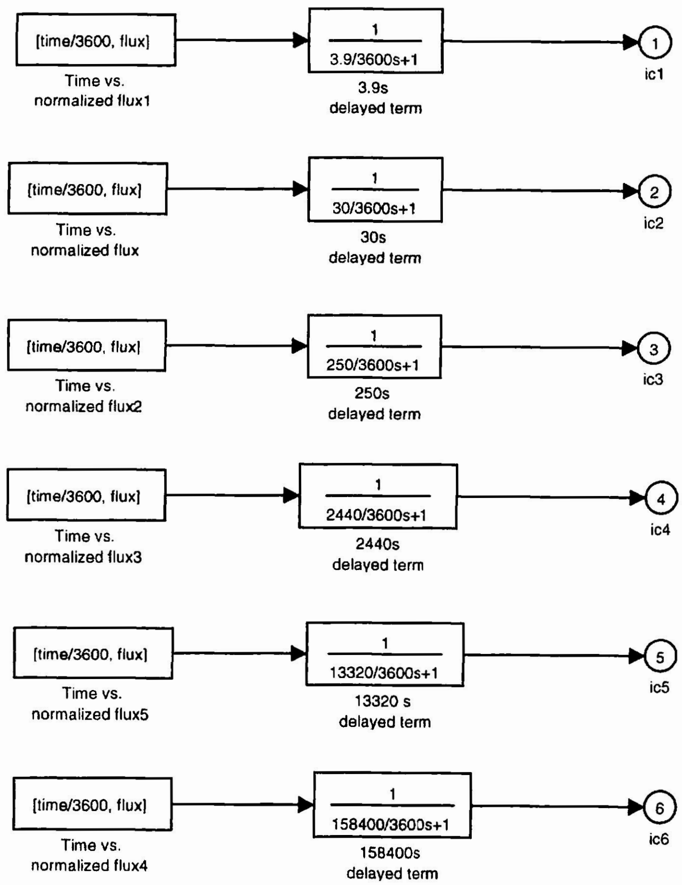

Figure 5 - Plot showing a typical RFSP simulated local detector flux, the MDRAP simulated detector reading using design values for delay amplitudes and the measured reading for the 1997 trip test at Point Lepreau.

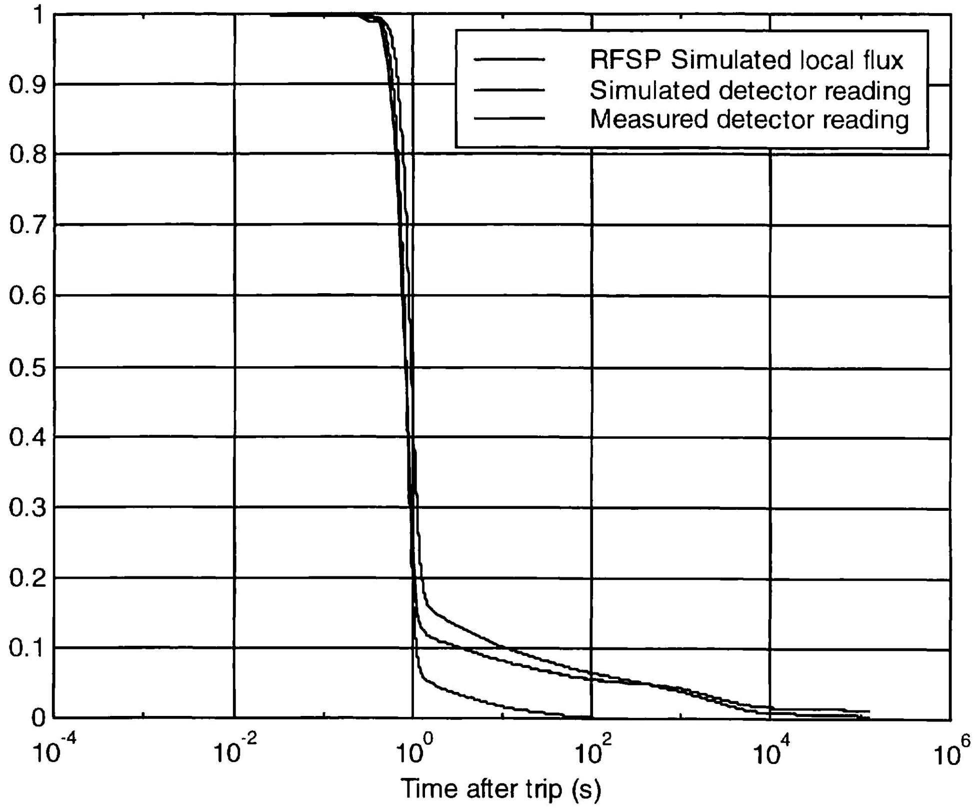

Table 1 - Design dynamic coefficients for Pt-clad SIR flux detectors.

Dynamic variable	Design value
a_1	0.02
a_2	0.021
a_3	0.017
a_4	0.045
a_5	0.008
τ_1	3.9 s
τ_2	30 s
τ_3	250 s
τ_4	2440 s
τ_5	158400 s
$1-\sum_i a_i$ = prompt fraction	0.889

Table 2 - Observed variation in delay amplitudes for Pt-clad SIR flux detectors.

Dynamic variable	Time-constant	Range in amplitude (%)
τ_1	3.9 s	0.1 to 1.5
τ_2	30 s	1.0 to 2.9
τ_3	4.17 m (250 s)	1.3 to 2.6
τ_4	40.7 m (2440 s)	3.9 to 4.9
τ_5	3.7 h (13320 s)	-0.5 to -4.2 [a]
τ_6	44 h (158400 s)	0.4 to 1.4

(a) This component has traditionally been ignored for design purposes.

Table 3 - MDRAP calculated delay amplitudes for 16 RRS Pt-clad SIR detectors with data from the 1997 Trip Test at Point Lepreau.

	Delay amplitudes						
Detector	**a1 (τ = 3.9 s)**	**a2 (τ = 30 s)**	**a3 (τ = 250 s)**	**a4 (τ = 2440 s)**	**a5 (τ = 13320 s)**	**a6 (τ = 158400 s)**	**Prompt fraction**
1A	0.00E+00	1.51E-02	0.00E+00	3.78E-02	-2.93E-03	1.09E-02	0.939
2A	0.00E+00	1.13E-02	0.00E+00	3.59E-02	-1.32E-03	9.80E-03	0.944
3A	2.78E-03	1.68E-02	4.26E-04	3.81E-02	-2.59E-03	1.14E-02	0.933
4A	1.12E-02	2.37E-02	5.15E-04	3.76E-02	0.00E+00	1.45E-02	0.912
5A	5.61E-03	5.93E-03	0.00E+00	3.29E-02	-5.11E-03	9.16E-03	0.952
6A	7.24E-04	1.29E-02	-1.01E-18	3.71E-02	-3.38E-03	1.07E-02	0.942
7A	5.63E-03	1.08E-02	0.00E+00	3.56E-02	-3.46E-03	1.05E-02	0.941
9A	2.25E-03	7.95E-03	-1.75E-19	3.38E-02	-3.90E-03	9.18E-03	0.951
10A	5.96E-03	1.79E-02	1.02E-03	3.83E-02	-1.50E-03	1.18E-02	0.926
11A	7.45E-03	1.52E-02	0.00E+00	3.58E-02	-1.95E-03	1.14E-02	0.932
14A	5.27E-03	5.27E-03	0.00E+00	3.43E-02	-5.50E-03	9.27E-03	0.951
8A	2.08E-03	1.52E-02	0.00E+00	3.79E-02	-2.25E-03	1.09E-02	0.936
12A	6.19E-03	4.37E-03	0.00E+00	3.19E-02	-5.43E-03	8.59E-03	0.954
13A	2.42E-03	1.37E-02	-2.41E-35	3.76E-02	-2.96E-03	1.12E-02	0.938
1C	0.00E+00	1.51E-02	0.00E+00	3.76E-02	-2.95E-03	1.08E-02	0.939
10C	8.82E-03	2.05E-02	2.30E-03	3.74E-02	-2.62E-04	1.23E-02	0.919
Mean	4.15E-03	1.32E-02	2.66E-04	3.62E-02	-2.84E-03	1.08E-02	0.938
Δ |Mean|	8.45E-04	1.36E-03	1.54E-04	5.06E-04	4.12E-04	3.61E-04	0.003

Table 4 - MDRAP calculated delay amplitudes for 16 RRS Pt-clad SIR detectors with data from the 1995 Trip Test at Point Lepreau.

Detector	Prompt fraction
1A	0.933
2A	0.931
3A	0.936
4A	0.928
5A	0.949
6A	0.949
7A	0.943
9A	0.958
10A	0.932
11A	0.952
14A	0.950
8A	0.943
12A	N/A [(a)]
13A	0.949
1C	0.934
10C	0.925
Mean	0.941
Δ |Mean|	0.003

(a) This detector was not analysed because of erratic readings during the 1995 SDS1 Trip Test.