DEVELOPMENT AND TESTING OF THE CONTROL ALGORITHM OF THE KOREAN MULTIPURPOSE RESEARCH REACTOR

by

C. Pappas (AECL CANDU, Montreal)
R. Henderson (AECL CANDU, Montreal)
D. McAllindon (AECL Research, Chalk River)

AECL CANDU
1155 Metcalfe Street
Montreal, Quebec, H3B 2V6

ABSTRACT

This paper describes the development and implementation of the Reactor Regulating System (RRS) control algorithm for the Korean Multipurpose Research Reactor (KMRR) on an industrial digital control computer. The general overview and description of the KMRR reactor together with the control requirements for the RRS system are presented. The paper also describes the hardware and software characteristics of the Multiloop Controllers (MLC) selected for the implementation of the control algorithm.

A real time testing verification is performed using the Dynamic Test Bed (DTB) that simulates the KMRR. The static and dynamic responses of the combined system are tested before site commissioning. The test process confirming the acceptability of the control algorithm is discussed and examples of corrective actions made during testing are described.

INTRODUCTION

In this paper we present the methodology which was followed to develop and implement the RRS control algorithm for the KMRR. We give a general overview of the KMRR and then state the specific control requirements and modes of operation for the Korean Atomic Energy Research Institute (KAERI). The RRS control algorithm is based on the simulation results from the KMRRSIM simulation [1]. The Multiloop Controller (MLC) is a sophisticated industrial process controller operating in real time and is used to control the reactor processes. A series of tests, including a real time dynamic simulation test [2] were done with the functional and fully programmed MLC to verify whether the implemented logic and the RRS control algorithm meets the specified objectives. The instrumentation interfaces were also tested.

KMRR

The Korean Multi-purpose Research Reactor (KMRR) is a 30 MW open pool type multi-purpose nuclear research reactor with forced light water cooling and moderator flows and heavy water annular reflector. The relatively small reactor core uses a low enriched -uranium-silicide-aluminum fuel and is designed to maximize the power density, thus providing the required neutron flux for various research activities. It is mainly used for radioisotope production, fuel testing and physics experiments.

The open pool concept of KMRR is attractive for many reasons such as low cost, accessibility and ease of operation. The reactor assembly consists of the coolant inlet plenum/gird plate (the lower structure), the reflector vessel and the chimney (Figure 1). The core consists of 23 hexagonal fuel sites, 8 cylindrical fuel sites and 8 outer fuelable sites. Cooling is accomplished through forced upward flow. Heat is transferred from the light water coolant to a secondary loop via plate type heat exchangers. The MLC regulates the reactor neutron flux and so the power by actuating a set of four hafnium absorber rods according to the RRS control algorithm, based on the measurements of various neutronics and process variables.

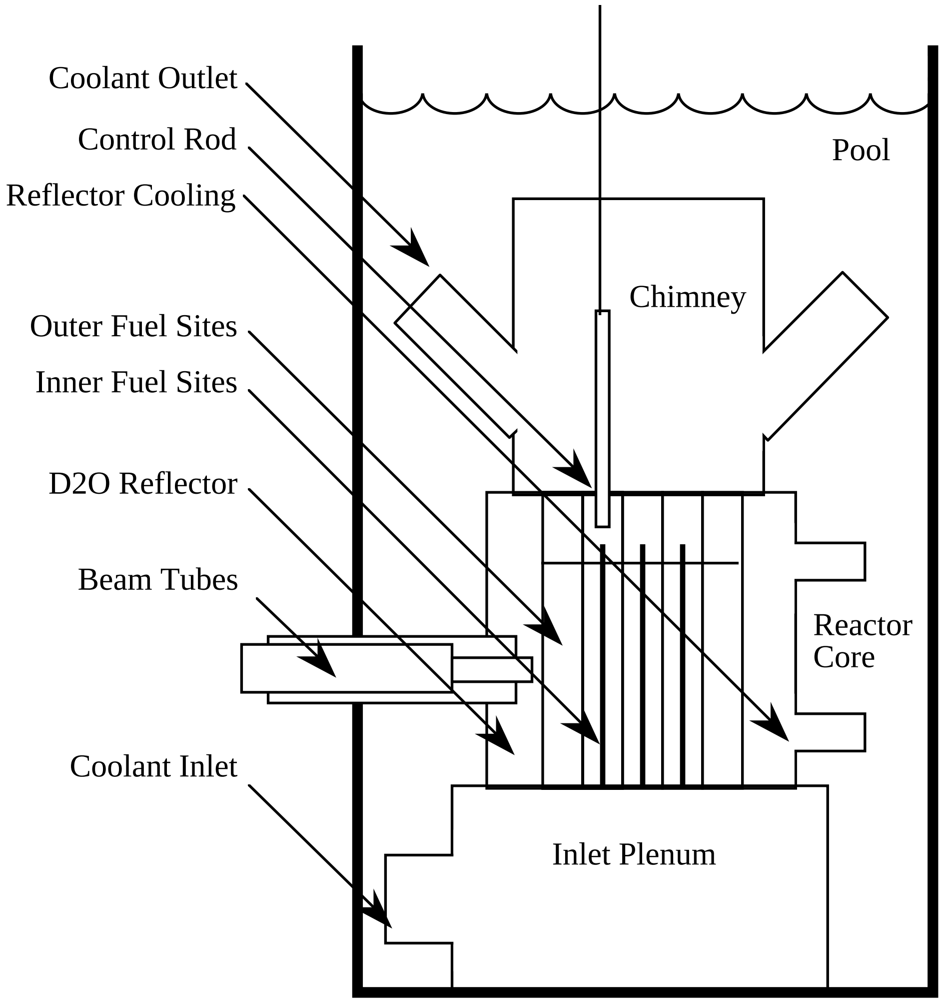

Figure 1 KMRR Reactor Schematic

The neutron flux is measured by three redundant fission chambers spaced symmetrically around the core.

A Reactor Protection System (RPS) is provided. The RPS is a hardwired safety system that shuts down the reactor in case the RRS cannot cope with the problem. The RPS provides a second set of rods used to safely shutdown the reactor in case of accident. The RRS control algorithm discussed in this paper is totally independent from the RPS.

CONTROL DESIGN REQUIREMENTS OF THE RRS

The RRS is designed to start up, maintain and shutdown the Reactor in a safe and controlled fashion. A block diagram of the RRS system is shown in Figure 2.

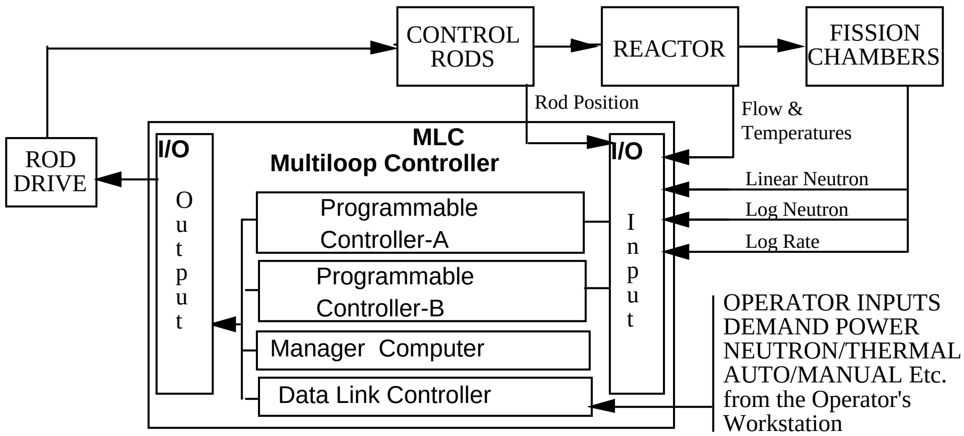

Figure 2 Reactor Regulating System of KMRR Block Diagram

The RRS Control algorithm has been designed and implemented taking into consideration the following basic control requirements established by KAERI.

- The control system should be able to maintain a predefined power from at least 10^{-6} % FP (Full Power) to 100% FP (30 MW thermal) automatically and permit manual operation at low power. The transfer between these modes should be smooth and bumpless;
- No single failure should impair the system;
- Software and hardware should have self checking capability;
- Control algorithm cycle speed should be less than 250 ms;
- The control system should be able to control the reactor with only three; out of four control rods in case one rod is frozen or is declared failed;
- The reactivity insertion rate should be limited below the accepted standard of 0.33mk/s;
- No more than one rod should move at a time except at shutdown;
- The control system should periodically perform the calibration of neutron fission chambers versus actual thermal power;
- The control system should monitor accurately the rod movement and take appropriate action when the actual rod movement differs from the computer calculated command.

KMRR ALGORITHM DEVELOPMENT AND IMPLEMENTATION

The strategy followed to develop and implement the RRS control algorithm is summarized as follows (see Figure 3):

- Interpretation of KMRRSIM control algorithm and simulation results;
- Implementation of KMRR operating control logic;
- Wernier-Orr diagrams, flowcharting and Pseudo-coding of the algorithm based on control requirement established by KAERI;
- Iterative walkthroughs, AECL internal review and Client approval of all design documentation and technical specifications;

- Functional Acceptance Test (FAT). This test is a static testing procedure where all logic inputs are tested and the expected response verified. The test also includes the control algorithm testing at boundary conditions. A static test does not have dynamic feed back therefore the full range of control possibilities can not be tested at this stage.
- Dynamic Test using an AECL designed Dynamic Test Bed (DTB)[2]. The Dynamic Test Bed is essentially another computer that simulates the dynamic behavior of the KMRR reactor core along with other dynamic process variables heat, flows, etc. The DTB is then wired to the MLC out putting standard industrial signals (4-20ma). The test specification defines which tests are to be performed. The testing verifies all previous testing and corrections with the added value of being able to exercise the MLC over the full range of expected values as well as response verification of abnormal process conditions.

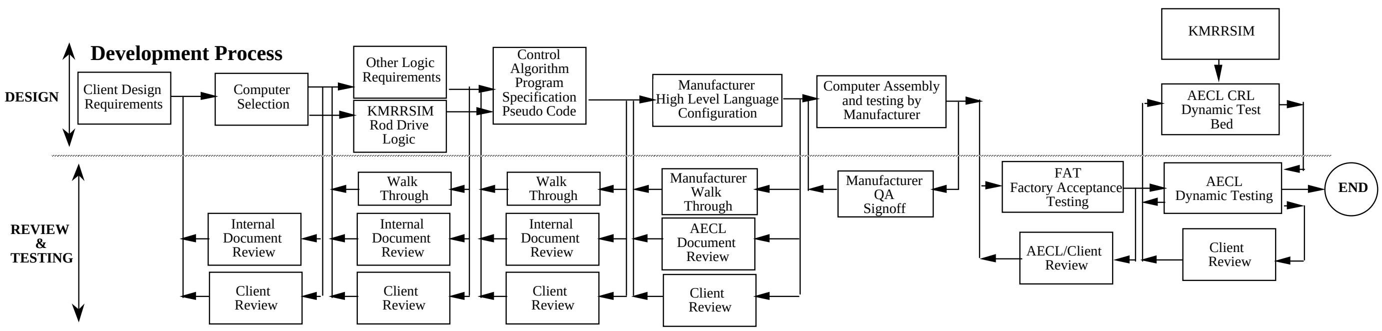

Figure 3 KMRR Design and Testing

KMRR SIMULATOR

A simulation study was done in order to design and develop a control algorithm for KMRR. The KMRR was numerically modeled by differential equations and simulated by a digital computer.

The KMRRSIM computer simulation has been developed by KAERI [1] to study the steady state and transient responses of the plant under automatic control.

The mathematical model of the plant includes:

- 2 - point neutron kinetics, representing the core and the reflector respectively;
- iodine and xenon dynamics;
- Primary and Secondary cooling system;
- Pump model system [3];
- Heat exchanger model [3];
- Control algorithm.

KMRR DYNAMIC TEST BED

The Dynamic Test Bed (DTB) was jointly developed by AECL CANDU and AECL Research for complete dynamic testing of the KMRR research reactor. The DTB is a testing computer that mimics in real time the process parameters of the reactor as developed by KMRRSIM. The DTB was verified against KMRRSIM simulation results[2].

ALGORITHM FEATURES

Modes of Power Control

There are two modes of Power control in RRS:

- Neutron mode of operation uses the fission chamber signals as feed back to control the neutron power;
- Thermal mode of operation uses the secondary side heat calculations to control the reactor and only at above 20% Full Power (FP). The control is however performed based on neutron signals (Figure 4).

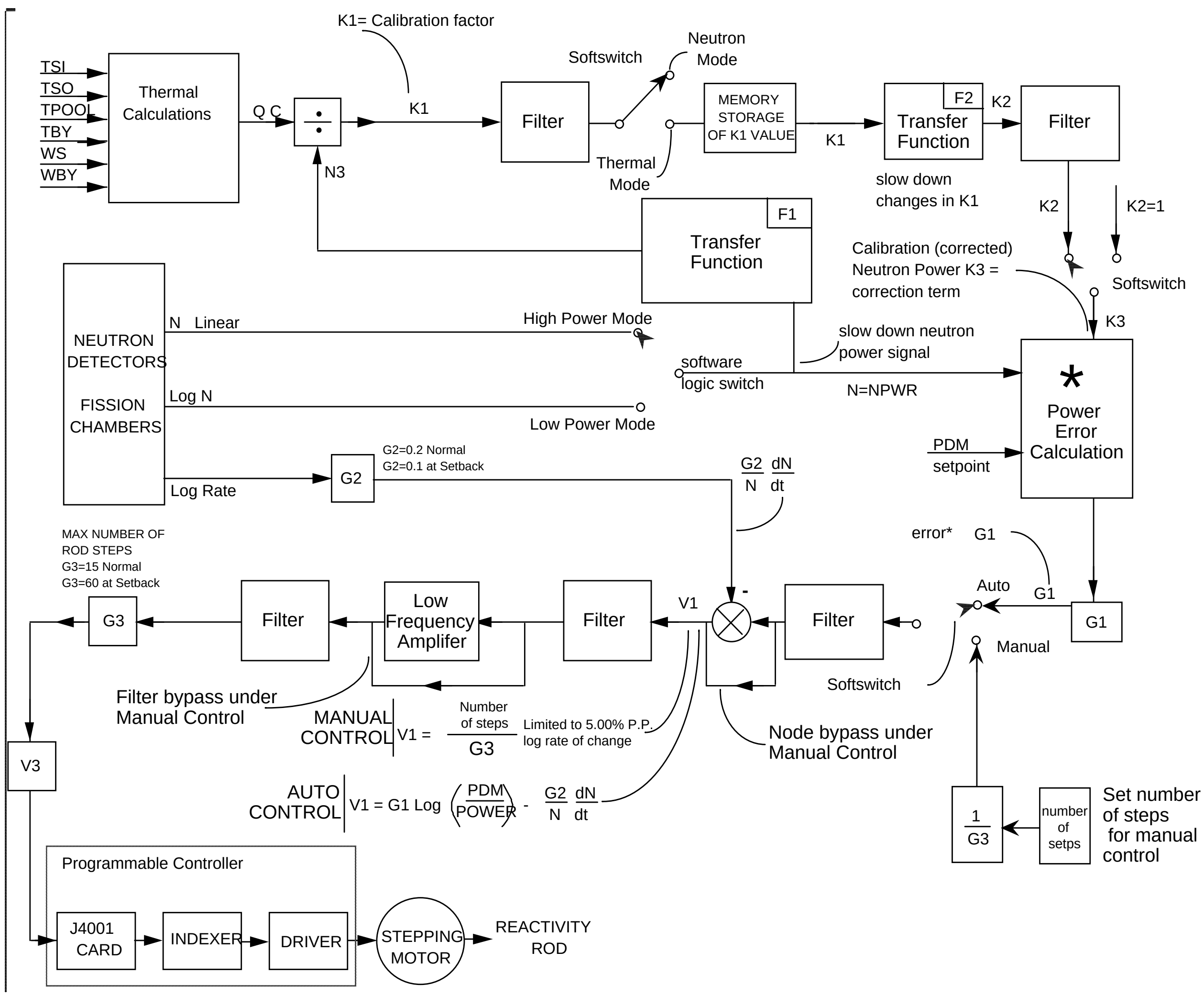

Figure 4 Simplified Schematic of the Reactor Power Control

On Line Calibration

On line fission chamber recalibration is based on the actual thermal output measured at the secondary side of the heat exchangers. This feature deals with instrumentation drift and allows longer periods between calibrations (Figure 4).

Since the reactor power from the fission chambers is not the calibrated power, we need to calibrate the fission chamber by a factor of K. The MLC calculates the reactor thermal power from the secondary cooling system. The calibration is done continuously only when the reactor power is higher than 20% FP because the thermal measurement error becomes high below 20% FP. The calibration factor (K) is defined as the ratio of measured thermal power (Q) to delayed neutron power (N3).

Signal Selection

During a transient, provision is made in the algorithm to select between the linear neutron signal or the log neutron signal. The algorithm automatically selects the linear output of the fission chambers when the linear power is >6.9% FP as the signal is considered more accurate during high power mode operation. The reverse is also true, if the linear neutron signal is <6.4%FP power the algorithm automatically selects the log signal from the fission chambers (Figure 4).

Modes Of Operation

There are four modes of operation in the RRS:

- Automatic (Auto)
- Manual
- Setback
- Shutdown

Auto

In Automatic control mode, the operator chooses a demand power level and the computer will raise or lower the control rods to attain and maintain that power level. The parameters involved in the automatic control have been determined by the KMRRSIM simulation study. Automatic operation is from 10^{-6} %FP to full power. Setback or shutdown will be automatically initiated if the predefined process limits are exceeded.

Manual

A manual control mode is available to increase the flexibility of the reactor operation. The operator can select any control rod and move it to regulate the reactor power below the power level of 0.1% FP. In order to satisfy the restriction imposed on the system during transient, the MLC limits the manual control mode (Figure 4). Manual operation is from 10^{-8} % FP to 0.1% FP . Manual mode is over ridden by the MLC and setback or shutdown will be automatically initiated if the predefined process limits are exceeded. Manual control mode is not available to the operator if the MLC is out of order. Manual control mode will be extensively used for the start up, testing, low power physics tests, and other specific experiments.

The reset of a failed rod or irrational signals in the control algorithm after clearing the cause can only be done in manual mode. Likewise the manual removal of any irrational signal from the algorithm can be done in manual mode.

RRS Setback

In Auto mode, when a process system fails in such a way that it is unable to remove the heat load generated then setback will be initiated. This avoids unnecessary shutdowns.
The process system parameter values causing the setback to occur are:

- PCS flow less than 90% of the flow at the common return line
- SCS flow less than 60% of the nominal flow
- Heat Exchanger inlet temperature on the secondary side higher than 33˚ C.

If any one setback condition is detected by the algorithm, a setback flag is set [3]. The RRS is required to setback the reactor to 50% FP (power setpoint of the reactor to operate with one PCS pump). To achieve the 50% FP before RRS Shutdown or the RPS trips, the Control Absorber Rod (CAR) motors move the rods into the core at a higher speed. The simulation showed that a speed of 60 steps/controller cycle was required [4]. Provision is also made for the operator to request manual setback whenever he detects partial failures of the primary cooling or the secondary cooling system.

RRS Shutdown

The conditions listed below cause a reactor shutdown under RRS control due to their importance for the reactor safety. Each cause of a shutdown is displayed to the operator. When the algorithm detects a shutdown condition, it sets a shutdown flag and initiates shutdown. The algorithm continues to run during the shutdown period. The shutdown flag can be reset only by the operator at reactor startup, provided the shutdown causes have already been corrected and startup conditions are satisfied. When the algorithm detects the shutdown flag set, it releases the control rods from their respective drivers which are electro-magnetically coupled. The rods free fall into the core, all at the same time. The 4 drive mechanisms are then driven down at full speed (60 steps/cycle) to be ready to couple to their respective rods in subsequent reactor startup.

The shutdown conditions are listed below:

- MULTIPLE ROD FAILURE
  Any 2 (out of 4) control rods declared failed. This can happen when the MLC that detects certain rod problems or when the operator initiates some action(explained later in this paper).
- MOTION OF FAILED ROD
  Any one rod that has already been declared failed may still drift due to a mechanical or interface fault. The algorithm can detect drift by comparing the calculated position before failure with the actual (measured) position and initiate an automatic shutdown
- OPERATOR INITIATED HARD SHUTDOWN
  This is the traditional hardwired 'panic' button.
- OPERATOR INITIATED SOFT SHUTDOWN
  Operator by means of a softkey from the workstation instructs the MLC to release the control rods' magnetic clutches and drive the rods into the reactor core.
- RPS INITIATED SHUTDOWN
  The RRS has no control links to the RPS. There is however an optical link from RPS to RRS. Whenever the RPS trips, the RRS will go to an automatic shutdown.
- IRRATIONAL REDUNDANT SIGNALS
  The Secondary Cooling System (SCS) temperatures and flows are duplicated. They are used for the calculation of the reactor thermal power. The fission chamber signals (neutron flux) are triplicated, and they are used for the calculation of the neutron power and for the control of the reactor power. If both SCS thermal variables or any 2 out of 3 neutron signals become irrational shutdown is initiated.
- LOSS OF BOTH PCs (LOSS OF COMPUTER CONTROL)

If both PCs fail the watchdogs relays interrupt the power to the control rod magnetic clutches. The rods free fall into the core.

- LOSS OF BOTH PCS PUMPS
- THERMAL -NEUTRON POWER MISMATCH

If the measured delayed neutron power differs from the net core thermal power by 10% FP, RRS goes to reactor shutdown.

- POWER EXCEEDS HIGH POWER LIMIT

If on a power surge, the net core thermal power or the measured neutron power exceed 110% FP, RRS goes to reactor shutdown.

- HIGH LOG RATE

If the neutron flux log rate exceeds 6% Present Power (PP)/s, RRS goes to reactor shutdown.

- PRIMARY-SECONDARY TEMPERATURE MISMATCH

If the PCS and SCS Heat exchanger outlets differ by more than 15.5˚ C, RRS goes to reactor shutdown.

- LOW REFLECTOR COOLING FLOW / HIGH REFLECTOR COOLING TEMPERATURE

If the reflector cooling system temperature is higher than 75˚ C or the flow lower than 30 kg/s for more than 60 s, RRS goes to reactor shutdown.

- ANY TWO CARs ARE FULLY WITHDRAWN FROM THE REACTOR CORE

This is detected by proximity switches.

- ROD NOT SELECTED BY THE ALGORITHM
- LOSS OF POWER SUPPLIES (CLASS I, II, IV)

Loss of any power class the RRS goes to reactor shutdown.

ALGORITHM IMPLEMENTATION

The Multiloop Controller (MLC)

The RRS control computer is an MLC and the associated Operator workstations interconnected on a distributed data communication link. The MLC hosts the RRS control algorithm.

The MLC used in this project contains two fully redundant programmable controllers (PC). The programmable controller is a flexible, powerful device that performs a wide variety of advanced control strategies, including PID control, override constraints and full sequential logic.

The PC consists of the following cards:

- Analog Bus interface;
- Discrete I/O interface;
- Analog A/D base card;
- Input high level expander card;
- Algorithm computer #1 performs predefined block algorithms (i.e. PID lead/lag etc.);
- Algorithm computer #2; is in step with algorithm computer #1
- Non volatile RAM;
- Manager computer;
- Multiloop data link computer.

The MLC's main characteristics are:

- Drive two fully independent Operator Workstations from which the Operator communicates with the MLC and consequently with the control algorithm.
- The Data Link computer performs the communications between the MLC and the operator workstations. It also includes hardware to format and decode the serial messages of the dual high level link.
- Fixed cycle time of 200 ms, this means to read all inputs do all control calculations and output to the field devices in a fixed cycle time. The cycle can neither be faster nor slower.
- Dual on-line redundant PCs have bumpless transfer should one of the two fail.
- On-board memory to contain the instructions of the control algorithm.

To achieve the required speed the MLC uses a high level language which is "linear", that is, there are no loops or subroutines. A "Block" language, popular in the industry, met these requirements. Each block is programmed to do a specific function, such as PID control or a logic function. These blocks are linked together to create the algorithm. The Block diagram of the RRS Control algorithm is shown in Figure 4.

The controller cycle is 200 ms. During each cycle the MLC is in any one of these 3 states:

- Read
- Calculate
- Output

Based on the above sequence, the RRS algorithm is organized in the following logical structure and all these tasks are divided into 26 functional modules. Each module consists of related actions.

READ / VALIDATE INPUTS

RATIONALITY CHECK

The algorithm reads in every computer cycle all input signals from the field and compares if they are within a given range of values. It sets flags for the irrational signals to be used for the rest of the cycle.

REJECT IRRATIONAL SIGNALS

Important input variables are redundant and the algorithm removes from the calculations any one of them which is irrational. The system will still operate using the remaining signals.

VALIDATE REDUNDANT(DUPL/TRIPL) SIGNAL

If the algorithm finds redundant signals that are valid but different, a choice is made. The lowest, highest, average or median value is selected depending on the process variable.

CHECK FOR OPERATOR REJECTED SIGNALS

Operator can remove from the algorithm any redundant signal or one rod without deterioration of the system's operation. If a rod is removed the rod selection logic in the algorithm will ignore that rod.

INITIAL CALIBRATION

During a startup, following a shutdown, the algorithm checks if the CARs are at the bottom of the core (proximity switches) and resets the rod position counters (calculated values) to match the linear encoders (attached to each rod) measured positions.

DETECT ERRORS/PROBLEMS

The control algorithm is designed to react to abnormal situations to avoid spurious or unnecessary shutdowns such as using only rational signal in calculations.

CALCULATIONS

THERMAL POWER

Calculate the thermal power using the rational thermal variables each cycle.

NEUTRON POWER AND CALIBRATION FACTOR

The calibration factor (K) is defined as the ratio of measured thermal power (Q) to delayed neutron power (N3). Therefore K= Q/N3.

The ratio compares the neutron and thermal power at the same instance of time. Thus the neutron power signal from the fission chamber (N) is delayed to match the dynamics of the measured thermal power. This is done by means of a 3rd order filter expressed by the transfer function [1]:

$$N3(s) = [1 / (1+8s)^2 (1+40s)]\ N(s) \qquad (1)$$

In order to solve this transfer function in a digital computer, we decompose eq.(1) into 3 simultaneous 1st order (2) equations [1]:

$$\begin{aligned} N1 &= N1\, e^{-0.2/8} + N\ [1 - e^{-0.2/8}] \\ N2 &= N2\, e^{-0.2/8} + N1\ [1 - e^{-0.2/8}] \qquad (2) \\ N3 &= N3\, e^{-0.2/40} + N2\ [1 - e^{-0.2/40}] \end{aligned}$$

The Neutron power is the rational selected values from the fission chambers.

CHOOSE THERMAL/NEUTRON CONTROL

Described in the modes of power control.

MANUAL/AUTO MODE

If during Manual mode the neutron power exceeds 0.1% FP then the algorithm will automatically switch to Auto mode. If during Auto mode the neutron power decreases to less than 10^{-6} %FP then the algorithm will automatically switch the Manual mode.

DETERMINE ROD MOVEMENT

To satisfy the restriction of no more than 0.33 mk/s reactivity insertion into the reactor, the maximum number of steps output to the control rod interface is 15 steps/200ms in normal mode.

OUTPUT OF STEPS TO THE SELECTED ROD

The purpose of the control algorithm is to control the reactor power to the level required by the operator while ensuring safe operation at all times. This is achieved by reading the various field process variables, process them according to the logic that has been implemented within the RRS control algorithm and output the required actions to the field. The reactor power is regulated by taking the neutron power error, subtracting a log rate, and converting these into a rod movement (Figure 4) .

$$V3 = G3\ [\ G1 \log(\text{error})\ |_{\pm 1} - G2 \log \text{rate}\ ]\ |_{\pm 1} \qquad (3)$$

where :

error = demand power / actual(measured) calibrated neutron power.

V3 = The number of steps output in a given MLC cycle

G1 = 12.3, G2=0.2 at normal mode and 0.1 at setback are the controller gains used. G2 is a constant tuned to minimize power overshoots during power increases.

G3 = 15 at normal operation and 60 at shutdown/setback is the maximum number of steps per MLC cycle (200 ms).

The log rate subtraction ensures the correct direction of the rod movement to maintain power set point during power increases or transient conditions.

During a transient, provision is made in the algorithm for the neutron measurement to be automatically selected from either the linear or the log output of the fission chambers based on the signal accuracy at different power levels (Figure 4).

The MLC communicates with the control rods via the Control Absorber Rod (CAR) interface.

This interface receives the number of steps and the control signals from the MLC and drives the CAR mechanism the required number of steps. It also returns to the MLC error/no error status of the rod mechanism which is used by the control algorithm.

Linear encoders pass the current position of the control rods to the MLC. This measured value is compared with the calculated value within the MLC and if the discrepancy exceeds a certain limiting value then the MLC will fail the rod. If two rods are failed the MLC will initiate a shutdown.

The algorithm selects one rod at each cycle and outputs the calculated number of steps to the selected rod. The control algorithm will not move more than one rod at each cycle, except during shutdown. The highest rod is selected when the direction is downward (reduce power) and the lowest rod is selected when the direction is upwards (increase power). In steady state the algorithm does not stay inert, but outputs zero steps.

TESTING

Testing is the process of establishing confidence that a product works as planned and expected. Each defect that is eliminated by testing improves quality and reduces the risk to have unexpected results during commissioning and operation.

WALKTHROUGH

A walkthrough is human-based testing for identifying defects in documents (including code) in the phase in which the document (code) is created.

Four walkthroughs were done both with people related to the project and independent reviewers. On the first pass we reviewed the code against the Design requirements established by the client. The other passes examined the logic, module by module to verify it meets the specified objectives. During these passes various cases and scenarios were proposed and the algorithm actions were tested. The reviewers, using pseudo coded form exercised each algorithm logical module with various possible input scenarios and examined the output. If the output conformed to the expected, the module was marked as successful, else corrective actions were taken and the module was reexamined at another iteration. The program was configured by the manufacturer only after the satisfactory completion of this phase.

FUNCTIONAL ACCEPTANCE TEST (FAT)

Once the coding was completed by the Manufacturer and loaded, a comprehensive I/O check was done, all inputs were exercised, all outputs verified and all logic checked.

A Test document "TEST FOR KMRR RRS ALGORITHM" was prepared describing step by step the actions required to test and verify each module of the algorithm independently. The purpose of this test was to verify that the algorithm meets the design objectives. The manufacturer representatives, AECL system designers and client representatives witnessed every test. The results of the FAT were tabulated in a Report.

During FAT several improvements and various corrective actions were added to the algorithm. Following are two examples:

Example 1: - Multi Rod movement During Shutdown.
The original requirement that one rod move at a time was modified to 'one rod moves at a time during normal operation, but all of them during shutdown'. This change reduces the shutdown reset time from 8

min. to 2 min. This gives more time for maintenance by the operator before iodine and xenon poisoning start.

Example 2: - Requested Movement Performed.
The manual mode was implemented on a fixed cycle basis. That is, if the operator requests 50 step movement of the rod, the system will perform the request in 4 MLC cycles; 3 cycles at the maximum of 15 steps and one cycle of 5 steps.

However, during the execution of the request the computer outputs steps based on the calculation per eq (3) of which the log rate term is practically never zero (even in steady state). This results in a number of steps less than the maximum and so the operator can never obtain the exact number of steps requested. The manual mode was modified to output the number of steps requested, regardless of the number of cycles required. The modified manual mode requires a longer execution time.

DYNAMIC TEST SIMULATION

The FAT was followed by a dynamic test at AECL Chalk River Laboratories (CRL). The MLC was connected to a digital simulator (DTB) where a more detailed simulation test was performed to check all functions of the algorithm under real conditions.

All MLC RRS I/O was individually wired to the DTB. After the wiring was checked, function testing proceeded. Initially, MLC operation was tested statically by controlling MLC inputs from the DTB. Once all the operational setpoints, shutdown conditions, and redundant instrument signal selection had been statically checked, full dynamic testing of all normal and abnormal operation continued. In total, MLC testing took six months.

During testing, a change control system was used to record observations of abnormalities about any part of the test system and ensure that the abnormality was satisfactorily explained. During testing, a number of observations were recorded and 1/2 of them resulted in changes to the MLC programming. Among the changes 1/3 were requested by the client witnessing the tests.

The remainder of the paper will give examples of changes to the MLC as a result of function testing.

EXAMPLES of MLC CHANGES

Example 1: - RRS Algorithm.
In the original RRS algorithm, the manual rod movement control followed exactly the same steps as automatic control (Refer to Figure 4). A switch on auto/manual control mode was present before the log rate feedback. Therefore, the step movement chosen by the operator was operated on by the low frequency amplifier (filter). One of the manual mode requirements is that the operator should be able to precisely control the number of steps of rod movement in manual rod control but the amplifier alters the number of steps. The RRS algorithm was modified to bypass the filter during manual rod movement and meet the revised manual mode requirement.

Example 2: - MLC Programming.
One type of subtle MLC programming consideration is execution sequence. In this example, a discrepancy in the CAR3 rod position counter was observed to occur over a period of hours. The number of steps output on any cycle is fed into the computer rod position counter for the selected rod. However the CAR3 rod selection signal was not available until after the CAR3 rod position counter had been updated. The execution sequence caused the CAR3 position counter to miss steps during gradual rod movement such as during the slow buildup of xenon concentration. The error in the CAR3 position would slowly accumulate until, over a period of several hours, CAR3 would be failed due to the position discrepancy between the rod position counter and the linear transducer.

Example 3: - Display or operation.

In the original MLC programming, some shutdowns would be reset as soon as the shutdown condition was no longer present. As a result, the operator could not tell what shutdown condition had caused the shutdown. The display was improved by programming a latch on all shutdown flags that resets only when the operator resets them.

Example 4 : - Oscillatory Response
Dynamic testing showed an oscillatory response during the transient that was not seen in KMRRSIM results. Several possibilities were separately investigated to determine their effect on the transient response. The effect of each possibility, if any, was reported as a separate abnormality.

1) KMRRSIM and the DTB had a different log amplifier instrument model. In the DTB, the log amplifier was modeled with a power-dependent time constant and gain whereas the KMRRSIM modeled the log amplifier with constant time constant and gain. When the DTB model was implemented in KMRRSIM, oscillations were observed on KMRRSIM results at low powers where the instrument time constant is the largest and most likely to cause oscillations.

2) The MLC was rounding the number of steps at the output whereas KMRRSIM was truncating the output steps. The MLC was modified to truncate the step output. Although the change did not affect the transient behaviour much, less rod motion occurred at steady-state.

3) The KMRRSIM model did not take into account the quantization of the flux instrument signals in the MLC. When a quantization model was added to KMRRSIM, similar oscillations were observed in the KMRRSIM results as in the DTB-MLC results. A comparison of the KMRRSIM dynamics and DTB-MLC dynamics during a transient to 0.1% FP are shown in Figure 5. In the Figures the log rates are different at the start because KMRRSIM starts from steady-state at 0.08% FP. Also the flux is plotted on a log scale on the DTB results and a linear scale for the KMRRSIM results.

4) A one cycle delay in the MLC response due to the programming sequence was removed. However, the improvement had little to no effect on the oscillations.

The above oscillatory response is viewed as acceptable because of it's small amplitude and damping.

CONCLUSION

The FAT and the DTB simulation test, assured us that the control algorithm safely, accurately and effectively control the RRS of the KMRR and meets the control design objectives established by the client. The whole process also assures that at commissioning time the number of problems will be minimal.

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