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Closed-Loop Timing Controller Design for Control Rod Drive Mechanism (CRDM) Control System in Pressurized Water Reactor

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Abstract

The method that the operating condition of Control Rod Drive Mechanism (CRDM) can be monitored without mounting sensors within CRDM housing was developed, and by using this developed method the closed-loop controller for the CRDM was designed which can optimize the performance and maximize the reliability of CRDM operation. Neural network is utilized as pattern recognition engine in detecting CRDM actuation. In this paper, most problems in previous open loop system are resolved. The control algorithms for closed-loop system were developed and implemented within the hardware of timing controller based on microprocessor. All functions in the timing controller were verified by means of real time CRDM simulator. The results show that the timing controller performs its intended functions properly.

1. Introduction

The CRDM control system is one of the important control systems in nuclear power plant whose function is to control the motive power and holding power applied to the CRDM and thus control the direction, rate and duration of rod motion. The function of the CRDM control system is to receive motion demand signals for the rod motion from the reactor regulating system or from a manual operation at the operator's module and to sequentially phase-firing the SCRs for each of the coils, i. e., lift coil and two gripper coils named by stationary gripper coil and movable gripper coil, respectively, on the magnetic jack in order to produce the demanded motion.

The rod is moved by magnetic jacks located above reactor vessel closure head. Magnetic coils are used to control rod motion. When no motion is demanded, a stationary coil is energized, forcing holding latches into teeth located on the rod extension shaft, holding the rod in a stationary position. When rod motion is raised, the coils are energized in sequence to control either insertion or withdrawal of the rod. The coils are energized by DC power obtained by phase-firing SCRs across three-phase AC source from the Motor-Generator set. [5]

In the previous CRDM controller such as Kori nuclear power plant, Units 1 and 2, open loop control concept was used, because there were no available sensors at that time which would have measured mechanical action of CRDM directly. [1] The CRDM controller designed with open loop concept is not appropriate in measuring rod position and controlling rod mechanism. So many countries have been trying to develop new methods which can be used in measuring rod position. The main reason of adoption of open loop control in old design is that the CRDM is operated under harsh environments of radiation, high temperature, and high pressure where the detecting sensors would be mounted on. There are no sensors available for the purpose of detecting CRDM motions which would be mounted within that harsh environments. The major problem of previous open loop system is rod position mismatches between demanded rod position and actual one during operation. The position mismatch will be integrated over plant operations if the correction is not performed periodically. Currently the position mismatch is fixed during overall plant test. The mismatch of rod position deteriorates the plant performance and complicates reactor power control.

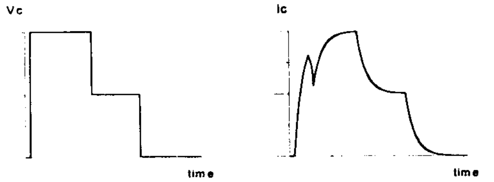
In order to resolve this problem French developed the annunciation system which can provide the alarm to operator whenever the rod position mismatch is detected by using position signals coming from safety system. Japan also developed the CRDM monitoring system by using small-sized microphone on the top of the housing to detect sounds emitted when CRDM is operated properly. [2] But these systems provide just information to operator only for the use of monitoring, and have some problems as follows. French system has an isolation problem between safety system and control system because of utilizing rod position signals derived from safety system into control grade system. Japanese system also has problems. (1) The microphone has a characteristic to detect the operating sounds of adjacent CRDMs, and it is, therefore, difficult to discriminate the operating sound of the aiming CRDM with the aid of microphone output. (2) And the microphone is not working properly at high temperature. ABB-CE, America, applied hole effect sensors to CRDM timing controller in order to detect mechanical action in YGN 3&4. [9]

In this paper new methods in measuring rod position are suggested which could be used to detect the operational conditions without mounting sensors within CRDM housing. By applying these methods, new control scheme for Kori Nuclear Power Plant, Unit 1 and 2 was developed in the closed-loop control concept. New hardware was also designed and all developed algorithms were implemented in it. The controller developed here can monitor and analyze the wave shapes of the electrical current powering the coils of the CRDM. These wave shapes provide a direct indication of the mechanical operation of a CRDM, through closed-loop control. The microprocessor continuously adjusts its control output to ensure proper sequencing of the CRDM based on the coil current feedback. Mechanical or electrical failures that would otherwise impair drive mechanism performance are directly detected. In addition the controller automatically adjusts its output to optimize drive mechanism performance over all operating conditions. The controller analyzes coil current signal in order to verify proper execution of each and every mechanical action occurring within the CRDM.

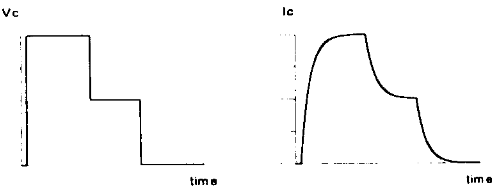
For the verification of performance of developed algorithms, real time CRDM simulator was used and the result shows that the developed algorithm performs intended functions properly. [2]

2. Closed-loop Control Using Neural Network

New rod position detecting method was developed without mounting sensor within CRDM housing. This method was devised after analyzing CRDM coil current shape. It is found that the current trend of normal condition and that of abnormal conditions have their specific characteristics in shape. Refer to Fig. 1. New methods were incorporated into design and the CRDM control algorithm of Kori Nuclear Power Plant was developed under closed-loop concept. Hardware named by timing controller was also designed which



(a) Normal.



(b) Abnormal.

Fig. 1. Characteristic of CRDM Electric Current on Normal and Abnormal Condition.

can analyze current shape and determine whether drive mechanism works properly or not. Based upon closed-loop concept, control algorithms were developed which are needed in designing closed-loop CRDM control system only using coil current values as input signal. Refer to Fig. 2. The timing controller acquires current from the shunt resistor serially connected to CRDM coils. And the timing controller analyzes the pattern of coil current shape through recognition subroutine for the use of determining CRDM actuation. For the pattern recognition, backpropagation neural network is utilized. [6]

Using backpropagation training algorithm, neural network is trained on two patterns, i. e., normal and abnormal conditions of coil current, as indicated in Fig. 1. The pattern of CRDM coil currents is read into neural network and compared against acceptable pattern. The network used here is 3 layer neural network which consists of 300 neurons in input layer, 20 neurons in hidden layer and 3 neurons in output layer. Fig. 3 shows neural network structure used. Values, [1 0 0], is applied as the target value of narmal pattern in supervised learning process and [0 0 1] for abnormal pattern. Following equations illustrate learning process of backpropagation. [7][8]

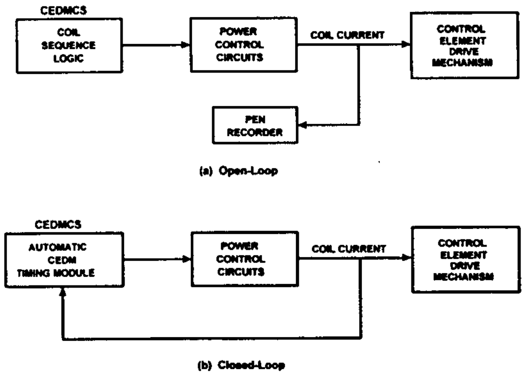


Fig. 2. Comparision of Open Loop System With Closed-Loop System.

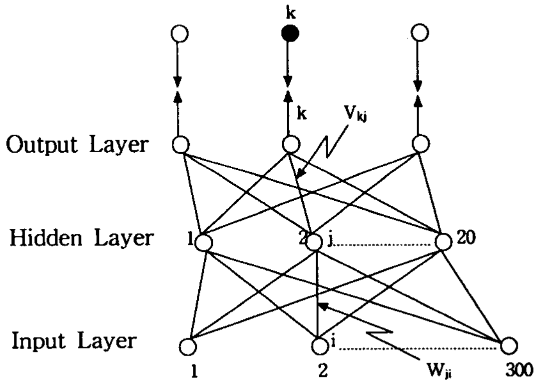


Fig. 3. Neural Network Structure

$$O_j = F(Net_j) \tag{1}$$

$$(Net_j = \sum_j W_{ji} * O_i)$$

$$O_k = F(Net_k) \tag{2}$$

$$(Net_k = \sum_k W_{kj} * O_j)$$

where

O_i = Output value for neuron i in input layer

O_j = Output value for neuron j in hidden layer

O_k = Output value for neuron k in output layer

W_{ji} = Weight value from input layer to middle layer

W_{kj} = Weight value from middle layer to output layer

$$F(x) = 1 \; / \; (1 + e^{-x}) \tag{3}$$

Equation (3) is sigmoid function used as an activation function.

$$E = \frac{1}{2} \sum_k (T_k - O_k)^2 \tag{4}$$

Each output in output layers is subtracted from its target value, T_k, to produce error signal, E, as shown by equation (4). ΔW_{kj} in Equation(5) is the value of a weight from neuron j in the hidden layer to neuron k in the output layer. An identical process is performed for each weight from a neuron in the hidden layer to a neuron in the output layer as shown by Equation (7).

$$\Delta W_{kj} = - \eta * \frac{\partial E}{\partial W_{kj}} = - \eta * \frac{\partial E}{\partial Net_k} * \frac{\partial Net_k}{\partial W_{kj}}$$

$$= \eta \; * \delta_k * O_j \tag{5}$$

$$\delta_k = - \frac{\partial E}{\partial Net_k} = - \frac{\partial E}{\partial O_k} * \frac{\partial O_k}{\partial Net_k}$$

$$= (T_k - O_k) * F'(Net_k)$$

$$= (T_k - O_k) * O_k * (1 - O_k) \tag{6}$$

$$\Delta W_{ji} = - \eta * \frac{\partial E}{\partial W_{ji}} = - \eta * \frac{\partial E}{\partial Net_j} * \frac{\partial Net_j}{\partial W_{ji}}$$

$$= \eta \; * \delta_j * O_i \tag{7}$$

where

η = Training Rate Coefficient

$$\delta_j = (\sum_k \delta_k * W_{kj}) * O_j * (1 - O_j) \tag{8}$$

Equations (11) and (12) show the value of the weight at step n+1.

$$\Delta W_{ji} = \eta \; \delta_j \; O_i \tag{9}$$

$$\Delta W_{kj} = \eta \; \delta_k \; O_j \tag{10}$$

$$W_{kj}(n + 1) = W_{kj}(n) + \alpha \; \Delta W_{kj}(n) \tag{11}$$

$$W_{ji}(n + 1) = W_{ji}(n) + \alpha \; \Delta W_{ji}(n) \tag{12}$$

where α is a momentum coefficient.

3. Timing Controller Software Description

Timing controller software[4] is divided up into four major functions: analog to digital converting, voltage monitoring, motion demand, and protection action. The timing controller normally executes the voltage monitoring routine. All of the other routines are enacted as needed through interrupts. In this way CRDM coil current monitoring and timing controller on-board functional tests are not slowed down by polling to see if a upper level routine is requested.

3.1. Analog to Digital Converting

A/D converter in the timing controller activates a microprocessor interrupt line when the conversion is complete. The multiplexer channel selected is chosen by the software routine presently being executed by the timing controller. In order to keep the timing controller updated as to the real time CRDM status, a separate hardware oscillator sends to the A/D converter, start pulses every 500 s and the A/D converter generates an interrupt to the microprocessor when the conversion is complete. The microprocessor reads the number contained in the A/D converter. The A/D converter interrupt runs asynchronously to the timing controller program execution and is continuous, except when the timing controller program enters a protection routine.

Within the A/D converter subroutine there are continuous checks of critical functions. The critical functions are gathering coil data patterning, coil high and low voltage output, and verifying adequate coil current to the holding gripper.

3.2. Voltage Monitoring

Timing controller program is primarily executing Voltage Monitoring for all normal operation and non-motion conditions. This routine contains the functions that monitor each CRDM coil current against a high level setpoint and also perform an onboard timing controller functional test. The routine is interrupted periodically at 500 s although the voltage monitoring routine is being executed repetitively during the normal non-motion conditions.

The software watchdog is incrementing a count on every pass through gripper current monitoring subroutine, toward a maximum limit. If the software watchdog count reaches the maximum value then an alarm is generated and program control is given back to the voltage monitoring routine. The software watchdog count is only reset at the beginning of the voltage monitoring section, this ensures that CRDM coil monitoring is never locked out by an unanticipated software loop. Should the timing controller be aborted due to the software watchdog, then all voltage outputs are shutoff except the holding stationary gripper coil low voltage. Program control is then given to the voltage monitoring section.

3.3. Motion Demand

When a motion demand interrupt which is enabled by voltage monitoring is received from the external control logic, the voltage monitoring loop is interrupted and program control is given to the motion control sequence. The motion demand routine first checks to see if the program was previously in a protection state. If the system was in a protection state, a routine to recover from the protection state is entered. If the program was not in a protection state the true purpose of the timing controller comes into play, cycling of CRDM coil voltages under closed-loop control for rod motion. From the start of a motion sequence until its completion, all CRDM actions are dependent upon the successful completion of the previous actions. Application of high voltage to each coil is timed to end either when an appropriate coil current pattern is recognized which is representative of CRDM mechanical action or when the duration of the engagement window reaches maximum.

If the CRDM does not respond in the proper manner, e. g., gripper coil does not pull in, then the alarm signal is activated. The motion demand request also serves the purpose of resetting alarm output signals and program status flags such that control action which may have been prevented, due to an attempt flag reaching full count, is re-enabled. Motion demand requests can also be initiated via the manual transfer switch. Without the corresponding motion direction signals being input from other external circuitry, no rod motion sequencing is begun, but alarm signals and status flags are reset as before. Also, if the rod is presently being held by the movable gripper coil, then the holding function is transferred to the stationary gripper coil. In special cases where a motion is requested and the rod is currently being held by the movable gripper coil, the normal sequence is altered to account for the step taken.

The current level of the engaged gripper is compared against a minimum setpoint value. Should this current level drop below the setpoint, the voltage to the engaged gripper is re-initialized using both the low and high voltage outputs and an immediate transfer to the other gripper is attempted. After a successful transfer, the low and high voltages to the original gripper are shut-off and the rod is now held on the other gripper. Should the transfer attempt to the other gripper be unsuccessful, it will be reattempted three times. While the transfers are being attempted, an alarm will be generated. Following a three unsuccessful transfer attempt, the program will attempt to hold the rod by applying low voltage to both the movable and stationary grippers, and enter an alarm mode.

3.4. Protection Function

If during normal operation, the timing controller software detects a combination of fault conditions involving inadequate holding current, sustained coil high current, or unsuccessful gripper engagement, it will attempt to prevent a dropped rod from occurring by jumping to one of the recovery routines. A motion demand interrupt will cause the program to exit a constantly looping protection routine. If the motion demand routine finds the protection flag set, it attempts to find a state whereby it can clear the protection condition. If the stationary coil engagement can be detected, the routine then advances to the normal motion sequence. Should there be no detectable engagement of the stationary gripper coil the program then attempts to engage the movable gripper coil.

4. Simulation Results and Discussions

After completion of source program, testing was performed to verify if the software works as expected. Testing consists of simulating normal CRDM operation, CRDM gripper misengagement and CRDM abnormal voltage conditions. During designing and testing of timing controller functions, real time simulator developed was used. [3] The results of testing are given as current traces. All functions were verified using simulator with a real data collected from site. Following is some results that were conducted.

4.1. Verification Test 1

This testing is conducted to verify normal CRDM operation for insert and withdrawal sequence. Fig. 4 shows the result for normal control sequence on insert and withdrawal. Dotted lines idicate input command for the control sequence and solid lines do current value caused by input command. This testing was completed satisfactorily.

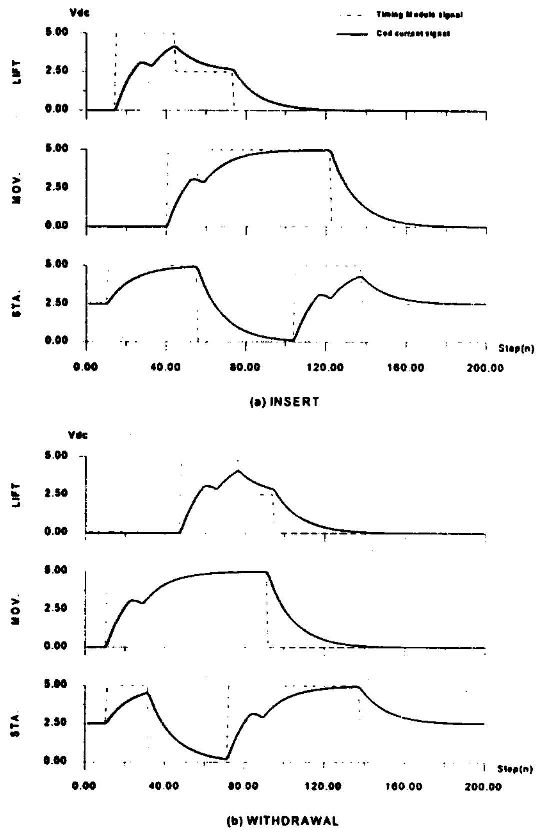


Fig. 4. Result of Normal Control Sequence

4.2. Verification Test 2

This testing is conducted to verify that CRDM will attempt to restep three times whenever a malfunction is sensed on the lift coil and the lift coil does properly engage after a three unsuccessful transfer. Fig. 5 shows the result of this for insert and withdrawal control sequence, respectively. The step was completed satisfactorily.

4.3. Verification Test 3

This testing is conducted to verify that CRDM will attempt to restep three times when a malfunction is sensed on the lift coil and the lift coil does not still

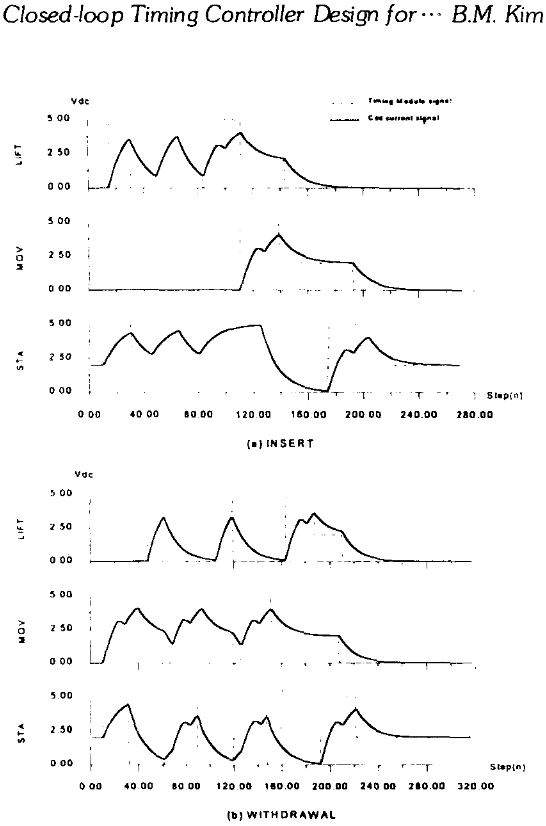


Fig. 5. Result of Re-Steping Three Times

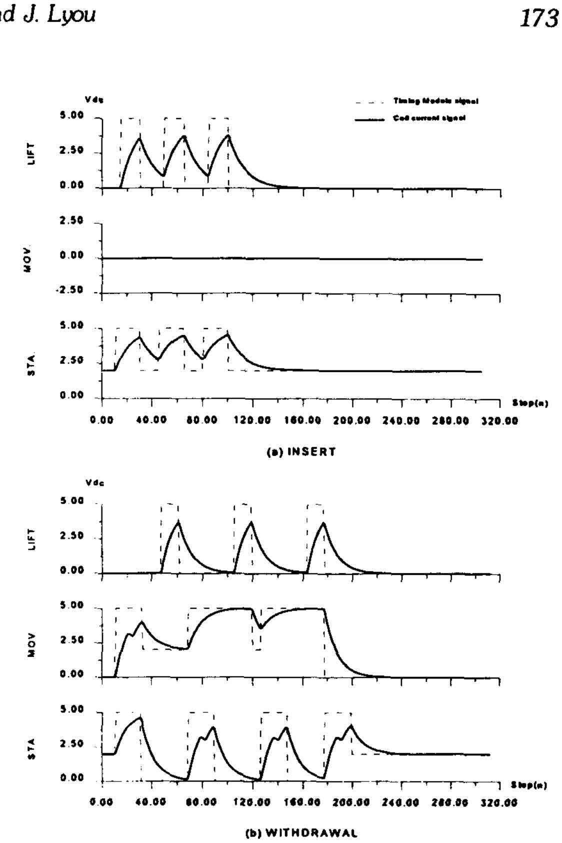


Fig. 6. Result of Re-Steping Control Sequence After an Unsuccessful Transfer

properly engage after a three unsuccessful transfer. Fig. 6 shows the result of the current traces after an unsuccessful transfer for the insert and withdrawal control sequence, respectively. The step was completed satisfactorily.

4.4. Verification Test 4

This testing is conducted to verify that CRDM will attempt to transfer movable gripper coil when high current or low current are sensed on the stationary gripper coil. Fig. 7 shows the result of the current traces for the high and low current of stationary gripper coil, respectively. The step was completed satisfactorily.

5. Concluding Remarks

In this paper, new method is proposed in detecting operating condition of CRDM. And timing controller has been designed as closed-loop system. For the verification of performance of developed system, real time CRDM simulator is used, and the result shows that the developed algorithm performed its intended functions properly. The algorithm developed under closed-loop control concept resolves most problems occurred in the old open loop controller, and improves the performance and reliability of the system. If further works such as software V&V, license and fault tolerant design are performed in the future, the algorithm together with timing controller developed in this paper will be applied to both future nuclear power plant design and the design improvement work of the old CRDM control system like Kori nuclear power plant, Units 1 and 2.

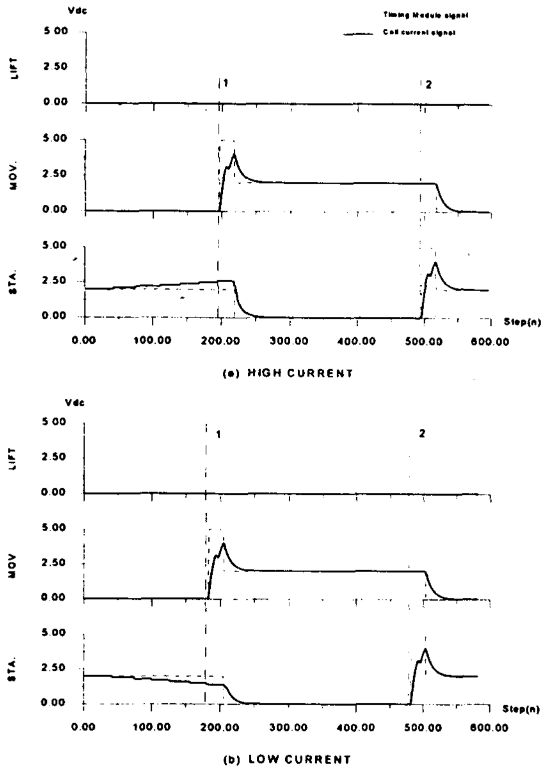


Fig. 7. Result of High and Low Current of Stationary Gripper Coil

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Nomenclature and Abbreviation

ABB-CE : ABB Combustion Engineering Inc.
AC : Alternative Current
A/D : Analog to Digital
CEDM : Control Element Drive Mechanism
CEDMCS : Control Element Drive Mechanism Control System
CRDM : Control Rod Drive Mechanism
DC : Direct Current
SCR : Silicon Controlled
V&V : Verification and Validation
YGN 3&4 : Yonggwang Nuclear Power Plant, Units 3 and 4

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