Operation and Control of TRIGA Nuclear Research Reactor with PLC

P. K. Bhowmik, S. K. Dhar, and S. Chakraborty

***Abstract*—Nuclear reactor operation and control is a sophisticated system involving modern equipments and techniques. This paper proposes an operation and control feature of TRIGA Mark-II research reactor and discusses the structure and implementation of smooth automatic operation and control using programmable logic controller (PLC). The automation of the reactor and accurate power generation by demand is carried out by inserting or withdrawing control rods. Four trip conditions and one external faults (generalized for any external mechanical or electrical fault) are taken into account to shut down the reactor suddenly (SCRAM). This paper proposes better flexibility in operation & control and low cost & time for trouble shooting with PLC compared to the instrumentation currently offered by General Atomics for TRIGA reactor.**

***Index Terms*—PLC, regulator rod, shim rod, transient rod, TRIGA Mark-II reactor, emergency core cooling system (ECCS), ladder logic program.**

I. Introduction

A nuclear reactor is a system in which a nuclear reaction named fission (splitting the atom) chain reaction is initiated, sustained and controlled. Reactors are used for generating electricity, moving aircraft carriers and submarines, producing medical isotopes for imaging and cancer treatment and for conducting research. The energy in form of heat produced by fission reaction is carried out by coolant generally water that produce steam. The thermal power generation is manipulated by control rods. When inserted (moved down) in the reactor core, control rods absorb neutron and reduce generation of power. On the other hand when control rods are withdrawn (moved up) the number of fission and power level increases.

But more sophisticated and reliable control system is needed for nuclear energy than any other energy sources to avoid a single hazard. In order to make the system safer with minimizing human intervention, it is an option to develop an automatic system that monitors the plant and helps to reduce the errors. TRIGA Mark II is a widely used research nuclear reactor of General Atomics, USA which is the only nuclear reactor in Bangladesh. This study proposes an operation and control of the reactor which will provide more flexibility and universality for the end user with ubiquitous PLC than the current control instrumentation by General Atomics.

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II. PLC Module Set up

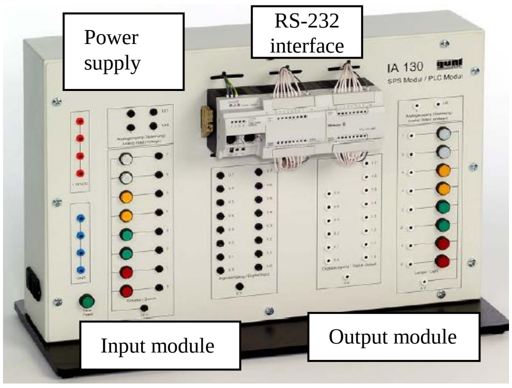

Fig. 1. GUNT Moeller programmable logic controller IA 130.

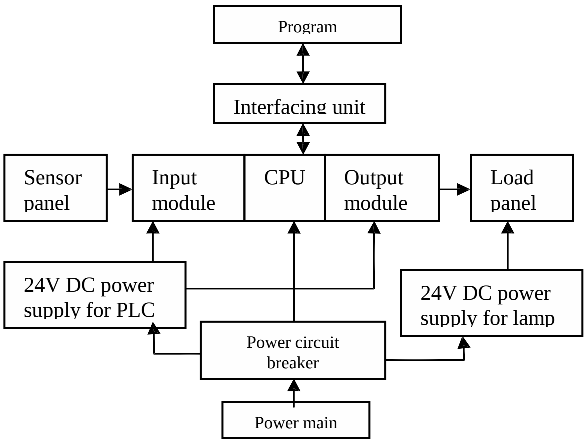

Fig. 2. Functional blocks of GUNT Moeller programmable logic controller.

A PLC is a digital operating system designed especially for usage in an industrial environment, which uses a programmable memory for its internal operation of user orientated instructions and to implement specific functions [1]. PLC can process digital and analog inputs and outputs. The Sucosoft V5.02 programming software that is used in this study conforms to the international standard IEC 61131-3 [2]. The GUNT Moeller PLC IA 130 is used to perform basic testing and operation of ladder logic and control for this study. The front panel of this PLC setup is designed as a laboratory patch board, where the input ports and output ports of the PLC can be connected to switches and displays via laboratory cables [3]. In order to write programs in the EEPROM of the PLC, it is connected to a PC with an RS-232 interface shown in Fig. 1. The functional blocks of complete set up is shown in Fig. 2 [4]. The sensor and load

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modules in the block diagram are marked as input and output module respectively in the photograph.

The set up consists of the following features in brief:

1) Programmable logic controller
2) Interface unit
3) Input and Output Module
4) Power supply for PLC input & output module
5) Input switches and output indication lamps
6) Power supply for lamps
7) 24V DC relay
8) Computer with Moller PLC software
9) Sucosoft V5.0.2 programming software

III. TRIGA MARK II NUCLEAR REACTOR

The reactor is a typical 3MW (thermal) capacity research reactor with an annular graphite reflector cooled by natural convection with water in steady state mode [5]. The side view of the reactor is shown in Fig. 3 [6]. The reactor core is placed at the bottom of the tank with 1m radius. Three types of control rods of fueled-follower type are used in the reactor: regulating, shim and safety rods [7]. They are identical in geometry and composition. Regulator rods are used for fine adjustments, shim rods are used for large changes to the reactivity and safety rods are used to rapidly decrease the reactivity in the event of accidents. When the control rods are in completely up position their position indicator is set to indicate 200 steps. It indicates 900 steps at completely down position [6]. These control rods are used in this study to manipulate the output power according to demand either inserting or withdrawing in the reactor shown in Fig. 4 [5].

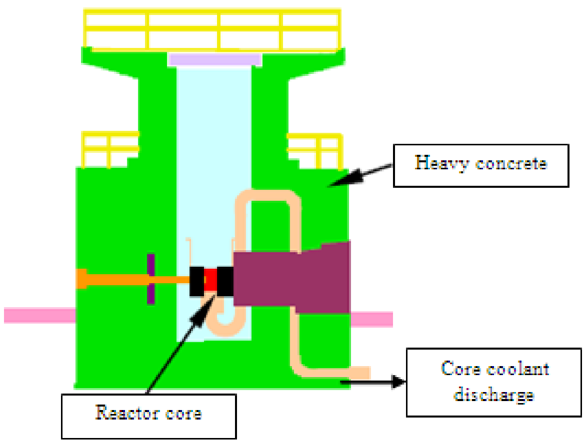

Fig. 3. Side view of TRIGA reactor.

Similar to the fueled-follower control rods, the transient rod consists of the absorber part and the so called air follower which replaces the fuel part in the fuel follower control rods. The purpose of the air follower which is in fact an empty tube is to reduce power peaking that could appear when the transient rod is in its fully withdrawn position. Transient rod is equipped with pneumatic system for rapid withdrawal. When the pneumatic valve is open by pressing the "fire" signal the air pressure pulls the rod from its completely inserted position to its preset final position defined by the transient rod drive mechanism. When the transient rod is in completely up position, its position indicator is set to indicate 0 steps. It indicates 900 steps at completely down position [4].

Specifications of control and transient rods are shown in Table I [7].

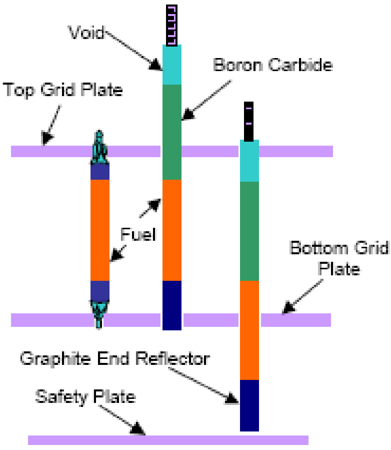

Fig. 4. Control rod withdrawn and inserted.

TRIGA reactor is fueled with LEU (low enriched uranium) which is composed of 19.7% enriched uranium (U^{235}), $ZrH_{1.6}$ (prime moderator) and burnable poison Er^{167} [5]. The fuel material is housed in a 0.5mm thick type 304 stainless steel cladding. The single most important safety feature of the TRIGA fuel is the Prompt Negative Temperature Coefficient of Reactivity (PNTCR). The nominal value of the PNTCR is about $1.07\times10^{-4}\%\ \Delta k/k/^{0}C$. Because of this characteristic of fuel, the reactor can be operated in pulse mode (with peak power of 852 MW and half maximum pulse width of about 18.6 milliseconds) [8]. The maximum fuel temperature recorded during pulse operation is about 438 ^{0}C. Fuel temperature is measured in two fuel elements instrumented with thermocouples. The thermocouples tip is in the center of the fuel element where the temperature is normally the highest. Instrumented fuel elements are inserted in the locations with maximum power density. The electrical signal equivalent to fuel temperature is directly fed to the analog input of PLC and necessary decision is made thereafter.

TABLE I: SPECIFICATION OF CONTROL ROD AND TRANSIENT ROD

Component	Dimension (inch)	Material
Control rod		
Outside diameter	1.4	
Element length	43.75	
Fuel material		U-ZrH
Inner diameter	0.25	
Transient Rod		
Outside diameter	1.25	
Element length	43.75	
Air follower		Air
Absorber		B_4C
Guide Tube		Al
Top and bottom fitting		Al

IV. PROCESS FLOW AND FEATURES OF PROTECTION AND CONTROL

In this study the trip conditions that are protection and control features of TRIGA MARK II reactor taken in account are as follows [6]:

1) Trip 1: % PWR (20% of 3MW), Fuel temperature

(270^{0}C), Period.

2) Trip 2: High water temperature, Low flow (Thermal power trip)
3) Trip 3: High RTD output.
4) Trip 4: Pool water level low (3 ft from normal level)
5) External SCRAM: External and manual SCRAM or circuit trouble.

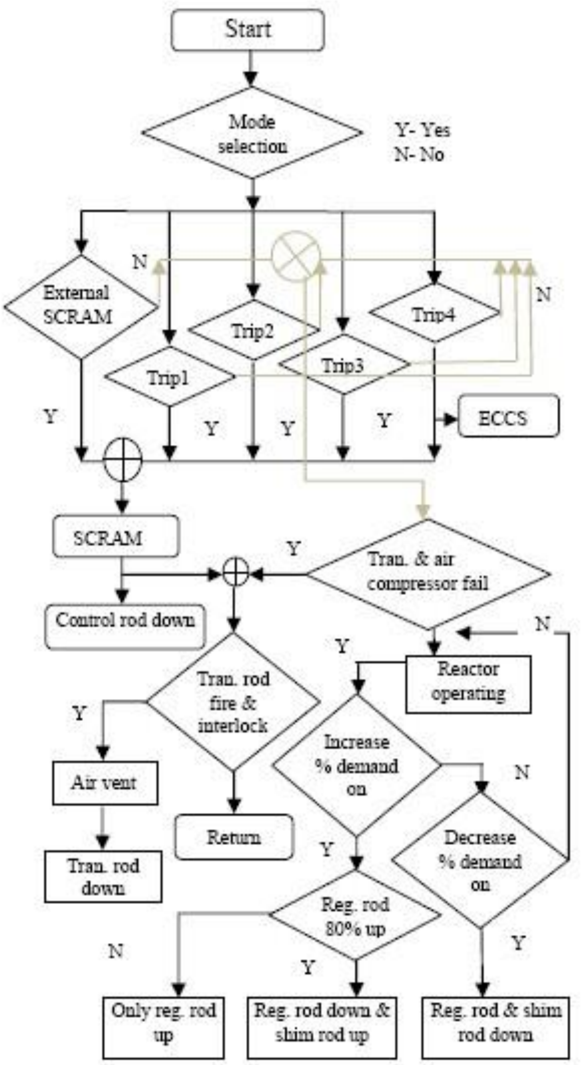

Fig. 5. Process flow diagram of control and operation.

The complete process flow of operation and control is shown in Fig. 5. Before start up there should be a thorough check up of the system, like valves, control trip, safety device and all mechanical and electrical systems [6]. A brief proposed operating procedure of TRIGA MARK-II reactor with PLC of this study is as follows [5]:

1) Start by a key switch, power switch and a ready switch.
2) Select the mode of reactor operation: natural mode or forced mode.
3) After mode selection, check all the protection criteria or trip conditions.
4) If any trip condition is occurred or any external SCRAM then SCRAM (Safety Control Rod Axe Man) the reactor.
5) SCRAM will get down all control rods automatically.
6) Activation of Trip 4 that is pool water level low turns on the Emergency Core Cooling System (ECCS).
7) Check the transient air pressure. If compressor fails or SCRAM is activated then air vent of transient rod occurs and transient rods are get down automatically.
8) If start switch is on, there is no SCRAM and transient rod air supply is alright then reactor is under safe operating condition and check the % demand switch.
9) If increase of % demand switch is in on position, check the regulating rod position and if regulating rod 80% up switch is on, get down the regulating rod and get up the shim rod simultaneously. If regulating rod 80% up switch is off then only the regulating rod gets up but not the shim rod.
10) If increase of % demand switch is off and decrease of % demand switch is on then both the regulating rod and the shim rod get down simultaneously.
11) If both increase and decrease of % demand switch are off then return to the reactor under safe operating condition.

V. Program Development and Execution

The program for proposed control and operation of TRIGA reactor is developed and simulated with Sucosoft V.5.0.2 comes along with Moeller PLC setup. The input and output process variables declared for the ladder logic program are shown in Table II.

TABLE II: PROCESS VARIABLE DECLARATION

Variable Name	Address	Comment
Start	%IO.0.0.0.0	Key, Power and Ready Sw
Airsupply_failure	%IO.0.0.0.1	Compressor and transient air failure
Natural	%IO.0.0.0.2	Natural mode of operation
Forced	%IO.0.0.0.3	Forced mode of operation
Trip1	%IO.0.0.0.4	%PWR, Fuel temp, Period
Trip2	%IO.0.0.0.5	Thermal power trip
Trip3	%IO.0.0.0.6	RTD low
Trip4	%IO.0.0.0.7	Pool water level low
MAN_SCRAM	%IO.0.0.1.0	External or manual SCRAM
Increase_demand_sw	%IO.0.0.1.1	Increase % demand
RegRod_80percent	%IO.0.0.1.2	
TranRodFired_Inlock	%IO.0.0.1.3	
Decrease_demand_sw	%IO.0.0.1.4	Decrease % demand
Reactor_operating	%QO.0.0.1.1	
SCRAM	%QO.0.0.0.0	
ECCS_on	%QO.0.0.0.1	
RegRod_up	%QO.0.0.0.2	Regulating rod upward
Regdown_Shimup	%QO.0.0.0.3	
Regdown_Shimdown	%QO.0.0.0.4	
Control_Rod_down	%QO.0.0.0.5	
Air_Vent	%QO.0.0.1.0	
TranRod_down	%QO.0.0.1.1	

The program is written in ladder logic PLC programming language shown in Fig. 6 according to the flow chart shown before. After successful compilation, the program is fed to the PLC with RS-232 interface. After test and commissioning with output lamps and dummy loads, the PLC is ready for real time operation [1]. If any change in the process is required, only change in the ladder logic program and corresponding process variable declaration will provide necessary change in the operation which offers better flexibility and universality with this system [2].

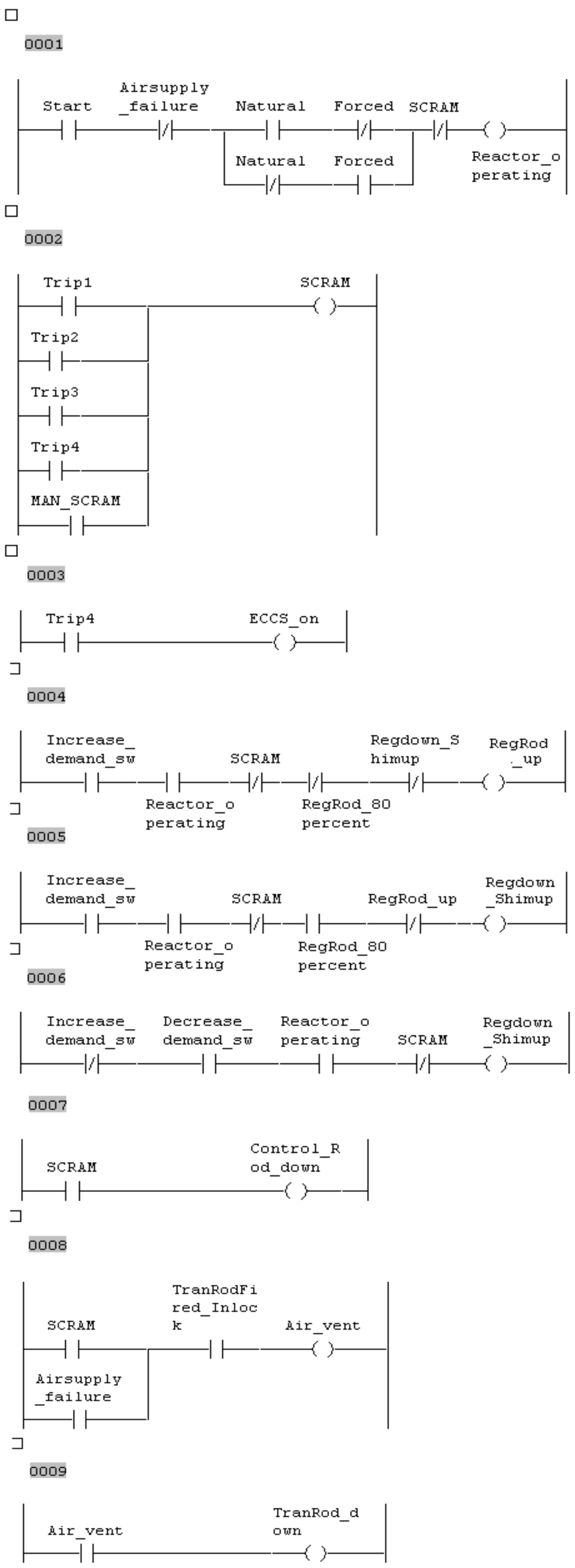

Fig. 6. Ladder logic PLC program.

VI. Comparison with Instrumentation by General Atomics

The present instrumentation by General Atomics for TRIGA research reactor consists of three major subsystems- the control rod drive and detector system, the data acquisition and signal processing system and control console system [8]. The data acquisition and signal processing system and control console system each have independent computers (DAC and CSC) for monitoring and control purposes with default programming. In general the complete system can be represented as the block diagram shown in Fig. 7, where the proposed system block diagram is in Fig. 8. The proposed control system will be better with following aspects compared to the control system by General Atomics [3]:

A. *Low Cost*

One single programmable logic controller is enough for control and operation.

B. *Correcting Errors*

With PLC control, any change in operation or sequence is as simple as retyping the logic. Correcting errors in PLC is extremely short and cost effective that is not possible with control system by General Atomics for the end user.

C. *Testing*

A Programmable Logic Control program can be tested and evaluated in a lab before its real time of operation. The program can be tested, validated and corrected which saves very valuable time.

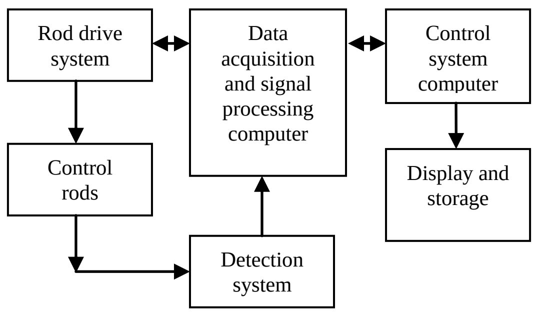

Fig. 7. Simplified research reactor control system block diagram of general atomics.

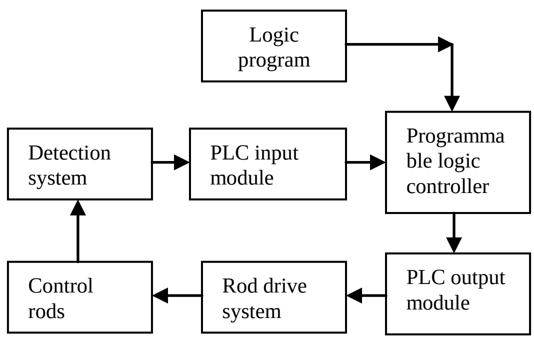

Fig. 8. Block diagram of proposed control system.

VII. Conclusion

The protection and control with minimum human involvement is the most important feature of operating a nuclear reactor. Several techniques can be implemented to control the nuclear reactor. The method that has to be used relies on various objectives like superior quality, increased efficiency and other such points depending upon the real time situation. The proposed operation and control feature will provide better flexibility in customization of operation and control with minimum effort. When running a PLC program, a visual observation on the screen of each operation at every point is also possible which will make troubleshooting and decision making really quick, easy and simple.

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