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Design of novel fractional order FPGA based reactor protection and safety controllers for ACP1000 nuclear power plant in LabVIEW

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KEYWORDS

FPGA

Protection Controllers

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ABSTRACT

In this research work, an advanced most modern ACP1000 Nuclear Power Plant is addressed. An enhanced fractional order model of ACP1000 nuclear power plant is adopted with an addition of protection and safety systems. The whole plant model is developed by using innovative hybrid technology of Visual Basic, LabVIEW, Fractional Order and Field Programmable Gate Array (FPGA). A reactor trip system is designed and modeled using FPGA technology in LabVIEW. Plant parameters are systematically modeled and panels are designed in LabVIEW for reactor protection controllers. Twenty one reactor trip controllers are designed and modeled based on complex digital logics using FPGA programming in LabVIEW. Two fractional order trip controllers are designed for over temperature protection and over power protection in LabVIEW. FPGA based safety controllers are designed for Engineered Safety Features (ESF) in LabVIEW. For enhanced model of ACP1000 nuclear power plant, 374 systems are modeled in modular form in Visual Basic Environment. Nine process controllers are configured in ANFIS framework in LabVIEW. In this research work, process controllers are used in conjunction with protection and safety controllers using FPGA. The parametric display of simulations is carried out in Visual Basic. The closed loop performance of proposed protection controllers is evaluated under reactor trip and turbine trip while that of safety controllers are evaluated under inadvertent opening of safety valves of pressurizer. Various parameters are simulated for severe transient conditions and the results are evaluated and validated against reference design data and Final Safety Analysis Report (FSAR) of ACP1000 nuclear power plant. All the results are well within the trip and safety systems design bounds under abnormal and severe operating conditions.

1. Introduction

This research work is encompassed on continuous and discrete FPGA based modeling, simulation, and analysis of ACP-1000 Nuclear Power Plant. In addition to process controllers; protection and safety controllers are addressed in detail. The dynamic simulation is carried out for abnormal and severe transient conditions.

In ACP1000 type Nuclear Power Plant, enhanced control oriented modeling is performed using protection loops and safety loops. In the original design of plant, these loops are implemented on microprocessor based Distributed Control System (DCS). In this research work, a reverse engineering approach is adopted as no design document is provided by the vendor, however some basic documents are provided for operational support.

ACP1000 nuclear power plant is basically the same design of HPR1000 nuclear power plant. Plant design data of all systems is obtained from [1]. All the process, control, protection and safety systems information is presented in [2]. ACP1000 nuclear power plant is a third generation three loop advanced PWR nuclear power plant. Plant systems and simulation aspects of three loop PWR have been reported in detail in [3]. Since ACP1000 is a load following power plant, therefore, detailed study has been conducted in [4]. ACP1000 reactor power control is accomplished by control rods and boron concentration control. Reactor power control using control banks in ACP1000 nuclear power plant has been thoroughly modeled in [5]. The primary circuit has been modeled in detail for large scale VVER type nuclear power in [6]. This model has been used for controller design. The primary systems of PWR has been modeled and transient analysis has been performed in [7]. Controllers have been synthesized for load following model of large AP1000 PWR plant in [8]. The secondary circuit of PWR based nuclear power plant has been analytically modeled in [9]. A comprehensive FO fractional order detailed model of ACP1000 NPP has been established with major emphasis on primary, secondary and balance of plant systems in [10]. ANFIS based robust intelligent controllers have been designed and optimized using LabVIEW as graphical programming tool.

Now, some research has been explored for nuclear power plants based FPGA technology. Fractional order integrators and differentiators are modeled and simulated on FPGA in [11]. A digital RRS for NPP has designed and modeled on FPGA in [12]. Reactor protection systems have been addressed in [13] for FPGA implementation for experimental nuclear power reactor. A PWR model covering safety aspects of control systems has been addressed in [14]. An intelligent modeling has been performed for safety management of nuclear power plant in [15]. Comprehensive modeling has been explored for PWR protection and accident monitoring loops in [16]. Accident analysis of inadvertent operation of residual heat removal system has been thoroughly studied in [17].

The suggested design is focused on novel continuous fractional order compensators oriented and discrete digital approach based on hybrid multi-programming platforms. Two visual programming platforms of Visual Basic and LabVIEW are adopted for state-of-the-art modeling and configuration of protection and safety controllers for the first time for ACP1000 nuclear power plant, using modern FPGA technology with improved, robust, very accurate and reliable performance.

2. Control Oriented Process Modeling

The comprehensive fractional order model of ACP1000 nuclear power plant developed in [10], is adopted as reference model. In this research work, the reference control oriented model is appended with the incorporation of protection and safety controllers. All the process controllers are ANFIS controllers configured in LabVIEW as reported in [10]. The model is capable of selecting any initial condition. Different malfunctions are designed such as reactor trip, turbine trip and excessive load flow. However, malfunctions pertaining transient scenarios are currently under design, testing and development phase. It is planned to include extensive verification against PSAR Safety Analysis Reports of ACP1000 nuclear power plant.

Currently, the proposed design is consisted of reactor kinetics model, reactor thermal hydraulics model, process controllers, protection controllers, safety controllers and severe accident model.

The new configuration is shown in Fig. 1.

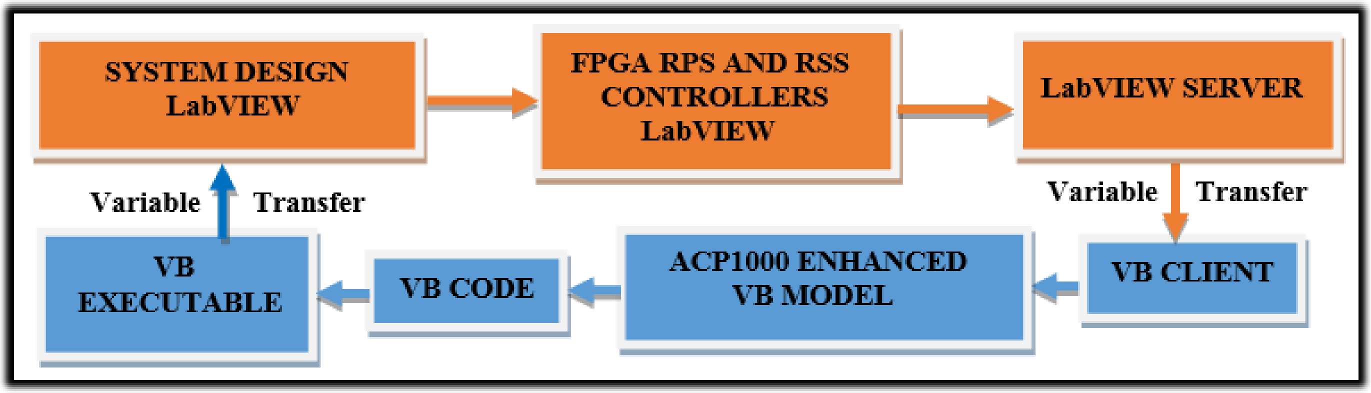


Fig. 1. Configuration of ACP1000 model and FPGA based protection (RPS) and safety (RSS) controllers

The framework of process, controllers and display system is shown in Fig. 2.

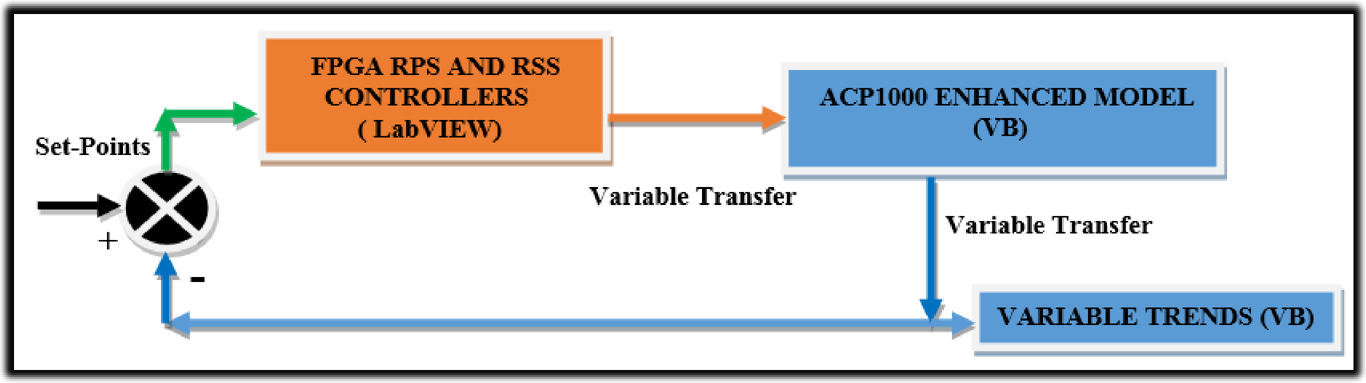


Fig. 2. Framework of process, controllers and display systems

The actuation logic of ACP1000 controllers with enhanced model is shown in Fig. 3.

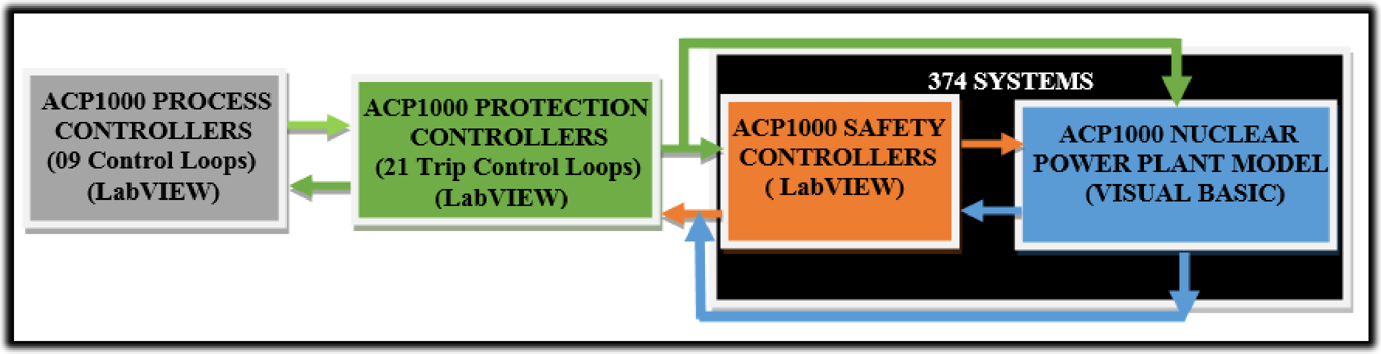


Fig. 3. Actuation logic of ACP1000 controllers

3. Protection and Safety Controllers

There are twenty one trips in the protection scheme. Nineteen are digital or discrete trips and two are compensator based. Compensator based trips do not have any set-points called Over Temperature Delta T (OTDT) and Over Power Delta T (OPDT). These are dynamic trips computed based on temperature measurements of hot and cold legs and reactor power that acts as inputs for rod control systems.

3.1 Fractional Order Compensators

The over temperature ΔT and over power ΔT protections are fractional order compensators based trips modeled as follows.

$$\Delta T_{setpoint} = \Delta T_0 \left[\begin{array}{l} K_1 + K_2(P - P_0) - K_3\left(\left(\frac{1+\tau_1 s^{\eta_{20}}}{1+\tau_2 s^{\eta_{20}}}\right)\left(\frac{1}{1+\tau_3 s^{\eta_{20}}}\right)T_{avg} - T_0\right) \\ + K_4\left(\frac{P_S}{P_{S_0}} - 1\right) - F_1(\Delta\phi) \end{array} \right] \quad (1)$$

$$\Delta T_{setpoint} = \Delta T_0 \left[\begin{array}{l} K_5 - K_6 \left(\frac{\tau_4 s^{\eta_{21}}}{1+\tau_4 s^{\eta_{21}}} \right) \left(\frac{1}{1+\tau_5 s^{\eta_{21}}} \right) T_{avg} - K_7 \left(\left(\frac{1}{1+\tau_6 s^{\eta_{21}}} \right) T_{avg} - T_0 \right) \\ - K_8 \left(\frac{1}{1+\tau_7 s^{\eta_{21}}} \right) \left(\frac{P_S}{P_{S_0}} - 1 \right) - F_2(\Delta\phi) \end{array} \right] \quad (2)$$

Where the symbols having their usual meanings.

3.2 FPGA Based Controllers

The purpose of reactor protection system to timely shuts down the plant and maintain the shutdown. It should be very reliable to ensure the plant availability. The reactor protection system has various digital logics for the actuation of process and reactor signals. The reactor protection system of ACP1000 nuclear power plant is a very huge system and has a very complex multivariable logic. In this research work, a part of RPS discrete logic diagram is shown in Fig. 4.

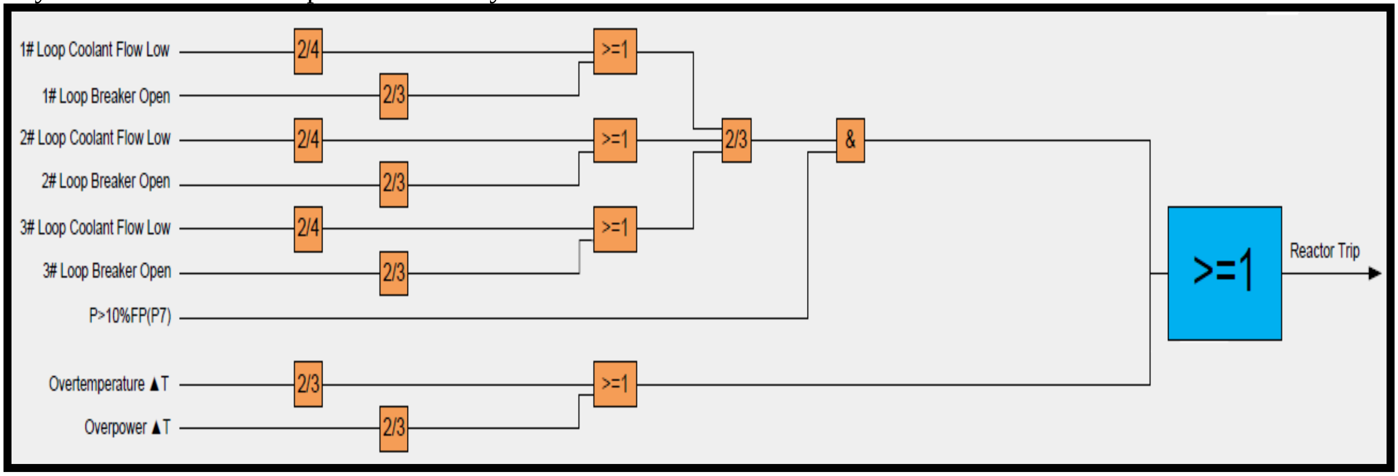


Fig. 4. Representative discrete logic diagram of RPS

The LabVIEW implementation diagram of 2/4 digital logic is shown in Fig. 5. The Fig. 5 is the practical representative hardware implementation of reactor protection system on FPGA in LabVIEW environment.

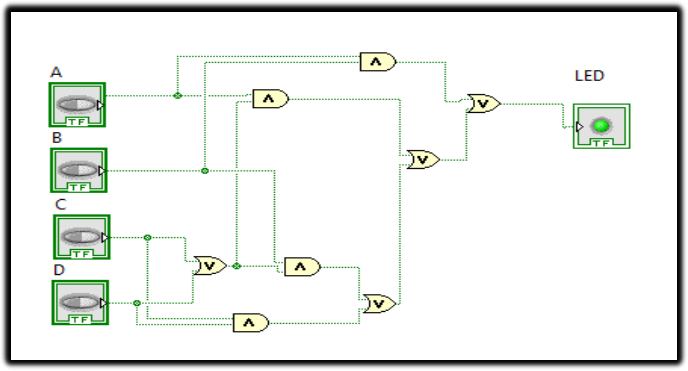


Fig. 5. 2 out of 4 voting logic design in LabVIEW

FPGA based system are more reliable, simple in implementation and most modern in technology.

3.3 Development of Digital Logics in LabVIEW

All the digital logics are designed using FPGA module of LabVIEW. The verification scheme of LabVIEW FPGA code is shown in Fig. 6.

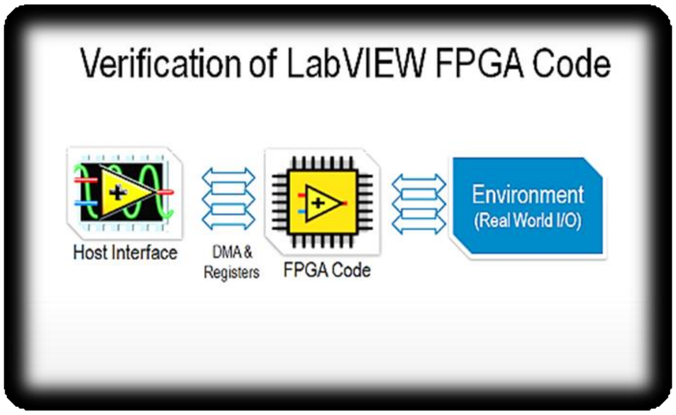
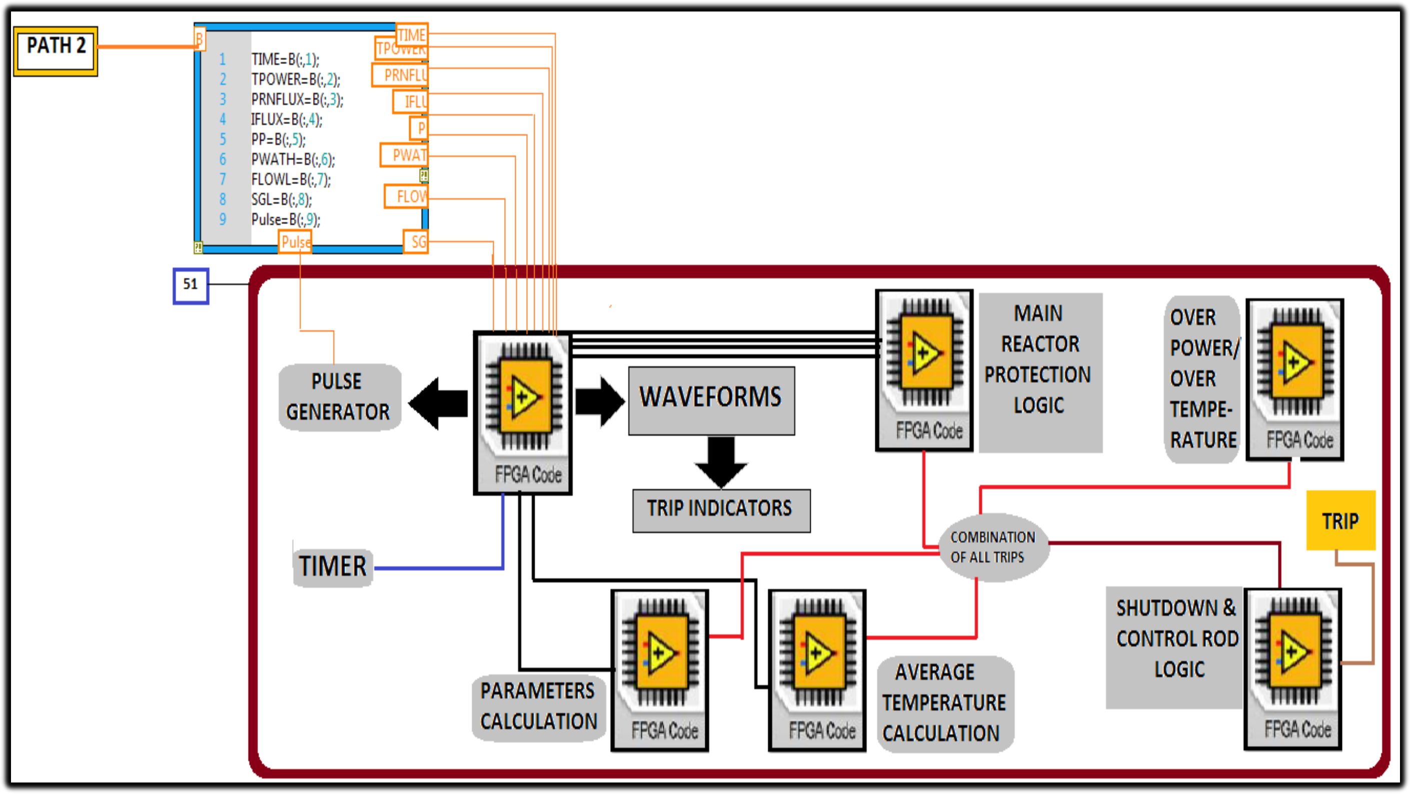


Fig. 6. Verification scheme of LabVIEW FPGA code

In this research work, various complex trip and safety actuation logics are designed in detail.

The overall FPGA based design of reactor protection system in LabVIEW is shown in Fig. 7.



```
TIME=B(:,1);
TPOWER=B(:,2);
PRNFLUX=B(:,3);
IFLUX=B(:,4);
PP=B(:,5);
PWATH=B(:,6);
FLOWL=B(:,7);
SGL=B(:,8);
Pulse=B(:,9);
```

Fig. 7. ACP1000 FPGA design of RPS controllers in LabVIEW

Similarly, the overall FPGA based reactor safety system is designed in LabVIEW. All the modeling flow and actuation logic is similar in design.

4. Development of Front Panels for Controllers

In Section-4, detailed front panel design of FPGA controllers is discussed. The plant either operates in normal condition or abnormal condition based on process conditions as shown in Fig. 8.

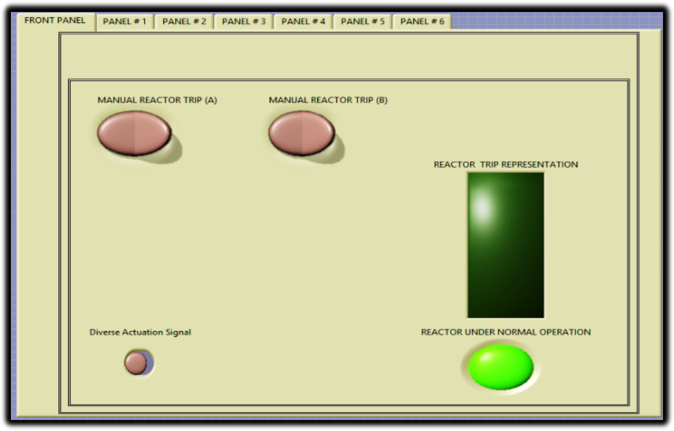


Fig. 8. ACP1000 normal and abnormal reactor operation display system in LabVIEW

The front panel is designed and portioned into six panels. These six panels represents the hardware implementation on FPGA in LabVIEW. The panel design for neutronics parameters is shown in Fig. 9.

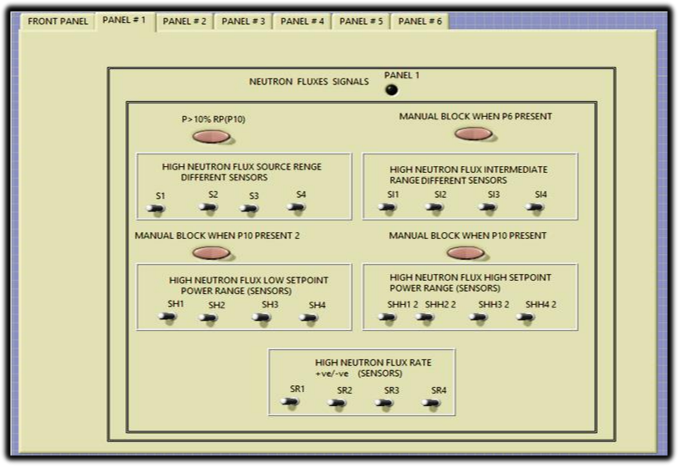


Fig. 9. ACP1000 neutronics parameters display system in LabVIEW

The panel design for excess temperature, power and level is shown in Fig. 10.

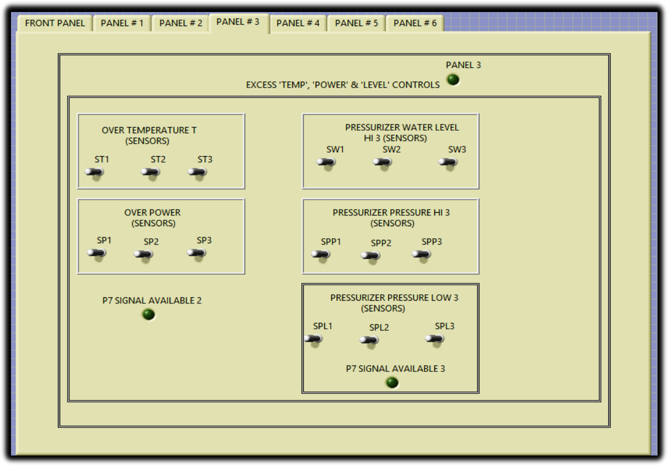


Fig. 10. ACP1000 excess temperature, power and level parameters display system in LabVIEW

The panel design for over temperature ΔT protection is shown in Fig. 11.

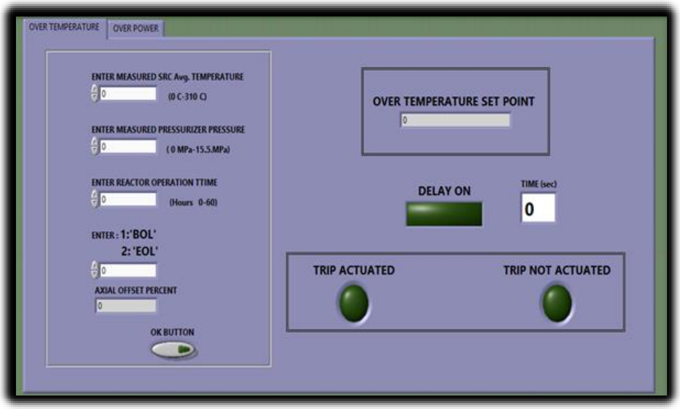


Fig. 11. ACP1000 over temperature parameter display system in LabVIEW

5. Evaluation of Protection Controllers

The proposed protection controllers are evaluated against reactor trip and turbine trip scenarios.

The performance of protection controllers is evaluated when the reactor is tripped from 100% RP, the dynamic behavior of various parameters of interest are shown in Fig. 12 to Fig. 15 respectively.

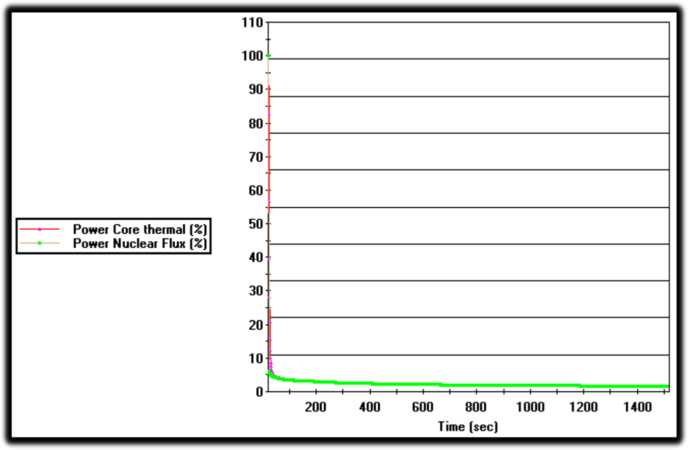


Fig. 12. Transient thermal and nuclear powers under reactor trip at 100% RP

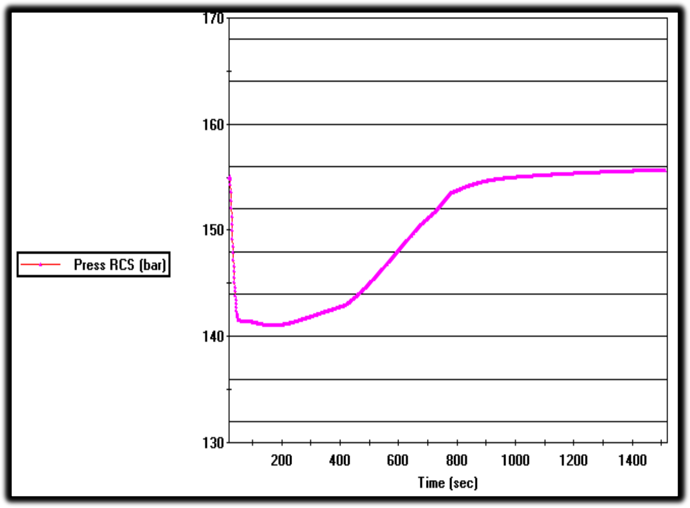


Fig. 13. Transient reactor coolant pressure under reactor trip at 100% RP

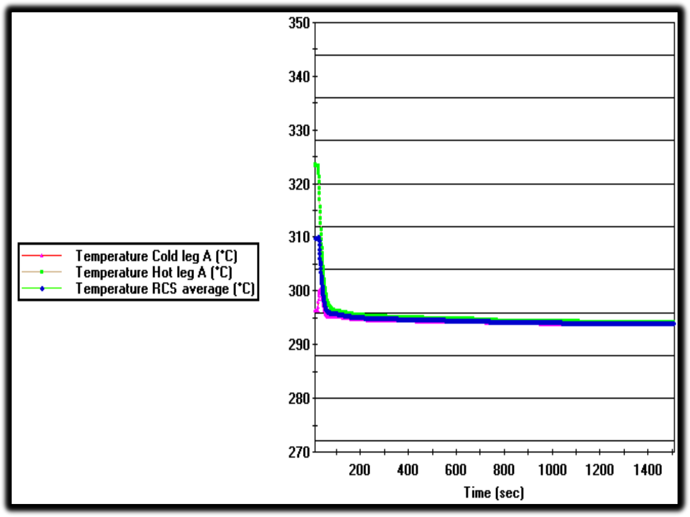


Fig. 14. Transient reactor coolant temperatures under reactor trip at 100% RP

Upon reactor trip, the reactor neutron flux and reactor thermal power closely tracks each other. The reactor coolant pressure initially decreases 141 bar and then stabilizes to 155 bar pressure. The cold leg, hot and average temperatures drops from their steady values to 294.5 °C. Rest of the all plant parameters are also found well within the design and safe limits.

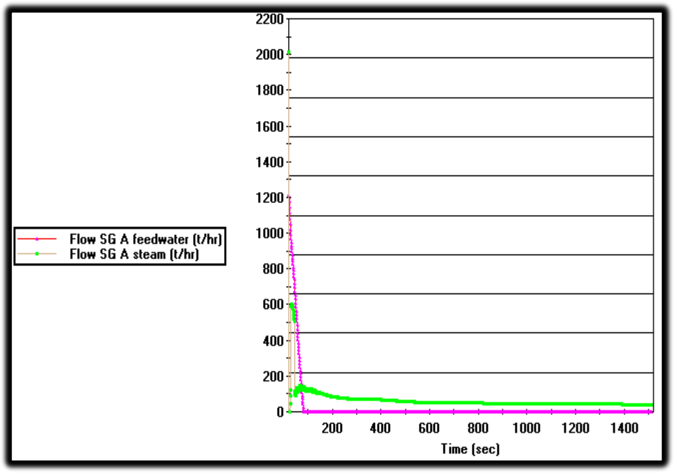


Fig. 15. Transient feed-water and steam flows under reactor trip at 100% RP

The performance of protection controllers is evaluated when the turbine is tripped from 100% RP with pressure control system is available, the dynamic behavior of various parameters of interest are shown in Fig. 16 to Fig. 17 respectively.

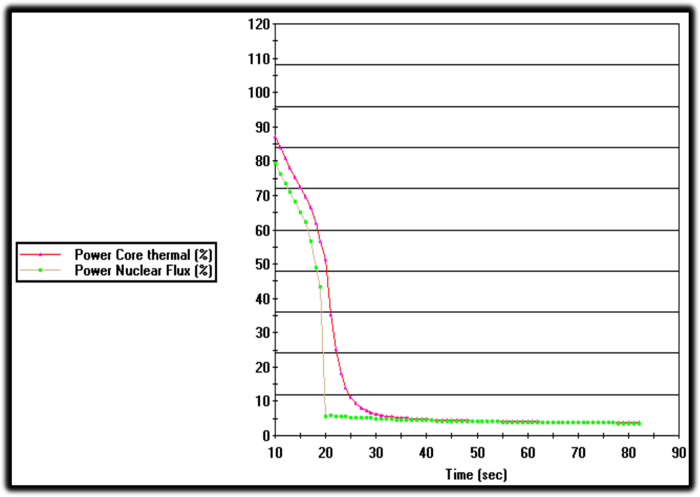


Fig. 16. Transient thermal and nuclear powers under turbine trip with pressure control system available at 100% RP

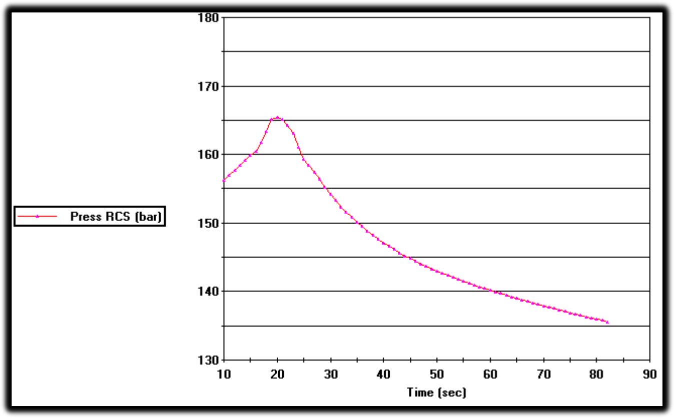


Fig. 17. Transient reactor coolant pressure under turbine trip with pressure control system available at 100% RP

Upon turbine trip with pressure control system available, the reactor neutron flux and reactor thermal power closely tracks each other. The reactor coolant pressure initially increases 165.5 bar then decreases and stabilizes to 155 bar pressure. The cold leg, hot and average temperatures drops from their steady values to 135.5 °C. Rest of the all plant parameters are also found well within the design and safe limits.

The optimized parameters of ΔT based reactor trips are tabulated in Table 1.

Table 1

Design Parameters compensator based trips

Parameter	Value
η_{20}	1.13
η_{21}	1.27

6. Evaluation of Safety Controllers

In this scenario, following assumptions are involved.

1. Steam generator relief valve logic is not modeled in the FPGA design.
2. The actuation logic of SG safety valves controller with set-point set point of 85 bar credit is not modeled in the FPGA design.
3. Main feed water is terminated manually at the time of turbine trip, with no credit taken for auxiliary feed water to mitigate the consequences.
4. Steam generator safety valves is assumed open at 88.9 bars.

In this scenario, following limitations are involved.

1. In PSAR and FSAR, it is assumed that at EOC, moderator temperature coefficient (MTC) is 0.54 (Δk/k) / (g/cm3).
2. Doppler fuel coefficient (DFC) is -11.42 pcm / FP%.

The proposed safety controllers are evaluated against malfunctioning of safety valves of pressurizer.

The Condition II event is analysed by using the proposed model in this section.

The purpose of this proposed design is to describe the following.

1. DNBR must stay above the limit value.
2. Primary and secondary pressure must not exceed Reactor coolant system limit.

Reactor trip occur on any of the over temperature ΔT or low pressurizer pressure.

The results of the analysis show that the DNBR does not decrease below the limiting value with some modelling restriction. The pressure of reactor coolant system remains much below 110% of the design value. Thus, no core damage or impairment of reactor coolant system would occur for this scenario.

The performance of safety controllers is evaluated when the safety valves of pressurizer are inadvertently opened when the plant is operating at 100% RP, the dynamic behavior of various parameters of interest are shown in Fig. 18 to Fig. 22 respectively.

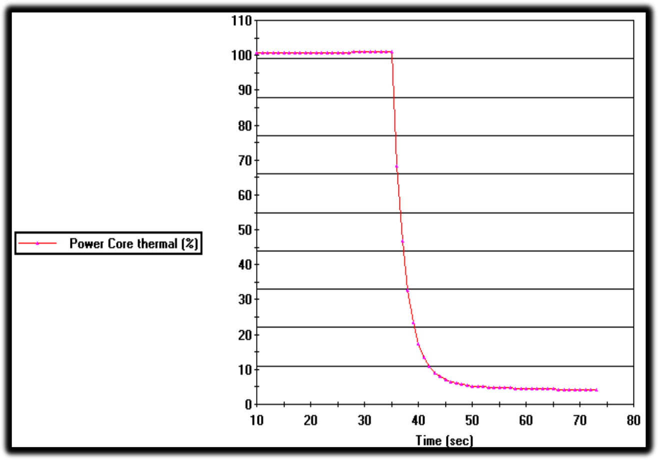


Fig. 18. Transient reactor thermal power under inadvertent opening of pressurizer safety valves

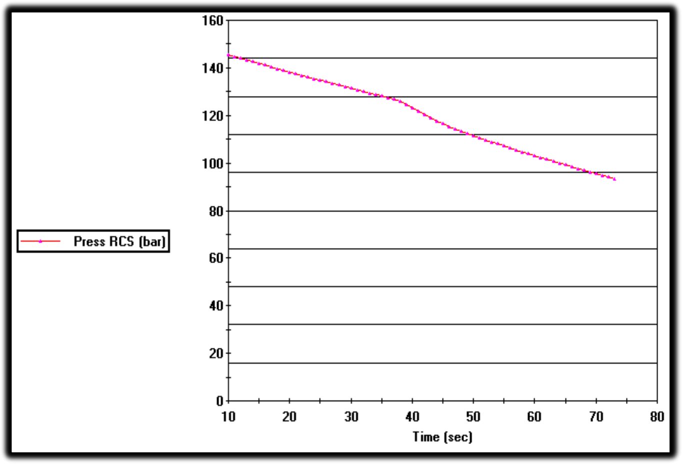


Fig. 19. Transient reactor coolant pressure under inadvertent opening of pressurizer safety valves

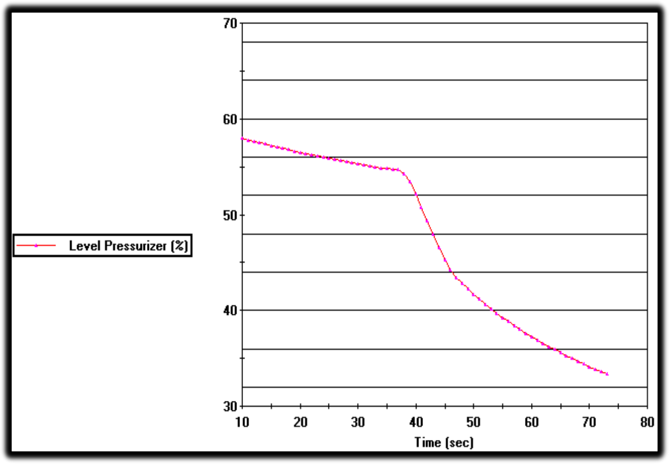


Fig. 20. Transient pressurizer level under inadvertent opening of pressurizer safety valves

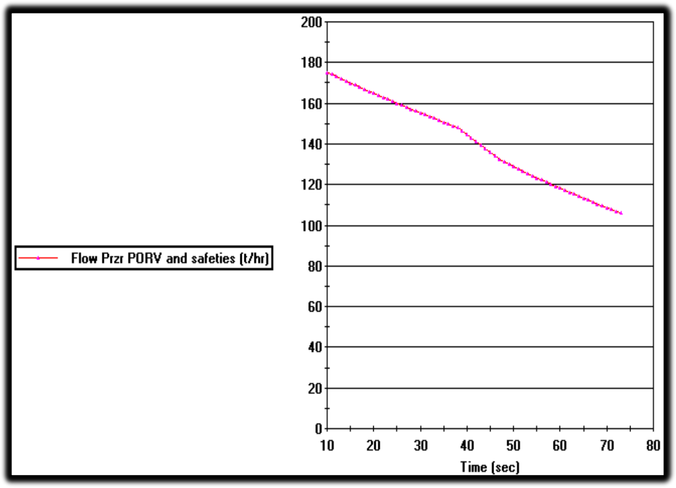


Fig. 21. Transient pressurizer PORV flow under inadvertent opening of pressurizer safety valves

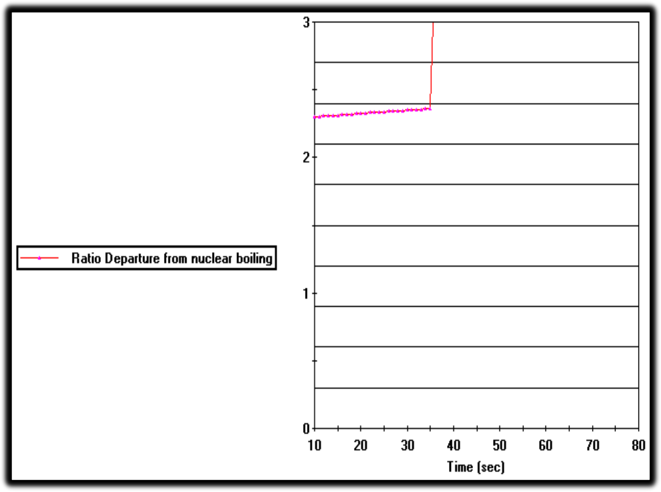


Fig. 22. Transient departure from nuclear boiling under inadvertent opening of pressurizer safety valves

The simulated data is in excellent agreement with the reference data of FSAR.

The performance comparison of microprocessor and FPGA based reactor protection system is shown in Fig. 23.

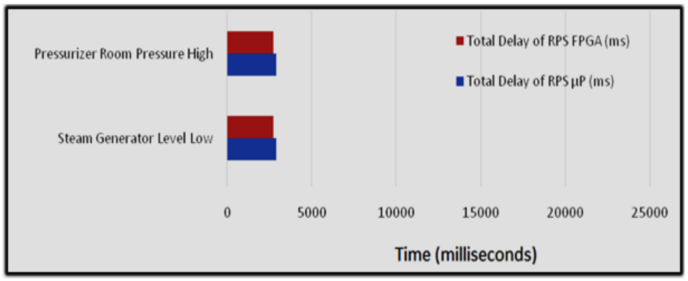


Fig. 23. Comparison of total delay between FPGA and microprocessor based RPS

7. Performance Analysis

In this section, performance of designed controllers are analyzed. The results of simulated and reference data are compared in Table 2.

Table 2

Comparison of Simulated and Reference Data under abnormal and severe conditions

Scenario	Design Variables	Reference Data	Simulated Data	Absolute Error
Reactor Trip under 100% RP at 1500 Sec	Reactor Thermal Power (%)	1	1	0
	RCS Pressure (bar)	155	154.2	-0.2
	RCS Average Temperature (°C)	295	294.5	-0.5
	Reactor Coolant Pressure (bar)	155	154.95	-0.05
	Feed Water Flow (t/hr)	0	0	0
	Steam Flow (t/hr)	2	4	2
Turbine Trip under 100% RP at 80 Sec	Reactor Thermal Power (%)	4	4.5	+0.5
	RCS Pressure (bar)	135	135.5	-0.2
Opening of Safety Valves	Reactor Thermal Power (%)	4	4.5	+0.5
	RCS Pressure (bar)	95	94.5	-0.5
	Pressurizer Level (%)	33	33.5	-0.5
	PORV Pressurizer Flow (t/hr)	105	104.75	-0.25
	DNBR	3	3	0

The overall the delay of FPGA based reactor protection system is improved as compared to microprocessor-based reactor protection system. Hence, it is proved that successful realization has been made.

A comparison table is prepared to prove the novelty or uniqueness of the FPGA based design over the microprocessor based existing design as shown in Table 3.

Table 3

Comparison of FPGA based RPS and RSS Controllers with Microprocessor Based Existing Controllers

FPGA based RPS and RSS Controllers	Microprocessor Based RPS and RSS Controllers
Less complex implementation logic	More complex implementation logic
Powerful graphical performance	Line by line coding scheme
Enhanced life	Less life before replacement
Excellent GUI	Difficult user interface
Easy simulation platform	Difficult simulation platform
Easy modifications in logic design	Difficult modification scheme
It is cheaper	It is expensive
Less execution delays	More execution delays

8. Conclusions

The fractional order model of ACP1000 type nuclear power plant has been enhanced with protection and safety systems in this research work. The enhanced model has continuous and discrete models and functions. The closed loop is configured with process controllers, protection controllers and safety controllers. FPGA based innovative and modern technology has been adopted for complex actuation logic and design in LabVIEW. The proposed scheme has been tested thoroughly for reactor trip, turbine and inadvertent actuation of safety valves and proved better than microprocessor based technology. The results have been found in excellent agreement with FSAR benchmark results under the adopted severe transient conditions. The proposed model and controllers have been proved a first step towards safety and accident analysis for ACP1000 nuclear power plant. Other Design Basis Accidents and beyond design basis accidents can be modeled, simulated and studied in future with some modifications in modeling scheme.

9. Acknowledgements

The support of the Pakistan Atomic Energy Commission, Chashma Centre of Nuclear Training and Information System Division of KNPGS is gratefully acknowledged.

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