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PCTRAN Westinghouse AP1000 Power Control of Pressurized Water Reactor Using Simulink of MATLAB

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Abstract

This paper introduces the simulation, and controls using Simulink of MATLAB for PCTRAN (Personal Computer Transient Analysis) of the power control system (PWR) type pressurized water reactor of PWR WESTINGHOUSE AP1000. The power controller model produces mathematical model description in nonlinear relation form in Simulink of MATLAB which is an important and popular program used at most universities for education. The power controller is described by a block diagram in this paper and some details introduce to clearly understand the work function. The results of action control compared with the PCTRAN programme in modes of automatic and manual control.

Keywords

Turbine Leading Mode, Reactor Leading Mode, Rod Speed Program, Rod Control Position, Turbine Load Power

1. Introduction

The plant power control function of a PWR type NPP (Nuclear Power Plant) is performed by two, separate control modes—one for the turbine generator called "turbine leading"; and the other one for the reactor called "reactor leading". These two distinct modes of overall plant control can be switched between other and are well coordinated for plant startup, shutdown, power operations of all kinds, and plant upset conditions [1]. The turbine leading mode is selected when a typical PWR (Pressurized Water Reactor) is operating normally, and the reactor leading mode is selected when a typical BWR (Boiling Water Reactor) is operating normally [2]. The Pressurized Water Reactor PWR has sophisticated automatic control systems. The control rod system and soluble boron control the core neutron flux. The Chemical and Volume Control System (CVCS) controls the primary coolant inventory and water chemistry. On the secondary side, steam output is controlled by the turbine control valve and steam dump system. The steam generator water level is controlled by the feedwater system. During the automatic control mode, they work in a synchronized way so that transition to stabilized conditions will be achieved smoothly [3]. However, the reactor leading mode is usually used in Boiling Water Reactors (BWRs) and not in PWRs, except during the reactor start-up operations [4].

This paper concerns and focuses on the control design method of Turbine leading mode in AP1000 Westinghouse reactor of PCTRAN. The power controller described by block diagram in this paper is accomplished in Simulink of MATLAB. The output response of this controller (ROD control Position) is approved and compared with the output (RODPOS) of PCTRAN. The reactor leading mode is not used in PCTRAN AP1000. Manual movement of Rod control work is the same as reactor leading mode, because the manual movement of rod control is affecting directly on the reactor power. The output response in manual movement is the Turbine Load Power (TBLD). The turbine load power in manual movement is calculated and compared with TBLD of AP1000 PCTRAN. The simulation is performed during power operation transients and Trip (shutdown).

2. Reactor Power Controller of PWR (Turbine Leading)

This controller of which the diagram is shown in **Figure 1** type turbine leading gives the reactor control rod speed when the controller works automatically. The reactor power is adjusted indirectly because this controller in fact controls the reactor average temperature, calculated as the mean value of the cold and hot leg temperature. This value is delayed, and lead/lag compensated. The transfer function the lead/lag compensation is equivalent to the diagram of **Figure 1** which gives the transfer function in terms of a simple integration (with time constants), and multiplication with lag measurement of time constant. The setpoint for the average temperature is calculated as a piecewise linear function of relative HP-turbine inlet pressure (which is a measure of turbine power) and further sent through first order lag compensator [3] [5].

A correction power mismatch between relative Turbine Load Power and nuclear power is made. The equivalent diagram for the mismatch transfer function is shown in **Figure 1** in terms of simple integration and multiplication. The power mismatch signal is sent through nonlinear and variable gains [3] [5]. The error signal, corrected for power mismatch is transformed into control rod speed in the rod speed program function of which the graph is shown in **Figure 2** below [3] [5] [6]. The outputs of speed program which is indicate the rod control position after integrating and program multiply with dimensionless factor to

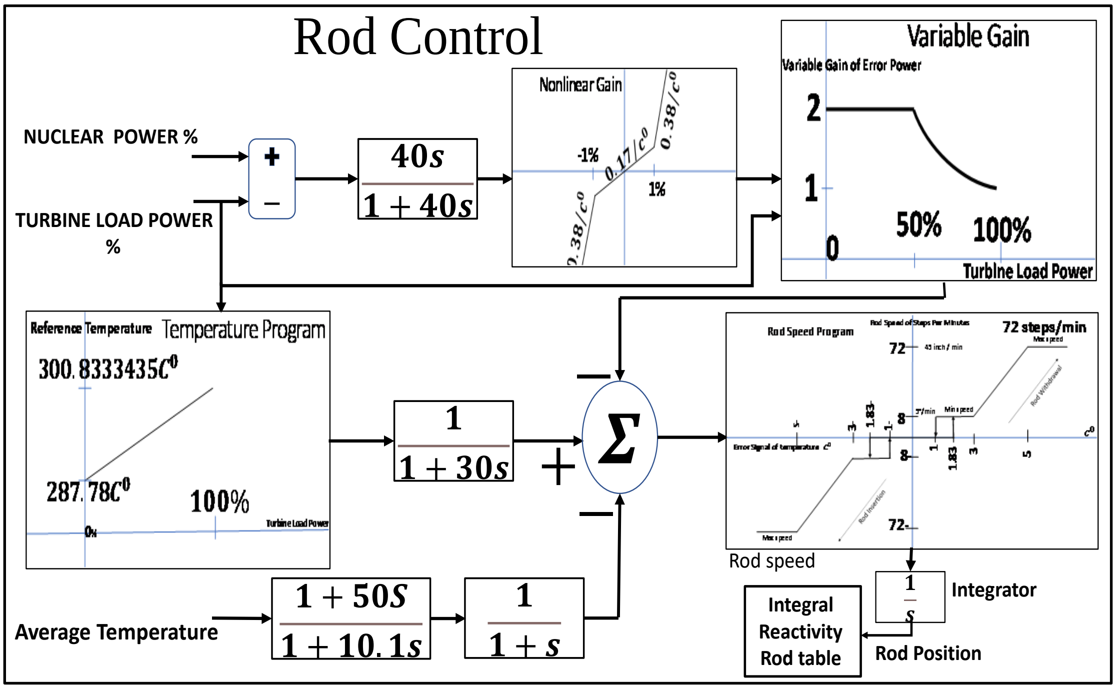


Figure 1. Rod control (Turbine Leading Mode).

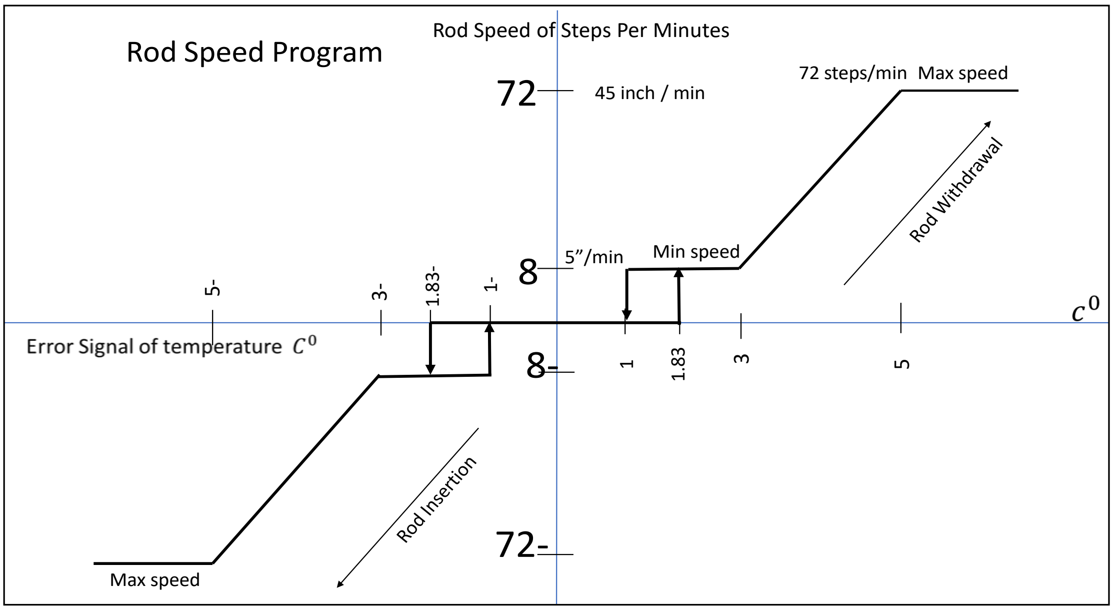


Figure 2. Rod speed program.

convert results to percentage of its position. The rod position according to table it will be found the reactivity rod function.

3. Rod Speed Program Function

A deadband of ±1.83˚C, which includes a 0.83˚C lock-up, is employed to eliminate continuous rod stepping and bistable chattering. The lock-up can be explained by referring to **Figure 2** and examining a signal for rod withdrawal.

When the total error signal reaches +1.83˚C, the output from the reactor control unit demands the minimum rod speed to return Tavg to program. As the rods step out, Tavg increases, reducing the total error signal. When the total error signal reaches +1˚C, the unit turns off, stopping rod motion.

This 0.83˚C difference between starting and stopping rod motion prevents the bistable from chattering (turning on and off continuously), which is performed by relay block function of Simulink MATLAB. Relay block parameters are set, of switch on point at 1.83, and switch off point at 1 of error signal in positive direction. As same as in negative direction parameters are set switch on point at 1- and switch off point at 1.83- of error signal, therefore output when on at 0, and output when off at 1 (reverse defaults). Rod speed is determined by the total error signal. For small error signals, ±1.83˚C to ±3˚C, the reactor control unit produces an output demanding a minimum speed of eight steps per minute. This minimum rod speed is based upon a minimum response of the rod control system for small errors generated by this system. A slow speed prevents excessive movement of the rods which could cause a temperature overshoot. Temperature overshoots could cause hunting by the rods, *i.e.*, excessive rod movement. As the temperature error signal increases from ±3˚C to ±5˚C, the rod speed program enters a proportional speed region. This region calls for 32 steps/min/˚C. This gain is selected to be consistent with the need for increased rod motion to limit transient temperature overshoot while, at the same time, preventing overcompensation and temperature oscillations. With an error of 5˚C or greater, the rod speed programmer of the reactor control unit generates a maximum rod speed of 72 steps/min. The maximum rod speed is based upon a maximum response to a large error signal and upon the physical limitations of the rod drive mechanism, with the latter being the limiting factor [6].

4. Manually Rod Control Moving

In reactor leading mode (or turbine following mode), the plant's operator specifies the reactor power output target (control rods demand) and the turbine power output changes accordingly [4]. The rod speed is adjustable between 8 and 72 steps/min. The speed normally selected for manual operation is 48 steps/min [6]. In the simulator displays the maximum rod speed is 10%/s. In reactor leading mode (or turbine following mode), the plant's operator specifies the reactor power output target (control rods demand) and the turbine power output changes accordingly. The user will change the rod position and rod speed manually and understand how they affect the reactor and turbine power outputs [4].

5. Turbine Load Power (TBLD) When the Rod Control Manually Moved

When the Rod control is moved manually, the reference power of turbine load changes accordingly. The plant's operator specifies the reactor power output target (control rods demand) and the turbine power output changes accordingly

[4]. The rod control system constantly compares the current rod position and the specified rod demand. When there is a difference between them, this system generates a signal which moves the control rods at the operator's specified rate to introduce positive or negative reactivity. Furthermore, change in thermal power alters the heat transfer in the SGs, which changes the amount of steam generation in the secondary side of the SGs. This, in turn, increases or decreases the pressure of the SGs [4]. The Turbine Load Power is a function of thermal core power as a found from results of PCTRAN program but quantized at several time when Rod control moved manually. Turbine load power is changing according to thermal core power as shown in Figure 3, which is used to control pressure first stage high pressure of turbine, and steam generator.

6. Protection and Control System

The function of the protection system is to protect the three barriers between the fuel and the public: fuel cladding, reactor coolant vessel and containment. The Control system function is to provide the changes needed to keep the operating parameters [2]. The purpose of the protection system is to provide automatic protection against unsafe operation conditions during steady state operation and power transients [2]. The Reactor Protection System (RPS) shuts down a PWR power plant when certain safety system settings, or setpoints, are reached or when commanded by the operator [5]. Whenever the reactor's operating parameters exceed certain defined safety limits; all control rods are dropped by gravity into the core to suppress the chain reactor. The following trip functions are typical for a PWR [3]:

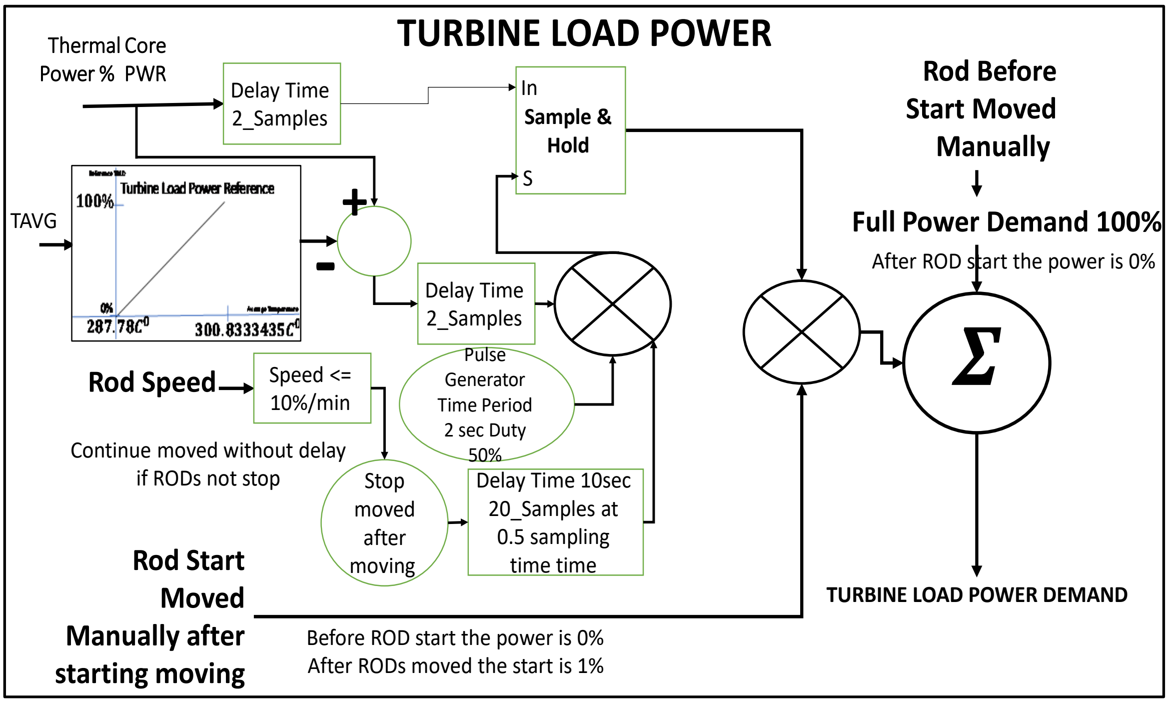


Figure 3. Turbine load power demand function (Manual Control Mode).

- High reactor pressure and/or pressurizer water level;
- High neutron flux;
- Over-temperature delta-T;
- Over-power delta-T;
- High RC outlet temperature;
- Low reactor pressure and/or pressurizer water level;
- Low SG water level;
- Low loop or core flow;
- Containment pressure.

7. Operating Modes of Control

Rods control modes, this control moves the rods in order to maintain average temperature if turbine leading mode is selected. If reactor leading mode is chosen, this control moves the rods in order to keep the reactor power demanded, and manual control moves the rod control manually to keep the reactor power demanded. Figure 4 shows these modes related together [2]. In a typical PWR uses turbine leading mode, or manual movement to control the reactor power. Reactor leading mode is accomplished as same as manual control movement in this paper.

8. Simulation and Results

This control moves the rods automatically in order to maintain average temperature if turbine leading mode is selected. The turbine leading mode is selected by using power demand and demand rate at turbine section. If reactor leading mode is chosen, this control moves the rods manually in order to keep the reactor power demanded. The reactor leading mode is selected by using rod demand and Rod speed at reactor core section. In this simulation uses run time as 900 seconds' period. The PCTRAN run time simulation will be 300 second only. The

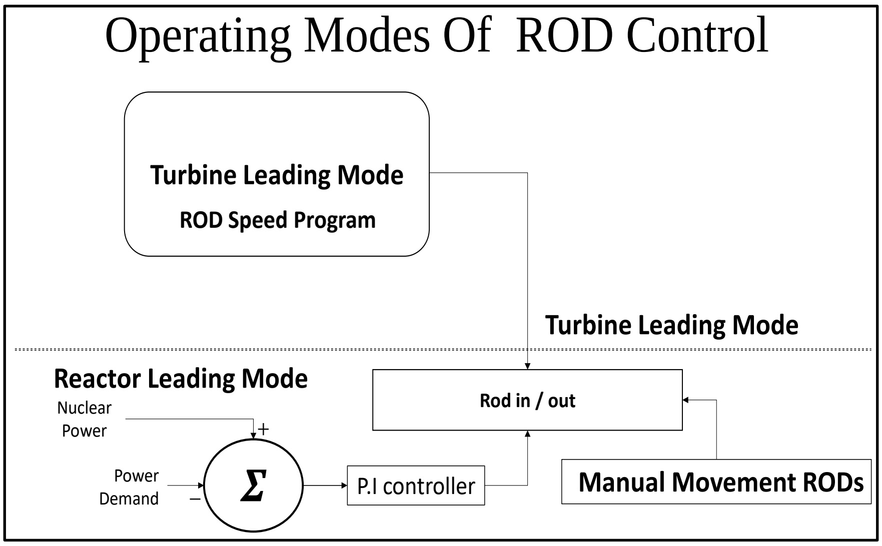
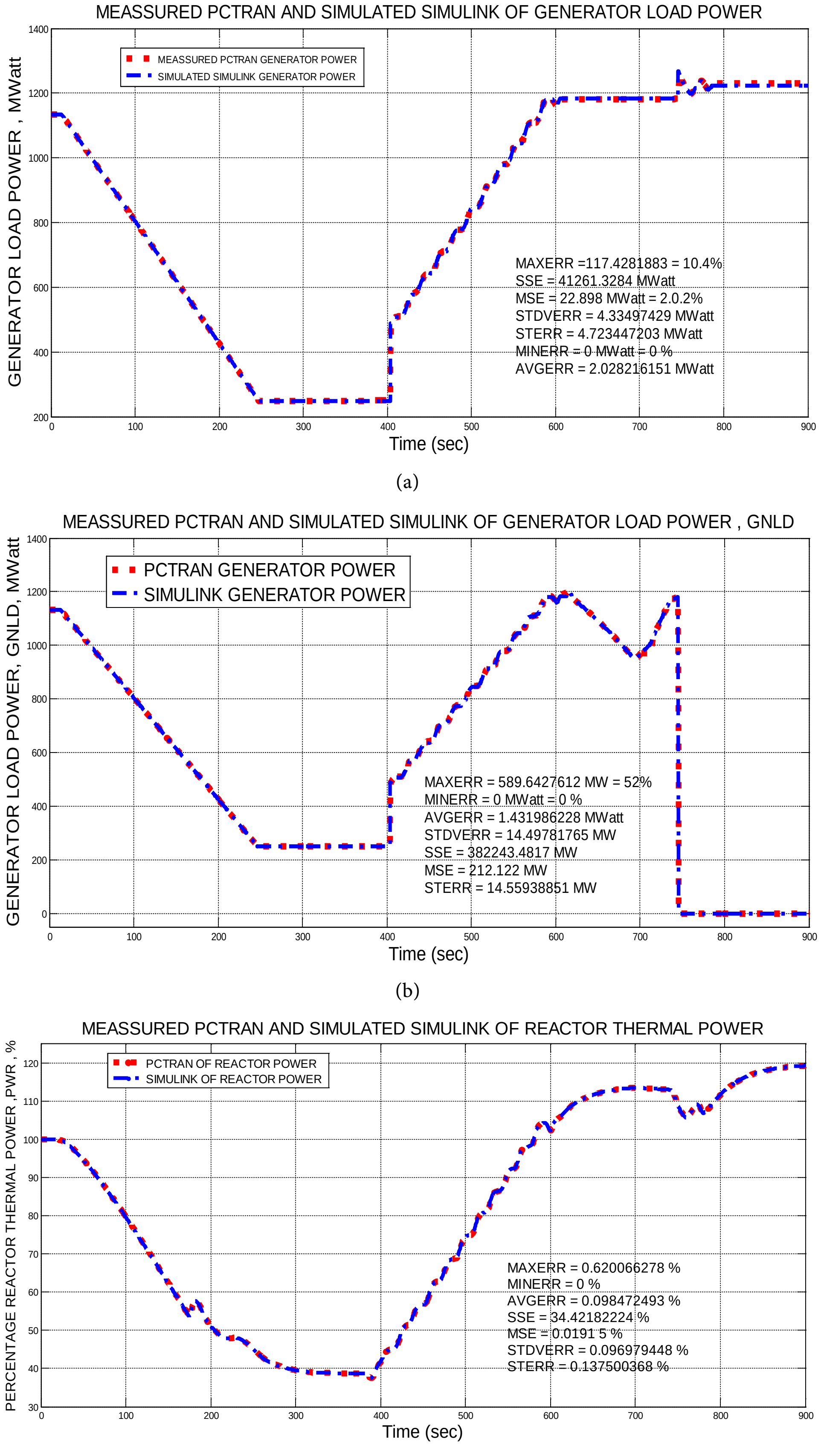


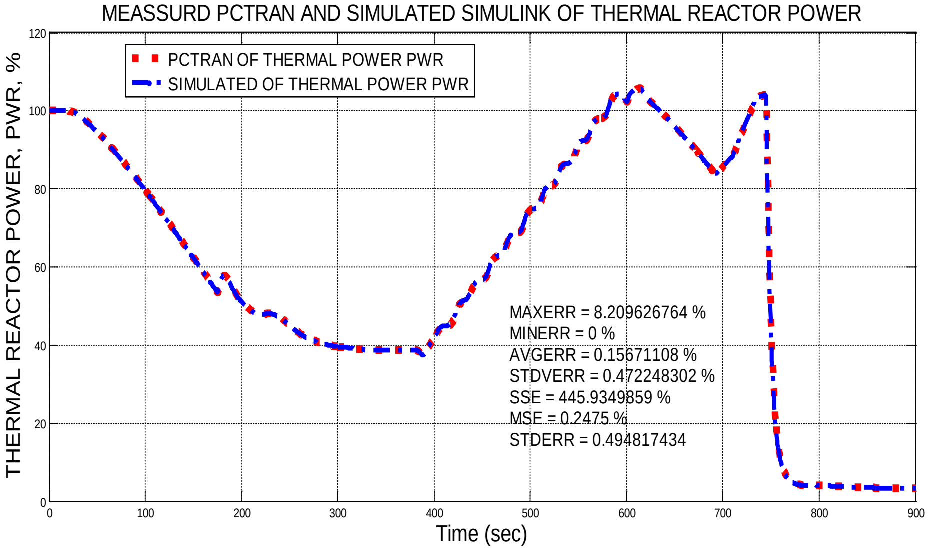
Figure 4. Operating modes of control rod.


MEASSURED PCTRAN AND SIMULATED SIMULINK OF GENERATOR LOAD POWER
GENERATOR LOAD POWER , MWatt
Time (sec)
MEASSURED PCTRAN GENERATOR POWER
SIMULATED SIMULINK GENERATOR POWER
1400
1200
1000
800
600
400
200
0
100
200
300
400
500
600
700
800
900
MAXERR =117.4281883 = 10.4%
SSE = 41261.3284 MWatt
MSE = 22.898 MWatt = 2.0.2%
STDVERR = 4.33497429 MWatt
STERR = 4.723447203 MWatt
MINERR = 0 MWatt = 0 %
AVGERR = 2.028216151 MWatt
MEASSURED PCTRAN AND SIMULATED SIMULINK OF GENERATOR LOAD POWER , GNLD
GENERATOR LOAD POWER, GNLD, MWatt
PCTRAN GENERATOR POWER
SIMULINK GENERATOR POWER
MAXERR = 589.6427612 MW = 52%
MINERR = 0 MWatt = 0 %
AVGERR = 1.431986228 MWatt
STDVERR = 14.49781765 MW
SSE = 382243.4817 MW
MSE = 212.122 MW
STERR = 14.55938851 MW
MEASSURED PCTRAN AND SIMULATED SIMULINK OF REACTOR THERMAL POWER
PERCENTAGE REACTOR THERMAL POWER ,PWR , %
PCTRAN OF REACTOR POWER
SIMULINK OF REACTOR POWER
120
110
100
90
80
70
60
50
40
30
MAXERR = 0.620066278 %
MINERR = 0 %
AVGERR = 0.098472493 %
SSE = 34.42182224 %
MSE = 0.0191 5 %
STDVERR = 0.096979448 %
STERR = 0.137500368 %

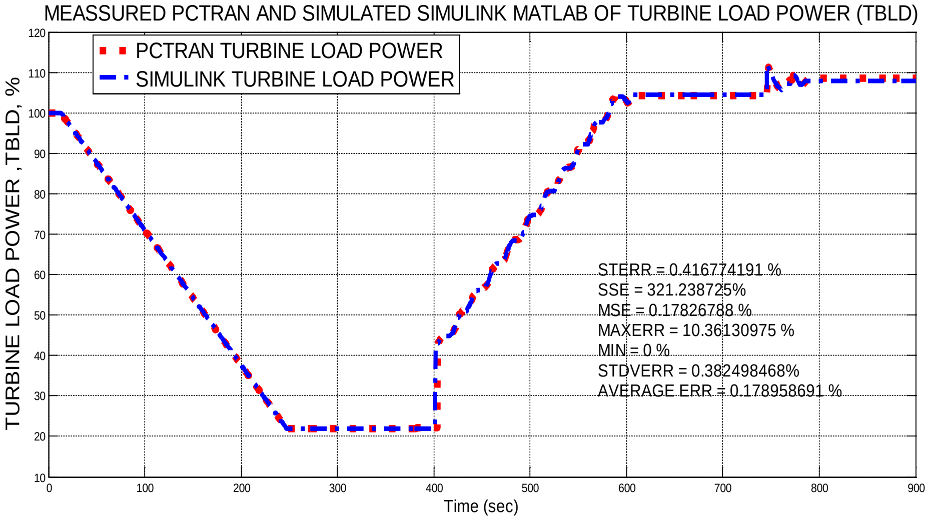
(a)

(b)

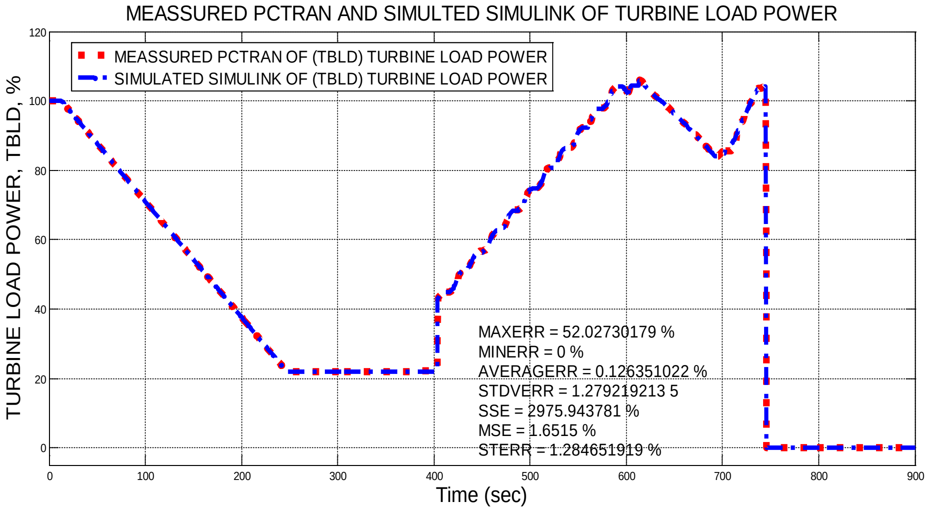
(c)


MEASSURD PCTRAN AND SIMULATED SIMULINK OF THERMAL REACTOR POWER
PCTRAN OF THERMAL POWER PWR
SIMULATED OF THERMAL POWER PWR
THERMAL REACTOR POWER, PWR, %
Time (sec)
0
20
40
60
80
100
120
0
100
200
300
400
500
600
700
800
900
MAXERR = 8.209626764 %
MINERR = 0 %
AVGERR = 0.15671108 %
STDVERR = 0.472248302 %
SSE = 445.9349859 %
MSE = 0.2475 %
STDERR = 0.494817434

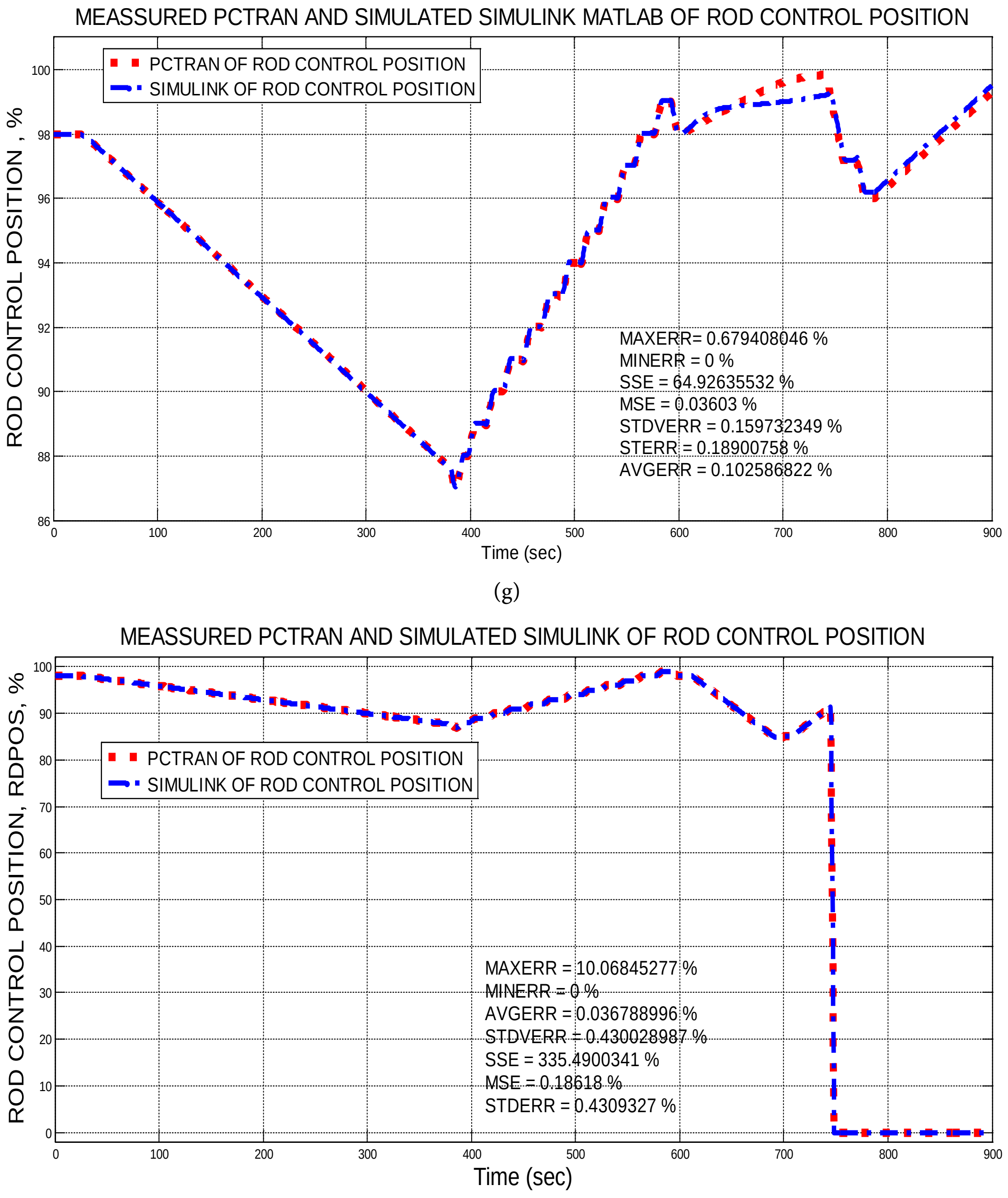
(d)


MEASSURED PCTRAN AND SIMULATED SIMULINK MATLAB OF TURBINE LOAD POWER (TBLD)
PCTRAN TURBINE LOAD POWER
SIMULINK TURBINE LOAD POWER
TURBINE LOAD POWER ,TBLD, %
Time (sec)
10
20
30
40
50
60
70
80
90
100
110
120
0
100
200
300
400
500
600
700
800
900
STERR = 0.416774191 %
SSE = 321.238725%
MSE = 0.17826788 %
MAXERR = 10.36130975 %
MIN = 0 %
STDVERR = 0.382498468%
AVERAGE ERR = 0.178958691 %

(e)


MEASSURED PCTRAN AND SIMULTED SIMULINK OF TURBINE LOAD POWER
MEASSURED PCTRAN OF (TBLD) TURBINE LOAD POWER
SIMULATED SIMULINK OF (TBLD) TURBINE LOAD POWER
TURBINE LOAD POWER, TBLD, %
Time (sec)
0
20
40
60
80
100
120
0
100
200
300
400
500
600
700
800
900
MAXERR = 52.02730179 %
MINERR = 0 %
AVERAGERR = 0.126351022 %
STDVERR = 1.279219213 5
SSE = 2975.943781 %
MSE = 1.6515 %
STERR = 1.284651919 %

(f)



(g)

(h)

Figure 5. (a) Generator load power normal operation, mega watts; (b) Generator load power trip operation, mega watts; (c) Thermal reactor power normal operation, percentage %; (d) Thermal reactor power trip operation, percentage %; (e) Turbine load power normal operation, percentage %; (f) Turbine load power trip operation, percentage %; (g) Rod control position normal operation, percentage %; (h) Rod control position trip operation, percentage %.

data are collected three time including initial conditions each run time. This total period of run time is divided in two periods. The first period is automatic control of rods (turbine leading mode), the second period is manually control of rod, the reactor leading mode is not accomplished, but considering that manual control of rods is the same as the reactor leading mode approximately at after 400 second of period. The full period is accomplished by three times over two stages once for normal operation, and other for a trip at before end of last 300 second period.

The thermal reactor power (PWR) is calculated from measured values from PCTRAN referred to PCTRAN manual, and a paper of Spatial Reactor Dynamics [3] [7]. In each period mode inputs and outputs data are illustrated in **Figure 1**, and **Figure 3**. The generator load power is equal to percentage turbine load power multiply by 1133.333 MWatt.

The results of simulation are illustrated in the following figures from **Figures 5(a)-(h)**.

9. Conclusions

The automatic control (Turbine Leading Mode) and manual rod control movement mode control are implemented in this paper. The simulation is accomplished by Simulink of MATLAB during a period run time of 900 seconds. The first interval of period run time is 400 seconds, turbine leading mode is selected, and the second interval time manual control is selected. The first running stage runs time of 900 seconds for power operation transient wide range decrease from 100% to 25% of power operation transient, and then increases manually. The second running stage for power operation with a trip occurs before the end of running time. Results from simulation are plotted and compared. The statistics calculations are computed and put in graphs. **Figure 5(a)** result points to minimum error of 0% and the maximum error is 10.4% during power transient. **Figure 5(b)** shows result maximum error is 52% which cause by sampling time shifting between PCTRAN and Simulink responses, the shapes of the two signals are identical well. **Figure 5(c)** shows maximum error is 0.68% for thermal reactor power. **Figure 5(d)** shows thermal power reactor at trip with maximum error of 8.2%, and the shapes of the waves are identical exactly. **Figure 5(e)** and **Figure 5(f)** show results as same as figures of **Figure 5(a)** and **Figure 5(b)** respectively for turbine load power. **Figure 5(g)** and **Figure 5(h)** show rod control positions with maximum error of 0.68%, and 10% respectively. The maximum error caused by shifting sampling time from PCTRAN results run sampling 1 second, and Simulink sampling time is 0.5 seconds. In general all signals are identical in form and behaviour.

From results, the maximum error occurs at trip transients because there is a shifting time between the sampling time of measured PCTRAN, and simulated SIMULINK simulations. The other maximum error occurs after moving Rod control manually and the rest of the time after moved manually, the control enters automatic control. But this control is not standard as same at the beginning. **Figures 5(a)-(h)** show calculations of standard deviation, maximum, minimum errors, average errors, Sum of Squares of Error, Mean Square Error, and Standard Error. These Errors are accepted in limit.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] IAEA (2005) Pressurized Water Reactor Simulator Workshop Material, 2nd Edition, Training Course Series No. 22. International Atomic Energy Agency, Vienna.

[2] IAEA (2017) Integral Pressurized Water Reactor Simulator Manual, 1st Edition, Training Course Series No. 65. International Atomic Energy Agency, Vienna.

[3] IAEA (2009) PCTRAN Personal Computer Transient Analyzer for a Two-Loop PWR and TRIGA Reactor. Micro-Simulation Technology, Trieste.

[4] International Atomic Energy Agency (2019) PCTRAN Generic Pressurized Water Reactor Simulator Exercise Handbook, Training Course Series No. 68. IAEA Publishing Section, Vienna.

[5] Larsen, N. (1987) Simulation Model of a PWR Power Plant. Risø National Laboratory, Roskilde.

[6] Westinghouse Electric Corporation (2016) Westinghouse Technology Systems Manual. Westinghouse Electric Corporation, Pittsburgh.

[7] Ansari, M.R. and Marzooghi, R. (2011) Spatial Reactor Dynamics and Thermo Hydraulic Behavior Simulation of a Large AGR Nuclear Power Reactor in Response to a Reactivity Step Change Disturbance. *Energy and Power Engineering*, **3**, 366-375. https://doi.org/10.4236/epe.2011.33047