CORE POWER CONTROL ANALYSIS AND DESIGN FOR TRIGA NUCLEAR REACTOR

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time. This work is dedicated to my wife and my beloved children, who always encouraged me with passion and endless support.

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ABSTRACT

An efficient nuclear core power control is essential in providing a safe and reliable nuclear power generation system. It is technically challenging to ensure that the core power output is always stable and operating within acceptable error bands. The core power control in TRIGA PUSPATI Reactor (RTP) Malaysia is designed based on the Feedback Control Algorithm (FCA), which includes the Proportional-Integral controller, Control Rod Selection Algorithm (CRSA), Control Rod Velocity Design (CRVD), and Power Change Rate Constraint (PCRC). However, the current setting generally produces an unsmooth transient response and a long settling time. The conventional CRSA suffers during transient and fine-tuning conditions due to the rod selection process only considers the rod position and ignores the rod worth value. The conventional PCRC has a constant gain, incapable of providing a sufficient amount of penalty and sensitivity effects on control rod velocity under all operating conditions. Thus, a new strategy for each component in the FCA is investigated to further improve overall core power tracking performance. To address the current CRSA problems, a novel CRSA called Single Control Absorbing Rod (SCAR) is designed based on the rod worth value and operational condition-based activation. The SCAR is not only reducing the complexity of the CRSA process but also reduces the time required for rod selection. In addition, a new saturation model and velocity value are studied for CRVD. On top of that, a fuzzy-based PCRC is proposed to produce a fast-tracking power response. Finally, a hybrid controller based on the integration of Model Predictive Control and Proportional controller is developed to exploit the benefits of both controllers via a switching control mechanism. In the present study, the RTP model is derived based on equations of neutronic, thermal-hydraulic, reactivity, and dynamic rod position. Both analytical and system identification models are considered. In the proposed design strategy, all of the safety design requirements based on the Final Safety Analysis Report are taken into account, ensuring that the outcome of the study is practical and reliable. The proposed strategy is designed via simulation with MATLAB Simulink and experimentation with actual hardware at the RTP. A stability analysis based on Lyapunov is derived to numerically guarantee the stability of the new power controller. An extensive comparison to the existing FCA is presented to demonstrate the compatibility and effectiveness of the proposed strategies in nuclear reactor environments. Overall, the results show that the response from hybrid Model Predictive Control-Proportional (MPC-P) offers better results than the FCA, in which reduces the rise time by up to 73 %, the settling time by up to 70 %, and the workload by up to 42 %. The hybrid MPC-P with multiple-component constraints is able to solve the unsmooth transient response and a long settling time tracking performance at the RTP and offers improvements in terms of fuel economic aspect in the long run and extending the lifetime of the plant operation.

ABSTRAK

Kawalan kuasa nuklear yang cekap sangat penting dalam menyediakan sistem penjanaan tenaga nuklear yang selamat dan boleh dipercayai. Secara teknikalnya, ia sangat mencabar untuk memastikan bahawa output kuasa teras sentiasa stabil dan beroperasi dalam jalur ralat yang boleh diterima. Kawalan kuasa teras di Reaktor TRIGA PUSPATI (RTP) Malaysia direka berdasarkan Algoritma Kawalan Maklum Balas (FCA), yang merangkumi pengawal *Proportional-Integral*, algoritma pemilihan rod kawalan (CRSA), reka bentuk kelajuan rod kawalan (CRVD), dan kekangan kadar perubahan kuasa (PCRC). Namun, secara umum, pengaturan semasa menghasilkan tindak balas sementara yang tindak lancar dan masa penyelesaian yang lama. CRSA konvensional terkesan semasa dalam keadaan sementara dan penalaan halus kerana proses pemilihan rod hanya mempertimbangkan kedudukan rod dan mengabaikan nilai rod bernilai. PCRC konvensional mempunyai pemalar tetap, tidak dapat memberikan kesan penalti dengan kepekaan yang mencukupi pada halaju rod kawalan dalam semua keadaan operasi. Oleh itu, strategi baru untuk setiap komponen dalam FCA dikaji untuk meningkatkan pengesanan kuasa teras secara keseluruhan. Untuk mengatasi masalah CRSA semasa, sebuah CRSA novel yang disebut *Single Control Absorbing Rod* (SCAR) dirancang berdasarkan nilai rod bernilai dan pengaktifan berdasarkan keadaan operasi. SCAR bukan sahaja mengurangkan kerumitan proses CRSA tetapi juga mengurangkan masa yang diperlukan untuk pemilihan rod. Di samping itu, model ketepuan baru dan nilai halaju dikaji untuk CRVD. Di samping itu, PCRC berasaskan *fuzzy* dicadangkan untuk menghasilkan tindak balas kuasa yang cepat. Akhirnya, pengawal hibrid berdasarkan integrasi *Model Predictive Control* dan pengawal *Proportional* dikembangkan untuk memanfaatkan kedua-dua pengawal melalui mekanisme kawalan pensuisan. Dalam kajian ini, model RTP dihasilkan berdasarkan persamaan neutronik, termal-hidraulik, kereaktifan, dan kedudukan rod dinamik. Kedua-dua model analisis dan pengenalan sistem dipertimbangkan. Dalam strategi reka bentuk yang dicadangkan, semua keperluan reka bentuk keselamatan berdasarkan Laporan Analisis Keselamatan Akhir dipertimbangkan, bagi memastikan hasil kajian adalah praktikal dan dapat dipercayai. Strategi yang dicadangkan dirancang melalui simulasi dengan MATLAB Simulink dan eksperimen dengan perkakasan sebenar di RTP. Analisis kestabilan berdasarkan Lyapunov dibuat untuk menjamin secara berangka kestabilan pengawalan kuasa baru. Perbandingan secara meluas dengan FCA yang sedia ada dibentangkan untuk menunjukan keserasian dan keberkesanan strategi yang dicadangkan dalam persekitaran reaktor nuklear. Secara keseluruhan, keputusan menunjukkan bahawa tindak balas daripada *Model Predictive Control-Proportional* (MPC-P) hibrid menawarkan hasil yang lebih baik daripada FCA, yang mana mengurangkan masa naik sehingga 73 %, masa penyelesaian sehingga 70 %, dan beban kerja sehingga 42 %. MPC-P hibrid dengan kekangan berbilang komponen mampu menyelesaikan tindak balas sementara yang tidak lancar dan prestasi penjejakan masa penyelesaian yang lama di RTP dan dipertingkatkan dari segi aspek ekonomi bahan api dalam jangka panjang serta memanjangkan hayat operasi loji.

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LIST OF ABBREVIATIONS

AELB	-	Atomic Energy Licensing Board, Malaysia
AI	-	Artificial Intelligence
ANN	-	Artificial Neural Networks
ARPC	-	Automatic Reactor Power Control
AWC	-	Anti-Windup Compensator
BPNN	-	Back-Propagation Neural Network
BR1	-	Belgian Reactor 1
cCRSA	-	conventional Control Rod Selection Algorithm
cCRVD	-	conventional Control Rod Velocity Design
CCS	-	Coordinated Control Strategy
cPCRC	-	conventional Power Change Rate Constraint
CRDM	-	Control Rod Drive Mechanism
CRSA	-	Control Rod Selection Algorithm
CRSE	-	Control Rod Sequence Exchange
CRVD	-	Control Rod Velocity Design
DACS	-	Data Acquisition and Control System
DCS	-	Distributed Control System
DE	-	Differential Evolution
DNN	-	Differential Neural Network
ETRR-2	-	Egyptian Second Testing Research Reactor
FCA	-	Feedback Control Algorithm
FLC	-	Fuzzy Logic Control
FOPID	-	Fractional Order PID
FP	-	Full Power
FRBS	-	Fuzzy Rule Based System
GA	-	General Atomics
GAs	-	Genetic Algorithms
GR	-	Generalized Regression
I&C	-	Instrumentation and Control
IAEA	-	International Atomic Energy Agency

ININ	National Nuclear Research Reactor of Mexico
ITU	Istanbul Technical University Turkish Research Reactor
KAERI	Korea Atomic Energy Research Institute
LTI	Linear Time-Invariant
LQG	Linear Quadratic Gaussian
LMIs	Linear Matrix Inequalities
LTR	Loop Transfer Recovery
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MFLNN	Multifeedback Layer Neural Network
MFs	Membership Functions
MIMO	Multi-Input Multi-Output
MNA	Malaysian Nuclear Agency
MOSTI	Ministry of Science, Technology and Science, Malaysia
MPC	Model Predictive Control
MPE	Mean Percentage Error
MPR	Multi-Purpose Research Reactor
MRAC	Model Reference Adaptive Control
MSE	Mean Square Error
MSHIM	Mechanical Shim
NDI	Non-Linear Dynamic Inversion
NDT	Non-Destructive Testing
NEMA	National Electrical Manufacturers Association
NMS	Neutron Measuring System
NNs	Neural Networks
NRHC	Non-Linear Receding Horizon Control
NRMSE	Normalized Root Mean Square Error
ODE	Ordinary Differential Equation
OPAL	Australia's Open Pool Australian Light Water Reactor
P	Proportional
PCRC	Power Change Rate Constraint
PD	Proportional-Derivative
PDM	Power Demand

PI	-	Proportional-Integral
PID	-	Proportional-Integral-Derivative
PSO	-	Particle Swarm Optimization
PTS	-	Pneumatic Transfer System
PUSPATI	-	Tun Ismail Atom Research Center
PWR	-	Pressurized Water Reactor
QP	-	Quadratic Programming
ReDICS	-	Reactor Digital Instrumentation and Control System
RG	-	Regulating Rod
RLS	-	Recursive Least Squares
RPS	-	Reactor Protection System
RTP	-	TRIGA PUSPATI Reactor
SAR	-	Safety Analysis Report
SCAR	-	Single Control Absorbing Rod
SCRAM	-	Safety Control Rod Axe Man
SF	-	Safety Rod
SH	-	Shim Rod
SISO	-	Single-Input Single-Output
SMC	-	Sliding Mode Control
SMR	-	Small Medium Reactor
STC	-	Self-Tuning Control
System ID	-	System Identification
TR	-	Transient Rod
TRIGA	-	Training, Research, Isotope production, General Atomics
TTFGC	-	Trajectory Tracking Fuzzy Genetic Controller
TTFLC	-	Trajectory Tracking Fuzzy Logic Controller
TTGFLC	-	Trajectory Tracking Genetic Fuzzy Logic Control
T-S	-	Takagi-Sugeno
USA	-	United States of America
UTM	-	Universiti Teknologi Malaysia

LIST OF SYMBOLS

C_m - Moderator Specific Heat Capacity

C_f - Fuel Specific Heat Capacity

M_m - Moderator Total Mass

M_f - Fuel Total Mass

Γ - Coolant Mass Flow Rate

K - Global Heat Transfer Coefficient

P^0 - Steady-State Power Level

P - Thermal Power Generated Within Core Volume by Fission

w - Weighting Factor for Computation of Moderator Temperature

f - Fraction of Power Deposited in The Fuel

T_f - Average Fuel Temperature

T_f^0 - Initial Fuel Temperature

T_{in} - Core Inlet Coolant Temperature

T_m - Average Coolant Temperature

T_m^0 - Initial Coolant Temperature

T_{out} - Core Outlet Coolant Temperature

P_d - Driving Pressure

δ_{in} - Stationary Density of Inlet Water

δ_{out} - Stationary Density of Outlet Water

g - Gravitational Acceleration

L - Core Height

P_f - Total Pressure Losses

α_2 - Factor for Friction along the Core Channel

v - Coolant Thermal Expansion Coefficient

ψ - Neutron Density

η_i - Density of Delayed Neutron Precursor Group i

n^0 - Stationary Neutron Number

${c_i}^0$ - Stationary Precursor Number

Λ - Mean Neutron Generation Time

k - Multiplication Factor

ρ - Reactivity

β - Delayed Neutron Fraction

β_i - Delayed Neutron Fraction for i-th Group

λ_i - Decay Constant for the i-th Group

ρ_{ext} - Reactivity due to External

$\rho_{feedback}$ - Reactivity due to Feedbacks

ρ_r - Reactivity due to Control Rod Motion

ρ_f - Reactivity due to Fuel Temperature Feedback

ρ_m - Reactivity due to Moderator Temperature Feedback

ρ_0 - Initial Reactivity at Critical Condition

α_h - Rod Worth Coefficient

α_f - Reactivity Due to Change in Temperature Fuel

α_m - Reactivity Due to Change in Temperature Moderator

$h@h_{cr}$ - Height of the Control Rod

h_{cr}^0 - Initial Height of the Control Rod

G_r - Control Rod Worth Coefficient

\$ - A Unit of Reactivity for a Nuclear Reactor, Calibrated to the Interval Between the Conditions of Delayed Criticality and Prompt Criticality

z_r - Control Rod Velocity

r - Reference Trajectory

u_{co} - Velocity Control Rod from the Controller

E - Error Deviation Signal

$\tilde{E}$ - Error Deviation Signal for Multi-Pronged

E_{fi} - Input Filter Calculation based on the Error Signal

t - Time

N - Neutron Power

x - State of the Model

u - Input of the Model

v_o - Measured Disturbance of the Model

d - Unmeasured Disturbance of the Model
y - Output of the Model or Actual Measure Output
$\hat{y}$ - Simulated or Predicted Model Output
$\bar{y}$ - Mean of Output Model
A, B, C, D - Coefficient Matrices in State-Space Model
A_{SID}, B_{SID}, C_{SID}, D_{SID} - Coefficient Matrices Estimate using System ID
K_{SID} - Noise Matrix of the Model using System ID
t_s - Sample Time
N - Number of Samples
T_s - Settling Time
T_r - Rise Time
P_{os} - Percent Overshoot
$V3$ - The Actual Calculated Velocity from the Controller
f_{sat} - Saturation Model
f_h - Hard Saturation Model
f_s - Soft Saturation Model
f_{sg} - Sigmoid Function Saturation Model
u_{max} - Maximum Velocity Control Rod Permitted
n - Non-Adaptive Shape Parameter for Soft Saturation Model
n_{max} - Maximum Non-Adaptive Shape Parameter for Soft Saturation Model
v - Tuning Parameter to Increase the Slope for Sigmoid Function Saturation
ξ - Maximum Steps per Cycle for Sigmoid Function Saturation
k_v - Gain Represents the Ratio of Rod Velocity After and Before Saturation
θ - Angle for Gain Control Rod Velocity
α - Switching Function between Hard and Soft Saturation
β - Switching Function to Select Sigmoid Function Saturation
$G1$ - Ratio of Power Demand and Output Power Gain for FCA
$G2$ - Log Rate Gain for conventional PCRC
$G3$ - Proportional Gain for FCA

$G4$ - Integral Gain for FCA

ξ_{rate} - Log Rate

e - Base of the Natural Logarithm

τ - Reactor Period

τ - Time Constant

u_c - Positive Constant for Fast Condition in Fuzzy CRVD

u_b - Positive Constant for Slow Condition in Fuzzy CRVD

u_{ab} - Positive Constant for Very Slow Condition in Fuzzy CRVD

u_a - Positive Constant for No Change Condition in Fuzzy CRVD

a_i - Positive Constant for Lower Limit in Triangular MFs Fuzzy CRVD

b_i - Positive Constant for Center Point in Triangular MFs Fuzzy CRVD

c_i - Positive Constant for Upper Limit in Triangular MFs Fuzzy CRVD

c_b - Positive Constant for Center Point in Bell Curve MFs Fuzzy CRVD

c_c - Positive Constant for Center Point in Gaussian MFs Fuzzy CRVD

w_i - Adjustable Weighting Parameter for the Power Change Rate Constraint

V_s^i - Scaled Control Rod Velocity Inputs

u_{step} - Control Rod Velocity in Steps per Cycle is calculated by Controller

$\hat{u}_{step}@u_{PCRC}$ - Control Rod Velocity in Steps per Cycle is calculated by Fuzzy PCRC

$\tilde{u}_{PCRC}$ - Control Rod Velocity in Steps per Cycle is calculated by Fuzzy PCRC for Multi-Pronged

$u_s@u_{CRVD}$ - Control Rod Velocity in Steps per Cycle is limited by CRVD

$\tilde{u}_{CRVD}$ - Control Rod Velocity in Steps per Cycle is limited by CRVD for Multi-Pronged

γ - Switching Function to select either cPCRC or Fuzzy PCRC

J - Objective Cost Function using MPC

J_{QP} - Quadratic Programming Optimization Objective Cost Function using MPC

U_{MPC} - Control Rod Velocity Matrix in Steps per Cycle is calculated by MPC

$u(k)@u_{MPC}$ - Control Rod Velocity in Steps per Cycle is calculated by MPC

u_P - Control Rod Velocity in Steps per Cycle is calculated by P Controller

R_s - Reference Trajectory or Power Demand Matrix using MPC

R_W - Weight Matrix using MPC

R_1 - Tuning Parameter using MPC

Np - Prediction Horizon using MPC

Nc - Control Horizon using MPC

M - Input Constraint Matrix using MPC

A_{QP} - A Unit Matrix using MPC

$\check{u}_{PCRC}$ - Control Rod Velocity in Steps per Cycle is calculated by MPC-Fuzzy PCRC

$\breve{u}_{CRVD}$ - Control Rod Velocity in Steps per Cycle is calculated by MPC-CRVD for Multi-Pronged

$\breve{u}_{PCRC}$ - Control Rod Velocity in Steps per Cycle is calculated by MPC-Fuzzy PCRC for Multi-Pronged

e_{ss} - Offset Error or Error at Steady-State

K_P - Proportional Gain for P-type Controller

ε - Switching Function to select either MPC or P-type Controller

$\hat{u}_{CRVD}$ - Control Rod Velocity in Steps per Cycle is calculated by hybrid MPC-P-CRVD

$\hat{u}_{PCRC}$ - Control Rod Velocity in Steps per Cycle is calculated by hybrid MPC-P-Fuzzy PCRC

ψ_{ref} - Reference Neutron Density or Reference Power Demand

V - Lyapunov Function

x_d - Desired State or Setpoint

R_o - Range of Operation for Switching Model

f_m - Switching Strategy Feedback Law

S - Constant Switching Function

K_c - Controller Gain

↑ - Indicate Increase When Compare to the Original or Benchmark Data

↓ - Indicate Decrease When Compare to the Original or Benchmark Data

→ - Indicate Almost or No Change When Compare to the Original or Benchmark Data

LIST OF APPENDICES

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CHAPTER 1

INTRODUCTION

1.1 Introduction

A nuclear reactor is designed to maintain the chain reaction generated by the fission process. There are many types of nuclear reactors with different purposes that exist in the world. The application of a nuclear reactor can be separated into two; nuclear power reactor and nuclear research reactor. The power reactor is used to generate electricity by using the steam turbine, and usually, it can be found in nuclear power plants. Meanwhile, the research reactor generates neutrons for various research purposes such as medical, material study, and industrial applications.

According to Research Reactor Database from International Atomic Energy Agency (IAEA), in 2021 [1], about 223 research reactors are in operation worldwide. Of the total number, only 17 are the Training, Research, Isotopes, General Atomics (TRIGA) type of reactor that are still in operation, with three are under decommissioning and 13 have been decommissioned. According to General Atomics (GA) [2], the manufacturer of the TRIGA reactor, initially, 66 TRIGA reactors have been installed at universities, government and industrial laboratories, and medical centers in 24 countries. The TRIGA reactors are utilised in a wide range of applications, including the production of radioisotopes for medicine and industry, tumour therapy, non-destructive testing, fundamental research on matter properties, and education and training [3]. There are three types of TRIGA reactors; Mark I, Mark II, and Mark III. The Mark I is the underground reactor equipped with multiple facilities for irradiation. The configuration of TRIGA Mark II is identical to Mark I, except the core is located at the surface of the reactor hall. TRIGA Mark III is designed with a mobile reactor core for experimental purposes [4].

According to the Institute of Engineering and Technology [5], nuclear plants use uranium fuel to produce energy through the fission process. The TRIGA reactor uses 19.9% enrichment of fuel element [6]. This process will split a large nucleus (uranium atoms) into two smaller ones and produce heat energy in the reactor core. The control rods made with neutron-absorbing material such as cadmium or boron are used in nuclear reactors to control the fission or the reactivity insertion rate [4], [7]. The neutron power will decrease when the control rods are inserted into the core due to the decrease in the number of neutrons produced by the fission process. On the other hand, the power generation will increase when the rods are withdrawn from the core. The neutron power production of the reactor is proportional to the fission chamber or neutron detector signal at a constant configuration. The full power reactor configuration can be described through the temperature distribution in the reactor core, known as thermal power. The generation of thermal power or core power is varied based on the movement of the control rods and can be regulated by the core power control system.

The automatic core power control is a part of the Instrumentation and Control (I&C) system which is designed to provide automatic control of the control rods in response to power level change pre-set by the operator and to maintain any pre-set power level. The system is responsible for responding to any failures or anomalies to ensure efficient and safe power production [8]. To control the movement of the rods, the TRIGA core power control uses either an old analogue tachometer feedback system or a digital Proportional-Integrated-Derivative (PID) controller. The TRIGA PUSPATI Reactor (RTP), TRIGA Mark II is the only research reactor available in Malaysia which uses a digital Feedback Control Algorithm (FCA) with Proportional-Integrated (PI) controller for its core power control system. At present, the tracking performance of the power control system at the RTP is deemed unsatisfactory due to slow tracking, unsmooth transient response, and a long settling time. As a result, continuous improvement is still required for developing a stable and safe core power control system.

1.2 Significance of Study

The present study investigates a multi-pronged core power control strategy to handle several design constraints simultaneously, including minimizing the settling time and overshoot, chattering error, maximizing the control rod velocity, and determining the appropriate value of power change rate constraint to control the reactor core power effectively.

The developed power control system is highly practical and expected to bring many benefits to the RTP, such as reducing the operational costs, improving efficiency, increasing operation speed by reducing settling time, improving product quality of irradiation samples and radioisotope production by enhancing tracking response, minimizing the chattering error and improving safety. Besides, by optimizing the energy released from the core, fuel economy is improved in the long run by extending the lifetime of the plant operation. Most importantly, the developed solution in this work can benefit research and power reactor of any capacity or design.

This study's contribution of knowledge can benefit both research reactors and power reactors with the large number of the plant still in operation status. In 2021, nuclear power plants still in operation are 444 for energy demand, and 51 are under construction with a total of 495 units. The economic growth of the country relies heavily on the energy sector. The demand from sectors such as medical, industry, research institutes, and universities requiring products and services from nuclear research reactors are about 223 still in operations, 11 are under construction, and 16 are planned with a total of 250 units.

Furthermore, it is envisaged that the developed control strategies will serve as a foundation for the future development of a robust power control system that can be used in a variety of complex environments.

1.3 Problem Statement

The efficient and safe operation of a nuclear reactor relies heavily on a reliable and robust power controller. The ideal controller should be capable of efficiently managing the nuclear core power output, which is time-varying and highly sensitive to load changes. Most importantly, the International Atomic Energy Agency (IAEA) requires this controller basic design to fulfil fundamental safety functions for nuclear reactors; to control reactivity using control rods and to allow power level increase in a safe manner. However, there are no firm international best operational practises or recommendations to control nuclear reactors in safe operation, and it is necessary to sacrifice its tracking control performance or higher operating costs in terms of economy. Besides that, it is technically challenging to operate a nuclear reactor within tight multiple parameter constraints while maintaining stable power output. Thus, an investigation study to improve the effectiveness of nuclear reactor control without compromising system security and reliability is required. To date, reactor power control at TRIGA PUSPATI Reactor (RTP) using Feedback Control Algorithm (FCA) has a 2% of full power chattering error with relatively three-minute settling time when the reactor power is increased over a wide range. The conventional control rod selection algorithm (cCRSA) based on the balancing position of control rod method suffers during fine-tuning in a steady-state to regulate reactor power due to different control rod worth values for each control rod at RTP. Besides chattering error and longer settling time, the performance of reactor power control at RTP has a non-smooth control surface due to strong negative temperature feedback from the reactor core. This tracking power control performance scenario will have a significant impact on the product quality of irradiation samples and radioisotope production for the TRIGA reactor. Furthermore, the complex interrelationship between multiple components in the FCA with different control rod selection algorithms (CRSA), types of saturation model and control rod velocity in the CRVD, penalizing value on the control rod velocity signal in the PCRC, and types of the controller has not yet been systematically studied in the context of the TRIGA reactor, hence hindering further optimization of the core power control system. The prediction ability and handling constraints provided by the MPC are still useful to be implemented in a nuclear reactor. However, the MPC relies heavily on an accurate plant model to ensure good performance and stability. To date, the main challenge of linear MPC in core power control has been to solve the global control issues for nonlinear nuclear plants over larger ranges or under transient load change working conditions without increasing the computational burden on the MPC. The combination of two or more controllers can overcome the limitation imposed by a single linear MPC, but it will increase design complexity. Thus, rather than combining controllers, integration of controllers to perform hybrid control is preferable. In this study, a new hybrid core power controller based on the integration of MPC and Proportional (P) controller is studied with multi-component constraints in order to enhance the current power control performance and address the aforementioned issues.

1.4 Objectives

The objectives of the research are :

(a) To formulate a new control rod selection algorithm (CRSA) for the RTP that can significantly offer a fast response with less complexity compared to the existing CRSA;

(b) To formulate a new model of power change rate constraint (PCRC) for the RTP that can optimize the power tracking performance using fuzzy logic;

(c) To design a new hybrid controller based on the integration of Model Predictive Control (MPC) and Proportional (P) controllers for the RTP that can provide better performance in terms of settling time and control effort;

(d) To validate new formulations of CRSA, PCRC, and MPC-P controller in an RTP reactor environment.

1.5 Research Scopes

(a) The system is represented by the RTP at Malaysian Nuclear Agency (MNA).

(b) The modelling of the RTP in a wide-range power level from a low power which is 10% of Full Power (FP) to a nominal power operation of 75% FP. This is due to the limitation of the neutron measurement system (NMS) and detector output characteristics. The plant modelling for RTP covers neutonics, thermal-hydraulic, reactivity equations, and the control rod drive actuator model. The simulation result for the output plant modelling, such as core power and velocity of the control rod, does not include white noise signal. The noise measurement only covers the actual output plant from the experimental data.

(c) The improvement in the core power system at the RTP will only involve the power controller, the control rod selection algorithm (CRSA), control rod velocity design (CRVD), and power change rate constraint (PCRC).

(d) Due to safety concerns, the maximum control rod velocity is limited to up to 3 mm/s, and the maximum power change rate constraint is 12.5%/s.

(e) The simulation works are performed using Matlab Simulink and ordinary differential equations solver (ode15s).

(f) Due to highly sensitive equipment and restriction imposed by the safety operating procedure, the experimental works are conducted only for the FCA with PI controller. For others, only the simulation works are considered.

(g) The experimental data is obtained by using the real console instrumentation and control at the RTP. To verify the results of simulation using Matlab Simulink, the CRSA, CRVD, and PCRC codes are converted to NetArrays code to be implemented on real Distributed Control System (DCS) hardware at RTP. The details of hardware specification implementation at RTP are; using HP Z440 Workstation, Intel Xeon E5-1620v3, Distribution Control System (DCS) model RTP3000, and software implementation using NetArrays v8.4 and graphical user interface using Wonderware Intouch 2014.

(h) All the technical data and specifications are obtained from the maintenance report provided by the MNA from the year 2016 to 2021.

1.6 Organization of the Thesis

This thesis is written in six chapters; Chapter 1 introduces the thesis structure overview, including motivation, problem statement, research objectives, and scopes. Chapter 2 presents the literature survey covering an overview of TRIGA PUSPATI Reactor (RTP), the existing core power control strategies, reactor modelling approach, and stability analysis. Chapter 3 presents the reactor modelling of the RTP and explains the research methodology for designing core power control with a multi-component constraints strategy. Chapter 4 presents the results and discussion on RTP model validation. Chapter 5 presents the results and analysis of core power control performance with multi-component constraints at RTP application, while Chapter 6 presents the conclusion of thesis and future work.

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