UNIVERSITI PUTRA MALAYSIA

MODIFIED MODEL REFERENCE ADAPTIVE CONTROL USING LYAPUNOV RULE FOR POWER MODULE IN NUCLEAR REACTOR SYSTEM

ANITH KHAIRUNNISA GHAZALI

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By

ANITH KHAIRUNNISA GHAZALI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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DEDICATION

I dedicate this thesis to:

My parents, Lt Col Ghazali Bin Othman and Madam Che Norlida Binti Ismail, who have been a great source of inspiration and support.

My beloved brothers, Abdul Qaiyum, Abdul Hakim, Abdul Rafie and Abdul Syakir for their encouragement and motivations.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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September 2017

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Reactor TRIGA PUSPATI (RTP) was successfully installed in 1982 at Malaysia Nuclear Agency and has been conducting safe operation for more than 35 years. It is the only research reactor in Malaysia. RTP is a TRIGA Mark II pool-type reactor, with 1 MW thermal power. The power system of the RTP was currently upgraded from relay mode to automated power control system. The safety features of the system also have been designed to avoid any abnormality in the electronic and associate components that may lead to uncontrolled rate of reactivity The reactivity and reactor power are controlled by the movements of four control rods, known as Safety, Shim, Regulating, and Transient. Currently, the RTP using PI controller indicates transient response with longer settling time and rise time. Thus, the efficiency of the reactor core is reduced and the reactor's lifetime is shortened. Since the RTP is very important in various research fields, transient performance is vital. To overcome this problem, are quite challenging using PI controller since this controller are not capable to improve the transient response without produce overshoot and keep maintaining the steady state error less than 1% FP. Therefore, to solve this problem, it is necessary to design a controller that good in tracking and confirms the stability of the system.

This research use Model Reference Adaptive Control MRAC controller to control the RTP power level because it good in adaptation and have a reference model. Even though the MRAC confirm the stability, but it gives unsatisfied performance to track the reference model. Thus, the modified (MRAC) with Lyapunov rule was proposed. The RTP model was modelled using a system identification method from its real-time power operation. Pole placement technique was applied to design the reference model with 47.8% ratio of movement. The stability of the proposed system was validated using transfer function test to ensure its capability. The Ziegler-Nichols technique was implemented to determine the adjustment mechanism. The adjustment mechanism will minimise the error of the reactor power to zero. The value of adjustment mechanism was determined by measuring the delay time and time constant from the operation data. The

stability of controller has been checked using Lyapunov stability derivation. Results from the conventional MRAC and modified MRAC were compared and analysed. The percentage of improvement in terms of settling time was 33%, rise time was 33%, and there were no changes of for steady state error and tracking error. In conclusion, the modified MRAC had performed well in transient response, with settling time of 123.36 sec and rise time of 93.76 sec, which are applicable for a nuclear reactor power control system.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENGUBAHSUAIAN KAWALAN PENYESUAIAN RUJUKAN MODEL MENGGUNAKAN PERATURAN LYAPUNOV UNTUK MODUL KUASA DALAM SISTEM REAKTOR NUKLEAR

Oleh

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Reaktor TRIGA PUSPATI (RTP) berjaya dibangunkan pada tahun 1982 di Agensi Nuklear Malaysia dan telah menjalankan operasi secara selamat selama lebih dari 35 tahun. Ia adalah satu-satunya reaktor penyelidikan di Malaysia. RTP adalah reaktor jenis kolam TRIGA Mark II, dengan kuasa terma 1 MW. Sistem kuasa RTP kini dinaik taraf dari mod geganti untuk sistem kawalan kuasa automatik. Ciri-ciri keselamatan sistem ini juga telah direka untuk mengelakkan sebarang ketidakstabilan dalam komponen elektronik dan boleh menyebabkan kadar reaktif yang tidak terkawal. Daya kereaktifan dan reaktor dikawal oleh pergerakan empat rod kawalan, yang dikenali sebagai Safety, Shim, Regulating, dan Transient. Tindak balas terkini RTP menggunakan pengawal PI menunjukkan masa penyelesaian dan masa meningkat yang lebih lama. Oleh itu,ini akan mengurangkan kecekapan teras reaktor dan memendekkan jangka hayat reaktor. Oleh kerana RTP sangat penting dalam pelbagai bidang penyelidikan, prestasi reaktor dalam menjana kuasa adalah penting. Oleh kerana RTP memainkan peranan penting dalam bidang penyelidikan, maka prestasi kenaikan kuasa sangat penting. Masalah ini tidak dapat di atasi dengan menggunakan pengawal PI kerana dengan menningkat prestasi kuasa semasa menaik akan menyebabkan terhasilnya kuasa lebihan.

Oleh itu, untuk mengatasi masalah ini memerlukan pengawal yang baik dan menjamin kestabilan sistem. Kajian ini menggunakan Pengawal Adaptasi Rujukan (MRAC) untuk mengawal kuasa RTP kerana ia baik dalam penyesusaian dan mempunyai model rujukan. Walaupun MRAC berjaya mengesahkan kestabilan, tetapi ia tidak memberi prestasi yang memuaskan untuk menjejaki model rujukan. Oleh MRAC menggunakan teori Lyapunov yang telah diubahsuai dicadangkan. menghasilkan pengawal untuk sistem kawalan kuasa RTP menggunakan. Model RTP dimodelkan menggunakan kaedah pengenalan sistem dari operasi kuasa masa sebenar. Teknik peletakan kutub digunakan untuk merancang model rujukan dengan nisbah pergerakan 47.8%. Kestabilan sistem yang dicadangkan telah disahkan untuk memastikan keupayaannya. Teknik Ziegler-Nichols telah dilaksanakan untuk menentukan mekanisme pelarasan. Mekanisme penyesuaian akan meminimakan ralat kuasa reaktor kepada sifar. Nilai mekanisme pelarasan ditentukan dengan mengukur masa kelewatan dan masa yang tetap dari data operasi. Kestabilan pengawal telah diperiksa dengan menggunakan kestabilan Lyapunov. Hasil daripada MRAC konvensional dan MRAC yang diubahsuai telah dibandingkan dan dianalisis. Peratusan penambahbaikan dari segi masa penyelesaian ialah 33%, kenaikan masa adalah 33%, dan tidak ada perubahan untuk keadaan stabil dan penjejakan. Kesimpulannya, MRAC yang telah diubahsuai telah dilakukan dengan baik dalam tindak balas sementara, dengan masa penyelesaian sebanyak 123.36 saat dan masa meningkat sebanyak 93.76 saat, yang boleh diterima pakai untuk sistem kawalan kuasa reaktor nuklear

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I certify that a Thesis Examination Committee has met on 5th September 2017 to conduct the final examination of Anith Khairunnisa Binti Ghazali on her thesis entitled "Modified Model Reference Adaptive Control using Lyapunov Rule for Power Module in Nuclear Reactor System" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the (insert the name of relevant degree).

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Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
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LIST OF ABBREVIATION

SMR	Small Module Reactor
TRIGA	Training, Research, Isotope, General Atomics
TPS	TRIGA Power System
IAEA	International Atomic Energy Agency
RTP	Reactor TRIGA PUSPATI
RBMK	Pressure-tube Boiling Water Reactor
PID	Proportional Integral Derivative
MRAC	Model Reference Adaptive Control
PWR	Pressurized Water Reactor
ARPC	Automatic Reactor Power Control
TTFLGC	Trajectory Tracking Genetic Fuzzy Logic Controller
MFLNN	Multifeedback Layer Neural Network
PSO	Particle Swarm Optimization
MPC	Model Predictive Control
QP	Quadratic Programming
PMG	Permanent Magnet
LTI	Local-Time-Invariant
FCA	Feedback Control Algorithm
PDM	Power Demand

LIST OF SYMBOLS

n	Neutron density (n/cm^3)
n_0	Initial equilibrium (steady-state) neutron density (n/cm^3)
c_{ri}	c_i/c_{i0}, relative density of precursor group $(atom/\ cm^3)$
c_i	Core averaged density of precursor group $(atom/\ cm^3)$
c_{i0}	Initial equilibrium (steady-state)of precursor group $(atom/\ cm^3)$
ρ	$(k-1)/k$, reactivity $(\Delta k/k)$
G_r	Total reactivity
z_r	Changes of control rod
α_f	Reactivity due to change in temperature fuel
α_m	Reactivity due to change in temperature moderator
Λ	Effective prompt neutron life time (s)
β	Total delayed neutron fraction
β_i	Group delayed neutron fraction
λ_i	Radioactive decay constant of group neutron precursor (s^{-1})
T_f	Average reactor fuel temperature (°C)
T_l	Temperature of water leaving the reactor (°C)
T_e	Temperature of water entering the reactor (°C)
T_c	Average reactor coolant temperature (°C)
f_f	Fraction of reactor power deposited in fuel
P_0	Initial Equilibrium power
μ_f	Total heat capacity of the fuel = weight of fuel times specific heat $(MW/°C)$
μ_c	Total heat capacity of the fuel = weight of coolant times specific heat $(MW/°C)$
Ω	Heat transfer coefficient between fuel and coolant $(MW/°C)$
y	Output plant
y_m	Output reference model
θ_1	Controller parameter
K_p	Proportional gain
T_i	Integral time
T_d	Derivative time
K_i	Integral time
K_d	Derivative time
G_p	Plant model
G_m	Reference model

CHAPTER 1

INTRODUCTION

1.1 Research Background

The nuclear reactor is the device that convert the energy stored in atoms into heat or electricity. The nuclear reactor consists of several components such as fuel source, moderator, control rods, coolant and encasement. The reaction fission process will produce the power from continuous of kinetic energy due to splitting of unstable nucleus. The power nuclear type reactor will use steam to generate electricity while research reactor provide a neutron source for research purpose. The purpose of reactor depends on it operation, and chemical composition of fuel.

The most common and widely used research reactor used is TRGA reactor. TRIGA stands for Training, Research, Isotope, and General Atomics and its main purposes include education programmes, research projects, and isotope production. Furthermore, this reactor is also used to provide training for students, physicists, nuclear power plant staff, regulatory staff, as well as operator and radio protection personnel. The development of TRIGA reactor began late in the 1950s in 23 countries. TRIGA reactors of less than 2 MW of thermal power are more friendly compared to higher power research reactors because they are easier to operate, have low burnup, as well as more economical and versatile. The International Atomic Energy Agency (IAEA) reported that there are 38 TRIGA reactors operating between 100 kW to 16 MW, 5 reactors that operate at higher than 1 MW and less than 5 MW, and the most common reactors range between 250 kW to 1 MW.The power control describes the output power that could be regulated on-demand or by reference value by moving the control rods. The controller drives the control rods that act as actuators to follow the desired value power in real-time (G. Li et al., 2016). Research Reactor (SMR) generates power of less than 100MW and is not for energy generation purposes. In addition, the research reactor is used to generate neutrons for various fields of scientific research and also for social purposes (Adorni, Bousbia-salah, D'Auria, & Hamidouce, 2007).

Nowadays, a TRIGA reactor can operate with less than 20% of fuel enrichment, light water as coolant, and graphite as reflector. For instrumentation and control field in a TRIGA reactor, nuclear channel, fuel temperature, interlocks, alarm and scram system, and neutron detectors are implemented (International Atomic Energy Agency, 2016).

1.2 Problem Statement

Accurate models of RTP are necessary to be determined before designing a controller. Since the RTP is a nonlinear plant and some parameters, such as fuel temperature, bulk temperature, and position of control rods may vary, it is imperative to reproduce the dynamic behaviour of the reactor core. A widely used technique to model the reactor core is by using an analytical model through point kinetic. The model of a reactor was investigated using the research reactor TRIGA Mark II at the University of Pavia, Italy, with a power range of 0 to 250 kW (Cammi et al., 2013). Since the power range of the RTP is between 0 to 1,000 kW, thus, this technique only accurate for low power range or log range. In addition, the limitation of some parameters, such as group of delay neutron fraction and group of neutron precursor are not applicable in RTP.

In order to overcome the modelling problem, system identification method has been applied as an alternative by computing the experimental data from RTP. The transfer function developed by system identification is able to establish the dynamic behaviour of RTP. This method is more accurate to be applied with the current RTP compared to point kinetic.

Currently, the RTP uses PI controllers to operate the reactor and the settling time ranges between 181 to 191 s, while the rise time ranges between 132 to 142 s at 1 MW of thermal power. This problem will lead to longer operation time, thus increases the burnup process and reduces the efficiency of the reactor core. However, fast transfer response will cause a rapid fission process and could possibly cause an accident. The limitation of this type of controller is its fixed gain but the MRAC is adaptation gain. Therefore, a good controller design is necessary for the stability and safety of the reactor power control. Furthermore, it is important to understand the trip limitations, such as overpower, rapid fission process, exceeded fuel temperature, and malfunction of the protection system at the reactor to preserve the efficiency of its components (Ponciroli, Cammi, Della Bona, Lorenzi, & Luzzi, 2015). In short, the controller is necessary to enhance the stability and safety of the reactor during operation. Since a model of the RTP had to be determined using system identification, the MRAC techniques were the best candidates to control the power system with the existing reference model. Therefore, the purpose of this study was to design a new RTP power control algorithm using a modified MRAC. In addition, the reference model was designed using pole placement by migrating 47.8% of the nearest pole from the origin.

In addition, an automated control would reduce the need for humans to update the system input. Based on this idea, it is relevant to implement the modified MRAC for the RTP power control system, which also requires less operator intervention for safety and security reasons. Even though MRAC with Lyapunov method assures the stability of the controlled system and offers minimal adaptation error (Pawar & Parvat, 2015), it never guarantees precision in tracking performances. In this study, the modification of MRAC using Lyapunov rules is obviously needed because the conventional MRAC produces oscillation. Furthermore, the reference model has been designed through movements of the plant pole in order to gain a more stable model. The modified MRAC applied the Ziegler-Nichols' approach as a tuning mechanism because it is excellent at tracking set points for closed-loop systems and the most extensive method used in the industry (Kanojiya, 2012).

The direct modification and testing for power control at the RTP are not allowed due to safety and security factors. The alternative method to overcome this problem is by developing and upgrading the RTP power control based on simulation.

1.3 Objectives

The aim of this research is to improve transient response performance in terms of settling time, and rise time of RTP power control system. The following objective are carried out to achieve this goal:

1) To investigate the behaviour of dynamic nuclear model through real time power operation.
2) To model the RTP plant using system identification.
3) To model the reference plant model using pole placement in accordance to safety requirements.
4) To propose the modified Model Reference Adaptive Control (MRAC) with Ziegler Nichols approach for adjustment mechanism of RTP power.

1.4 Contribution

The research focuses on modelling and control part in order to obtain the satisfied performance for RTP. The main contribution of this research is reproduce the RTP model and introducing the modified MRAC using Ziegler Nichols adjustment mechanism. The modified MRAC able to provides better performance with shorter settling time and rise time at different power level of desired power demand.

1.5 Limitation of Research

The scope of this thesis includes the following:

i. The modelling of RTP only consider for automatic mode operation at 20%-100% full power (FP) due to linear range and the reactor power critically stable at this range.
ii. The real time RTP power operation only consider Regulating rod for modelling purpose due to high sensitivity and the most precise rod.
iii. The research focuses on controller design using modified MRAC for RTP power control system.
iv. The modified MRAC design only consider the Lyapunov rules and Ziegler Nichols approach to determine the adjustment mechanism.
v. The power range only selected at 10%-75% for daily operation and 10% to 100% for maximum power operation.

1.6 Thesis Organization

This thesis is organized in five chapters consecutively. In the first chapter consist of the introduction of the research work. In this chapter briefly explained background of nuclear reactor, problem statement, objectives research contribution and thesis organizations.

In the second chapter, demonstrate the introduction to RTP. Next, the literature review of previous research on nuclear reactor power control system modelling and control technique has been done.

In the third chapter, process of modelling the RTP through real time power operation data and system identification method presented. Next the controller design using conventional MRAC and modified the MRAC using Lyapunov rules were done. The Ziegler Nichols approach was discussed to determine the adjustment mechanism. The stability test for the model and controller also explained in this chapter.

Then, the fourth chapter reported the result and discussion RTP performance using conventional MRAC and modified MRAC control techniques.

In the fifth chapter, the conclusion of the findings and suggestion for future work is presented.

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