A multipronged core power control strategy for Reaktor TRIGA PUSPATI

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Abstract. At present, the power tracking performance of nuclear Reaktor TRIGA PUSPATI (RTP) is considered unsatisfactory performance due to relatively long settling time during transient and a chattering noise during steady-state power output. Application of the conventional Feedback Control Algorithm (FCA) as a power control technique is proven to be inadequate to keep the core power output stable and within tight multiple parameter constraints for the safety demand of the RTP. Hence, the present study proposed a multipronged core power control strategy improvement through manipulation of the current Control Rod Selection Algorithm (CRSA), Control Rod Speed Design (CRSD), and Power Change Rate Constraint (PCRC) which are part of the core power control design. In this paper, the profiling and analysis of the multipronged core power control strategy are presented. The model for core power control consists of mathematical models of the reactor core, FCA controller, and a series of multipronged models. The mathematical models of the reactor core are based on the point kinetics model, thermal-hydraulic model, and reactivity model. The reactor model is integrated with the FCA controller and a combination of CRSA-CRSD-PCRC models. The power tracking performance of the proposed control strategy and conventional FCA is compared via computer simulation. Overall, the results show the multipronged FCA offers a wider options for optimum operation of the TRIGA reactor.

1. Introduction

The Reaktor TRIGA PUSPATI (RTP), made by General Atomics is the only nuclear research reactor in Malaysia. The reactor is mainly used for research and development (R&D), isotope production, education, and training purposes. One of the main safety concern in nuclear operation is the core power control system design which is vital for the safe operation of the reactor and minimize any possibilities of failures or malfunctions of the reactor control system which may lead to abnormal behavior of the reactor. Thus, the development of safe, rapid, and efficient core power control for nuclear plants is attracting ongoing research interest [1].

In general, there is no universal solution to resolve all the problems related to power tracking performance in nuclear reactor operation. Hence, a comprehensive countermeasures strategy needs to be identified towards improving efficiency and enhancing safety. One of the powerful methods is known...
as a multipronged strategy that has been implemented for optimisation problems in non-nuclear applications [2][3]. Surprisingly, no previous study has investigated a multipronged approach in a nuclear power tracking system.

The core power control is physically designed based on common safety parameter constraints such as step reactivity limiting [4], reactor period limiting [5], power change rate-limiting [6], and control rod speed limiting [7]. To date, the effects of the combination of all these safety parameter constraints in the single-core power control system have not been extensively studied. Generally, these distinct parameters can be categorized into three-pronged elements in core power control design; Control Rod Selection Algorithm (CRSA), Control Rod Speed Design (CRSD), and Power Change Rate Constraint (PCRC).

The RTP uses a conventional core power control known as Feedback Control Algorithm (FCA) [8] for the power maneuvering up to 1 MWth based on the conventional CRSA (cCRSA), conventional CRSD (cCRSD), and conventional PCRC (cPCRC). In our recent works, the new CRSA based on Single Control Absorbing Rod (SCAR) algorithm [9], new CRSD based on different saturation types and changes in the maximum rod speed limiter values [10], and new PCRC based on fuzzy approach [11] have been designed separately to provide better results than conventional methods. However, the results produced are not fully optimized and do not have a simple analytic link to the choice of the prongs. Hence, in this paper, the three-pronged and combination prongs of the strategies in [9-11] are studied, analyzed, and profiled to further improve the power tracking performance of the RTP.

The current core power control operates within tight multiple parameter constraints for the safety demand of the RTP. The power tracking performance measurement is based on the sudden change of power demand which currently leads to significant power output delayed known as settling time during transient and a chattering noise during steady-state. The effect of all prongs is evaluated through the power maneuvering performance of the core power control and actuation signal of the Control Rod Drive Mechanism (CRDM).

This paper is organized as follows. The modelling of RTP in state space form is presented in Section 2 and the RTP core power control system is briefly described in Section 3. The proposed multipronged core power control strategy is presented in Section 4. The results and discussion on the implementation of a multipronged core power control strategy are given in Section 5. Finally, conclusions are given at the end of the paper.

2. State space Reaktor TRIGA PUSPATI model

2.1. State Space Model

The RTP model is built according to the point kinetics with six groups of delayed neutrons, reactivity feedback due to control rod movement, fuel temperature, and moderator temperature changing are considered. The equations of the RTP reactor core model are shown as [9]:
\[
\begin{align*}
\frac{d\psi}{dt} &= \frac{\beta - \beta}{A} \psi + \sum_{i=1}^{6} \lambda_i \eta_i \\
\frac{d\eta_i}{dt} &= \frac{\beta_i}{A} \psi - \lambda_i \eta_i \\
\frac{d\tau_m}{dt} &= \frac{\Omega}{\mu_m} T_f - \frac{(\Omega+2M)}{\mu_m} T_m + \frac{2M}{\mu_m} T_{in} \\
\frac{dT_f}{dt} &= \frac{N_0}{\mu_f} \psi - \frac{\Omega}{\mu_f} T_f + \frac{\Omega}{\mu_m} T_m \\
\mu_m &= C_m \Gamma \\
\rho &= \rho_r + \alpha_m T_m + \alpha_f T_f \\
N &= \psi N_0
\end{align*}
\]

(1)

where, \(\psi\) is relative neutron density, \(\rho\) is total reactivity, \(A\) is mean neutron generation time, \(\lambda_i\) is decay constant of the \(i\)-th group of delayed neutron precursor, \(\eta_i\) is the \(i\)-th group of normalized precursor concentration, \(\beta_i\) is the \(i\)-th group of delayed neutron, \(T_m\) is average temperature of coolant, \(N_0\) is nominal core power, \(M_m\) is moderator total mass, \(C_m\) is moderator specific heat capacity, \(\mu_m\) is heat capacity of moderator, \(T_f\) is average temperature of fuel, \(\Omega\) is global heat transfer coefficient, \(\Gamma\) is coolant mass flow rate, \(T_{in}\) is average inlet temperature of coolant, \(M_f\) is fuel total mass, \(C_f\) is fuel specific heat capacity, \(\mu_f\) is heat capacity of fuel, \(\rho_r\) is reactivity due to control rod movement, \(G_r\) is reactivity worth of the control rod, \(Z_r\) is velocity of the control rod, \(\alpha_m\) is reactivity due to change in temperature moderator, \(\alpha_f\) is reactivity due to change in temperature fuel and, \(N\) actual core power.

The linearized model is widely used in TRIGA reactor modelling [12] and can be represented in state-space form as:

\[
A = \begin{bmatrix}
-\frac{\beta}{A} & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & \lambda_5 & \lambda_6 & \frac{\alpha_f}{A} \psi_0 & \frac{\alpha_m}{A} \psi_0 & \psi_0 \\
\frac{\beta_1}{A} & -\lambda_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{\beta_2}{A} & 0 & -\lambda_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{\beta_3}{A} & 0 & 0 & -\lambda_3 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{\beta_4}{A} & 0 & 0 & 0 & -\lambda_4 & 0 & 0 & 0 & 0 & 0 \\
\frac{\beta_5}{A} & 0 & 0 & 0 & 0 & -\lambda_5 & 0 & 0 & 0 & 0 \\
\frac{\beta_6}{A} & 0 & 0 & 0 & 0 & 0 & -\lambda_6 & 0 & 0 & 0 \\
\frac{N_0}{\mu_f} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{\Omega}{\mu_f} & \frac{\Omega}{\mu_f} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\Omega}{\mu_m} & \frac{(\Omega+2M)}{\mu_m} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
1 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]

\[
D = [0]
\]

(2)
where \( A \) is the state matrix, \( B \) is the input matrix, \( C \) is the output matrix, \( D \) is the disturbance matrix, core state \( x = \begin{bmatrix} \delta N \delta \eta_1 \delta \eta_2 \delta \eta_3 \delta \eta_4 \delta \eta_5 \delta T_m \delta T_f \delta \rho \end{bmatrix}^T \), core input \( u = [z_r] \), and core output \( y = [N] \).

3. RTP core power control system

The RTP feedback core power control system for power maneuvering is illustrated in Figure 1. The term input refers to a Power Demand (PDM) and the output is the neutron power at the core. The core power is measured by an ex-core neutron detector and Neutron Measurement System (NMS) as signal processing. The NMS provides two signals which are core power \( (N) \) and the rate of power change \( (\text{Log Rate}) \). The error deviation in percentage between the PDM and the core power output is subtracted with conventional Power Change Rate Constraint (cPCRC) based on the constant gain rate \( (G2) \), which then are used as the inputs for the signal filter and Proportional-Integral (PI) controller. The controller output in form of the control rod velocity is fed to the Control Rod Speed Design (CRSD) to constraint the reactivity insertion rate in the core. The conventional Control Rod Selection Algorithm (cCRSA) is used to determine the sequence of control rod movement at Control Rod Drive Mechanism (CRDM) based on rod position balancing pattern to regulate the reactor power. Using the said configuration, the core power control has 1% full power chattering error with a large settling time in the case of a sudden change in power demand.

\[
\begin{align*}
E_f(k) &= 1.47197E(k) + 0.882[E_f(k-1) - E(k-1)] \\
\end{align*}
\]

where \( u_c \) is the output signal from the controller, \( G_1, \alpha G_2, G_3, G_4 \), are controller tuning gain for FCA, and \( E_f \) is input filter calculation based on the error signal \( (E) \).

Figure 1. Block Diagram of Conventional Three-pronged in Core Power Control System of the RTP.
Profilersing and analysis of three-pronged control strategy of CRSA, PCRC and CRSD, all possible combination of conventional and the new three-pronged control strategy need to be taken into account. All parameters in Eq. (3) are considered as constant throughout this study.

4. Multipronged core power control strategy

In this section, the three-pronged control strategies in core power control system are presented based on our works in [9-11] which consists of conventional and new CRSA, CRSD, and PCRC.

In [9], the CRSA model is represented as follows:

\[
\rho_r(s) = G_r(iCRSA)Z_r(s) = \begin{cases} 
1.25s + 0.02752 & s > 0 \\
\frac{s^3 + 0.2202s^2 + 2.519e^{-16}s}{5s + 0.3854} & s < 0 
\end{cases}
\]

where the velocity of the control rod \( Z_r \) is calculated from the controller \( u_c \) and the control rod position dynamics in both cCRSA and nCRSA models are derived based on the set of actual input and output data from the CRDM using System ID. In [9], the nCRSA is modelled to improve the pattern control rod movement by providing the most responsive reactivity during transient region.

In the CRSD, the maximum allowable control rod speed and the saturation models are determined to produce optimum tracking performance without exceeding the predetermined safety limit stated in the Final Safety Analysis Report (FSAR) [13]. The cCRSD and nCRSD are both represented by the hard saturation models following our recent work in [10], at 2 mm/s and 3 mm/s respectively. The model is defined as:

\[
u_{CRSD} = f_{sat}(u_c) = \begin{cases} 
-u_{max}, & u_c < -u_{max} \\
u_c, & -u_{max} \leq u_c \leq u_{max} \\
u_{max}, & u_c > u_{max} 
\end{cases}
\]

where \( u_{max} \) is the maximum velocity control rod permitted. Hence, the application of saturation prevents power output overshoot for safety concern.

In conventional PCRC (cCPRC), the constant gain is used which represented by \( G2 \) in Figure 1. However, this approach is not satisfying to introduce a different level of penalizing value on the control rod speed signal to improve the drivability of the CRDM. Thus, to solve the problem, the nPCRC based on Fuzzy Logic with straight lines membership function is designed for the RTP as

\[
\hat{u}_{PCRC} = \left[ 1 - \left( \frac{u_a w_1 + u_b w_2 + u_c w_3 + u_d w_4}{u_a + u_b + u_c + u_d} \right) \right] u_{CRSD}
\]

where \( u_a, u_b, u_c \) and \( u_d \) are designed based on linear membership functions, and \( w_i \) (for \( i = 1, 2, 3, 4 \)) is an adjustable weighting parameter that can be varied at different levels of the penalty based on the rate of power change as shown in [11].
The three-pronged control strategy is unified into a single model with PI controller in Eq. (3) as follows:

\[
\rho_r = G_r(i_{CRSA}) \left[ 1 - (1 - \alpha) \left( \frac{u_aw_1 + u_bw_2 + u_cw_3 + u_bw_4}{u_a + u_b + u_c + u_ab} \right) \right] \left[ \frac{G_3E_{fi} + G_4\int_{t_0}^{t} E_{fi} dt}{u_c \pm u_{\text{CRSD}}} \right] \pm u_{\text{max}}
\]

Referring to Eq. (7), switching function is employed to select either cPCRC or nPCRC where \( \alpha \) is set to 1 for cPCRC and \( \alpha = 0 \) for nPCRC. The integration of the three new prongs is illustrated in Figure 2.

**Figure 2.** Block Diagram of the Multipronged Core Power Control.

The improved version of FCA using the single-prong control strategy has been published in [9-11] with the sequence prong as shown in Figure 3. The design of nPCRC prong based on [11] requires minimum changes of original structure FCA.

The combination of new two-prongs and the new three-prongs which defines the new multiprong control strategy. The input signal starts with an error deviation that leads to actuation signal at the CRDM. The new prong component in the block diagram is marked with green colour.
Figure 3. Block Diagram of RTP Core Power Control Design Framework.

In this study, for easier to reference the strategy name from Figure 3 will need to be defined with an alphabet in Table 1. To investigate the capability of the proposed control strategy in Table 1, the strategy is simulated in the next section.

Table 1. Defined strategy name for types of core power control system in RTP

| Type                        | Label                  |
|-----------------------------|------------------------|
| Original                    | FCA-cCRSA-cCRSD-cPCRC  |
| New Single-Prong Control Strategy | FCA-nCRSA-cCRSD-cPCRC  |
| New Multiprong Control Strategy | FCA-nCRSA-nCRSD-cPCRC  |
|                             | FCA-cCRSA-nCRSD-nPCRC  |
|                             | FCA-nCRSA-cCRSD-nPCRC  |
|                             | FCA-nCRSA-nCRSD-nPCRC  |
5. Results and discussion

The linearized model of the TRIGA reactor is modeled using Eq. 2 with the existing FCA in Eq. 3. The validation of the RTP simulation model using the experimental data has been reported in our previous work [9-10]. The FCA parameters are set to 12.3, 0.08, 10 and 1e-7 for G1, G2, G3, and G4, respectively.

The combination of the conventional, new single-prong and, the new multiprong control strategy in Figure 3 produce eight types of core power control system. The performance for each combination is profiled and analyzed to determine its suitability for the system. To observe the effect of nPCRC, the rate of power change is set to ±12.5%FP/s as maximum allowable limit set by the Final Safety Analysis Report.

In the simulation, an initial low power of 10% FP is set for 0 ≤ t < 200s and 75% nominal core power is set for 200s ≤ t ≤ 700s to simulate condition of sudden power demand. The performance of the tested prongs are evaluated through the power maneuvering of the core power control and actuation signal of the CRDM as shown in Figure 4 and Figure 5 respectively.

![Figure 4. The power tracking performance with a single and multiprong control strategy approach.](image)

The performance of the new single-prong and multiprong control strategy are benchmarked with the existing (A) control strategy represented by the red line in Figure 4 and Figure 5. The quantitative performance characteristic of the existing, new single-prong, and new multiprong control strategy are presented in Table 2. In addition, workload and energy released are calculated based on the accumulation signal and area under the graph.
Figure 5. The comparison of velocity control signal between single and multiprong control strategy approach.

Generally, Figure 4 shows that the new multiprong control strategy which is indicated by yellow, turquoise, brown, grey lines able to significantly improve the power tracking performance than the original FCA. However, prong combination such as (F) which represented by the turquoise line generate limited effect on tracking control performance that is inferior to the single-prong control strategy such as (B) which indicated by green line. All multipronged control strategy able to improve the smoothness of the velocity signal which is beneficial in reducing the possibilities of mechanical drive damage at CRDM as shown in Figure 5. Also, minimise the power output overshoot for wide-range operation at RTP is guaranteed.

Table 2. Transient and steady-state response for multipronged core power control at 750kW.

| Type                      | Settling Time, $T_s$ (s) | Rise Time, $T_r$ (s) | Percent Overshoot, $P_{os}$ (%) | Chattering Error, $\Delta e_{ce}$ (%) | Work Load (mm/cycle) / Energy Released (kW-h) |
|---------------------------|--------------------------|----------------------|-------------------------------|--------------------------------------|-----------------------------------------------|
| Original                  | (A) 112.5                | 84.0                 | 0.001076                       | 0.027155                             | 105.56 / 5334.69                             |
| New Single-Prong Strategy | (B) 62.0                 | 40.0                 | 0.000639                       | 0.002947                             | 60.00 / 5774.26                              |
|                           | (C) 90.0                 | 59.5                 | 0.000868                       | 0.015175                             | 105.63 / 5590.44                             |
|                           | (D) 113.5                | 86.0                 | 0.001308                       | 0.026213                             | 105.55 / 5299.06                             |
| New Multiprong Strategy   | (E) 57.5                 | 31.5                 | 0.000562                       | 0.002544                             | 60.00 / 5830.51                              |
|                           | (F) 88.5                 | 58.8                 | 0.001067                       | 0.013630                             | 105.63 / 5594.64                             |
|                           | (G) 63.5                 | 42.0                 | 0.000863                       | 0.002940                             | 59.98 / 5723.76                              |
|                           | (H) 55.5                 | 23.0                 | 0.000744                       | 0.002263                             | 60.01 / 5837.95                              |

By referring to Table 2, the (B) design provides the most responsive reactivity compared to other single-prong control strategy with reduced settling and rise times. In addition, it is also capable of significantly reducing the workload and optimizes energy release from the reactor core. By changing the control rod speed in (C), this prong can still produce a small settling time and chattering error better
performance compare to (D). However, (C) still unable to reduce non-smooth control surface during transient. The higher control rod speed can overcome the wind-up problem and provide high reactivity insertion rate. However, it may not be the best velocity signal to reduce the workload without the help from nCRSA prong.

The core power tracking performance based on the application of fuzzy logic for PCRC such as (D) produced result almost similar to the original FCA (A) except for small chattering error due to less sensitivity effect introduced by nPCRC prong. Therefore, (D) is not sufficient to improve the current tracking performance without combination with other prong.

In the case of multiprong control strategy, the combination of nCRSA and increase of the control rod speed (nCRSD) label as (E) able to boost up the tracking performance to be at par with the single-prong strategy (B). The (E) is the best solution to eliminate the unsmooth control surface during the transient region. Based on the data from Table 2, the (H) is the best performing control strategy in term of reducing settling time, rise time, and minimum chattering error with high optimal energy release. However, there is still room for improvement in term of the smooth control surface and actuation signal performances during transient which mainly caused by the effect nPCRC.

Based on several predefined performance criteria [10], the performance of all multipronged types are summaries in Table 3. Overall, all multipronged types produced small settling time and chattering error which fulfil the two main criteria in designing the core power system. However, the (E) type is advantageous since it able to produce better result in controlling the reactor power in all aspects. With nPCRC, (H) control strategy is a better choice in the case for a long period of operation which produce less chattering error, better drivability of the CRDM, and better optimization for high energy release in the core.

| Type | Small settling time | Fast response | Smooth control surface during transient | Smooth actuation signal during transient | Small chattering error during steady-state | Small actuation signal during steady-state | High Energy Released |
|------|---------------------|---------------|----------------------------------------|----------------------------------------|------------------------------------------|------------------------------------------|----------------------|
| New Single-Prong Control Strategy | (B) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| (C) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| (D) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

| New Multiprong Control Strategy | (E) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| (F) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| (G) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| (H) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

**6. Conclusion**

A study of the multipronged core power control strategy for the TRIGA reactor is presented to provide greater level of operational safety with a realistic design towards solving practical problems. The new multiprong control strategy is analyzed and profiled to improve the current tracking performance of core power control at RTP. Instead of using new single-prong control strategy with nCRSA, nCRSD, and nPCRC, the new multiprong control strategy consider other alternative to offer wide solutions in optimizing the core power control performance reactor. The significant finding from this study is that the new multipronged core power system able to provide better understanding about the relationship between element in the core power control system and provide insight for future research on this area.
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