Adaptive control method for core power control in TRIGA Mark II reactor

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Abstract. The 1MWth Reactor TRIGA PUSPATI (RTP) Mark II type has undergone more than 35 years of operation. The existing core power control uses feedback control algorithm (FCA). It is challenging to keep the core power stable at the desired value within acceptable error bands to meet the safety demand of RTP due to the sensitivity of nuclear research reactor operation. Currently, the system is not satisfied with power tracking performance and can be improved. Therefore, a new design core power control is very important to improve the current performance in tracking and regulate reactor power by control the movement of control rods. In this paper, the adaptive controller and focus on Model Reference Adaptive Control (MRAC) and Self-Tuning Control (STC) were applied to the control of the core power. The model for core power control was based on mathematical models of the reactor core, adaptive controller model, and control rods selection programming. The mathematical models of the reactor core were based on point kinetics model, thermal hydraulic models, and reactivity models. The adaptive control model was presented using Lyapunov method to ensure stable close loop system and STC Generalised Minimum Variance (GMV) Controller was not necessary to know the exact plant transfer function in designing the core power control. The performance between proposed adaptive control and FCA will be compared via computer simulation and analysed the simulation results manifest the effectiveness and the good performance of the proposed control method for core power control.

Keywords: Core Power Control, Adaptive Control, Model Reference Adaptive Control, Self-Tuning Generalised Minimum Variance Controller, Reactor TRIGA PUSPATI

1. Introduction

In this paper, the nuclear Reactor TRIGA PUSPATI (RTP) operating at Malaysian Nuclear Agency is modelled adopting a zero dimensional approach, in order to reproduce the dynamic behaviour of the reactor on the entire operative range. TRIGA Mark II is a nuclear reactor widely used as non-power nuclear reactor in many applications, including production of radioisotopes, neutron radiography, basic research on the properties of material and for education and training.

The RTP has recently been equipped with a new Feedback Control Algorithm (FCA) capable of controlling reactor power [4]. Currently, the system is working not satisfied power tracking performance. In order to improve the current controller, the development of a non-linear dynamic control method is necessary. In this paper, the model reference adaptive control (MRAC) and self-tuning control (STC) were applied for the control of core power. The performance between proposed adaptive control and FCA will be compared via computer simulation and analysed the simulation results manifest the effectiveness and the good performance of the proposed control method for core power control.
model of the reactor and adaptive control were necessary. The model was validated by comparing the experimental results of the behaviour of the power of the reactor controlled by the FCA.

2. Modelling

2.1. Non-Linear Model  
The behaviour of the whole TRIGA reactor can be described by combine the equation of point kinetic, thermal-hydraulic, mass flow rate and reactivity [12].

2.1.1. Point Kinetics Equations:

\[
\begin{align*}
\frac{d\psi}{dt} &= \frac{\beta - \beta}{A} \psi + \sum_{i=1}^{6} \lambda_i \eta_i \\
\frac{d\eta_i}{dt} &= \frac{\beta_i}{A} \psi - \lambda_i \eta_i \quad i = 1, \ldots, 6
\end{align*}
\]  

(1)

2.1.2. Thermal-Hydraulic Equation:

\[
\frac{dT_m}{dt} = \frac{P(1-f)}{r_m K} + \frac{T_f - T_m}{r_m} - \frac{\gamma_m (T_m - T_{in})}{r_m K}
\]

(2)

2.1.3. Mass Flow Rate Equation:

\[
\Gamma = \frac{\rho w (T_f - T_m)}{c_m (T_m - T_{in})}
\]

(3)

2.1.4. Reactivity Equation:

\[
\rho = a_h \Delta h_{cr} + \alpha_m (T_m - T_m) + \alpha_f (T_f - T_f^0)
\]

(4)

2.2. Linear Model  
The behaviour of the whole TRIGA reactor can be described by combine the equation of point kinetic, thermal-hydraulic, mass flow rate and reactivity [12].

\[
\begin{align*}
\psi(t) &= 1 + \delta \psi(t) \\
\eta_i(t) &= 1 + \delta \eta_i(t) \\
\rho(t) &= \delta \rho(t)
\end{align*}
\]

(5)

According perturbations theory, the linearization of the nonlinear equation system is achieved:

2.2.1. Point Kinetics Equations:

\[
\begin{align*}
\delta \psi &= \frac{-\beta}{A} \delta \psi + \sum_{i=1}^{6} \frac{\beta_i}{A} \delta \eta_i + \frac{\alpha_m}{A} \delta T_m + \frac{\alpha_f}{A} \delta T_f + \frac{\alpha_h}{A} \delta h_{cr} \\
\delta \eta_i &= \lambda_i \delta \psi - \lambda_i \delta \eta_i \quad i = 1, \ldots, 6
\end{align*}
\]

(6)

2.2.2. Thermal-Hydraulic Equation:

\[
\begin{align*}
\delta T_m &= \left[ \frac{\rho c(1-f)}{r_m K} \right] \delta \psi - \xi_1 \delta T_m + \frac{1}{r_m} \delta T_f + \xi_2 \delta T_{in} \\
\delta T_f &= \left[ \frac{\rho c}{r f K} \right] \delta \psi + \frac{1}{r f} \delta T_m - \frac{1}{r f} \delta T_f
\end{align*}
\]

(7)
where,

\[
\tau_m = \frac{M_m C_m}{K}, \quad \tau_f = \frac{M_f C_f}{K},
\]

\[
\xi_1 = \frac{1}{\tau_m} + \frac{C_m r}{\tau_m K w}, \quad \xi_2 = \frac{C_m r}{\tau_m K w} \tag{9}
\]

2.2.3. Reactivity Equation:

\[
\delta \rho = \alpha_h \delta h_{cr} + \alpha_m \delta T_m + \alpha_f \delta T_f \tag{10}
\]

Since the transient response of a linear system is characterized by the poles of the transfer function, it will be appropriate to formulate the linear stability problem in terms of transfer function and block diagram. Applying the Laplace Transform to the above equations, the system transfer function of neutron density over control rod position, \((\delta h_{cr} = \delta h)\) is obtained [12].

\[
\psi(s) = \frac{\alpha_h}{s^4 + \beta - \sum_{i=1}^{6} (\beta_i s^{n_i})} \left( \frac{\alpha_m}{s^4 + \beta - \sum_{i=1}^{6} (\beta_i s^{n_i})} \right) \frac{1}{\tau_m (s \tau_f + 1)} \tag{11}
\]

where,

\[
\alpha = \frac{\rho^o}{K}, \quad \gamma = \frac{\rho^o (1-f)}{K} \tag{12}
\]

In this way, normalized neutron density in the reactor core is possible and equivalent to power density. The reactor power level in percentage can be obtained by multiplied neutron density with 100. In table 1 all the physical quantities and parameters of the model are summarized [16].

**Table 1. RTP Model Parameters.**

| Group | \(B_i\) | \(\lambda_i\) |
|-------|---------|-------------|
| 1     | 0.00023 | 0.0124     |
| 2     | 0.00153 | 0.0305     |
| 3     | 0.00137 | 0.1114     |
| 4     | 0.00277 | 0.3014     |
| 5     | 0.00081 | 1.1363     |
| 6     | 0.00029 | 3.0137     |

| Symbol | Quantity | Value            |
|--------|----------|------------------|
| \(T_{in}^0\) | Initial inlet water temperature | 32°C |
| \(C_m\) | Moderator specific heat capacity | 4187 J kg\(^{-1}\)K\(^{-1}\) |
| \(C_f\) | Fuel specific heat capacity | 601.95 J kg\(^{-1}\)K\(^{-1}\) |
| \(M_m\) | Moderator total mass | 846 kg |
| \(M_f\) | Fuel total mass | 207.45 kg |
| \(\Gamma\) | Coolant mass flow rate | 6.7 kg s\(^{-1}\) |
| \(K\) | Global heat transfer coefficient | 5000 W \(^0\)C\(^{-1}\) |
| \(\rho^0\) | Steady-state power level | 1x10\(^{-6}\) W |
| \(W\) | Weighting factor for computation of moderator temperature | 0.5 |
| \(F\) | Fraction of power deposited in the fuel | 1 |
| \(\Lambda\) | Mean neutron generation time | 36 \(\mu\)s |
| \(\beta\) | Delayed neutron fraction | 700x10\(^{-5}\) | \(\Delta k/k\) |
| \(\alpha_f\) | Reactivity due to change in temperature fuel | -0.1 m \(\Delta k/k^0\)C |
| \(\alpha_m\) | Reactivity due to change in temperature moderator | 1x10\(^{9}\) \(\Delta k/k^0\)C |
2.3. Low Order Nominal Plant Model

The control design objective for this research is to obtain a low order controller that can deal with a defined range of power levels. It is important to note that the model representing the RTP is essentially a linearized model of the nonlinear point kinetics with two temperature feedback.

The method of specifying low order nominal plant order for this control design by using an approximation based on the analytical method or ‘physics’ of the process.

The analytical method approach for choosing \(\psi(s)\) uses a one delayed neutron group representing an average response of the delayed neutrons and, uses the singular perturbation techniques to eliminate the fast dynamics represented by the first state. The 2\(^{rd}\) order linear model without temperature feedback, based on this approximation of the ‘physics’, is [18]:

\[
\frac{\psi(s)}{h(s)} = \frac{\alpha_n}{s + \beta} - \frac{\beta x}{s + \lambda}
\]  
(13)

The dynamics of the system in the frequency domain can be summarised in block diagram form shown in figure 1 [19]:

![Block diagram of the dynamic system](image)

**Figure 1.** Block diagram of the dynamic system.

The transfer function from reactivity input, \(G_r\), to neutron density in reactor core, \(\psi(s)\) is [20]:

\[
\frac{\psi(s)}{\rho_r(s)} = \frac{\frac{1}{A} (s + \lambda)}{s^2 + (\lambda + \frac{1}{s}) s + \frac{\beta x}{s + \lambda}} \approx \frac{\frac{1}{A} (s + \lambda)}{s^2 + \left(\frac{\beta x}{A}\right) s}
\]  
(14)

By initially assuming ideal signal conditioning and rod drive dynamics which instantaneously provides a speed that matches the speed demand signal, \(Z_d(s)\), control rod position dynamics can be represented as a pure integral function which has a Laplace transform equal to \(\frac{1}{s}\). The control rod transfer function \(G_r\) can be simply represented as \(\frac{W}{s}\) where \(W\) is the total reactivity worth of the rod and rod speed, \(Z_d(s)\) is computed in units of fraction of core length per second:

\[
\delta \rho_r = G_r Z_d
\]  
(15)

Applying the Laplace Transform to the Eq. (14), the reactivity due to control rod movement is obtained:

\[
\rho_r(s) = \left(\frac{W}{s}\right) Z_d(s)
\]  
(16)

The resulting 3rd order linear model, based on this approximation of the ‘physics’, is:
\[ \frac{\psi(s)}{Z_d(s)} = \frac{w(s+\lambda)}{s^{\frac{1}{2}} + \frac{\Delta k}{k}} = \frac{W(s+\lambda)}{As^3 + \beta s^2} \]  

(17)

Table 2 shows parameters which were used in the above dynamic equation.

| Symbol | Value |
|--------|-------|
| \( \beta \) | \( 0.007 \) |
| \( \lambda \) | \( 0.1 \text{ s}^{-1} \) |
| \( W \) | \( 0.002274 \text{ cm}^{-1} \) |
| \( A \) | \( 36 \mu\text{s} \) |

### 3. Adaptive controller design

Adaptive control is a type of controller that has the ability to adjust itself to any parameter variations occurring in a control system. It has been applied to many e.g. in Selamat et al. (2008). In classical control strategies, the coefficients of the controller are fixed and pre-specified by the designer. This may not be sufficient to provide satisfactory performance for systems that are time-varying, subject to changes in operating conditions or disturbance acting on them.

Adaptive control is needed to overcome difficulties in determining suitable control laws there are satisfactory over a wide range of operating conditions [23].

Adaptive control such as MRAC and STC are dealing with complex systems that have unpredictable parameter deviations and uncertainties. The basic objective to maintain consistent performance of a system in the presence of uncertainty and variations in plant parameters. Adaptive control is superior to robust control in dealing with uncertainties in constant or slow-varying parameters [32].

MRAC and STC can be designed using both Direct and Indirect approaches. We consider Direct MRAC design rely on the Lyapunov Stability Theory and Indirect STC design combine with an online recursive plant parameter estimator for this research.

#### 3.1. MRAC controller

The structure of MRAC system is shown in figure 2 below [23]. Basically the MRAC consist of four main components: 1) Plant to be controlled, 2) Reference model to generate desire closed loop output response, 3) Controller that is the time-varying and whose coefficients are adjusted by adaptive mechanism, and 4) Adaptive mechanism that uses error to produce controller coefficient.

![Figure 2. General structure of an MRAC system](image)

Regardless of the actual process parameters, adaptation in MRAC takes the form of adjustment of some or all of the controller coefficients so as to force the response of the resulting closed-loop control
system to that of the reference model. Therefore, the actual parameter values of the controlled system do not really matter.

The MRAC can be designed such that the globally asymptotic stability of the equilibrium point of the error different equation is guaranteed. To do this, the Lyapunov Second Method is used. It requires an appropriate Lyapunov function to be chosen, which could be difficult. This approach has stability consideration in mind and is also known as the Lyapunov Method. A closed-loop system with a controller that has the following parameters is considered: 1) \( r(t) \) = Reference input signal, 2) \( u(t) \) = Control signal, 3) \( y(t) \) = Plant output, 4) \( y_m(t) \) = Reference model output, and 5) \( e(t) \) = Difference between plant and reference model output = \( y(t) - y_m(t) \).

In this research, a PI-controller with adjustable parameter is parameterized and provides tracking [25]. A PI-controller can be described by the following equation:

\[
u(t) = K \left( e(t) + \frac{1}{T_i} \int_0^t e(t) \, dt \right)
\]

where \( T_i \) is the integration time constant, \( K \) is a constant and \( e \) is the error. If the controller is tuned to be slow and \( T_i \) is large, then the controller first acts like P-controller, but later the as the integration starts to take effects, the steady-state deviation goes slowly to zero. In PI-controller, the steady state deviation will finally go to zero. If the controller is tuned to be fast and \( T_i \) is small, then both terms (P and I) will affect the control signal all the way from the beginning. The system becomes faster, but the output signal might oscillate.

The reference model specifies the ideal response \( y_m(t) \) to the external command \( r(t) \). The use of a reference model for control can be traced to the nuclear reactor system. Often, the situation therein is such that the controls designer are sufficiently familiar with the plant to be controlled and its desired properties. Thus, by choosing the structure and parameters of a reference model suitably, its outputs can be used as the desired plant response. While in principle such a model can be linear or nonlinear, considerations of analytical tractability have made linear reference models more common in practice.

In order to design the controller we have linearized the system and obtain a low order nominal plant model, and then designed a linear controller for it. RTP model in this work is described by a third order transfer function. For the reactor power to have a smooth tracking, a reference model is used to provide the reactor with appropriate power changes to get to the desired power (Z.S. Alavi et al., 2009). The reference model used is given by Equation (21). The PI-controller has the form given in Equation (22).

3.1.1. Plant:

\[
G_p(s) = \frac{w(s+0.1)}{(36\times10^{-9})s^2+0.007s^2}
\]

(19)

3.1.2. Reference Model:

\[
G_m(s) = \frac{0.2}{s^2+s+0.2}
\]

(20)

3.1.3. PI-Controller:

\[
u = -ky + k_i \frac{d}{s}(r - y) = \theta_1r - \theta_2
\]

where,

\[
\theta_1 = \frac{k_i}{s} , \quad \theta_2 = \frac{sk + k_i}{s}
\]

(21)
In designing an MRAC using Lyapunov the following step should be followed:

- Derived a differential equation for error, \( e = y - y_m \) (i.e. \( e, \dot{e}, \ddot{e} \)) that contains the adjustable parameter, \( \theta \).

\[
\begin{align*}
    e &= y - y_m \\
    \dot{e} &= \dot{y} - \dot{y}_m \\
    \ddot{e} &= \ddot{y} - \ddot{y}_m \\
    \dddot{e} &= \dddot{y} - \dddot{y}_m
\end{align*}
\]  \hspace{1cm} (22)

- Find a suitable Lyapunov function \( V(e, \theta) \) – usually in quadratic form to ensure positive definiteness:

\[
V(\dddot{e}, e, X_1, X_2, X_3, X_4) = \lambda_1 \dddot{e}^2 + \lambda_2 \dot{e}^2 + \lambda_3 e^2 + \lambda_4 X_1^2 + \lambda_5 X_2^2 + \lambda_6 X_3^2 + \lambda_7 X_4^2
\]  \hspace{1cm} (23)

where \( \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6 > 0 \) positive definite.

The derivative of \( V \) become,

\[
\dot{V} = 2\lambda_1 \dddot{e} \dddot{e} + 2\lambda_2 \dot{e} \dot{e} + 2\lambda_3 e \dot{e} + 2\lambda_4 X_1 \dot{X}_1 + 2\lambda_5 X_2 \dot{X}_2 + 2\lambda_6 X_3 \dot{X}_3 + 2\lambda_7 X_4 \dot{X}_4
\]  \hspace{1cm} (24)

where for stability \( \dot{V} < 0 \).

- Derive an adaptation mechanism based on \( V(e, \theta) \) such that \( e \) goes to zero.

\[
\dot{X}_1 = \dot{\theta}_2 = \frac{w \lambda_1}{36 \times 10^{-6} \lambda_4} \dddot{y} \dot{e}
\]  \hspace{1cm} (25)

\[
\dot{X}_2 = \dot{\theta}_2 = \frac{0.1w \lambda_1}{36 \times 10^{-6} \lambda_5} \dot{y} \dot{e}
\]  \hspace{1cm} (26)

\[
\dot{X}_3 = \dot{\theta}_1 = -\frac{w \lambda_1}{36 \times 10^{-6} \lambda_6} \dddot{r} \dddot{e}
\]  \hspace{1cm} (27)

\[
\dot{X}_4 = \dot{\theta}_1 = -\frac{0.1w \lambda_1}{36 \times 10^{-6} \lambda_7} \dddot{r} \dddot{e}
\]  \hspace{1cm} (28)

The summing equation from (26) to (29) obtained:

\[
\begin{align*}
    \theta_1 &= \frac{k_i}{s} = -\frac{w \lambda_1}{2(36 \times 10^{-6}) \lambda_6} \dddot{r} \dddot{e} - \frac{0.1w \lambda_1}{2(36 \times 10^{-6}) \lambda_7} \dddot{r} \dddot{e} \\
    \theta_2 &= \frac{sk + k_i}{s} = \frac{w \lambda_1}{2(36 \times 10^{-6}) \lambda_4} \dddot{y} \dddot{e} + \frac{0.1w \lambda_1}{2(36 \times 10^{-6}) \lambda_5} \dddot{y} \dddot{e}
\end{align*}
\]  \hspace{1cm} (29)

The adjustable parameter for MRAC design using Lyapunov method:

\[
\begin{align*}
    \frac{d\theta_1}{dt} &= \dot{\theta}_1 = -y_1 e r \\
    \frac{d\theta_2}{dt} &= \dot{\theta}_2 = y_2 e y
\end{align*}
\]  \hspace{1cm} (30)

The closed loop system block diagram designed as shown in figure 3 below:
3.2. GMVC controller

In this section we look at how the self-tuning GMVC is used to control the RTP. In self-tuning GMVC it is not necessary to know the exact plant transfer function since the controller parameters are estimated directly.

The discrete-time transfer function can be obtained from converted continuous transfer function in previous 3rd order linear model. The plant can be represented as:

\[ G_p(z^{-1}) = \frac{z^{-k}B(z^{-1})}{A(z^{-1})} = \frac{z^{-1}(157.07W-142.78Wz^{-1})}{1-2z^{-1}+2z^{-2}-3.58x10^{-8}z^{-3}} \] (31)

In GMVC controller, a pseudo output as in Eq. (31) is introduced

\[ \phi(t + k) = Py(t + k) - Rw(t) + Qu(t) \] (32)

where: \( y(t+k) = \) Output, \( w(t) = \) Set point or Servo signal, \( u(t) = \) Input, and \( P, R, Q \) value = set by designer.

In GMV controller, the identity is given by equation (33) below:

\[ AE + z^{-k}G = PC \] (33)

where

\[ E = 1 + e_1z^{-1} + \cdots e_{n_e}z^{-n_e} \]
\[ G = g_0 + g_1z^{-1} + \cdots + g_{n_g}z^{-n_g} \] (34)

For a unique solution, the following are ensured:

\[ n_e = k - 1 \]
\[ n_g = max\{n_a - 1, n_p + n_c - k\} \] (35)

The GMV controller law used:

\[ u(t) = \frac{H}{F} w(t) - \frac{G}{F} y(t) \] (36)

where, \( F = BE + QC \) and \( H = RC \).
Figure 4 illustrates the general structure of a GMV controller block diagram (S.F. Sulaiman et al., 2013).

![GMV Controller Block Diagram](image)

**Figure 4. The structure of the Self-Tuning GMVC**

The self-tuning GMV controller algorithm used in this study can be summarized as follows, at each controller sample time $t$:

- **Step 1**
  
  Based on equation (33), equation as below is determined:
  
  $$\emptyset(t) = P y(t) - R w(t - k) + Q u(t - k)$$

- **Step 2**
  
  Estimate the controller parameter $F$, $G$ and $H$ using the recursive least square (RLS) estimation algorithm.
  
  Replacing $k=1$, equation (37) can be written in regression from as below:
  
  $$\emptyset_{RLS}(t) = [y(t - 1) \ y(t - 2) \ y(t - 3) \ u(t - 1) \ u(t - 2) - w(t - 1)] \ \begin{bmatrix} \hat{\phi}_0 \\ \hat{\phi}_1 \\ \hat{\phi}_2 \\ \hat{f}_1 \\ \hat{f}_2 \\ \hat{f}_0 \end{bmatrix}$$

- **Step 3**
  
  Calculate and apply the GMVC control to the system.
  
  $$u(t) = \frac{\hat{F}}{F} w(t) - \frac{\hat{G}}{F} y(t)$$

- **Step 4**
  
  The algorithm is repeated for the next iteration or sampling time.

As mentioned earlier in (32), the value of parameters $P$, $Q$ and $R$ was set by the designer. Thus, in this work, the value of $P$ and $R$ is assumed to be 1, while $Q$ value to be 0.64.

### 4. Results and analysis

The MRAC Lyapunov approach is simulated using Matlab SIMULINK with the reference input of a square wave signal with the amplitude of 1 and frequency 0.0025Hz. Figure 5 shows the outputs for $y$.
and $y_m$ of the system with model reference adaptive controller designed based on the Lyapunov method, with the same adaptation gain value, $\gamma_1$ and $\gamma_2$, of 10 respectively.

![The Output of Lyapunov Method](image)

**Figure 5.** Output signal of the system using the Lyapunov method.

Based on observation from the above output signal, designing an MRAC using the stability approach will ensure a stable closed loop system.

Figure 6 shows the output performance of the GMV controller. From a simulation result obtained, response from Self-Tuning GMV controller gives the best stability result and allowable value of percentage overshoot which is only less than 10% of overshoot.

![Output response of GMV controller](image)

**Figure 6.** Output response of GMV controller

4.1. **Adaptive Controller Applied to RTP Model**

Dynamic equations of a RTP are nonlinear equations. So some part of complexity of designing a controller and getting answer is because of its nonlinearity. The system has ten states and the ten state equations which increases the complexity.

In our designs the controller is designed in a classic way (a linear controller) and the attempt was to use the reactor model as precise as possible. So we have used all ten states completely and we have used the precise values of coefficients in non-linear RTP model.

The performance of MRAC design based on the reference model shown in Figure 7. The rising time was very short and rated of power change more than 33.3% per second and overshoot more than 110% FP that causing the reactor to TRIP. However, if the TRIP limit parameters are not considered in this simulation the reactor power is still converges to zero and reached steady-state. The error between the reference model output and the reactor output become relatively large at the moment of sudden change of Power Demand (PDM) at 1000 seconds, but eventually converges to zero quickly. Based on this result shown that modification of MRAC are needed during transient.
4.2. Modification of Adaptive Controller

The modification of MRAC and GMVC are for safety and operation purpose. Basically the reactor power tracking power during transient is the main issues to be considered. The current controller which is FCA controller was designed based on control theory and calculate the motor control command using error between actual power and PDM. The rate of power change limitation and increment power limitation included during the design of FCA.

The drawback of FCA is slow tracking compare to the adaptive controller. The proposed combination of adaptive and FCA should produce better performance during transient and steady-state. The propose controller for modified MRAC (M-MRAC) shown in figure 9 [26], while for the modified GMVC (M-GMVC) shown in figure 10.
4.2.1. Controller MRAC:

\[ u_{MRAC} = -ky + \frac{k_1}{s}(r - y) = \theta_1 r - \theta_2 y \]  

(39)

4.2.2. Controller M-MRAC:

\[ u_{M-MRAC} = u_{MRAC} + u_{FCA} \]  

(40)

4.2.3. Controller GMVC:

\[ u_{GMVC} = gain \cdot \left( \frac{g}{F}y - \frac{h}{F}w \right) \]  

(41)

4.2.4. Controller M-GMVC:

\[ u_{M-GMVC} = u_{GMVC} + u_{FCA} \]  

(42)

Figure 11 shows the result of estimated self-tuning M-GMVC controller parameter. The sampling time used is 0.2s. The solid lines that indicate in yellow, purple, cyan, red, green and blue colours are shows the estimated values, \( \theta_0, \theta_1, \theta_2, f_1, f_2 \) and \( \hat{h}_0 \) over the simulation period. It can be observed that the estimated, whose initial value is \( \theta(t) = 0 \), slowly converge to the actual values showing that the RLS estimator has effectively estimated the system parameters.
Figure 11. Estimated self-tuning M-GMVC controller parameters.

The result of feedback controller and modified adaptive controller shown in Figure 12. From the graph below, the set point PDM signal which is unit step indicate in the red colour. While the blue represent the FCA controller that need the improvement in this research. The green colour for M-MRAC and black colour for M-GMVC both present the improvement result after modification.

Figure 12. Feedback Controller vs Adaptive Controller.

The summary performance of three controller shown in table 3 quantitatively. Based on table 3, clearly describe the behaviour of each controller. Adaptive controller provide a good result in term of rise time and settling time. However, both type of controller good in eliminating error and make the reactor power output follow the PDM at steady-state.
6. Activities are necessary in order to reach the best optimum of the new adaptive controller for RTP.

5. Conclusion
A dynamic model of the RTP was developed in order to design FCA and adaptive controllers. Experimental results of the controller in FCA from RTP were compared with the simulation results FCA and adaptive controller (M-MRAC and M-GMVC) showing the goodness of the model. The analysis shows that an M-GMVC offers generally better results than the FCA which reduce settling time up to 25% of the nominal settling time. However further investigations and experimental activities are necessary in order to reach the best optimum of the new adaptive controller for RTP.

6. References
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