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# REAL TIME IMPLEMENTATION OF FIRST ORDER MODEL REFERENCE ADAPTIVE CONTROL (MRAC) WITHOUT INTEGRAL ON REGULATING TEMPERATURE OF GLYCERIN BLEACHING PROCESS

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## ABSTRACT

This paper presents the design and implementation of model reference adaptive control (MRAC) on temperature regulation of glycerin bleaching process. The established first order MRAC design based on Lyapunov approach is considered. For developing robust MRAC performance, simple modification has been made by removing the integral term on the adaptation rule of MRAC in order to prevent the controller from windup phenomenon. The performance analysis of the controller was carried out using standard transient analysis with 2% band, while mean square error (MSE) is used for steady state analysis. Initially, the performance of MRAC without integral was analyzed via simulation scheme and followed by real time implementation afterward. Both of the results, from the simulation and real time execution, indicate the effectiveness of this modification towards the performance of MRAC. Also, it offers robust performance throughout temperature regulation of glycerin bleaching process. A comparative study with real time performance of PID with back calculation anti windup controller denote that MRAC without integral is capable to provide better performance on regulating temperature of glycerin bleaching process.

**Keywords:** glycerin bleaching process, model reference adaptive control, windup, PID, integral, and actuator constraint.

## INTRODUCTION

The aim of bleaching process is to remove the colour pigment and turns crude glycerin into white translucent colour using adsorption process. During this process, temperature is regulated to a specific temperature and maintained for certain period around 15 to 120 minutes depending on the characteristic of crude glycerin, adsorption material and also dosage of the adsorption material. At this stage, temperature influence significantly the successful of bleaching process. An optimum temperature will lead on higher efficiency of adsorption process [1]. This is due to the capability of bleaching agent to adsorb pigment colour onto its outer and pore surface at high temperature whereas under low temperature the bleaching agent is only capable to adsorb pigment color onto its outer surface only. However, unwanted side reaction such as darkening process intead of discoloration process due to increment of temperature beyond the desired value and too long heating process[2].

Nevertheless, controlling temperature for bleaching process is challenging and tough, particularly in providing fast response with small overshoot and maintaining desired transient performance. This is due to the characteristics of bleaching process itself that possess slow dynamic response and nonlinearities that concern with the scale of the plant and system constraint. Moreover, this process is conducted in batch process where several existing characteristics of batch process that will degrade the performance of controller are frequent start-up and shutdown[3], raw material purity level[4] and incorrect reactor loading[5]. All of the mentioned factors, will cause the transient response to deteriorate and produce undesirable response such as large overshoot. One of the impacts of large overshoot is large settling times that will slowdown the production rate. This situation will get worsen if the bleaching process do not have specific cooling system and solely depending on its ambient environment. By considering all of these aspects, it is desirable to have a robust and reliable control technique to precisely regulate the temperature in glycerine bleaching process.

Nowadays, advanced controller is being used widely in industry as to improve the system performance whilst increasing the rate of production, maintaining end product quality and fulfill the safety requirement. There are many approach of avalaible advanced controllers such as adaptive controller. MRAC is one of the most popular adaptive controllers and commonly used in control system that enclose unknown dynamic, parameter variation or change over time. Unique characteristics of MRAC allow desired performance specification to be given in terms of reference model, where the controller is continuously adjusted so that the system output approaches asymptotically to the output of reference model which provide desired response to command signal[6]. This feature allows designers to set the desired transient performance simply by adjusting the reference model either to acquire fast or slow transient output. Currently, MRAC become potential controller in solving industrial problem and has been implemented in many process such as in temperature control [7], pH control[8], and level control[9]. Motivates by these successful implementations of MRAC, this study are focusing on implementation of MRAC in temperature control of glycerine bleaching process.

Careful MRAC design is needed to ensure the controller capability in compensating the nonlinearities of the system and promote robust temperature regulation for glycerin bleaching process. The established Lyapunov approach in [10] is designed by assuming that there are no nonlinearities involve in the process and this MRAC approach is working well as well as be able to achieve the desired performance[11]. However, during actual operating, most of the control systems face nonlinear characteristics such as actuator constraint. The occurrence of actuator saturation will lead MRAC to instability problems due to divergence of adaptation gain when process output is mismatch with reference model. This situation is initiates by the existence of integral term in adaptation law that are continuously accumulates the integral gain due to integration of error that caused the controller output accumulates beyond the maximum and minimum operating point of the actuator. This situation is also known as windup phenomenon.

For preventing the MRAC from windup phenomenon and to provide robust performance while regulating temperature of glycerin bleaching process, the simple modification has been carried out by removing the pure integral inside the adaptation rule of MRAC. Eventhough, the preliminary study that emphasis on the effectiveness of this modification has been presented in [12], it only focuses on simulation study. Therefore, as advancement from the previous outcome, both of simulation and real time performance are discussed intensively. Moreover the comparative study of the performance MRAC without integral with PID controller with back calculation also discussed in this paper.

## SYSTEM DESCRIPTION AND MODELING STRATEGY

The study is based on glycerin pilot plant located at Distributed Control System (DCS) Laboratory of Electrical Engineering in UiTM, Shah Alam. The plant is being interface with computer using NI data acquisition card and LabVIEW programming tool is used as control platform. Detail descriptions of the plant and system interfacing are as described in [13].

The heating process model of glycerin bleaching process is derived using empirical approach. In this case, linear Auto-Regressive with Exogenous Input (ARX) model is employed. Methodology on model development, including data collection, experiment setup, data organization and model validation used in this study are as described in [13].The resulted first order ARX model is as shown in Equation (1) with best fit 99.67%.

$$y_p(s) = \frac{B(s)}{A(s)} = \frac{0.01078}{s + 0.0001411} \tag{1}$$

## MODEL REFRERENCE ADAPTIVE CONTROL

The formulations of MRAC for heating process of glycerine bleaching process are based on established Lyapunov approach for first order system. Considering a system with the following first order model:

$$y_p = \frac{b_p}{s + a_p} u_c \tag{2}$$

where $b_p$ represent the process gain, $u_c$ represent the control input and $a_p$ represent the poles of the system.

The desired system dynamic is set to first order reference model as described in Equation. (3) where $b_m$ and $a_m$ stands for known constant and $r$ is the reference input. The parameter of $b_m$, $a_m$ and $r$ are needed to be chosen so that $y_m$ represents the desired process dynamic.

$$y_m = \frac{b_m}{s + a_m} r \tag{3}$$

In this case, controller output, $u_c$ is updating based on the following formula:

$$u_c = \theta_1 r - \theta_2 y_p \tag{4}$$

where $\theta_1$ and $\theta_2$ are adaptation laws that being continuously update to track the $y_p$ as closely as possible with $y_m$ in which the error signal, $e = y_p - y_m$.

For deriving an adaptation law based on Lyapunov theory, the following Lyapunov function defined in [14] is used.

$$V(e,\theta_1,\theta_2) = \frac{1}{2}\left(e^2 + \frac{1}{b\gamma}(b\theta_1 - b_m)^2 + \frac{1}{b\gamma}(b\theta_2 + a_p - a_m)^2\right) \tag{5}$$

By taking derivatives of Equation. (5), the change of error with respect to time can be described with the following equation.

$$\dot{V}(e,\theta_1,\theta_2) = -e\dot{e} + \frac{1}{\gamma}\dot{\theta}_1(b\theta_1 - bm) + \frac{1}{\gamma}\dot{\theta}_2(b\theta_2 + a_p - a_m) \tag{6}$$

Then, by substituting $\dot{e} = \dot{y}_p - \dot{y}_m$ into Equation. (6) as described in [10] yields

$$\dot{V}(e,\theta_1,\theta_2) = -a_m e^2 + \frac{1}{\gamma}(b\theta_2 + a_p - a_m)(\dot{\theta}_2 - \gamma y_p e) + \frac{1}{b\gamma}(b\theta_1 - b_m)(\dot{\theta}_1 + \gamma r e) \tag{7}$$

According to Lyapunov theorem, the stable equilibrium is achieved when the time derivative $\dot{V}$ is negative semidifinite in which $\dot{V}(e,\theta_1,\theta_2) \le 0$ [15]. Then the resulted adaptation laws in the form of s-domain are as described below:

$$\theta_1 = -\frac{\gamma r e}{s} \tag{8}$$

$$\theta_2 = \frac{\gamma y_p e}{s} \quad (9)$$

where $\gamma$ is represent for the adaptation gain.

The existence of pure integral on the adaptation laws trigger deterioration of MRAC performance especially when the nonlinearities, such as input constraint, exist within the system and cause the controller to suffer windup phenomenon [16, 17]. To overcome this undesirable behavior, it is necessary to modify the adaption law so that robust MRAC that has capability to compromise with nonlinearities is designed. Tremendeous work was conducted upon several decade with one of the basis concept in modification of MRAC adaptation law is by focusing on elimination of integral action effect [18] either by adding the feedback loop on adaptation law [19] or by stopping the adaptation under certain condition [20]. Based on these basis idea, simple modification of adaptation law has been made to avoid unsatisfactory performance of MRAC which is caused by pure integral action while regulating temperature of glycerin bleaching process. The modification is accomplished by removing the integral term of adaptation laws as similar as discussed in [12], thus the resulting adaptation laws are described as

$$\theta_1 = -\gamma u_c e \quad (10)$$

$$\theta_2 = \gamma y e \quad (11)$$

The resulting block diagram of MRAC without integral is as shown in Figure-1.

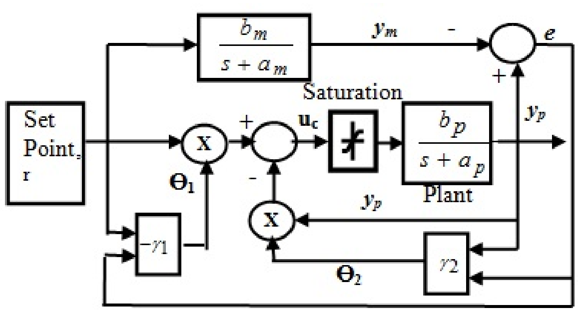


**Figure-1.** Block diagram MRAC without integral.

The reference model has been design based on the desired settling time, Ts. During plant operation, the temperature is regulated from 30 °C to 85 °C (desired setpoint). Based on ±2% band, the desired settling time is achieved at 83.9 °C. From the open loop experiment data shown in [13], the time required to achieved from 30 °C to 83.9 °C is approximated to 2200 second. However, this desired settling Time, Ts is based on sampling time of 1 second. In order to change the sampling time of the desired settling time, Ts into 2 second as similar as sampling time used for model development, it necessary to divide this desired settling time, Ts with two. Then, from the desired settling time, the reference model are defined formulation described in [21]. Then the reference model can be described as follow;

$$G_m = \frac{1}{275s+1}. \quad (12)$$

## RESULTS AND DISCUSSION

This section is arranged as follows, where the results of adaptation gain selection for MRAC without integral will be described first. Secondly the simulation results of comparative performance between MRAC without integral with standard MRAC is presented.This is followed by real time performance of MRAC without integral. Lastly the comparative performance of real time operation between MRAC without integral with PID with backcalculation anti-windup is discussed. During the experimental work, the desired set point, r is set to 85°C with initial temperature is set at 30 °C. All of the experiment was conducted within 12000 second duration. The transient analysis of the controller performances is conducted based on percentages overshoot, %μ(s) and settling time, Ts based on 2% band while for steady state analysis mean square error (MSE) is used and the measurement is taken starting at 4000 second to 12000 second. The robustness evaluation for the controller is confirmed via two separate tests which are set point changes, and load disturbances recovery. The set point change test was conducted with the following temperature set point, r, condition;

$$r = \begin{cases} 60^o C, & 0 < t < 6000 \\ 90^o C & 6001 < t < 12000 \end{cases} \quad (13)$$

where t is referred as time. For load disturbances test, the test is carried out by injecting step input with a magnitude -15 °C during steady state conditions.

The selection of adaptation gain for MRAC without integral is carried out depending on the following response criteria which are the speed to reach settling time with minimal overshoot, small value of mean square error (MSE) and the aggressiveness of controller output. During this process, trial and error approach is used. Due to space limitations, only three different adaptation gain value are presented including the best one as shown in Table-1 while Figure-2 shows the behaviour of the controller output.

**Table-1.** Analysis of MRAC without integral with difference value adaptation gain.

| No. | Adaptation Gain, γ | | Settling Time, Ts | Percent Overshoot ,%μ(s) | MSE |
|---|---|---|---|---|---|
| | $\gamma_1$ | $\gamma_2$ | | | |
| 1. | -0.1 | 0.1 | 2158s | 0.05% | $4.7\times10^{-4}$ |
| 2. | -0.01 | 0.01 | 2158s | 0% | $1\times10^{-4}$ |
| 3. | -0.001 | 0.001 | 2158s | 0% | 0.0028 |

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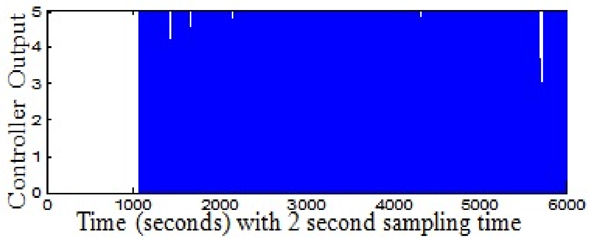

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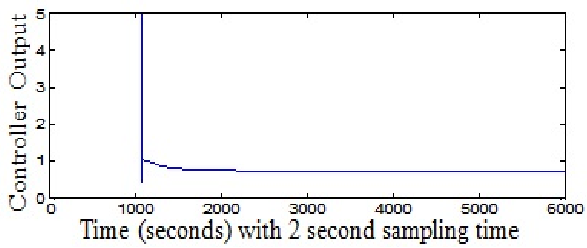

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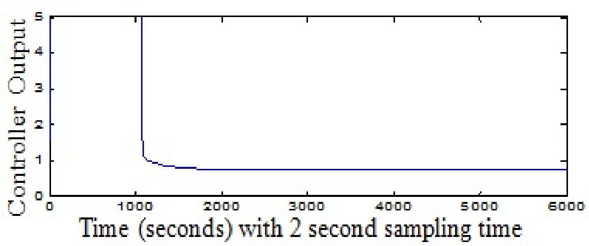
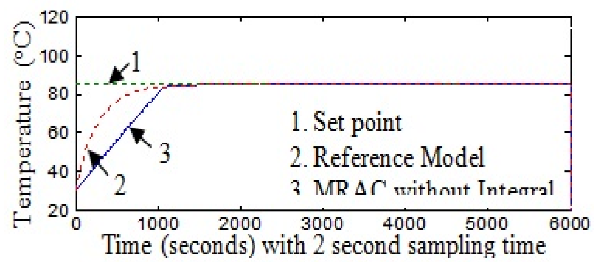


(c)

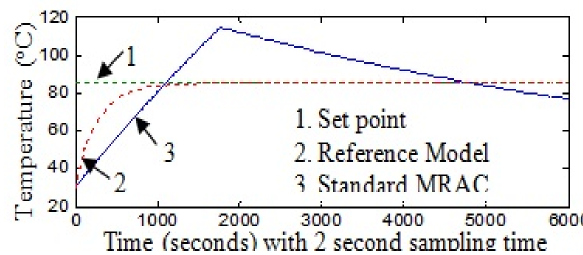
**Figure-2.** Controller bahaviour with difference value adaptation gain; (a) ±0.1, (b) ±0.01, (c) ±0.001.

From the results shown in Table-1, all of the tested adaptation gain value provide almost similar transient behavior. However the 0% overshoot is achieved by using adapataion gain equal to ±0.01 or ±0.001 while for MSE analysis, the smallest value of MSE is obtained by using the adaptation gain value equal to ±0.01. For controller output bahaviour shown in Figure-2, too aggressive controller is obtained when adapation gain value is equal to ±0.1 when compared to controller output behavior with adaptation gain value equal to ±0.01 or ±0.001. Therefore, based on this results, the best performance of MRAC without integral is obtained by choosing the adaptation gain equal to ±0.01 due to 0% overshoot, smallest value MSE and nonaggressive controller output behavior.

The comparative simulation performance of MRAC without integral and standard MRAC with adaptation gain equal to ±0.01 is shown in Figure-3 and Figure-4 and the analysis are as shown in Table-2 and Table-3 respectively. For load disturbances recovery, the comparative of MRAC without integral with standard MRAC does not carried out due to fact that the standard MRAC does not reach steady state condition along the test period. The simulation results of MRAC without integral in recovery load disturbances is shown in Figure-5. Based on this results, it is clearly shown that, the MRAC without integral provide robust performance and has the capability to compensate the impact of nonlinearities (actuator constraint) compared with the standard MRAC in regulating temperature of glycerin bleaching process.

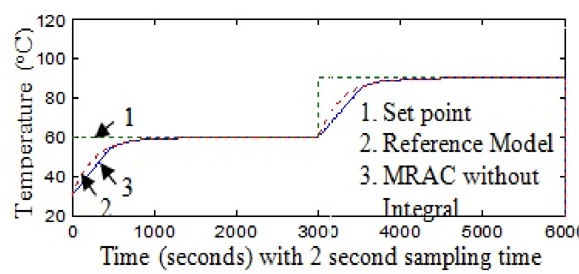


(a)

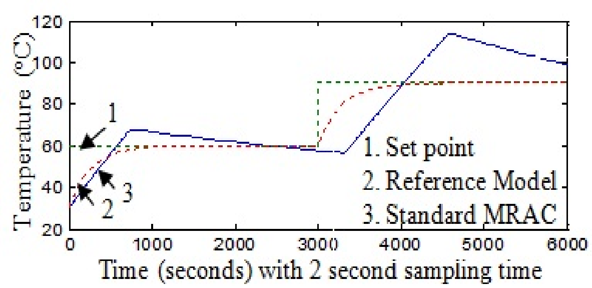


(b)

**Figure-3.** Comparative performance at temperature 85 °C; (a) MRAC without integral, (b) standard MRAC.



(a)



(b)

**Figure-4.** Comparative performance on set point change ; (a) MRAC without integral, (b) standard MRAC.

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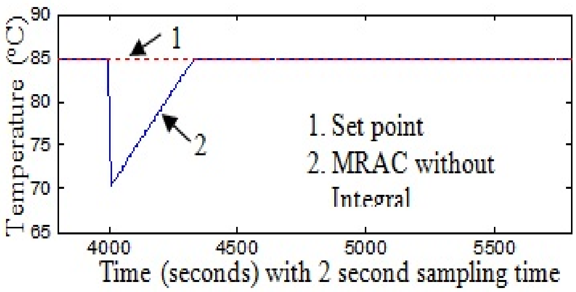



**Figure-5.** Performance of MRAC without integral on recovery load disturbances.

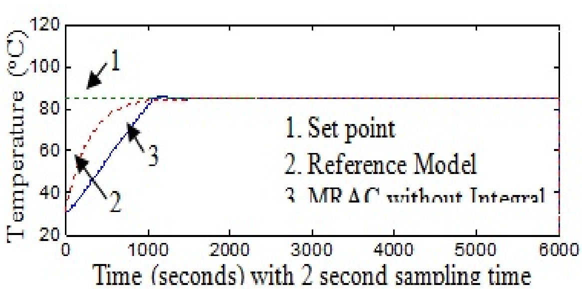
In order to verify the simulation performance of MRAC without integral, real time test was carried out and the results are as shown in Figure-6. These results demonstrate the capability of the MRAC without integral in providing robust performance while regulating temperature of glycerin bleaching process.

**Table-2.** Performance analysis of standard MRAC and MRAC without integral.

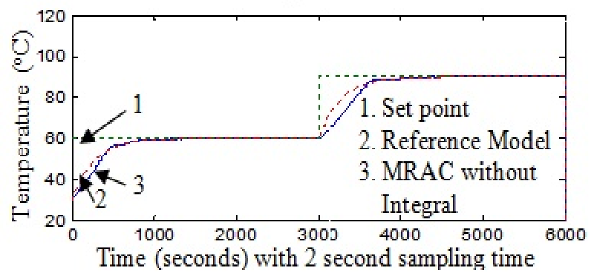
| No. | MRAC | Settling Time, Ts (second) | Percent Overshoot ,%μ(s) | Time recovery Disturbances (second) |
|---|---|---|---|---|
| 1. | Without Integral | 2158 | 0% | 620 |
| 2 | Standard | Not reach | 53.9% | - |

**Table-3.** Performance analysis of standard MRAC and MRAC without integral for set point tracking.

| No. | Set point (°C) | MRAC | Settling Time, Ts (second) | Percent Overshoot ,%μ(s) |
|---|---|---|---|---|
| 1. | 60°C | Without Integral | 2158 | 0% |
| | | Standard | Not reach | 26.7% |
| 2. | 90°C | Without Integral | 2158 | 0% |
| | | Standard | Not reach | 80.5% |




(a)

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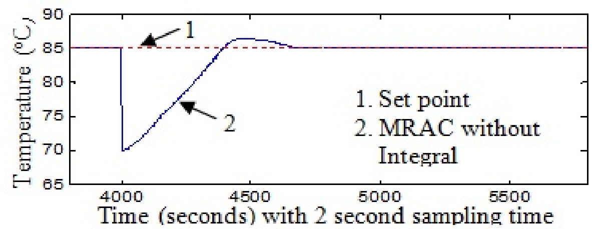
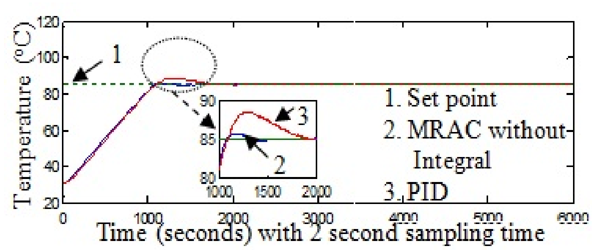


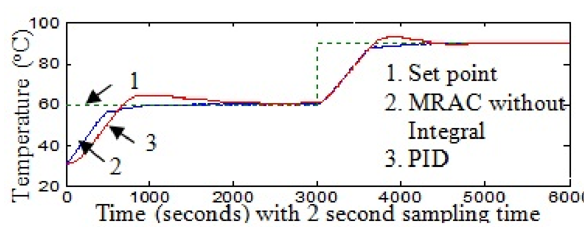

(c)

**Figure-6.** Real time performance of MRAC without integral; (a) Set point at 85oC, (b) Set point Tracking, and (c) Recovery load disturbances.

The real time performance of MRAC without integral has been compared with PID with back calculation antiwindup to facilitate the extent of improvement given by MRAC. In this case, PID with ISE-Load tuning with tracking time constant equal to Td is choosen as the candidate for comparative purpose. The selection of PID tuning is based on implementation of PID with back calculation antiwindup on temperature regulation of glycerin bleaching process as discussed in [13]. The comparative performance of MRAC without integral with PID with back calculation anti windup are shown in Figure-7 and the analysis of the performance are as shown in Table-4 and Table-5.




(a)

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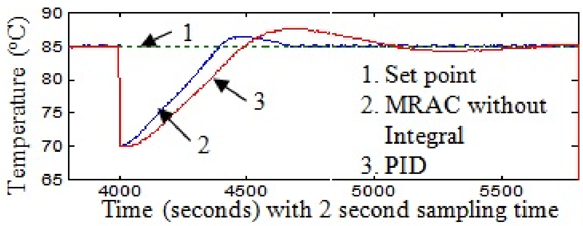


(c)

**Figure-7.** Real time comparative performance of MRAC without integral with PID controller; (a) Set point at 85oC, (b) Set point Tracking, and (c) Recovery load disturbances.

**Table-4.** Analysis of MRAC without integral and PID controller.

| No. | Controller | Settling Time, Ts (second) | Percent Overshoot, %μ(s) | Time recovery Disturbances (second) |
|---|---|---|---|---|
| 1. | MRAC Without Integral | 2102 | 1.2% | 1124 |
| 2. | PID | 3356 | 6.4% | 1814 |

**Table-5.** Analysis of MRAC without integral and PID controller for st point tracking.

| No. | Set point (°C) | Controller | Settling Time, Ts (second) | Percent Overshoot ,%μ |
|---|---|---|---|---|
| 1. | 60°C | MRAC Without Integral | 2152 | 0% |
| | | PID | 4600 | 15% |
| 2. | 90°C | MRAC Without Integral | 2152 | 0% |
| | | PID | 2672 | 10.7% |

These comparative results and analysis signify the capability of MRAC without integral in towards providing faster settling time, low overshoot and faster recovery time during load disturbances, as compared with PID controller.

## CONCLUSIONS

The simulation and real time study of implementation MRAC without integral has been discussed in this paper. Results obtained highlight the capability of MRAC without integral, in improving the performance of standard MRAC while regulating temperature for glycerin bleaching process. Comparison with PID with back calculation anti windup results a better controller performance especially in preventing overshoot, providing fast settling time and recovery of load disturbances. Based on these findings, this research offers an alternative method on the implementation of MRAC towards the efficiency enhancement in controlling temperature of glycerin bleaching process.

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