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# Studies on Implementation of PI Control Techniques in Direct Methanol Fuel Cell

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**Abstract:** Direct Methanol Fuel Cell (DMFC) offers one of the most promising alternatives to the replacement of fossil fuels. However the effective design of the fuel cell may be, it cannot perform effectively without proper control system. PI controller is the most widely used in electrochemical process due to their simplicity, robustness and successful practical applications. Many tuning rules have been proposed for PI controller tuning and design. This paper takes a qualitative look at six PI controller tuning methods, with comparison of accuracy and effectiveness. PI Controller has been designed from the DMFC model parameters (K, T, and L). Its performances are analysed based on the servo response curve. Controller objective values are obtained from the step response. To strengthen the performance of the best controller, error signal analysis and effect of control signal actuating the final control element and good control criteria are recorded and analysed. Robustness of the model is verified with ±15% step changes in the model parameters.
**Keywords**: DMFC, Step response, Tuning rule, PI Controller, ISE, IAE.

## Introduction

During early days of the century, three mode controllers with proportional, integral, and derivative (PID) actions became commercially available and gained widespread industrial acceptance. These types of controllers are still the most widely used controllers in process industries. This success is a result of many good features of this algorithm. Many tuning methods have been proposed from 1942 to till date for gaining better and more acceptable control system response based on our desirable control objectives such as percent of overshoot, integral square error (ISE), integral of absolute value of the error (IAE), settling time, manipulated variable behaviour The open loop tuning techniques refer to methods that tune the controller when it is in manual state and the plant operates in open loop. The tuning rules considered for design of PI controllers [1] are Ziegler-Nichols openloop tuning method, AMIGO tuning method, SIMC tuning method, Wang-Juang-Chan tuning method, Padmasree-Chidambaram tuning method, AR tuning method. Before proceeding with a brief discussion of these methods it is important to note that the PI controller transfer function is:

$$C(s) = K_c \left(1 + \frac{1}{\tau_i s}\right) ,$$

Where, $K_c$= Proportional gain, $\tau_i$= Integral time

DMFC is showing great potential in the replacement of fossil fuels. The chief advantage of DMFC over other variants of fuel cells are that, methanol can be transported and handled with ease. Direct alcohol fuel cells are expected to replace the conventional PEM fuel cells in the foreseeable future with DMFC taking the lead [2]. The direct methanol fuel cell is a proton exchange membrane fuel cell that is fed with an aqueous solution of methanol. The two catalytic electrodes where the methanol oxidation (anode) and the oxygen reduction (cathode) occur are separated by a membrane which conducts protons from anode to cathode, while other compounds diffusion is blocked. The mere design of fuel cells does not essentially mean fuel cells are of higher efficiency. Modeling and control [3] plays a vital role in the improvement of the fuel cell efficiencies and better understanding of the DMFC operation. Even though numerous articles regarding the various processes occurring in DMFC has been published, very few deal with the modeling and control of fuel cells. This led to the development of various models and control system designs which intends to solve the problems encountered in DMFC.

## Design of Proportional Integral (PI) Controller

## Ziegler-Nichols Tuning Method

Ziegler Nichols Open loop tuning rule (1942) is the most popular method used in process control to determine the design parameters of a PI controller [4]. The open loop step response is used for getting the parameter of PI controller. The step response is based on an open-loop operation of the process. The controller gain($K_c$) and Integral time constant ($\tau_I$) are calculated from the process model parameters according to Ziegler and Nichols open loop tuning rule.

$$K_c = \frac{0.9}{K} * \frac{T}{L} \qquad \tau_I = 3.33L$$

### AMIGO tuning method

Astrom and Hagglund proposed a tuning method that accomplishes the design of controller [5] in a simple way. The method which is known as AMIGO (Approximate M Constrained Integral Gain Optimisation), which consist in applying a set of equation to calculate the parameter of the controller in a similar way to the procedure used in Ziegler- Nichols method. The AMIGO tuning rules are based on the KLT-process model obtained with a step response experiment. The suggested AMIGO tuning rule for PID Controller is

$$K_C = \frac{1}{K}\left(0.2 + 0.45 * \frac{T}{L}\right) \qquad \tau_I = \left(\frac{0.4L+0.8T}{L+0.1T}\right)L$$

### SIMC tuning method

An important advantage of the SIMC (Sigurd Skogestad IMC,2001) rule is that there is a single tuning parameter ($\tau_c$) that gives a good balance between the PI parameters ($K_c$,$T_i$), and which can be adjusted to get a desired trade-off between performance (“tight” control) and robustness (“smooth” control). SIMC rules apply to processes that can be reasonably well approximated by first order plus delay models[6]. Based on this process model parameters SIMC tunings are derived analytically.

$$K_C = \frac{0.5}{K} * \frac{T}{L} \quad \tau_I = Min(\mathrm{T}, \mathrm{8L})$$

### Wang-Juang-Chan (WJC) tuning method

Based on the optimum ITAE criterion, simple and efficient tuning algorithm (Wang, Juang, and Chan) is proposed for PI controller design [6]. If the K, L, T parameters of the plant model are known, the controller parameters can be calculated using the WJC tuning method.

$$K_P = \frac{\left(0.7303 + \frac{0.5307T}{L}\right)(T+0.5L)}{K(T+L)} \qquad \tau_I = T + 0.5L$$

### Padmasree - Chidambaram Tuning Method

A simple tuning method (PadmaSree-Chidambaram, 2003) is proposed to design PI controllers for first order plus time delay systems [7]. The method is based on matching the coefficient of corresponding first power of *s* in the numerator and that in the denominator of the closed loop transfer function for a servo problem and by specifying the initial (inverse) jump. This method gives simple equations for controller settings in terms of model parameters.

$$K_c = \frac{1}{K}\left[0.09719\left(\frac{L}{T}\right)^{-0.8915}\right] \qquad \tau_I = \frac{1}{T}\left[10059\left(\frac{L}{T}\right)^2 - 2.3588\left(\frac{L}{T}\right) + 0.8985\right]$$

**AR TUNING method**

Ala Eldin Abdallah Awouda and Rosbi Bin Mamat (AR,2008) tuning rule is used to design the PI controller based on the optimization rule [8] of ITAE performance criteria. It is an analytical method for calculating the gain of the controller (Kc) and integral time (τi) whose process is modelled in first order lag plus time delay (FOLPD) form. The objective function is selected so as to minimize the integral of Time Absolute Error (ITAE) performance index. Using crave fitting technique, design equations that define the controller parameters are driven.

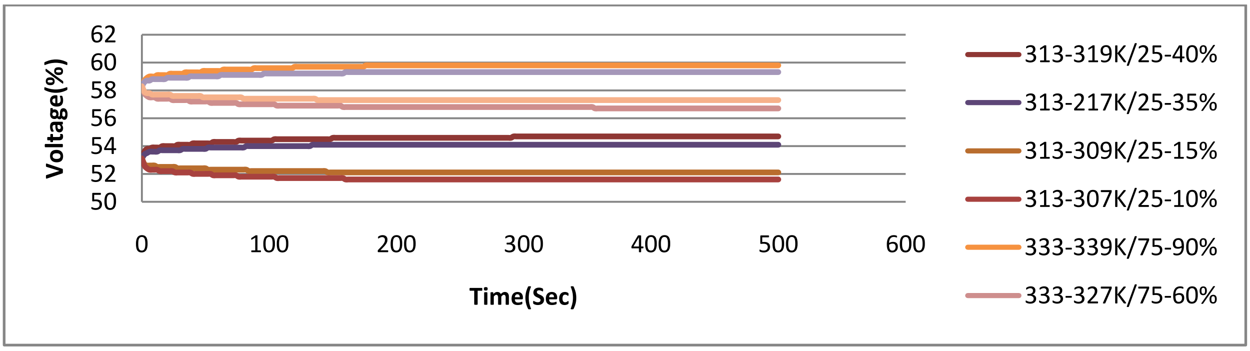
$$K_c = \left[0.3 + 0.38 * \frac{\mathrm{T}}{\mathrm{L}} + 0.007 * \left(\frac{L}{T}\right)^2\right] \qquad \tau_I = L * \left[0.5 + 0.5 * \frac{T}{L} + 0.01 * \left(\frac{L}{T}\right)^{1.5}\right]$$

## Result and Discussion

### Design of Control system for DMFC

Step responses are recorded for ±10% and ±15% step changes in the operating temperatures of the DMFC. It is observed from the step response curves (Figure- 1) that step responses are smooth and linear for the positive and negative step changes. Transfer function model parameters namely process gain, time constant and time delay are derived from the temperature based step responses 9. The most suitable model parameters are identified and used to represent the DMFC system in laplace domain. Later these model parameters (K,L,T) are used to design the PI controller using various controller tuning rules [10].

**Figure 1: Step responses at 25% and 75% of operating temperature**




$$G_p(s) = \frac{0.1}{18s + 1} e^{-2s}$$

To check the robustness of the model, ± 15% changes in model parameters [11] namely process gain, time constant and delay are calculated (Table- 1). Based on the calculated values, six different transfer function models are derived. Robustness of the process model parameters are analysed with PI controller using good control criteria and found that model under test is robust in nature.

**Table 1: Robustness test of Laplace domain model**

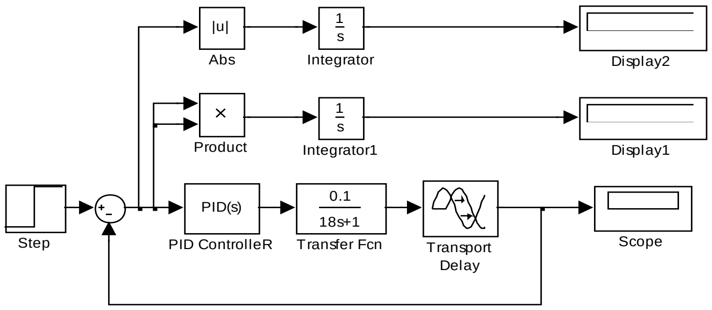
| S.No | Changes in the Process Parameters | IAE | ISE |
|---|---|---|---|
| 1 | G (Actual Process gain) | 3.107 | 0.838 |
| 2 | Gg+ (Process gain with +15%) | 3.111 | 0.839 |
| 3 | Gg- (Process gain with - 15%) | 3.103 | 0.836 |
| 4 | Gd+ (Process delay with +15%) | 3.493 | 0.937 |
| 5 | Gd- (Process delay with +15%) | 2.707 | 0.731 |
| 6 | Gtc+ (Time constant with +15%) | 3.211 | 0.865 |
| 7 | Gtc- (Time constant with +15%) | 2.980 | 0.805 |

Before proceeding with the closed loop operation of DMFC, PI controller has been designed using six different controller tuning rules namely Ziegler-Nichols tuning method , AMIGO tuning method, SIMC tuning method, Wang-Juang-Chan tuning method, Padmasree-Chidambaram tuning method, AR tuning method. The calculated PI Controller tuning parameters namely, controller gain and integral time are listed in (Table- 2). Closed loop block diagram of DMFC (Figure- 2) with PI controller is developed in MATLAB Simulink environment.

**Table 2: Controller design parameters**

| Tuning rule | $K_c$ | $K_I$ |
|---|---|---|
| Z-N | 70.4 | 9.2 |
| AMIGO | 39.7 | 4.97 |
| SIMC | 45.0 | 2.81 |
| WJC | 12.2 | 0.65 |
| PC | 6.9 | 0.49 |
| AR | 4.3 | 0.41 |

**Figure 2: Closed loop block diagram**




## Servo response analysis

The designed six different PI controller performances are evaluated in a closed loop operation using servo response [12] in the process output variable (voltage). Closed loop step responses of individual controller with DMFC are recorded and analyzed. Performance of PI ontroller is evaluated from the overall servo response curve (Figure- 3) of all designed controllers for a given step change.Further their performances are assessed with error signal analysis (Figure- 4) and control signal analysis (Figure- 5). Apart from these, performance of the controllers [3] are investigated with controller objectives and good control criteria analysis as listed in (Table- 3).

**Figure 3: Closed loop DMFC response**

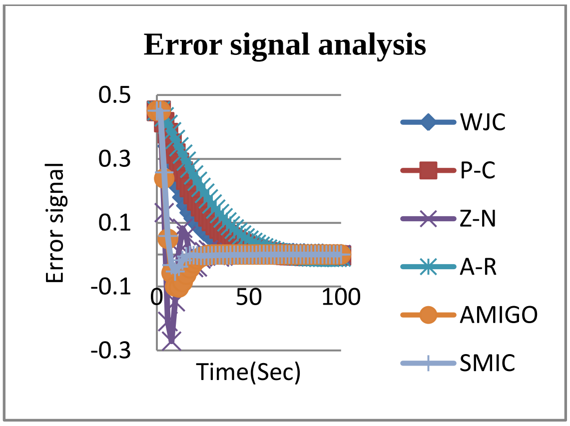


**Figure 4: Error signal curves**

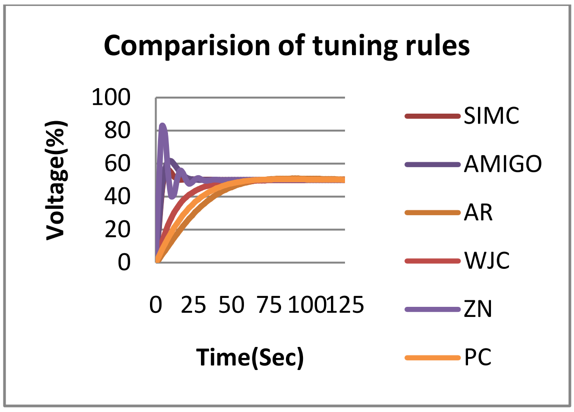



**Figure 5: Control signal curves**

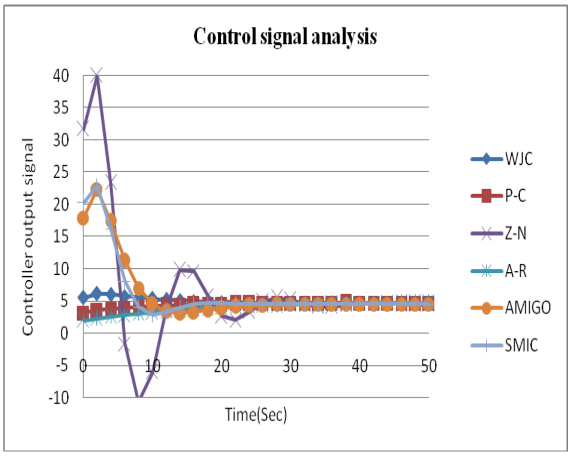



**Table 3: Controller performance analysis**

| Tuning rule | ISE | IAE | $e_{ss}$ | $t_r$ | $t_s$ | % OS |
|---|---|---|---|---|---|---|
| Z-N | 0.68 | 3.22 | 0 | 4 | 46 | 7.3 |
| AMIGO | 0.62 | 2.89 | 0 | 7 | 29 | 2.7 |
| SIMC | 0.60 | 2.34 | 0 | 7 | 38 | 1.3 |
| WJC | 1.41 | 6.8 | 0 | 85 | 85 | 0 |
| PC | 2.01 | 9.35 | 0 | 75 | 125 | 0.1 |
| AR | 2.65 | 11.9 | 0 | 72 | 148 | 0.2 |

## Conclusion

In this work, the performances of the six PI controller tuning methods are qualitatively analyzed in a direct methanol fuel cell (DMFC) system Performance of DMFC with these control techniques for a set point tracking cases are analyzed using time domain indices and error indices. Based on the said performance analysis, it is concluded that the SIMC tuning rule based PI Controller performs better than other tuning method in DMFC operation.

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