NEW TUNING RULES FOR 2-DOF PI/PID CONTROL SYSTEM USING SIMPLE DESIGN PROCEDURE

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Abstract

Using simple analytical procedure, a tuning rules for two degree of freedom (2-DOF) PI/PID controllers are presented. The proposed tuning algorithm assumes first order plus delay time and second order plus delay time as plant models to be controlled. The validity and features of the proposed tuning rules have been investigated by computer simulation study. Simulation study showed that the presented controllers have high performance response for step input changes and also that these rules are robust for load disturbance.

قواعد تنغيم جديدة لمتحكمات درجة الحرية الثنائية المكونة من المسيطرات تناسب-تكامل وتناسب-تكامل-تفاضل من خلال استخدام اجراء تصميمي بسيط

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الخلاصة:

من خلال استخدام اجراء تحليلي بسيط, تم تقديم معادلات تنغيم للمتحكمات ذات الحرية الثنائية المكونة من المسيطرات من النوع تناسب-تكامل و تناسب-تكامل-تفاضل. طريقة التنغيم المستخدمة افترضت ان المنظومات المراد السيطرة عليها من نوع الدرجة الاولى ذات الزمن الميت و الدرجة الثانية ذات الزمن الميت. صلاحية معادلات التنغيم وكذلك ميزاتها تم اثباتها من خلال دراسة استخدمت المحاكاة بالحاسب. المحاكاة هذه بينت ان معادلات التنغيم المقترحة تمتلك استجابة عالية الجودة لتغيرات الادخال التي تكون على شكل خطوات وكذلك ان المتحكمات المقترحة تكون صلبة تجاه الاضطرابات الناتجة من تغيرات الحمل.

1. Introduction

For control systems, the degree of freedom (DOF) is defined as the number of closed loop transfer functions (T.Fs.) that can be adjusted [1]. So, a 2- DOF has advantages over a 1- DOF control systems because the control design often a multi-objectives problem [1]. In spite of this fact, 2-DOF did not attract a considerable attention until recent years. Nowadays, a considerable attention has been devoted to these systems [2-4].

Proportional-Integral-Derivative (PID) controllers are with no doubt the most extensive controllers used in industrial control applications. Its simple structure and ease of use and understand are the main reasons for their success.

There are many methods for the design or tuning of PID controller. The first systematic tuning rules presented in literature was Ziegler-Nichols [5] tuning rules which had been presented in 1942. Since then, many other tuning rules have been presented. Some of these rules consider only the performance of the closed loop system [6,7], while other consider its robustness only [8,9]. Also, a combination of performance and robustness has been considered in other works [10-14].

Two control requirements are often considered in most of the industrial process control applications. These are the regulatory and servo control operation [2]. The regulatory control is the ability of the control system to reject or cancel the effect of load variations or disturbances. While, servo control is the ability of the controller to track the set point changes with good transient response. By using 1- DOF control system, we often cannot establish the two control operation satisfactory. These two requirements can more easier be established by using 2-DOF systems, where these controller can be managed to have two separate T.Fs., one for regulatory control operation and the other for servo one.

Control design for PID controllers based on optimization techniques with the aim of good stability and robustness have received attention in the literature [15,16]. Although, these methods proved their effectiveness, however, a great drawbacks involved with them:- They rely on complex numerical optimization procedures and do not provide tuning rules.

The popularity of tuning rules over the optimization technique comes from their ease to use and their wide applicability over wide range of processes.

Most of the tuning rules presented in literature like Ziegler-Nichols, Cohen-coon and others, are based on the low order plus delay time approximation of the plant model. FOPDT and SOPDT are the most commonly models used for this purpose. This is due to the fact that most processes can be effectively approximated by these two models.

In this work, we adopted simple procedure to obtain tuning rules for a 2-DOF PI/PID control system. Two sets of efficient tuning rules, one for FOPDT and the other for SOPDT have been presented.

2. Problem formulation

Fig.1 shows one possible structure for 2-DOF control systems.

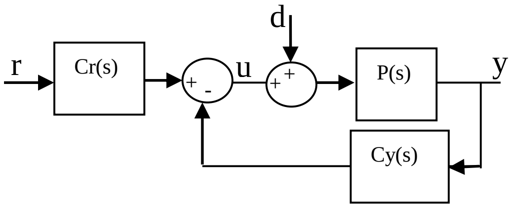

Fig.1 a 2-DOF control system.

In this figure, P(s) is T.F. of The controlled process, $C_r(s)$ is T.F of the set point controller T.F., $C_y(s)$ T.F of the feedback controller, r the set point, d is the load disturbance and y is the output of the system.

C_r and C_y are PI or PID controller with the following T.Fs.:-

-PI controller

$$C(s) = K_c\left(1 + \frac{1}{T_i s}\right) \quad (1)$$

-PID controller

$$C(s) = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) \quad (2)$$

From Fig.1, The output of the controller (U(s)) is given by:-

$$U(s) = C_r(s).r(s) - C_y(s).y(s) \quad (3)$$

The output of the system (Y(s)) is given by:-

$$Y(s) = \frac{C_r(s)P(s)}{1+C_y(s)P(s)} r(s) + \frac{P(s)}{1+C_y(s)P(s)} d(s) \quad (4)$$

From Eq.4, the output of the system is a result of two T.Fs., these are:-

$$T_{fr} = \frac{C_r(s)P(s)}{1+C_y(s)P(s)} \quad (5)$$

$$T_{fd} = \frac{P(s)}{1+C_y(s)P(s)} \quad (6)$$

T_{fr} is the T.F. from set point to system output, in other words it represents the servo control operation. T_{fd} is T.F. from load disturbance to system output, then it should play as a regulator T.F. of the overall control system.

Our aim is to design or tune the two controllers (Cy and Cr) so that T_{fr} and T_{fd} be a servo and a regulatory T.Fs. respectively with high performance. For that aim, a simple design procedure have been used to design Cr and Cy as PI and PID controllers for FOPDT or SOPDT.

3. Design procedure

The T.F. for FOPDT is given by:-

$$p(s) = \frac{K_p e^{-ls}}{Ts+1} \quad (7)$$

Where K_p is the process gain, T is the time constant and l is the dead time.

The T.F. used for SOPDT is:-

$$p(s) = \frac{K_p e^{-ls}}{t_2 s^2 + t_1 s + 1} \quad (8)$$

The design procedure for the two controllers can be summarized as follow:-

1- Substitute the equations for $C_r(s)$, $C_y(s)$ and P(s) into Eq.5 and 6.

2- Propose desired T.Fs. for T_{fr} and T_{fd} 'say T_{frd} and T_{fdd} respectively'.

3- Equate T_{fdd} with T_{fd} which result from step 1. Then manipulate the resultant equation to obtain a homogeneous polynomial equation with s. Each term in this polynomial represent homogeneous equation. The number of these equations should be equal to the number of controller (C_y) parameters. Now, these equations can be solved simultaneously to obtain controller parameters.

4- After the parameters of C_y have been obtained, the procedure described in step 3 can be applied for T_{frd} and T_{fr} to obtain C_r(s) parameters.

3.1 Controllers design for FOPDT

The T.F. for FOPDT model is described by Eq.7. Cr and Cy are selected as a PI controller with the following T.Fs.:-

$$C_r(s) = K_{cr}(1 + \frac{1}{T_{ir}s})$$

$$C_y(s) = K_{cy}(1 + \frac{1}{T_{iy}s}) \quad (10)$$

To find tuning rules for C_y(s), the procedure begins with selecting a desired regulatory T.F. 'T_{fdd}', which has been selected as follow:-

$$T_{fdd} = \frac{K_y s e^{-ls}}{(t_y T s+1)^2} \quad (11)$$

Where, Ky and t_y are design parameters. T_{fdd} is a regulatory T.F. which can be fully adjusted by their two parameters Ky and t_y. Our design procedure will lead to make one of these two parameters as an independent variable, while the other will be dependent variable related to the independent variable by an algebraic equation. So , design problem will be converted to a problem of guessing one design parameter which determine the desired regulatory behavior.

Substituting Eq.7 and 10 into 6 and equating the resulting equation with the desired regulatory T.F. described by Eq.11, then by some manipulation, the following equation can be obtained:-

$$\sigma_1 s^3 + \sigma_2 s^2 + \sigma_3 s = 0 \quad (12)$$

Where,

$$\sigma_1 = (K_y\, k_{cy}\, K_p\, l\, T_{iy} - T_{iy}(K_y T - K_p T^2 {t_y}^2)) \quad (13)$$

$$\sigma_2 = \left(K_y\, k_{cy}\, K_p\, l - T_{iy}(K_y - 2\, K_p\, T\, t_y) - K_y\, k_{cy}\, K_p\, T_{iy}\right) \quad (14)$$

$$\sigma_3 = \left(K_p\, T_{iy} - K_y\, k_{cy}\, K_p\right) \quad (15)$$

In this derivation, we have used the Pade first order approximation for time delay:-

$$e^{-ls} = 1 - ls$$

To ensure that Eq.12 is true for all values of S, we should force Eqs.13 to 15 to be equal to zero, and mathematically:-

$$K_y\, k_{cy}\, K_p\, l\, T_{iy} - T_{iy}(K_y T - K_p T^2 {t_y}^2) = 0 \quad (16)$$

$$K_y k_{cy} K_p\, l - T_{iy}(K_y - 2\, K_p\, T\, t_y) - K_y\, k_{cy}\, K_p\, T_{iy} = 0 \quad (17)$$

$$K_p\, T_{iy} - K_y\, k_{cy} K_p = 0 \quad (18)$$

Eqs.16 to 18 contains four unknown variables, the controller parameters 'K_{cy} and T_{iy}' and the two design parameters 'K_y and t_y'. We solved these equations for K_{cy}, T_{iy} and K_y, leaving t_y to be the independent design parameter to be suitably chosen. The result was the following equations:-

$$k_{cy} = \frac{2\,T^2\,t_y\ +\ l\,T - \ T^2\ t_y{}^2}{K_p(l^2\ +\ 2\,l\,T\ \ t_y\ \ \ +\ T^2\ \ t_y{}^2)}$$

$$T_{iy} = \frac{2\,T^2\,t_y + l\,T - T^2\ \ t_y{}^2}{l+T} \tag{20}$$

$$K_y = \frac{K_p(l^2 + 2\,l\,T\,t_y + T^2\ \ t_y{}^2)}{l+T} \tag{21}$$

Eqs.19 and 20 represent the tuning rules for *Cy*, while Eq.21 represents the relationship between the desired regulatory T.F. parameters *Ky* and t_y. It is clear that Ky in Eq.21 do not have to be calculated.

Now, to tune *Cr(s)*, the following T.F. for the servo control desired T.F. can be used:-

$$T_{frd} = \frac{Kre^{-ls}}{(t_r Ts + Kr)} \tag{22}$$

Eq.22 represents a servo T.F. with unity gain and the speed of response can determined by the parameter t_r.

Substituting Eqs.7, 9 and 10 into 5, and simplifying the resultant equation. Then equating the resulting equation with the right part of Eq.22. Finally, the following equation can be obtained:-

$$\sigma_1 s^3 + \sigma_2 s^2 + \sigma_3 s = 0 \tag{23}$$

With,

$$\sigma_1 = K_{cr}\,K_p\,Tty\,T_{ir}\,T_{iy}\ -\ Kr\,T_{ir}\big(TT_{iy}\ - K_{cy}\,K_p l\ \ T_{iy}\big) \tag{24}$$

$$\sigma_2 = K_r\ \ k_{cr}\,K_p\,T_{ir}\,T_{iy} - \ K_r\,T_{ir}\big(T_{iy}\ - k_{cy}\,K_p l\ +\ k_{cy} K_p T_{iy}\big) \tag{25}$$

$$\sigma_3 = K_r\ \ k_{cr} K_p\,T_{iy}\ -\ K_r\ \ k_{cy}\,K_p T_{ir} \tag{26}$$

Equating Eqs.24 to 26 to zero and solving the resultant three homogeneous equations for *Kcr*, T_{ir}, and *Kr*, the following equations can be obtained:-

$$K_{cr} = \frac{\rho}{2T_{iy}(T -\ k_{cy} K_p l)} \tag{27}$$

$$T_{ir} = \frac{\rho}{2\,K_p T t_y T_{iy}} \tag{28}$$

$$K_r = \frac{\rho}{2k_{cy} K_p T t_y} \tag{29}$$

Where,

$$\rho = \mu + Tt_y T_{iy} - k_{cy} K_p l t_r + KC_y K_p T t_r T_{iy}$$

In which;

$$\mu = \frac{\sqrt{\mathrm{Tt}_r(\,k_{cy}{}^2 K_p{}^2 \mathrm{l}^2 +\ 2\,k_{cy}{}^2 K_p{}^2 \mathrm{lT_{iy}} +\ \ k_{cy}{}^2 K_p{}^2 \mathrm{T_{iy}}^2 - 2\,k_{cy} K_p \mathrm{lT_{iy}} + 2\,k_{cy} K_p \mathrm{T_{iy}}^2 - 4\mathrm{T}\,k_{cy} K_p \mathrm{T_{iy}} + \mathrm{T_{iy}}^2)}}{2K_p \mathrm{Tt}_r \mathrm{T_{iy}}}$$

Eqs.27 and 28 represent the tuning rules for C_r, while Eq.29 represents the relationship between the desired servo T.F. parameters K_r and t_r.

3.1 Controllers design for SOPDT

The same procedure described for FOPDT is applied here.

The T.F. for SOPDT model is described by Eq.8. C_r and C_y are selected as a PID controller with the following T.Fs.:-

$$C_r(s) = K_{cr}(1 + \frac{1}{T_{ir}s} + T_{dr}s)$$

$$C_y(s) = K_{cy}(1 + \frac{1}{T_{iy}s} + T_{dy}s) \tag{31}$$

To tune Cy(s), the desired regulatory T.F. 'T_{fdd}', has been selected as follow:-

$$T_{fdd} = \frac{K_y s e^{-ls}}{(t_y t_1 s+1)^2 (t_y t_2 s+1)} \tag{32}$$

Where, as before, Ky and t_y are design parameters.

Substituting Eqs.31 and 8 into 6 and equating the resulting equation with the desired regulatory T.F. described by Eq.32. The following can be obtained:-

$$\sigma_1 s^4 + \sigma_2 s^3 + \sigma_3 s^2 + \sigma_4 s = 0 \quad (33)$$

In which,

$$\sigma_1 = K_y K_{cy} K_p l T_{dy} T_{iy} - T_{iy}(K_y t_2 - K_p {t_1}^2 {t_y}^3) \quad (34)$$

$$\sigma_2 = T_{iy}\left(K_p {t_1}^2 {t_y}^2 + 2K_p t_1 t_2 ty^2\right) + K_y K_c K_p l - K_y K_c K_p T_{dy} T_{iy} \quad (35)$$

$$\sigma_3 = T_{iy}\left(2K_p t_1 t_y - K_y + K_p t_2 t_y\right) + K_y K_c K_p l - K_y K_c K p T_{iy} \quad (36)$$

$$\sigma_4 = K_p T_{iy-} K_y K_{cy} K_p \quad (37)$$

.Now, Eqs.34 to 37 should all be equal to zero for Eq.33 to be true. Solving these equations for Kcy, T_{iy}, T_{dy} *and* Ky after equating them to zero, the following equations will result:-

$$Kcy = \frac{\delta 2}{\delta 3} \quad (38)$$

$$T_{iy} = \frac{\delta 2}{\delta 1} \quad (39)$$

$$T_{dy} = \frac{\delta 4}{\delta 2} \quad (40)$$

$$Ky = \frac{\delta 3}{\delta 1} \quad (41)$$

In these equations:-

$$\delta 1 = l^2 + t_1 l + t_2$$

$$\delta 2 = l^2 t_1 - l {t_1}^2 {t_1}^2 {t_y}^2 + 2l {t_1}^2 t_y - 2l t_1 t2 {t_y}^2 + l t_1 t_2 t_y + l t_2 - {t_1}^2 t_2 {t_y}^3 + 2 t_1 t_2 t_y + {t_2}^2$$

$$\delta 3 = K_p(l^3 + 2l^2 t_1 t_y + t_2 l^2 t_y + l {t_1}^2 {t_y}^2 + 2l t_1 t_2 {t_y}^2 + {t_1}^2 t_2 {t_y}^3 +)$$

$$\delta 4 = l^2 t_2 - l {t_1}^2 t_2 {t_y}^3 + 2l t_1 t_2 t_y - {t_1}^3 t_2 {t_y}^3 + {t_1}^2 t_2 {t_y}^2 + 2 t_1 {t_2}^2 {t_y}^2$$

Now, to tune $C_r(s)$, the following T.F. for the servo control desired T.F. have been selected:-

$$T_{frd} = \frac{K_r e^{-ls}}{(t_r t_2 t_1 s + Kr)} \quad (42)$$

Eq.42 represents a servo T.F. with unity gain and the speed of response can determined by the parameter t_r.

Substituting Eqs.8, 30 and 31 into 5, and simplifying the resultant equation. Then equating the resulting equation with the right part of Eq.42, the following equation can be obtained:-

$$\sigma_1 s^4 + \sigma_2 s^3 + \sigma_3 s^2 + \sigma_4 s = 0 \quad (43)$$

With,

$$\sigma_1 = K_p t_1\, t_2\, t_y\, T_{dr}\, T_{ir}\, T_{ir} - K_y\, T_{iy}(t_2\, T_{iy} - K_p\, l\, T_{dy}\, T_{iy}) \quad (44)$$

$$\sigma_2 = K_y\, K_p\, T_{dr}\, T_{ir}\, T_{iy} - K_y\, T_{ir}(t_1\, T_{iy} + K_p\, T_{dy} T_{iy} - K_{cy}\, K_p\, l\, T_{iy}) + K_{cr}\, K_p\, t_1\, t_2\, t_y\, T_{ir}\, T_{iy} \quad (45)$$

$$\sigma_3 = K_y\, K_{cr}\, K_p\, T_{ir} T_{iy} - K_y\, T_{ir}(T_{iy} - K_{cy} K_p\, l + K_{cy}\, K_p\, T_{iy}) + K_{cr} K_p\, t_1\, t_2\, t_y\, T_{iy} \quad (46)$$

$$\sigma_4 = K_y\, K_{cr}\, K_p\, T_{iy} - K_y\, K_{cy}\, K_p\, T_{ir} \quad (47)$$

Equating Eqs.44 to 47 to zero and solving the resultant four homogeneous equations for K_{cr}, T_{ir}, T_{dr} and K_r, the following equations can be obtained:-

$$kcr = \frac{Kp\, l\, T_{dy}\, \beta^2 - t_2\, \beta^2 + t_1 t_2\, t_y\, \beta + \ldots}{K_p\; t_1{}^2 t_2{}^2\; t_y{}^2} \ldots \frac{}{K_p\, t_1\, t_2\;\, t_y T_{dy}\;\, \beta \;-\; K_{cy}\, K_p l\;\, t_1 t_2\;\, t_y\, \beta} \quad (48)$$

$$T_{ir} = \frac{t_1{}^2 t_2{}^2\;\, t_y\, T_{iy}\, \beta - t_2\, T_{iy}\, \beta^2 + K_p\; l\, T_{dy} T_{iy}\, \beta^2 + \ldots}{K_{cr}\, K_p\;\, t_1{}^2 t_2{}^2\, t_y{}^2} \ldots \frac{}{K_p\;\; t_1 t_2\;\; t_y\, T_{dy}\, T_{iy}\, \beta\;\; - K_{cy} K_p\; l\, t_1 t_2\, t_y\, T_{iy}\, \beta} \quad (49)$$

$$T_{ir} = \frac{\beta(t_2 - K_p l T_{dy})}{K_p\, t_1\, t_2\;\, t_y} \quad (50)$$

$$Ky = \beta \quad (51)$$

Where, β is one of the real roots of z of the following third order polynomial:-

$$\begin{aligned}(K_p\; l\, T_{dy}\, T_{iy} - t_2\, T_{iy})z^3 &\\ + \big(K_p\; t_1\; t_2\; t_y\; T_{dy}\; T_{iy} &\\ - K_{cy}\; K_p l\; t_1 t_2\; t_y\; T_{iy} &\\ +\;\; t_1{}^2\, t_2\;\; t_y T_{iy}\;\big) z^2 &\\ + \big(\; K_{cy}\; K_p\; l\; t_1{}^2\; t_2{}^2\;\; t_y{}^2 &\\ -\;\; t_1{}^2\, t_2{}^2\;\; t_y{}^2\, T_{iy} &\\ -\; K_{cy}\; K_p\; t_1{}^2\; t_2{}^2\;\; t_y{}^2\, T_{iy}\big) z &\\ +\; K_{cy}\; K_p\; t_1{}^3 t_2{}^3\; t_y{}^3 = 0 &\end{aligned}$$

Eqs.48 to 50 represent the tuning rules for C_r, while Eq.51 represents the relationship between the desired servo T.F. parameters K_r and t_r.

4. Simulation study

In this section, the tuning rules presented in this paper are applied to control two randomly selected FOPDT and SOPDT models. 0 to 100% normalized range for the set point and the controlled variable (the output) have been assumed in the normal operation. These variables are assumed close to 70%. All of these assumptions have been chosen to have results close to industrial practice situations.

4.1 FOPDT

The following equation describes the FOPDT chosen for our simulation study:-

$$p(s) = \frac{5e^{-0.6s}}{10s + 1}$$

Selecting t_y= t_r =0.12 and applying Eq.19, 20, 27 and 28, we have K_{cy}=0.72, T_{iy}=1.5, K_{cr}=1.53 , T_{ir}=3.18.

The selection of the independent design parameters t_y and t_r depends on simple guess which can be obtained by noticing the desired servo and regulatory T.Fs. which are described by Eqs.11 and 22 respectively. From these equations the designer can easily predict that the suitable values of t_y and t_r depend mainly on the time constant of the process model T, because the time constant for desired servo and regulatory T.Fs. are t_yT and t_rT respectively. Then, for larger T smaller t_y and t_r should be selected and vice versa. The process of guessing t_y and t_r 'which can be selected as the same value' may be need for some trial and error process to obtain perfect values.

To investigate the performance of the presented tuning rules, the system has been simulated by using Simulink tool of Matlab for 50 seconds, zero initial condition was assumed, then a step input of 70% has been applied at the beginning of simulation to reach the normal operation (70%), then at second 20, an 20% step change has accrued, a load disturbance of 10% has been applied at the second 30 and continues applied till the end, then at the second 40 the set point have returned to normal operation.

Fig.2 shows the output of the controlled system during the simulated 50 seconds, while Fig.3 shows the output during the first 10 seconds.

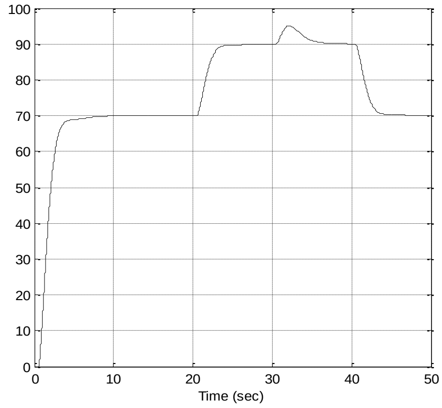

Fig.2 The output of the FOPDT system for the 50 seconds of simulation

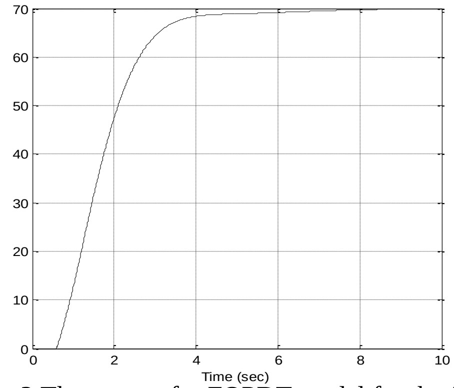

Fig.3 The output for FOPDT model for the first 10 seconds of simulation

4.2 SOPDT

The SOPDT model used is described by the following equation:-

$$p(s) = \frac{7e^{-0.5s}}{5s^2 + 10s + 1}$$

Choosing t_y= t_r =0.15 and applying the tuning rules described by equations 38 to 40 and 48 to 50, we get K_{cy}=0.43, T_{iy}=0.92, T_{dy}=0.24 K_{cr}=1.47 , T_{ir}=3.19, T_{dy}=0.43.

We have simulated the system for 50 seconds also and for the same events described for the previous case.

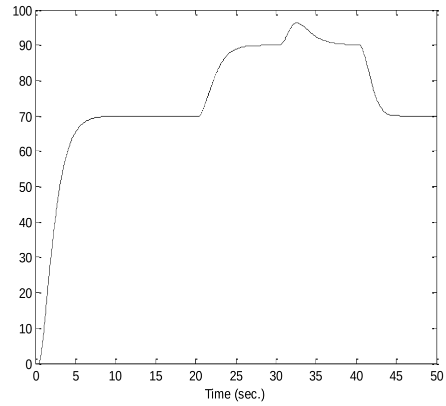

Fig.4 The output SOPDT for the 50 minutes of simulation

Fig.4 shows the output of the system for all time of simulation, while Fig.5 shows the output for the first 10 seconds.

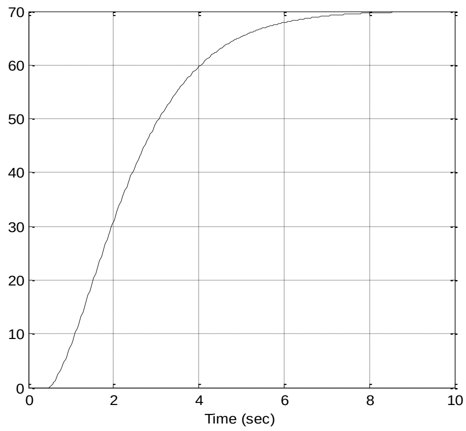

Fig.5 The output SOPDT for the first 10 minutes of simulation

5. Conclusion

A new and not difficult to apply tuning rules for 2-DOF PI/PID controllers have proposed. The procedure used to design these tuning rules is simple and straightforward, however it needs for some hard manipulation. FOPDT and SOPDT models which extensively used to approximate high order plants by low order with input delay are the two models used as controlled plants models for the proposed tuning rules. Simulation study assuming circumstances similar to that faced in industrial conditions has been made. All of the targets for simulation study have been obtained, and as demonstrated through the following points:-

1- The proposed tuning rules are valid and easy to apply to obtain the controller parameters
2- The proposed tuning rules for both FOPDT and SOPDT give excellent transient response for step inputs changes, where they give fast and negligibly overshoot. Also, they give perfect steady state error.
3- The proposed tuning rules give very good for response for load disturbance, where cancelation of load change has been taken place in relatively small time.

Extending the design procedure for more general models is our suggestion for future works.

6. References

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