DETERMINATION OF OPTIMUM CONTROL PARAMETERS OF PI (PROPORTIONAL INTEGRAL) CONTROLLER IN FEEDBACK CONTROLLER SYSTEMS BY NEW CORRELATIONS

GERİ BESLEMELİ KONTROL SİSTEMLERİNDE PI (ORANSAL İNTEGRAL) KONTROL EDİCİNİN OPTİMUM KONTROL PARAMETRELERİNİN YENİ KORELASYONLARLA SAPTANMASI

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GAMZE İŞ

ABSTRACT

DETERMINATION OF OPTIMUM CONTROL PARAMETERS OF PI (PROPORTIONAL INTEGRAL) CONTROLLER IN FEEDBACK CONTROLLER SYSTEMS BY NEW CORRELATIONS

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Most of the chemical processes can be controlled with proportional-integral controllers. For this reason, it is crucial to determine the optimum control parameters of proportional integral controllers. In this thesis, it is aimed to obtain the correlations which relate the optimum proportional integral controller parameters to process parameters for different types of process models.

With this study, servo and regulatory control correlations for proportional integral controllers are obtained and presented in several tables for the process model types of first order plus time delay (FOPTD) and second order plus time delay (SOPTD) for the objective of minimizing each performance criteria value (integral of absolute value of the error (IAE), integral of the time-weighted absolute value of the error (ITAE), integral of the squared value of the error (ISE) and integral of the time - weighted squared value of the error (ITSE)), separately. Then, the performance of these proposed correlations are compared with that of the well-known tuning methods: Ziegler-Nichols continuous cycling method, Ziegler-Nichols reaction curve method, Cohen-Coon method and the other proposed tuning methods in literature in terms of values of overshoot, rise time, settling time and integral performance criteria and the advantages and disadvantages of the proposed correlations are discussed.

At the end of the study, it is generally seen that the correlations obtained for first order plus time delay and second order plus time delay processes provide less values of overshoot, settling time and integral performance criteria than classical tuning methods do. Besides, it is also seen that the regulatory control correlations proposed for first order plus time delay processes provide less values of integral performance criteria than some of the other proposed methods for the same purpose in literature provide.

Keywords: Process Control, Design of Feedback Controllers, PI Controller, Tuning

ÖZET

GERİ BESLEMELİ KONTROL SİSTEMLERİNDE PI (ORANSAL INTEGRAL) KONTROL EDİCİNİN OPTİMUM KONTROL PARAMETRELERİNİN YENİ KORELASYONLARLA SAPTANMASI

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Kimyasal proseslerin bir çoğu oransal integral kontrol ediciler ile kontrol edilebilirler. Bu nedenle oransal integral kontrol edicinin optimum kontrol parametrelerinin elde edilmesi büyük önem taşır. Bu çalışmada ise, oransal integral konrol edicinin farklı proses modelleri için optimum proses kontrol parametrelerini, proses parametrelerinin fonksiyonu olarak belirten korelasyonları elde etmek amaçlanmıştır.

Bu çalışma ile, oransal integral kontrol edicinin; birinci dereceden gecikmeli proses modeli tipi (FOPTD) ve ikinci dereceden gecikmeli proses modeli tipi (SOPTD) için; her bir performans ölçütü değerlerinin minimizasyonunu ayrı ayrı amaçlayan (hatanın mutlak değerinin integrali (IAE), zaman ağırlıklı hatanın mutlak değerinin integrali (ITAE), hatanın karesinin integrali (ISE), ve zaman ağırlıklı hatanın karesinin integrali (ITSE)); set noktası değişimi ile yük değişimi korelasyonları ayrı ayrı elde edilmiş ve tablolar halinde sunulmuştur. Ayrıca bu çalışmada, elde edilen korelasyonların performansı, en çok bilinen ayar yöntemleri olan Ziegler-Nichols kapalı çevrim ayar yöntemi, Ziegler-Nichols açık çevrim ayar yöntemi, Cohen-Coon ayar yöntemi ve literatürde ileri sürülen diğer kontrol ayar yöntemlerinin performansı ile en büyük aşım, yükselme zamanı, yerleşme zamanı ve integral performans kriterleri değerleri açısından karşılaştırılmış ve ileri sürülen korelasyonların avantaj ve dezavantajları tartışılmıştır.

Çalışma sonunda birinci dereceden ve ikinci dereceden gecikmeli sistemler için elde edilen korelasyonların, klasik ayar yöntemlerinden genel olarak daha düşük en büyük aşım, yerleşme zamanı ve integral performans kriterleri değerleri sağladığı görülmüştür. Ayrıca, birinci dereceden gecikmeli sistemler için geliştirilen yük değişimi korelasyonlarının bu çalışmada incelenen literatürde aynı amaç için belirtilmiş ayar yöntemlerinden genel olarak daha düşük integral performans kriterleri değerleri sağladığı görülmüştür.

Anahtar Kelimeler: Proses Kontrol, Geri Beslemeli Kontrol Edici Tasarımı, PI Kontrol Edici, Tuning

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SYMBOLS AND ABBREVIATIONS

Symbols

$G_p(s)$	process transfer function
K_p	process gain
τ_1, τ_2	process time constants
θ	time delay (dead time)
$y(s)$	output of the process system (controlled variable)
$d(s)$	disturbance variable
$m(s)$	manipulated variable
$r(s)$	set point
$y_m(s)$	measured value of the output
$e(s)$	the error
$u(s)$	the actuating signal
$G_c(s)$	transfer function of the controller
K_c	proportional gain
τ_i	integral time constant (reset time)
τ_D	derivative time constant
O_s	overshoot
T_r	rise time
T_s	settling time
K_u	ultimate gain
P_u	ultimate period
$G_m(s)$	transfer function of the measuring device
$G_f(s)$	transfer function of the final control element
R^2	regression coefficient

Abbreviations

P	proportional
PI	proportional - integral
PID	proportional-integral-derivative
FOPTD	first order plus time delay
SOPTD	second order plus time delay
SOPTDLD	second order plus time delay with lead
IAE	integral of absolute value of the error
ITAE	integral of the time-weighted absolute value of the error
ISE	integral of the squared value of the error
ITSE	integral of the time - weighted squared value of the error
ZN-1	Ziegler-Nichols continuous cycling method
ZN-2	Ziegler-Nichols process reaction curve method
C-C	Cohen-Coon method
PMIAE	proposed correlations for the minimization of IAE
PMITAE	proposed correlations for the minimization of ITAE
PMISE	proposed correlations for the minimization of ISE
PMITSE	proposed correlations for the minimization of ITSE

1. INTRODUCTION

It is known that the majority of processes in the chemical industry can be satisfactorily controlled by using proportional – integral (PI) feedback controller configuration. Reports show that more than 90% of the industrial controllers are PID, mostly PI, controllers [1-4]. Furthermore, it is said that approximately 90% of all industrial PID controllers have the derivative action turned off [5-6]. For this reason, many control tuning techniques, correlations and formula have been improved and presented in literature and many of them are available in [7-8]. Every new approach has important contribution to controller tuning theory, which can lead to many crucial improvements in industry.

Madhuranthakam et al. [9] proposed a new approach to PID controller tuning. They used Matlab optimization toolbox and Simulink software simultaneously to obtain PID controller tuning correlations which relate the PID controller parameters to process parameters considering the minimization of integral of absolute value of the error (IAE) for three different types of process models: first order plus time delay (FOPTD), second order plus time delay (SOPTD) and second order plus time delay with lead (SOPTDLD), separately. This thesis is an extension of their work. Since PI controller is commonly used in industry as mentioned before, their approach is used to obtain the correlations for PI controller.

The purpose of this thesis is to present new correlations for the optimal tuning of proportional – integral (PI) feedback controllers. These correlations involve the optimization of the PI controller parameters to achieve the minimization of the integral of absolute value of the error (IAE), integral of the time-weighted absolute value of the error (ITAE), integral of the squared value of the error (ISE) and integral of the time - weighted squared value of the error (ITSE), separately. The correlations are proposed for two different process types: first order plus time delay (FOPTD) and second order plus time delay (SOPTD), separately. Additionally, the correlations are presented for the unit step change in set point (servo control) and load change (regulatory control), separately.

It is aimed that by using the correlation tables presented in this thesis for PI controller, one can easily determine the PI controller settings according to the desired response (minimization of IAE, ITAE, ISE and ITSE) for any of two process models mentioned above. But, it should be added that these correlations are still needed to be tested in real systems.

In this work, after giving general information about the design of feedback controllers in section 2 and brief literature review in section 3, the method of obtaining the correlations is explained in the section of proposed method (section 4). Then, the correlations are presented in different parts according to their process model type (FOPTD and SOPTD) in section of proposed correlations (section 5). After presenting the related correlation graphics and tables, the performance of the proposed correlations are compared with that of other conventional tuning techniques which are well-known and available in many process control textbooks in section 6 and some other proposed techniques in literature in section 7. The advantages and disadvantages of proposed correlations are investigated and discussed in these comparison sections.

2. GENERAL INFORMATION

The system which has specified input and output variables can be called as process [10]. In chemical engineering industry, the processes can be effectively modeled by one of these types of models: first order plus time delay (FOPTD) and second order plus time delay (SOPTD). These process models are shown in the equations 2.1 and 2.2:

$$\text{FOPTD process:} \quad G_P(s)=\frac{K_P e^{-\theta s}}{\tau_1 s+1} \tag{2.1}$$

$$\text{SOPTD process:} \quad G_P(s)=\frac{K_P e^{-\theta s}}{(\tau_1 s+1)(\tau_2 s+1)} \tag{2.2}$$

where, $G_p(s)$ is the process transfer function, K_p is process gain; τ_1 and τ_2 are process time constants and θ is the time delay (or dead time).

Process control discipline deals with the question of how a process can be controlled in order to exhibit a certain desired response in the presence of input changes. There can be two types of input changes influence the output of the process systems, y(s): the change in disturbance variables, d(s) or manipulated variables, m(s). The inputs and the output of a process are shown in Figure 2.1.

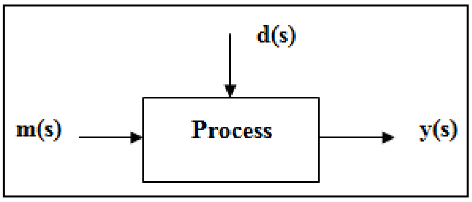


Figure 2.1. Open loop process

When the value of disturbance, d(s) or manipulated variable, m(s) changes, the response of the process system shown in Figure 2.1 is called open - loop response, and this means there is no control in the system. There should be a control configuration applied to the process system to get the desired response, namely to keep the output of the system, y(s) in the set point, r(s). There are several control configurations defined in process control area, such as feedback, feedforward, cascade, ratio, override, split range, and multivariable. Feedback control configuration which is the most common control configuration is worked on in this thesis. A feedback-controlled system is shown in Figure 2.2.

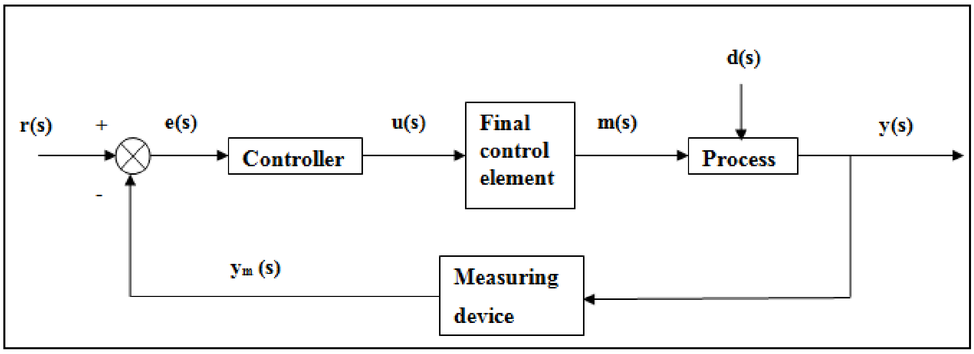


Figure 2.2. Feedback control loop

When the value of disturbance variable, d(s) or manipulated variable, m(s) changes, the response of the process system shown in Figure 2.2 is called closed-loop response, and this means there is a controller available in the system. In this feedback control action; firstly the value of the output, y(s) which is also called as controlled variable is measured with an appropriate measuring device and measured value of the output, $y_m(s)$ is obtained. Then, controller mechanism compares this measured value $y_m(s)$ to the set point, r(s) and calculates the error e(s) as in equation 2.3.

$$e(s) = r(s) - y_m(s) \tag{2.3}$$

The controller's aim is to eliminate this error, e(s) in order to get output, y(s) equal to set point, r(s) through another device known as the final control element (e.g. a control valve). For this purpose, controller produces the actuating signal, u(s) which is input of the final control element. So, the transfer function of the controller, $G_c(s)$ which relates the error, e(s) to actuating signal, u(s) is given in equation 2.4. The various types of continuous feedback controllers differ in the way they relate the error, e(s) to actuating signal, u(s) which is the reason why it is important to choose the best controller appropriate for the system. There are three basic types of feedback controllers: Proportional (P), Proportional – Integral (PI), Proportional – Integral – Derivative (PID) and their transfer functions are given in equations 2.5, 2.6 and 2.7, respectively.

$$G_c(s)= \frac{u(s)}{e(s)} \tag{2.4}$$

$$\text{P controller: } G_c(s)= K_c \tag{2.5}$$

$$\text{PI controller: } G_c(s)= K_c \left(1+\frac{1}{\tau_i s}\right) \tag{2.6}$$

$$\text{PID controller: } G_c(s)= K_c \left(1+\frac{1}{\tau_i s}+\tau_D s\right) \tag{2.7}$$

In these equations, $G_c(s)$ is controller transfer function, K_c is proportional gain, τ_i is integral time constant (also called reset time, in minutes) and τ_D is derivative time constant (in minutes). Each of these parameters has important effect on the control action. Because of this reason, their values should be specified with the purpose of achieving the desired response.

As a result, the selection of the type of controller (P, PI or PID) and the determination of controller transfer function parameters (K_c, τ_i, τ_D) in the feedback controller are the parts of an important process, which is called as the design of the feedback controller. Stephanopoulos [11] mentioned about three design questions arise in the design of feedback controllers:

1) What type of feedback controller should be used to control a given process?

2) How do we select the best values for the adjustable parameters of a feedback controller?

3) What performance criterion should be used for the selection and the tuning of the controller?

For the first question, the basic types of controllers (P, PI or PID), or any other controller type defined in process control discipline can be selected by considering the dynamics of the process and the other elements of the feedback loop and the desired response of the system. In this thesis, one of the basic types of controller, PI controller, is examined. There are continual advances in process control theory, but the PI controller is still the most commonly used controller in the process control industry [1], [12]. Tavakoli and Fleming explain the reason of that as PI controller's noticeable effectiveness and its simple structure which is easy to understand [1].

The second question is known as the controller tuning problem in process control discipline. After deciding the controller type, the values of the parameters of the selected controller type are still needed to be adjusted. It is substantial because the values of each of these parameters have an important effect on the response of the controlled process. The wrong selection of these parameters can lead to unstable responses and undesired or even dangerous consequences in process systems. Therefore, there are plenty of methods, correlations and formulas proposed for controller tuning in process control literature since 1940s. Thereby, this thesis presents a set of new correlations for PI controller tuning.

The third question is about the performance criterion which is the quantitative measure of the response. The selection and the tuning of the controller are made to obtain the response which achieves this performance criterion. There is various performance criteria defined in literature. One of the performance criteria defined in literature based on some characteristic features of the closed-loop response of the system: such as overshoot, rise time, settling time, and decay ratio which are defined as below (definitions are taken from [11]) and shown in Figure 2.3:

Overshoot (O_s): the ratio A/B, where B is the ultimate value of the response and A is the maximum amount by which the response exceeds its ultimate value.

Rise Time (T_r): time needed for the response to reach the desired value for the first time.

Settling Time (T_s): time needed for the response to settle within ± 5% of the desired value.

Decay Ratio: the ratio C/A, the ratio of the amounts of the ultimate value of two successive peaks.

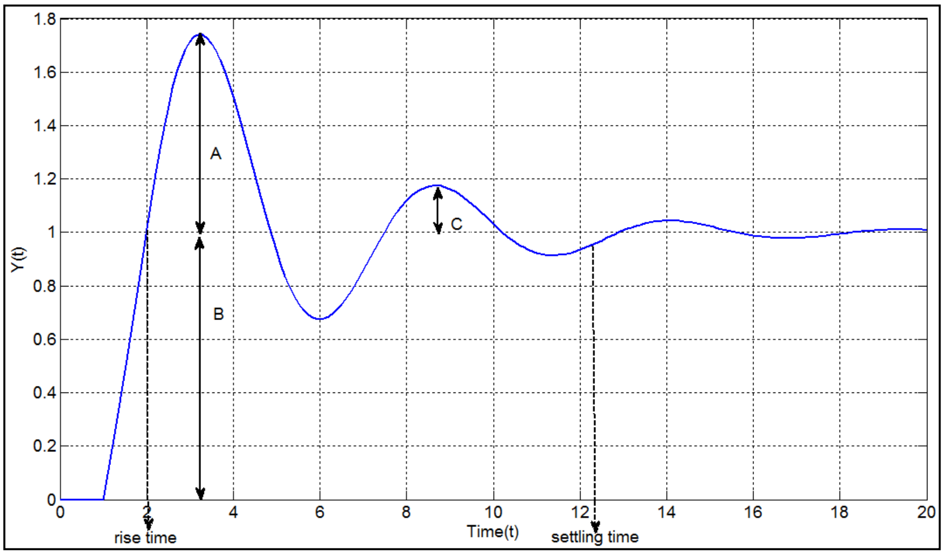


Figure 2.3. Characteristic features of the response.

The minimization of the settling time, rise time or overshoot can be the performance criterion of the controller design. Moreover, these values can also be used to compare the performances of different control systems.

Another dynamic performance criteria seen in literature are the time-integral performance criteria which consider all the response from time t=0 until the steady state is reached. The integral performance criteria are integral of the absolute value of the error (IAE), integral of the time-weighted absolute value of the error (ITAE), integral of the squared value of the error (ISE) and integral of the time - weighted squared value of the error (ITSE) and their formulas are shown in equations 2.8, 2.9, 2.10 and 2.11.

$$IAE=\int_0^{\infty}|e(t)|dt \qquad (2.8)$$

$$ITAE= \int_0^\infty t|e(t)|dt \tag{2.9}$$

$$ISE= \int_0^\infty e^2(t)dt \tag{2.10}$$

$$ITSE= \int_0^\infty te^2(t)dt \tag{2.11}$$

The minimization of these time–integral performance criteria can be the performance criteria in the design of the controllers and they are considered as performance criteria for the proposed correlations in this thesis.

3. LITERATURE REVIEW

Many PI/PID controller tuning techniques have been proposed in literature. Three of the earliest methods which are known as classical or conventional PID tuning techniques in literature are Ziegler-Nichols Continuous Cycling Method [13], Ziegler-Nichols Process Reaction Curve Method [14] and Cohen-Coon Method [15] and they are looked over in this section. Moreover, these three methods are explained in many process control textbooks in detail and they are usually used as initial controller settings in industry. The performance of these three conventional methods will be also compared with that of the proposed tuning correlations in section 6.

On the other side, internal model control (IMC) design [16-19] direct synthesis method [20] , tuning rules based on the minimization of different error criteria [21-22], gain and phase margins formula [23], different closed loop and open loop techniques explained and compared briefly in [24] are some of the controller tuning methods presented in literature. It is not possible to explain and analyze all of these methods, but some selected tuning methods from literature will be explained briefly and their performance will be compared with the performance of the proposed tuning correlations in section 7.

3.1. Ziegler-Nichols Continuous Cycling Method

Ziegler and Nichols examined the three principal control effects in 1942 [13]. Their work is accepted as the basis of the control tuning theory and their method presented in that work is known as the 'Ziegler-Nichols Continuous Cycling Method' or 'Ziegler-Nichols Closed-Loop Method'.

They took a common control circuit in which the pen movement in inches is translated into behavior of the valve by changing the output of air pressure. The three controller effect which can be called as proportional, automatic reset and pre-act were examined in this circuit and their optimum settings were investigated. They aimed to give a method for arriving quickly at the optimum settings of each of these control effects.

Their method proposes firstly, the integration (τ_i) and derivative (τ_D) terms of the controller are disabled, which means that only proportional control is available. Then, the value of the proportional gain (K_c) is increased until continuous (sustained) oscillations are seen in the response, which means that the system is critically stable. If the proportional gain is increased more, the system becomes unstable. If it is decreased, the system becomes stable and has under damped response. The value of the proportional gain (K_c) which this response with continuous (sustained) oscillations occurs at is called ultimate gain and symbolized with K_u. The oscillating period of this system is called as ultimate period and symbolized with P_u. After determining the ultimate gain (K_u) and ultimate period (P_u), the optimum control parameters are determined according to the Table 3.1.

This method has the advantage that it does not need the information about the process parameters (K_c, τ_1, θ), but it does need the information about ultimate data (K_u and P_u). So, this method requires an ultimate test that can unnecessarily destabilize the system. Additionally, it is said that inherently causes to oscillatory response to the set point changes in the process systems [1], [25-26]. Another deficiency about this method is that it does not work for plants whose root loci do not cross the imaginary axis for any value of gain [27].

Table 3.1. Ziegler-Nichols Continuous Cycling Tuning Method

Control Type	K_c	τ_i	τ_D
P	$0.5*K_u$	-	-
PI	$0.45*K_u$	$1.2/P_u$	-
PID	$0.6*K_u$	$2/P_u$	$P_u/8$

3.2. Cohen-Coon Method

Another conventional tuning technique which is known as ‘Cohen–Coon process reaction curve method’ was proposed by Cohen and Coon in 1953 [15]. They opened the control system by disconnecting the controller from the final control element and then introduced a step change of magnitude A in the variable which actuates the final control element. They observed that when this input change was introduced to a process system, most of the process systems give a response (process reaction curve) which had a sigmoidal shape. Additionally, this shape can be approximated by the response of a first order system with dead time whose transfer function is given in equation 2.1. From the response of the process system, the process parameters (K_p, θ and τ_1) are easily can be determined. The response is shown in Fig. 3.1 and from this figure the process parameters are found by using equations 3.1, 3.2 and 3.3 (equations taken from [11]).

$$K_p = \frac{\text{output (at steady state)}}{\text{input (at steady state)}} = \frac{B}{A} \tag{3.1}$$

$\tau_1 = \frac{B}{S}$, where S is the slope of the sigmoidal response at the point of inflection (3.2)

$$t_d = \theta = \text{time elapsed until the system responded} \tag{3.3}$$

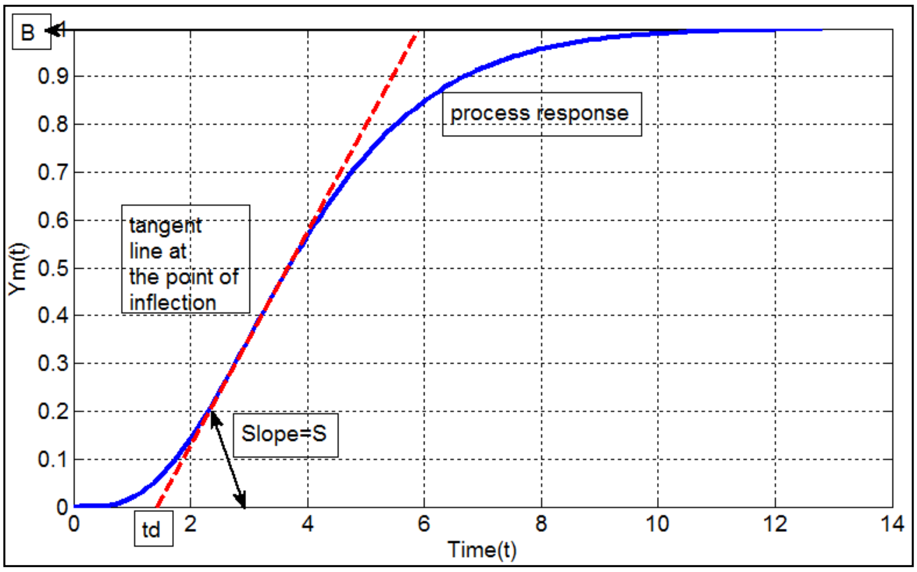


Figure 3.1. The process reaction curve and its approximation with a first order plus dead-time system.

Finally, the best controller settings are determined according to their rules which are summarized in Table 3.2.

Table 3.2. Tuning Formulas of Cohen-Coon Tuning Method

Control Type	**K_c**	**τ_i**	**τ_D**
P	$\frac{1}{K_p}\frac{\tau_1}{\theta}\left(1+\frac{\theta}{3\tau_1}\right)$	-	-
PI	$\frac{1}{K_p}\frac{\tau_1}{\theta}\left(0.9+\frac{\theta}{12\tau_1}\right)$	$\theta\left(\frac{30+3\theta/\tau_1}{9+20\theta/\tau_1}\right)$	-
PID	$\frac{1}{K_p}\frac{\tau_1}{\theta}\left(\frac{4}{3}+\frac{\theta}{4\tau_1}\right)$	$\theta\left(\frac{32+6\theta/\tau_1}{13+8\theta/\tau_1}\right)$	$\theta\left(\frac{4}{11+2\theta/\tau_1}\right)$

This method is based on a combination of a decay ratio of ¼, minimum ISE and minimum offset tuning for a FOPTD process model. It is a disadvantage that Cohen – Coon method requires a FOPTD process model, which is difficult and time consuming to develop [28]. Similar to the Ziegler-Nichols continuous cycling method, this method sometimes can cause oscillatory responses since it was designed to give closed loop responses with a damping ratio of 25% [1], [27].

3.3. Ziegler-Nichols Process Reaction Curve Method

In addition to their continuous cycling tuning method, Ziegler and Nichols (1942) proposed a set of formulas based on the parameters of a first-order model fit to the process reaction curve. Their tuning formulas are given in Table 3.3.

Table 3.3. Tuning formulas for Ziegler-Nichols Process Reaction Curve Method

Control Type	K_c	τ_i	τ_D
P	$\frac{1}{K_p}\left(\frac{\tau_1}{\theta}\right)$	-	-
PI	$\frac{0.9}{K_p}\left(\frac{\tau_1}{\theta}\right)$	3.3θ	-
PID	$\frac{1.2}{K_p}\left(\frac{\tau_1}{\theta}\right)$	2θ	$\frac{\theta}{2}$

4. THE PROPOSED METHOD

This proposed method presents the optimal tuning of proportional-integral parameters for different process systems whose dynamics can be modeled with: first order plus time delay (FOPTD) or second order plus time delay (SOPTD) process models. These process models were shown in the equations 2.1 and 2.2. It should be pointed out again that most of the chemical processes can be effectively modeled by one of these types of models.

For every feedback control system, there can be two types of control problems: the set point can undergo a change (servo problem) and the feedback controller tries to keep the controlled variable close to the changing set point (servo control) or there can be load changes in the system (regulator problem) and the feedback controllers tries to eliminate the effect of the load changes to keep the controlled variable at the desired set point (regulatory control). For this reason, these two types of controls are examined in this work and the unit step change is introduced in the set point and load in the indicated systems, respectively to get the servo control and regulatory control correlations separately. The block diagram of the PI feedback control system in Figure 4.1 is considered in this work and the simulink models formed for this system are available in Appendix 2 and 4.

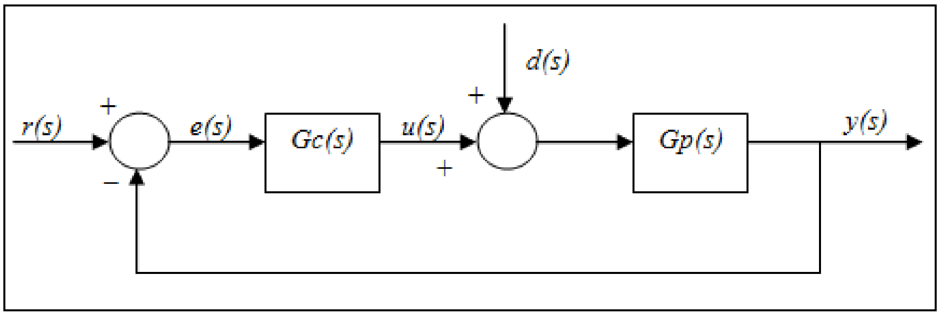


Figure 4.1. The block diagram of the feedback control system

In this diagram, while $G_p(s)$ represents the process transfer function which can be FOPTD or SOPTD process type, $G_c(s)$ represents the PI controller whose transfer function is given in equation 2.6. Also, d(s) is disturbance and u(s) is the controller output as indicated in the previous sections. The error is shown as e(s) and is calculated as in equation 4.1 for this system.

$$e(s) = r(s) - y(s) \tag{4.1}$$

In this diagram, r(s) is the deviation in the set point from the steady-state and y(s) is the deviation in the output (controlled variable) from the steady-state as indicated in the previous sections.

The transfer functions of the measuring device, $G_m(s)$ and the final control element, $G_f(s)$ are assumed as in equation 4.2. Either, the combined dynamics of the process, final control element and the sensor can be assumed to be conveniently presented by FOPTD and SOPTD process model type.

$$G_m(s)= G_f(s)= 1 \qquad (4.2)$$

While the feedback controllers are designed, it was mentioned before that the quantitative measure which is known as performance criterion is needed to be defined to be able to compare the alternatives and select the optimal values of control parameters. Different performance criteria are specified in this work: the minimization of the values of integral absolute error (IAE), integral time - weighted absolute error (ITAE), integral squared error (ISE) and integral time - weighted squared error (ITSE). These criteria were shown in equations 2.8, 2.9, 2.10 and 2.11. So, each of these minimization criterion is used while the optimization is executed in Matlab and Simulink softwares, respectively. In this equations, e(t) is the error in time domain defined according to equation 4.1. Although, the upper time bound on integral is infinity, in the simulations the integration is performed over a sufficiently long time as compared to the closed loop settling time, i.e. after the response reaches a steady state.

Finally; a set of new and generalized tuning correlations relating the the proportional-integral control parameters to the process parameters are obtained for each minimization criterion (IAE, ITAE, ISE and ITSE) for each process type (FOPTD and SOPTD) for step changes in set point and load, separately. The obtained and proposed algebraic correlations are presented in the tables in the next section (section 5).

To optimize the objective function (minimization of the specified performance criteria) and then to obtain the simple and useful optimal tuning correlations, the following steps are employed:

1) For each process model type (FOPTD and SOPTD); sets of process models which has different values of parameters τ_1 and τ_2 (process time constants) and θ (dead time) are defined. These sets of processes are available in appendix 5 for FOPTD process type and in appendix 6 for SOPTD process type. The intervals and the ratios of the process parameter values are also given in Appendix 7.
2) For each process defined in step 1, Ziegler-Nichols continuous cycling method is applied and the optimal proportional-integral control parameters (proportional gain,

K_c and integral time constant, τ_i) according to this method are found. These optimal control parameters are used as the initial guesses in the optimization process which is executed in Matlab software.

3) The feedback control system which involves the process model and the PI controller is formed in Simulink software. The unit step change in set point and the unit step change in load are simulated with the help of this Simulink model. Additionally, all of the minimization performance criteria (IAE,ITAE,ISE and ITSE) are calculated with the addition of required simulink blocks in this Simulink models. Simulink models used in this thesis are available in Appendix 2 for servo control and in Appendix 4 for regulatory control.
4) The optimization process is executed in Matlab software. For this purpose, the matlab nonlinear least squares algorithm which is known as 'lsqnonlin' function is used. This function uses the outputs (the values of IAE, ITAE, ISE and ITSE) of the Simulink models which is created in step 3 to calculate the objective function. At the end, this matlab program gives the optimum PI control parameters as the output of the optimization process. (Related matlab m-file codes are available in Appendix 1 for servo control and Appendix 3 for regulatory control.)
5) After all, the simulink model and the matlab codes are executed simultaneously to find out the optimum process control parameters at which each minimization performance criteria is minimum for each processes defined in step 1 separately. As a result, optimum control parameters are obtained corresponding to process parameters.
6) These PI controller parameters and process parameters are made dimensionless by multiplying/dividing by the appropriate scale factors.
7) The graphics of the dimensionless process control parameters are drawn versus the dimensionless process parameters.
8) Bu using regression techniques, simple correlations are obtained for the controller parameters as fuctions of process parameters for the corresponding two process models and four minimization criteria. Several sets of dimensionless groups are tried and their trendline fit and coefficients of correlations (R^2) are examined and compared and the ones that suitable most (usually the ones have highest R^2 values) are retained in the proposed tuning rules.
9) Finally, the proposed PI controller tuning correlations which are relating the control parameters to the process parameters are obtained for each process type, for each

minimization criteria and for servo and regulatory control, separately. The function of these correlations are shown as in equations 4.3 and 4.4.

$$K_c = f_1(K_P, \tau_1, \tau_2, \theta) \tag{4.3}$$

$$\tau_i = f_2(K_P, \tau_1, \tau_2, \theta) \tag{4.4}$$

The correlations graphics are formed as dependent variables (dimensionless control parameters) versus independent variables (dimensionless process parameters). The independent variable for the tuning correlations are selected as the fraction dead time, i.e. the ratio of the dead time of the process and the sum of all the time constants including the dead time. The fraction dead time for the FOPTD process and SOPTD process are shown in Table 4.1. The dependent variables for each process for set point or load change (separately) is obtained by a trial procedure. Proportional gain, K_c, and the process gain K_p are expressed in reciprocal units. So, the dependent variable for proportional gain is indicated as 'K_c*K_p'. But, for the integral time constant,τ_i, the dependent variable is obtained by iterating the different possible dimensionless groups as a function of τ_i with different combinations of the process parameters (θ, τ_1, τ_2) until a high degree of correlation (R^2) between the independent and the dependent variables are obtained.

Table 4.1. The fraction dead time for process models

Process (K_PG_P)	**Fraction dead time**
FOPTD	$\theta/(\theta+\tau_1)$
SOPTD	$\theta/(\theta+\tau_1+\tau_2)$

Finally, the correlations are got from the graphics of these independent variables versus dependent variables mentioned above.

5. THE PROPOSED METHOD CORRELATIONS

5.1. Optimal Tuning Correlations for First Order Plus Time Delay Process

The tuning correlations for PI controller with the aim of IAE, ITAE, ISE and ITSE minimization as performance index for FOPTD process type are presented in this part. The unit step change is introduced to this kind of process system in set point and load separately to be able to obtain the correlations for regulatory and servo control. Figures 5.1, 5.2, 5.3 and 5.4 show the graphics of the correlations for IAE, ITAE, ISE and ITSE minimization criteria, respectively. These figures involve the graphics of proportional gain and integral time constant relationship with the process parameters obtained from the simulations and the tuning model for servo control and for regulatory control. All the tuning correlations relating the control parameters to the process parameters for FOPTD process model, for IAE, ITAE, ISE and ITSE minimization, for servo and regulatory control are shown in Table 5.1.

The selected process parameters for FOPTD model are given in Appendix 5. The simulation and the optimization process are executed and the graphics of possible dimensionless control parameters versus fraction dead time ($\theta/(\theta+\tau_1)$) values are drawn. The dependent variable selected for proportional gain is the multiplication of proportional gain and process gain 'K_c*K_p'. For all correlation graphics, this dependent variable provides high regression coefficients ($R^2>0.94$). For the integral action constant (τ_i), several possible dependent variables are tried such as 'τ_i/θ', 'τ_i/'τ_1' and '$\tau_i/(\theta+\tau_1)$'. Each of these correlation graphics drawn with possible dependent variables is examined, their trend line is drawn and the regression coefficients (R^2) are obtained. Mostly, the ones which have the largest regression coefficient (R^2) are selected as the dependent variable and their graphics and trend line equation are retained as the correlations for integral time constant parameter. But, in some cases since the one which has the largest regression coefficient (R^2) does not have good fit with the data in the edge points of the fraction dead time, the other dependent variable which has better fit in the edge points is preferred. Although the trend line for 'τ_i/τ_1' gives higher regression coefficient than 'τ_i/θ', the correlations are selected for 'τ_i/θ' instead of 'τ_i/τ_1' for load changes for IAE and ITAE minimizations because of this reason.

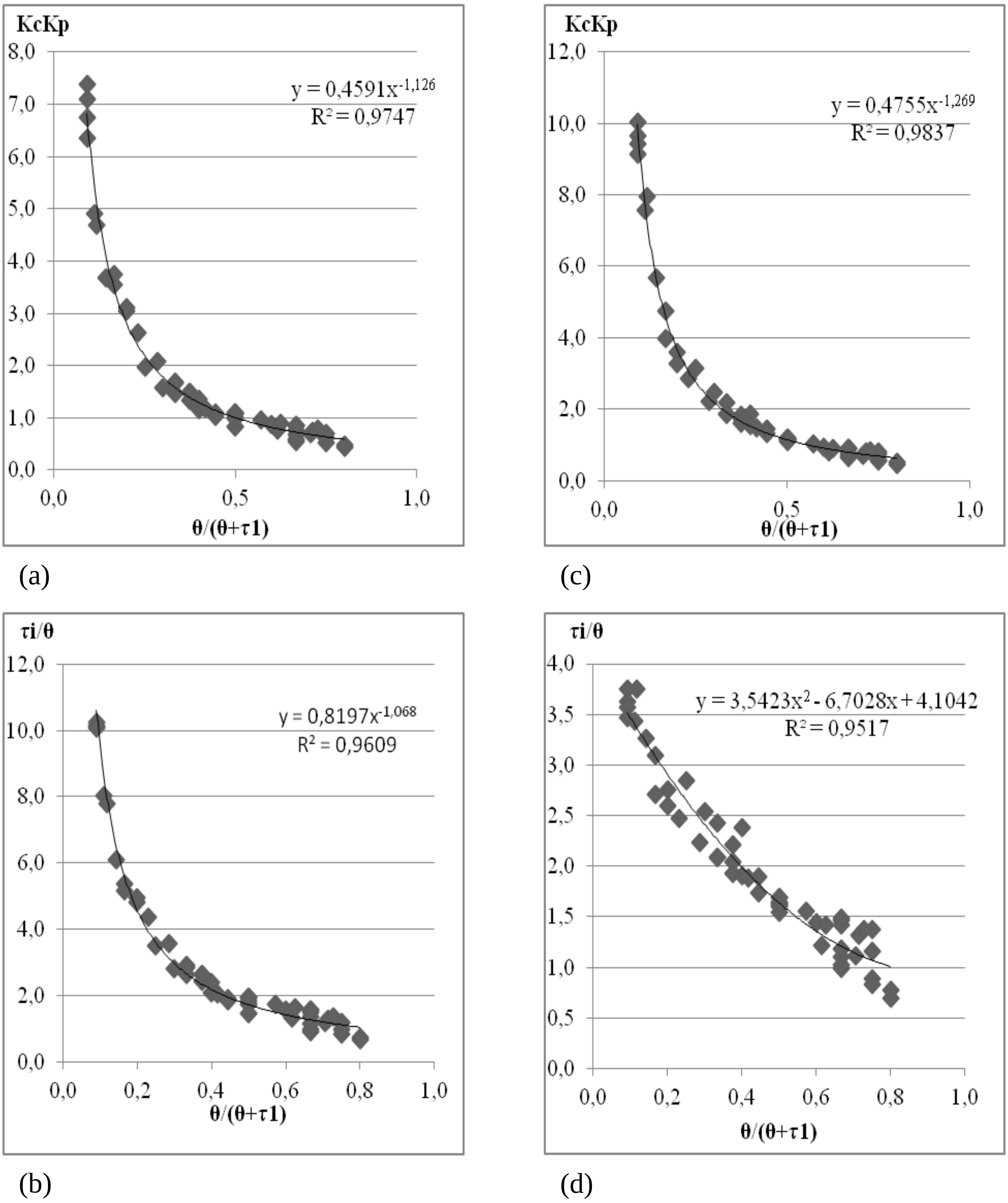


Figure 5.1. The relation graphics of proportional gain parameter vs. process parameters for FOPTD model and IAE minimization (a) for servo control (c) for regulatory control. The relation graphics of integral time parameter vs. process parameters for FOPTD model and IAE minimization (b) for servo control (d) for regulatory control.

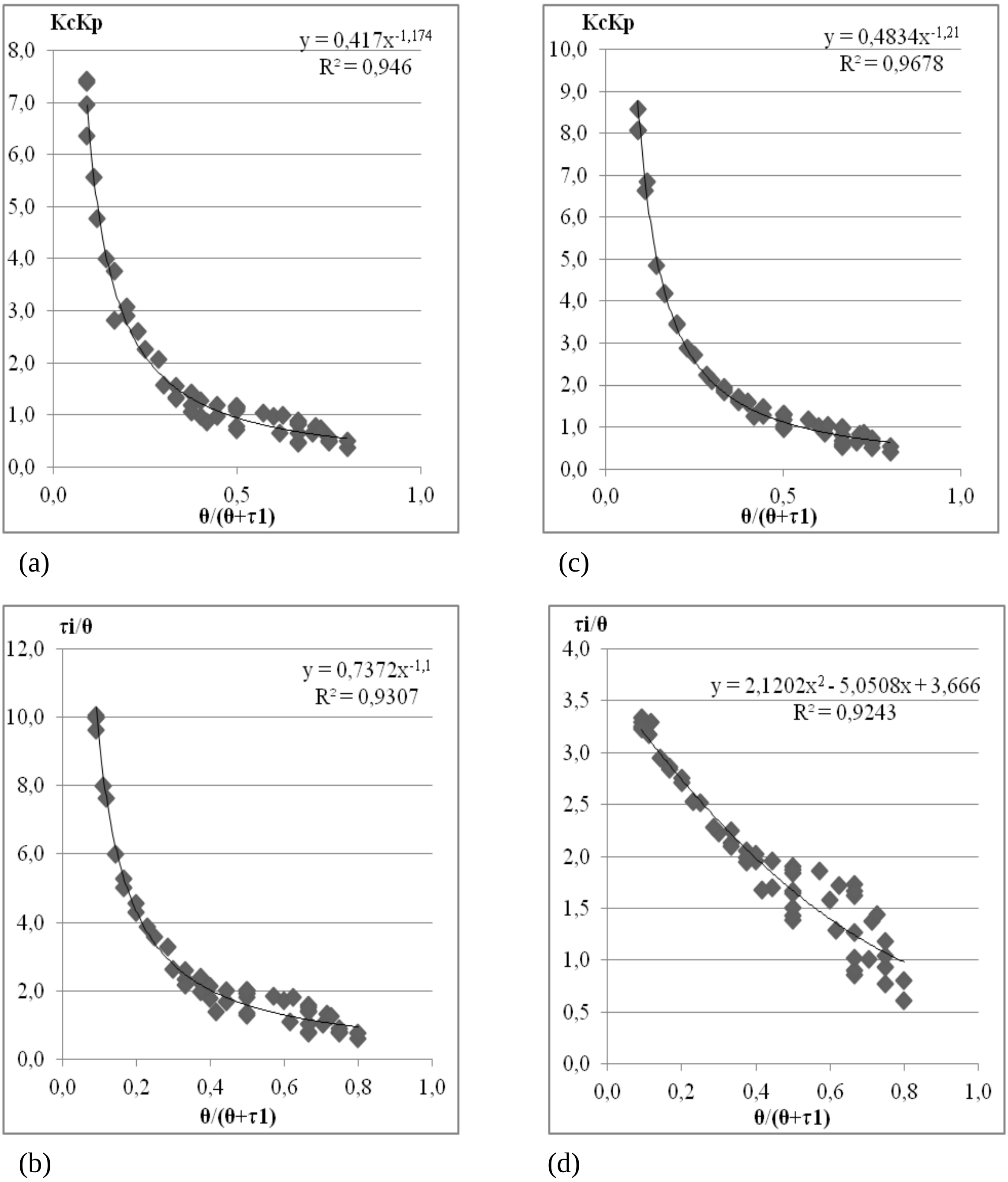


Figure 5.2. The relation graphics of proportional gain parameter vs. process parameters for FOPTD model and ITAE minimization (a) for servo control (c) for regulatory control. The relation graphics of integral time parameter vs. process parameters for FOPTD model and ITAE minimization (b) for servo control (d) for regulatory control.

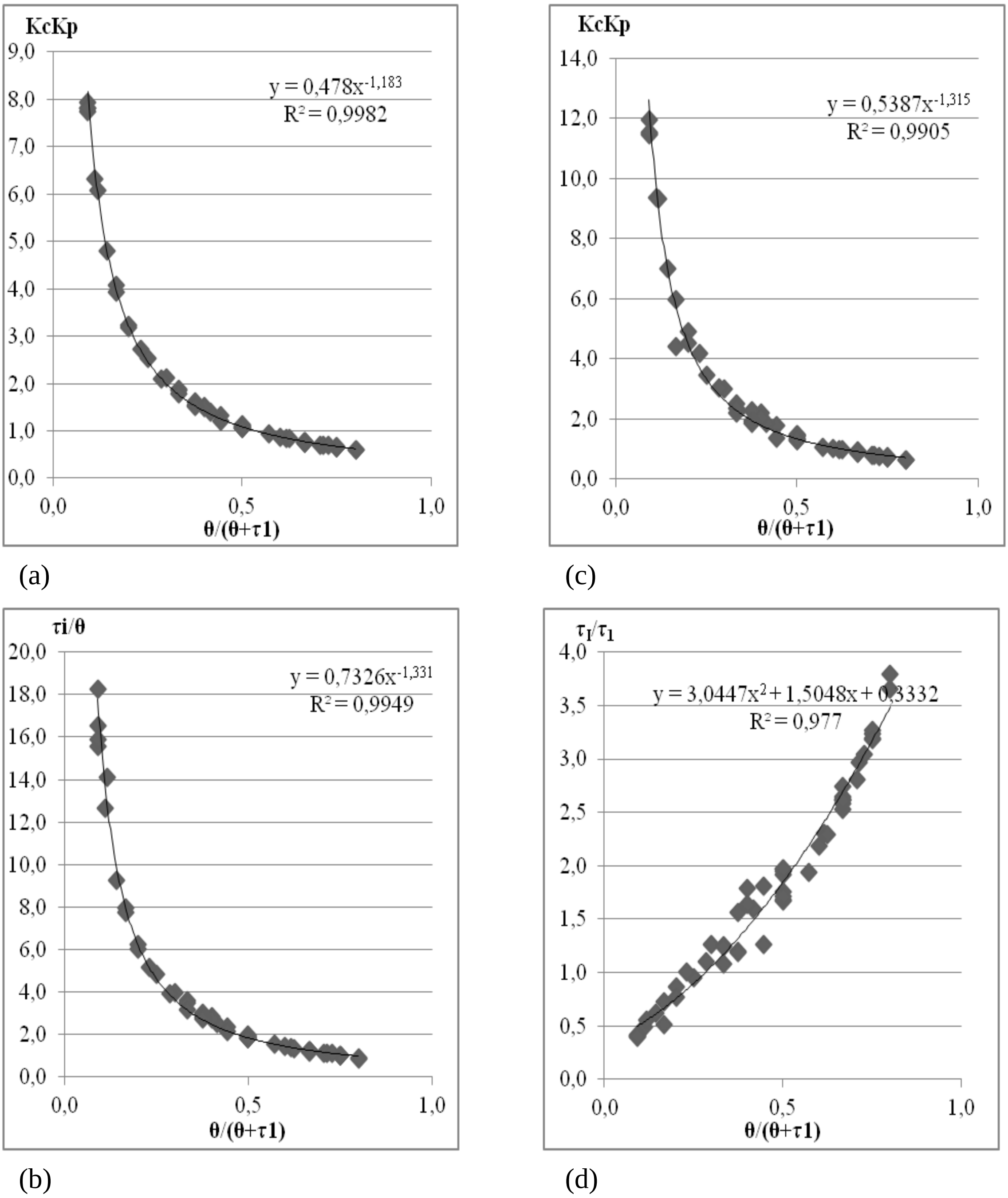


Figure 5.3. The relation graphics of proportional gain parameter vs. process parameters for FOPTD model and ISE minimization (a) for servo control (c) for regulatory control. The relation graphics of integral time parameter vs. process parameters for FOPTD model and ISE minimization (b) for servo control (d) for regulatory control.

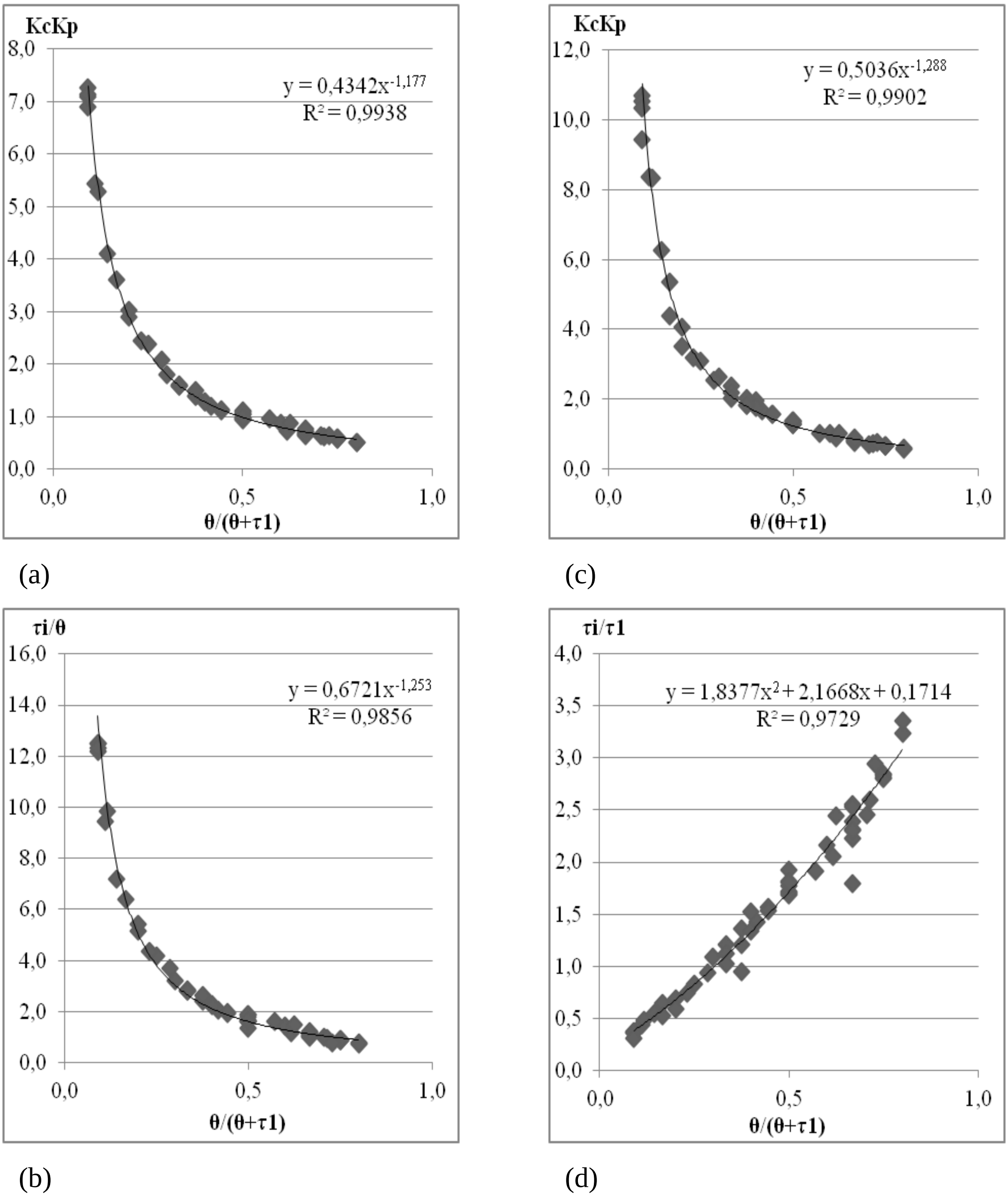


Figure 5.4. The relation graphics of proportional gain parameter vs. process parameters for FOPTD model and ITSE minimization (a) for servo control (c) for regulatory control. The relation graphics of integral time parameter vs. process parameters for FOPTD model and ITSE minimization (b) for servo control (d) for regulatory control.

Table 5.1. Proposed tuning relations for FOPTD model and IAE, ITAE, ISE and ITSE minimization criteria.

FOPTD Model - IAE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.4591}{K_P}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.126}$	$\frac{0.4755}{K_P}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.269}$
τ_i	$0.81970\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.068}$	$\theta\left[3.5423\left(\frac{\theta}{\theta+\tau_1}\right)^{2} - 6.7028\left(\frac{\theta}{\theta+\tau_1}\right) + 4.1042\right]$
FOPTD Model - ITAE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.417}{K_P}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.174}$	$\frac{0.4834}{K_P}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.21}$
τ_i	$0.73720\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.1}$	$\theta\left[2.1202\left(\frac{\theta}{\theta+\tau_1}\right)^{2} - 5.0508\left(\frac{\theta}{\theta+\tau_1}\right) + 3.666\right]$
FOPTD Model - ISE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.478}{K_P}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.183}$	$\frac{0.5387}{K_P}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.315}$
τ_i	$0.73260\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.331}$	$\tau_1\left[3.0447\left(\frac{\theta}{\theta+\tau_1}\right)^{2} + 1.5048\left(\frac{\theta}{\theta+\tau_1}\right) + 0.3332\right]$
FOPTD Model - ITSE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
K_c	$\frac{0.4342}{K_P}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.177}$	$\frac{0.5036}{K_P}\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.288}$
τ_i	$0.67210\left(\frac{\theta}{\theta+\tau_1}\right)^{-1.253}$	$\tau_1\left[1.8377\left(\frac{\theta}{\theta+\tau_1}\right)^{2} + 2.1668\left(\frac{\theta}{\theta+\tau_1}\right) + 0.1714\right]$

When the correlation graphics and the table of the correlations for IAE minimization for FOPTD process type are examined, it can be obviously seen that the optimum controller gain increases with an increase in the ratio of process time constant to process time delay (τ_1/θ). The dependent variable for the integral time constant is selected as 'τ_i/θ' and found out that it decreases with the increase in the fraction dead time for both set point change and load change. The controller gain proposed for load change is slightly greater than the one proposed for set point change, which can be seen from Table 5.1. The power relation in between dimensionless control parameters and process parameters are obtained for set point change and for proportional gain in load change. But a polynomial relation is found for integral time constant for load change. All the correlations obtained in this part have high coefficient of regression (R^2 >0.95).

For the ITAE minimization, the similar relations between the control parameters and process parameters as the IAE minimization are seen in this section. The only difference is the small differences in coefficients of the correlations.

For the ISE minimization, the similar relations between the control parameters and process parameters as the previous minimizations (IAE and ITAE) are seen except the small differences in coefficients of the correlations and for load change, integral time constant is differently related with the process parameters from the previous sections. Hence, there is an increase in 'τ_i/τ_1' with an increase in fraction dead time. All the correlations obtained in this part have high coefficient of regression (R^2 >0.97).

For the ITSE minimization, the similar relations between the control parameters and process parameters as the ISE minimization are seen except the small differences in coefficients in correlations. All the correlations obtained in this part have high coefficient of regression (R^2 >0.97).

5.2. Optimal Tuning Correlations for Second Order Plus Time Delay Process

The second order plus time delay process systems that have a transfer function equation as described in equation 2.2 are examined in this section. These process systems have two real and distinct poles ($-1/\tau_1$ and $-1/\tau_2$) or two equal poles (if τ_1 and τ_2 are equal) which means that the simulations of over damped or critically damped second-order process plus time delay dynamics are performed in this section.

Many process systems may be described by second order processes with time delay such as two blending tanks in series/parallel, two CSTRs in series with first order dynamics for each CSTR, etc. [9]. Since, many combinations for the dead time and the two process time constants are possible, the ratios of the process parameters are selected in the interval given in Appendix 7 and the SOPTD parameters used are available in Appendix 6. In all the simulations, τ_1 is always greater than or equal to τ_2 and the dead time is never greater than the sum of τ_1 and τ_2.

The simulation and the optimization process are executed and the graphics of possible dimensionless control parameters versus fraction dead time ($\theta/(\theta+\tau_1+\tau_2)$) values are drawn. The dependent variable selected for proportional gain is the multiplication of proportional gain and process gain 'K_c*K_p'. For all correlation graphics, this dependent variable provides high regression coefficients (R^2>0.95). For the integral time constant (τ_i), since there are two process time constants (τ_1 and τ_2), there are more possible dependent variables for SOPTD process type than FOPTD process type. Several combinations of process parameters (τ_1, τ_2, θ) and integral time constant (τ_i) are tried to create dependent variables such as 'τ_i/θ', 'τ_i/τ_1', '$\tau_i*\tau_1/(\theta*(\theta+\tau_1+\tau_2))$', '$\tau_i*\tau_2/(\theta*(\theta+\tau_1+\tau_2))$', '$\tau_i/(\theta+\tau_1+\tau_2)$' etc. Each of these possible correlation graphics is examined, their trend line is drawn and the regression coefficients (R^2) are obtained and the correlations are selected as in the same way as in previous section for FOPTD process type. It is noticed that the selected correlations have high regression coefficients (R^2>0.95) and they are simple correlations.

The tuning correlations for PI controller with the aim of IAE, ITAE, ISE and ITSE minimization as performance index for SOPTD process type are presented in this part. The unit step change is introduced to this kind of process system in set point and load separately to be able to obtain the correlations for regulatory and servo control. Figures 5.5, 5.6, 5.7 and 5.8 show the graphics of the correlations for IAE, ITAE, ISE and ITSE minimization criteria, respectively. These figures involve the graphics of proportional gain and integral time relationship with the process parameters obtained from the simulations and the tuning model for servo control and for regulatory control. All the tuning correlations relating the control parameters to the process parameters for SOPTD process model, for IAE, ITAE, ISE and ITSE minimization, for servo and regulatory control are shown in Table 5.2.

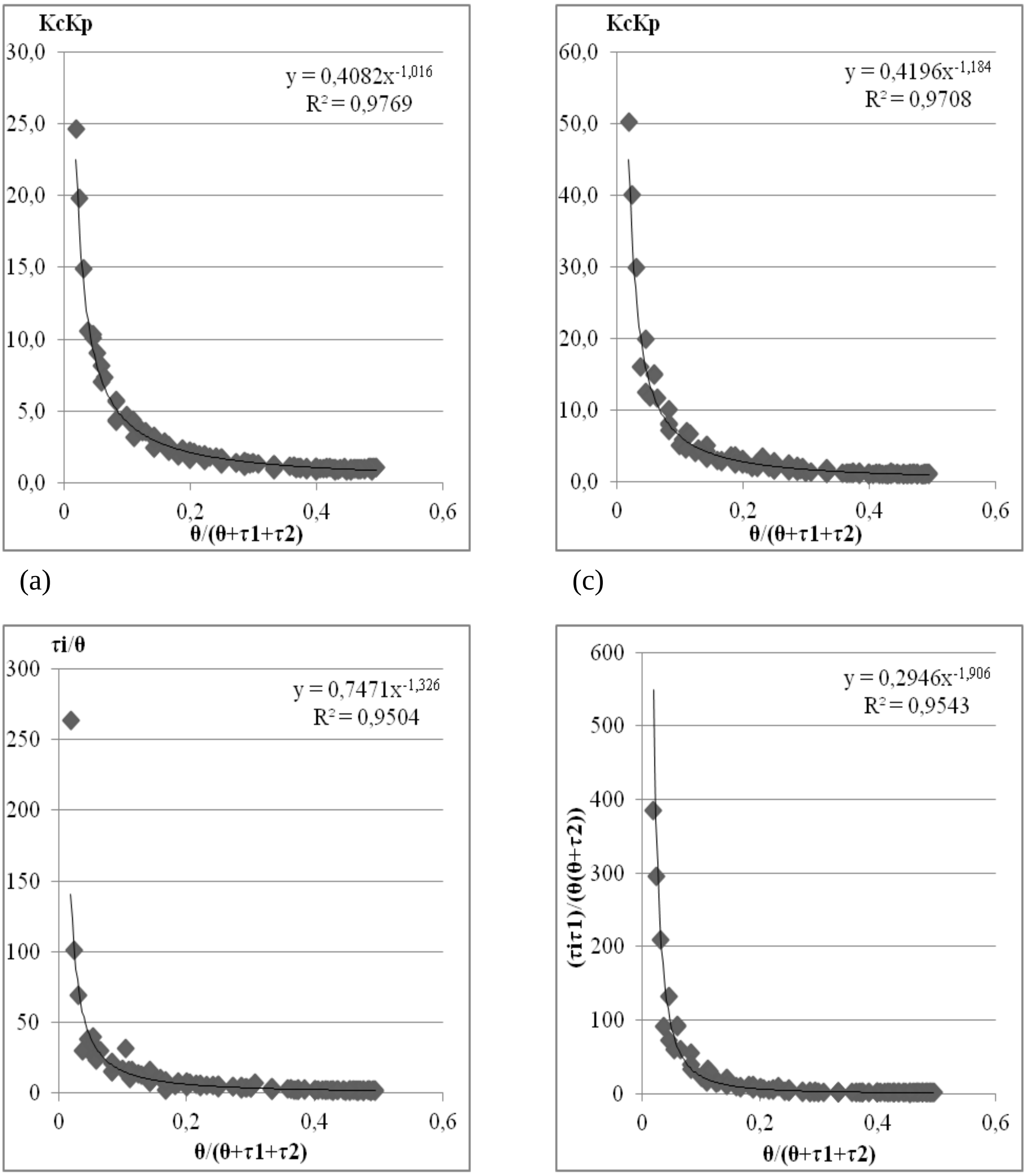
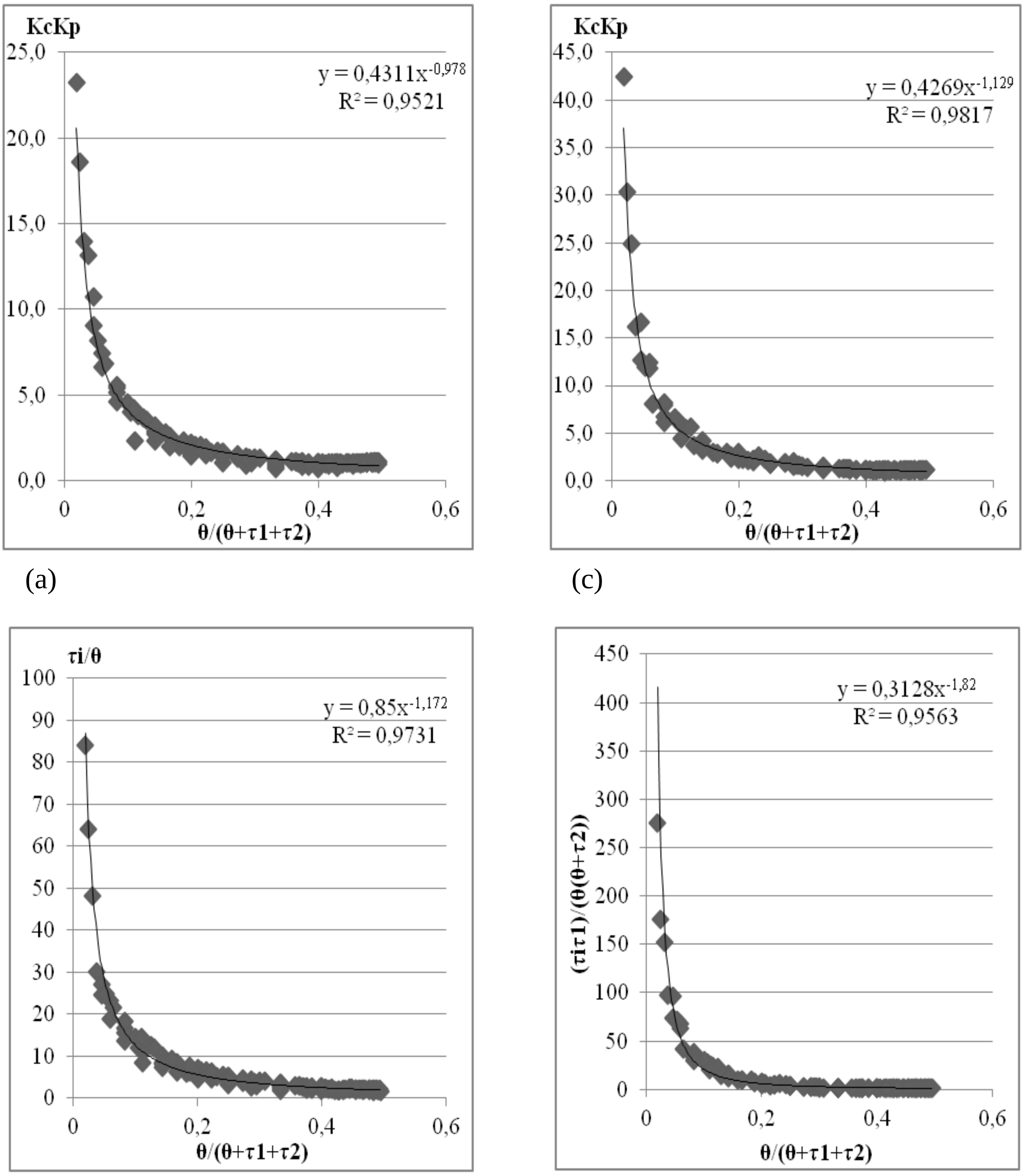


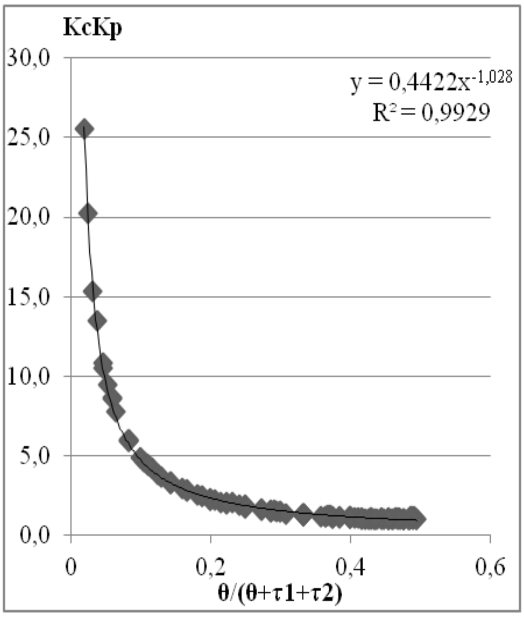
Figure 5.5. The relation graphics of proportional gain parameter vs. process parameters for SOPTD model and IAE minimization (a) for servo control (c) for regulatory control. The relation graphics of integral time parameter vs. process parameters for SOPTD model and IAE minimization (b) for servo control (d) for regulatory control.



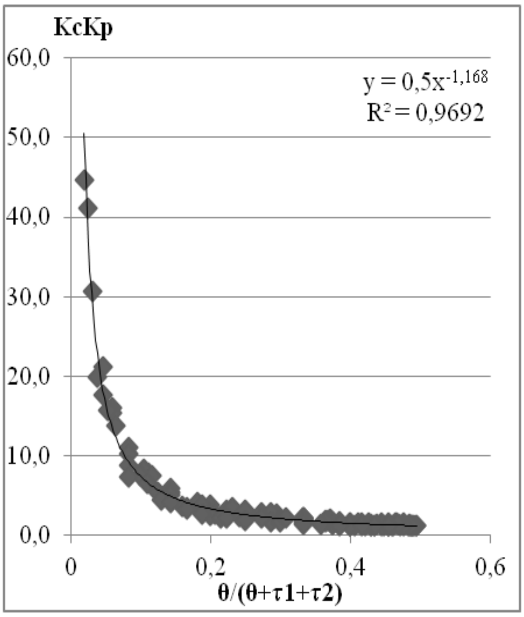
(a) (c)

(b) (d)

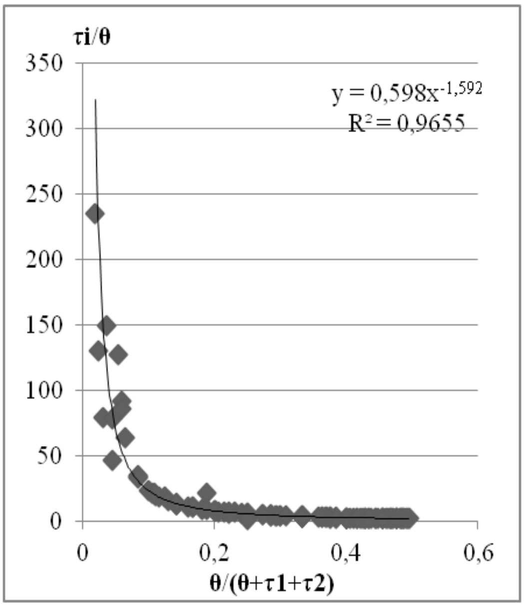
Figure 5.6. The relation graphics of proportional gain parameter vs. process parameters for SOPTD model and ITAE minimization (a) for servo control (c) for regulatory control. The relation graphics of integral time parameter vs. process parameters for SOPTD model and ITAE minimization (b) for servo control (d) for regulatory control.



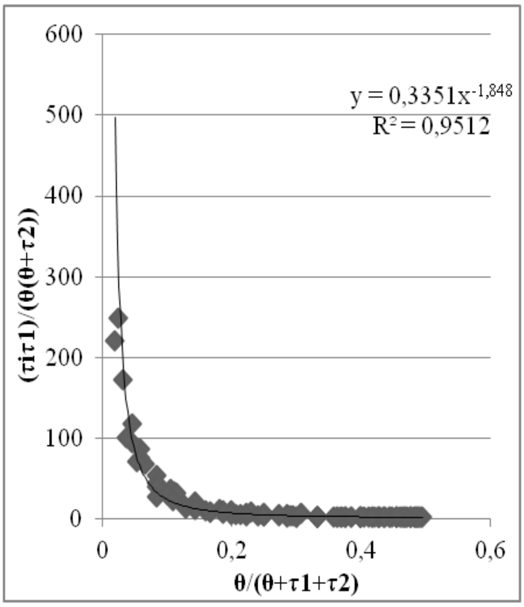
(a)



(c)



(b)



(d)

Figure 5.7. The relation graphics of proportional gain parameter vs. process parameters for SOPTD model and ISE minimization (a) for servo control (c) for regulatory control. The relation graphics of integral time parameter vs. process parameters for SOPTD model and ISE minimization (b) for servo control (d) for regulatory control.

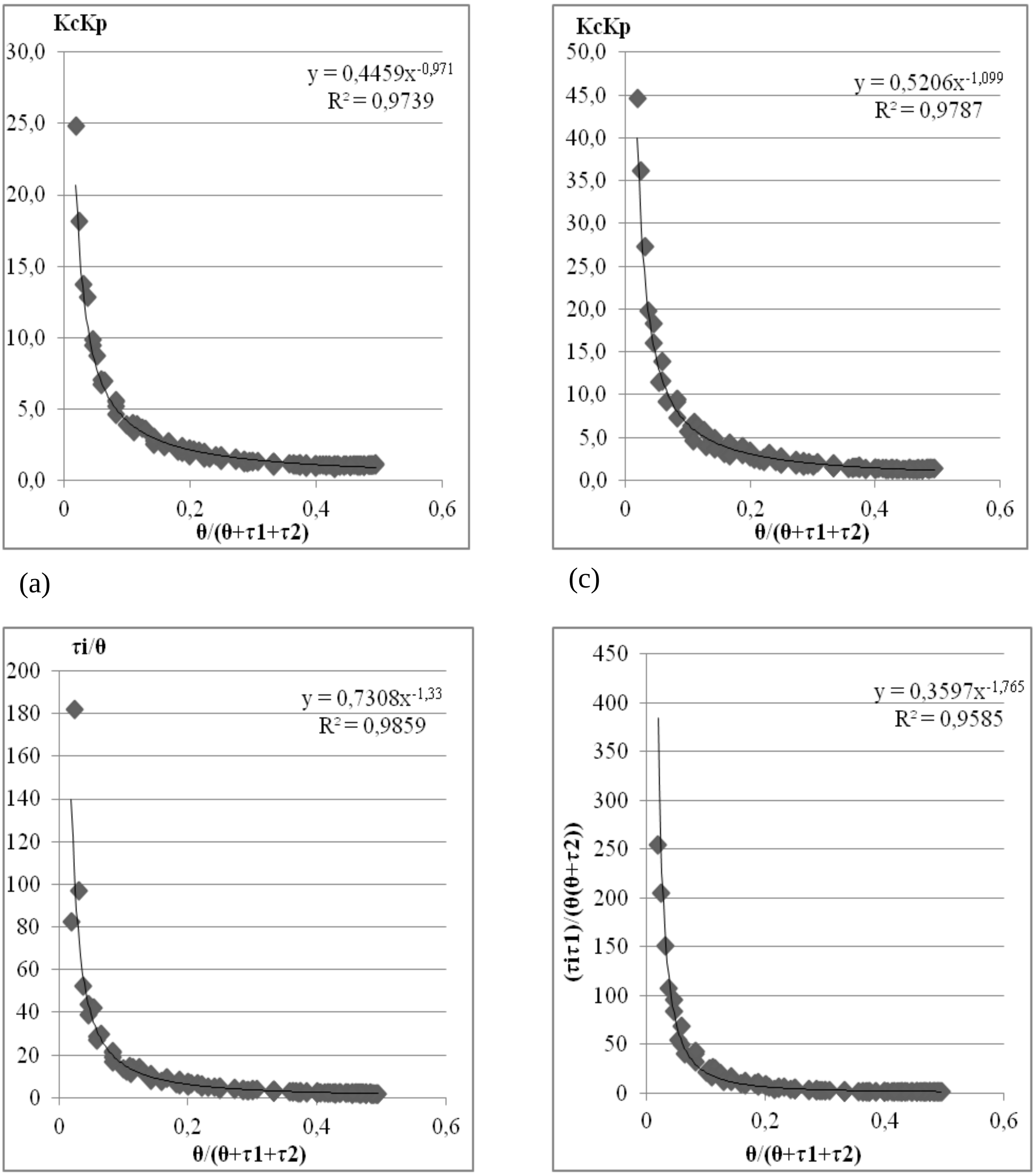


Figure 5.8. The relation graphics of proportional gain parameter vs. process parameters for SOPTD model and ITSE minimization (a) for servo control (c) for regulatory control. The relation graphics of integral time parameter vs. process parameters for SOPTD model and ITSE minimization (b) for servo control (d) for regulatory control.

Table 5.2. Proposed tuning relations for SOPTD model and IAE, ITAE, ISE and ITSE minimization criteria.

SOPTD Model - IAE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
$\mathbf{K_c}$	$\frac{0.4082}{K_P}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.016}$	$\frac{0.4196}{K_P}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.184}$
$\boldsymbol{\tau_i}$	$0.7471\theta\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.326}$	$0.2946\left(\frac{\theta}{\tau_1}\right)(\theta+\tau_2)\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.906}$
SOPTD Model - ITAE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
$\mathbf{K_c}$	$\frac{0.4311}{K_P}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-0.978}$	$\frac{0.4269}{K_P}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.129}$
$\boldsymbol{\tau_i}$	$0.850\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.172}$	$0.3128\left(\frac{\theta}{\tau_1}\right)(\theta+\tau_2)\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.82}$
SOPTD Model - ISE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
$\mathbf{K_c}$	$\frac{0.4422}{K_P}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.028}$	$\frac{0.5}{K_P}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.168}$
$\boldsymbol{\tau_i}$	$0.598\,\theta\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.592}$	$0.3351\left(\frac{\theta}{\tau_1}\right)(\theta+\tau_2)\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.848}$
SOPTD Model - ITSE Minimization Correlations		
Tuning Parameter	**Set point change**	**Load change**
$\mathbf{K_c}$	$\frac{0.4502}{K_P}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-0.963}$	$\frac{0.5206}{K_P}\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.099}$
$\boldsymbol{\tau_i}$	$0.7106\,\theta\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.354}$	$0.3597\left(\frac{\theta}{\tau_1}\right)(\theta+\tau_2)\left(\frac{\theta}{\theta+\tau_1+\tau_2}\right)^{-1.765}$

The graphics which show the relation in between dimensionless control parameters obtained from model and dimensionless process parameters for (critically damped and over damped) SOPTD process are examined, it is seen that the same conclusions as in FOPTD process part can be generally made. The optimum controller gain increases with an increase in the ratio of process time constant to process time delay (τ_1/θ and/or τ_2/θ). The controller gains proposed for load change are slightly greater than the ones proposed for set point change, which can also be seen from Table 5.2. The difference in between the correlations for the FOPTD process type and SOPTD process type is the integral time constant correlation for load change. This time, the dependent variable is selected as '$(\tau i*\tau_1)/(\theta*(\theta+\tau_2))$' not as (τ_i/θ) or (τ_i/τ_1) for load change for all minimization criteria correlations, since it has generally bigger coefficient of correlation regression (R^2) than the other possible dependent variables. It is found out that this dependent variable $((\tau i*\tau_1)/(\theta*(\theta+\tau_2)))$ decreases with the increase in the fraction dead time for load change. Besides, the dependent variable for the integral time constant for set point change correlations is selected as 'τ_i/θ' and found out that it decreases with the increase in the fraction dead time for all minimization criteria correlations. Additionally, the power relation in between dimensionless control parameters and process parameters are obtained for both set point change and load change. All the correlations obtained in this part have high coefficient of regression (R^2 >0.95).

6. COMPARISON OF PROPOSED METHOD WITH THE CONVENTIONAL DESIGN TECHNIQUES

After obtaining correlations, these correlations are examined in the case studies and the performance of the proposed correlations are compared with that of Ziegler-Nichols continuous cycling method, Ziegler-Nichols process reaction curve method and Cohen-Coon method in this section. In this comparison, the control parameters that obtained from the proposed method, Ziegler-Nichols continuous cycling method and process reaction curve method and Cohen-Coon method are applied to the case studies with the help of Matlab software and the values of overshoot (O_S), rise time (T_r), settling time (T_s) and also the values of minimization criteria (IAE, ITAE, ISE and ITSE) are compared in the dynamic responses. In this section, Ziegler-Nichols continuous cycling method, Ziegler-Nichols process reaction curve method, Cohen-Coon method, the proposed method for the minimizations of IAE, ITAE, ISE and ITSE are represented as 'Z-N1', 'Z-N2', 'C-C', 'PMIAE', 'PMITAE', 'PMISE', 'PMITSE', respectively.

6.1. Comparison for FOPTD Process Type

Three case studies are selected to compare the tuning methods for FOPTD process type and the process transfer functions of these case studies are given in the equations 6.1, 6.2 and 6.3. These case studies are selected so that the ratio of process time constant and time delay is 5, 1 and 0.5. Hence, these tuning methods are compared in the situation that there is a time constant (lag) dominant system; and the system has equal time constant and time delay values; and a dead time dominant system.

$$G_{P1}(s)= \frac{e^{-s}}{5s+1} \tag{6.1}$$

$$G_{P2}(s)= \frac{e^{-5s}}{5s+1} \tag{6.2}$$

$$G_{P3}(s)= \frac{e^{-10s}}{5s+1} \tag{6.3}$$

6.1.1. Comparison for FOPTD Process Type and Servo Control

For FOPTD process type and servo control; the comparison results of three case studies mentioned above (equations 6.1, 6.2 and 6.3) are shown in Figures 6.1, 6.2 and 6.3, respectively. The related performance values are presented in Table 6.1.

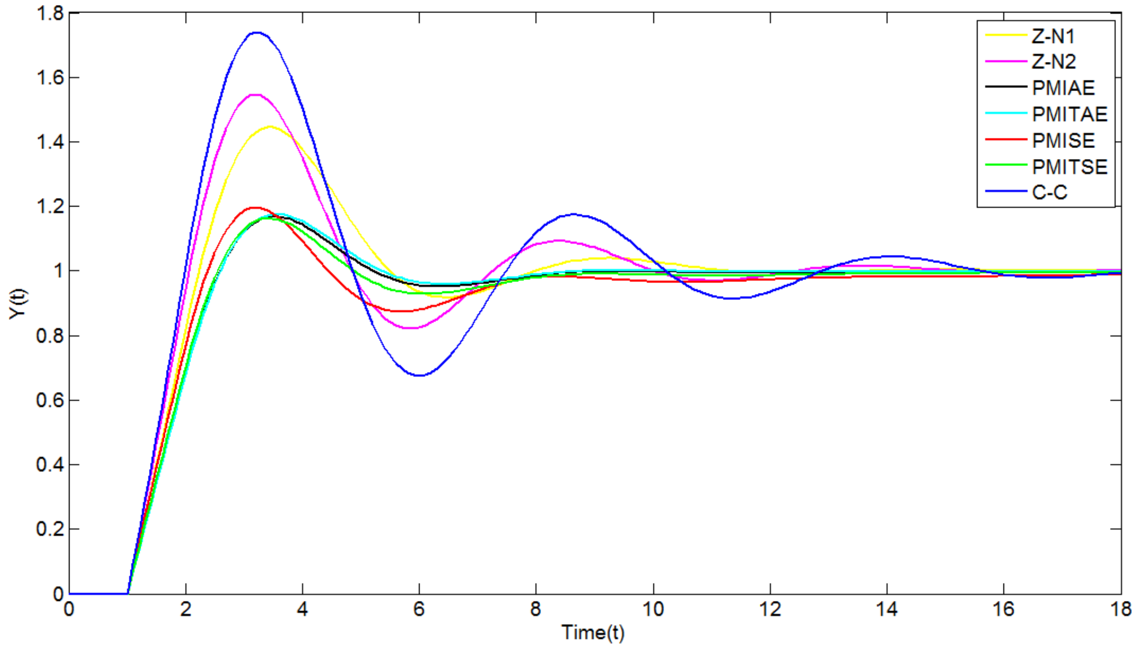


Figure 6.1. The comparison of tuning methods for the case study 1. (τ_1=5, θ=1)

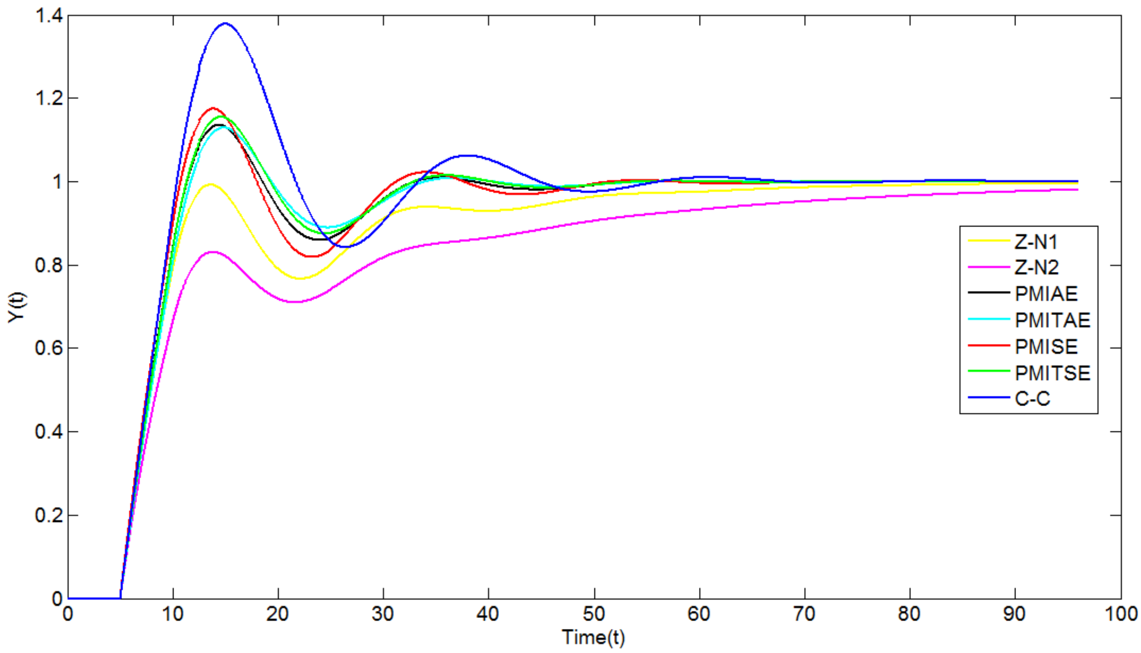


Figure 6.2. The comparison of tuning methods for the case study 2. (τ_1=5, θ=5)

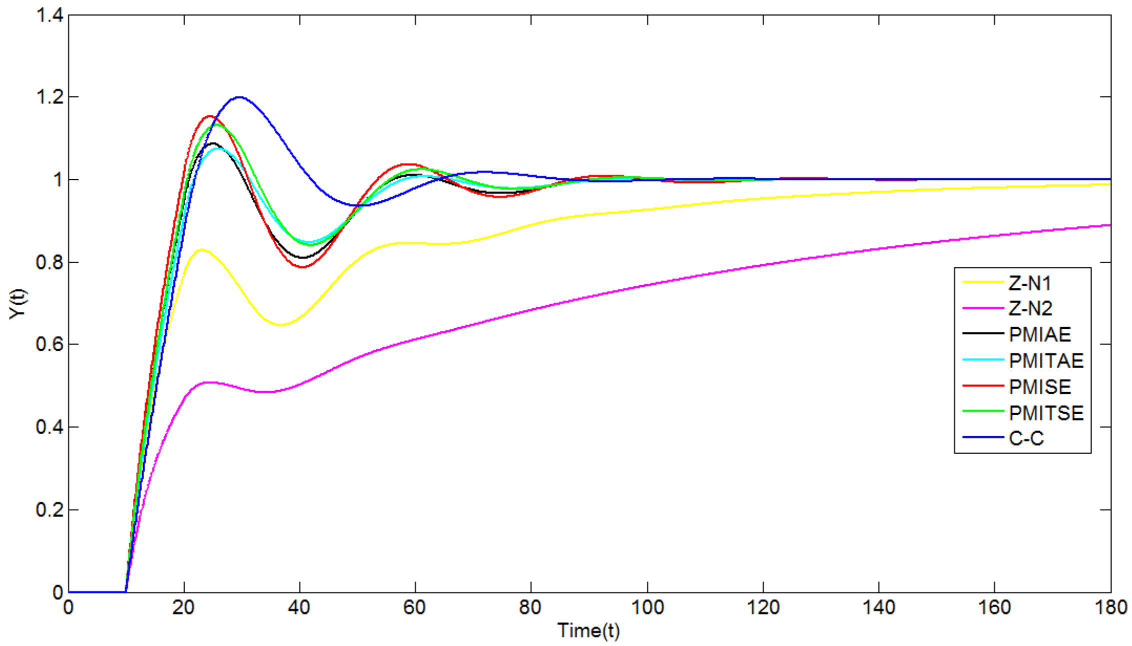


Figure 6.3. The comparison of tuning methods for the case study 3. (τ_1=5, θ=10)

When these three figures (Figures 6.1, 6.2 and 6.3) and Table 6.1 are examined for the case studies, it can be obviously said that the proposed method presents better control than the conventional techniques (Ziegler-Nichols Continuous Cycling method, Ziegler-Nichols Process Reaction Curve method and Cohen-Coon method), especially in respect to settling time (T_s), overshoot (O_s) and the values of minimization criteria (IAE, ITAE, ISE and ITSE).

For the first case study, a system which can be an example for time constant dominant system (or lag dominant system) is examined and the responds of each controller method is analyzed. It is seen from Figure 6.1 that all responds go beyond the value of set point (which is selected as 1 in the case studies), and do oscillations around the set point. All of three conventional techniques reach to set point earlier than the proposed method for the first time, which means the conventional techniques have shorter rise times (T_r) than the proposed method. Even so, there are not big differences in the rise time values which can be seen from the table. The important advantage of the proposed method can be seen when the settling time (T_s) values are compared. The proposed method provides shorter settling times than the conventional methods. In fact, the settling time values obtained from the proposed method (the ones proposed for IAE and ITAE minimization) are nearly half as the ones obtained from the conventional methods. The other advantage of the proposed method is that they give shorter overshoot (O_S) values than the conventional techniques. The proposed methods provide less minimization criteria values (IAE, ITAE, ISE and

ITSE) than the conventional techniques, which is the main purpose to propose these new correlations.

For the case study 2, a system which has equal time constant (τ_1) and dead time (θ) is selected. When the Figure 6.2 and the related results shown in table are examined, it is observed that the same comments can be made as in the case study 1. The proposed method gives shorter settling time, less overshoot value and less minimization criteria values than the conventional techniques. It is really needed to be pointed out in this case study is the response got from the two Ziegler-Nichols methods. The Ziegler-Nichols methods' responds do not go beyond the value of set point, and stay below the set point and they only are able to reach the set point in their settling times. Especially, Ziegler-Nichols process reaction curve method's respond is very slow. When the proposed method and Cohen-Coon method are compared in this section, the proposed method gives shorter settling time, overshoot and less minimization criteria values as mentioned before. The only advantage of the Cohen-Coon method is that it gives shorter rise time but, again there are not big differences in rise time values as seen in Table 6.1. Especially in case study 1 and 2, it is seen that Cohen-Coon method gives more oscillatory response than the proposed method correlations do. This is absolutely not surprising that the Cohen-Coon formula produces very oscillatory set-point responses and it was derived to give quarter damping (one quarter decay ratio) for the load disturbance response for FOPTD process models [29].

For the case study 3, a system which can be an example for dead time dominant system is examined and the responds of each controller method is analyzed. Again, the Ziegler-Nichols methods' responds do not go beyond the value of set point, and stay very below the set point and they only are able to reach the set point in their settling times. Additionally, their responses get even worse since dead time is bigger than the one in case study 2. It is already known that the Ziegler-Nichols continuous cycling method tuned PI controller produces sluggish set point and load-disturbance responses for large dead-time systems and that is the reason why it is thought to increase the integral action to overcome this problem while refining the Ziegler-Nichols closed-loop tuning formulas [29]. In this case study, the proposed method provides better response than Cohen-Coon method in every respect. The proposed method gives shorter rise time, settling time, overshoot and less minimization criteria values than Cohen-Coon method. It is a kind of prove that the proposed method gives good responses even in dead time dominant systems, which is really a good advantage in process control.

Table 6.1. Tuning parameters and performance characteristics for FOPTD process type and servo control

Servo Control										
Process	**Method**	K_c	τ_i	T_r	T_s	O_s	**IAE**	**ITAE**	**ISE**	**ITSE**
$G_{P1}(s)$	Z-N1	3.86	3.08	2.20	7.25	1.44	2.71	6.24	1.72	2.10
	Z-N2	4.50	3.30	2.10	9.15	1.55	2.99	8.31	1.81	2.51
	C-C	4.58	2.35	2.00	12.25	1.74	3.97	15.48	2.30	4.68
	PMIAE	3.45	5.56	2.50	4.55	1.17	2.15	-	-	-
	PMITAE	3.42	5.29	2.50	4.65	1.18	-	3.44	-	-
	PMISE	3.98	7.95	2.30	7.15	1.20	-	-	1.50	-
	PMITSE	3.58	6.34	2.50	7.05	1.16	-	-	-	1.24
$G_{P2}(s)$	Z-N1	1.03	12.9	11.9	46.4	-	12.57	194	7.45	38.6
	Z-N2	0.90	16.5	68.5	68.9	-	18.33	454	8.83	72.4
	C-C	0.98	5.69	10.1	40.2	1.38	12.18	136	7.69	40.0
	PMIAE	1.00	8.59	10.9	29.6	1.14	9.91	-	-	-
	PMITAE	0.94	7.90	11.2	29.8	1.13	-	74.3	-	-
	PMISE	1.09	9.22	10.3	28.9	1.17	-	-	7.02	-
	PMITSE	0.98	8.01	10.8	29.6	1.16	-	-	-	28.1
$G_{P3}(s)$	Z-N1	0.69	22.9	117	117	-	33.10	1350	16.63	247.8
	Z-N2	0.45	33.0	256	256	-	71.72	5957	31.52	1245
	C-C	0.53	7.35	21.1	55.2	1.20	19.12	269.4	13.97	108.54
	PMIAE	0.72	12.6	20.1	51.4	1.09	18.75	-	-	-
	PMITAE	0.67	11.5	20.7	52.0	1.07	-	265.0	-	-
	PMISE	0.77	12.6	19.2	50.6	1.15	-	-	13.31	-
	PMITSE	0.70	11.2	19.9	51.6	1.13	-	-	-	100.5

6.1.2. Comparison for FOPTD Process Type and Regulatory Control

For FOPTD process type and regulatory control; the comparison results are shown in Figures 6.4, 6.5 and 6.6. The related performance values are presented in Table 6.2.

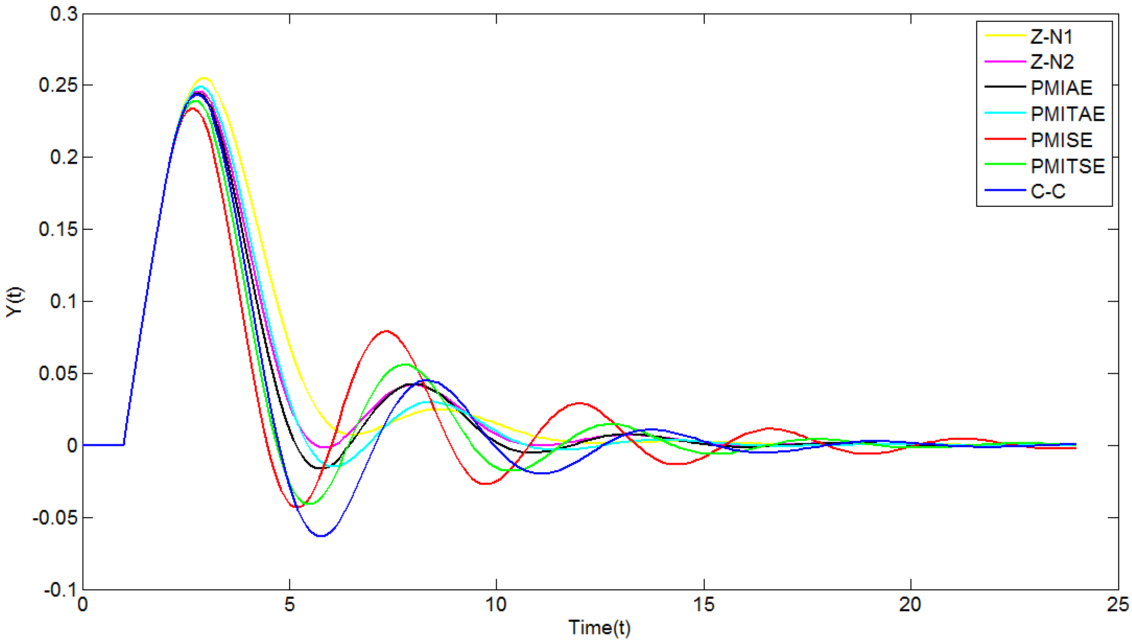


Figure 6.4. The comparison of tuning methods for the case study 1. (τ_1=5, θ=1)

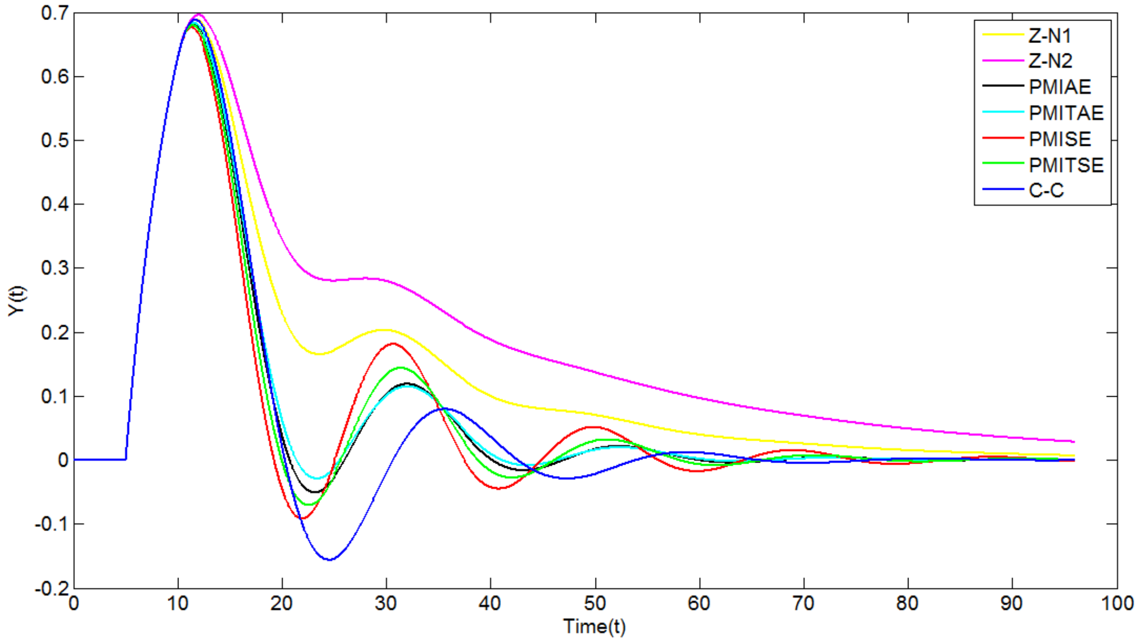


Figure 6.5. The comparison of tuning methods for the case study 2. (τ_1=5, θ=5)

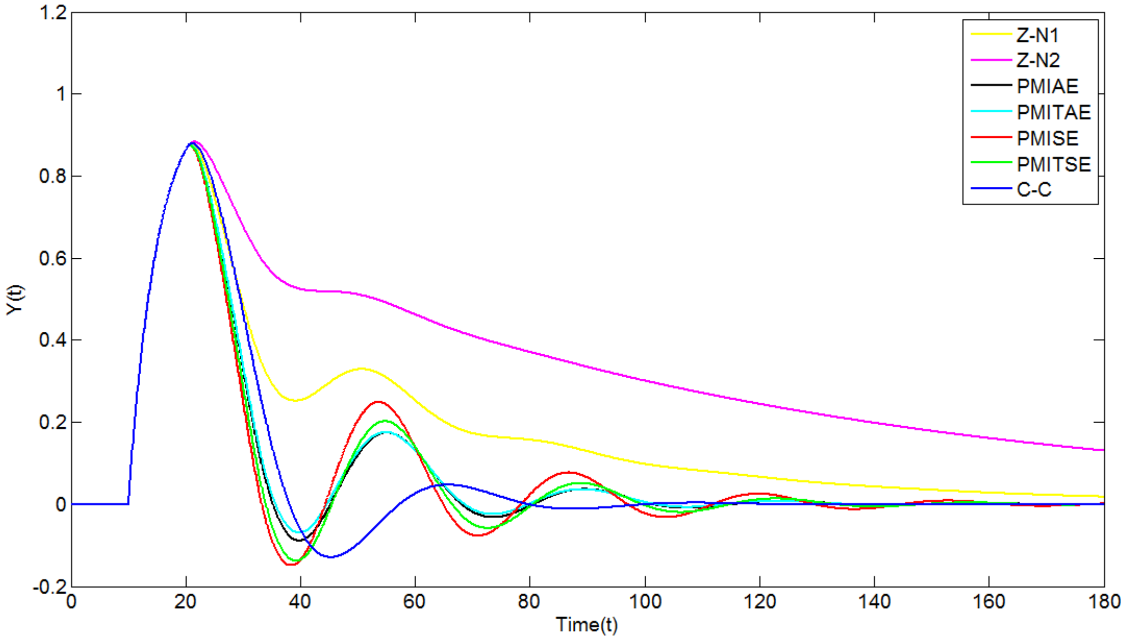


Figure 6.6. The comparison of tuning methods for the case study 3. (τ_1=5, θ=10)

The proposed method correlations are compared with the conventional tuning methods for regulatory control for FOPTD process models in three case studies in this section. The process models whose transfer functions are given in the equations 6.1, 6.2 and 6.3 are used in the case studies.

For the case study 1, the Figure 6.4 shows the comparisons of the responds of the tuning methods for regulatory control system. Two Ziegler-Nichols methods give the response that it reaches set point after doing oscillations over the set point (set point is 0 in this case). On the other hand, Cohen-Coon method gives the response that it is doing oscillations around the set point and reaches set point by doing more oscillations than Ziegler-Nichols method. When the proposed method response is examined, it is seen that it has better respond than the conventional methods. Especially, when the correlations for IAE and ITAE minimization are used, it provides a response that it is doing oscillations around set point and reaching to the set point by doing fewer oscillations than the Cohen-Coon method. When the dead time to process time constant ratio gets bigger which is the case in the case studies 2 and 3 (dead time values are 5 and 10 for the case studies 2 and 3, respectively), it can be obviously seen that the response of two Ziegler-Nichols methods are getting worse. The same consequence was mentioned in the servo control section (section 6.1.1). It should be underlined again that the Ziegler-Nichols continuous cycling method tuned PI controller produces sluggish set point and load-disturbance responses for large dead-time systems and that is the reason why it is thought to increase the integral action to overcome this problem while refining the Ziegler-Nichols closed-loop tuning formulas [29]. It can be concluded that Ziegler-Nichols methods (process reaction curve and continuous cycling method) do not provide good PI control when the system has efficient dead time. When the Table 6.2 which has the minimization criteria values are examined, it is seen that the proposed method provide less minimization criteria values than the conventional methods except for the ITAE minimization in the case study 3. In case study 3, proposed method for the ITAE minimization gives less ITAE value than Ziegler – Nichols methods but more ITAE value than Cohen-Coon method.

Table 6.2. Tuning parameters and performance characteristics for FOPTD process type and regulatory control

Regulatory Control							
Process	**Method**	K_c	τ_i	**IAE**	**ITAE**	**ISE**	**ITSE**
$G_{P1}(s)$	Z-N1	3.86	3.08	0.802	3.09	0.136	0.419
	Z-N2	4.50	3.30	0.735	2.93	0.116	0.348
	C-C	4.58	2.35	0.790	3.69	0.110	0.340
	PMIAE	4.62	3.09	0.712	-	-	-
	PMITAE	4.23	2.88	-	2.70	-	-
	PMISE	5.68	3.34	-	-	0.099	-
	PMITSE	5.06	2.92	-	-	-	0.310
$G_{P2}(s)$	Z-N1	1.03	12.9	12.56	319.5	4.43	68.96
	Z-N2	0.90	16.5	18.33	637.7	6.10	122.6
	C-C	0.98	5.69	8.309	142.4	3.52	44.49
	PMIAE	1.15	8.19	7.70	-	-	-
	PMITAE	1.12	8.35	-	125.4	-	-
	PMISE	1.34	9.23	-	-	3.20	-
	PMITSE	1.23	8.57	-	-	-	40.72
$G_{P3}(s)$	Z-N1	0.69	22.9	33.09	1844	13.44	428.3
	Z-N2	0.45	33.0	71.44	6930	28.80	1662
	C-C	0.53	7.34	17.16	462.6	10.12	224.1
	PMIAE	0.80	12.1	17.11	-	-	-
	PMITAE	0.79	12.4	-	519.0	-	-
	PMISE	0.92	13.4	-	-	9.17	-
	PMITSE	0.85	12.2	-	-	-	207.3

6.2. Comparison for SOPTD Process Type

Three case studies are selected to compare the tuning methods for SOPTD process type and the process transfer functions of these case studies are given in the equations 6.4, 6.5 and 6.6. In the first case study, the time constant 1(τ_1) is bigger than the other time constant (τ_2) and dead time (θ). In the case study 2, time constants (τ_1 and τ_2) and time delay (θ) are the same. In the case study 3, time delay (θ) is bigger than the time constants (τ_1 and τ_2).

$$G_{P4}(s)= \frac{e^{-s}}{(15s+1)(3s+1)} \tag{6.4}$$

$$G_{P5}(s)= \frac{e^{-5s}}{(5s+1)(5s+1)} \tag{6.5}$$

$$G_{P6}(s)= \frac{e^{-7s}}{(5s+1)(3s+1)} \tag{6.6}$$

It has been said that all the second order or high order systems can be approximated to FOPTD process model type. For this reason and to be able to use the Ziegler Nichols tuning methods and Cohen-Coon methods, these transfer functions given in the equations above are approximated to the FOPTD process models in the equations 6.7, 6.8 and 6.9, respectively. For this approximation process, matlab files generated by Yi Cao [30] are used.

$$G_{P7}(s)= \frac{0.9961*e^{-2.5949s}}{22.3956s+1} \tag{6.7}$$

$$G_{P8}(s)= \frac{0.9992*e^{-6.4038s}}{13.5985s+1} \tag{6.8}$$

$$G_{P9}(s)= \frac{0.9971*e^{-8.0707s}}{10.7359s+1} \tag{6.9}$$

6.2.1. Comparison for SOPTD Process Type and Servo Control

For SOPTD process type and servo control, the comparison results are shown in Figures 6.7, 6.8 and 6.9. The related performance values are presented in Table 6.3.

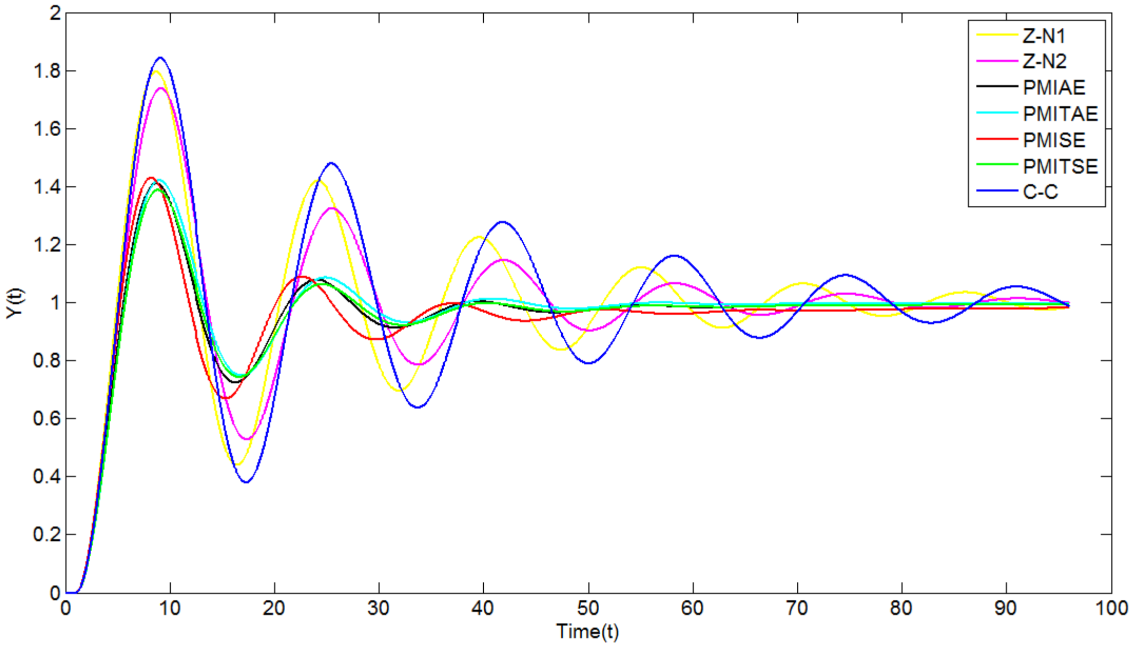


Figure 6.7. The comparison of tuning methods for the case study 1. (τ_1=15, τ_2=3, θ=1)

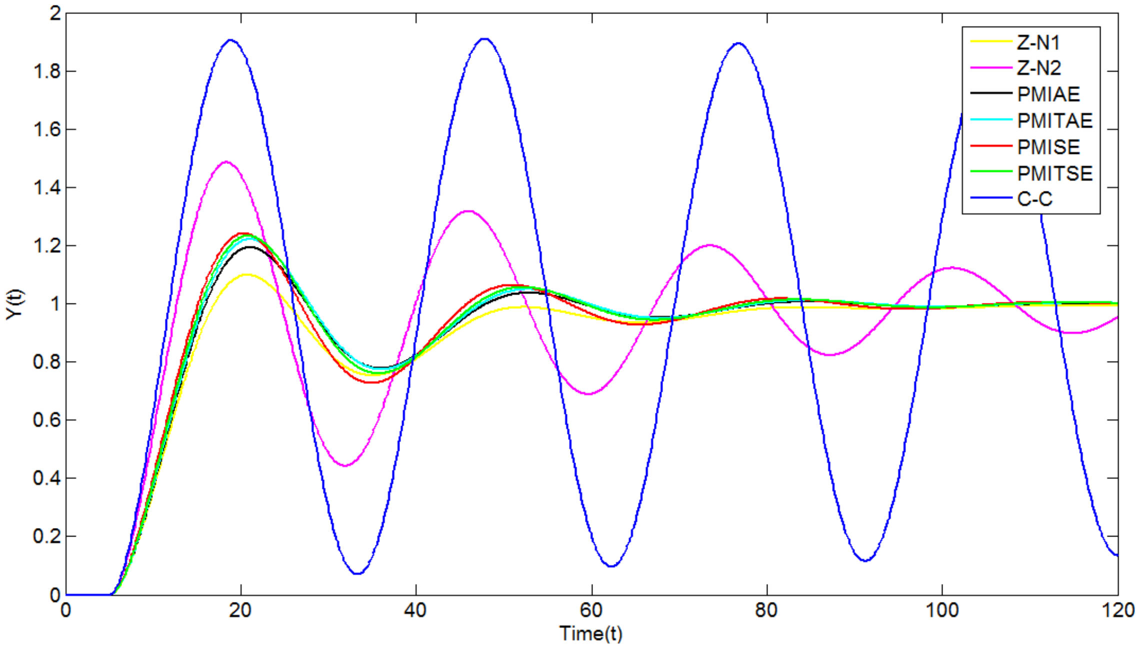


Figure 6.8. The comparison of tuning methods for the case study 2. (τ_1=5, τ_2=5, θ=5)

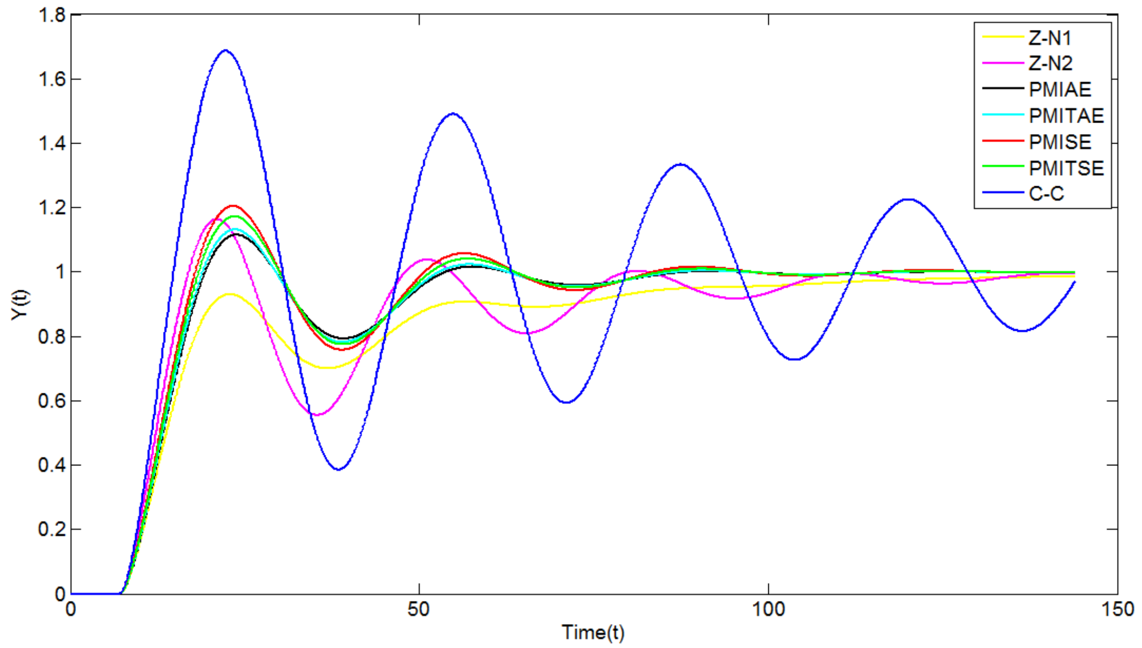


Figure 6.9. The comparison of tuning methods for the case study 3. (τ_1=5, τ_2=3, θ=7)

The responses of the proposed method and the conventional tuning methods are compared for servo control in SOPTD systems in this section. For this purpose, three case studies are defined and their transfer functions are given in the equations 6.4, 6.5 and 6.6. The dynamic responses obtained from the tuning methods for each case study are given in Figures 6.7, 6.8 and 6.9. The values of overshoot (O_s), rise time (T_r), settling time (T_s) and also the values of minimization criteria (IAE, ITAE, ISE and ITSE) obtained from these case studies are given in Table 6.3.

For the case study 1, when the Figure 6.7 and related results in Table 6.3 are analyzed, it can be concluded that the proposed method correlations have many superiority. The rise time values seem to be the only disadvantage of proposed method in this case study. The same conclusion was made for the FOPTD systems in section 6.1.1. Ziegler-Nichols continuous cycling method has the smallest rise time. Although, the differences in rise time values in between the tuning methods are small. But, the proposed method correlations have smaller settling time, overshoot and minimization criteria values than the all conventional methods. Additionally, the settling time values of proposed methods are nearly as half as the ones of conventional methods. The proposed method has important advantage for the values of minimization criteria, especially for the time weighted minimization criteria (ITAE and ITSE), which can be seen from the table.

For the case study 2, when the Figure 6.8 and related results in Table 6.3 are analyzed, the first thing which draws the attention is how badly the Cohen-Coon method gives responds.

Cohen-Coon method gives a response that is nearly continuously cycling around the set point. It is significant to mention about the differences in the responses of two Ziegler-Nichols methods in this case study. The Ziegler-Nichols continuous cycling method gives a really good response. It has small overshoot; it is doing only a few oscillations and reaches to set point in a small time interval (small settling time). But, Ziegler-Nichols process reaction curve method gives a response which has many oscillations around the set point and reaches to the set point after a long time. Hence, it has bigger minimization criteria values than the continuous cycling method and proposed method correlations. The proposed method correlations provide smaller rise time, settling time and minimization criteria values than the Ziegler-Nichols continuous cycling method.

For the case study 3, the proposed method superiority over the conventional methods can be seen in Figure 6.9 and Table 6.3. The Ziegler-Nichols continuous cycling method's response does not go beyond the value of set point, and stay below the set point until it is able to reach the set point in its settling time. On the other side, Cohen-Coon method's response is doing many oscillations around the set point and its settling time is nearly three times bigger than the proposed method. Ziegler-Nichols process reaction curve method seems to have better response than the other conventional methods, but it has bigger settling time and minimization criteria values than the proposed method.

Table 6.3. Tuning parameters and performance characteristics for SOPTD process type and servo control

Servo Control										
Process	**Method**	K_c	τ_i	T_r	T_s	O_s	**IAE**	**ITAE**	**ISE**	**ITSE**
$G_{P4}(s)$	Z-N1	8.71	8.59	4.9	72	1.80	17.8	432	8.04	93.8
	Z-N2	7.80	8.56	5.1	60	1.74	15.0	300	6.96	66.1
	C-C	7.88	6.96	5.0	92	1.84	21.4	619	9.64	137
	PMIAE	8.13	37.1	5.4	35	1.41	8.83	-	-	-
	PMITAE	7.68	26.8	5.6	35	1.42	-	97.7	-	-
	PMISE	9.12	64.9	5.1	46.8	1.43	-	-	4.17	-
	PMITSE	7.78	36.7	5.6	32.25	1.39	-	-	-	16.9
$G_{P5}(s)$	Z-N1	1.23	20.0	16.2	71.0	1.10	17.3	363	10.4	77.9
	Z-N2	1.91	21.1	12.4	145	1.48	31.2	1327	14.3	278
	C-C	2.00	10.9	11.7	-	1.91	104	9003	73.7	6155
	PMIAE	1.25	16.0	15.4	45.0	1.20	16.4	-	-	-
	PMITAE	1.26	15.4	15.2	68.2	1.22	-	288.7	-	-
	PMISE	1.37	17.2	14.7	70.4	1.24	-	-	10.3	-
	PMITSE	1.30	15.8	15.0	70.0	1.24	-	-	-	75.0
$G_{P6}(s)$	Z-N1	0.86	22.14	89.7	89.7	-	25.4	791	13.6	153
	Z-N2	1.20	26.60	16.4	102	1.16	24.1	749	13.4	169
	C-C	1.28	10.87	14.5	180	1.68	47.38	2637	22.9	731
	PMIAE	0.88	14.37	18.5	50.0	1.12	17.9	-	-	-
	PMITAE	0.91	14.53	18.2	49.6	1.13	-	311	-	-
	PMISE	0.97	14.08	17.3	75.4	1.20	-	-	12.1	-
	PMITSE	0.94	14.10	17.7	49.0	1.17	-	-	-	93.8

6.2.2 Comparison for SOPTD Process Type and Regulatory Control

For SOPTD process type and regulatory control, the comparison results are shown in Figures 6.10, 6.11 and 6.12. The related performance values are presented in Table 6.4.

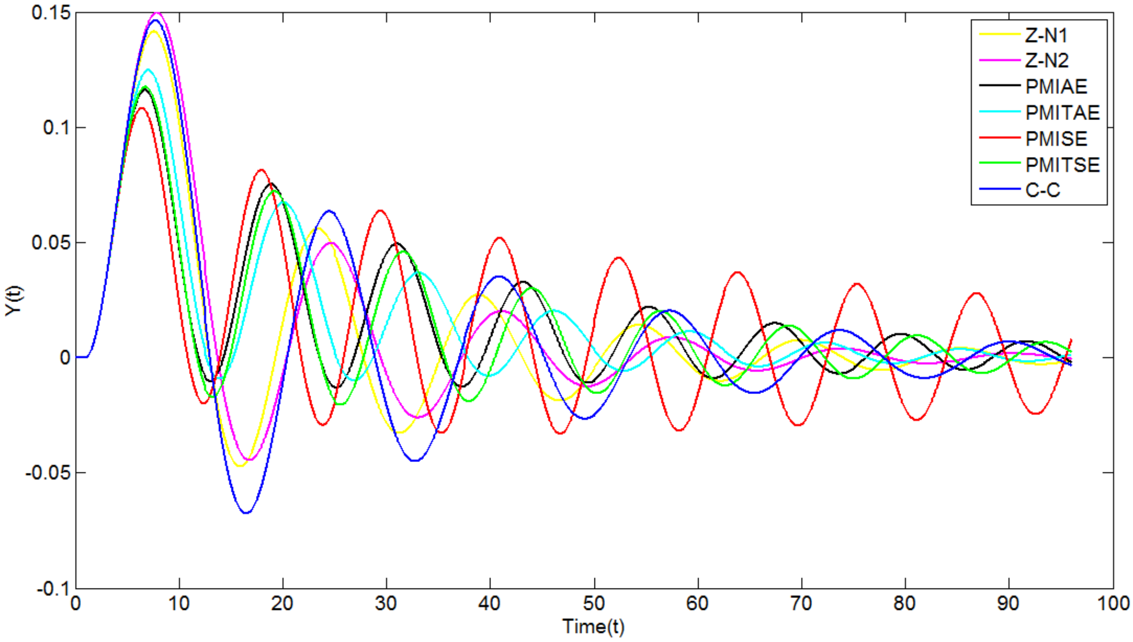


Figure 6.10. The comparison of tuning methods for the case study 1. (τ_1=15, τ_2=3, θ=1)

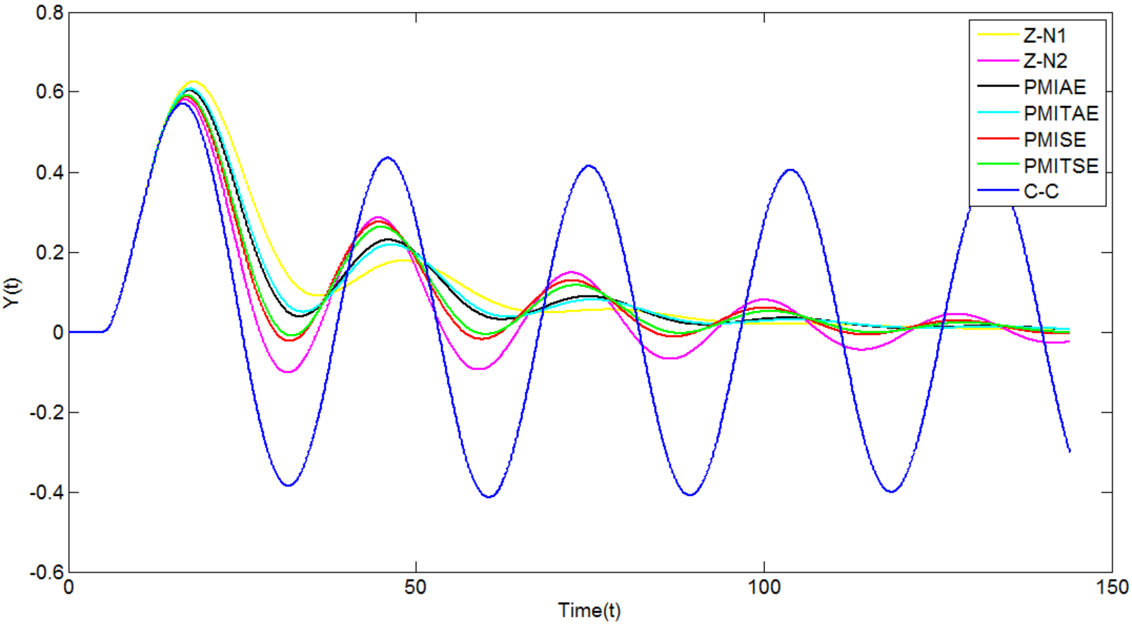


Figure 6.11. The comparison of tuning methods for the case study 2. (τ_1=5, τ_2=5, θ=5)

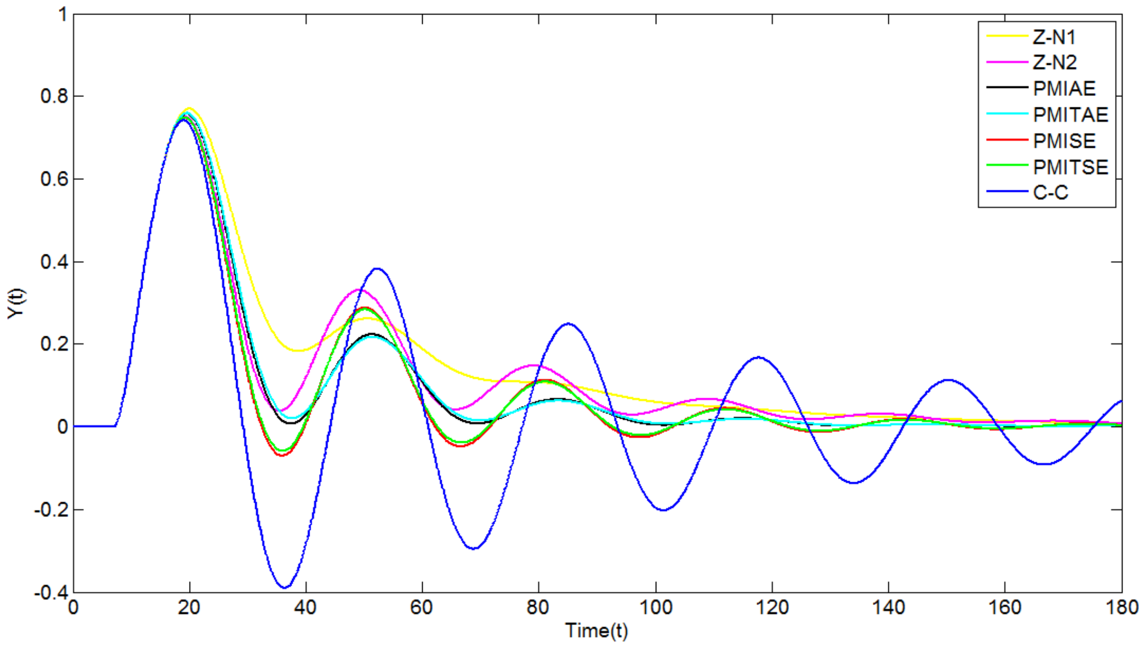


Figure 6.12. The comparison of tuning methods for the case study 3. (τ_1=5, τ_2=3, θ=7)

The proposed method correlations are compared with the conventional tuning methods for regulatory control for SOPTD process models in three case studies in this section. The process models whose transfer functions are given in the equations 6.4, 6.5 and 6.6 are used in the case studies. The FOPTD process model transfer functions given in the equations 6.7, 6.8 and 6.9, which are the approximate process transfer functions of equations 6.4, 6.5 and 6.6, are used to calculate the tuning parameters according to Ziegler-Nichols methods and Cohen-Coon method. For the case study 1, the Figure 6.10 and Table 6.4 show the comparisons of the responds of the tuning methods for regulatory control system. The proposed method correlations for ISE minimization give more oscillatory respond than the other proposed correlations and conventional tuning methods. The Ziegler-Nichols process reaction method gives the smallest minimization criteria values in this case study. The proposed method correlations have nearly the same minimization criteria values as Ziegler-Nichols process reaction method except the IAE value. For the case study 2, the Figure 6.11 and Table 6.4 show the comparisons of the responds of the tuning methods for regulatory control system. In this case study, the superiority of the proposed correlations becomes more apparent. The proposed method correlations have the smallest minimization criteria with one exception for ITAE value (Ziegler-Nichols continuous cycling method has smaller ITAE value than the proposed ITAE minimization correlation). Cohen-Coon method gives a respond that is nearly continuously cycling around the set point. For this reason, it has the biggest minimization criteria values among the tuning methods. Ziegler-Nichols continuous cycling method give the response that it reaches to set point after doing oscillations over the set point. Ziegler-Nichols process reaction curve method is giving more oscillatory respond than the proposed methods. For the case study 3, the Figure 6.12 and Table 6.4 show the comparisons of the responds of the tuning methods for regulatory control system. In this case study, the superiority of the proposed correlations becomes even more apparent than the case study 2. The proposed method correlations give better response than the conventional methods and they have smaller minimization criteria than the conventional methods.

Table 6.4. Tuning parameters and performance characteristics for SOPTD process type and regulatory control

Regulatory Control							
Process	**Method**	**K_c**	**τ_i**	**IAE**	**ITAE**	**ISE**	**ITSE**
$G_{P4}(s)$	Z-N1	8.71	8.59	2.07	50.7	0.13	1.58
	Z-N2	7.80	8.56	1.97	40.4	0.14	1.55
	C-C	7.88	6.96	2.62	77.3	0.16	2.40
	PMIAE	13.7	21.5	2.02	-	-	-
	PMITAE	11.9	17.7	-	40.3	-	-
	PMISE	15.6	20.6	-	-	0.14	-
	PMITSE	13.2	17.3	-	-	-	1.54
$G_{P5}(s)$	Z-N1	1.23	20.0	16.2	580	5.38	121
	Z-N2	1.91	21.1	15.9	744	4.33	115
	C-C	2.00	10.9	46.6	4194	15.6	1335
	PMIAE	1.54	23.9	15.4	-	-	-
	PMITAE	1.48	23.1	-	590	-	-
	PMISE	1.80	25.5	-	-	4.44	-
	PMITSE	1.74	25.0	-	-	-	107
$G_{P6}(s)$	Z-N1	0.86	22.1	25.3	1152	9.63	270
	Z-N2	1.20	26.6	21.8	1005	8.04	224
	C-C	1.28	10.9	30.5	1919	9.96	406
	PMIAE	1.03	17.6	17.0	-	-	-
	PMITAE	1.01	17.5	-	599	-	-
	PMISE	1.22	19.2	-	-	7.10	-
	PMITSE	12.0	19.3	-	-	-	174

7. COMPARISON OF PROPOSED METHOD WITH THE OTHER PROPOSED DESIGN TECHNIQUES IN LITERATURE

There are several proposed tuning methods for the proportional-integral controllers with different objectives in literature. Some of them are compared with the proposed method in this section. For that purpose, the case studies are specified and the PI controller parameters that obtained from the proposed method and the other tuning methods proposed in literature are applied to these case studies with the help of Matlab software and the values of overshoot (O_s), rise time (T_r), settling time (T_s) and also the related values of minimization criteria (IAE, ITAE, ISE and ITSE) are compared in the dynamic responses.

7.1. Comparison for FOPTD Process Type and IAE Minimization for Servo Control

The proposed correlations for the IAE minimization criterion, for servo control, for FOPTD process model type is compared with the other tuning correlations which are defined for the same purpose in literature in this section.

Three case studies are defined and their transfer functions are given in equations 7.1, 7.2 and 7.3, respectively. The ratios of process time delay to process time constant (θ/τ_1) are 0.25, 1 and 3 in these case studies, respectively.

$$G_{P10}(s)= \frac{e^{-s}}{(4s+1)} \tag{7.1}$$

$$G_{P11}(s)= \frac{e^{-4s}}{(4s+1)} \tag{7.2}$$

$$G_{P12}(s)= \frac{e^{-12s}}{(4s+1)} \tag{7.3}$$

Smith and Corripio took a different approach to control design called as controller synthesis and they provided a table that summarizes the selection of controller modes and tuning parameters those results from the synthesis procedure for Dahlin's response in their book [31-32]. They proposed the formulas given in Table 7.1 for PI controller tuning, for IAE minimization, for FOPTD process type. Their formulas are compared with the proposed method in only case study 1, since they recommended using PID controller instead of PI controller for the processes whose transfer function has the ratio of process time delay to process time constant (θ/τ_1) more than 0.25.

Tavakoli and Fleming [1] proposed optimal tuning of PI controllers for FOPTD models using dimensional analysis and numerical optimization techniques. They obtained these optimal equations for determining PI parameters given in equations through minimizing IAE and for considering a step change in set point. They also constrained the optimization process to guarantee a minimum gain margin of 2 and a minimum phase margin of 60^o. Their proposed formulas can also be used for FOPTD systems which has long dead times. Because of this reason, their formulas are compared with the proposed method in three different case studies.

Rovira [21] developed servo control tuning formulas for the IAE and ITAE minimization criteria separately for PI and PID controllers. His empirical tuning formulas are valid for the FOPTD process models whose ratio of process time delay to process time constant (θ/τ_1) is in between 0.1 and 1.0. Because of this reason, his formulas are compared with the proposed correlations in the case studies 1 and 2.

The tuning correlations of Smith and Corripio, Tavakoli and Fleming and Rovira are given in Table 7.1.

Table 7.1. Tuning formulas of the proposed methods in literature for FOPTD process type, IAE minimization and servo control.

Method	K_c	τ_i	**The range**
Smith and Corripio	$\frac{0.6*\tau_1}{K*\theta}$	τ_1	$0.1 \leq \frac{\theta}{\tau_1} \leq 0.25$
Tavakoli and Fleming	$\frac{1}{K}\left[0.4849*\frac{\tau_1}{\theta}+0.3047\right]$	$\tau_1\left[0.4262*\frac{\theta}{\tau_1}+0.9581\right]$	$0.1 \leq \frac{\theta}{\tau_1} \leq 10$
Rovira	$\frac{0.758}{K}\left(\frac{\theta}{\tau_1}\right)^{-0.861}$	$\frac{\tau_1}{1.02 - 0.323\left(\frac{\theta}{\tau_1}\right)}$	$0.1 \leq \frac{\theta}{\tau_1} \leq 1.0$

The results of the case studies are given in Figures 7.1, 7.2 and 7.3. The related performance values are presented in Table 7.2. The abbreviations of ‘PM’, ‘SC’, ‘TF’ and ‘R’ are used for Proposed method, Smith and Corripio, Tavakoli and Fleming and Rovira, respectively.

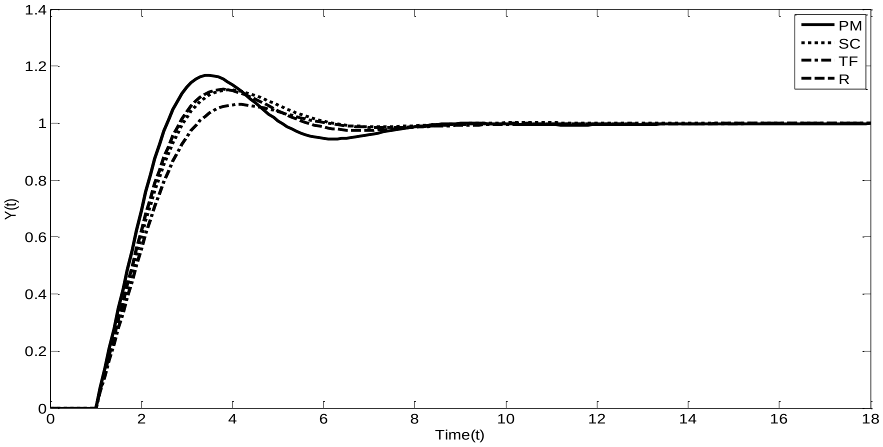


Figure 7.1. The comparison of tuning methods for the case study 1. (τ_1=4, θ=1, K_p=1)

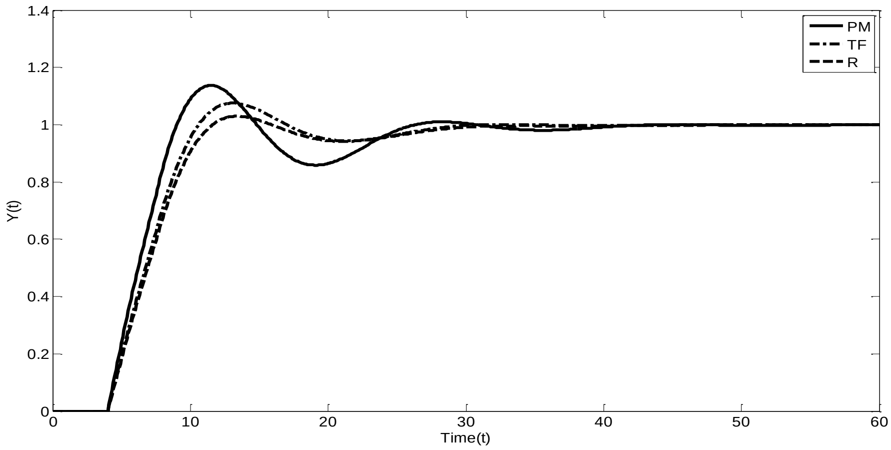


Figure 7.2. The comparison of tuning methods for the case study 2. (τ_1=4, θ=4, K_p=1)

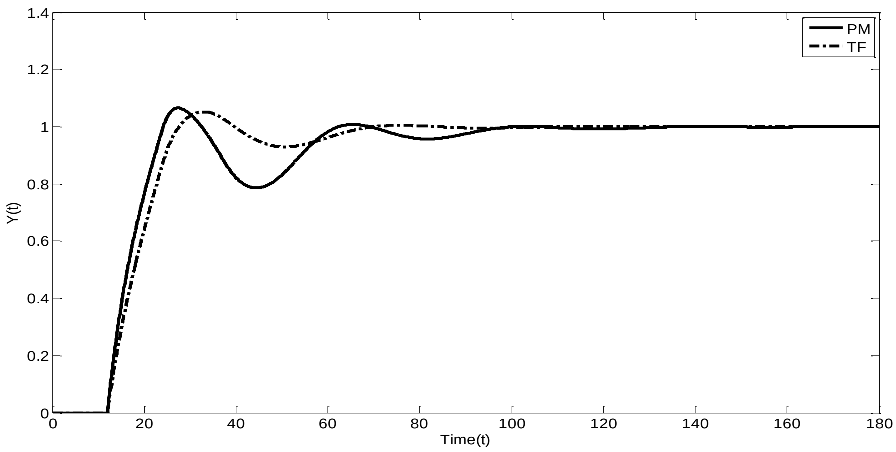


Figure 7.3. The comparison of tuning methods for the case study 3. (τ_1=4, θ=12, K_p=1)

In all case studies, there is not big difference in IAE values in between the tuning methods but it can be said that the proposed method has worse response than the others in respect to overshoot and settling time values. In all case studies, the proposed method gives a more oscillatory response than the other tuning methods. But, the proposed method provides the smallest rise time value among these tuning methods.

Table 7.2. Tuning parameters and performance characteristics for FOPTD process type, IAE minimization and servo control

Servo Control							
Process	**Method**	**K_c**	**τ_i**	**T_r**	**T_s**	**O_s**	**IAE**
$G_{P10}(s)$	PM	2.81	4.57	2.5	6.65	1.17	2.13
	SC	2.40	4.00	2.8	4.95	1.12	2.10
	TF	2.24	4.26	3.0	4.55	1.06	2.11
	R	2.50	4.26	2.7	4.75	1.12	2.10
$G_{P11}(s)$	PM	1.00	6.87	8.7	23.6	1.14	7.93
	TF	0.79	5.54	10	23.2	1.08	7.62
	R	0.76	5.74	10.7	23.4	1.03	7.73
$G_{P12}(s)$	PM	0.63	13.37	23.3	57.2	1.06	21.8
	TF	0.47	8.95	25.8	57.6	1.05	20.1

7. 2. Comparison for FOPTD Process Type and IAE Minimization for Regulatory Control

The proposed correlations for the IAE minimization criterion, for regulatory control, for FOPTD process type model is compared with the other tuning correlations which are defined for the same purpose in literature in this section. Three case studies are defined and their transfer functions are given in equations 7.4, 7.5 and 7.6, respectively. The ratios of process time delay to process time constant (θ/τ_1) are 0.25, 0.5 and 1 in these case studies, respectively.

$$G_{P13}(s)=\frac{2*e^{-2s}}{(8s+1)} \tag{7.4}$$

$$G_{P14}(s)=\frac{2*e^{-2s}}{(4s+1)} \tag{7.5}$$

$$G_{P15}(s)=\frac{2*e^{-4s}}{(4s+1)} \tag{7.6}$$

Smith and Corripio's approach to control design called as controller synthesis provides PI controller tuning formulas for regulatory control as well [31]. Their formulas are compared with the proposed method in the case studies 1 and 2 in this section.

Ciancone and Marlin [33] proposed correlations for dimensionless gain (K_c*K_p), dimensionless reset time ($\tau_i/(\theta+\tau_1)$) and dimensionless derivative time ($\tau_D/(\theta+\tau_1)$) as a function of the fractional dead time ($\theta/(\theta+\tau_1)$) and Marlin [34] explained them in his book as well. These correlations are based on tuning with three goals: minimization of IAE performance, consideration of ± 25% (correlated) error in the model process parameters (K_p, θ and τ_1) and limitation on the variation of the manipulated variable. They proposed different correlation figures which relates the dimensionless controller parameters to fractional dead time for two controller algorithm types (PI and PID controller) and for two control (regulatory and servo control), separately. These correlation figures are also available as 'Ciancone correlations for dimensionless tuning constants' in Marlin's process control book [34]. Their correlations for regulatory control for the PI controllers are also compared with the proposed method for regulatory control in the case studies in this section.

Lopez [22] developed regulatory control tuning formulas for the IAE, ITAE and ISE minimization criteria separately for P-only, PI and PID controllers. His empirical tuning formulas are valid for the FOPTD process models whose ratio of process time delay to process time constant (θ/τ_1) is in between 0.1 and 1.0. His formulas are also compared with the proposed correlations in the case studies in this section.

The tuning correlations of Smith and Corripio and Lopez are given in Table 7.3. The correlation figures available in [34] are used to find the proposed controller parameters for Ciancone and Marlin's method.

Table 7.3. Tuning formulas of the proposed methods in literature for FOPTD process type, IAE minimization and regulatory control.

Method	$\mathbf{K_c}$	$\boldsymbol{\tau_i}$	**The range**
Smith and Corripio	$\frac{\tau_1}{K*\theta}$	τ_1	$0.1 \leq \frac{\theta}{\tau_1} \leq 0.5$
Lopez	$\frac{0.984}{K}\left(\frac{\theta}{\tau_1}\right)^{-0.986}$	$\frac{\tau_1}{0.608}\left(\frac{\theta}{\tau_1}\right)^{0.707}$	$0.1 \leq \frac{\theta}{\tau_1} \leq 1.0$

The results of the case studies are given in Figures 7.4, 7.5 and 7.6. The related performance values are presented in Table 7.4. The abbreviations of 'PM', 'SC', 'M' and 'L' are used for proposed method, Smith and Corripio, Ciancone and Marlin and Lopez, respectively.

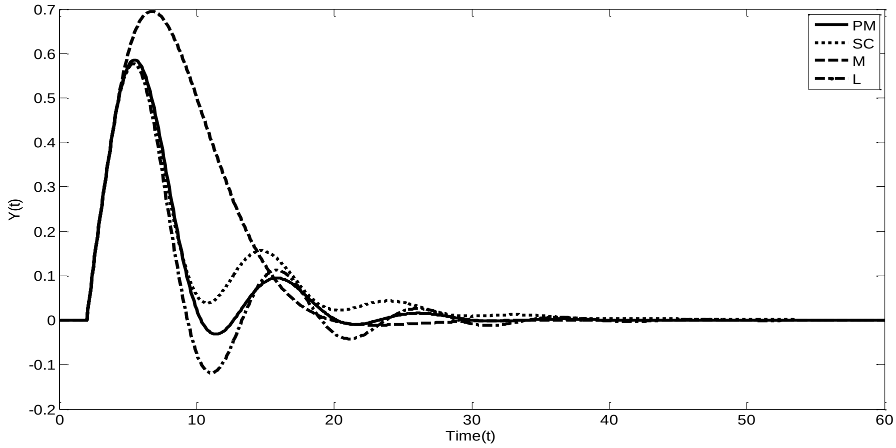


Figure 7.4. The comparison of tuning methods for the case study 1. (τ_1=8, θ=2, K_p=2)

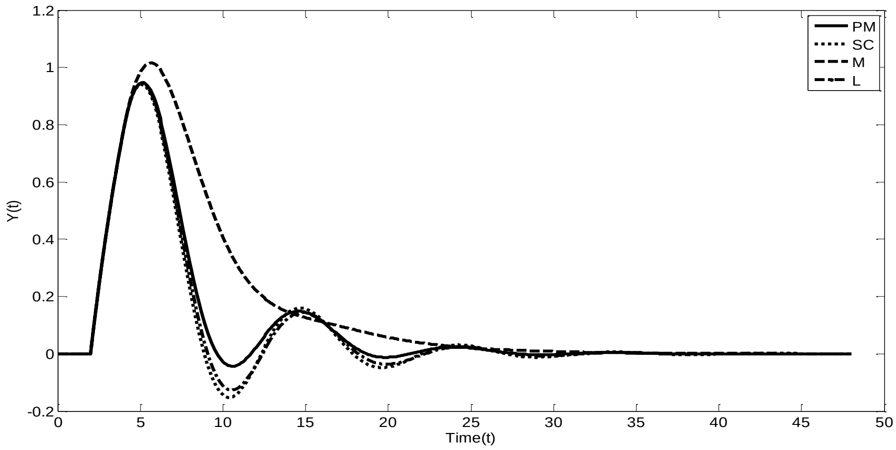


Figure 7.5. The comparison of tuning methods for the case study 2. (τ_1=4, θ=2, K_p=2)

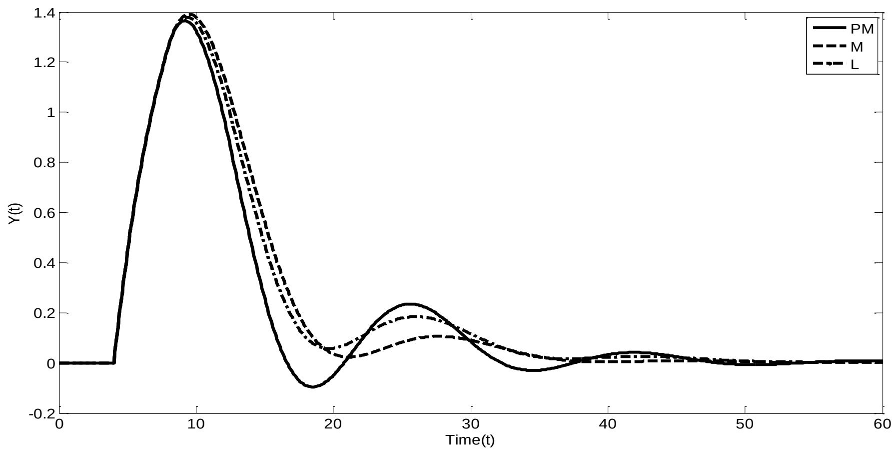


Figure 7.6. The comparison of tuning methods for the case study 3. (τ_1=4, θ=4, K_p=2)

In all case studies, the proposed method provides better control than the other tuning formulas and the proposed method provides the smallest IAE value among these tuning methods. Especially, when the Figure 7.4 and 7.5 are examined the superiority of the proposed method over the other methods can be clearly seen.

Table 7.4. Tuning parameters and performance characteristics for FOPTD process type, IAE minimization and regulatory control

Regulatory Control				
Process	**Method**	**K_c**	**τ_i**	**IAE**
G_{P13}(s)	PM	1.83	5.81	3.32
	SC	2.00	8.00	4.00
	M	0.90	5.20	5.93
	L	1.93	4.94	3.51
G_{P14}(s)	PM	0.96	4.53	4.89
	SC	1.00	4.00	5.02
	M	0.62	4.65	7.50
	L	0.97	4.03	4.94
G_{P15}(s)	PM	0.57	6.55	12.27
	M	0.43	5.62	13.06
	L	0.49	6.58	13.40

7. 3. Comparison for FOPTD Process Type and ITAE Minimization for Servo Control

The proposed correlations for the ITAE minimization criterion, for servo control, for FOPTD process type model is compared with the other tuning correlations which are defined for the same purpose in literature in this section.

Two case studies are defined and their transfer functions are given in equations 7.7 and 7.8, respectively. The ratios of process time delay to process time constant (θ/τ_1) are 0.33 and 1 in these case studies, respectively.

$$G_{P16}(s)= \frac{e^{-s}}{(3s+1)} \tag{7.7}$$

$$G_{P17}(s)= \frac{e^{-3s}}{(3s+1)} \tag{7.8}$$

Rovira's tuning formulas [21] for ITAE minimization criteria for PI controllers are compared with the proposed correlations in the case studies in this section.

Martins [35] presented software modules developed in Simulink and Matlab for tuning PID controller using ITAE criterion. He developed the process model including the controller algorithms in Simulink, created a Matlab m-file with an objective function that calculates the ITAE index and used a function of matlab optimization toolbox to minimize the ITAE index. The matlab m-file which is developed by him is used to calculate his proposed optimum control parameters for the case studies.

The tuning correlations of Rovira for ITAE minimization is given in Table 7.5.

Table 7.5. Tuning formulas of the proposed methods in literature for FOPTD process type, ITAE minimization and servo control.

Method	$\mathbf{K_c}$	$\boldsymbol{\tau_i}$	**The range**
Rovira	$\frac{0.586}{K}\left(\frac{\theta}{\tau_1}\right)^{-0.916}$	$\frac{\tau_1}{1.03 - 0.165\left(\frac{\theta}{\tau_1}\right)}$	$0.1 \le \frac{\theta}{\tau_1} \le 1.0$

The results of the case studies are given in Figures 7.7 and 7.8. The related performance values are presented in Table 7.6. The abbreviations of 'PM', 'Martins' and 'Rovira' are used for proposed method, Martins and Rovira, respectively.

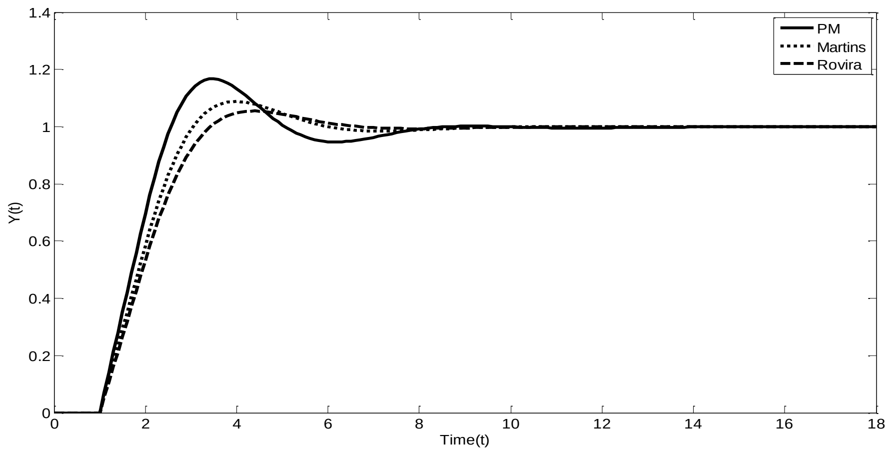


Figure 7.7. The comparison of tuning methods for the case study 1. (τ_1=3, θ=1, K_p=1)

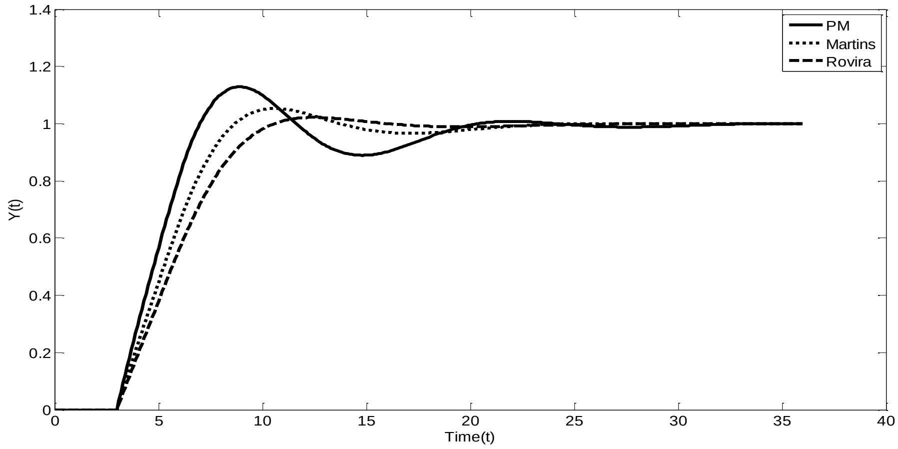


Figure 7.8. The comparison of tuning methods for the case study 2. (τ_1=3, θ=3, K_p =1)

In all case studies, unfortunately, it can be said that the proposed method has worse response than the others in respect to overshoot and settling time values and its ITAE value is larger than the others. In all case studies, the proposed method gives a more oscillatory response than the other tuning methods. But, the proposed method provides the smallest rise time value among these tuning methods.

Table 7.6. Tuning parameters and performance characteristics for FOPTD process type, ITAE minimization and servo control

Servo Control							
Process	**Method**	K_c	τ_i	T_r	T_s	O_s	**ITAE**
$G_{P16}(s)$	PM	2.12	3.39	2.5	6.55	1.17	3.30
	Martins	1.76	3.14	2.9	4.75	1.09	2.82
	Rovira	1.60	3.08	3.2	4.55	1.06	2.74
$G_{P17}(s)$	PM	0.94	4.74	6.7	18.0	1.13	26.2
	Martins	0.71	3.85	8.1	11.0	1.05	21.1
	Rovira	0.59	3.47	9.4	9.35	1.02	21.3

7. 4. Comparison for FOPTD Process Type and ITAE Minimization for Regulatory Control

The proposed correlations for the ITAE minimization criterion, for regulatory control, for FOPTD process type model is compared with the Lopez [22] tuning correlations which are defined for the same purpose in literature in this section. Two case studies are defined and their transfer functions are given in equations 7.7 and 7.8, respectively. The ratios of process time delay to process time constant (θ/τ_1) are 0.33 and 1 in these case studies, respectively. The tuning correlations of Lopez for ITAE minimization is given in Table7.7.

Table 7.7. Tuning formulas of the proposed methods in literature for FOPTD process type, ITAE minimization and regulatory control.

Method	K_c	τ_i	The range
Lopez	$\frac{0.859}{K}\left(\frac{\theta}{\tau_1}\right)^{-0.977}$	$\frac{\tau_1}{0.674}\left(\frac{\theta}{\tau_1}\right)^{0.680}$	$0.1 \le \frac{\theta}{\tau_1} \le 1.0$

The results of the case studies are given in Figures 7.9 and 7.10. The related performance values are presented in Table 7.8.

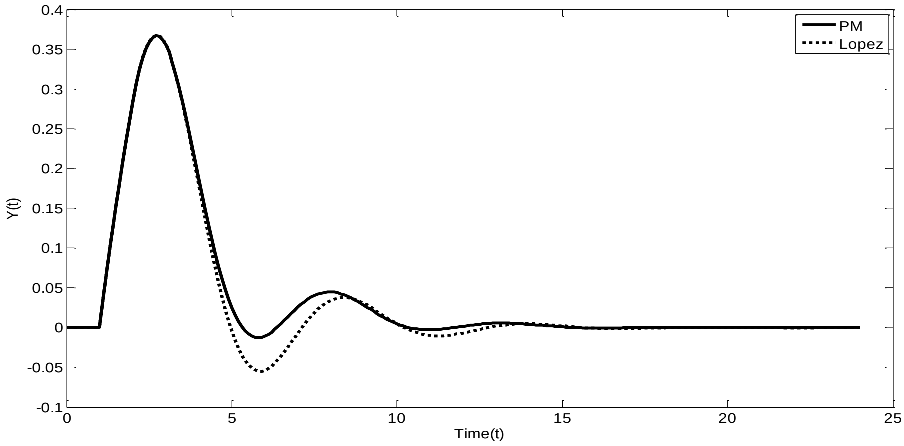


Figure 7.9. The comparison of tuning methods for the case study 1. (τ_1=3, θ=1, K_p=1)

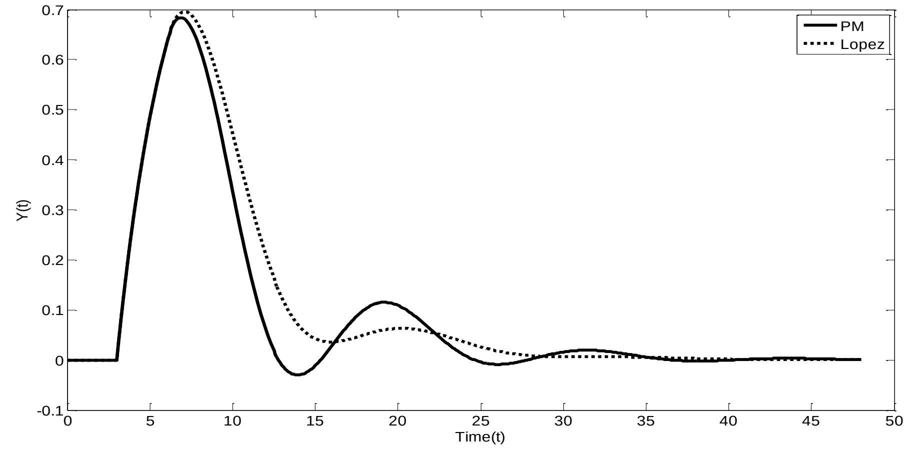


Figure 7.10. The comparison of tuning methods for the case study 2. (τ_1=3, θ=3, K_p=1)

In both case studies, it is obviously seen that the proposed method provides better control than Lopez tuning formulas and the proposed method provides smaller ITAE value than Lopez's method.

Table 7.8. Tuning parameters and performance characteristics for FOPTD process type, ITAE minimization and regulatory control

Regulatory Control				
Process	**Method**	**K_c**	**τ_i**	**ITAE**
G_{P16}(s)	PM	2.59	2.54	3.58
	Lopez	2.51	2.11	3.81
G_{P17}(s)	PM	1.12	5.01	44.8
	Lopez	0.86	4.45	49.4

7. 5. Comparison for FOPTD Process Type and ISE Minimization for Servo Control

The proposed correlations for the ISE minimization criterion, for servo control, for FOPTD process type model is compared with another tuning correlations which is defined for the same purpose in literature in this section.

Two case studies are defined and their transfer functions are given in equations 7.9 and 7.10, respectively. The ratios of process time delay to process time constant (θ/τ_1) are 0.5 and 1.5 in these case studies, respectively.

$$G_{P18}(s)= \frac{e^{-2s}}{(4s+1)} \tag{7.9}$$

$$G_{P19}(s)= \frac{e^{-6s}}{(4s+1)} \tag{7.10}$$

Zhuang and Atherton [36] proposed tuning correlations for optimization of the integral of time error squared criterion for FOPTD process type model. Their proposed formulas for ISE minimization, for servo control are presented in Table 7.9 and compared with the proposed method in defined two case studies above.

Table 7.9. Tuning formulas of the proposed methods in literature for FOPTD process type, ISE minimization and servo control.

Method	**K_c**	**τ_i**	**The range**
Zhuang	$\frac{0.980}{K}\left(\frac{\tau_1}{\theta}\right)^{0.892}$	$\frac{\tau_1}{0.690-0.155\left(\frac{\theta}{\tau_1}\right)}$	$0.1 \leq \frac{\theta}{\tau_1} \leq 1.0$
Zhuang	$\frac{1.072}{K}\left(\frac{\tau_1}{\theta}\right)^{0.560}$	$\frac{\tau_1}{0.648 - 0.114\left(\frac{\theta}{\tau_1}\right)}$	$1.1 \leq \frac{\theta}{\tau_1} \leq 2.0$

The results of the case studies are given in Figures 7.11 and 7.12. The related performance values are presented in Table 7.10.

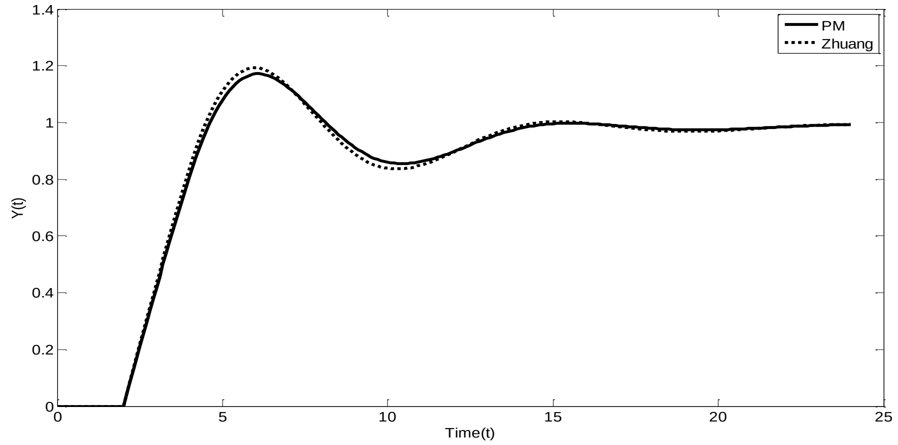


Figure 7.11. The comparison of tuning methods for the case study 1. (τ_1=4, θ=2, K_p=1)

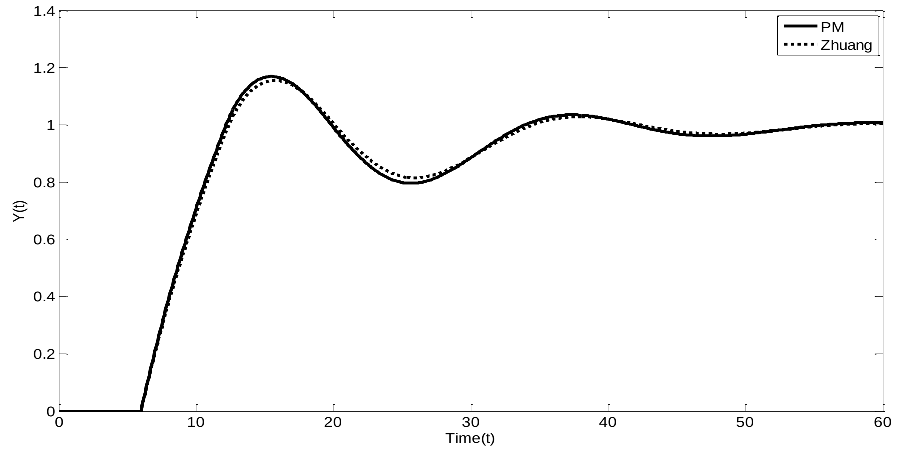


Figure 7.12. The comparison of tuning methods for the case study 2. (τ_1=4, θ=6, K_p=1)

In both case studies, it is seen that the proposed correlations and Zhuang's tuning formulas give similar responses and have very close ISE values.

Table 7.10. Tuning parameters and performance characteristics for FOPTD process type, ISE minimization and servo control

Servo Control								
Process	**Method**	K_c	τ_i	T_r	T_s	O_s	**ISE**
$G_{P18}(s)$	P.M.	1.75	6.32	4.5	13.2	1.17	2.92
	Zhuang	1.82	6.53	4.4	13.0	1.19	2.92
$G_{P19}(s)$	P.M.	0.88	8.68	11.8	32.0	1.17	8.18
	Zhuang	0.85	8.39	12.0	32.4	1.16	8.17

7. 6. Comparison for FOPTD Process Type and ISE Minimization for Regulatory Control

The proposed correlations for the ISE minimization criterion, for regulatory control, for FOPTD process type model is compared with other tuning correlations which is defined for the same purpose in literature in this section. Two case studies whose transfer functions are given in equations 7.9 and 7.10 respectively are used. The ratios of process time delay to process time constant (θ/τ_1) are 0.5 and 1.5 in these case studies, respectively.

Zhuang and Atherton [36] and Lopez proposed formulas for ISE minimization, for regulatory control are presented in Table 7.11 and compared with the proposed method in defined two case studies above.

Table 7.11. Tuning formulas of the proposed methods in literature for FOPTD process type, ISE minimization and regulatory control.

Method	K_c	τ_i	**The range**
Zhuang	$\frac{1.279}{K}\left(\frac{\tau_1}{\theta}\right)^{0.945}$	$\frac{\tau_1}{0.535}\left(\frac{\theta}{\tau_1}\right)^{0.586}$	$0.1 \le \frac{\theta}{\tau_1} \le 1.0$
Zhuang	$\frac{1.346}{K}\left(\frac{\tau_1}{\theta}\right)^{0.675}$	$\frac{\tau_1}{0.552}\left(\frac{\theta}{\tau_1}\right)^{0.438}$	$1.1 \le \frac{\theta}{\tau_1} \le 2.0$
Lopez	$\frac{1.305}{K}\left(\frac{\theta}{\tau_1}\right)^{-0.959}$	$\frac{\tau_1}{0.492}\left(\frac{\theta}{\tau_1}\right)^{0.739}$	$0.1 \le \frac{\theta}{\tau_1} \le 1.0$

The results of the case studies are given in Figures 7.13 and 7.14. The related performance values are presented in Table 7.12.

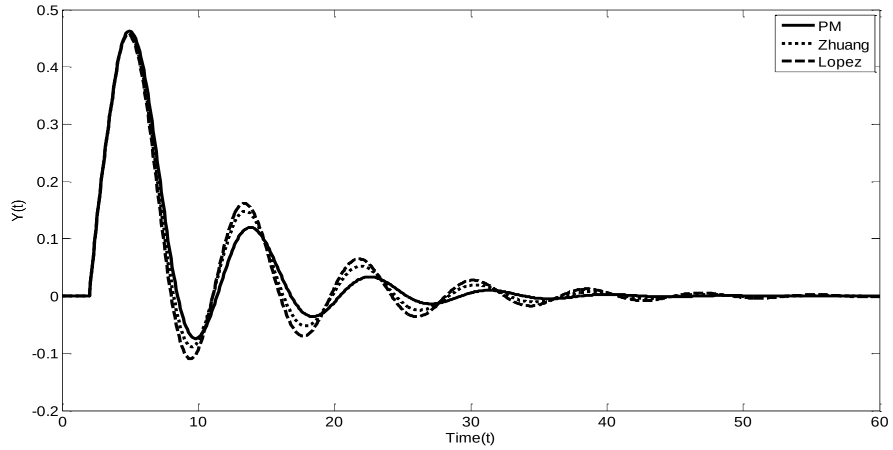


Figure 7.13. The comparison of tuning methods for the case study 2. (τ_1=4, θ=2, K_p=1)

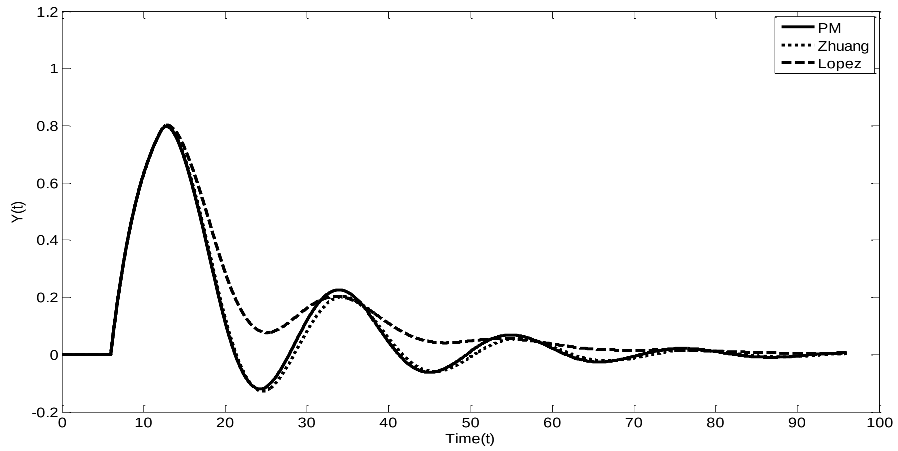


Figure 7.14. The comparison of tuning methods for the case study 2. (τ_1=4, θ=6, K_p=1)

In case study 1, when the Figure 7.13 is examined, it can be observed that the proposed method gives better response than Zhuang and Lopez method, but there is not big difference in ISE values. In case study 2, the proposed method and Zhuang method give similar response and have close ISE values, but Lopez method gives worse response than the others and has higher ISE value than Zhuang and proposed method. This can be natural, because Lopez's method is proposed for the range of the ratios of process time delay to process time constant (θ/τ_1) in between 0.1 and 1.

Table 7.12. Tuning parameters and performance characteristics for FOPTD process type, ISE minimization and regulatory control

Regulatory Control				
Process	**Method**	**K_c**	**τ_i**	**ISE**
$G_{P18}(s)$	P.M.	2.28	4.69	0.68
	Zhuang	2.46	4.98	0.68
	Lopez	2.54	4.87	0.69
$G_{P19}(s)$	P.M.	1.06	9.33	4.87
	Zhuang	1.02	8.66	4.86
	Lopez	0.88	11.0	5.50

7. 7. Comparison for SOPTD Process Type and IAE Minimization for Regulatory Control

The proposed correlations for the IAE minimization criterion, for regulatory control, for SOPTD process type model is compared with other tuning correlations which is defined for the same purpose in literature in this section. Two case studies whose transfer functions are given in equations 7.11 and 7.12 respectively are used.

$$G_{P20}(s)= \frac{e^{-5s}}{(10s+1)(2s+1)} \tag{7.11}$$

$$G_{P21}(s)= \frac{3*e^{-10s}}{(10s+1)(5s+1)} \tag{7.12}$$

Harriott [37] proposed optimum controller settings for processes with dead time and he also considered the effects of type and location of disturbance in his study. His formula which is proposed for the disturbances introduced before the process is compared with the proposed correlations in this section.

Table 7.13. Tuning formulas of the proposed methods in literature for SOPTD process type, ISE minimization and regulatory control.

Method	**K_c**	**τ_i**	**The range**
Harriot	$0.5*K_u$	$0.65*P_u$	$\theta/\tau_1=0.5$ and $\tau_2/\tau_1=0.2$
Harriot	$0.5*K_u$	$0.55*P_u$	$\theta/\tau_1=1.0$ and $\tau_2/\tau_1=0.5$

The results of the case studies are given in Figures 7.15 and 7.16. The related performance values are presented in Table 7.14.

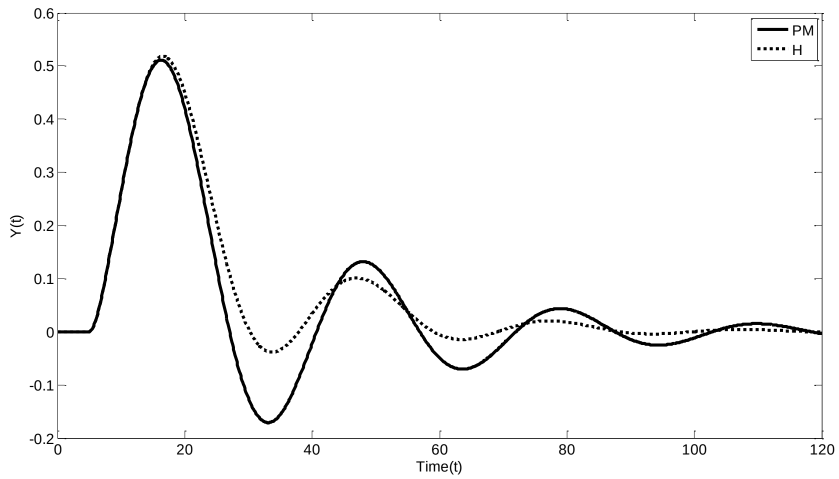


Figure 7.15. The comparison of tuning methods for the case study 1. (τ_1=10, τ_2=2, θ=5, K_p=1)

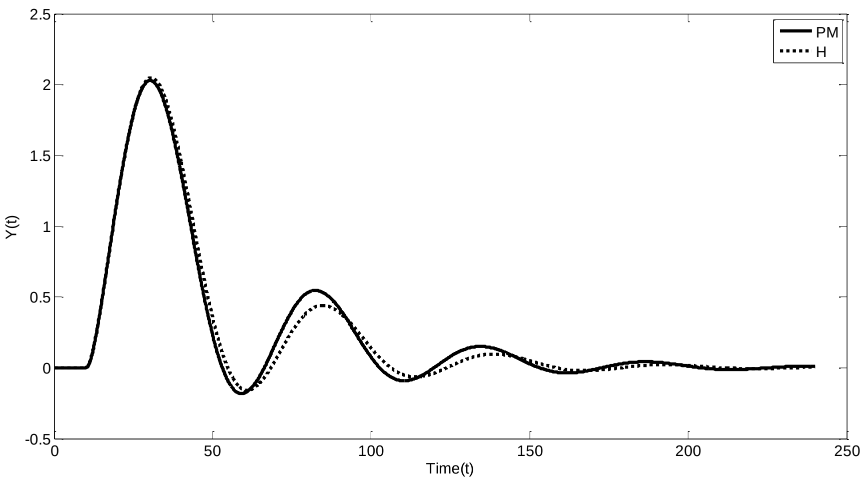


Figure 7.16. The comparison of tuning methods for the case study 2. (τ_1=10, τ_2=5, θ=10, K_p=3)

In case study 1 and 2, when the Figure 7.15 and Figure 7.16 are examined, it can be observed that the proposed method gives worse response than Harriot's method and his method also provides less IAE value. Still, there is not much difference between the IAE values.

Table 7.14. Tuning parameters and performance characteristics for SOPTD process type, IAE minimization and regulatory control

Regulatory Control				
Process	**Method**	**K_c**	**τ_i**	**IAE**
$G_{P20}(s)$	PM	1.79	10.62	10.82
	H	1.71	14.37	9.06
$G_{P21}(s)$	PM	0.41	25.34	67.57
	H	0.38	22.9	65.51

8. CONCLUSION

This thesis was aimed to present new PI controller tuning correlations by using the same approach as Madhuranthakam et al. [9] presented. At the end of the study, the PI controller tuning correlations are obtained and presented in tables for two different process model types: first order plus time delay (FOPTD) and second order plus time delay (SOPTD) for different minimization criteria (IAE, ITAE, ISE and ITSE) and for the step change in set point (servo control) and load change (regulatory control), separately.

There are many PID/PI controller tuning techniques proposed in literature. Three of the earliest methods which are known as classical or conventional tuning techniques in literature are looked over in literature review section (section 3). But, Ziegler-Nichols process reaction curve method, Cohen-Coon method and many other tuning methods in literature are proposed for FOPTD process models. To use them for tuning the SOPTD model, the process model is needed to be approximated to FOPTD model as it was done in section 6.2. But, in this work, different correlations are proposed for different types of process models (FOPTD and SOPTD). Furthermore, different correlations are proposed for each minimization objective (IAE, ITAE, ISE and ITSE) and for servo and load control, separately.

After obtaining correlations, these correlations are examined in the case studies and the performance of the proposed correlations are compared with that of Ziegler-Nichols continuous cycling method, Ziegler-Nichols process reaction curve method and Cohen-Coon method in section 6. Although, there are some exceptions in case studies, for FOPTD and SOPTD model, it is generally seen that the proposed method provides less values of settling time (T_s), overshoot (O_s) and minimization criteria (IAE, ITAE, ISE and ITSE) than the conventional techniques. Moreover, for FOPTD model, Ziegler–Nichols methods produce more sluggish servo and load control responses as dead time is increased. On the other hand, the proposed method gives good responses even in dead time is increased, which is really a good advantage in process control.

The performance of the proposed correlations is also compared with that of the other tuning methods which are defined for the same purpose in literature in section 7. For FOPTD process type for servo control, the proposed correlations generally do not provide better responses than the other tuning methods mentioned in section 7. But, for FOPTD process type for regulatory control, the proposed correlations give less minimization criteria values (IAE, ITAE and ISE) than the other tuning methods mentioned in section 7. For SOPTD process type, there is rare information about controller tuning in literature. Because of this reason, the proposed method is only compared with Harriot's [37] method. In both case studies, Harriot's method provides less minimization criteria (IAE) than the proposed correlations.

As a result, new PI controller tuning correlations are presented in this thesis. These correlations can be used in different systems as initial guesses since they provide better responses than the conventional techniques. But, it should be added that these correlations are still needed to be tested in real systems. Apart from this, these correlations are good to show the relation in between the control parameters and process parameters. Furthermore, they show some of the differences between tuning for servo control and regulatory control.

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APPENDIX

Appendix 1: M-files for Optimization Process for Servo Control

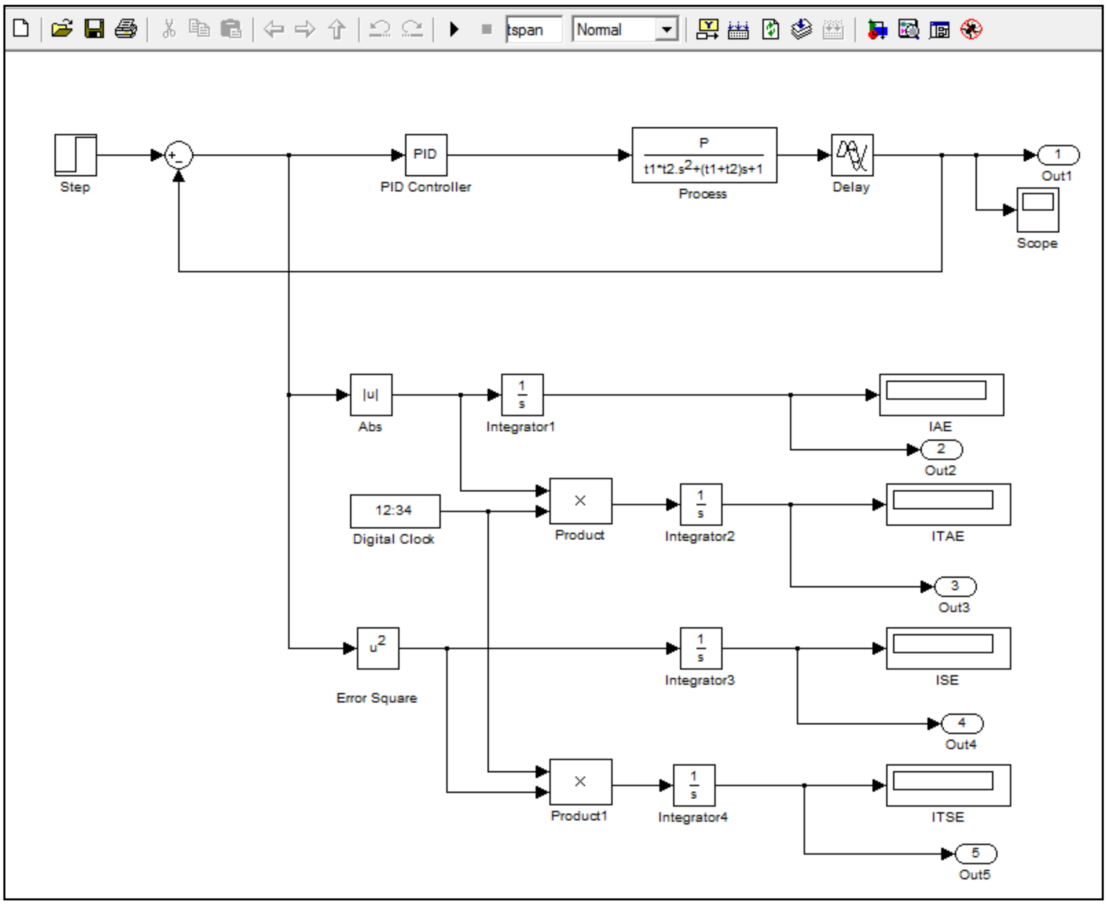
```
% runpidtracklsq.m file

function [Kc,Ti] = runpidtracklsq

global t1 t2 Tdelay P tspan pid0

 Pidcontrolstepchange

options=optimset('LargeScale','off','Display','iter','TolX',0.00001,'TolFun',0.001,'maxFunEvals',300);

pid = lsqnonlin(@pidtracklsq, pid0,[],[],options);

Kc = pid(1);Ti = pid(2);

    function F = pidtracklsq(pid)

    global t1 t2 Tdelay P tspan pid0

    Kc = pid(1);

    Ti = pid(2);

    simopt = simset('solver','ode5','SrcWorkspace','Current');

    [tout, xout, yout]=sim('Pidcontrolstepchange',[0 tspan],simopt);

    F = sqrt(yout(:,2)); % For IAE minimization

    %  F = sqrt(yout(:,3)); % For ITAE minimization

    %  F = sqrt(yout(:,4)); % For ISE minimization

    %  F = sqrt(yout(:,5)); % For ITSE minimization
```

```
% Pidcontrolsimulation.m file
global t1 t2 P Tdelay tspan pid0
A = xlsread('parameters');
tau1 = A(:,1);
tau2 = A(:,2);
theta = A(:,3);
KUlt = A(:,4);
PUlt = A(:,5);
Tsp = A(:,6);
P = 1;
n = length(tau1);
pm = zeros(n,2);
for i = 1:n
    t1 = tau1(i);t2 = tau2(i);Tdelay = theta(i);
    Kc0 = (KUlt(i))/2.2;Ti0 = (PUlt(i))/(1.2); %Z-N closed loop method
     i
    pid0 = [Kc0 Kc0/Ti0];tspan = 1.2*Tsp(i);
    [Kc,Ti] = runpidtracklsq
    pm(i,:) = [Kc Ti];
    Y(i,:) = [tau1(i) tau2(i) P Tdelay pm(i,:)];
end

for i = 1:n
t1 = Y(i,1);
t2 = Y(i,2);
Tdelay = Y(i,4);
Kc = Y(i,5);
Ti = Y(i,6);

simopt = simset('solver','ode5','SrcWorkspace','Current');
[tout, xout, yout]=sim('Pidcontrolstepchange',[0 tspan],simopt);



%This program finds the Overshoot, Rise Time and Settling Time
 Over_a = yout(:,1);
```

```
fid = fopen('PIspchange1.table','w');
fprintf(fid,'%4.1f\n',Over_a);
fclose(fid);
load PIspchange1.table
y = PIspchange1(:,1);
yss = y(end);
t = tout;
idex2 = find(y==1.0);
Rise_Time (i) = tout(idex2(1,1));
sp=5;
idx1=find(abs(y-yss)>abs(yss*sp/100));
if isempty(idx1) || idx1(1)==length(y)
   error('Not Enough Data to Find Settling Time.')
end
if y(idx1)>yss
   alpha=(y(idx1)-(1+sp/100)*yss)/(y(idx1)-y(idx1+1));
   ts=t(idx1)+alpha*(t(idx1+1)-t(idx1));
else
   alpha=((1-sp/100)*yss-y(idx1))/(y(idx1+1)-y(idx1));
   ts=t(idx1)+alpha*(t(idx1+1)-t(idx1));
end
Settling_time (i) = ts(end);
Overshoot (i) = max(yout(:,1));

y4 = yout(:,2);
IAE (i) = y4(end);
 y5 = yout(:,3);
ITAE (i) = y5(end);
 y6 = yout(:,4);
ISE (i) = y6(end);
 y7 = yout(:,5);
ITSE (i) = y7(end);

Z(i,:) = [Y(i,:) IAE(i) ITAE(i) ISE(i) ITSE(i) Overshoot(i) Rise_Time(i) Settling_time(i) ];
 end
```

```
fid = fopen('SimulationResults.dat','w');
fprintf(fid,'                              PID  Table                                  \n');
fprintf(fid,'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ \n');
fprintf(fid,'    tau1      tau2       P      Tdelay      Kc           Ki           IAE           ITAE
ISE           ITSE           OS           Tr           Ts           \n');
fprintf(fid,'    %4i     %4i    %4i     %4.1f      %8.4f       %8.4f      %8.4f       %8.4f
%8.4f       %8.4f      %8.4f       %8.4f      %8.4f       \n', Z');
fclose(fid);
```

Appendix 2: Simulink Model for Servo Control



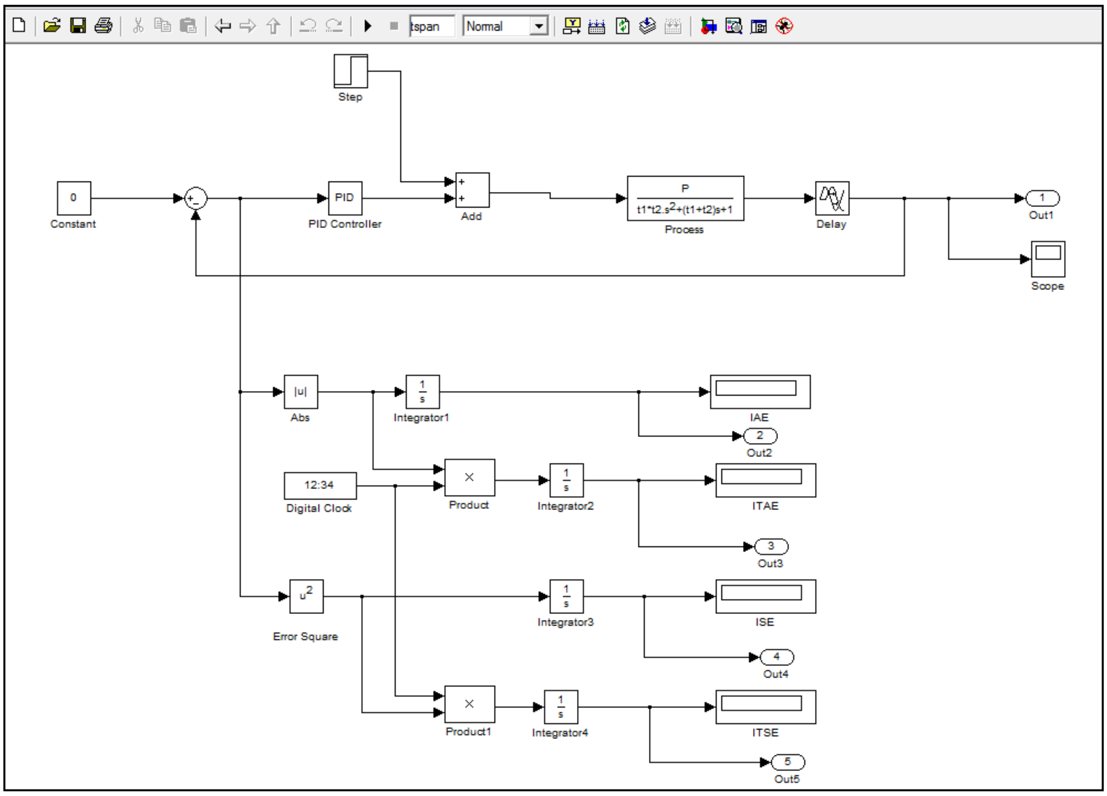
Appendix 3: M -files for Optimization Process for Regulatory Control

```
% runpidloadtracklsq.m file

function [Kc,Ti] = runpidloadtracklsq
global t1 t2 Tdelay P tspan pid0

Pidcontrolloadchange
options=optimset('LargeScale','off','Display','iter','TolX',0.00001,'TolFun',0.001,'maxFunE
vals',300);
pid = lsqnonlin(@pidloadtracklsq, pid0,[],[],options);
Kc = pid(1);Ti = pid(2);
   function F = pidloadtracklsq(pid)
   global t1 t2 Tdelay P tspan pid0
   Kc = pid(1);  Ti = pid(2);
   simopt = simset('solver','ode5','SrcWorkspace','Current');
   [tout, xout, yout]=sim('Pidcontrolloadchange',[0 tspan],simopt);
   F = sqrt(yout(:,2)); % For IAE minimization
   %  F = sqrt(yout(:,3)); % For ITAE minimization
   %  F = sqrt(yout(:,4)); % For ISE minimization
   %  F = sqrt(yout(:,5)); % For ITSE minimization
```

```
% Pidcontrolloadsimulation.m file
global t1 t2 P Tdelay tspan pid0
A = xlsread('parameters_load');
tau1 = A(:,1);
tau2 = A(:,2);
theta = A(:,3);
KUlt = A(:,4);
PUlt = A(:,5);
Tsp = A(:,6);
P = 1;
n = length(tau1);
pm = zeros(n,2);
for i = 1:n
    t1 = tau1(i);t2 = tau2(i); Tdelay = theta(i);
     Kc0 = (KUlt(i))/2.2;Ti0 = (PUlt(i))/(1.2); %Z-N closed loop method
    i
    pid0 = [Kc0 Kc0/Ti0]; tspan = Tsp(i);
    [Kc,Ti] = runpidloadtracklsq
    pm(i,:) = [Kc Ti];
    Y(i,:) = [tau1(i) tau2(i) P Tdelay pm(i,:)];
end

for i = 1:n
    t1 = Y(i,1);
    t2 = Y(i,2);
   Tdelay = Y(i,4);
   Kc = Y(i,5);
   Ti = Y(i,6);

    simopt = simset('solver','ode5','SrcWorkspace','Current');
    [tout, xout, yout]=sim('Pidcontrolloadchange',[0 tspan],simopt);
```

```
y4 = yout(:,2);
IAE (i) = y4(end);
y5 = yout(:,3);
ITAE (i) = y5(end);
y6 = yout(:,4);
ISE (i) = y6(end);
y7 = yout(:,5);
ITSE (i) = y7(end);

Z(i,:) = [Y(i,:) IAE(i) ITAE(i) ISE(i) ITSE(i)];
end

fid = fopen('SimulationResultsLoad.dat','w');
fprintf(fid,'                    PID  Table                    \n');
fprintf(fid,'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ \n');
fprintf(fid,'   tau1    tau2    P    Tdelay    Kc        Ki        IAE        ITAE
ISE        ITSE        \n');
fprintf(fid,'   %4i    %4i    %4i    %4.1f     %8.4f     %8.4f     %8.4f     %8.4f
%8.4f     %8.4f     \n',Z');
fclose(fid);
```

Appendix 4: Simulink Model for Regulatory Control



Appendix 5: FOPTD Parameters

τ_1	τ_2	θ	K_u	P_u	tspan
1	0	2	1,52	5,4	50
1	0	4	1,2	9,7	100
2	0	2	2,27	6,2	30
2	0	4	1,535	11	50
2	0	6	1,3	15,3	70
2	0	8	1,2	19,5	100
3	0	0,5	10,17	1,9	30
3	0	2	3,04	6,4	20
3	0	3	2,27	9,3	40
3	0	6	1,52	16,5	60
3	0	9	1,3	23	120
4	0	0,5	13,33	1,9	20
5	0	3	3,3	10	40
5	0	4	2,65	12,8	50
5	0	8	1,7	22,8	140
5	0	12	1,415	31,8	200
5	0	15	1,3	38	180
7	0	3	4,33	10,4	50
7	0	5	2,9	16,2	100
7	0	7	2,27	21,6	120
7	0	14	1,53	38,4	120
7	0	21	1,3	53,6	300
10	0	5	3,81	17,1	60
10	0	10	2,27	31	160
10	0	15	1,77	43,4	200
10	0	25	1,39	66	300
15	0	2	12,47	7,6	30
15	0	5	5,4	17,8	80
15	0	10	3,04	32,9	140
15	0	20	1,9	59	300
15	0	30	1,52	82,6	400
15	0	40	1,36	104,6	500
15	0	3	8,5	11,2	80
20	0	2	16,36	7,7	40
20	0	5	6,95	18,3	100
20	0	10	3,82	34,2	160
20	0	20	2,28	62	220

20	0	40	1,53	110	500
30	0	3	16,34	11,6	80
30	0	9	5,9	32,5	160
30	0	18	3,3	60,2	220
30	0	30	2,28	92,7	340
30	0	50	1,68	142,4	600
30	0	60	1,528	164,4	800
40	0	4	16,36	15,4	200
40	0	10	6,91	36,7	200
40	0	20	3,82	68,5	300
40	0	40	2,28	123,8	500
50	0	5	16,32	19,3	200
50	0	10	8,52	37,3	200
50	0	20	4,6	70,1	300
50	0	30	3,3	100,1	400
50	0	40	2,65	128,3	500
50	0	50	2,265	154,8	600

Appendix 6: SOPTD Parameters

τ_1	τ_2	θ	K_u	P_u	tspan
1	1	1	2,715	4,8	20
2	1	1	3,76	5,5	20
3	1	1	4,86	5,9	20
5	1	1	7,12	6,4	20
7	1	1	9,36	6,6	20
10	1	1	12,74	6,8	20
15	1	1	18,43	6,9	20
20	1	1	24,1	7	20
30	1	1	35,4	7,1	20
40	1	1	46,9	7,2	20
50	1	1	58,2	7,2	20
1	2	2	2,27	8,3	30
2	2	2	2,7	9,7	30
3	2	2	3,22	10,5	30
5	2	2	4,32	11,5	40
7	2	2	5,4	12,1	40
10	2	2	7,16	12,7	40
15	2	2	9,92	13,2	40
20	2	2	12,76	13,5	40
30	2	2	18,4	13,9	40
40	2	2	24,1	14	60
50	2	2	29,74	14,1	60
1	3	3	2,175	11,6	60
2	3	3	2,4	13,2	40
3	3	3	2,7	14,4	40
5	3	3	3,4	16	40
7	3	3	4,12	17	40
10	3	3	5,24	18	60
15	3	3	7,1	19	60
20	3	3	9	19,6	60
30	3	3	12,7	20,3	60
40	3	3	16,5	20,6	60
50	3	3	20,3	20,9	60
1	5	5	2,14	17,9	60
2	5	5	2,2	20	60
3	5	5	2,34	21,6	60
5	5	5	2,7	24,1	60
7	5	5	3,12	25,8	60
10	5	5	3,76	27,6	60

15	5	5	4,86	29,6	80
20	5	5	5,98	30,9	80
30	5	5	8,22	32,4	80
40	5	5	10,5	33,2	100
50	5	5	12,74	33,8	100
1	7	7	2,145	24,2	80
2	7	7	2,155	26,4	80
3	7	7	2,225	28,3	80
5	7	7	2,44	31,3	80
7	7	7	2,72	33,6	100
10	7	7	3,14	36,2	100
15	7	7	3,92	39,2	100
20	7	7	4,72	41,1	120
30	7	7	6,33	43,5	120
40	7	7	7,92	45,1	120
50	7	7	9,54	46	120
1	10	10	2,16	33,5	100
2	10	10	2,14	35,8	100
3	10	10	2,165	38	100
5	10	10	2,275	41,6	100
7	10	10	2,435	44,5	100
10	10	10	2,72	48	120
15	10	10	3,22	52,3	120
20	10	10	3,76	55,3	140
30	10	10	4,86	59,2	140
40	10	10	6	61,7	160
50	10	10	7,12	63,4	160
1	15	15	2,18	49	140
2	15	15	2,15	51,5	140
3	15	15	2,14	53,8	140
5	15	15	2,18	58	140
7	15	15	2,26	61,4	160
10	15	15	2,42	66	160
15	15	15	2,72	72	160
20	15	15	3,06	76,6	180
30	15	15	3,76	82,9	220
40	15	15	4,52	87,1	220
50	15	15	5,26	90,2	220
1	20	20	2,22	64,5	220
2	20	20	2,16	67	220
3	20	20	2,145	69,4	220

5	20	20	2,14	73,9	220
7	20	20	2,18	78	220
10	20	20	2,275	83,2	220
15	20	20	2,48	90,4	220
20	20	20	2,7	96,2	240
30	20	20	3,22	104,6	280
40	20	20	3,74	110,6	280
50	20	20	4,3	115,1	280
1	30	30	2,225	95,4	280
2	30	30	2,19	98	280
3	30	30	2,165	100,5	280
5	30	30	2,14	105,3	280
7	30	30	2,14	109,8	280
10	30	30	2,17	116	280
15	30	30	2,27	124,8	300
20	30	30	2,41	132,4	340
30	30	30	2,71	144,2	340
40	30	30	3,055	153,1	340
50	30	30	3,42	159,9	380
1	40	40	2,22	126,7	380
2	40	40	2,2	129	380
3	40	40	2,18	131,6	380
5	40	40	2,16	136,3	380
7	40	40	2,14	141,1	380
10	40	40	2,15	147,8	380
15	40	40	2,195	157,7	380
20	40	40	2,275	166,5	380
30	40	40	2,48	180,7	440
40	40	40	2,71	192,3	440
50	40	40	2,96	201,6	440
1	50	50	2,23	157,5	440
2	50	50	2,215	159,9	440
3	50	50	2,195	162,5	440
5	50	50	2,16	167,5	440
7	50	50	2,155	172,4	440
10	50	50	2,14	179,3	440
15	50	50	2,154	190	440
20	50	50	2,21	199,4	480
30	50	50	2,34	216	500
40	50	50	2,52	229,2	500
50	50	50	2,72	240,1	500

Appendix 7: Interval and Ratio of Process Parameters

Process Model Type	Parameter Inverval	Ratio of Process Parameters
FOPTD	$1 \le \tau_1 \le 50$	$0.25 \le \frac{\tau_1}{\theta} \le 10$
	$0.5 \le \theta \le 60$	
SOPTD	$1 \le \tau_1 \le 50$	$0.02 \le \frac{\tau_1}{\tau_2} \le 50$
	$1 \le \tau_2 \le 50$	$0.02 \le \frac{\tau_1}{\theta} \le 50$
	$1 \le \theta \le 50$	$\frac{\tau_2}{\theta} = 1$

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