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Controller Design and Stability Analysis of Intensification Process using Analytical Exact Gain-Phase Margin approach

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Abstract

Controllable intensified process has received immense attention by the researchers in order to deliver the benefit of process intensification to be operated in a desired way in order to provide a more sustainable process towards reduction of environmental impact, improve of intrinsic safety and process efficiency. This paper proposed the Exact Gain and Phase Margin (EGP) through analytical method to develop suitable controller design for intensified system using PID controller formulation and it was compared to conventional Direct Synthesis Methods (DS), Internal Model Control (IMC) and Industrial IMC method in terms of the performance and stability analysis. Simulation results showed that EGP method provides good setpoint tracking and disturbance rejection as compared to DS, IMC and Industrial IMC while retaining overall performance stability as time delay increases. The Bode Stability Criterion was used to determine the stability of the open-loop transfer function of each method and the result demonstrated decrease in stability as time delay increases for controller design using DS, IMC and Industrial IMC and hence control performance degrades. On the other hand, the proposed EGP controller maintains the overall robustness and control performance throughout the increase of time delay and outperform the other controller design methods at higher time delay. Another highlight of this work is that the proposed EGP controller design method provides overall overwhelming control performance with lower overshoot and shorter rise time compared to other controllers when process time constant is smaller in magnitude ($\boldsymbol{\tau}_{\mathbf{p}} = 0.01\ and\ 0.1$) than the instrumentation element, which is one of the major concerns during the design of intensified controllers, resulting in a higher order of overall system. The desired selection of gain margin and phase margin were suggested at 2.5 to 4 and 60° – 70° respectively

for a wide range of control condition for intensified process where higher instrumentation dynamic would be possible achieve robust control as well. As a result, the proposed EGP method controller is thought to be more reliable design strategy for maintaining the overall robustness and performance of higher order and complex systems that are highly affected by time delay and high dynamic response of intensified processes.

Keywords: *Process Intensification; Process Control; Control Strategies; Stability Analysis; Gain Margin; Phase margin*

1. Introduction

The advantages of intensified system such as high surface to volume ratio, high heat and mass transfer as well as precise controlled condition which result in a more sustainable process in term of capital and energy cost reduction along with environmental impact, improvement of intrinsic safety and process efficiency have attracted the attention of many researchers (Zanati et al., 2016). However, there are only limited study on process control of the intensified system to achieve operability and controllability in order to enjoy the benefit of intensification process. In the study green chemistry, Mestres (2005) proposed that implementation of real time process control in continuous intensified process would provide a safer reaction condition and improve the selectivity of the reaction in order to reduce the secondary by-product in chemical reaction (Mestres, 2005). Thus, the study of process control is necessary to enable safe, economical and environmentally optimal performance of intensified process (Dias & Ierapetritou, 2019).

PID controller are the dominant strategy in controlling industrial processes as it is relatively simple to understand and to provide satisfactory control for most of the process and are generally more cost-effective approach (Demirci & Özbeyaz, 2019). However, due to the fast process dynamic of an intensified system, it is required to take into account instrumentation dynamics which is usually neglected in traditional system, resulting high order process model which is uncommon for classical PID tuning method (R. Jones & Tham, 2015). Furthermore, time delays caused by measurement delays which is dominant in continuous flow intensified system make the implementation of classical control technique such as PID controller becoming more difficult (Tahir et al., 2018).

Barzin et. al (2007) and Jones et. al (2006) designed PID controllers for intensified processes using Direct Synthesis, IMC and Industrial IMC methods respectively considering first order plus time delay process model . Those methods result in higher order controller formulation in term of the time constant for every element in the closed-loop and found to be difficult in mathematical derivation when dealing with higher order process model. Due to the controller formulation depends on the time constant of each element and time delay, it may lead to instability and performance deterioration when the time constant and time delay is beyond the acceptable range. Barzin et. al. (2007) found that the designed system showed unstable response when time delay greater than the process time constant (Barzin et al., 2007;

R. W. Jones & Tham, 2006). Abd Shukor and Tham (2004) also found that the controller performance deteriorate with large Integral of Absolute Error (IAE) when time delay and time constant of transmitter are lower than 1 and 0.2 respectively (Shukor & Tham, 2004). Thus, it is important to design the controller that is able to maintain the desired stability and performance at various condition.

In order to maintain the closed-loop system stability and performance throughout, Exact Gain and Phase margin method associated with the frequency response technique was employed to achieve good control characteristic while still essentially working on a simple PID structure. Gain and Phase margin metrics were used to quantify the relative performances and robustness, in which both provide the amount of gain and phase lag which due to time delay could be added before the system run into unstable (Seborg et al., 2010). Phase margin is further related to the damping of the system and therefore could also be served as a performance measured (Lee, 2004). Thus with a robust controller design exact gain and phase margin are used as a hard target in the design (Nie et al., 2016). The method is also benefit to countenance for the modelling error that may lead to instability in order to maintained the performance to be stable and acceptable at a safety margin selection (Marlin, 2000). Despite many PID tuning methods are available to achieve the specified gain and phase margins, but most of the methods proposed are either limited towards only specific classes of plants or based on less efficient graphical approaches where only approximation were achieved (M.-T. Ho & Wang, 2003; Hu et al., 2011; Lee, 2004).

Ho and Wang (2003) design PID controller with guaranteed gain and phase margin using Hermite-Biehler Theorem, however the design procedure only applicable to plant describe by rational transfer functions, Padé approximation would require for time delay while fix controller gain assigned prior design turn out in less flexibility (M.-T. Ho & Wang, 2003). It is found that most of the tuning method adopt linear equation to approximate the arctan function as to simply the gain-phase margin formulas (W. K. Ho et al., 1995; Hu et al., 2011; Lee, 2004). Thus result in the gain and phase margin unable to meet the specification efficiently owing about 10% error of margin which may cause unstable controller or unstable system for some specification (Lee & Teng, 2002). Hu et. al., also show about 13.38% of the relative estimation error during controller design based on gain and phase margin (Hu et al., 2011). Therefore, high accurate tuning formulas for controller are required to obtain specific gain and phase margin.

In this paper, different approaches are considered for the design of PID controllers for intensified system. Each designed controller was used to study the closed-loop performance for setpoint tracking and disturbance rejection as well as stability analysis at different time delay. The feasibility of each controller design for different process dynamic from very fast to very slow process was also studied in order to understand suitable controller for intensified system. Last but not least, Exact Gain Phase Margin approach were further study toward performance of the closed loop over a range of Gain Margin and Phase Margin as well as the control of higher order process transfer function.

2. Controller Design

As the philosophy of the process intensification is the reduce of equipment sizes and residence times without compromising on throughputs, while the instrumentation of the same size as those employed in conventional units will continue utilized. Thus, the process order of magnitude could be the same order magnitude as instrumentation in which the dynamic behaviour of instrumentation cannot be negligible as conventional system and should be considered in the controller design Figure 1 represent the closed-loop block diagram of an intensified system in which it includes all the instrumentation transfer function. G_c, G_v, G_p, G_d and G_m represent transfer function of the controller, control element, process, process time delay and the feedback transmitter respectively. For simplicity, the component for G_v, G_p, G_d and G_m are assumed to be linear and expressed as below from equation (1) – (4). Different controller design method was employed based on the closed-loop system as shown in Figure 1 and presented in the following section.

$$G_v(s) = \frac{K_v}{\tau_v s+1} \quad (1)$$

$$G_p(s) = \frac{K_p}{\tau_p s+1} \quad (2)$$

$$G_m(s) = \frac{K_m}{\tau_m s+1} \quad (3)$$

$$G_d(s) = e^{-\theta s} \quad (4)$$

2.1. Direct Synthesis (DS) Method

Direct Synthesis method show a straight forward approach in which the performance requirements are incorporated directly through specification of the closed loop transfer function (Chen & Seborg, 2002). Abd Shukor and Tham (2004) applied Direct Synthesis method to design a controller for process intensified system which resulted in a Proportional-Integral-Derivative-Derivative (PID^2) form in series with a first order filter as in equation (5). Barzin et. al. also shown similar controller formulation through DS method. The respective parameter of controller formulation is expressed as below from equation (6) - (10). Abd Shukor and Tham showed that the significant effect of dynamic transmitter would likely required further action which resulted in second order derivative term thus would need a low pass filter to dampen the effect (Barzin et al., 2007; Shukor & Tham, 2004).

$$G_{c,D}(s) = G_f(s)K_{c,D}\left(1 + \frac{1}{T_{I,D}s} + T_{D,D}s + T_{D^2,D}s^2\right) \tag{5}$$

where: -

$$G_f(s) = \frac{1}{\left(\frac{\tau_m\tau_d}{\tau_m+\tau_d+\theta}\right)s+1} \tag{6}$$

$$K_{c,D} = \frac{\tau_p+\tau_v+\tau_m}{\tau_m+\tau_d+\theta} \tag{7}$$

$$T_{I,D} = \tau_v + \tau_p + \tau_m \tag{8}$$

$$T_{D,D} = \frac{\tau_v\tau_p+\tau_v\tau_m+\tau_p\tau_m}{\tau_m+\tau_v+\tau_p} \tag{9}$$

$$T_{D^2,D} = \frac{\tau_p\tau_v\tau_m}{\tau_m+\tau_v+\tau_p} \tag{10}$$

2.2. Internal Model Control (IMC) Method

IMC based design approach was used to provide controller formulation for intensified process by Jones et. al. (2006) The full IMC implementation is shown in Figure 2 and was rearranged into classical feedback form as shown in Figure 3. This method also resulted in a PID^2 controller formulation with restricting low pass filter into first order and using a low-order approximation for the time delay (R. W. Jones & Tham, 2006). The controller formulation obtained using IMC method was shown in equation (11) – (15).

$$G_{c,imc}(s) = K_{c,imc}\left(1 + \frac{1}{T_{I,imc}s} + T_{D,imc}s + T_{D^2,imc}s^2\right) \quad (11)$$

where: -

$$K_{c,imc} = \frac{\tau_p+\tau_v+\tau_m}{k_p(\lambda+\theta)} \quad (12)$$

$$T_{I,imc} = \tau_v + \tau_p + \tau_m \quad (13)$$

$$T_{D,imc} = \frac{\tau_v\tau_p+\tau_v\tau_m+\tau_p\tau_m}{\tau_m+\tau_v+\tau_p} \quad (14)$$

$$T_{D^2,imc} = \frac{\tau_p\tau_v\tau_m}{\tau_m+\tau_v+\tau_p} \quad (15)$$

2.3. Industrial IMC Method

Jones et. al (2006) also carried out the IMC based design of the industrial PID controller which include the setpoint weighting by using the equivalence of the industrial PID controller formulation with a two-degree freedom (2-DOF) process control structure PID-P control (R. W. Jones & Tham, 2007). The PID-P control scheme is presented in Figure 4. The forward path PID controller was developed in the same manner as in Section 2.2 and presented in equation (16) while the inner loop P controller was presented in equation (17). Each parameter formulation was presented in equation (18) – (21).

$$G_{c1}(s) = K_{c,ind}\left(1 + \frac{1}{T_{I,ind}s} + T_{D,ind}s\right) \quad (16)$$

$$G_{c2}(s) = k_f \quad (17)$$

$$K_{c,ind} = \frac{(\tau_v+\tau_p+\tau_m-k_pk_f\theta)}{k_p(\lambda+\theta)} \quad (18)$$

$$T_{I,ind} = \frac{(\tau_v+\tau_p+\tau_m-k_pk_f\theta)}{1+k_pk_f} \quad (19)$$

$$T_{D,ind} = \frac{(\tau_v\tau_p+\tau_p\tau_m+\tau_m\tau_v)}{(\tau_v+\tau_p+\tau_m-k_pk_f\theta)} \quad (20)$$

$$k_f = \frac{0.4}{k_p(\theta+0.75)} \quad (21)$$

2.4. Exact Gain and Phase Margin (EGP) Method

Gain and phase margins are classical control loop specification associated with the frequency response technique. They reflect on the performance and stability of the system and are widely used for controller design. In this section, a new way of tuning the PID controller through a simple and straightforward controller design based on specific gain margin, A_m and phase margin, ϕ_m through analytical method in which subject to A_m >1 and $0 < \phi_m < \frac{\pi}{2}$ (Marlin, 2000).

In order to use frequency response analysis to design control system, substitute $s = j\omega$ into the general formulation of PID controller as present in equation (22). It is then following the margin definition and employ into frequency domain at ω_p and ω_g respectively as equation (23) and (24).

$$G_{c,EGP} = K_{c,EGP}\left(1 + \frac{1}{T_{I,EGP}s} + T_{D,EGP}s\right) \tag{22}$$

$$\mathrm{G}(j\omega_p)\left[K_{C,EGP} + jK_{C,EGP}\left(T_{D,EGP}\omega_p - \frac{1}{T_{I,EGP}\omega_p}\right)\right] = -\frac{1}{A_m} \tag{23}$$

$$\mathrm{G}(j\omega_g)\left[K_{C,EGP} + jK_{C,EGP}\left(T_{D,EGP}\omega_g - \frac{1}{T_{I,EGP}\omega_g}\right)\right] = -e^{j\phi_m} \tag{24}$$

Given that $\mathrm{G} = G_v G_p G_m$ while ω_p and ω_g are the phase and gain crossover frequency of the open-loop respectively. In order to allow equation (23) and (24) to be solvable to obtain the unknown, extra constraints were added to reduce the number of unknown from five ($K_{C,EGP}$, $T_{I,EGP}$, $T_{D,EGP}$, ω_g and ω_p) to four ($K_{C,EGP}$, $T_{I,EGP}$, $T_{D,EGP}$ and ω_g) by relating the bandwidth of the process between closed loop and open loop process which is usually describe to be very closed to each other by the equation (25) in which α represent the bandwidth ratio of closed loop to open loop.

$$\omega_p = \alpha\omega_c, \alpha \in [0.5,2] \tag{25}$$

where ω_c and ω_p was the phase cross over frequency of G and $GG_{c,EGP}$ respectively. ω_c can be readily available from the process frequency response and it is the point which satisfying equation (26). If α is too large, the control signal will be saturated, in contrast if is too small, a sluggish response will occur. Therefore, as defaults value of α is chosen as 1. Ultimately, ω_p can be readily obtained from equation (25) by the plot of $\mathrm{G}(j\omega)$ and satisfying equation (26),

$$\angle \mathrm{G}(j\omega_c) = -\pi \tag{26}$$

Thus, by obtaining ω_p, equation (23) and (24) can be solved and rearrange to obtained equation (27) – (29) which directly provide the parameter of $K_{C,EGP}$, $T_{I,EGP}$ and $T_{D,EGP}$ respectively where ω_g satisfies the equation (32)

$$K_{C,EGP} = Re\left[\frac{-1}{A_m G_p(j\omega_p)}\right] \tag{27}$$

$$T_{I,EGP} = \frac{K_{C,EGP}}{(X_p\omega_g - X_g\omega_p)}\left(\frac{\omega_p}{\omega_g} - \frac{\omega_g}{\omega_p}\right) \tag{28}$$

$$T_{D,EGP} = \frac{\left(\frac{X_p}{\omega_g} - \frac{X_g}{\omega_p}\right)\left(\frac{\omega_p\omega_g}{\omega_g\omega_p}\right)^{-1}}{K_{C,EGP}} \tag{29}$$

where:

$$X_p = \mathrm{Im}\left[\frac{-1}{A_m G_p(j\omega_p)}\right] \tag{30}$$

$$X_g = \mathrm{Im}\left[\frac{-e^{j\phi m}}{G_p(j\omega_g)}\right] \tag{31}$$

$$Re\left[\frac{-e^{(j\phi m)}}{G_p(j\omega_g)}\right] = Re\left[\frac{-1}{A_m G_p(j\omega_p)}\right] \tag{32}$$

3. Simulation

The method described in the previous section was used to design controller for the following system. The transfer function of the actuator, process and transmitter are assumed to be first order transfer function and without the loss of generality, the gains of the actuator, process and transmitter transfer functions are set equal to 1 as described below.

$$G_v = \frac{1}{s+1}; \qquad G_p = \frac{1}{s+1}; \qquad G_m = \frac{1}{s+1}; \qquad G_d = e^{-\theta s}$$

The time delay θ, is taken as $\theta = 1, 2, 3\ and\ 4$ while τ_d and λ were set at values of 2 for each time delay consideration for DS, IMC and Industrial IMC method. However, for EGP method, the choice for gain and phase margins is set to be 3.0 and 60° respectively, while the α from equation (25) is set to be 1 by default (Lee, 2004). In general, a well-tuned controller should have a gain margin between 2 and 5 while phase margin between 30° and 60° (Wang & Cai, 2002).

The controller parameters for all of the above-mentioned methods were truncated into PID form and calculated with respective time delay setting. The stability analysis for each design method was analyse through the Bode-plot of open-loop system and presented in term of gain and phase margin. The controller performance was identified using the Integral Absolute Error (IAE), as shown in equation (33) because it is simpler value to analyses when the integral error measure is small and the control performance is linear with the deviation magnitude. All simulation for the system investigation was done analytically using the MATLAB_R2020a and SIMULINK environments.

$$\text{IAE} = \int_0^\infty |e(t)|dt \tag{33}$$

where the error signal $e(t)$ is the difference between the setpoint and the measurement.

4. Results and Discussion

From Table 1, it is notice that when the time delay increase, the controller gains for all controllers decrease to reduce the effect of time delay which to prevent aggressive control response. As expected, the overshoot of controller design method using DS, IMC, and Industrial IMC increase during step change when time delay increases from 1-4 which can be observed from Figure 5-8. However, EGP designed controller was robust and showed stable performance, where the overshoot decreases as time delay increases. From the controller formulation, the decrease of proportional gain and increase in the integral time reduce the aggressiveness of the response. On the other hand, the increase in the derivative time in a greater extent contributed to the rapidness of response toward the error, thus result in a robust and satisfy response towards setpoint changes. In overall, IMC and Industrial IMC method show rapid response for both setpoint tracking and disturbance rejection followed by EGP then

DS method. However, in term of robustness, EGP method performed much better compared to the others and maintaining the fast responsiveness toward changes when time delay increase. This can be observed from Table 1 where EPG method show smaller increase in Integral Absolute Error (IAE) for setpoint tracking when time delay increases compare to other method and showing lowest IAE value when $\theta = 4$.

The stability of a system is analyses by the amplitude ratio (AR), gain margin (A_m) and phase margin (ϕ_m). A_m is the inverse of AR which determined the amount of gain that still can be added in the feedback loop before instability happened. While ϕ_m determined the allowable time delay can be included into the system before it becomes unstable. Figure 9 shows the Bode diagram of the open loop system at τ_d, λ and θ equal to two for respective methods. According to Bode stability criterion, for a closed-loop linear system is said to be stable when the AR is less than 1 at its critical frequency. Thus, it is important to determine and analyze the AR value, in order to prevent any instability of a system occurs due to the inaccuracies in modelling and nonlinearities in the process. As the time delay increase, AR increases while A_m and ϕ_m decreases which indicate the negative effect of time delay towards the system's stability performance. It is noticed that, DS method will be more desired to accept the additional gain and time delay change followed by IMC then Industrial IMC. However, the acceptance level decrease as time delay increase. On the other hand, the benefit of EGP method able to maintain the stability of the system and adequate amount on the tolerance of time delay and gain added to the system due to process modelling error by fixing the desired A_m and ϕ_m. As presented in Table 2, the A_m and ϕ_m for DS, IMC and Industrial IMC designed method decrease as time delay increase. With the EGP method, the resultant open loop response able to achieve desired specified A_m and ϕ_m which show the benefit of the analytical EGP approach.

Figure 10–13 show the closed-loop performance for both setpoint tracking and disturbance rejection for different process time constant from 0.01 to 10 to represent very fast to very slow process. The result showed that EGP method provide superior performance at lower τ_{p} of 0.01 and 0.1 as compared to the other methods which can also be observed from the lowest IAE value obtained for setpoint tracking from Table 3. This result from the higher controller gains and derivative time constant for EPG method compared to DS, IMC and Industrial IMC which can be seen from Table 3. It is notice that for disturbance rejection at τ_{p}

value of 0.01 and 0.1, the response is about stagnant for two seconds which equal to the time delay before rejection happened as shown in Figure 10 and Figure 11. This is due to the very fast process dynamic response toward the disturbance compared to the time delay and instrumentation dynamic. The effect of time delay on difference process time constant was significant as evidenced by the response of disturbance rejection in Figure 10-13, where the overshoot at lower τ_p is greater than at higher τ_p ranging from 50% to 20%. As a result, it demonstrates the significant effect of time delay on the closed-loop response. This implied that the time delay, which is normally tolerated by conventional process with a couple minutes of process time constant, had a significant effect on the low volume of intensified systems because the time delay was sometimes greater than the process time constant, resulting in control difficulties and unstable performance.

When τ_p increase, performance of EPG controller become more sluggish for both setpoint tracking and disturbance rejection, while the other three controller method show better performance at higher τ_p. This is due to the controller gain and derivative time constant for the DS, IMC and Industrial IMC methods are functions of τ_p, and show an increasing trend with τ_p. EPG method show superior performance at lower τ_p and become more sluggish when τ_p increases in order to maintain its stability and robustness toward any changes. Thus, the EPG method prompt to achieve better performance and stability at low τ_p while prompt toward maintain stable response when dealing with higher τ_p. However, the performance of EPG method can be further improved by adjusting the gain and phase margin as desired.

Further investigation on the feasibility of EGP method on controller performance at various gain and phase margin for τ_p ranging from 0.01 to 1 which correspond from very fast to slow process. Figure 14 show the relationship between IAE with various gain and phase margin with different τ_p value. It is notice that a convex function kind of relationship obtain where the IAE value for all τ_p were converge within the gain margin of 3-3.5 and phase margin of 63°-66° which to provide an optimal performance and robustness of control. Lower gain and phase margin would result in highly oscillatory response in contrast higher gain and phase margin produce sluggish response. It is also notice that the τ_p does not affect the selection of gain and phase margin significantly. Nie at. al., (2016) state that to achieve good system performance the phase margin should kept at between 60° to 70°(Nie et al., 2016). The lowest

IAE values for τ_p = 0.01, 0.1 and 1 are 1.8506, 1.9558 and 2.7594 respectively at correspond gain and phase margin as shown in Figure 14.

Higher process order transfer function was also used determined the effectiveness of EGP controller design to tradeoff between robustness and performance. Second order and third order transfer function were subject to the controller design using EGP method with different gain and phase margin. Figure 15 show the controller performance at different gain and phase margin for 2nd and 3rd order process transfer function. It can be observed, there is no significant changes of gain and phase margin where the lowest IAE value obtained where it maintains at 3 and 63.5 for gain margin and phase margin respectively when the process order increase from first order to third order. This shows the benefit of EGP method by maintaining the stability of the system and performance of the system at certain range of gain and phase margin. However as compare to first order as shown in Figure 14 (c), the controller performance tend to degrade at higher gain margin and lower phase margin or vice versa. On the other hand, for the higher order system, the performance degrade at higher gain and phase margin. Thus, it is suitable for complex and higher order intensification process where the stability and performance of the system can be achieved by setting suitable gain and phase margin.

The controller parameter for different process order was showed in Table 4. As the process order increase the controller gain decreases while the integral time constant and derivative time constant increases to diminish the oscillatory and aggressiveness of the response to produce a rapid and robust control performance with a low IAE value as shown in Figure 16. The respond curve shows low overshoot show almost similar overshoot which is within 10%, this result from the same phase margin obtained and used in the controller design as phase margin is account well for dynamic precision especially for the step response overshoot (Krajewski et al., 2004). Over a variety of process order, EGP method show a robust and good control performance with low overshoot and less oscillatory response.

On the others hand, the selection of actuator and transmitter in intensification process play an important role to provide a desired feedback toward the system. Figure 17 show the effect of transmitter time constant, τ_m, actuator time constant τ_v and time delay, θ with respect to τ_p on closed loop performances. In each case, the closed loop responses had track a unit step changes in set point, and the IAE was determined with the help of MATLAB. As expected, the smaller value of time delay produce a better overall control performances as indicated by the lower IAE value. However, the control performance degrades rapidly when $\frac{\tau_m}{\tau_p}$ and $\frac{\tau_v}{\tau_p}$ greater than 5 at $\theta = 1$. It is also interesting to notice that for a range of $\frac{\tau_m}{\tau_p}$ and $\frac{\tau_v}{\tau_p}$ which below the threshold value for each θ, the system performances were almost similar, this indicates that the controller is relatively insensitive to the variation of the dynamic of transmitter and actuator. On the others hand, when the θ increase, the closed loop performances start degrade at higher $\frac{\tau_m}{\tau_p}$ and $\frac{\tau_v}{\tau_p}$. Thus, it show the important of the selection of τ_m and τ_v which are also strongly influence by θ and would require to take into consideration. The magnitude of the time constant of instrumentation should be control below four times of the time delay to ensure the system stability and performance. For any particular value of θ, the control performance may deteriorate severely with the increase of IAE value even if the fastest transmitter is used. Thus, with correct selection between ratio of instrumentation unit, intensification process can be control well with EGP method. This result was somehow in contrast with Abd Shukor and Tham (2004) where the result show identical control performance at lower τ_m (< 0.2) and θ (< 1) via direct synthesis method. This might due to the different design approach in which the parameter of τ_m and θ were appear in the controller formulation for synthesis method while EGP method use gain margin and phase margin to manipulate the controller performance as well as stability. Thus, it provide an insight that conventional instrumentation might be possible to apply toward intensified system.

5. Conclusion

Different controller design method was presented were studies as well as the effect of time delay and process time constant toward the controller performance and stability analysis. As time delay increases, the controller performance become more aggressive and overshoot increase in correspond to the decrease in the gain and phase margin. On the others hand, EPG method provide a stable yet good performance closed loop response compares to the others with increasing time delay. This is result from the constant gain and phase margin selection which allow the controller to perform in order to maintain desired stability. Moreover, EPG controller show excellent performance when deal with fast process dynamic than others three method. Further feasibility study of EGP method also show the excellent controller performance over various order process plant and process dynamic at range of for gain and phase margin respectively. Relationship between instrumentation dynamic and time delay with respect to process dynamic play an crucial effect toward controller performance which need to take in account. Therefore, EGP method show it benefit to trade-off between robustness and performance of a control system compare to others controller design method in which EGP method provide better handling on intensified systems dealing with higher process time delay, higher order as well as higher dynamic. Future work will be employ on implementation of the EGP method with the limit of sensitivity and complementary sensitivity of the plant.

References

Barzin, Reza, Abd Shukor, Syamsul Rizal, & Ahmad, Abdul Latif. (2007). An Overview of Difficulties in Controlling Intensified Process. *AIChE*, *7*, 8–15. https://doi.org/10.22146/ajche.50123

Chen, Dan, & Seborg, Dale E. (2002). PI/PID Controller Design Based on Direct Synthesis and Disturbance Rejection. *Industrial & Engineering Chemistry Research*, *41*(19), 4807–4822. https://doi.org/10.1021/ie010756m

Demirci, Yavuz, & Özbeyaz, Abdurrahman. (2019). Wastewater treatment in electrocoagulation systems: investigation of the impact of temperature using a fuzzy logic control algorithm. *Environmental Science and Pollution Research*, *26*(30), 30893–30906. https://doi.org/10.1007/s11356-019-06279-4

Dias, Lisia S., & Ierapetritou, Marianthi G. (2019). Optimal operation and control of intensified processes — challenges and opportunities. *Current Opinion in Chemical Engineering*, *25*, 82–86. https://doi.org/https://doi.org/10.1016/j.coche.2018.12.008

Ho, Ming-Tzu, & Wang, Hsing-Sen. (2003). Pid Controller Design With Guaranteed Gain And Phase Margins. *Asian Journal of Control*, *5*(3), 374–381. https://doi.org/https://doi.org/10.1111/j.1934-6093.2003.tb00129.x

Ho, Weng Khuen, Hang, Chang Chieh, & Cao, Lisheng S. (1995). Tuning of PID controllers based on gain and phase margin specifications. *Automatica*, *31*(3), 497–502. https://doi.org/https://doi.org/10.1016/0005-1098(94)00130-B

Hu, Wuhua, Xiao, Gaoxi, & Li, Xiumin. (2011). An analytical method for PID controller tuning with specified gain and phase margins for integral plus time delay processes. *ISA Transactions*, *50*(2), 268–276. https://doi.org/https://doi.org/10.1016/j.isatra.2011.01.001

Jones, R. W., & Tham, M. t. (2006). Control Strategies for Process Intensified Systems. *2006 SICE-ICASE International Joint Conference*, 4618–4623. https://doi.org/10.1109/SICE.2006.315173

Jones, R. W., & Tham, M. T. (2007). IMC based tuning of set-point weighting. *2007 European Control Conference (ECC)*, 1038–1045. https://doi.org/10.23919/ECC.2007.7068608

Jones, Richard, & Tham, Ming. (2015). PID design approaches for higher-order plants. *2007 European Control Conference, ECC 2007*, 5858–5865.

Krajewski, W., Lepschy, A., & Viaro, U. (2004). Designing PI controllers for robust stability and performance. *IEEE Transactions on Control Systems Technology*, *12*(6), 973–983. https://doi.org/10.1109/TCST.2004.833619

Lee, Ching-Hung. (2004). *A survey of pid controller design based on gain and phase margins*.

Lee, Ching-Hung, & Teng, Ching-Cheng. (2002). Tuning of PID controllers for unstable processes based on gain and phase margin specifications: A fuzzy neural approach. *Fuzzy Sets and Systems*, *128*, 95–106. https://doi.org/10.1016/S0165-0114(01)00051-3

Marlin, Thomas. (2000). *Process Control: Designing Processes and Control Systems for Dynamic Performance. New York: McGraw-Hill.*

Mestres, Ramon. (2005). Green Chemistry - Views and Strategies * (5 pp). *Environmental Science and Pollution Research*, *12*(3), 128–132. https://doi.org/10.1065/espr2005.04.253

Nie, Zhuo Yun, Liu, Rui Juan, Jin, Fu Jiang, et al. (2016). Analysis and design of scaling optimal GPM-PID control with application to liquid level control. In *International Journal of Automation and Computing* (Vol. 13, Issue 6, pp. 624–633). https://doi.org/10.1007/s11633-016-0998-y

Seborg, D. E., Mellichamp, D. A., Edgar, T. F., et al. (2010). *Process Dynamics and Control*. John Wiley & Sons. https://books.google.com.my/books?id=_PQ42kOvtfwC

Shukor, Syamsul Rizal Abd, & Tham, Ming T. (2004). Performance Envelopes of Process Intensified Systems. *IFAC Proceedings Volumes*, *37*(1), 191–195. https://doi.org/https://doi.org/10.1016/S1474-6670(17)38730-X

Tahir, Furqan, Mercer, Ewan, Lowdon, Ivan, et al. (2018). Advanced process control and monitoring of a continuous flow micro-reactor. *Control Engineering Practice*, *77*, 225–234. https://doi.org/https://doi.org/10.1016/j.conengprac.2018.06.003

Wang, Ya-Gang, & Cai, Wen-Jian. (2002). Advanced Proportional−Integral−Derivative Tuning for Integrating and Unstable Processes with Gain and Phase Margin Specifications. *Industrial & Engineering Chemistry Research*, *41*(12), 2910–2914. https://doi.org/10.1021/ie000739h

Zanati, E., Abdallah, H., & Elnahas, G. (2016). Micro-reactor for Non-catalyzed Esterification Reaction: Performance and Modeling. *International Journal of Chemical Reactor Engineering*, *15*. https://doi.org/10.1515/ijcre-2016-0099

Statement and Declaration

Ethical Approval and consent to participate

Not Applicable

Consent for Publish

Not Applicable

Availability of data and materials

The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author's Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Cheong Sheng Lee. The first draft of the manuscript was written by Cheong Sheng Lee and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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List of Figure

Figure 12 Controller Performance for Setpoint Tracking and Disturbance Rejection at time delay, $\theta = 2$, when process time constant, $\tau_{\mathrm{p}} = 5$

Figure 13 Controller Performance for Setpoint Tracking and Disturbance Rejection at time delay, $\theta = 2$, when process time constant, $\tau_{\mathrm{p}} = 10$

Figure 14 Controller performance at different gain and phase margin a) $\tau_{\mathrm{p}} = 0.01$ ($A_{\mathrm{m}} = 3.5, \emptyset_{\mathrm{m}} = 65.5°$); b) $\tau_{\mathrm{p}} = 0.1$ ($A_{\mathrm{m}} = 3.5, \emptyset_{\mathrm{m}} = 65.5°$) and c) $\tau_{\mathrm{p}} = 1$ ($A_{\mathrm{m}} = 3.0, \emptyset_{\mathrm{m}} = 63.5°$)

Figure 15: Controller performance at different process plant order: a) Second order process plant, b) Third order process plant

Figure 16 : Controller Performance for Setpoint Tracking and Disturbance Rejection with different process order

Figure 17: Effect of τ_{m}, τ_{v} and θ with respect to τ_{p} toward closed loop performances at $A_{\mathrm{m}} = 3$ and $\emptyset_{\mathrm{m}} = 63.5°$.

List of Table

Table 1 : Controller formulation with PID form at time delay, θ from 1-4.

Design Method	θ	t_f/k_f	K_c	T_I	T_D	IAE
DS	1	0.500	0.750	3.000	1.000	3.033
	2	0.400	0.600	3.000	1.000	4.229
	3	0.333	0.500	3.000	1.000	6.013
	4	0.286	0.429	3.000	1.000	8.017
IMC	1	-	1.00	3.000	1.000	2.029
	2	-	0.750	3.000	1.000	3.380
	3	-	0.600	3.000	1.000	5.332
	4	-	0.500	3.000	1.000	7.567
Industrial IMC	1	0.229	0.924	2.256	1.083	2.032
	2	0.146	0.677	2.365	1.107	3.522
	3	0.107	0.536	2.422	1.119	5.210
	4	0.084	0.444	2.456	1.127	7.749
EGP	1	-	0.832	2.578	0.462	2.798
	2	-	0.587	2.616	0.832	4.091
	3	-	0.494	2.848	1.174	5.539
	4	-	0.445	3.136	1.499	6.971

Table 2 : Stability analysis of different controller at time delay, θ ranged from 1-4.

Design Method	$\boldsymbol{\theta}$	**AR**	$\boldsymbol{A_m}$	$\boldsymbol{\phi_m}$
DS	1	0.300	3.339	69.114
	2	0.346	2.887	62.837
	3	0.372	2.688	58.378
	4	0.397	2.519	55.057
IMC	1	0.346	2.893	71.391
	2	0.400	2.498	61.680
	3	0.418	2.394	55.836
	4	0.438	2.282	51.946
Industrial IMC	1	0.388	2.577	61.789
	2	0.446	2.241	55.210
	3	0.463	2.159	50.874
	4	0.480	2.083	47.896
EGP	1	0.333	3.000	60.000
	2	0.333	3.000	60.000
	3	0.333	3.000	60.001
	4	0.333	3.000	60.001

Table 3 : Controller formulation with PID form at different process time constant, τ_p at τ_d, λ and θ =2.

Design Method	$\boldsymbol{\tau_p}$	$\boldsymbol{t_f/k_f}$	$\boldsymbol{K_c}$	$\boldsymbol{T_I}$	$\boldsymbol{T_D}$	**IAE**
DS	0.01	0.400	0.402	2.010	0.508	4.361
	0.1	0.400	0.420	2.100	0.571	4.348
	5	0.400	1.400	7.000	1.571	4.433
	10	0.400	2.400	12.000	1.750	4.538
IMC	0.01	-	0.503	2.010	0.508	3.431
	0.1	-	0.525	2.100	0.571	3.408
	5	-	1.750	7.000	1.571	3.930
	10	-	3.000	12.000	1.750	4.029
Industrial IMC	0.01	0.146	0.4300	1.501	0.593	4.457
	0.1	0.146	0.452	1.579	0.663	3.809
	5	0.146	1.677	5.857	1.640	4.038
	10	0.146	2.927	10.222	1.794	4.120
EGP	0.01	-	0.578	2.076	0.655	3.144
	0.1	-	0.567	2.100	0.685	3.264
	5	-	1.138	6.588	0.593	5.610
	10	-	1.905	12.978	0.363	6.565

Table 4: Controller formulation with PID form at different process order

Process Order	A_m	ϕ_m	K_c	T_I	T_D	**IAE**
First Order	3.0	63.5	0.8316	2.7816	0.4279	2.7594
Second Order	3.0	63.5	0.7395	3.2291	0.6326	3.7256
Third Order	3.0	63.5	0.6676	3.6452	0.8553	4.7548

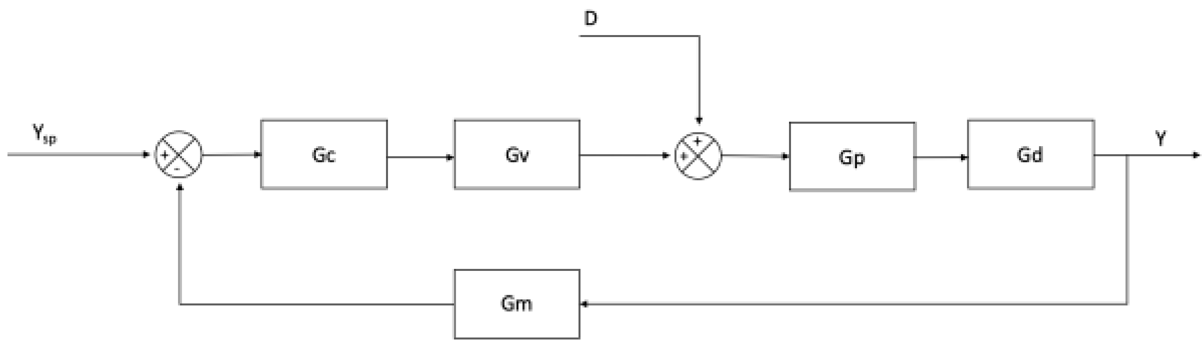


Figure 1 : Feedback control loop

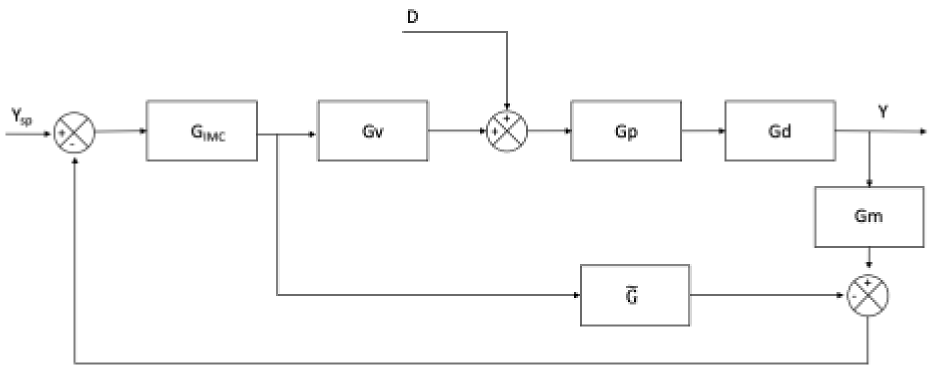


Figure 2 : IMC scheme including instrumentation (R. W. Jones & Tham, 2006).

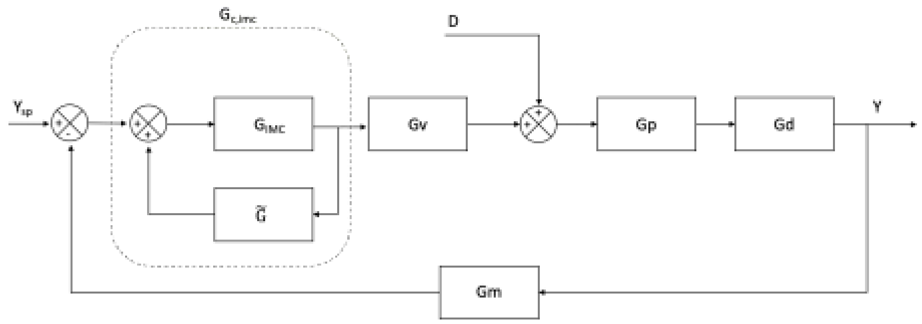


Figure 3 : Rearranged IMC block diagram in classical feedback form (R. W. Jones & Tham, 2006).

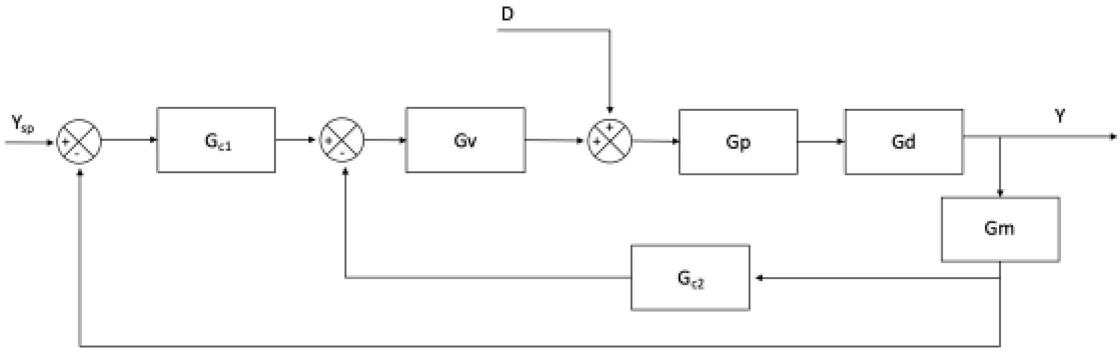


Figure 4 :	PID-D control scheme (R. W. Jones & Tham, 2006).

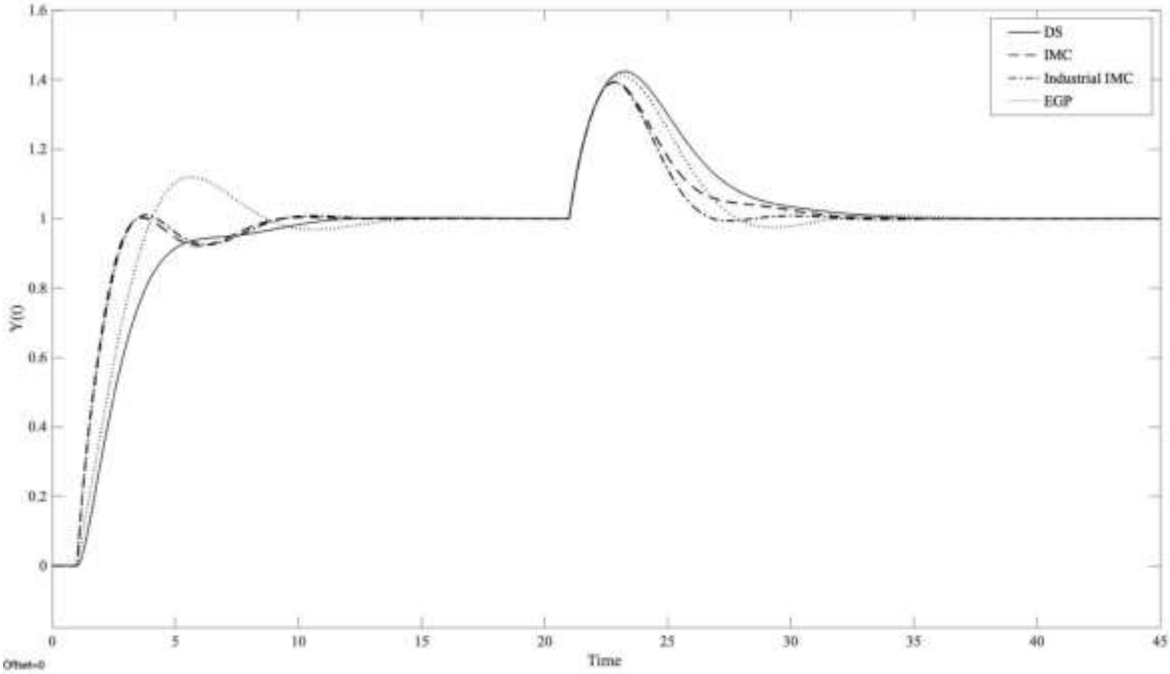


Figure 5 : Controller Performance for Setpoint Tracking and Disturbance Rejection at time delay, $\theta = 1$

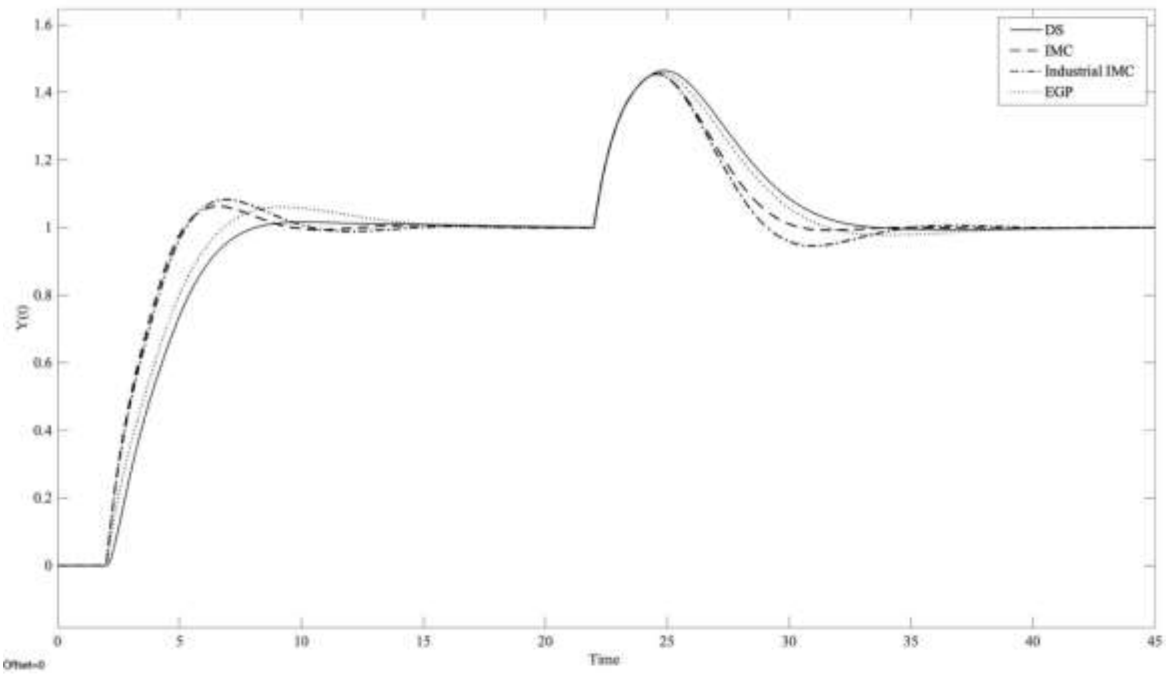


Figure 6 : Controller Performance for Setpoint Tracking and Disturbance Rejection at time delay, $\theta = 2$

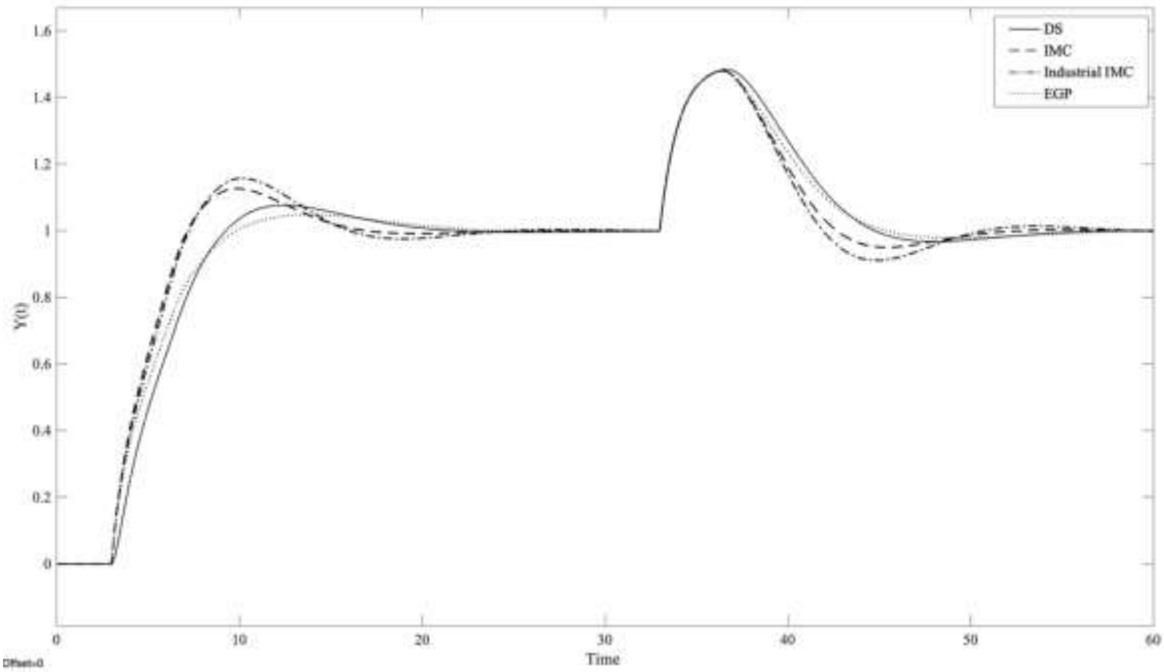


Figure 7 : Controller Performance for Setpoint Tracking and Disturbance Rejection at time delay, $\theta = 3$

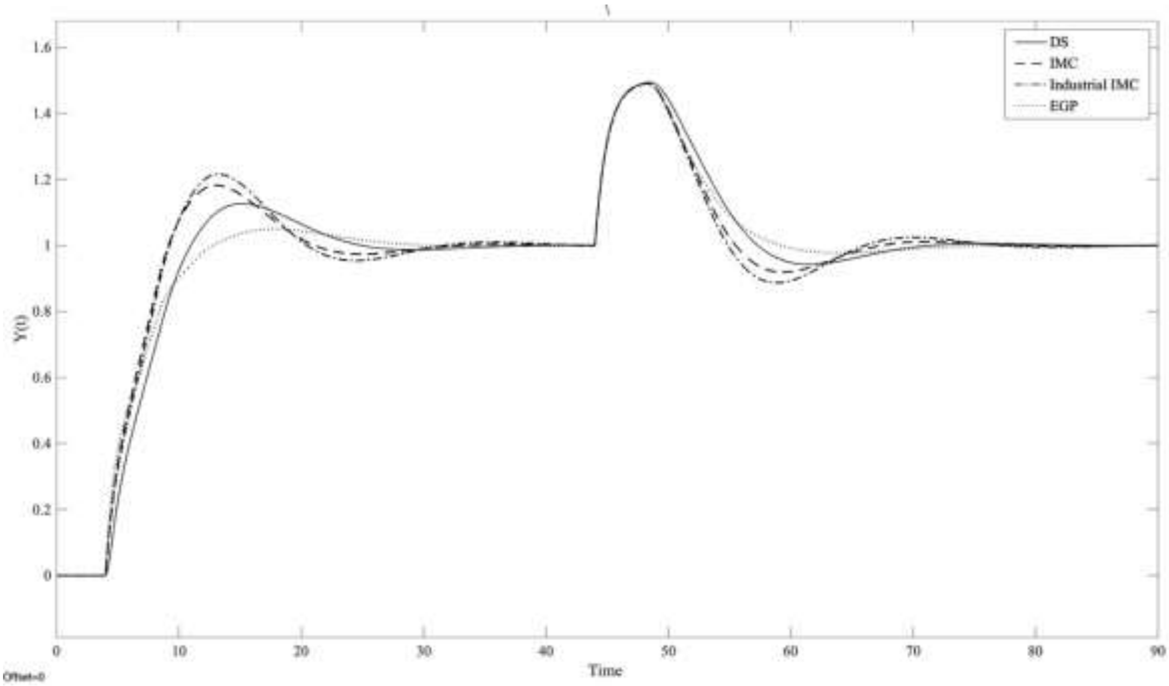


Figure 8 : Controller Performance for Setpoint Tracking and Disturbance Rejection at time delay, $\theta = 4$

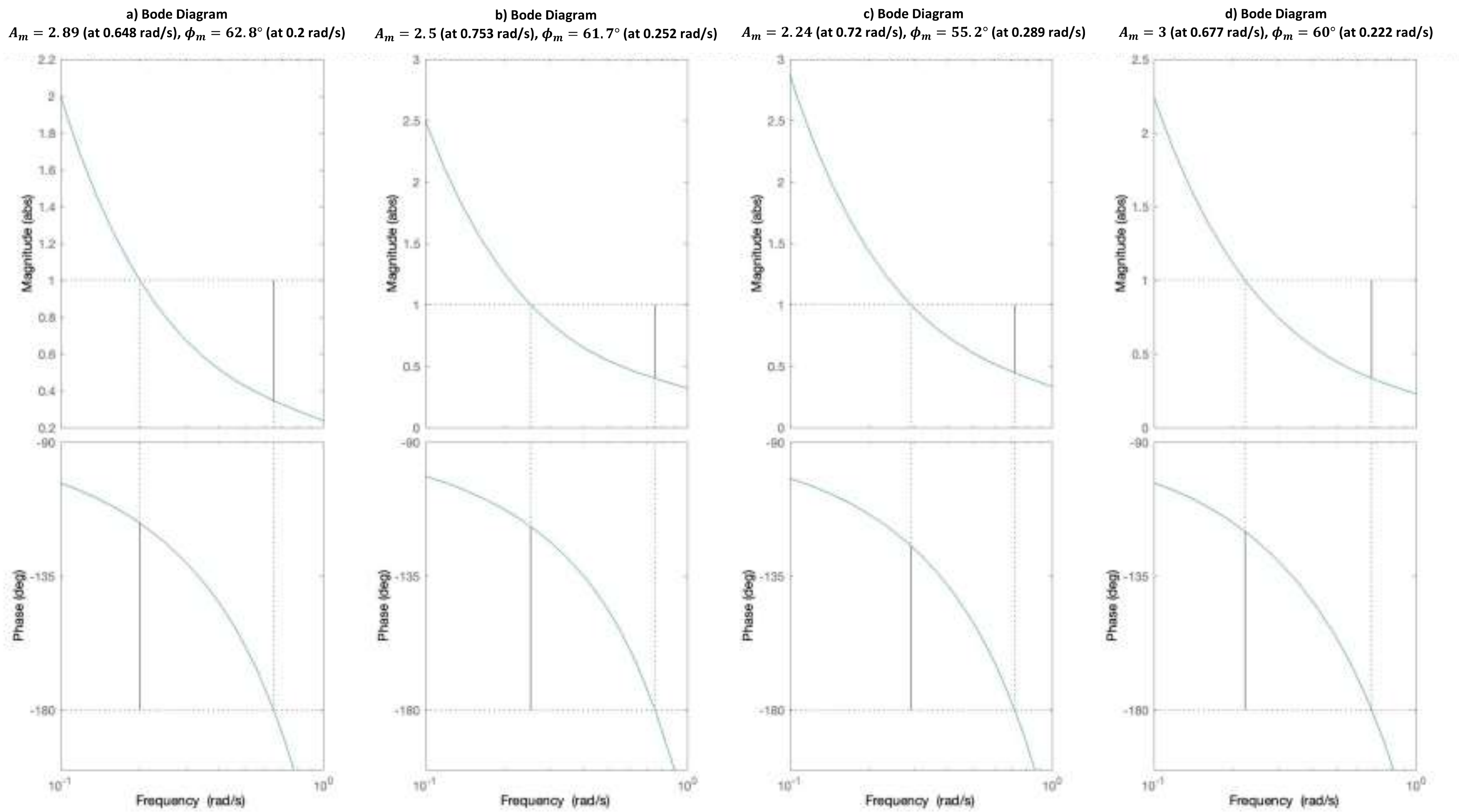


Figure 9 : Bode diagram of the open loop system at τ_d, λ and θ equal to two for different controller design method. a) DS, b) IMC, c) Industrial IMC, d) EGP

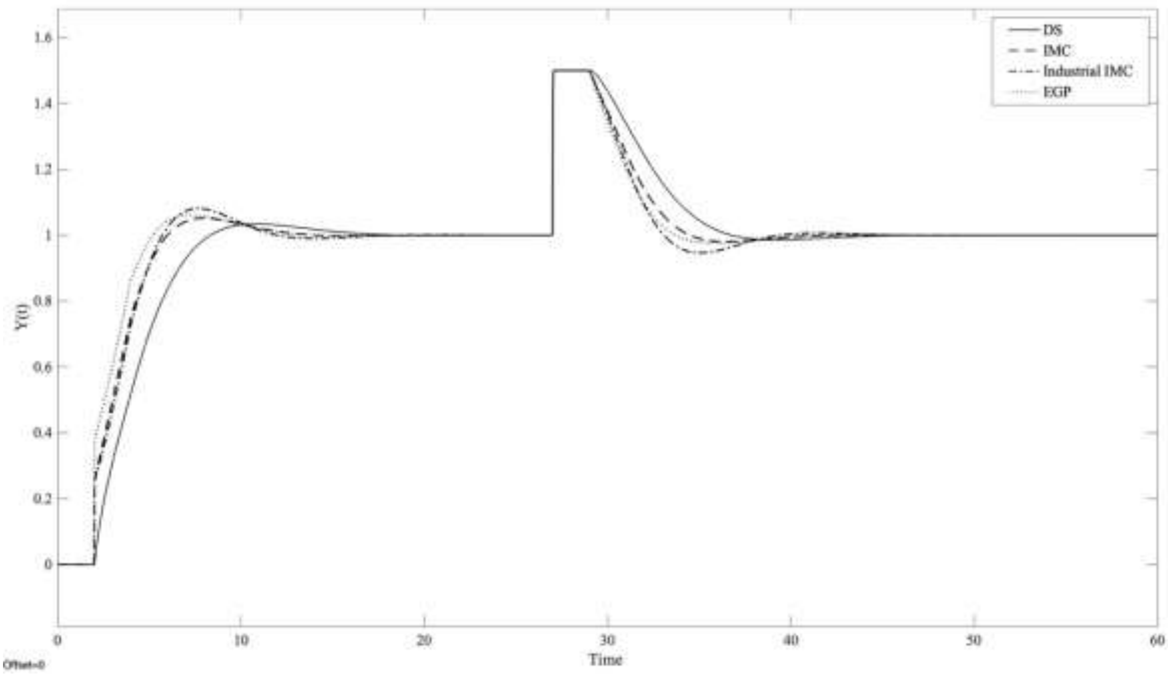


Figure 10 : Controller Performance for Setpoint Tracking and Disturbance Rejection at time delay, $\theta = 2$, when process time constant, $\tau_{\mathrm{p}} = 0.01$

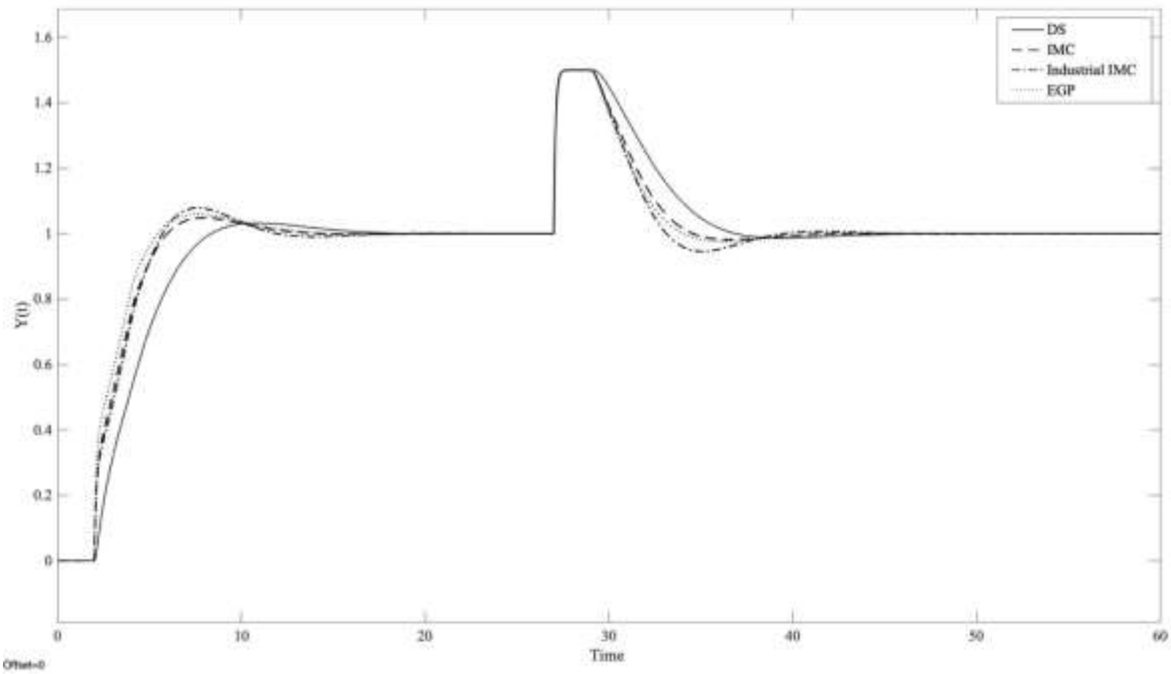
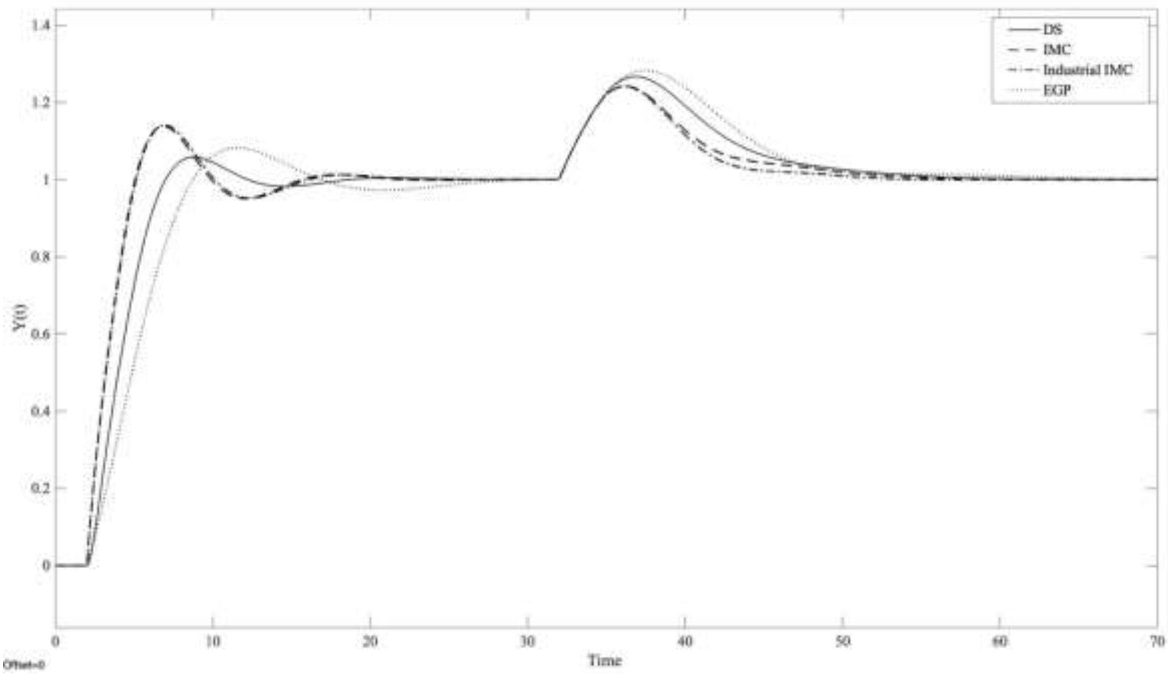


Figure 11 : Controller Performance for Setpoint Tracking and Disturbance Rejection at time delay, $\theta = 2$, when process time constant, $\tau_{\mathrm{p}} = 0.1$



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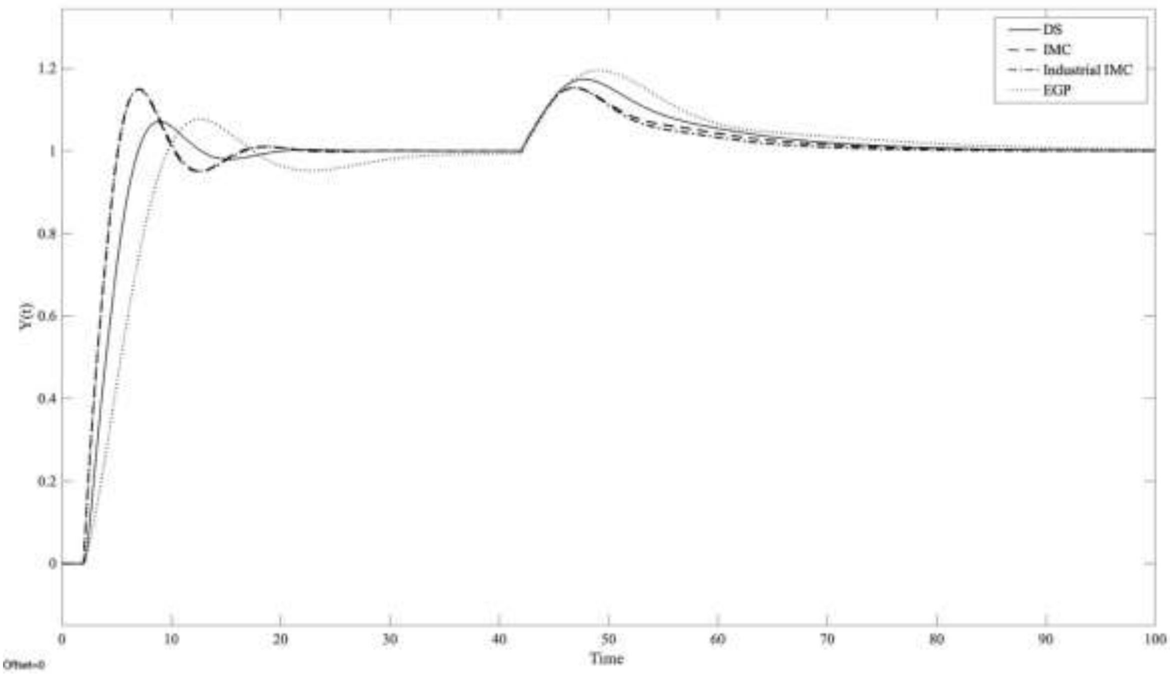

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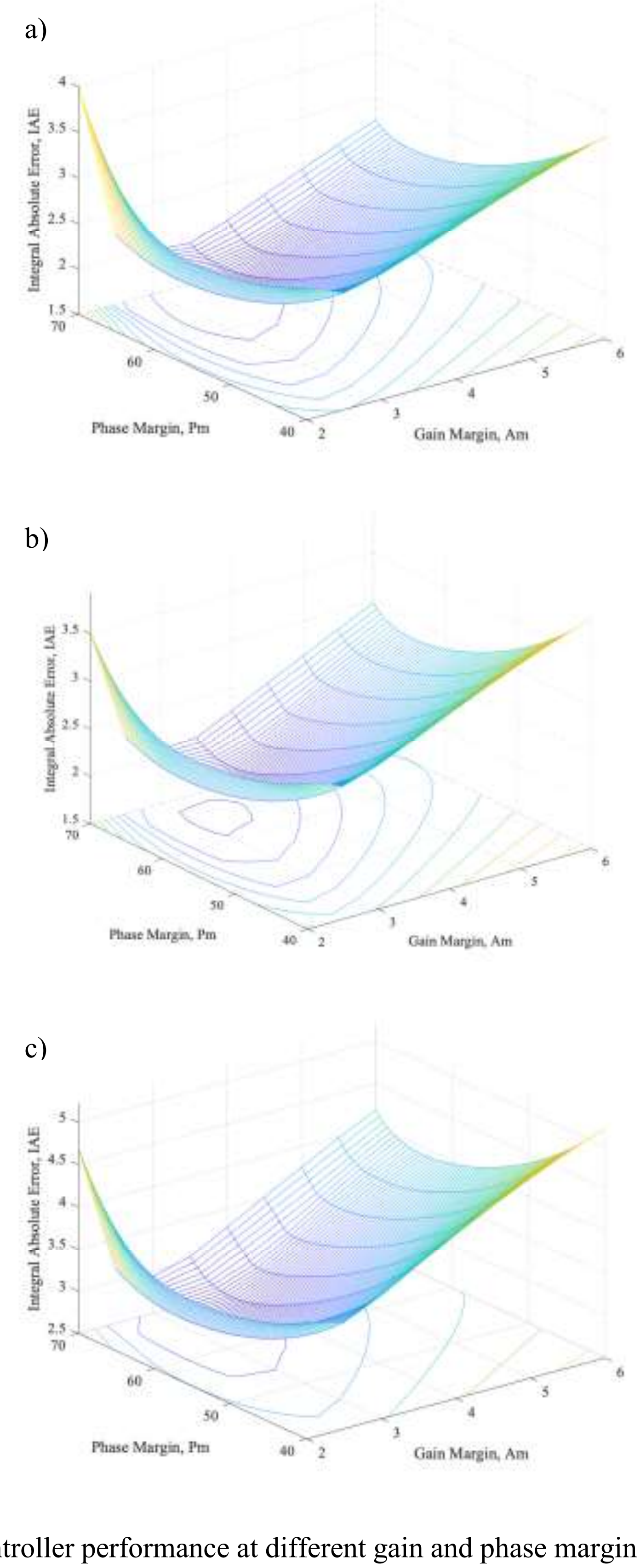

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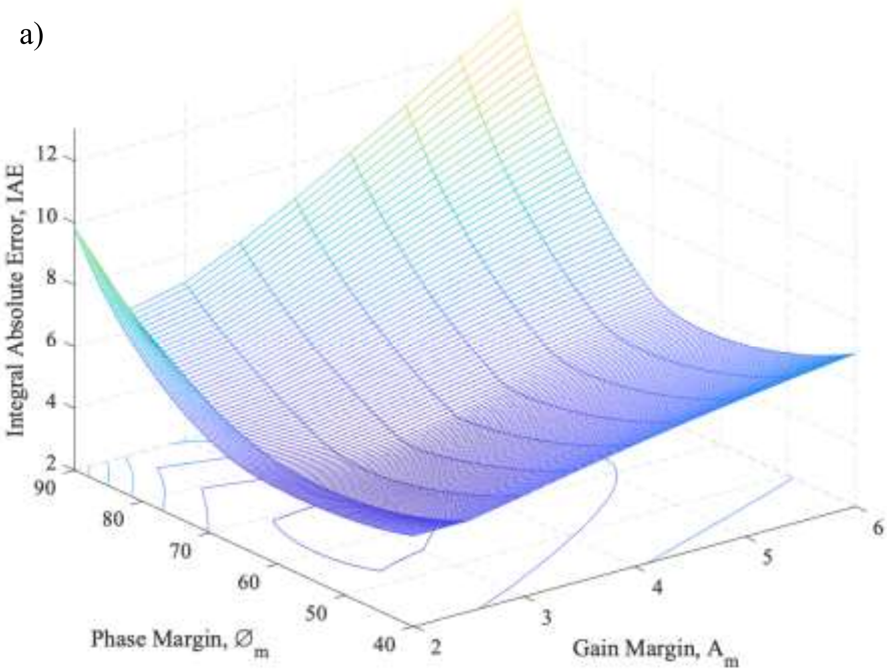
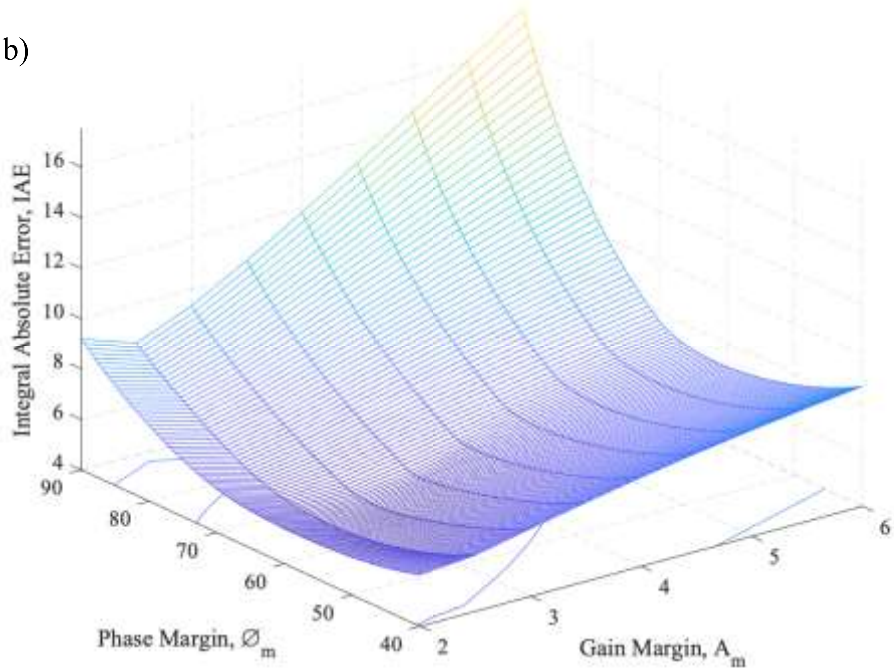
a)



b)



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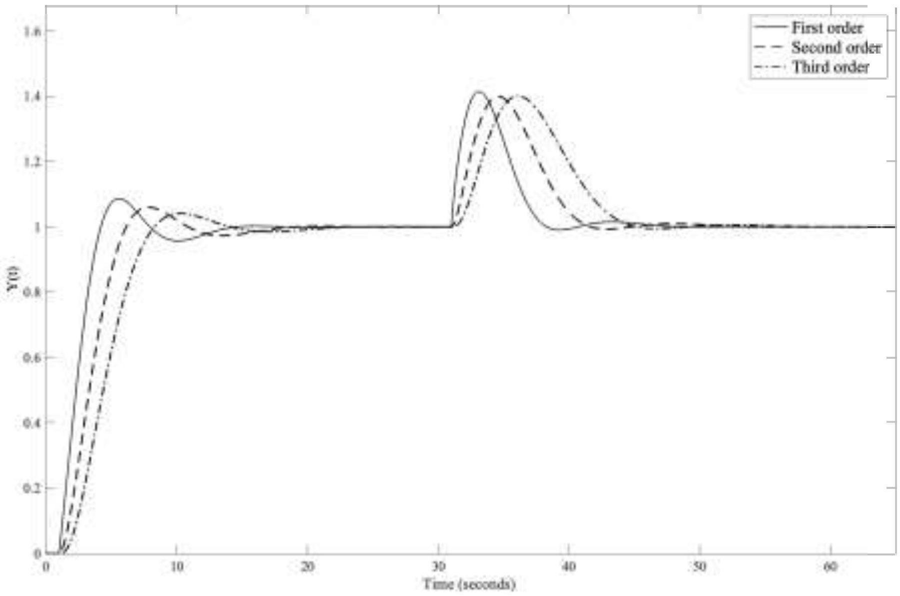

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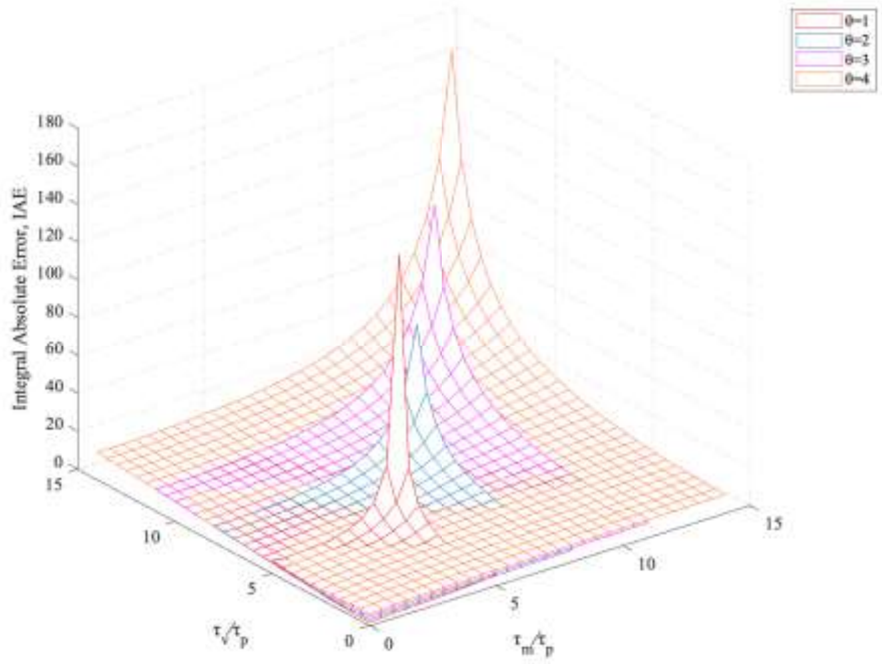

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