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Review article

A comprehensive review of modified Internal Model Control (IMC) structures and their filters for unstable processes

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ABSTRACT

This paper reviews the evolution of Internal Model Control (IMC) techniques developed so far for unstable processes. The IMC strategy has shown significant results over the past two decades, including recent inclusions of fractional-order approaches. After a comprehensive study of various methods, the critical tuning methods and structural changes are clearly accumulated with their significance and limitation concerning controlling unstable time-delay systems. The comparisons with main structural changes and filter designs are also included in the numerical study and in discussion. Finally, the key research gaps and future motivations are indicated in the IMC approaches, considering available methods in the literature.

1. Introduction

In the process industry, Proportional-Integral-Derivative (PID) control is the most common scheme and has been universally accepted in industrial control. The popularity of PID can be attributed partly to their robust performance in a wide range of operating conditions, feasible and partly to their functional simplicity, which allows engineers to implement very quickly (Knospe, 2006). Tuning is the process of setting the optimal gains for P, I and D values to get an ideal response from a control system. A PID controller continuously calculates an error value as the difference between the desired set point and a measured process variable and applies a correction based on proportional, integral, and derivative terms. The early methods of PID controller tuning include the trial and error method, Ziegler–Nichols (Z-N) method (Ziegler & Nichols, 1993), relay tuning method (Åström & Hägglund, 1984) and Cohen–Coon method (Cohen, Coon, & Rochester, 1953). These methods yield satisfactory tracking responses. However, they do not provide the desired results (in the sense of disturbance rejection, optimally and robustness) due to assumptions made and further tuning is required.

Internal model control (IMC) is an efficient control method and achieved a superior effect to PID control (Saxena & Hote, 2012). Despite several advantages of PID, in industrial process control, many processes are complex, unstable and with input time delays. In the case of PID, it is difficult to adapt to a wide range of uncertain systems and to obtain satisfactory control effects. While the IMC has more immunity and robustness for large time-delay stable and unstable plants, it is simple in structure, has an easy and intuitive design, and has fewer adjustable parameters.

Firstly, the IMC scheme was presented to design using process model parameters, and PID (Rivera, Morari, & Skogestad, 1986). It was better than traditional PID concerning load disturbance rejection. Then some notable works were presented on IMC-PID tuning and found attraction by industrial researchers. Many PID tuning methods have been developed by applying IMC techniques using the low order plus time delay model (Shamsuzzoha & Lee, 2007). It is noted that the IMC-PID was performing well for setpoint tracking but sluggish in disturbance response (Chen & Seborg, 2002; Morari & Zafiriou, 1989). In every IMC scheme, a tuning parameter is essential to set correctly in design techniques. While considering tuning of controller, the issue appears with mismatch at high frequency. Therefore, a low pass filter should be added to make the controller versatile (Lee, Lee, & Park, 2000; Ranjan & Mehta, 2022; Saxena & Hote, 2017a; Shamsuzzoha & Lee, 2008b). A filter design is also the central unit in IMC theory for setpoint and disturbance rejection. In literature, various modifications were presented to enhance performances in the presence of disturbance, model mismatch and measurement noise; for example, see Saxena and Hote (2013, 2016b).

The key contributions can be summarized as follows:

- A comprehensive study presented types of IMC filters and IMC structures applied in unstable processes, considering works shown from 2000 onwards.
- The paper also discusses the tuning techniques and control strategies adopted in each work.

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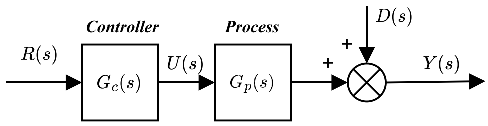


Fig. 1. Open-loop strategy.

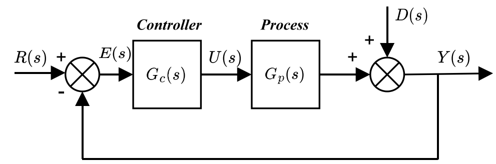


Fig. 2. A classical structure.

- A latest fractional-order theory applied in IMC together cascade structures are also captured with technical advantages.
- The advantages and constraints of various IMC filters and IMC schemes are tabulated for fare understanding of applications.
- A numerical example is shown to compare the main contributed structures and IMC filters.
- The critical research gaps are identified with existing challenges, and then some future motivations are accumulated for the IMC theory.

The paper is organized as follows. In Section 2, covers the evolution of IMC structure and properties. Section 3 discusses about IMC controller design procedure followed by literature review about the development and different strategies based on IMC for the past two decades in Section 4. Various IMC structures, including integer and fractional controllers, Cascaded IMC and various IMC filter used are given in Section 5. Then, Section 6 covers the numerical simulations. Some challenges are discussed in Section 7. Finally, the last Section 8 provides the conclusion along with future prospects.

2. Evolution of IMC

The majority of the systems identified in the process industry are either slow, overdamped, nonlinear or may need to be more adequately simulated. They also needed to be aware of the lower and upper bounds of the stability region. Researchers have concentrated on innovative control techniques such as Model Algorithmic Control (1978), Dynamic Matrix Control (1980), Inferential Control (1979), and Internal Model Control (1982) for effectively tackling issues. Garcia and Morari introduced IMC as model-based control widely adopted in the process industry and provides a basic parametrization of all stabilizing controllers for stable or unstable processes. The IMC design is fundamentally developed under the exact model of the process available and so, the perfect control cannot achieve without the complete knowledge about the process. However, this limitation is no longer available in recent variations and this makes the approach more special case of classical feedback structure. The research conducted by Rotstein and Lewin (1991) can be regarded as the first study of an IMC-PID tuning rule for an unstable process (Rotstein & Lewin, 1991). They developed IMC based PI and PID techniques with and without time delay.

Let us start with the first objective of any control system is to achieve accurate setpoint tracking and good regulatory behavior. It should also be insensitive to modeling error. A simple open-loop arrangement can be effective if a process model and controller are stable. In that case a controller can be easy to design. As shown in Fig. 1, $G_c(s) = 1/G_m(s)$, where $G_m(s)$ represents the model exactly same as the actual process $G_p(s)$. However, the disadvantageous of the open-loop scheme include mismatch with process and model, and their inability to handle unmeasured disturbances $D(s)$. These drawbacks can be addressed with a feedback system, as shown in Fig. 2. Still, in case of model uncertainty, there is a need to retune the controller to ensure stability. A perfect control is mathematically achievable if the control architecture was created using an accurate model of the process (Daniel, Manfred, & Sigurd, 1986).

This idea can be demonstrated by adding and subtracting the plant model $G_m(s)$ from the feedback controller's path as shown in Fig. 3

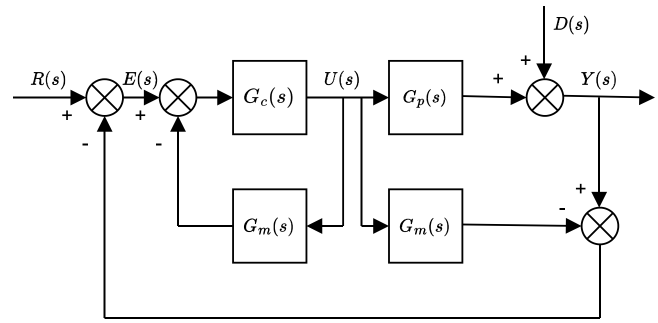


Fig. 3. Alternate representation of IMC.

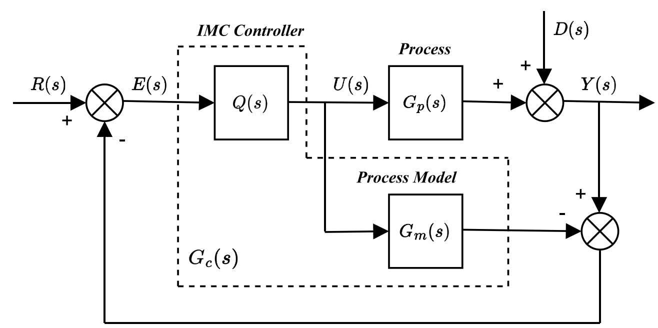


Fig. 4. A standard IMC structure.

without affecting the control and output signals. The plant model fed back to the controller, gives a new controller $Q(s)$ and it is given by

$$Q(s) = \frac{G_c(s)}{1 + G_m(s)G_c(s)}. \tag{1}$$

Now, a process model along with new controller $Q(s)$ is represented by a dash box in Fig. 4. Then, $G_c(s)$ can be written as

$$G_c(s) = \frac{Q(s)}{1 - G_m(s)Q(s)}. \tag{2}$$

To note that the classical feedback structure follows in the IMC theory. From Fig. 4, the control signal is given by

$$U(s) = \frac{Q(s)(R(s) - D(s))}{1 + Q(s)(G_P(s) - G_m(s))}. \tag{3}$$

Same way, the error signal is obtained as

$$E(s) = \frac{R(s) - D(s)}{1 + Q(s)(G_p(s) - G_m(s))}. \tag{4}$$

The above relation can easily obtain the output,

$$Y(s) = \frac{G_p(s)Q(s)}{1 + Q(s)(G_p(s) - G_m(s))}R(s) + \frac{1 - G_m(s)Q(s)}{1 + Q(s)(G_p(s) - G_m(s))}D(s). \tag{5}$$

If $G_p(s) = G_m(s)$, one can see $Y(s) \cong R(s)$, assuming $D(s) = 0$, same as for open-loop control. We can therefore understand that the IMC structure provides benefits for both closed and open-loop systems. A controller can be constructed with the simplicity of an open-loop strategy while maintaining the advantages of a feedback system. From the elaborated structure's signals, the following observations on the IMC can be noted as below.

- Dual stability: If the model is perfectly matched and disturbance is not present, the closed-loop system becomes stable, provided $G_p(s)$ and $G_c(s)$ are stable.
- Perfect control: If $Q(s) = G_m^{-1}(s)$, then the closed-loop system will always become stable.
- Zero offset: If $Q(0) = G_m^{-1}(0)$, then an offset free control will be obtained and closed-loop system will become stable. For any asymptotically constant setpoint and disturbances, there will be no offset.

3. IMC controller design procedure

The schematic of IMC scheme is shown in Fig. 4, where let us take $G_p(s)$ as unstable process to be controlled. Though such process makes the overall system unstable, the IMC can make the equivalent feedback structure stable. In the nominal scenario, the controller design using IMC method follows into four steps. In the first step, decompose the model $G_m(s)$ into two parts as in (6).

$$G_m(s) = G_{m+}(s)G_{m-}(s) \tag{6}$$

where $G_{m+}(s)$ contains all time delays and unstable zeros (non-invertible) and $G_{m-}(s)$ contains minimum phase elements (invertible). The processes with time delay should be approximated with Taylor series or Padé approximations. In the second step, one can choose the IMC controller as the inverse of the invertible portion of process model. Thus, it becomes

$$Q(s) = G_{m-}^{-1}(s). \tag{7}$$

In the third step, the filter selection is necessary to meet the robustness requirement. The filter makes the controller robust and also helps to minimize the discrepancies between plant and its model at high frequency, where mismatch generally occurs. In short, the effects of process model mismatch should be minimized using the user-specified low-pass filter. Finally, the IMC-based controller becomes

$$Q(s) = G_{m-}^{-1} f(s). \tag{8}$$

The section of filter $f(s)$ for unstable processes studied initially in Morari (1983) and Rotstein and Lewin (1991). As per the procedure developed by Morari and Zafiriou (1989), the IMC approach to designing a controller for an unstable process is possible for $G_p(s) = G_m(s)$. The following conditions, also known as standard interpolation conditions, should be satisfied for the internal stability of the closed-loop system:

- $Q(s)$ is stable.
- $G_p(s)Q(s)$ is stable.
- $(1 - G_p(s)Q(s))G_p(s)$ is stable.

The following two conditions should be satisfied to stabilize the closed-loop response.

- If the process $G_p(s)$, has unstable poles, $p_1, p_2, \ldots, p_m$, then $Q(s)$ should have zeros at $p_1, p_2, \ldots, p_m$.
- $(1 - G_p(s)Q(s))$ should have zeros at $p_1, p_2, \ldots, p_m$.

Through properly selecting the filter, the above condition could be satisfied. Let us take the filter expression

$$f(s) = \frac{\sum_{i=1}^{m} \alpha_i s^i + 1}{(\lambda s + 1)^n} \tag{9}$$

where, n is chosen to make $Q(s)$ proper (usually semi-proper) and a parameter λ is main tuning parameter in the design, which has to be chosen by the user and m is the number of the poles to be canceled. However, one can see that the higher the tuning parameter value, the higher the robustness of the controller, but the tracking speed

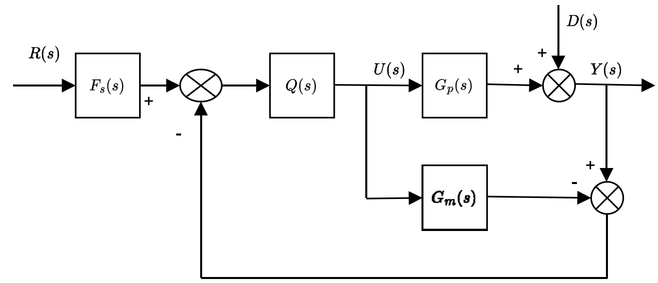


Fig. 5. IMC with SpF.

decreases. Also, the α helps in improving disturbance rejection. A value of α is found to satisfy the following condition: it helps cancel the unstable pole of $G_p(s)$. As per the IMC structure, one can write

$$[1 - G_p(s)Q(s)]_{s=p_1,p_2,\ldots,p_m} = 0. \tag{10}$$

Authors have considered the various order unstable process models. The general expression of the nth−order process can be represented, considering at least one unstable pole, as

$$G_p(s) = \frac{K e^{-\theta s}}{(\tau_1 s - 1)\Pi_{i=1}^{n-1}(\tau_i s \pm 1)} \tag{11}$$

where K is static gain, θ is time delay and τ is time constant.

The literature also found that the methods recommended include the setpoint filter (SpF) or Setpoint weighting to reduce undesirable overshoots. Because of numerator expression $\sum_{i=1}^{m} \alpha_i s^i + 1$ in (9) in filter structure causes undesirable overshoot in servo response. To eliminate the overshoot, researchers have used a low-pass filter of the form, $F_s(s) = 1/\sum_{i=1}^{m} \alpha_i s^i + 1$, Begum, Rao, and Radhakrishnan (2018), Shamsuzzoha and Lee (2008a) and Vanavil, Anusha, Perumalsamy, and Rao (2014) as shown in Fig. 5. Then, the expression of the output after adding SpF can be written as

$$Y(s) = \frac{G_c(s)G_p(s)}{1 + G_c(s)G_p(s)} R(s)F_s(s). \tag{12}$$

In some works authors added setpoint weighting technique (Kumar, Prasad, & Singh, 2020; Wang, Lu, & Pan, 2016), in which PID controller is implemented in the form of

$$u(t) = K_c \left\{ [br(t) - y(t)] + \frac{1}{\tau_i}\int_0^t [r(t) - y(t)]d\tau + \tau_d \frac{d[cr(t) - y(t)]}{dt} \right\} \tag{13}$$

where b is the weighting parameter of set-point and c denotes the weight for the derivative time constant. The range of values of these parameters lie in between 0 to 1. It is seen that the overshoot decreases upon decreasing b. After knowing the basics of the IMC principle, the following section discusses the significant IMC designs in the literature for the unstable processes with their structure and tuning approach.

4. Various IMC design methodologies

In this review article, the main emphasis is to elaborate on the situation around the unstable processes. Some unstable processes include distillation, polymerization reactors, heat exchangers, exothermic stirred reactors with back mixing, batch reactors, pump with liquid storage tanks and combined feed/effluent heat exchanger with an adiabatic exothermic reactor. Naturally, the unstable processes are challenging to deal with, and time delays experience large overshoots and settling time. In order to deal with such processes, the Smith predictor (SP) structure is very effective (Smith, 1959). The SP is a model-based controller that was effective for processes with long dead time. It has an inner loop with the primary controller that can be designed without dead time, and the outer loop corrects the effects of load disturbance and modeling error. As it is the most widely accepted dead-time compensation technique, it provides a faster response with almost no overshoot for most processes. Another approach is helpful with IMC modified with two-degree-of-freedom control (2DOF). A 2DOF PID controller can fast disturbance rejection without a significant increase of overshoot in setpoint tracking as it has two controllers, one for setpoint tracking and another for disturbance rejection. It is also recommended for unstable processes with time-delay (Huang & Chen, 1997). The application of IMC could be seen in most cascade controller designs, in which the IMC controller in the inner loop helps simplify the design and discard the amount of disturbances entering the secondary loop.

Let us consider the progression of IMC for unstable processes. A simple PID was developed on the IMC concept for the unstable plant based on gain uncertainty (Rotstein & Lewin, 1991). However, it does not perform well significantly. Some modifications using the Maclaurin series combined with a setpoint filter (SpF) helped reduce overshoot for integrating and unstable processes (Lee et al., 2000). Then, Wang, Bi, and Zhang (2001) developed a concept of partial IMC to remove the unstable pole by selecting damping factor, ζ and natural frequency, ω_0 as design parameters. Further, it was improved by Yang, Wang, Hang, and Lin (2002) with a feedback controller. A SpF was also added to eliminate the overshoot and made this technique automatic for online tuning. By using a complex design method (Tan, Marquez, & Chen, 2003), three compensators were added to the IMC structure. This approach was beneficial for unstable delayed processes. A PID filter structure from the IMC principle is applied in Shamsuzzoha and Lee (2008a). But, only one tuning parameter is determined by the time constant and delay. It could result in worse outcomes during mismatch conditions. The SpF is also added to remove the overshoot in the servo response. Further, the IMC-PID tuning rules were designed using Laurent series expansion (Panda, 2009) and the 2DOF-IMC (Wen & Caifen, 2010) in order to improve robust performance. These methods have shown good responses for a class of unstable processes but are not suitable for processes with two unstable poles or large time-delay.

Further modification enhanced the 2DOF-IMC structure for unstable and integrating processes with slow dynamics (Liu & Gao, 2011). It shows better load disturbance rejection as it allows different optimization for load disturbance rejection. Nasution, Jeng, and Huang (2011) developed an IMC-PID controller based on H_2-optimal law and using Maclaurin series. It enhanced setpoint tracking with additional weighting parameters for both proportional and derivative actions. However, the tuning steps employed two desired closed-loop transfer functions to follow; thus, it is not easy to handle. Shamsuzzoha and Lee (2012) presented a generalized IMC-PID tuning with optimal filter for a wide range of lag-time constant to time-delay. However, when the unstable model's time delay to time constant ratio is greater than 1.2, the PID cannot deliver a stabilized response. Anusha and Rao (2012) demonstrated further extension but used the Maclaurin series again. Then it is shown using a lead–lag filter, the IMC can perform better than classical IMC (Vanavil et al., 2014). In this approach, the systematic analysis was carried out to select the tuning parameter based on maximum sensitivity and checked ISE values. Though the output was improved, the method could not handle large time-delay processes. The maximum sensitivity criteria were further utilized with a SpF in Shamsuzzoha (2014). The setpoint tracking controller was developed using the direct synthesis approach, and the IMC-PID controller for disturbance rejection was designed with 2DOF structure and modified SP by Yin, Gao, and Sun (2014). As per recent research on a fractional-order controller, 2DOF with the fractional filter was presently firstly by Titouche, Mansouri, Bettayeb, and Al-Saggaf (2015). Interestingly, the approach started taking the benefit of an extra degree of the freedom tuning parameter. Based on robustness, there is a frequency relation in which time constant related to phase margin (ϕ_m) and fractional-order in a filter related to crossover frequency (ω_c). Again, the previous methods are modified around IMC structure with or without SP delay compensation.

Another approach was used in the IMC technique with sliding mode control (SMC). It is a robust variable structure method. A new strategy, namely, SP-based sliding mode control (SP-SMC) for unstable processes with time-delay was developed in Mehta and Rojas (2015). The method has used optimization to satisfy the required control performance indices. Such a hybrid control method has returned better robustness to process dynamics changed but may experience a chattering issue. A new IMC-PID tuning method was developed for stable and unstable processes with time delay by implementing pole-zero conversion, and a first-order lead–lag compensator (Wang et al., 2016). Again the setpoint weighting (SpW) was used to reduce the undesirable overshoot. Begum, Rao, and Radhakrishnan (2016) developed analytical tuning rules using H_2 norms for IMC-PID. Further, the method was studied (Begum et al., 2018; Begum, Rao, & Radhakrishnan, 2020) using optimal H_2 minimization for one right half plane pole and dead-time. These methods however, required some assumptions on pre-filter parameters. Kumar et al. (2020) studied the unstable second-order time-delay system. A SpW parameter required to choose in order to handle undesirable overshoot. Recently, a simple tuning method for unstable lag-dominated first-order process with dead-time was proposed in Karan and Dey (2020). To be noted that the scheme was developed similar way with IMC-PI and SP for setpoint tracking and additional PD controller for disturbance rejection.

Several IMC-PID methods could be seen for single-input single-output (SISO) processes. Generally, most industrial processes are multi-input multi-output processes (MIMO), which is very difficult because of more control loops and the coupling effects. If the system is unstable, it will be more challenging in design. During the earlier periods, Zafiriou and Morari designed an IMC design procedure for MIMO processes (Zafiriou & Morari, 1991). In recent work, the unstable multivariable systems have been controlled using the decentralized and centralized PI, and the IMC principles (Besta & Chidambaram, 2017). Several IMC related works are also available in literature (Dasari, Kuncham, & Rao, 2016; Pandeya, Deyb, & Banerjeeb, 2021). Recently, a new double-loop control technique was presented by Pulakraj and Lloyds (2022) for integrating and unstable with dead time processes. Using the Routh stability and IMC procedure, the initial settings of the inner and outer-loop controllers were calculated, respectively. It also required following an optimization routine to minimize the integrated squared error in finding the optimal values of the parameters. However, the simulated result was observed with more control efforts than the previous reported method.

A recent development in PID says that fractional-order derivative and integral may provide significant results for future control domains (Kothari, Mehta, & Prasad, 2019). Researchers are focusing on fractional-order PID (FOPID) controllers to improve the closed-loop response of time-delay systems. The first occurrence of fractional-order controller was done by Oustaloup (1991) who introduced Commande Robuste d'Ordre Non Entire (CRONE) controller, which is a non-integer-order robust controller. Podlubny proposed the FOPID controller (Podlubny, 1999). The two more tuning parameters ρ (fractional integrating order) and μ (fractional differential order) in FOPID compared with traditional PID help add more flexibility to control design. Then, the transfer function of FOPID is, $G_c(s) = K_p + \frac{K_i}{s^\rho} + K_d s^\mu$, where ρ and μ are the real positive orders for integration and differentiation, respectively. Most common interval of real (fractional) order is limited in the range (0, 2) (Yüce, Tan, & Atherton, 2016). The combination of IMC and FOPID has also proven significant (Saxena & Hote, 2022). One such work (Rayalla, Ambati, & Gara, 2019) shows an improved analytical design of the fractional filter IMC-PID for the noninteger (fractional) processes. In other work, designing FO-IMC based on the frequency domain approach is presented to satisfy desired gain, and phase margins (Arya & Chakrabarty, 2020). However, the method is limited to stable plants. Later, a new double-loop control approach is

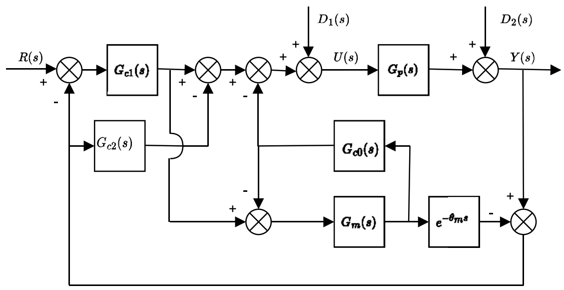


Fig. 6. Scheme proposed by Tan et al. (2003).

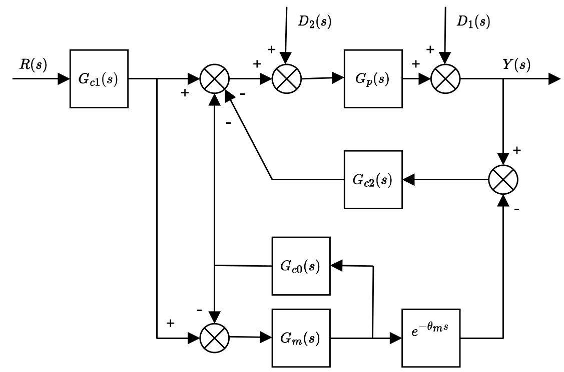


Fig. 7. Scheme proposed by Liu et al. (2005).

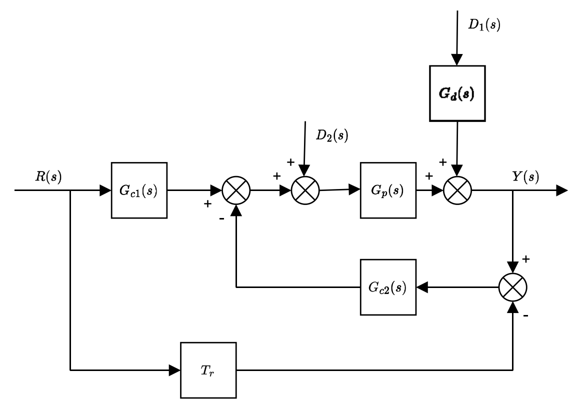


Fig. 8. Scheme proposed by Liu and Gao (2011).

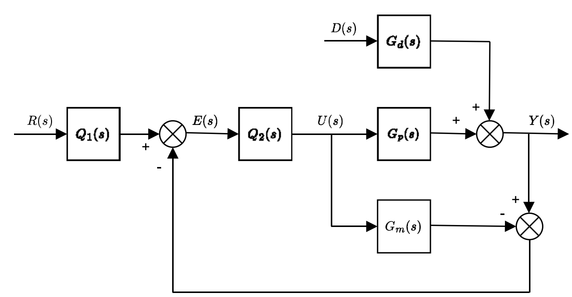


Fig. 9. Scheme proposed by Nasution et al. (2011).

proposed for a time-delayed unstable system that uses a PD/P controller in its inner loop, and a fractional-order internal model controller (FOIMC) in its outer loop (Kumari, Aryan, & Raja, 2021). Later on, authors developed a novel dual-loop hybrid control method for second-order unbounded plants with dead-time and zeros (Shweta, Pulakraj, Deepak, & G. Lloyds, 2022). The external-loop controller is designed using the FOIMC technique, whereas the internal-loop controller is still the PID. A dual loop controller is designed based on fractional-order using a frequency-shifted version. It obtained an overall good performance compared to previous methods (Kumar & Raja, 2022). To note that Routh–Hurwitz criterion was used to construct the internal-loop PD setting together required to check ITAE value. In another work, dead-time, compensator-based series cascade control using FOIMC was proposed for unstable processes (Mukherjee, Raja, & Kundu, 2020). Recently, a series cascaded controller was designed with fractional theory order for large dead time unstable processes (Chandran et al., 2020). In this approach, the inner loop consists of FOIMC, and the outer loop consists of FOPI-FOPD controllers. It shows superior performances compared to recent studies, however it considered more number of tuning parameters.

In order to see the journey of IMC and its strategy for unstable processes, Table 1 is summarized with various structures and tuning support. It has been noticed that most approaches depend on the maximum sensitivity index (M_s) as a primary tuning principle. A very few are using the phase- and gain margins. Recently, metaheuristic algorithms are being used for obtaining the optimal tuned parameters from the various performance measures. The major IMC structures with respect to unstable processes are presented in the following section.

5. Various IMC structures

Several structures have been proposed for unstable and integrating processes, especially the plant with time-delay, which brings more challenge in controlling. In some cases, the 2DOF helps in avoiding the deficiencies associated with setpoint tacking. Since the extra degree of freedom can give an advantage to tune independently for tracking and disturbance rejection. Especially for unstable process, the standard 2DOF structure cannot guarantee internal stability. So, the performance should be improved by changing the structure, for example IMC with SP techniques. Tan et al. (2003) presented the improvement in both setpoint tracking and disturbance rejection by modified IMC. As seen Fig. 6, the modified IMC structure had three controllers namely, $G_{c0}(s)$ for stabilizing the original unstable plant, $G_{c1}(s)$ as IMC controller for setpoint tracking and $G_{c2}(s)$ for load disturbance rejection. To note that $G_m(s)$ is modified without delay. Later same authors improved the design by introducing tuning based on structured singular value (SSV) and robustness measure (Wen & Caifen, 2010). The method was limited with a single unstable pole model. The response is improved by good setpoint tracking and load disturbance rejection, but the main drawback is the complexity of adding additional controllers with more control signal variations

For further enhancing the performance, Liu, Zhang, and Gu (2005a) proposed analytical design procedure for the structure as shown in Fig. 7. Again this method used three controllers, $G_{c0}(s)$ for stabilizing, $G_{c1}(s)$ for setpoint and $G_{c2}(s)$ for disturbance thus adding more number of controllers and adding more complexity in the design. After the structure was modified with less number of controllers as shown in Fig. 8 (Liu & Gao, 2011). In this scheme, $G_{c1}(s)$ was used as feedforward controller and $G_{c2}(s)$ as feedback controller for load disturbance rejection. However, the additional transfer function T_r was added for better setpoint tracking. Even though that method shows good performances, it is highly depended on a single tuning parameter.

Another design was presented using 2DOF IMC as seen from Fig. 9 (Nasution et al., 2011). In this method, two IMC controllers were used, $Q_1(s)$ for setpoint tracking and $Q_2(s)$ for disturbance rejection. If $Q_1(s) = 1$, the method reduces to 1DOF structure. The tuning was developed using H_2 optimal control law and Maclaurian series expansion. To note that due to the performance limitations, the SpW parameters included on the basis of 2DOF. It showed improved performance over

Table 1
Various IMC approaches for unstable processes.

Ref.	Year	IMC structure and its variants	Figure Ref.	Primary tuning principle	Total controller+filter
Pulakraj and Lloyds (2022)	2022	IMC	14	ISE index, Equilibrium optimizer algorithm	2
Kumar and Raja (2022)	2022	FOIMC-PD	15	ITAE index	2
Shweta et al. (2022)	2022	FOIMC	16	Coefficient matching technique	2
Kumari et al. (2021)	2021	FOIMC-PD/P	14	M_s	2
Li, Xu, Zhang, Hongbo, and Furong (2020)	2020	2DOF-IMC	11	Analytical approach	3
Ahmadi, Nikravesh, and Moradi (2020)	2020	IMC+SP, SpF, SpW	12	M_s	3
Pashaei and Bagheri (2020)	2020	Parallel cascade IMC+SP	20	Adams Bashforth Moulton algorithm	3
Mukherjee et al. (2020)	2020	Series cascade IMC+SP, FOIMC	18	Artificial Bee Colony algorithm	3
Begum et al. (2020)	2020	IMC, lead–lag filter	4	M_s	2
Kumar et al. (2020)	2020	IMC, SpW	4	M_s	2
Chandran et al. (2020)	2020	Series cascade, FOIMC -secondary, FOPI-FOPD-Primary	17	M_s	3
Karan and Dey (2020)	2020	IMC+SP	13	Random	3
Dasari, Chidambaram, and Seshagiri (2018)	2018	IMC, SpW	4	M_s	1
Begum et al. (2018)	2018	IMC, Set-point filter	5	M_s	2
Ranganayakulu, Babu, and Rao (2017)	2017	IMC	4	λ (random), β (ISE, IAE)	2
Besta and Chidambaram (2017)	2017	IMC	4	Analytical technique	1
Begum, Rao, and Radhakrishnan (2016)	2016	IMC	4	M_s	1
Wang et al. (2016)	2016	IMC, SpW	4	M_s	1
Raja and Ali (2016)	2015	Parallel cascade IMC+SP, PI-PD primary	19	M_s	3
Titouche et al. (2015)	2015	2DOF-IMC	10	ϕ_m, w_c	3
Vanavil et al. (2014)	2014	IMC, lead–lag filter	5	M_s	2
Shamsuzzoha (2014)	2014	IMC, SpF	5	M_s	2
Anusha and Rao (2012)	2012	IMC	5	M_s	1
Shamsuzzoha and Lee (2012)	2012	IMC, SpW, SpF	5	M_s	2
Nasution et al. (2011)	2011	1DOF-IMC, SpW	9	ISE index	1
Liu and Gao (2011)	2011	2DOF-IMC	8	Analytical approach	3
Wen and Caifen (2010)	2010	2DOF-IMC	6	$\mu_{\Delta}(M)$	3
Panda (2009)	2009	IMC	4	As per model parameters and M_s	1
Shamsuzzoha and Lee (2008a)	2008	IMC, lead–lag filter, SpF	5	M_s	3
Liu, Zhang, and Gu (2005b)	2005	2DOF-IMC	7	ISE index	3
Tan et al. (2003)	2003	IMC, SP	6	Analytical approach	3
Yang et al. (2002)	2002	IMC	5	Recursive least squares algorithm	1
Wang et al. (2001)	2001	IMC	5	ζ and ω_o	2
Lee et al. (2000)	2000	IMC, SpF	5	Analytical approach	2

preceding methods, but again having more complex tuning. Titouche et al. (2015) suggested 2DOF structure again, as seen in Fig. 10, where an integer order controller is utilized to stabilize the inner-loop first and a fractional-order controller to improve performance. However, there is scope for investigating choosing the non-integer parameter.

A modified type of 2DOF-IMC control structure has been proposed by Li et al. (2020) as shown in Fig. 11. The system consists of two loops. One loop for ensuring stability of unstable process and the other loop possess 2DOF. It consists of a feedforward controller G_{c1} which is designed based on IMC principle and only single tuning parameter. While $G_{c2}(s)$ is used for disturbance rejection which is designed based on direct synthesis (Li et al., 2020). Recently, the filtered SP approach was proposed by Ahmadi et al. (2020) and seen in Fig. 12. This method used the IMC based PI/PID tuning technique, considering also only a single tuning parameter. In addition, it was implemented with SpW method and extra $F_r(s)$ predictor filter was suggested to enhance the quality of prediction. To note that the filter $F_s(s)$ was also required for better setpoint tracking.

Sometimes the single loop control will not give the desired performance, for instance, the system having large time-delays and strong disturbances. In such case, the SP is an effective tool for a time delay process. However, the original SP itself is not applicable for unstable processes. When applied to very unstable systems with high time delays, many of these control design strategies do not, however, produce satisfying outcomes. For the controller design, a number of published methods utilized two or more control loops, such as the modified SP. The limited research has been carried out with IMC design together SP structure for unstable processes. In one of the recent works by Karan and Dey (2020), the IMC based modified SP structure was presented as shown in Fig. 13. To note that there were three controllers used for stabilizing, setpoint and disturbance rejection. The main $G_{c1}(s)$ was designed from a single tuning parameter. To get the final desirable steady-state value, this method may need more efforts. It has been established that double-loop control is superior for managing unstable processes. It gives design engineers more flexibility by enabling the controller parameters to be aggressively built against certain disturbances and obtained appropriate tracking behavior. In the latest work by Kumari et al. (2021) and Pulakraj and Lloyds (2022), the inner-loop stabilized the plant while the outer-loop helped to achieve the desired setpoint. The same type of structure, where the inner-loop is created using the Routh–Hurwitz criterion and the outer-loop controller is designed using the IMC principle, as shown in Fig. 14.

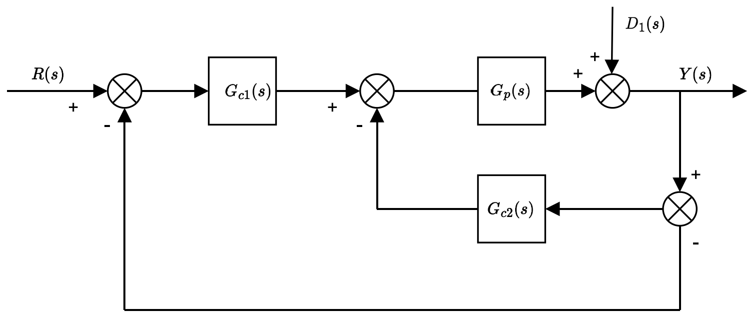


Fig. 10. Scheme proposed by Titouche et al. (2015).

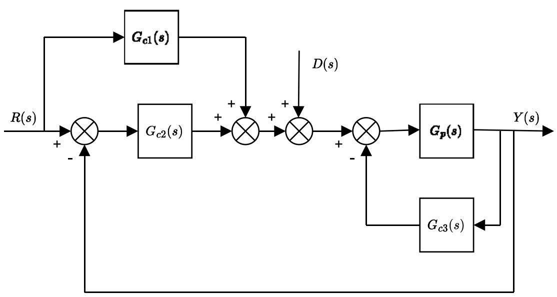


Fig. 11. Scheme proposed by Li et al. (2020).

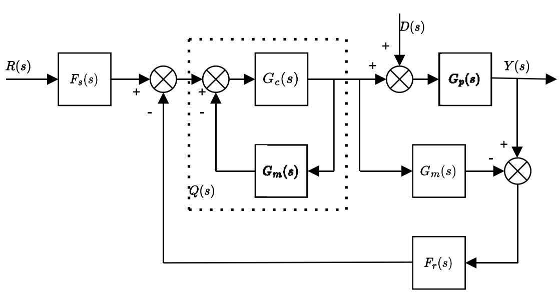


Fig. 12. Scheme proposed by Ahmadi et al. (2020).

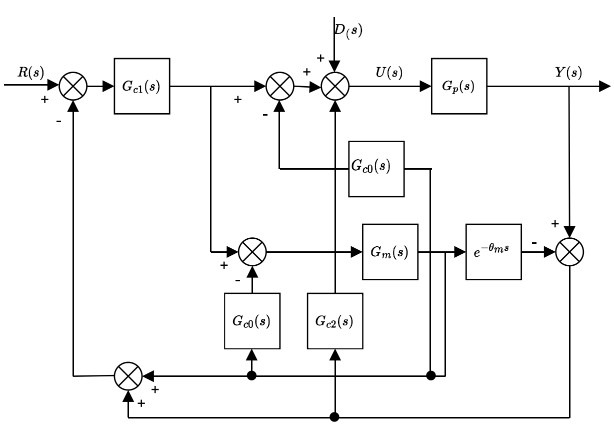


Fig. 13. Scheme proposed by Karan and Dey (2020).

To achieve a sufficient servo response, authors Kumar and Raja (2022) have created an external-loop controller utilizing a modified indirect FOIMC technique as shown in Fig. 15. Again, the internal-loop PD was developed from the Routh–Hurwitz and ITAE. For second-order unbounded time-delayed plant models with positive/negative zero, a novel dual-loop hybrid control technique was provided in Shweta et al. (2022) as per structure in Fig. 16. Here, a PID is suggested for the internal loop, while a FOIMC for an external loop. These two structures resulted in improved output, but the control signal variation was higher than the previously reported methods. In general, it is observed that the internal-loop controller can be used to stabilize the unstable plant, and the outer-loop is finally looked into the stabilized plant.

5.1. IMC scheme in cascade processes

In some application areas, the cascade structure is more applicable such as controlling temperature, flow and pressure. The IMC scheme was also incubated in the cascade structure. In general, this structure consists of primary (master) and secondary (slave) loops. The disturbances introduced in the inner loop are reduced to great extent in secondary loop itself, before entering the outer loop. This helps in faster disturbance attenuation. The normal feedback control during unstable process control may not give the desired result with large time delay. It was found in the literature that the dead time compensation like SP and IMC in the inner loop may handle the disturbance input effectively. Such approaches in cascade control strategies have been discussed by several authors, for example, Begum, Radhakrishnan, Chidambaram, and Rao (2016), Bhaskaran and Rao (2020), Dasari, Alladi, Rao, and Yoo (2016), García, Santos, and Normey-Rico (2010), Kaya and Atherton (2008), Lee and Oh (2002), Liu et al. (2005b), Padhan and Majhi (2012), Uma, Chidambaram, and Rao (2009), Yin, Wang, Sun, and Zhao (2019) and recently Begum (2016). There were two different cascade types studied namely series cascade and parallel cascade. In parallel control, the control signal and disturbance simultaneously affect the primary and secondary outputs. Whereas in series connection, first they affect a secondary loop and then a primary loop. A recent work by Chandran et al. (2020) suggested a fractional IMC for the inner loop and then, an outer loop was designed with FOPI-FOPD controllers. The presented scheme is given in Fig. 17. To be noted that such idea may require more tuning parameters and complex design steps. Mukherjee et al. (2020) also developed three controllers method as seen in Fig. 18. This scheme has the SP with IMC, having three different controllers for stabilizing, setpoint and disturbance compensation. The primary and secondary controllers were designed using a fractional-order IMC approach. The IMC technique in the parallel cascade structure can be seen in Fig. 19 (Raja & Ali, 2016). Another type of structure seen in Fig. 20, where the authors implemented the advantage of SP with IMC along with a fractional theory for designing disturbance and setpoint tracking controllers (Pashaei & Bagheri, 2020).

So far we have seen different types of modified IMC structures, including cascade IMC and SP-IMC. The limitations of these structures include: (a) complexity in design due to multiple controllers and parameters, (b) disturbance rejection is poor for large time delay, and (c) multi-loop often creates stability issues and is difficult to employ in practice. The new research scope can be seen by developing the method to be simple, less tuning parameters and easy to adopt in industries. Having the scheme with more than two controllers would be complex in real cases. There is a need to check the load rejection performance with optimal input usage.

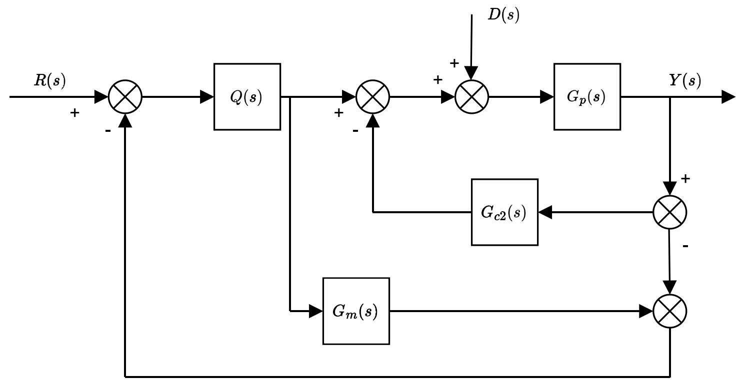


Fig. 14. Scheme proposed by Kumari et al. (2021).

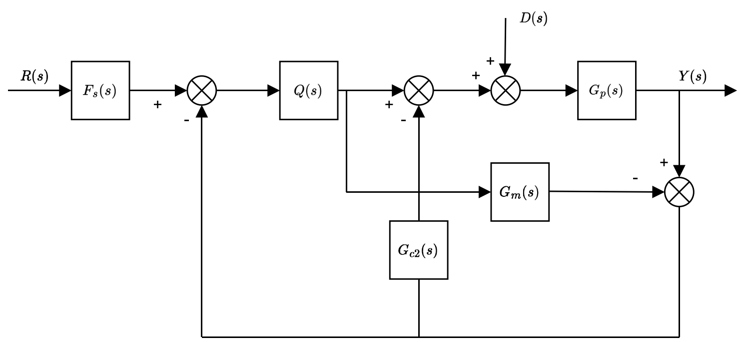


Fig. 15. Scheme proposed by Deepak et al. (2022).

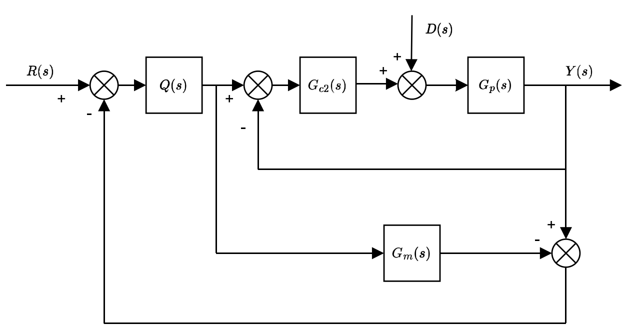


Fig. 16. Scheme proposed by Shweta et al. (2022).

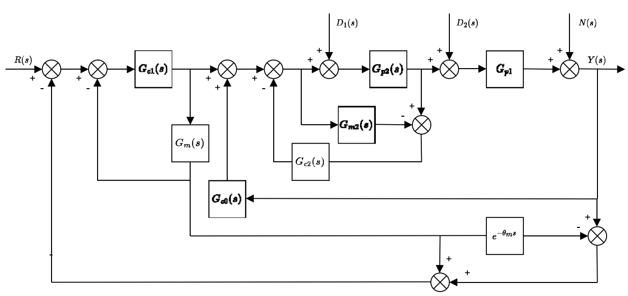


Fig. 18. IMC cascade scheme by Mukherjee et al. (2020).

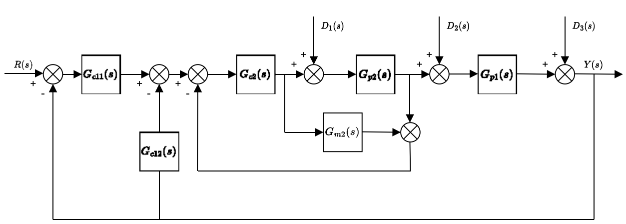


Fig. 17. IMC cascade scheme by Chandran et al. (2020).

5.2. Applications of IMC structures in real time

The performance of the IMC theory, specifically on unstable time delay processes, is being noticed in the literature. However, most previously reported works had been seen with numerical simulations. Some have verified the laboratory applications with their new principles and control methods. The unstable inverted pendulum system was investigated using FOIMC with PID in real-time (Ranganayakulu et al., 2017). It is also used to verify the real-time use of the tuned approach proposed in Begum et al. (2018). The application was proven to offer better responses. When controlling the temperature of a continuous stirred tank reactor during a first-order irreversible exothermic process, the control strategies in Kumar and Raja (2022) maintained the desired temperature and rejected changes in the presence of measurement noise. It is to note that researchers from theoretical assessments shall investigate some more field applications.

5.3. Various IMC filters proposed in the literature

Literature presented with modification in IMC structure with the filter transfer function. The most common filter structures are Type 1 and Type 2 as below.

$$\text{Type 1}: f(s) = \frac{1}{(\lambda s + 1)^n} \tag{14}$$

and

$$\text{Type 2}: f(s) = \frac{n\lambda + 1}{(\lambda s + 1)^n}. \tag{15}$$

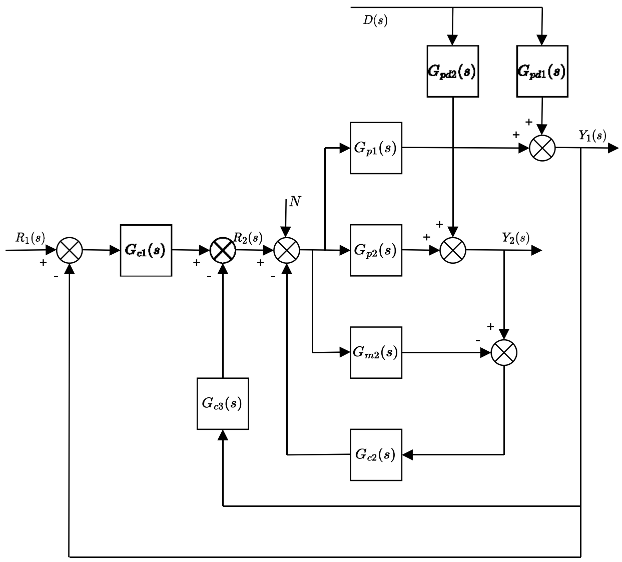


Fig. 19. IMC cascade scheme by Raja and Ali (2016).

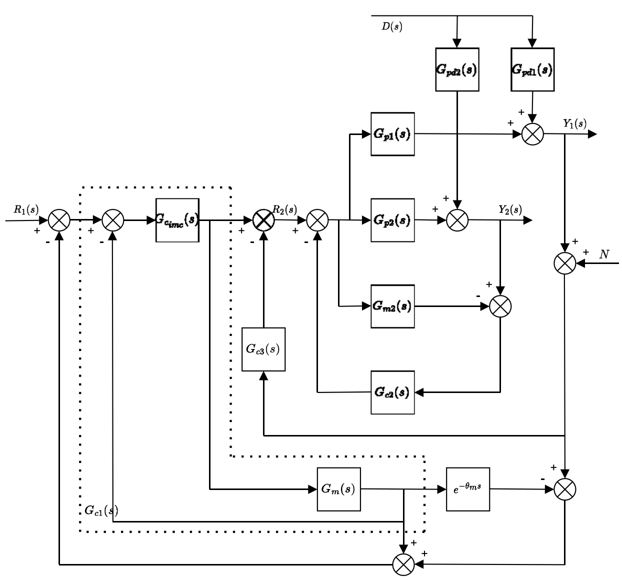


Fig. 20. IMC cascade scheme by Pashaei and Bagheri (2020).

The more generalized form (Lee et al., 2000) was presented as below.

$$\text{Type 3}: f(s) = \frac{1}{(\lambda s+1)^n}\frac{\sum_{i=1}^{m}\alpha_i s^i + 1}{(\lambda s+1)^m}. \tag{16}$$

Here n is chosen to make controller realizable and m represents the number of unstable poles to be canceled. It is required to tune λ as per the desired performance. The simple Type 1 filter, is used in the latest work and tuning parameter obtained using equilibrium optimizer algorithm (Pulakraj & Lloyds, 2022). The Type 3 filter structure was modified with adding higher terms, but a good response seen than other works developed that time. Another modification was presented in Yang et al. (2002) for a IMC filter. As seen before in (9), the Type 4 structure is,

$$\text{Type 4}: f(s) = \frac{\alpha s+1}{(\lambda s+1)^{n+1}}, \tag{17}$$

where n is again a positive integer to guarantee controller realizable. To note that such filter still has only one tuning parameter λ. It is responsible for satisfying the desired performance. It is also necessary to define a range of λ for robust stability.

In a particular case, Authors Shamsuzzoha and Lee (2008a) suggested the same form of filter structure (16), with less complexity. The tuning parameter λ was selected from knowledge of θ/τ_1 (the ratio of time delay over time-constant). Therefore, such filter form has more flexibility and ability to obtain the robustness in the system. Then after, the filter structure in (18) was suggested for first-order dead time unstable process (FODUP) and second-order dead time unstable process (SODUP) (Panda, 2009).

$$\text{Type 5}: f(s) = \frac{\sum_{i=1}^{m}\alpha_i s^i + 1}{(\lambda s+1)^n} \tag{18}$$

For ease in selection of λ, firstly it was suggested following rules in Luyben (1998). The Type 2 filter in Nasution et al. (2011) was tuned for the IMC-PID through robustness measures. It has been found that the traditional approach for IMC filter design was simply to find the optimal PID controller. However, it was highly depended on dead time approximation and model approximation error.

Authors in Shamsuzzoha and Lee (2012) also suggested Type 6 filter with different orders. The parameters were obtained from the desired maximum sensitivity. However, their method also considered the SpW and SpF to make the overall response comparable.

$$\text{Type 6}: f(s) = \frac{(\alpha s+1)^m}{(\lambda s+1)^n}. \tag{19}$$

Similarly, in Anusha and Rao (2012) and Shamsuzzoha (2014), Type 3 filter's constant was obtained from the maximum sensitivity value, M_s. Some cases the authors considered additional measures to decide the optimal value of parameters such as IAE and TV. Like the Type 5 filter in Dasari et al. (2018) was developed from the IAE and TV indices.

Furthermore, the modified IMC using SP and 2DOF structures have shown a remarkable result for unstable processes. Same way the lead–lag filter was introduced in order to further improved the result. In Vanavil et al. (2014), the IMC structure was presented with PID in series with lead–lag filter. Any filter even with one tuning parameter and systematic guidelines may help for better performances. The Type 2 filter in Begum, Rao, and Radhakrishnan (2016) simplified as PID from the derived relation with M_s value. Same filter was used in Wang et al. (2016) for a class of stable and unstable plants and tuning formulas were suggested with relation to time delay and time constant. A filter Type 5 in (18) with different orders ($m = 2, n = 4$) was used in Kumar et al. (2020). Again the method developed with M_s performance index. Furthermore, the under-damped IMC filter (Begum et al., 2018, 2020) was presented to improve the reset action and to reach desired setpoint smoothly. Such filter transfer function is shown as below.

$$\text{Type 7}: f(s) = \frac{(\alpha s+1)^m}{(\lambda^2 s^2 + 2\zeta\lambda s + 1)(\lambda s+1)^n}. \tag{20}$$

To be noted that the filter parameter λ in (20) has to be selected between 0.6 and 0.8. Together it is required to select M_s as constraint with the lower bounds of gain and phase margins, suggesting for proper selection of λ parameter. In this filter, ζ was set to 0.7 to make better reset action. In Begum et al. (2020), they considered robustness measures such as IAE and TV.

All previous filters were classical integer-order, easy to implement but had some limitations. Say for example, it is very sensitive to variation in time constant and even small variation can result in instability. Also, it may affect the reaction time of the output with the input change. The fractional filter has isodamping robustness property and more degrees of freedom in order to meet the specifications. Some authors have recently adopted a fractional theory into filter transfer function. With addition of fractional-order in filter structure, one can get one more degree of freedom to tune the responses. Obviously, it is not easy to implement or realize the fractional-order transfer function. In Titouche et al. (2015) the fractional-order filter design was proposed firstly using IMC method for unstable process and performance checked using IAE. The technique was employed the 2DOF structure with the fractional filter of the form,

$$\text{Type 8}: f(s) = \frac{1}{(\lambda s^{\beta+1}+1)^n}. \tag{21}$$

In this filter, λ is positive real number and β is noninteger positive number. The stability of IMC controller was shown through stability of fractional filter. The Walton–Marshall's method, is used to establish the internal stability condition of the closed-loop system, specifically the fractional part of the controller. Then, the IMC-PID with fractional filter (Titouche et al., 2015) was presented for unstable time delay process. Similarly, a fractional IMC filter consisted of two tuning parameters, λ and β (Ranganayakulu et al., 2017) was given as

$$\text{Type 9}: f(s) = \frac{1}{(\lambda s^{\beta}+1)^n}. \tag{22}$$

Both variables are chosen separately, λ should be taken as the smallest of the process time constant and β should satisfy least square performance indices (ISE and IAE). Considering $n = 1$, Type 9 filter was used recently in Kumar and Raja (2022) and Kumari et al. (2021). Note that a fractional parameter was considered to be fixed and from performances with rising time, settling time and robust behavior, the λ was selected. The systematic assessment with fractional-order β is yet to be explored in the research.

In summary, the benefits of IMC and variants in a filter form have been studied for claiming various controlling benefits. Also, it has started to apply in cascade control schemes recently. Overall, the IMC proved a robustness and superior almost all control purposes. The most common filter in all was Type 1 with only one tuning parameter. As per recent trends, researchers have focused on fractional theory, as seen from Type 8 and −9 filters. In Chandran et al. (2020), Pashaei and Bagheri (2020), the secondary controller was designed from the fractional-order IMC and those methods provided obviously more flexibility in the design. The various filter forms for unstable processes are now summarized in Table 2 for easy understanding to subject researchers.

5.4. IMC filter parameter selection

The IMC filter in unstable plant is critical to decide the stable output. For the case of stable plant, a lower value of λ can offer a fast response with better disturbance rejection. Though some works have verified with large value of λ and obtained robust controller. The most methods suggested to choose the value from plant model's parameters such as delay and time constant. However, it is not always true in the unstable scenario. In Anusha and Rao (2012), the M_s versus λ plot was presented especially for integer-order filter. It is noted that there are two values resulted for same M_s. The result may be poor or less robust if it is chosen before the maximum as per the relation. The literature such as Begum et al. (2018, 2020), Kumar et al. (2020) and Vanavil et al. (2014) have adopted same method with M_s.

The graphical analysis for numerous process models was presented for range of θ/τ_1 values in Shamsuzzoha and Lee (2008a). This was effective to choose a tuning parameter. Authors suggested different robustness levels with M_s over wide range of θ/τ_1. In recent work Titouche et al. (2015), the fractional-order degree was used to establish stability condition using the Walton-Marshall approach. The explicit relation is obtained as given in first row of Table 3. The similar approach proposed by Yang et al. (2002) for integer filter. It is seen in most cases, θ and τ_1 are used to calculate the filter time constant. To achieve the appropriate level of robustness, the explicit formulae used to calculate the adjusting parameter, λ (Wang et al., 2016). The direct selection rule was given as $\lambda = 2\min(\theta, \tau_1)$. In Dasari et al. (2018), λ was selected from a given M_s and values of IAE and TV measured. The tuning parameter expressions are listed concisely in Table 3. In general, it is necessary developing a new method for selecting the tuning parameter of IMC filter together fractional type.

6. Performance assessments

In this section, we have selected various IMC strategies from the literature for numerical assessments. In order to verify the effect of filter type and IMC schemes, we have simulated one most studied example and compared the performances. The parameters like overshoot (O_v), settling time (t_s, s), ITSE and TV are calculated to comment on structure and filter function.

6.1. Considering modified IMC structures

Here we have considered three IMC structures from Karan and Dey (2020), Shamsuzzoha and Lee (2008b), Tan et al. (2003) and Wang et al. (2016) for the example below:

$$G_p(s) = \frac{e^{-0.4s}}{s-1} \tag{23}$$

The outputs are plotted in Fig. 21. A negative disturbance signal of magnitude 0.5 was inserted at 10 s. For the reference, the controller settings and assessment measures are tabulated in Table 4. As per numerical analysis and output plots, the three controller's method (Karan & Dey, 2020; Tan et al., 2003) proved the better output in setpoint tracking, but obviously it is complex in tuning. The method by Wang et al. (2016) has shown the balance results with less number of tuning parameters. It can be understood that the proper tuning method in IMC approach can result in better outcomes, even with less controllers.

6.2. Considering different IMC filter structure

Begum et al. (2020), Kumari et al. (2021) and Panda (2009) have adopted the same IMC structure, but a different IMC filter. Let us consider an unstable first-order plant with time delay as,

$$G_p(s) = \frac{4e^{-2s}}{4s-1} \tag{24}$$

In both works Begum et al. (2020) and Panda (2009) the parameter was tuned from M_s. Here authors used same controller structure for tuning, but with different filter structure namely Type 9, Type 7 and Type 5. If we observe the results from Fig. 22, one can easily distinguish the difference. A disturbance signal of magnitude 0.1 was inserted at 60 s after the output regained the steady state. From numerical values measured as Table 5, the poor performance is concluded from Begum et al. (2020), having higher order filter transfer function, but the setpoint tracking shows significant improvement in Kumari et al. (2021) with less TV. The performance is comparatively better with fractional IMC controller.

7. Some challenges and future motivations

The control of the unstable process is challenging, and tremendous efforts may need to stabilize them. The survey conducted in this paper states that IMC-based approaches either require a tedious mathematical burden or the control structure (undoubtedly the fractional-order version) is complex. Though the multi-loop solution outperforms, it often creates stability issues and sometimes requires more effort to employ in practical applications. In practice, simple control schemes are more feasible. It was noted in every IMC scheme, the issue may come with mismatch at high frequency. Therefore, even with FOIMC design a low-pass filter should be added to make the controller versatile. It is vital to note from the review that almost all fractional-order control strategies have followed a hit and trial approach to select the fractional-order parameters. A simple and user-friendly control approach is still missing, particularly for industrial personnel. As far as the IMC-based approach is concerned, if it is applied, then there is no ready-made formula for λ tuning, and in return, the controller parameters are difficult to set. In most cases, the λ tuning relies on the approximation approach, and these approaches create complexity when the system is marginally

Table 2
Various filters in IMC strategies.

Reference	Year	Filter model	Order	Remark
Lee et al. (2000)	2000	Type 5 $\vert_{m=1,n=1}$, Type 5 $\vert_{m=2,n=2}$	2, 4	2/2 Pade Maclaurian series
Yang et al. (2002)	2002	Type 4		–
Tan et al. (2003)	2003	Type 1 $\vert_{n=1}$, Type 1 $\vert_{n=2}$	1, 2	First-order Pade
Liu et al. (2005b)	2005	Type 1 $\vert_{n=1}$, Type 1 $\vert_{n=2}$	1, 2	All pass Pade Maclaurian series
Shamsuzzoha and Lee (2008a)	2008	Type 5 $\vert_{m=1,n=3}$	3	1/2 order Pade
Panda (2009)	2009	Type 5 $\vert_{m=2,n=2}$, Type 5 $\vert_{m=1,n=2}$	2	Laurent series
Nasution et al. (2011)	2011	Type 5	2,3	Maclaurian series
Liu and Gao (2011)	2011	Type 1$\vert_{n=2}$, Type 5	2	Maclaurian series
Shamsuzzoha and Lee (2012)	2012	Type 6 $\vert_{m=2,n=3}$, Type 6 $\vert_{m=2,n=4}$	3, 4	Maclaurin series
Anusha and Rao (2012)	2012	Type 5 $\vert_{m=2,n=4}$	2,4	Maclaurin series
Shamsuzzoha (2014)	2014	Type 5 $\vert_{m=1,n=2}$	2	Taylor series
Vanavil et al. (2014)	2014	Type 5 $\vert_{m=1,n=3}$	3	1/2 order Pade
Titouche et al. (2015)	2015	Type 8$\vert_{n=1}$	Fractional-order	First order Pade Taylor series
Raja and Ali (2016)	2016	Type 1 $\vert_{n=1}$	1	First-order Pade
Wang et al. (2016)	2016	Type 5 $\vert_{m=1,n=2}$	2	–
Begum, Rao, and Radhakrishnan (2016)	2016	Type 5 $\vert_{m=1,n=3}$	3	Maclaurian series
Besta and Chidambaram (2017)	2017	Type 5 $\vert_{m=1,n=2}$	2	Maclaurian series
Ranganayakulu et al. (2017)	2017	Type 9$\vert_{n=1}$	1	–
Begum et al. (2018)	2018	Type 7 $\vert_{m=2,n=2}$	4	Maclaurian series
Dasari et al. (2018)	2018	Type 5 $\vert_{m=1,n=3}$	3	Maclaurian series First order Pade
Karan and Dey (2020)	2020	Type 5 $\vert_{m=1,n=2}$	2	First-order Pade
Chandran et al. (2020)	2020	Type 8	Fractional-order	–
Kumar et al. (2020)	2020	Type 5 $\vert_{m=2,n=4}$	4	Taylor series
Begum et al. (2020)	2020	Type 7 $\vert_{m=1,n=1}$	3	Maclaurian series Half order Pade
Mukherjee et al. (2020)	2020	Type 9 $\vert_{n=2}$	Fractional-order	First-order Pade
Pashaei and Bagheri (2020)	2020	Type 8$\vert_{n=2}$ and Type 8$\vert_{n=1}$	Fractional-order	First-order Pade
Ahmadi et al. (2020)	2020	Type 1 $\vert_{n=1}$, Type 5 $\vert_{m=1,n=2}$	1, 2	–
Li et al. (2020)	2020	Type 1 $\vert_{n=1}$	1	First-order Pade
Kumari et al. (2021)	2021	Type 9 $\vert_{n=1}$ and Type 9 $\vert_{n=2}$	Fractional-order	First-order Pade
Kumar and Raja (2022)	2022	Type 9 $\vert_{n=1}$ and Type 9 $\vert_{n=3}$	Fractional-order	Second-order Pade
Shweta et al. (2022)	2022	Type 9 $\vert_{n=1}$	Fractional-order	Taylor series
Pulakraj and Lloyds (2022)	2022	Type 1 $\vert_{n=1}$, Type 1 $\vert_{n=2}$ Type 5 $\vert_{m=1,n=3}$	1, 2, 3	First order Pade

Table 3
Various formulae for filter's parameter.

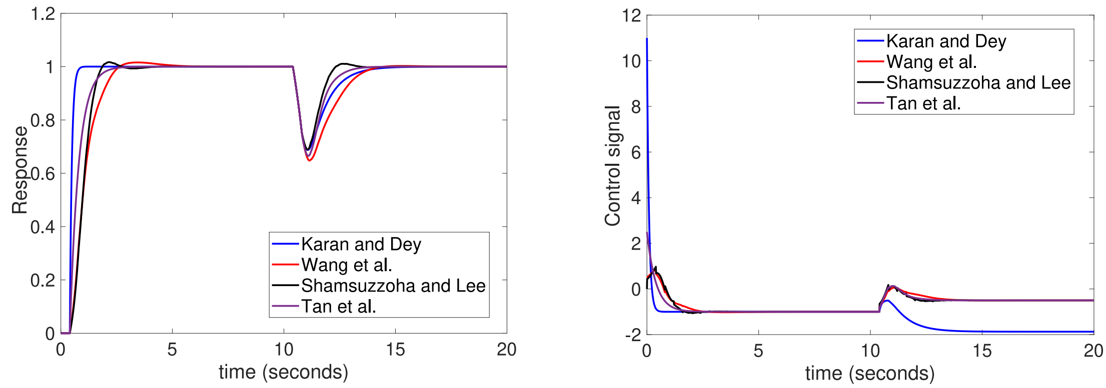
Reference	Tuning formula	Remark
Titouche et al. (2015)	$\lambda > \frac{2\sin\left(\frac{\beta\pi}{2}\right)\theta^{\beta+1}}{[(2-\beta)\pi]^{\beta+1}}$	With fractional-order
Wang et al. (2016)	$\lambda = 2\min(\theta, \tau_1)$	Direct selection
Karan and Dey (2020)	$\lambda = \theta/4$	Direct selection
Kumar and Raja (2022)	$\lambda = \theta/2.5$	For second-order plant
	$\lambda = \theta/0.8$	For first-order plant
Kaya and Atherton (2008)	$\lambda = \theta/2$	For cascaded inner loop
Dasari, Alladi, Rao, and Yoo (2016)	$\lambda = 0.4\theta - 2\theta$	For cascaded inner loop
Yin et al. (2019)	$\lambda = 0.5\theta$	For cascaded inner loop
	$\lambda = 0.5\theta - 0.8\theta$	For cascaded outer loop (setpoint)
	$\lambda = 0.5\theta - 1.5\theta$	For cascaded outer loop (disturbance)

Table 4
Performance comparison with IMC structures.

Structure	Controller	O_v	t_s	ITSE	TV	Remark
Karan and Dey (2020), Fig. 13	$G_{c1}(s) = 11 + \frac{52.38}{s}$, $G_{c2} = 5.72$ $G_{c3}(s) = 1.57 + 0.157s$	0.011	0.669	0.036	24.862	Fast settling time with improved ITSE Improved load disturbance rejection, but high TV
Wang et al. (2016), Fig. 4	$G_c(s) = 2.500(0.2R(s) - Y(s)) + \frac{2.670}{s} + 0.170s$	13.091	1.570	4.738	1.831	Optimal ITSE and low TV, but poor disturbance rejection and setpoint tracking.
Shamsuzzoha and Lee (2008b), Fig. 5	$G_c(s) = 0.461 + \frac{0.266}{s} + 0.10s$ lead–lag filter= $\frac{1+1.5779s}{1+0.1053s}$ SpF(s)= $\frac{1}{1+1.5779s}$	1.680	1.616	1.029	6.835	Better setpoint tracking and load disturbance rejection, but more tuning parameters.
Tan et al. (2003), Fig. 6	$G_{c0}(s) = 2.0$ $G_{c1}(s) = \frac{s+1}{0.4s+1}$ $G_{c2}(s) = 2.079(0.156s + 1)$	0.0	1.598	1.130	7.842	Best setpoint tracking and load disturbance rejection, better ITSE but high TV.

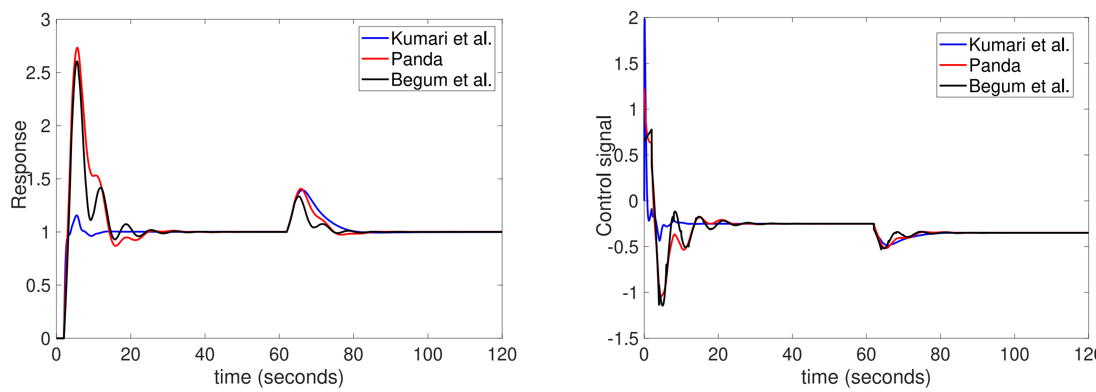
stable or has integrating type dynamics. For all classes of unstable systems, both those with and without RHP zeros, a generalized method for selecting the tuning value shall be established.

In addition, fractional-order controllers have seen the improved closed-loop performance for many applications compared to their integer-order counterparts. But, they involve extra parameters (for



(a) Process output (b) Control output

Fig. 21. Results with modified structures.



(a) Process output (b) Controller output

Fig. 22. Results with different IMC filters.

Table 5
Performance comparison with filter type.

Methods	Filter type	Controller	O_v	t_s	ITSE	TV	Remarks
Kumari et al. (2021)	Type 9 $\|_{n=1}$	$G_c(s) = \frac{4s^2+1.72s+0.28}{(4+4s)(1+0.28s^{1.1})}$ $K_p = 0.32$	15.563	6.439	2.9175e+03	5.336	Better setpoint tracking. Poor load disturbance rejection.
Begum et al. (2020)	Type 7 $\|_{m=1,n=1}$	$G_c(s) = 0.058 + \frac{.044}{s} + \frac{0.029s}{s+1}$ lead–lag filter= $\frac{11.395s+1}{0.541s+1}$	173.316	17.365	111.792	5.363	High overshoot. Poor load disturbance rejection.
Panda (2009)	Type 5 $\|_{m=1,n=2}$	$G_c(s) = 0.653 + \frac{.063}{s} + 0.592s$	160.513	14.155	66.753	6.392	Improved load disturbance rejection. High overshoot.

example: FOPID or FOIMC scheme has two extra parameters to introduce a fractional-order integrator and differentiation when compared to a classical IMC-PID). The analysis would be more interesting if it could be extended to different plant models, such as fractional-order unstable plant models with time delay. Even for the existing methods for unstable processes, stability constraints are not properly presented. Hence, it is worth developing a new method that gives some discussion on the stability. Achieving stability is troublesome when the unstable system has indefinite time delays, which are time-varying. We practice handling such uncertainties by considering the upper bounds on the delays (for instance, say $\theta(t) < \theta_M$ for all t in (11) where θ_M is the maximum limit of the time-delay). However, there is no guarantee that the control or manipulated signal is unbounded for certain values of delay. In addition, finding the stabilizing upper bound is a tricky task.

The majority of existing control methods developed for unstable processes, as previously stated in the literature, were designed in the continuous-time or frequency domain and so must be discretized for use in digital control systems. Developing methods for discrete domain implementation will make it more interesting. The design of controllers for fractional-order systems with time delays is more demanding as per recent trends and can be considered a future scope of the study.

In case of large-scale systems, the model-order reduction concept is generally used to capture the dominant features of the system. Order reduction brings fruitful results for the design of PID controllers in the stable system (Saxena & Hote, 2016a, 2017b); however, unstable systems with large dimensions are still a problem. It is also challenging to stabilize the system when the unstable modes are significant in number due to the large-scale system.

Last but not least, achieving the robustness and the (sub-) optimality simultaneously in the controller design is a big deal in the IMC-based approach for unstable systems. A unified approach to bringing both performances is still an open challenge.

8. Conclusions

In this paper, an exhaustive survey of IMC-based control for unstable systems familiarized the reader with advances of the last two decades. From the literature analysis, it can be seen that the IMC structure is capable of only setpoint tracking. One of the modifications was seen with two degrees of freedom to improve robustness with load disturbances. A very few practical verifications were presented in papers. Most works selected a tuning parameter from a trade-off between robustness and setpoint tracking. In some methods, the tuning parameter is selected based on a trial and error approach and could not find any proper tuning technique developed for unstable models. From the practical point of view, a suitable controller shall contain fewer tuning parameters and fewer variations in control input, yet it can improve better tracking and robustness. Thus, the summary table is prepared to compare the structures with controller numbers and filter types. A concluding discussion of the challenges of stabilizing the unstable system with the existing IMC-based approaches is also provided in this paper.

Research works are in progress for developing proper tuning mechanisms for unstable systems. Since new works focus on fractional-order, techniques can be developed on two parameters' tuning to improve the optimal performance in IMC. We could see fewer methods with the fractional-order controller by going through the literature. Future works may include designing the IMC with fractional-order actions for significant time delay processes, MIMO type, and proper guidelines for IMC filter selection. Thus, the new method must be attractive and straightforward for industrial applications.

Declaration of competing interest

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.

Data availability

No data was used for the research described in the article.

Appendix. Common performance measures and definitions

The various performance indices are used in the literature to tune the IMC controller's parameters. These are defined as below.

- Integral Square Error (ISE), ISE $= \int_0^\infty e^2(t)dt$
- Integral Absolute Error (IAE), IAE $= \int_0^\infty |e(t)|dt$
- Integral Time Squared Error (ITSE), ITSE $= \int_0^\infty te^2(t)dt$
- Integral Time Absolute Error (ITAE), ITAE $= \int_0^\infty t|e(t)|dt$

In general, the value of each index indicates the quality and speed of responses. Another criterion was defined to evaluate the total input usage. It is called the total variations (TV) in the control signal. It is defined as, TV $= \sum_{j=1}^{N} |u_{j+1} - u_j|$, where N is number of sampled of control signal $u(t)$. Another well-known index is called the maximum sensitivity, to measure the robustness of the controlled system. It is written as, $M_s = \max |(1 + G_p(j\omega)G_c(j\omega))^{-1}|$. The suitable value of M_s recommended between 1.4 to 2.0.

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