A NEW TUNING METHOD FOR TWO-DEGREE-OF-FREEDOM INTERNAL MODEL CONTROL UNDER PARAMETRIC UNCERTAINTY

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ABSTRACT

The purpose of controller tuning is to determine the parameters of controller in order to ensure the time response of close-loop control system at the desired performance. Proportional Integral Derivative (PID) controller has been used in the industry since 1940's for this purpose. However, the PID controller can not completely compensate for the complexity of industrial processes and desired high product quality due to interactions, nonlinearities, and time delay of the process variables. Internal model control (IMC) has been developed to overcome the deficiencies of the PID. Unfortunately, IMC yields very good performance for set point tracking, but gives sluggish response for disturbance rejection problem. The present study has developed a controller for disturbance rejection based on feedback / feedforward IMC structure. The controller is then called as feedback 2DOF-IMC. A new tuning method has been proposed for the controller. The proposed tuning method consists of three steps: Firstly, determine the worst case of the model uncertainty. Secondly, specify the parameter of set point controller using maximum peak (Mp) criteria. And thirdly, obtain the parameter of the disturbance rejection controller using gain margin (GM) criteria. The proposed method is called Mp-GM tuning method.

The effectiveness of the proposed feedback 2DOF-IMC and Mp-GM tuning method has evaluated and compared with standard 2DOF-IMC using IMCTUNE and Kaya 2DOF-IMC using Mp-GM tuning as bench mark. The evaluation and comparison are investigated through simulation and implementation on a number of first order plus dead time (FOPDT) and higher order processes. The FOPDT process tested include processes with controllability ratio in the range 0.7 to 2.5. The higher processes include second order with underdamped and third order with nonminimum phase processes. Although the two of higher order process are considered difficult processes, the proposed feedback 2DOF-IMC and Mp-GM tuning method were able to obtain the optimal controller even under process uncertainties. The proposed feedback 2DOF-IMC and the proposed Mp-GM tuning are also successfully implemented in real-time on a laboratory scale air heater pilot plant. The process model is divided into two regions. The time responses show that the proposed feedback 2DOF-IMC and the proposed Mp-GM tuning gave faster set point tracking and disturbance rejection responses than 1DOF-IMC and standard 2DOF-IMC in both regions.

ABSTRAK

Tujuan dari talakan kontroler adalah untuk menentukan parameter pengawal iaitu memastikan waktu sambutan sistem kawalan gelung tertutup pada prestasi yang dikehendaki. Kawalan kamiran terbitan berkadaran (PID) telah digunakan dalam industri sejak tahun 1940 an untuk tujuan ini. Namun, pengawal PID tidak boleh sepenuhnya mengimbangi kekompleksan proses-proses industri dan kualiti produk yang dikehendaki. Ini karena tingginya interaksi antara proses, proses tak lelurus, dan masa tunda pembolehubah proses yang lama. Kawalan model dalam (IMC) telah dibangunkan untuk mengatasi kekurangan PID. Malangnya, IMC memberikan sambutan lamban untuk masalah penolakan gangguan. Penyelidikan ini telah membangunkan sebuah pengawal untuk penolakan gangguan berdasarkan struktur suap balik / suap depan IMC. Pengawal ini kemudian disebut sebagai suap balik 2DOF-IMC. Sebuah kaedah penalaan yang kuat dan sederhana telah dicadangkan untuk pengawal ini. Kaedah penalaan yang dicadangkan terdiri daripada tiga langkah: Pertama, menentukan kes terburuk dari ketidakpastian model.Kedua, menentukan parameter daripada pengawal titik set menggunakan kriteria puncak maksimum (Mp). Dan ketiga, menentukan parameter daripada pengawal penolakan gangguan menggunakan kriteria jidar gandaan (GM). Kaedah penalaan yang dicadangkan ini disebut Mp-GM.

Keberkesanan daripada suap balik 2DOF-IMC dan kaedah penalaan Mp-GM yang dicadangkan dikaji dan dibandingkan dengan piawai 2DOF-IMC dengan penala IMCTUNE dan Kaya 2DOF-IMC dengan penala Mp-GM. Pengkajian dan perbandingan dilakukan melalui penyelakuan dan pelaksanaan di beberapa proses urutan pertama plus waktu mati (FOPDT) dan proses urutan yang lebih tinggi. Proses FOPDT yang diuji termasuk proses dengan nisbah kebolehkawalan daripada 0.7 sehingga 2.5. Proses urutan tinggi yang diuji adalah proses urutan kedua dengan tak teredam dan proses urutan ketiga dengan sistem fasa tak minimum. Walaupun dua proses urutan tinggi itu termasuk proses yang sukar, suap baik 2DOF-IMC dan kaedah penalaan Mp-GM yang dicadangkan boleh memberikan parameter pengawal yang optimum pada ketakpastian proses. suap baik 2DOF-IMC dan kaedah penalaan Mp-GM yang dicadangkan juga berjaya dilaksanakan secara masa nyata dengan skala makmal pada loji pandu pemanas udara. Model proses dibagi menjadi dua daerah. sambutan waktu menunjukkan bahawa maklum balas yang dicadangkan suap balik 2DOF-IMC dengan penala Mp-GM memberi sambutan penolakan yang lebih cepat dan mencapai set yang lebih cepat dibandingkan oleh 1DOF-IMC atau piawai 2DOF-IMC pada kedua-dua daerah.

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LIST OF SYMBOLS

d	Disturbance input
e	Error between measurement and model
E	Error between e and set point
Gc	Transfer function of controller
Gc_1	Transfer function of set point controller
Gc_2	Transfer function of disturbance rejection controller
Gc_f	Transfer function feedforward controller
Gd	Transfer function of disturbance
Gp	Transfer function of process
Gp_m	Treansfer function of model
k	Gain of process
Kc	Proportional gain
*l*a	Additive uncertainty
*l*m	Multiplicative uncertainty
N	Order of Butterworth filter
r	Order of controller
s	Laplace domain
S	Sensitivity function
T	Complementary sensitivity function
w	Weighting function
y	Measurement
y_{sp}	Set point

Δ	Any stable transfer function which at each frequency is less than or equal to 1 magnitude
α	Lead constant of Gc_2 controller
β	Lead constant of adding transfer function
λ	Filter time constant
θ	Time delay
τ	Time constant of process
τ_D	Derivative time constant
τ_I	Integral time constant
ω	Frequency

LIST OF ABBREVIATIONS

1DOF-IMC	One- degree-of-freedom Internal Model Control (generally as IMC)
2DOF-IMC	Two-degree-of-freedom Internal Model Control
AFPT	Air Flow Pressure Temperature Control system Pilot Plant
FOPDT	First Order plus Dead Time
GM	Gain Margin
IAE	Integral Absolute Error
IMC	Internal Model Control
MIMO	Multi Input Multi Output
Mp	Maximum peak (or resonant peak)
MPC	Model Predictive control
PID	Proportional Integral Derivative
SISO	Single Input Single Output
SOPDT	Second Order Plus Dead Time
SP	Smith Predictor controller

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

A chemical industry generally consists of many unit operations, which must be operated on a specific operating condition such as: temperature, pressure, and flow. This operating condition(s) is maintained for the purpose of safety and product quality. Proportional Integral Derivative (PID) controller has been used in the industry since 1940's for this purpose because the PID controller uses a simple algorithm (Willis, 1999). Various designs and tuning strategies were developed for the PID controller so that the controller can be used for various process characteristics. However, the PID controller can not completely compensate for the complexity of industrial processes and desired high product quality due to interactions, nonlinearities, and time delay of the process variables (Anandanatarajan et al., 2006; Normey-Rico and Camacho, 2007). The rapid development of computer technologies has encouraged the development of various types of controllers to overcome the deficiencies of the PID. These controllers include Artificial Neural Network (ANN) controller (Hussain and Ho, 2004; Mohanty, 2009), Fuzzy Logic controller (Galluzzo and Cosenza, 2009; Sarma and Rengaswamy, 2000) and Model Predictive Control (MPC) (Bezzo et al., 2005; Nikandrov and Swartz, 2009; Qin and Badgwell, 2003).

Internal Model Control (IMC) is a class of model based control proposed by Garcia and Morari (1982). The structure of IMC controller is shown in Figure (1.1). IMC uses a model explicitly and it is internally stable. This implies that if a plant is stable, the stability of the process response can be guaranteed by using a controller with stable model.

1.2 INTERNAL MODEL CONTROL (IMC)

The principle of IMC structure can be explained from (Figure 1.1); Gp_m is process model. Difference between model response and actual measurement (e) is used as input signal to IMC controller (Gc_1). In general, e $\neq$ 0, due to the modeling error and unknown disturbances (d Gd) that are not accounted in the process model (Seborg et al., 2004). Unfortunately, IMC controller provides a very slow response to the case of disturbance rejection. Therefore, several researchers have attempted to overcome this weakness by developing two-degree-of freedom-IMC (2DOF-IMC) (Morari and Zafiriou, 1989). Figure 1.2 shows the standard structure of 2DOF-IMC controller.

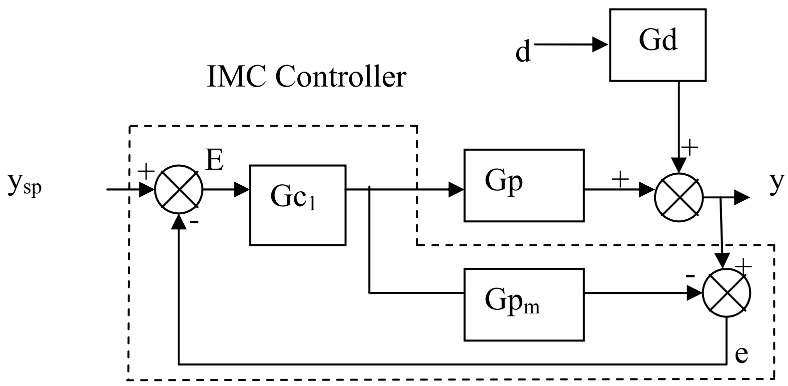

Figure 1.1 Structure of standard IMC controller

Where e is error between measurement and model, E is error between set point and e, Gp is transfer function of the process, Gp_m is transfer function of the model and Gc_1 is transfer function of the controller, y_{sp} is set point value, y is controlled variable, d is disturbance input, and Gd is disturbance transfer function.

1.3 TWO-DEGREE-OF- FREEDOM INTERNAL MODEL CONTROL (2DOF-IMC)

Figure 1.2 shows the controller for set point (Gc_1) and the controller for disturbance rejection (Gc_2) in a 2DOF-IMC structure. The set point controller is in an open loop form and the disturbance rejection controller is in a feedback structure. The parameter of set point controller is designed as 1DOF-IMC controller, while the disturbance rejection controller is designed such that the disturbance can be rejected as soon as possible.

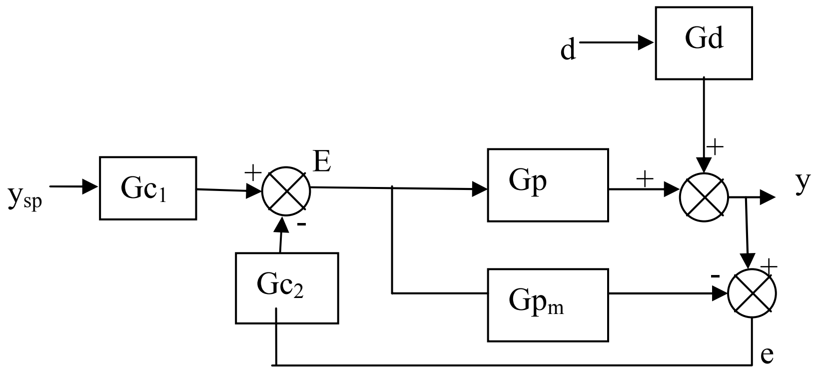

Figure 1.2 Structure of standard 2DOF-IMC

These tuning parameters can be easily obtained in the case of no error in the model. However, the setting of parameter becomes a complicated matter if there is an uncertainty model. On the other hand, the models developed will always contain inaccuracies or contain uncertainty.

The model uncertainty comes from several sources as follows (Laughlin et al, 1986);

(i) The variation of real parameters affecting plant operation.
(ii) The inherent non-linearity of the processes.
(iii) The experimental identification of the process.
(iv) The mathematical model development.

1.4 PROBLEM STATEMENTS

As mentioned in the previous section the tuning parameters in the case of model uncertainty is difficult to obtain. Many researchers have tried at different ways in tuning of 1DOF-IMC based on model uncertainty (Brosilow and Joseph, 2001; Laughlin et al., 1986; Liu et al., 1998; Morari and Zafiriou, 1989). Several works concentrating on the 2DOF-IMC tuning based on model uncertainty has done by Brosilow and Joseph (2001), Morari and Zafiriou (1989) and Stryczek et al. (2000). One of the difficulties of Morari and Zafiriou's method is the use of weighting transfer function in the formulation of robust performance. Stryczek (1996) has introduced Mp-tuning method to facilitate the completion of tuning that does not involve the weighting transfer function. This method is easily applied in obtaining the parameter of 1DOF-IMC based on model uncertainty. Unfortunately, for 2DOF-IMC structure, the Mp-tuning method uses partial sensitivity function that involved disturbance transfer function (Stryczek et al., 2000). Disturbance is very difficult to be modeled, because disturbance can come from more than one sources. Besides, the use of partial sensitivity function is restricted to overdamped system (Brosilow and Joseph, 2001). As a consequence, tuning of 2DOF-IMC using Mp-tuning method has its limitation. Recent research on the structure and tuning of 2DOF-IMC is very limited. Kaya (2004b) has developed a 2DOF-IMC structure and how to design the controller based on the gain and phase margins. He used IMC algorithm for controller tuning, however PD (Proportional Derivative) was used for this structure. It was because the structure and the tuning were only tested on integrating process. Meanwhile, the attention of recent researchers is the application of IMC on specific cases rather than on IMC tuning, for example unstable and integrating process (Chia and Lefkowitz, 2010; Liu and Gao, 2011; Tan, 2010; Tan et al., 2003; Wang and Watanabe, 2007), nonlinear process (Cheng and Chiu, 2007; Ganeshreddy Kalmukale et al., 2005; Toivonen et al., 2003). Therefore, study on the structure and tuning of 2DOF-IMC for general purpose (stable process) is needed to develop a tuning method which simplifies the existing tuning of the 2DOF-IMC under model uncertainty.

1.5 OBJECTIVES AND SCOPE OF THE RESEARCH

The main objectives of the research are stated as follows:

1. To develop and analyze the 2DOF-IMC based on feedback control structure for both set point and disturbance rejection controllers.
2. To develop tuning method for 2DOF-IMC to meet robust performance criteria.
3. To implement and validate the performance and tuning method of 2DOF-IMC.

The scope of this research covers the followings:

1. Theoretical development of the structure of 2DOF-IMC

2. Theoretical review of the maximum peak and gain margin for 2DOF-IMC tuning.
3. Determine the optimal constants that involved in the tuning of 2DOF-IMC.
4. Simulation of several process characteristics that employ the structure and the tuning method of 2DOF-IMC.
5. Application of the proposed method to experimental study in AFPT (air flow pressure and temperature control system) pilot plant made by Syntec Sdn Bhd. The plant is installed in laboratory of Chemical and Natural Recourses Engineering University Malaysia Pahang. The experimental process is modeled as FOPDT.

1.6 METHODOLOGY OF THE RESEARCH

The objectives of the research can be realized by creating a new structure of 2DOF-IMC into feedback control structure. By using feedback control structure, the principle of robust performance that is usually used in conventional control such as maximum peak (Mp) or resonant peak and gain margin (GM) can be applied.

Resonant peak (Mp) and its relationship between time responses of IMC structure has been studied by (Brosilow and Joseph, 2001) using Mp-Tuning (maximum peak) method. The maximum peak is the maximum of magnitude of frequency response of complementary sensitivity function set as 1.05. This value corresponds to about 10% overshoot of time response. With this method the parameters of the set point controller on the model uncertainty can easily be determined.

The difficulties in tuning of disturbance rejection controller can be solved by the principle of Gain Margin. Gain margin is a criterion that often used to measure the stability of a control system (Kuo, 1995). In the Nyquist plot, gain margin is the frequency response of open loop transfer function on the real and imaginary axis (Seborg et al., 2004). Open loop transfer function of proposed feedback 2DOF-IMC can be derived easily. The disturbance rejection controller parameters can be determined using this method after the set point controller parameter is calculated.

There are three specifications in the Mp-GM tuning that needs to be specified i.e; Mp, λ_2/λ_1 and GM. The best Mp value is determined where the overshot of the worst case should not exceed than 10%. The value of the λ_2/λ_1 and GM is determined from the closed loop response, where the corresponding minimum average of ISE (Integral Square Error) value in the worst case, nominal case and slowest case will be selected as tuning parameter. The Specifications above are selected with FOPDT simulation process with $\theta/\tau = 1$, $\theta/\tau > 1$ and $\theta/\tau <1$.

The proposed feedback 2DOF-IMC structure and proposed Mp-GM tuning method are evaluated both in simulation and experimental. For simulation, this work studies;

(i) FOPDT (first order plus dead time) transfer function. It is because; typically chemical process can be approximated by FOPDT form. Three characteristics of FOPDT are analyzed i.e FOPDT with θ/τ (ratio between time delay and time constant) equal to 1, less than 1 and more than 1.

(ii) Higher order process i.e SOPDT (second order plus dead time) with underdamped and third order with non-minimum phase system.

The proposed structure and tuning method is also evaluated in nonlinear process of AFPT (air flow pressure temperature) control system pilot plant. The detail of AFPT pilot plant is presented in experimental study (Chapter 4).

Closed-loop response of the proposed feedback 2DOF-IMC with Mp-GM tuning is compared with the standard 2DOF-IMC with IMCTUNE and Kaya 2DOF-IMC with Mp-GM tuning. However, when IMCTUNE could not calculate the controller parameters then standard 1DOF-IMC with IMCTUNE is performed. If standard 1DOF-IMC with IMCTUNE still could not calculate the parameters then 1DOF-IMC with Mp-GM is applied.

1.7 CONTRIBUTIONS OF THE RESEARCH

The main research contributions from this study are as follows:

1. New 2DOF-IMC structure based on feedback/feedforward control structure was proposed. It is designed and simulated for open loop stable process which commonly representing the chemical process system.
2. New robust and simple method to tune parameters of 2DOF-IMC was employed using Mp-GM (Maximum peak and Gain Margin) criteria.
3. An air heater control system has been developed in laboratory for experimental study in order to validate the above finding.

1.8 STRUCTURE OF THE THESIS

Chapter 2 reviews the related literatures about the weaknesses, advantages, design and tuning of 1DOF-IMC controller structure. The design and tuning of 2DOF-IMC under model uncertainty are reviewed and the chemical process uncertainty is described.

Chapter 3 discusses the proposed Mp-GM tuning for 2DOF-IMC. The proposed tuning method is derived from proposed design of 2DOF-IMC based on feedback/feedforward structure control system (feedback 2DOF-IMC). The method can then be implemented to a standard 2DOF-IMC structure. The results are compared with some existing tuning method of 2DOF-IMC. The Mp-GM tuning is applied to several FOPDT process from small to long time delay. There are three specifications that affect to closed loop time response using Mp-GM tuning i.e; maximum peak (Mp), ratio filter time constant of set point and disturbance rejection controller (λ_1/λ_2), and gain margin's values. The specifications are determined by simulating of FOPDT model. The effects of simplification model are described with examples by using simulation of difficult higher order process such as underdamped and nonminimum phase system. The closed loop responses of proposed structure 2DOF-IMC and Mp-GM method are compared to standard 2DOF-IMC with IMCTUNE and Kaya 2DOF-IMC with Mp-GM.

Chapter 4 describes the implementation of feedback 2DOF-IMC and Mp-GM tuning method to the air heater system in AFPT pilot plant. The AFPT pilot plant is a nonlinear plant particularly in the low to medium temperature range. It has nearly linear model at high temperature range. Therefore, the effects of nominal model selection in different range of operating conditions are presented in this chapter.

Finally, chapter 5 concludes the research study. Summarizes the results obtained from previous chapters. The recommendations for future work are outlined. The recommendations are given based on assessment of the significant findings, limitations, conclusions obtained and difficulties encountered in this study.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The IMC was developed by Morari and coworkers (Garcia and Morari, 1982; Morari and Zafiriou, 1989; Rivera et al., 1986). Internal Model Control (IMC) is a type of model based control that has applied in the process industry (Brosilow and Joseph, 2001). IMC uses model explicitly in controller algorithm. This controller is actually a generation of Smith predictor (SP) controller which was designed for a process with long time delay (Smith O, 1959). The standard PID controller can not handle them optimally because (Kaya, 2003; Normey-Rico and Camacho, 2007; Romagnoli and Palazoglu, 2005);

- The disturbances are not detected immediately (detected until certain time with delay).
- The control actions based on the delay is not in accordance with the purposes of information.
- The control action took some time to determine its effects on the process.

Smith (1959) proposed delay compensator that aims to eliminate the delay element of the feedback loop. This was done by including delay model in the controller algorithm (Romagnoli and Palazoglu, 2005). SP controller has some weaknesses. If the primary controller is not properly tuned, may be unstable when a small mismatch in the dead time is considered (Palmor, 1980) and the disturbance rejection response can not be faster than the open loop (Normey-Rico and Camacho, 2007). These weaknesses could be overcome by IMC. SP can be considered as part of IMC. Modified version of SP controller such as Filtered-SP (FSP), Filtered Predictive Proportional Integral (FPPI), Two Degree of Freedom-Dead Time compensator (2DOF-DTC) and Dead Time Observer disturbance compensator (DO-DTC) can be represented by the 2DOF- IMC (Normey-Rico and Camacho, 2007). The advantages and weaknesses of IMC are further discussed in section 2.2.

2.2 STRUCTURE OF STANDARD INTERNAL MODEL CONTROL

2.2.1 Principle of IMC controller

The structure of a standard IMC controller illustrated in Figure 1.1 can be simplified into classical control feedback (Figure 2.1) (Chia and Lefkowitz, 2010).

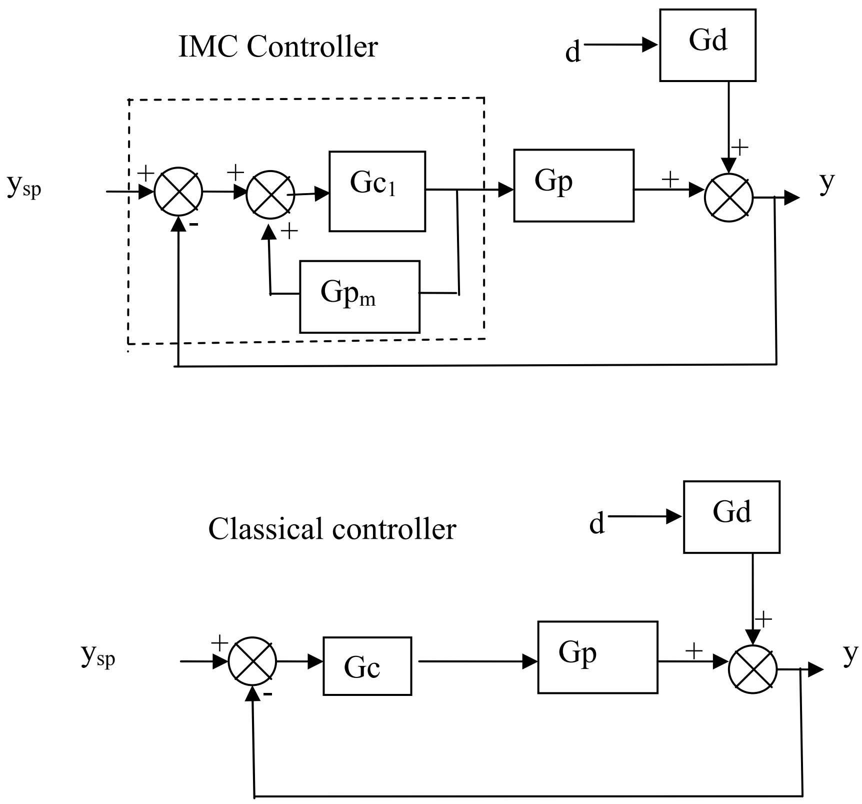

Figure 2.1 Simplified IMC controller to classical feedback control

From Figure 2.1 the classical controller (Gc) can be derived as follow

$$Gc = \frac{Gc_1}{1 - Gc_1.Gp_m} \qquad (2.1)$$

It shows that the classical controller can be derived from IMC controller structure, or the IMC controller can be analogous to the classical controller Gc. However, it is very easy to design Gc_1 than to design Gc. this is because some properties following IMC structure (Economou and Morari, 1986):

Property 1: Assuming that the process model is the same as the plant then the closed loop stability can be guaranteed if the plant and the controller is stable.

Property 2: Assuming that the controller $Gc_1 = 1 / Gp_m$ generate a stable IMC structure, then a perfect set point controller can be achieved.

Property 3: For all Gc_1 with $Gc_1 (0) = 1 / Gp_m (0)$ produces a stable IMC structure, then an offset free control can be achieved.

The first property can be seen from equation 2.1 in which the stability of the closed loop response is only affected by the stability of the plant and controller. While the second character can be derived as follows. For the SISO system, the IMC controller can be derived from Eq. (2.2) to (2.4) (Morari and Zafiriou, 1989).

$$y_{sp} - e = E \qquad (2.2)$$

$$e = y - Gp_m Gc_1 E \qquad (2.3)$$

Then,

$$y_{sp} - y = E - Gp_m Gc_1 E \qquad (2.4)$$

$$E^* = (1 - Gp_m Gc_1)E \qquad (2.5)$$

Where e is error between measurement and model, E is error between set point and e (see Figure 1.1), Gp is transfer function of the process, Gp_m is transfer function of the model and Gc_1 is transfer function of the controller. The other abbreviations that are used in Figure 2.1 and in the next figures are; Gd is transfer function of disturbance, d input of the disturbance, y_{sp} is setpoint input and y is a process variable (measurement / controlled variable).

In the nominal case Gp = Gp_m. Gc_1 is designed to yield minimum value of E*;

$$\min_{Gc_1}\|E^*\|_2 = \min_{Gc_1}\|(1 - Gp_m Gc_1)E\|_2 \tag{2.6}$$

In order to get minimal value of E*,

$$Gc_1 = 1/Gp_m. \tag{2.7}$$

Eq. (2.6) states that optimal controller can be achieved if $Gc_1 = 1/Gp_m$ (Eq.2.7) or the error will be zero. It means that the process variable is always the same with set point. However, Gc = $1/Gp_m$ does not apply in some cases such as processes which has right half plane zero and time delay. Fortunately, It can be done by following two steps as below (Rivera et al., 1986):

Step 1. Factor the model,

$$Gp_m = Gp_m^+ Gp_m^- \tag{2.8}$$

The Gp_m^+ consists of all of the time delay and the right half plane (RHP) zeros. It has the general form of

$$Gp_m^+ = e^{-\theta s} \prod_i (-\beta_i s + 1) \quad \text{Re}(\beta_i)>0 \tag{2.9}$$

Where θ is time delay of the process, β_i is zeros constants of the process transfer function.

Step 2. Make the IMC controller with,

$$Gc_1 = \frac{1}{Gp_m^-} f \tag{2.10}$$

Where, f is the low pass filter which must be chosen so Gc_1 is proper. The simplest form of filter is

$$f(s) = \frac{1}{(\lambda s + 1)^r} \tag{2.11}$$

Where, r is a scalar to make Gc_1 proper.

The value of λ affects the speed of response. The smaller is the value of λ, the faster is the response (more sensitive controller). In order to maintain stability of the system, for FOPDT model, Rivera et al.(1986) suggested that $\lambda = 0.8\ \theta$, Chien and Fruehauf (1990) proposed $\tau > \lambda > \theta$ and Skogestad (2003) recommended $\lambda = \theta$.

2.2.2 Advantages of IMC controller

The relationship between the response variable (y) and set point (y_{sp}) and disturbance (d) can be expressed by Eq. (2.12)

$$y = \frac{GpGc_1}{1 + Gc_1(Gp - Gp_m)} y_{sp} + \frac{1 - Gp_m Gc_1}{1 + Gc_1(Gp - Gp_m)} d \tag{2.12}$$

Eq. (2.12) shows that, if there is no error in the model ($Gp = Gp_m$), the IMC structure is open-loop system for set point tracking. In this situation, the speed of time response is function of filter time constant. The smaller in the filter time constant the faster time response will be achieved. IMC structure is internally stable, if both of the model and controller are stable. A control system is internally stable if bounded signals is injected at any point of the control system generates bounded responses at any other point. The internally stable is more comprehensive than the usual stability concept,