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A Review on Classical and Fuzzy PID Controllers

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Abstract- **The industrial evidence shows that a classical PID controller is the most popular controller due to its simplicity of operation and low cost. It has been realized that classical PID controllers are effective for linear systems but not suitable for nonlinear and complex systems. Scientists and researchers use fuzzy logic to enhance them due to its ability to translate the operator's control action into the rule base. This paper presents a survey of classical and fuzzy PID controllers. Here, an attempt is made to present the history of the development of classical PID controllers and their enhancement using fuzzy logic theory.**

Index Terms— **Classical PID, Fuzzy PID Controller, Formula-based fuzzy PID controllers**

1. INTRODUCTION

The conventional theory is well suited for applications where the process can be reasonably described in advance. However when plant dynamics is hard to characterize precisely or is subject to environmental uncertainties, one may encounter difficulties in using the conventional controller design methodologies. For achieving high degree of performance, the fine tuning of controller parameters is a tedious task. Therefore, in recent years, the control of systems with complexities, uncertain dynamics and nonlinearities, has become a topic of considerable importance in the literature and several advanced strategies have been developed [21, 27, 51].

Intelligent process control systems with high degree of autonomy should perform well under significant uncertainties in the systems and environment for extended period of time and they must be able to compensate for certain system failures without external intervention. Such control systems evolve from conventional control systems by adding intelligent techniques and their development requires interdisciplinary research [107, 108, 132]. Recently, excitement over the field of intelligent process control has risen due to progress in the areas of fuzzy control, neural networks, genetic algorithms, and expert systems to name a few [24, 87, 88, 105, 109, 153]. Chiu has highlighted the aspects of development of commercial applications of intelligent control in [152].

Fuzzy control, occupying the boundary line between artificial intelligence and control engineering, can be considered as an obvious solution, which is confirmed by engineering practice [72, 123]. According to the survey of the Japanese control technology industry conducted by the Japanese Society of Instrument and Control Engineering [56], fuzzy and neural control constitutes one of the fastest-growing areas of control technology development, and has even better prospects for the future. Also, fuzzy logic control has been suggested as an alternative approach for complex systems with uncertain dynamics and those with nonlinearities. Some progress has been made in both the theoretical aspects and the implementation of the same for application to industrial control systems [26, 64, 106, 128]. Actually, Fuzzy logic techniques represent application of human knowledge and expertise for dealing effectively with complex and nonlinear systems. Basically, it provides an effective means of capturing the approximate and inexact nature of the real world. Therefore, the essential part of a fuzzy logic controller (FLC) is a set of linguistic control strategies based on expert knowledge into an automatic control strategy. FLC is considered as a good methodology because it yields results superior to those obtained by conventional control algorithms [41, 44, 69, 79, 86, 90, 145, 159].

Actually, fuzzy logic was first proposed by L. A. Zadeh in 1965 [118] and it is based on the concept of fuzzy sets. He gives more general ideas regarding the fuzzy logic in [35, 112, 116, 117, 119 – 121]. Further, he introduces the concept of "linguistic variables", which in his article equates to a variable defined as a fuzzy set [113–115]. Control engineering belongs to the most famous application areas of fuzzy set theory and has attracted most attention of researchers and scientists. In 1975, the first successful application of fuzzy logic to the control of a laboratory-scale process was reported by Mamdani and Assilian in [31, 33, 36]. They suggested advances in linguistic synthesis of a fuzzy controller in [32, 34]. Further, they published the analysis of a fuzzy controller in [169]. Also, Kingt and Mamdani suggested the application of fuzzy logic control systems to industrial processes [133]. The first industrial application of fuzzy logic was in the area of fuzzy controllers. It was done by two Danish civil engineers, Holmblad and Østergaard, who around 1980 at the company F.L. Schmidt developed a fuzzy controller for cement kilns. Their results were published in 1982 [122]. In 1990, Lee published two papers for the use of fuzzy logic in control systems. He has given a survey about the role of fuzzy logic in control systems. Also, he discussed the fuzzy logic controller and its applications from laboratory level to industrial process control [22, 23]. Fuzzy control is being applied to various systems in the process industry [154, 160], consumer electronics [91, 136], automatic train operation in Japan [158], traffic systems in general [54], and in many other fields [91, 161]. An excellent review of the Fuzzy Controller design, as well as its relationship with classical control, is given in [53]. Another very good survey on analysis and design of model based fuzzy control systems is given in [46].

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2. CLASSICAL AND FUZZY PID CONTROLLERS

Classical proportional plus integral plus derivative (PID) controllers are still the most widely adopted method in industry for various control applications, due to their simple structure, ease of design, and low cost in implementation. Different sources estimate the share taken by PID controllers at between 90 and 99% [43, 84, 89, 93 – 95, 100, 123, 124, 129, 157]. However, conventional PID controllers are generally insufficient to control processes with additional complexities such as time delays, significant oscillatory behavior (complex poles with small damping), parameter variations, nonlinearities, and Multi Input and Multi Output (MIMO) plants [87, 105]. Also, there are some practical implication with the conventional structure of a PID controller, such as, proportional kick and derivative kick, i.e., a sudden change in the PID controller output resulting from proportional and derivative action applied to error signal after a change in setpoint value. In practice, this control signal could be driving an actuator device like a motor or a valve, and the kick would create serious problems for electronic circuitry used in the device. Due to these industrial process problems, the classical PID controller structure is modified to integral minus proportional minus derivative (I–P–D) controller form [8, 11, 48, 71, 85, 99, 100, 125, 147, 156, 173]. The wide application of PID control has stimulated and sustained research and development to “get the best out of PID’’ [70], and “the search is on to find the next key technology or methodology for PID tuning” [134]. Therefore, one of the research directions in advancing the existing PID controllers is to combine fuzzy logic control technology with the conventional PID controller to obtain behaviour better than that of a regular PID controller.

2.1 Brief Review of Classical PID Controllers

In the 18th century, the most significant control development was the steam engine governor. In 1788, James Watt introduced a flyball governor into his steam engine. It was the first mechanical feedback device with only proportional control capabilities. The flyball governor, acting as a proportional controller, controlled the speed by releasing more steam to the engine when the speed dropped lower than a set point, and vice versa [74, 131, 146, 147, 151, 162].

One of the first examples of PID-type controls that were developed was by Sperry. In 1911, this type of systems was used for automatic ship steering. Note that Sperry did much work involving gyroscopic compasses as well. Sperry's device compensated for disturbances in the water as sea conditions changed. Although Sperry used a type of PID control in 1911, the control law that we commonly associate with the modern PID loop comes from Minorsky. In 1922, he observed a helmsman controlling a ship and came up with the proportional, integral, and derivative type of control we know of today. Proportional is the control required to steer the ship based on actual ship direction compared to the desired course setpoint. Integral is the amount of reset required to correct an amount of error. For example, if the ship is off course by a small amount, and correcting it to the left brings it back on bearing, then turning the wheel all the way to the left is inappropriate. Only a slight adjustment to the left is required. Derivative is the attempt to see how far a process variable (ship course) has been from the set point in the past, and anticipating where the course correction will need to be in the future. In 1922, Minorsky in his paper on the “Directional stability of automatically steered bodies” analyzed and discussed the properties of the three-term controller [130, 146, 148].

In 1933, the Taylor Instrument Company introduced Model 56R Fulscope controller, the first pneumatic with a fully tunable proportional controller feature. However, a proportional controller is not sufficient to control a process variable thoroughly, as it amplifies error by multiplying it by some proportional constant (K_c). The error generated is eventually small, but not zero. In other words, it generates a permanent error or offset or steady state error each time the controller responds to the load [146, 147, 149, 150, 162, 163].

In the mid 1930s, control engineers found out that steady state error/offset could be eliminated by resetting the setpoint to some artificial higher or lower value, as long as the error was nonzero. This resetting operation integrates the error, and the result is added to the proportional term; today this is known as Proportional-Integral (PI) controller. In 1934-1935, Foxboro introduced the first PI controller. Unfortunately, integral action does not guarantee perfect feedback control. A PI controller can cause closed-loop instability if the integral action is too aggressive. The controller may over-correct for an error and create a new one of even greater magnitude in the opposite direction. When that happens, the controller eventually starts driving its output back and forth between fully on and fully off, a phenomenon known as hunting [146, 147, 149, 150, 162].

In 1935, Taylor Instrument Companies introduced a completely redesigned version of its “Fulscope” pneumatic controller: this new instrument provided, in addition to proportional and reset control actions, an action which the Taylor Instrument Companies called “pre-act”. In the same year the Foxboro Instrument Company added “Hyper-reset’’ to the proportional and reset control actions provided by their “Stabilog” pneumatic controller. Pre-act and Hyper-reset actions each provided a control action proportional to the derivative of the error signal. Reset (also referred to as “floating”) provides a control action proportional to the integral of the error signal and hence both controllers offered PID control [146, 147, 149, 150, 162]. Compared to a two-term PI controller, a full PID controller can even appear to anticipate the level of effort that is ultimately required to maintain the process variable at a new setpoint. On the other hand, dramatic swings in the control effort can be troublesome in applications that require slow and steady changes in the controller's output [149, 150, 162].

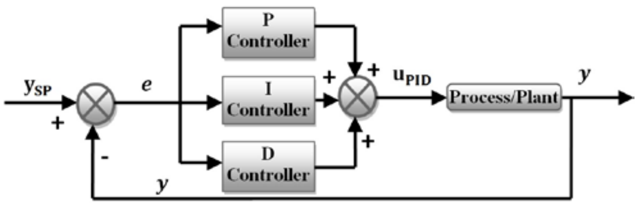

Fig. 1 The classical PID control system

The block diagram of classical PID control system is shown in Fig. 1.The output of the classical continuous-time PID controller, as shown in Fig. 1, is given by

$$u_{PID}(t) = K_C e(t) + \frac{K_C}{\tau_I}\int e(t)dt + K_C \tau_D \frac{de}{dt} \qquad (1)$$

where $e(t)$ is the error, K_C is the proportional constant, τ_I is the integral time constant , τ_D is the derivative time constant and $u_{PID}(t)$ is the output of the classical PID controller.

Derivative action also tends to add a dramatic spike or "kick" to the controller's output in the case of an abrupt change in the error due to a new setpoint [11, 37, 71, 85, 100, 125, 175]. This forces the controller to start taking corrective action immediately without waiting for the integral or proportional action to take effect. For such cases it is advantageous to forego derivative action altogether or calculate the derivative from the negative of the process variable rather than directly from the error. If the setpoint is constant, the two calculations will be identical. If the setpoint only changes in a stepwise manner, the two still remain identical except at the instant when each step change is initiated. The negative derivative of the process variable lacks the spike present in the derivative of the error. Most modern controllers offer this option for applications that cannot withstand "kicking". With an extra derivative action, problems such as overshoot and hunting are reduced. However, issues like finding the appropriate parameter of PID controllers were yet to be solved [149, 150, 162].

Taylor engineers Ziegler and Nichols solved the problem by developing the well-known "Ziegler-Nichols" method of tuning, still in use today. The outcome of their work was two papers published by them in 1942 and 1943 [75, 76]. In these papers Ziegler and Nichols showed how optimal controller parameters could be chosen based first on open-loop tests on the plant; and second on closed-loop tests on the plant [147]. Further, Cohen and Coon [47, 147] of the Taylor Instrument Companies during the 1950s, proposed alternative choices of parameters accepted for certain types of plants.

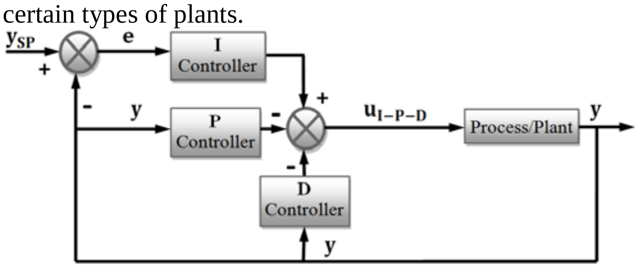

Fig. 2 The classical I – P – D control system

Their modified structure of classical PID controller, i.e., I – P – D controller is shown in Fig. 2. The output of the classical I – P – D controller, as shown in Fig. 2, is given by

$$u_{I-P-D}(t) = \frac{K_C}{\tau_I}\int e(t)dt - K_C y(t) - K_C \tau_D \frac{dy}{dt} \qquad (2)$$

where $y(t)$ is the process variable and $u_{I-P-D}(t)$ is the output of the I – P – D controller.

By the mid 1950's, automatic controllers were firmly established and adopted in various industries. A report from the Department of Scientific and Industrial Research of United Kingdom states, "Modern controlling units may be operated mechanically, hydraulically, pneumatically or electrically. The pneumatic type is technically the most advanced and many reliable designs are available. It is thought that more than 90 percent of the existing units are pneumatic" [30]. The report indicated the need to implement controllers in electrical and electronic form [149, 150].

Young, in 1954, described six electronic PID controllers, based on vacuum tube technology, developed by various manufacturers around the world [4, 149, 150]. In 1957, Williams [50] of George Kent commented that electronic instruments were capable of performing all the functions previously only available with pneumatic instruments and that these included, in addition to PID, the ability to carry out various mathematical operations [103, 149, 150]. He also noted that the instrument manufacturers started to realize the possibility of implementing the controllers using transistors [149, 150]. In 1959, the first solid-state electronic controller was introduced by Bailey Meter Co. The advantage of using electronic instruments to implement PID controllers was explored more deeply years later. They are not only capable of including the functions available in pneumatic instruments, but even more complicated mathematical operations can be carried out as well [50, 149, 150]. Electronic PID controllers have become more common and more acceptable since then [149, 150, 162].

During the 1960s, the digital computer became involved in industrial process control. The catalytic polymerisation unit plant at Texaco's Port Arthur (Texas) was the first plant, where closed loop control was implemented by a digital computer on March 15, 1959. By 1960, many control instrument companies responded to this new technology and offered computer-based systems. "Analog controllers should gradually evolve into digital devices, providing accuracy at low cost. These controllers will be relatively simple to combine into multipoint configurations, which can be applied to optimize unit processes on a local basis." [7]. More discoveries concerning digitizing PID controllers were made, and arguments for implementing controllers on microprocessors were brought up as microprocessors could handle calculations directly in engineering units [28, 82, 149, 150, 162]. Further, various structure of PID algorithms and tuning methods are discussed in detail in [5, 6, 83].

Around 1990, it was realized that conventional PID controllers were effective for simple linear systems, but generally not suitable for nonlinear systems, higher order, time-delayed systems, complex and vague systems that had no precise mathematical models. For these reasons, various types of modified conventional PID controllers such as auto-tuning and adaptive PID controllers are proposed [92, 103, 155]. Also, during this period it was suggested that if the process was too complex to achieve a good physical description, conventional methods were not able to guarantee the final control aims, and the controller synthesis had to be based mainly on intuitions and heuristic knowledge. So, expert control strategies are favored since they are based on the process operator's experience and do not need accurate models [97, 98, 101, 102, 104, 127, 142].

One of the most successful expert system techniques applied to a wide range of control applications has been the Fuzzy Set Theory, which has made possible the establishment of *"intelligent control"*. Its attraction, from the Process Control Theory point of view, comes because the fuzzy approach provides a good support for translating the heuristic skilled operator's knowledge about the process and control procedures expressed in imprecise linguistic sentences into numerical algorithms [51, 87, 96, 97, 101, 102, 105, 106, 108, 127, 141].

2.2 Brief Review of Fuzzy PID Controllers

In the 1990s, scientists and researchers were trying to use intelligent techniques, such as, fuzzy logic, to enhance the capabilities of classical PID controllers and their family. They were trying to combine fuzzy logic control technology with a conventional PID controller to obtain behavior similar to that of a regular PID controller [25, 26, 43, 178]. It is thus believed that by combining these two techniques together a better control system can be achieved.

The majority of the research work on fuzzy PID controllers focuses on the conventional two-input PI or PD type controller proposed by Mamdani [31, 33, 36]. However, fuzzy PID controller design is still a complex task due to the involvement of a large number of parameters in defining the fuzzy rule base. Wang and Kwok [139] have done the analysis and synthesis of an intelligent control system based on fuzzy logic and the PID principle. They propose the combination of fuzzy PD and fuzzy I controllers. Li and Gatland [59] introduce a simple fuzzy three-term controller with a small modification in a fuzzy PI controller and normal two dimensional rule base is used. Ketata *et al.* [144] introduce a new design concept of fuzzy controllers. They studied the design and properties of structures such as fuzzy control, commutation between fuzzy and PID controllers and fuzzy supervision of a PID controller. After having described two fuzzy controller implementations (fuzzy PD and fuzzy PI controllers), the comparison with a PID algorithm is a base for the design of the parallel PID-fuzzy controller combination. The proposed fuzzy supervisor leads to promising results concerning the development of combined control structures.

Li and Gatland [57] propose a new methodology for designing a fuzzy logic controller (e.g. Fuzzy PI). A phase plane is used to bridge the gap between the time-response and rule base. Further, they [58] introduce more systematic analysis and design for the conventional fuzzy control. A general robust rule base is proposed for fuzzy two-term control, leaving the optimal tuning to the scaling gains, which greatly reduces the difficulties of design and tuning. Li [60] adds a new methodology for designing and tuning the scaling gains of the conventional fuzzy logic controller (FLC) based on its well-tuned linear counterpart. Mann *et al.* [49] investigate different fuzzy PID controller structures, including the Mamdani-type controller. By expressing the fuzzy rules in different forms, each PID structure is distinctly identified.

Huang and Yasunobu [174] propose a general practical design method for fuzzy PID control from conventional PID control. Based on the analysis of relationship between conventional PID controller and fuzzy PID controller, they propose a method on how to choose the type of fuzzy PID controllers suitable for a plant. Li *et al.* [170] propose a design of an enhanced hybrid fuzzy P+ID controller for a mechanical manipulator. A function-based evaluation approach is proposed by Hu *et al.* [10] for a systematic study of fuzzy PID-like controllers. This approach is applied for deriving process-independent design guidelines from addressing two issues: simplicity and nonlinearity. To examine the simplicity of fuzzy PID controllers, they conclude that direct-action controllers exhibit simpler design properties than gain-scheduling controllers. Further, Michail *et al.* [135] introduce fuzzy PID control of a nonlinear plant. Kumar *et al.* [167] evaluate the performance of a fuzzy PI + fuzzy PD controller for a liquid-flow process in real-time and find that a fuzzy controller outperforms a classical controller.

The basic structure of a fuzzy logic controller is shown in Fig. 3. Its fundamental components are fuzzification, control rule base, inference mechanism and defuzzzification.

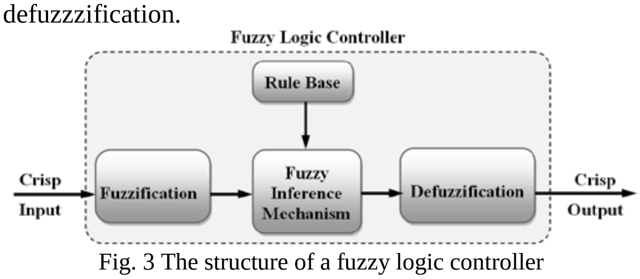

Fig. 3 The structure of a fuzzy logic controller

The structure of a fuzzy PID controller is based upon the classical PID controller as shown in Fig. 1. The output of PID controller in an absolute form is expressed in Eq. (1). Its discrete-time version is [49]

$$u_{PID}(n) = K_C e(n) + \frac{K_C}{\tau_I}\sum_{j=0}^{n} e(j)T_S + (K_C \tau_D / T_S)\Delta e(n) \quad (3)$$

Index n refers to time instant and T_S sampling time. Further, the output of PID controller in an incremental form may be expressed as

$$\Delta u_{PID}(n) = K_C \Delta e(n) + \frac{K_C}{\tau_I} T_S e(n) + (K_C \tau_D / T_S) \Delta^2 e(n) \quad (4)$$

where $u_{PID}(n) = u_{PID}(n-1) + \Delta u_{PID}(n)$ (5)

Thus the basic structural elements of fuzzy PID controllers are shown in Fig. 4.

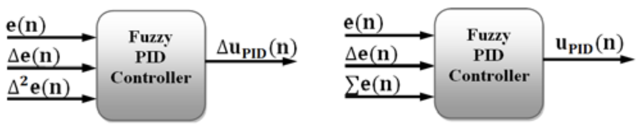

Fig. 4 Fuzzy PID structure [49]

where error is $e(n)=y_{SP}(n)-y(n)$; error change $\Delta e(n)=e(n)-e(n-1)$; rate of error change $\Delta^2 e(n)= \Delta e(n)- \Delta e(n-1)$; and sum-of-error $\sum e(n) = \sum_{j=0}^{n} e(j)$ with $y(n)$ being the feedback response signal, and $y_{SP}(n)$ the desired response or the reference input at the n^{th} sampling instant.

2.3 Brief Review of Analytical Formula-Based Fuzzy PID Controllers

Another class of fuzzy PID controllers with analytical formulas was proposed during the 1990s. Siler and Ying [171] define a linear fuzzy PI controller with one input and one output in terms of piecewise linear membership function for fuzzification, control rules, and defuzzification algorithm. Further, Ying *et al.* [65] prove analytically that a simplest possible fuzzy controller is equivalent to a proportional-integral controller when a linear defuzzification algorithm is used or to a nonlinear proportional-integral controller when a nonlinear defuzzification algorithm is used. Buckley and Ying [78] describe a fuzzy controller based on their general purpose fuzzy expert system shell FLOPS. They take a decision theoretic view in designing an optimal fuzzy controller.

Further, Chen and Ying [40] study the stability of nonlinear fuzzy PI control systems. Malki *et al.* [52] propose a new design method and stability analysis of a fuzzy proportional-derivative control system. They have derived the structure of fuzzy controllers, with simple analytical formulas as the final results by considering two fuzzy sets on each input variable and three fuzzy sets on output variable in the fuzzification process, rule base with four control rules, intersection T-norm, Lukasiewicz or T-conorm, drastic product inference method, and center of area (COA) defuzzification method. Further, Chen and Malki [38] study the bounded-input and bounded-output (BIBO) stability of a fuzzy PD controller using the small gain theorem. Li *et al.* [55] conduct the performance analysis of a fuzzy PD control system proposed by Malki *et al.* [52]. Also, Lu *et al.* [81] have performed an experiment, to evaluate the performance of a fuzzy PD controller in real time.

Hsu *et al.* [172] propose a new fuzzy PD controller for multi-link robot control and perform the stability analysis. Chen *et al.* [45] study the fuzzy PI controller design and its stability. Further, Chen and Ying [39] establish the BIBO stability conditions for nonlinear fuzzy PI control systems using the small gain theorem. The structure of nonlinear fuzzy PI controller is similar to the structure of a fuzzy PD controller as proposed by Malki *et al.* [52]. Chen has reported that fuzzy logic based PID controllers have strong capabilities of handling not only linear but also many complex nonlinear, higher-order, time delayed, as well as ill-defined systems [43].

Ying [66, 67] proposes the construction of nonlinear variable gain controllers via the Takagi-Sugeno fuzzy control and performs an analytical study on the structure, stability and design of general Takagi-Sugeno fuzzy control systems. Further, he [68] develops the theory and application of a novel fuzzy PID controller using a simplified Takagi-Sugeno rule scheme. Carvajal *et al.* [73] introduce a three term fuzzy PID controller with three dimensional rule base. The final version of the fuzzy PID controller is a computationally efficient analytical scheme. Lu *et al.* [80] propose the design of predictive fuzzy PID control and perform simulation study. Ying [63] investigates the analytical structure of TITO (two-input two-output) Mamdani fuzzy PI/PD controllers with respect to conventional PI/PD control and variable gain control.

Patel and Mohan [9] introduce an analytical structure and analyze the simplest fuzzy PI controllers. The fuzzy PI controllers employ two fuzzy numbers on the universe of discourse (UOD) of each input variable, and three fuzzy numbers on the UOD of an output variable. Analytical structures of such controllers are derived using triangular membership functions for fuzzification, different combinations of T-norms and T-conorms, different inference methods, and center of area (COA) method for defuzzification. Moreover, sufficient conditions for BIBO stability of fuzzy PI control systems are established using the small gain theorem. Further, Mohan and Patel [19] introduce an analytical structure and analyze the simplest fuzzy PD controllers and perform stability analysis using the small gain theorem.

Liu *et al.* [177] perform a study to control wing rock using a fuzzy PD controller. Ding *et al.* [176] propose the analytical structure and perform stability analysis of a typical Takagi-Sugeno PI and PD controller. Further, Ying [61, 62] proposes a general technique for deriving the analytical structure of fuzzy controllers using arbitrary trapezoidal input fuzzy sets and Zadeh's AND operator and then derives analytical input-output relationship for fuzzy controllers using arbitrary input fuzzy sets and Zadeh's fuzzy AND operator. Alwadie *et al.* [1] study a practical two-input two-output Takagi-Sugeno fuzzy controller. Haj-Ali and Ying [2] study the input-output structural relationship between fuzzy controllers using nonlinear fuzzy input sets and PI or PD control. Further, Haj-Ali and Ying [3] perform the simple analysis of fuzzy controllers with nonlinear input fuzzy sets in relation to nonlinear PID control with variable gains.

Mohan and Sinha [16] introduce an analytical structure and analyze the stability of a simplest fuzzy PID controller. Further, Mohan and Sinha [12] discuss the mathematical models for the simplest fuzzy PID controllers which employ two fuzzy sets for each of the three input variables and four fuzzy sets for the output variable. Mathematical models are derived via left and right trapezoidal membership functions for each input, singleton or triangular membership functions for output, algebraic product triangular norm, different combinations of triangular co-norms and inference methods, and center of sums (COS) defuzzification method. For the structure which is suitable for control, BIBO stability proof is presented. Mohan and Sinha [15] in reference to the earlier work [9] state that the analytical structure of the simplest fuzzy PI controller, derived via algebraic product t-norm, bounded sum t-conorm and Mamdani minimum inference, is not suitable for control purpose. In [15] they show that the above statement is incorrect, and the above analytical structure is very much suitable for control. Moreover, using the small gain theorem they establish sufficient conditions for BIBO stability of feedback systems containing the above controller as a subsystem.

Arya [143] proposes the analytical structure of a fuzzy PD controller and performs the analysis of simplest fuzzy PD controller with asymmetrical/symmetrical, trapezoidal/triangular/singleton output membership function. Mohan and Sinha [20] study the analytical structures for fuzzy PID controllers. These fuzzy PID controllers are derived by using triangular membership functions for inputs, singletons, or triangular membership functions for output, minimum triangular norm, maximum or drastic sum triangular conorm, Mamdani minimum, drastic or Larsen product inference, nonlinear control rules, and center-of-sum defuzzification. It is shown that these analytical structures are not suitable for control purpose. They found that in this context, it is extremely important to note that the analytical structures reported by Carvajal *et al.* [73] are also not valid for control.

Further, Mohan and Sinha [17] introduce the analytical structure for a fuzzy PID controller by employing two fuzzy sets for each of the three input variables and four fuzzy sets for the output variable. This structure is derived via left and right trapezoidal membership functions for inputs, trapezoidal membership functions for output, algebraic product triangular norm, bounded sum triangular co-norm, Mamdani minimum inference method, and center of sums (COS) defuzzification method. Conditions for BIBO stability are derived using the small gain theorem. Mohan and Sinha [14] introduce a mathematical model of the simplest fuzzy PID controller with asymmetric fuzzy sets. Further, Mohan and Sinha [18] introduce mathematical models of simplest fuzzy PI/PD controllers with skewed input and output fuzzy sets. Also, Mohan and Sinha [13] introduce mathematical models and BIBO stability analysis of simplest fuzzy two-term controllers. Kumar *et al.* [166] present the design, performance and stability analysis of formula-based fuzzy PI (FPI) controller. They use a large number of fuzzy sets for input and output variables to obtain more formulae for corrective action. The performance of FPI controller is evaluated for control of outlet flow concentration of a nonlinear non-thermic catalytic continuous stirred tank reactor (CSTR) for setpoint tracking, disturbance rejection and noise suppression. The performance of the proposed formula-based FPI controller is considerably better than that of the conventional FPI controller. Its computational time delay is approximately 6μs which validates its use for very fast process in real time. The analytical structure of simplest FPI controller is presented next.

The discrete-time version of classical PI controller is

$$\Delta u_{PI}(n) = K_C r(n) + (K_C / \tau_I) e(n) \tag{6}$$

where $r(n)$ is the rate of change of the error and $\Delta u_{PI}(n)$is the incremental control output.

The analytical formula-based FPI controller is based on Eq. (6). The error signal "$(K_C/\tau_I)e(n)$" and the rate of change of the error signal "$K_C r(n)$" are input to the FPI controller to obtain the corresponding output "$\Delta u_{PI}(n)$".

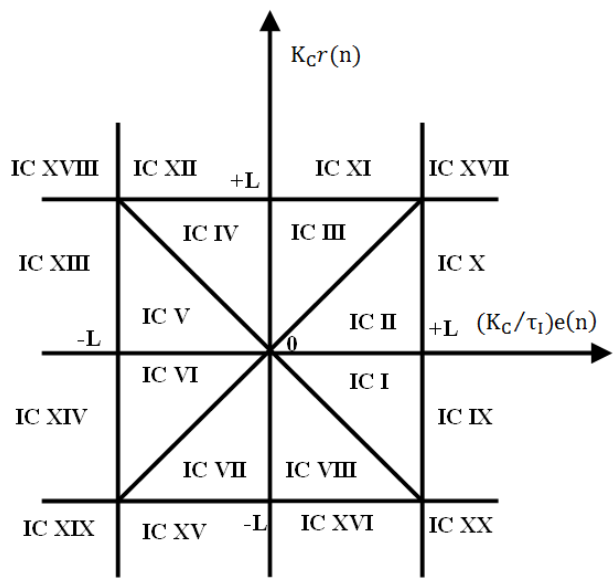

Fig. 5 Regions of FPI controller input IC values [41]

The structure of FPI controller is derived, with simple analytical formulas as the final results by considering two triangular fuzzy sets on each input variable and three singleton fuzzy sets on output variable in the fuzzification process, rule base with four control rules, intersection T-norm, Lukasiewicz or T-conorm, drastic product inference method, and center of area (COA) defuzzification method. The value-ranges of two inputs, the error and the rate of change of the error signal are decomposed into 20 adjacent input combinations (IC) regions, as shown in Fig. 5. The analytical formulas are obtained by the projection of "$(K_C/\tau_I)e(n)$" and "$K_C r(n)$" on different IC regions as in [41]. The flowchart of FPI control operation is shown in Fig. 6.

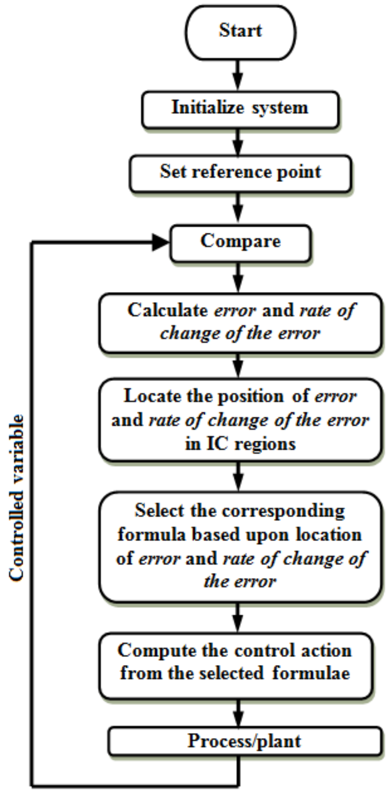

Fig. 6 Flowchart of FPI control operation [166]

2.4 Brief Review of Analytical Formula-Based Hybrid Fuzzy PID Controllers

The hybrid architecture of fuzzy PID with analytical formulas is reported in literature. Misir *et al.* [29] have developed a fuzzy PID controller, which is a combination of fuzzy PI and fuzzy D controller, with the same structure as mentioned by Chen earlier [41, 44]. Here a derivative function is performed on a process variable rather than error signal. In the continuation of this, Tang *et al.* [111] have developed an optimal fuzzy PID controller, having the same structure as discussed earlier [29]. They successfully implement it in to control a solar plant [110]. Chen [42] proposes a GA-optimized Fuzzy PD+I controller for a nonlinear system. Sooraksa and Chen [137] develop a fuzzy $(PD+I)^2$ control scheme for both vibration suppression and set-point tracking of a "shoulder-elbow-like" single flexible link robot arm model with damping. Simulations results show that fuzzy logic controller perform very well.

Kim and Oh [77] have proposed another configuration of fuzzy PID controllers (fuzzy PI + fuzzy ID) with the analytical structure as discussed above [41, 44]. Sooraksa *et al.* [138] perform a comparative study of a conventional proportional-integral plus derivative controller versus a fuzzy proportional-integral plus derivative controller for a subsystem failure. Veeraiah *et al.* [126] have proposed a fuzzy PI-PD controller and studied its performance. Chatrattanawuth *et al.* [168] propose a hybrid fuzzy controller with the structure suggested by Chen [41, 44]. Here integral function is performed on error signal while proportional and derivative functions are performed on a process/controlled variable. Li and Shen [140] propose a new incremental fuzzy PD + fuzzy ID controller and perform the comparative study with a conventional PID controller.

Kumar and Mittal [165] have attempted a hybrid structure of a fuzzy PID controller. It is a parallel formula-based fuzzy P + fuzzy I + fuzzy D (FP + FI + FD) controller. It is based upon the parallel architecture of a conventional PID controller. It preserves the linear structure of the corresponding conventional controller and having simple analytical formulas. They evaluate the performance of a formula-based FP + FI + FD controller for some complex processes in simulation and real time and find that its setpoint tracking and disturbance rejection performance is much better than a classical PID controller. Further, they [164] present the architecture, performance assessment and stability analysis of a formula-based fuzzy I – fuzzy P – fuzzy D (FI – FP – FD) controller. It is based upon the architecture of a conventional I–P–D controller with simple analytical formulas. The setpoint tracking and disturbance rejection performance of formula-based FI – FP – FD controller is evaluated for some complex processes, such as, first- and second-order processes with delay, inverse response processes with and without delay and higher order processes in simulation. It is found that it outperforms a classical PID controller. BIBO stability of formula-based FI – FP – FD controller is performed using the small gain theorem.

3. Conclusions

This paper has presented the review of the classical and fuzzy PID controllers. Firstly, the history of the development of classical PID controllers and their anomalies are presented in the chronological order. Further, the advancement of classical PID controllers using fuzzy logic is presented. It has been observed that due to the heuristic approach of fuzzy logic, it plays a significant role in the enhancement of classical PID controllers. The literature survey shows that fuzzy PID controllers perform much better than classical PID controllers.

Analytical formula-based fuzzy PID controllers have advantages due to their structure. Since the fuzzy control law has analytical formulas, controller designers can effectively implement these formula-based fuzzy PID controllers in real-time systems, such as FPGA and microcontroller, without any computational burden because the computational delay is quite small. It strongly validates its candidature for very fast processes, such as, control of an electromagnetic shaker. Also, due to the self tuning capabilities, these controllers are suitable for a non-stationary process. It has been noted that due to the advancement of fuzzy PID controllers, its acceptance is rapidly increasing in various industrial applications.

For analytical formula-based fuzzy PID controllers, the literature survey reveals that people have tried out the triangular membership function due to its convenience in calculating formulae for different input combination regions. Hence, it is open to use another type of a membership function in place of triangular membership function. Also, fuzzy sets of input and output variables should increase in order to have a better accuracy with more corrective action formulae. Further, optimization techniques, such as genetic algorithm and particle swan optimization, may be used to perform optimal tuning of controllers gain. We hope this survey will be useful to the readers interested in classical PID controllers and its enhancement using fuzzy logic.

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