Comprehensive Library of Digital Fuzzy PID Control Structures for Power Electronic Systems

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***Abstract*— This paper presents a comprehensive library of digital Fuzzy PID (FPID) control structures for power electronic applications. Unlike many papers, which focus on a single control solution, this paper takes systematic approach to convert all 27 possible conventional digital PID (CPID) structures to a digital FPID equivalent. Importantly, several key microprocessor compatible control FPID paradigms are depicted; including general feedback, forward (direct) and feed-forward. The derived FPID control library allows the practicing power electronic power control engineer to directly select and implement state-of-the-art Fuzzy PID control schemes for a target application.**

Keywords—Fuzzy PID; Digital PID; Hybrid Controller.

I. INTRODUCTION

The Conventional Proportional-Integral-Derivative (CPID) controller is well understood and widely applied in many industrial applications. Typically, the CPID controller is simple to implement and the controller gains are easy to vary [1]. However, many systems that are reliant upon the CPID controller demonstrate poor dynamic performance [2]. Key issues in state-of-the-art industrial applications include; component tolerances, poor knowledge of load characteristics, non-linearity, temperature dependency, unexpected external disturbances, and general long term degradation. All affect the transient performance of the system [3, 4]. Therefore, for optimal control performance, the dynamic characteristics should be known in advance. From this prospective, an appropriate system model and controller design process can be developed [5]. However, many systems are difficult to describe by simple mathematical models. Typically, this includes complex non-linear and time varying systems; such as PWM switched power converters. In these applications, implementing an optimally tuned CPID controller can be very challenging [2]. For this reason, more advanced control techniques are now playing an increasingly important role in power electronic applications. Intelligent controllers, such as non-linear controllers [6], self-tuning and adaptive controllers, [7] and fuzzy logic controllers (FLC) [8], are some of the most attractive approaches. However, the non-linear controller is difficult to design and, in many adaptive control schemes, an accurate estimation of the plant model is essential. This can be computationally intensive to implement and the controller tuning is often based upon on-line system identification techniques [5].

Among the intelligent controllers it has been found that the Fuzzy Logic Control (FLC) is relatively easy to design and implement. The system model is generally not required in the design process and it often provides superior performance when controlling systems that are time varying, non-linear, contain uncertainty, or are completely unknown [9]. It is worth noting that the FLC deals with linguistic variables rather than numerical values to achieve the design goal, without a mathematical model of the process. This is accomplished by converting the expert linguistic description into a desired controller strategy [10].

Research demonstrates several productive FLC implementations that have been employed in a wide range of different applications. FPID have become increasingly popular in many research fields and industrial applications; which can be used to replace existing CPID controllers with more intelligent control laws. For instance, control of electric drives [11] and regulation of switched mode power supplies [9]. Furthermore, in the field of power electronic systems, hybrid FLC schemes have been effectively employed in state-of-the-art digitally controlled power electronic applications [9, 10, 12, 13]. In other literature, hybrid FPID controllers have also been considered, and these paradigms appear to demonstrate excellent performance; typically better than the ,CPID [9, 14]. However, the optimal choice of control structure is not always well understood and correctly applied in many situations. This is particularly true in complex power electronic systems. Moreover, variety of PID control structures and tuning methods exist, and selecting the appropriate technique for implementation can cause problems.

Most existing literature typically focuses on a single FPID solution for a particular application of interest. The specific performance of the control system is then analyzed in detail, and practically demonstrated to achieve improved performance in a number of key areas. Such a narrow focus, whilst rigorous and fully justified, can make it very difficult for a practicing power electronic engineer to readily review, select, and directly apply an optimal control solution for alternative applications. It is important to emphasis that many papers present the mathematical principle of replacing a specific CPID controller with a specific FPID equivalent controller, especially in [14, 15]. However, only a small number of variants have been truly derived, and the methods of conversion are often limited to a few simple schemes. To the best of the author's knowledge, feed-forward FPID controllers are rarely considered.

In this paper, the authors attempt to make a significant contribution to knowledge and practice, by presenting the derivation of all possible structures of digital FPID controller, including feed-forward FPID structures. The library is of potential importance to power electronic engineers and control experts; since it will contain a ready-made optimal FLC structures for any target application. Secondly, unlike most existing literature, here a backward Euler rule approach is applied to convert from *s*-to-*z* domain, instead of the direct bilinear transformation presented in [14, 15]. This is a significant advance, as importantly compared to other work; it simplifies the hybrid FPID structures and allows an equivalent match between the derived CPID library and the FPID structures. From an implementation point of view, simplicity and ease of application is obviously a major advantage.

II. DIGITAL PID CONTROL STRUCTURES

In previous literature, Jasim [16] derived 27 continuous time domain PID structures (*ie. s*- domain). A similar analytical process is followed in this paper; however, here discrete domain PID structures are presented, and furthermore their FPID equivalents are also derived. Importantly, unlike the work in [16], this allows for direct controller design in state-of-the-art microprocessor based systems which are increasingly the popular in modern power electronic applications.

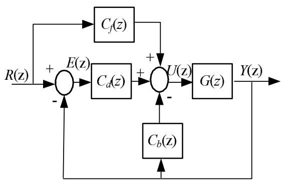

Fig. 1. Generic closed loop control structure.

Fig. 1 illustrates a block diagram of a generic closed loop control system. Here, the PID controller can be inserted in the feed-forward, feedback, or cascade path; transfer functions $C_f(z)$, $C_b(z)$, and $C_d(z)$ respectively. To develop the maximum number of PID structures, the transfer function blocks may consist of one or more of the PID elements (K_P, K_I, and K_D). From this, one can define 27 ($3^3 = 27$) potential structures of PID controller [16]. Generally, in the discrete domain, the control action can be defined as:

$$PU(z) = FR(z) - HY(z) \tag{1}$$

Where, $R(z)$ is the reference signal, $U(z)$ is the control action, and $Y(z)$ is the output signal. P, F, and H are z-domain polynomials. To clearly define these polynomials, for all possible PID control structures, it is preferable to start with the well-known parallel scheme of PID controller, described as follows:

$$U(s) = (K_P + \frac{K_I}{s} + K_D s)E(s) \tag{2}$$

By using the Backward Euler rule ($s = 1- z^{-1}/ T_s$) a digital PID controller is defined as:

$$U(z) = [K_P + \frac{T_s K_I}{1-z^{-1}} + \frac{K_D}{T_s}(1-z^{-1})]E(z) \tag{3}$$

Where, $E(z)$ is the control error signal which is given as [$E(z) = R(z) - Y(z)$], and T_s is the sampling rate. Letting:

$$K'_P = K_P, K'_I = T_s K_I, \text{and } K'_D = \frac{K_D}{T_s} \tag{4}$$

Then, the control action can generally be written as:

$$(1-z^{-1})U(z) = (K'_p(1-z^{-1}) + K'_I + K'_D(1-z^{-1})^2)[R(z) - Y(z)] \tag{5}$$

Now, by comparing (5) with (1), we have:

$$\begin{aligned} P &= (1-z^{-1}) \\ F &= K'_D(1-z^{-1})^2 + K'_P(1-z^{-1}) + K'_I \\ H &= K'_D(1-z^{-1})^2 + K'_P(1-z^{-1}) + K'_I \end{aligned} \tag{6}$$

The polynomial expressions in (6) are based on the arrangement of PID terms in the classic feedback control scheme. The equivalent block diagrams for all 27 possible digital PID structures can be easily derived. From this, we can also derive 27 expressions for the polynomials P, F, and H to comprehensively describe all 27 possible PID implementations. These are shown in Table 1. Note, all structures have the same expression for polynomial P; F describes the feedback path of the control system (if applicable), and H characterizes the feedforward path (if applicable).

III. FUZZY PID STRUCTURES

In general, there are two types of two-input fuzzy controller. The first type is the fuzzy PD type controller. In this structure, the control action is generated from the two input signals: "error" and "change in error". The second type is the fuzzy PI controller; the input signals are the same as the fuzzy PD controller but the control action is increased incrementally [17]. It is well known that controlling a closed loop system with a PD filter has limited contribution to the steady state performance. On the other hand, a PI controller alone has limited ability to optimize the dynamic performance of the system [18]. From this perspective, a "hybrid fuzzy PD and PI" controller is highly desirable [19], since this is capable of delivering the benefits of each controller type. However, several different control structures are available to construct the hybrid FPID controller. One classic method uses the three main variables of the CPID controller (loop error, derivative of the loop error and the integral of loop error) [19]. In this scheme, several design steps and rule bases are required to implement and tune the FPID parameters, hence it is not a trivial task to implement [2, 19]. To deal with this situation, a parallel connected FPI and FPD controller is more readily realized. Here, each part of the fuzzy controller has two input signals (error and change in error) [17]. There are two approaches to build the rule base of the FPID controller; either based on the characteristics of the CPID control or from heuristic knowledge [2]. With this in mind, the following section presents the development of the key FPID controller types. In the next sections we focus on driving all the possible structures of the FPID controllers that are matched with the derived digital CPID schemes presented in Table 1.

A. Forward Fuzzy [PD, PI, I, D, P] Controllers

1. *Forward Fuzzy PD (FPD) Controller*

By considering the PD terms in (3) only, the control action of the discrete PD controller is given as:

$$u_{PD}(z) = [K_P + \frac{K_D}{T_s}(1 - z^{-1})]E(z) \tag{7}$$

$$u_{PD}(nT_s) = K'_P e(nT_s) + K'_D[e(nT_s) - e(nT_s - T_s)] \tag{8}$$

Then, by dividing (8) by T_s [14], yields:

$$\frac{u_{PD}(nT_s)}{T_s} = K'_P \frac{e(nT_s)}{T_s} + K'_D \Delta e(nT_s) \tag{9}$$

Where:

$$\Delta e(nT_s) = \frac{e(nT_s) - e(nT_s - T_s)}{T_s} \tag{10}$$

Finally, replacing the term $u_{PD}(nT_s)/T_s$ by the term $K_{PD}u_{PD}(nT_s)$ [14], we obtain:

$$K_{PD}u_{PD}(nT_s) = K'_P \frac{e(nT_s)}{T_s} + K'_D \Delta e(nT_s) \tag{11}$$

Table 1. PID controller structures: summary of *P, H, F* polynomials.

Control Type	*P*	*H*	*F*
PID-1	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$
PID-2	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$	$K'_P(1-z^{-1})+K'_I$
PID-3	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$	K'_I
PID-4	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$	$K'_D(1-z^{-1})^2+K'_P(1-z^{-1})$
PID-5	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$	$K'_D(1-z^{-1})^2$
PID-6	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$	$K'_P(1-z^{-1})$
PID-7	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$	$K'_D(1-z^{-1})^2+K'_I$
PID-8	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$	$(1-z^{-1})$
PID-9	$(1-z^{-1})$	$K'_P(1-z^{-1})+K'_I$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$
PID-10	$(1-z^{-1})$	$K'_P(1-z^{-1})+K'_I$	$K'_D(1-z^{-1})^2+K'_P(1-z^{-1})$
PID-11	$(1-z^{-1})$	$K'_P(1-z^{-1})+K'_I$	$K'_D(1-z^{-1})^2+K'_I$
PID-12	$(1-z^{-1})$	$K'_P(1-z^{-1})+K'_I$	$K'_D(1-z^{-1})^2$
PID-13	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_I$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$
PID-14	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_I$	$K'_D(1-z^{-1})^2+K'_P(1-z^{-1})$
PID-15	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_I$	$K'_P(1-z^{-1})+K'_I$
PID-16	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_I$	$K'_P(1-z^{-1})$
PID-17	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_P(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$
PID-18	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_P(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_I$
PID-19	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_P(1-z^{-1})$	$K'_P(1-z^{-1})+K'_I$
PID-20	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_P(1-z^{-1})$	K'_I
PID-21	$(1-z^{-1})$	K'_I	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$
PID-22	$(1-z^{-1})$	K'_I	$K'_D(1-z^{-1})^2+K'_P(1-z^{-1})$
PID-23	$(1-z^{-1})$	$K'_P(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$
PID-24	$(1-z^{-1})$	$K'_P(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_I$
PID-25	$(1-z^{-1})$	$K'_D(1-z^{-1})^2$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$
PID-26	$(1-z^{-1})$	$K'_D(1-z^{-1})^2$	$K'_P(1-z^{-1})+K'_I$
PID-27	$(1-z^{-1})$	$(1-z^{-1})$	$K'_D(1-z^{-1})^2+K'_p(1-z^{-1})+K'_I$

Here, K_{PD} is a fuzzy output gain [14]. Equation (12) clearly shows that the control action is a non-linear function of the error $[e(nT_s)]$ and the change in error $[\Delta e(nT_s)]$:

$$K_{PD}u_{PD}(nT_s) = f\left[K'_P e(nT_s), K'_D \Delta e(nT_s)\right] \quad (12)$$

Practically, the input gains represented in Fig. 2 can be used for scaling the input signals within the universe of discourse. This improves the output response of the controlled system [2].

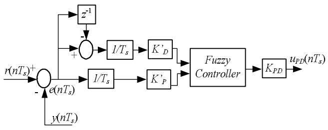

Fig. 2. Fuzzy PD control block diagram.

2. *Forward Fuzzy PI (FPI) Controller*

In this control scheme, we consider the control action output of the PI controller only in (3), and this can be rewritten in difference equation form as:

$$\begin{aligned} u_{PI}(nT_s) - u_{PI}(nT_s - T_s) = \\ K'_P[e(nT_s) - e(nT_s - T_s)] + K'_I e(nT_s) \end{aligned} \quad (13)$$

Here, $K'_P = K_P$ and $K'_I = K_I T_s$. Again, by dividing (13) by T_s, yield [14]:

$$\Delta u_{PI}(nT_s) = K'_P \Delta e(nT_s) + K'_I \frac{e(nT_s)}{T_s} \quad (14)$$

Where:

$$\begin{aligned} \Delta u_{PI}(nT_s) &= \frac{u_{PI}(nT_s) - u_{PI}(nT_s - T_s)}{T_s} \\ \Delta e(nT_s) &= \frac{e(nT_s) - e(nT_s - T_s)}{T_s} \end{aligned} \quad (15)$$

Now, the control action can be described as:

$$u_{PI}(nT_s) = u_{PI}(nT_s - T_s) + T_s \Delta u_{PI}(nT_s) \quad (16)$$

From this, the term $T_s \Delta u_{PI}(nT_s)$ of (16) can be replaced by the term $K_{PI} \Delta u_{PI}(nT_s)$ [15]:

$$u_{PI}(nT_s) = u_{PI}(nT_s - T_s) + K_{PI} \Delta u_{PI}(nT_s) \quad (17)$$

Where, K_{PI} is a fuzzy output gain of FPI controller (illustrate in Fig. 3). Equation (18) showing the non-linear functionality of the incremental control action with the error and the change in error:

$$K_{PI} \Delta u_{PI}(nT_s) = f\left[K'_P \Delta e(nT_s), K'_I e(nT_s)\right] \quad (18)$$

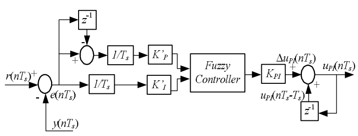

Fig. 3. Fuzzy PI control block diagram.

3. *Forward Fuzzy D (FD) controller*

The control action of the digital D controller in difference form can be described as:

$$u_D(nT_s) = K'_D[e(nT_s) - e(nT_s - T_s)] \quad (19)$$

Where, $K_{D'} = K_D/T_s$. Similar to the previous derivation, by dividing (19) by T_s we arrive at:

$$\frac{u_D(nT_s)}{T_s} = K'_D \Delta e(nT_s) \quad (20)$$

Now, we can replace the term $u_D(nT_s)/T_s$ by the term [14], $Ku_D u_D(nT_s)$ thus:

$$Ku_D u_D(nT_s) = K'_D \Delta e(nT_s) \quad (21)$$

Assume that Ku_D is the fuzzy output gain of FD controller.

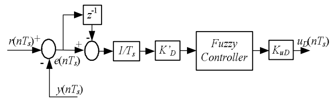

Fig. 4. Illustrates the forward FD controller.

4. *Forward Fuzzy I (FI) Controller*

The control action of the digital I in difference form control is given by:

$$u_I(nT_s) - u_I(nT_s - T_s) = K'_I e(nT_s) \quad (22)$$

Where, $K'_I = T_s K_I$. Now, dividing (22) by T_s:

$$\Delta u_I(nT_s) = K'_I \frac{e(nT_s)}{T_s} \quad (23)$$

Consequently:

$$u_I(nT_s) = u_I(nT_s - T_s) + Ku_I \Delta u_I(nT_s) \quad (24)$$

In this structure (Fig. 5), the Ku_I is the fuzzy output gain of FI controller.

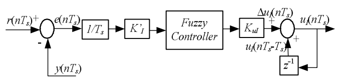

Fig. 5. Fuzzy I block diagram.

5. *Forward Fuzzy P (FP)*

Simply, the controller action of the P controller is defined as:

$$u_P(z) = K_P E(z) \quad (25)$$

As shows in Fig. 6, the control action is a function of the error signal only. Therefore, a simple fuzzy control design can be achieved by the fuzzy rule-base. An output gain (Ku_p) is added to the output of the FP controller for enhancing the output performance.

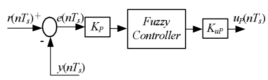

Fig. 6.Fuzzy P block diagram.

B. Feedback Fuzzy [PD, PI, I, D, P] Controllers

A similar procedure to the abovementioned derivative is followed to determine the Feedback fuzzy [PD, PI, P, I, D] controllers. The modification made in these paradigms is to change the error signals in the forward path with the output signal [$y(nT_s)$] in the feedback path. The following equations apply [15]:

$$u_{PD}(nT_s) = K'_P y(nT_s) + K'_D[y(nT_s) - y(nT_s - T_s)] \quad (26)$$

$$u_{PI}(nT_s) - u_{PI}(nT_s - T_s) = K'_P[y(nT_s) - y(nT_s - T_s)] + K'_I y(nT_s) \quad (27)$$

$$u_D(nT_s) = K'_D[y(nT_s) - y(nT_s - T_s)] \quad (28)$$

$$u_I(nT_s) - u_I(nT_s - T_s) = K'_I y(nT_s) \quad (29)$$

$$u_P(nT_s) = K'_P y(nT_s) \quad (30)$$

Blocks diagrams of the Feedback fuzzy [PD, PI, I, D, P] controllers can also be depicted similarly in the forward form; with the notable replacement of the error signal by the output signal. Appendix I clearly shows the result of this replacement. Ultimately, the fuzzy controller rule-base determines the final dynamic and steady state performance of the selected controller.

C. Feed-forward Fuzzy [PD, PI, I, D, P] Controllers

To derive the final equations in the feed-forward form, the signal $e(nT_s)$ in forward scheme or the signal $y(nT_s)$ in feedback form is substituted by the signal $r(nT_s)$ in the feed-forward form. This leads to the following equations:

$$u_{PD}(nT_s) = K'_P r(nT_s) + K'_D[r(nT_s) - r(nT_s - T_s)] \quad (31)$$

$$u_{PI}(nT_s) - u_{PI}(nT_s - T_s) = K'_P[r(nT_s) - r(nT_s - T_s)] + K'_I r(nT_s) \quad (32)$$

$$u_D(nT_s) = K'_D[r(nT_s) - r(nT_s - T_s)] \quad (33)$$

$$u_I(nT_s) - u_I(nT_s - T_s) = K'_I r(nT_s) \quad (34)$$

$$u_P(nT_s) = K'_P r(nT_s) \quad (35)$$

Once again, block diagrams for this controller variant are presented in Appendix I, Figs. II. (10, 11, 13, 14).

IV. HYBRID FUZZY PID CONTROLLER SCHEMES

In many applications, a hybrid fuzzy PID controller can be desirable; this is where elements of the CPID controller are combined with the FPID controller. This can be accomplished by inserting a conventional proportional, integral or derivative term in parallel with one of the derived FPD, FPI, FI or FD controller types. This modification reduces computational complexity, achieves simplicity of implementation, and the hybrid structure can offer superior dynamic performance [18, 20]. Usually, most structures have a hybrid combination which consists of a conventional forward path term, and a fuzzy feedforward or feedback path term. For instance, consider FPID structures with a FP control element in the final controller design (Appendix I; Figs. II. 10, 13, 14); the FP term can be replaced by a conventional gain (K_P). Examples of such hybrid implementations can be found in Appendix II.

V. CONCLUSION

Whilst it is relatively easy to implement a functional closed loop PID controller in industrial applications, finding and implementing an optimal solution can be more difficult. For this reason, this paper presents a comprehensive library of 27 different CPID/FPID control structures. By following the derivations described in this paper, state-of-the art control algorithms can readily be realized. Importantly, the schemes are based on the mathematical model of a digital PID controller, and are particularly relevant to microprocessor based control systems. Notably, in this paper a backward Euler rule approach is applied to convert from s-to-z domain, instead of the direct bilinear transformation. As a result, all control structures presented have single, or two-input, FPID controllers to reduce the complexity of the rule base. Furthermore, all derived forms have input scaling gains and fuzzy output gains to satisfy the operational range and improve the final dynamic performance. Conventional PID control methods can be applied to determine the scaling gains. Ongoing research focuses on the real-time implementation of the optimal FPID control structure for different topologies of DC-DC switch mode power converters.

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APPENDIX I: DIGITAL FPID CONTROLLERS

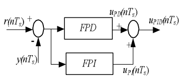


Fig. II.1 Hybrid FPID-1

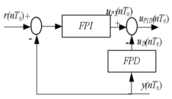


Fig. II.2 Hybrid FPID-2

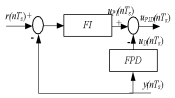
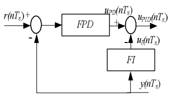


Fig. II.3 Hybrid FPID-3



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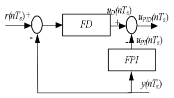

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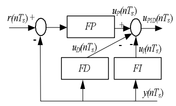

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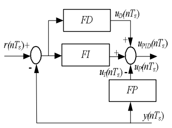

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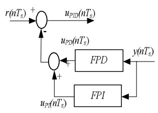


Fig. II.8 Hybrid FPID-8

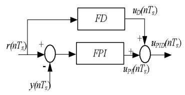


Fig. II.9 Hybrid FPID-9

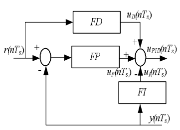


Fig. II.10 Hybrid FPID-10

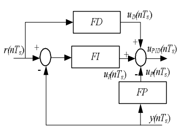


Fig. II.11 Hybrid FPID-11

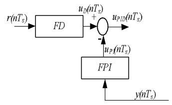
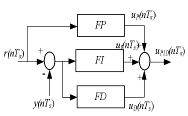


Fig. II.12 Hybrid FPID-12



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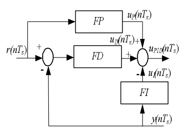

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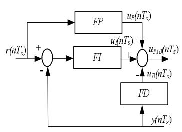

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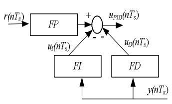

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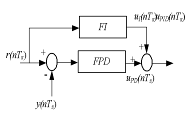

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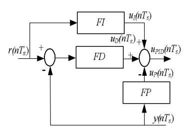

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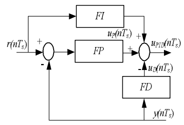

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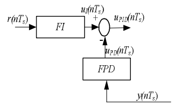
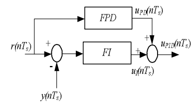


Fig. II.20 Hybrid FPID-20



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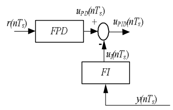

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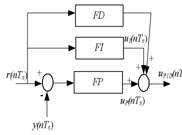

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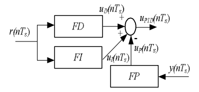

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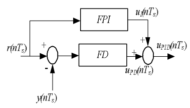

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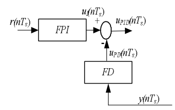

Fig. II.26 Hybrid FPID-26

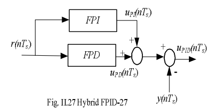

Fig. II.27 Hybrid FPID-27

APPENDIX II: EXAMPLES OF HYBRID CONVENTIONAL/DIGITLA FPID CONTROLLERS

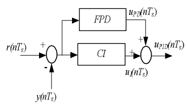

Fig. III.1 Hybrid FPD+I

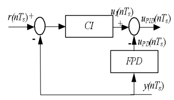

Fig. III.2 Hybrid I+FPD

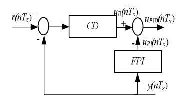

Fig. III.3 Hybrid D+FPI