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# Fractional order PID Controller: Design and Comparison with Conventional PID Controller for the Robust Control of DC Motor using Fuzzy SMC

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***Abstract:*** *This paper presents a robust control of DC Motor using fuzzy sliding mode control scheme and the additional Fractional PID controller. The additional controller relaying on the sliding-mode theory is used to improve the dynamical characteristics of the drive system. Sliding mode control method is studied for controlling DC motor because of its robustness against model uncertainties and external disturbances. In this method, using high control gain to overcome uncertainties lead to occur chattering phenomena in control law which can excite unmodeled dynamics and maybe harm the plant. In order to enhancement the sliding mode controller performance, we have used fuzzy logic. For this purpose, we have used a Fractional PID outer loop in the control law then the gains of the sliding term and Fractional PID term are tuned on-line by a fuzzy system, so the chattering is avoided and response of the system is improved against external load torque here. Presented implementation results on a DC motor confirm the above claims and demonstrate the performance improvement in this case.*

***Keywords:*** *Fractional PID Controller, PID Controller, Sliding Mode, Fuzzy logic, DC Motor.*

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## I. Introduction

The PID controller is by far the most dominating form of feedback in use today. Due to its functional simplicity and performance robustness, the proportional-integral-derivative controller has been widely used in the process industries. The PID controllers have remained, by far; the most commonly used in practically all industrial feedback control applications. PID controllers have been used for several decades in industries for process control applications .The reason for their wide popularity lies in the simplicity of design and good performance including low percentage overshoot and small settling time for slow process plants. The most appreciated feature of the PID controllers is their relative easiness of use, because the three involved parameters have a clear physical meaning. This makes their tuning possible for the operators also by trial-and error and in any case a large number of tuning rules have been developed. Although all the existing techniques for the PID controller parameter tuning perform well, a continuous and an intensive research work is still underway towards system control quality enhancement and performance improvements. On the other hand, in recent years, it is remarkable to note the increasing number of studies related with the application of fractional controllers in many areas of science and engineering. This fact is due to a better understanding of the fractional calculus potentialities. In the field of automatic control, the fractional order controllers which are the generalization of classical integer order controllers would lead to more precise and robust control performances. Although it is reasonably true that the fractional order models require the fractional order controllers to achieve the best performance, in most cases the researchers consider the fractional order controllers applied to regular linear or non-linear dynamics to enhance the system control performances. For design and tuning of PID controller parameters we use optimization method. Specifications, stability, design, applications and performance of the PID controller have been widely treated, but generalization of the PID controller, namely the $PI^{\lambda}D^{\mu}$ controller, involving an integrator of order λ and a differentiator of order μ has the better response in comparison with the classical PID controller. The form of fractional PID followed by:

$$c(s) = K_p + \frac{K_i}{S^{\lambda}} + K_d S^{\mu} \qquad (1)$$

The interest of this kind of controller is justified by a better flexibility, since it exhibits fractional powers (λ□,μ□) of the integral and derivative parts, respectively. Thus, five parameters can be tuned in this structure (λ, μ,□ $K_p$, $K_i$, $K_d$ ), that is, two more parameters than in the case of a conventional PID controller (λ=1,μ=1).

They are widely use in industry A genetic algorithm was used to find the optimum tuning parameters of the Fractional PID controller by taking integral absolute error as fitting function .

Sliding mode control (SMC) is one of the popular strategies to deal with uncertain control systems. The main feature of SMC is the robustness against parameter variations and external disturbances. The sliding mode control is robust to plant uncertainties and insensitive to external disturbances. It is widely used to obtain good dynamic performance of controlled systems. However, the chattering phenomena due to the finite speed of the switching devices can affect the system behaviour significantly. Additionally, the sliding control requires the knowledge of mathematical model of the system with bounded uncertainties. Reduced chattering may be achieved without sacrificing robust performance by combining the attractive features of fuzzy control with SMC. Fuzzy logic is a potent tool for controlling ill-defined or parameter-variant plants. By generalizing Fuzzy rules, a Fuzzy logic controller can cope well with severe uncertainties. Fuzzy schemes with explicit expressions for tuning can avoid the heavy computational burden. It is necessary to know system's mathematical model or to make some experiments for tuning PID parameters. However, it has been known that conventional PID controllers generally do not work well for non-linear systems, and particularly complex and vague systems that have no precise mathematical models. To overcome these difficulties, various types of modified conventional PID controllers such as auto-tuning and adaptive PID Controllers were developed lately. Also Fuzzy Logic Controller (FLC) can be used for this kind of problems. When compared to the conventional controller, the main advantage of Fuzzy logic is that no mathematical modelling is required

In this the combined solution we have proposed and designed a robust controller. We have used a Fractional PID outer loop in the control law then the gains of the sliding term and Fractional PID term are tuned on-line by a Fuzzy system.

## II. Fundamentals Of Fractional Calculas

Fractional calculus has gained wide acceptance in last couple of years. J Liouville made the first major study of fractional calculus in 1832. In 1867 A. K. Grunwald worked on the fractional operations. G. F. B. Reimann developed the theory of fractional integration in 1892. Fractional order mathematical phenomena allow us to describe and model real object more accurately than the classical integer methods.

The past decade has seen an increase in research efforts related to fractional calculus and use of fractional calculus in control system. For a control loop perspective there are four situations like (i) integer order plant with integer order controller. (ii) Integer order plant with fractional order controller. (iii) Fractional order plant with integer order controller. (iv) Fractional order plant with fractional order controller. Fractional order control enhances the dynamic system control performance.

Fractional order calculus is an area where mathematicians deal with derivatives and integrals from non integer orders. Gamma function is simply the generalization of factorial for all real numbers. The definitions of gamma function is given by

$$\Gamma(\boldsymbol{x}) = \int_{\boldsymbol{0}}^{\infty} \boldsymbol{z}^{\boldsymbol{x-1}}\, \boldsymbol{e}^{-\boldsymbol{z}} \boldsymbol{dz}$$

$$\Gamma(x) = (x-1)! \qquad (2)$$

Differ integral operator is denoted by ${}_aD_t^{\alpha}$. It is the combination of differentiation and integration operation commonly used in fractional calculus. Reimann- Liouville definition for ${}_aD_t^{\alpha}$ is

$$aD_t^{\alpha} = \begin{cases} \frac{d^{\alpha}}{dt^{\alpha}} & \alpha > 0 \\ 1 & \alpha = 0 \\ \int_a^t (dt)^{-\alpha} & \alpha < 0 \end{cases} \qquad (3)$$

Here α is the fractional order, a and t are the limits.

## III. Fractional Order PID Controllers

One of the primary controllers is PID controller, which is widely used. Fractional controller is denoted by $PI^{\lambda}D^{\mu}$ was proposed by Igor Podlubny in 1997, here λ and μ have non-integer values. Figure 1 shows the block diagram of fractional order PID Controller.

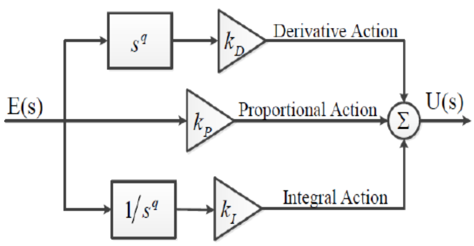


**Fig.1** Fractional order PID Controller

The transfer function for conventional PID controller is

$$G_{PID}(S) = \frac{u(s)}{e(s)} = K_c\left(1 + \frac{1}{T_i S} + T_d S\right) \qquad (4)$$

The transfer function for fractional order PID controller is

$$G_{FOPID}(S) = \frac{u(s)}{e(s)} = K_c\left(1 + \frac{1}{T_i S^{\lambda}} + T_d S^{\mu}\right) \qquad (5)$$

Where λ and μ are an arbitrary real numbers, Kc is amplification (gain), Ti is integration constant and Td is differentiation constant. Taking λ=1 and μ=1, a classical PID controller is obtained. For further practical digital realization, the derivative part has to be complemented by first order filter. The filter is used to remove high frequency noise.

$$G_{FOPID}(S) = \frac{u(s)}{e(s)} = K_c\left(1 + \frac{1}{T_i S^{\lambda}} + \frac{T_d S^{\mu}}{\frac{T_d}{N}S+1}\right) \qquad (6)$$

The $PI^{\lambda} D^{\mu}$ controller is more flexible and gives an opportunity to better adjust the dynamics of control system. Its compact and simple but the analog realization of fractional order system is very difficult.

Intuitively, the FOPID has more degree of freedom than the conventional PID. It can be expected that the FOPID can provide better performance with proper choice of controller parameters. However, with more parameters to be tuned, the associated optimization problem will be more difficult to deal with. It is motivated to develop a systematic procedure for the FOPID optimization to achieve a certain performance.

## IV. Model of Dc Motor

DC motors are widely used in industrial and domestic equipment. The control of the position of a motor with high accuracy is required. The electric circuit of the armature and the free body diagram of the rotor are shown in fig .2.

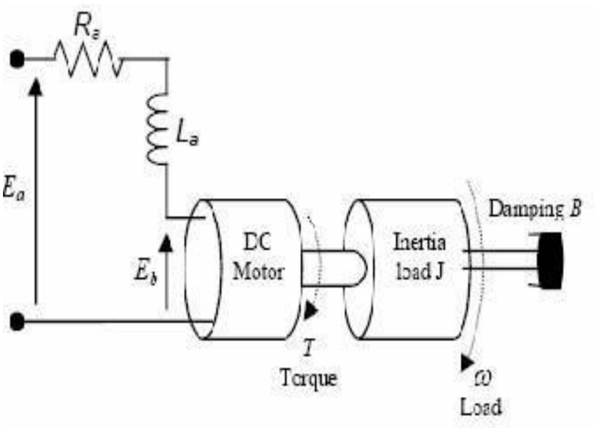


**Fig.2** The Structure Of a DC Motor

A desired speed may be tracked when a desired shaft position is also required. In fact, a single controller may be required to control both the position and the speed. The reference signal determines the desired position and/or speed. The controller is selected so that the error between the system output and reference signal eventually tends to its minimum value, ideally zero. There are various DC motor types. Depending on type, a DC motor may be controlled by varying the input voltage whilst another motor only by changing the current input. In this paper a DC motor is controlled via the input voltage. The control design and theory for controlling a DC motor via current is nearly the same. For simplicity, a constant value as a reference signal is injected to the system to obtain a desired position. However, the method works successfully for any reference signal, particularly for any stepwise time-continuous function. This signal may be a periodic signal or any signal to get a desired shaft position, i.e. a desired angle between 0 and 360 degrees from a virtual horizontal line. The dynamics of a DC motor may be expressed as:

$$E_a = R_a I_a + L_a\left(\frac{dI_a}{dt}\right) + E_b$$

$$T = J\left(\frac{d\omega}{dt}\right) + B\omega - T_l$$

$$T = K_T I_a \ ; \quad E_b = K_b \omega \qquad (7)$$

$$\left(\frac{d\omega}{dt}\right) = \Theta$$

With the following physical parameters: $E_a$: The input terminal voltage (source), (v);
$E_b$: The back emf, (v); $R_a$: The armature resistance, (ohm);
$I_a$: The armature current (Amp);
$L_a$: The armature inductance, (H);

J: The moment inertial of the motor rotor and load, (Kg.m2/s2);
T: The motor torque, (Nm)
ω: The speed of the shaft and the load (angular velocity), (Rad/s);
ϴ; The shaft position, (rad);
B: The damping ratio of the mechanical system, (Nms);
$K_T$: The torque factor constant, (Nm/Amp);
$K_b$: The motor constant (v-s/ rad). Block diagram of a DC motor is shown in fig.3.

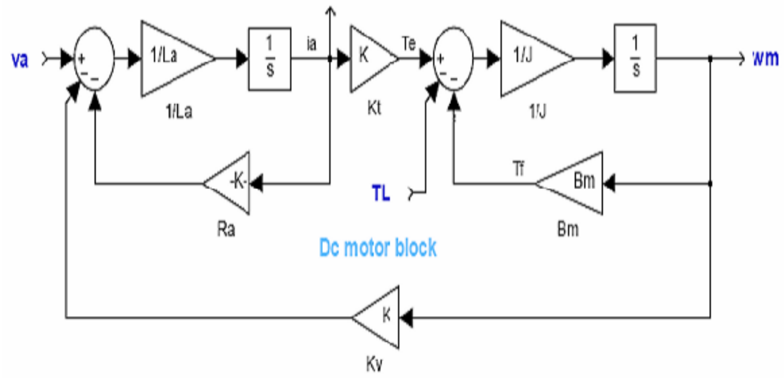


**Fig.3** Block diagram Of a DC Motor

## V. Sliding Mode Controller

A Sliding Mode Controller is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that can map plant state to a control. Surface and the switching among different functions are determined by plant state that is represented by a switching function. Without lost of generality, consider the design of a sliding mode controller for the following second order system: Here u(t) is the input to the system:

$u=u_s+u_{eq}$ (8)

Where u= -ksat(s/φ) and constant factor φ defines thickness of the boundary layer.
Sat(s/φ) is a saturation function that is defined as:

$$sat\left(\frac{s}{\varphi}\right) = \begin{cases} \frac{s}{\varphi}, & if\left|\frac{s}{\varphi}\right| \leq 1 \\ sgn\frac{s}{\varphi}, & if\left|\frac{s}{\varphi}\right| > 1 \end{cases} \qquad (9)$$

The function between $u_s$ and s/φ is shown in fig.4.

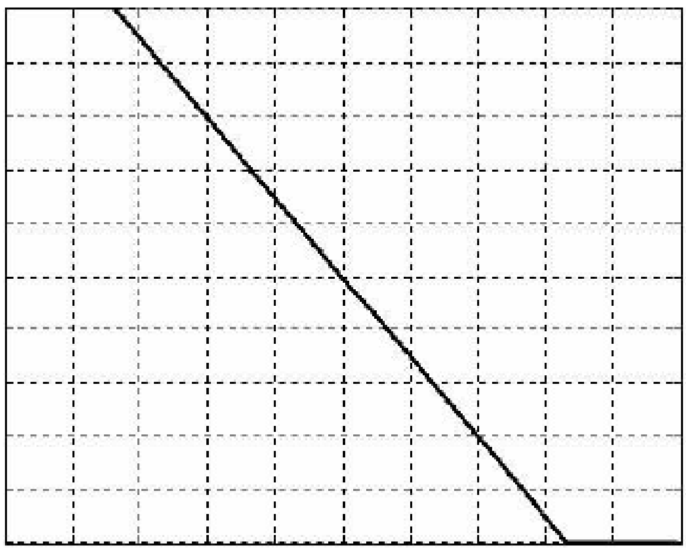

**Fig 4.** Switching surface in the phase plane

The control strategy adopted here will guarantee the system trajectories move toward and stay on the sliding surface s=0 from any initial condition if the following condition meets

$ss \leq \boldsymbol{\eta}\,|s|$ (10)

Where $\boldsymbol{\eta}$ is a positive constant that guarantees the system trajectories hit the sliding surface infinite time .Using a sign function often causes chattering in practice. One solution is to introduce a boundary layer around the switch surface. This controller is actually a continuous approximation of the ideal relay control. The consequence of this control scheme is that invariance of sliding mode control is lost. The system robustness is a function of the width of the boundary layer. The principle of designing sliding mode control law for arbitrary-order plants is to make the error and derivative of error of a variable is forced to zero. In the DC motor system the position error and its derivative are the selected coordinate variables those are forced to zero. Switching surface design consists of the construction of the switching function. The transient response of the system is determined by this switching surface if the sliding mode exists. First, the position error is introduced

$e(k)=\Theta_{ref}(k)-\Theta(k)$ (11)

Where $\Theta_{ref}$ (k), $\Theta$ (k) are the respective responses of the desired reference track and actual rotor position, at the K the sampling interval and e(k) is the position error. The sliding surface (s) is defined with the tracking error (e) and its ◎◎integral (∫edt) and rate of change ( e )

$S=\dot{e}+\lambda_1 e+\lambda_2 \int e\,dt$ (12)

Where $\lambda_1$, $\lambda_2$>0 are strictly positive real constant. The basic control law of Sliding Mode Controller is given by

$u=-k\,sgn(s)$ (13)

Where k is a constant parameter, sgn( ) is a sign function and s is the switching function.

## VI. Design Of Fuzzy Fractional Pid Sliding Mode Control

**In** this section, a fuzzy sliding surface is introduced to develop a sliding mode controller. Which the expression ksat(s/φ) is replaced by an inference fuzzy system for eliminate the chattering phenomenon.In addition, to improve the response of system against external load torque, the sliding mode controller designs with a Fractional PID out loop. The designed fuzzy logic controller has two inputs and an output. The inputs are sliding surface (s) and the change of the sliding surface in a sample time, and output is the fuzzy gain ($k_{fuzz}$).The fuzzy controller consists of three stages: Fuzzyfication, inference engine and Defuzzyfication. Then, a 3*3 rule base was defined (Table 1) to develop the inference system. Both Fuzzyfication and inference system were tuned experimentally.

The membership function of inputs variable and control variable are depicted in Fig. 5, 6 resp.

TABLE I FUZZY FRACTIONAL PID RULE TABLE

| S / $\dot{s}$ | N | Z | P |
|---|---|---|---|
| N | NB | NM | Z |
| Z | NM | Z | PM |
| P | Z | PM | PB |

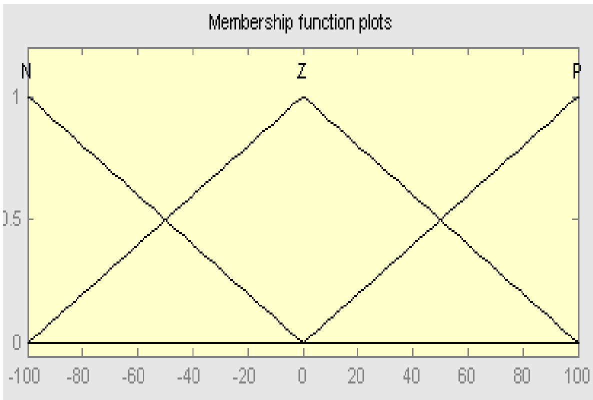


**Fig 5.** Membership function for Input variables

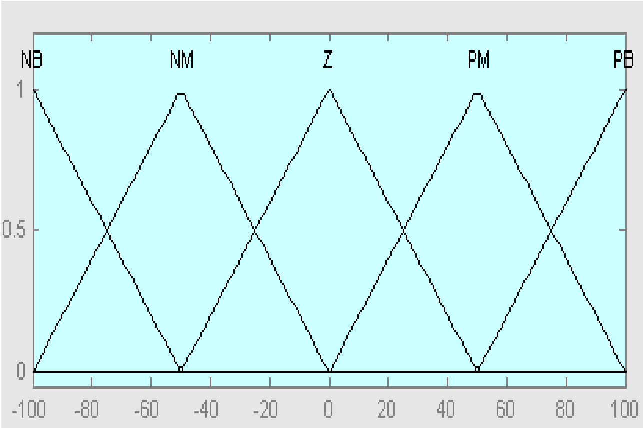


**Fig 6.** Membership function for Control variable

Fig.7 shows the Simulink model for the DC Motor using PID Controller along with Fuzzy sliding mode control. For the robust control of DC Motor the fractional order PID Controller & PID Controller are designed and simulated using Simulink model

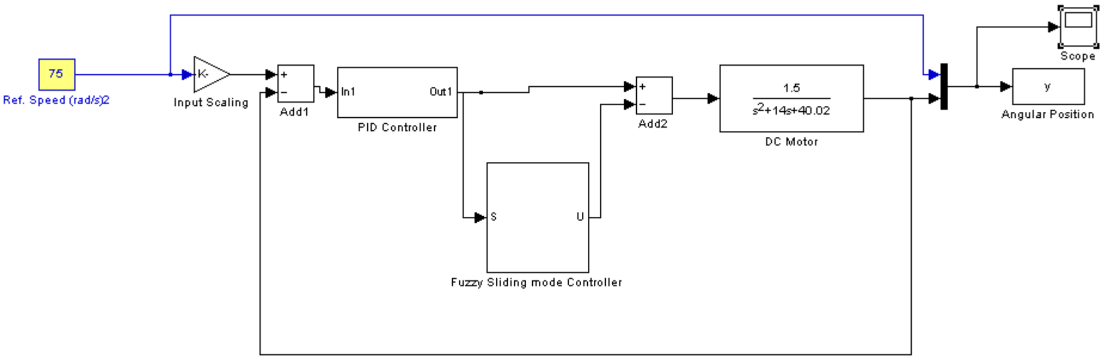


**Fig.7** Simulink Model of DC Motor using PID Controller with Fuzzy sliding Mode Control

Fig.8 shows the Simulink Model of DC Motor using Fractional order PID Controller with Fuzzy SMC

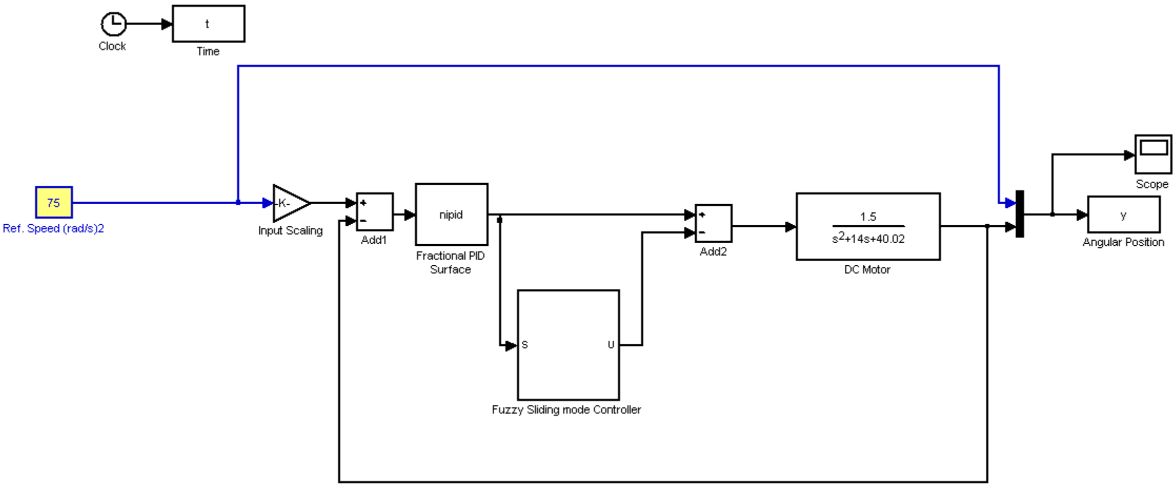


**Fig.8** Simulink Model of DC Motor using FOPID Controller with Fuzzy Sliding Mode Control.

## VII. Simulation Results

**I**n this section, the overall model of DC motor with sliding mode controller and fuzzy logic and Fractional PID is implemented in MATLAB/Simulink. The simulink model of the PID with Fuzzy SMC is shown in Fig. 7. And the Simulink Model of FOPID with Fuzzy SMC is shown in Fig.8. The system is tuned for the following parameter for the PID Controller.

$K_P = 12$
$K_i = 0.01$
$K_d = 0.01$

PID controller works well for the system with fixed parameters. However, in the presence of large parameter variations or major external disturbances, the PID controllers usually face trade-off between:
i. Fast response with significant overshoot.
ii. Smooth but slow response.

For a DC Motor system a controller with more number of tuning parameters and which works well for the complex non-linear systems is to be used. Fractional PID controller is one such controller which is to be design for the DC Motor control. A fractional PID controller is designed for the system by experimental method with following parameters:

Kp = 12
Ki = 0.01
$\lambda = 0.2$
Kd= 0.01
$\mu = 0.5$

Fig.9 shows the comparison of the response of the system using conventional PID with FSMC and Fractional PID Controller with FSMC.

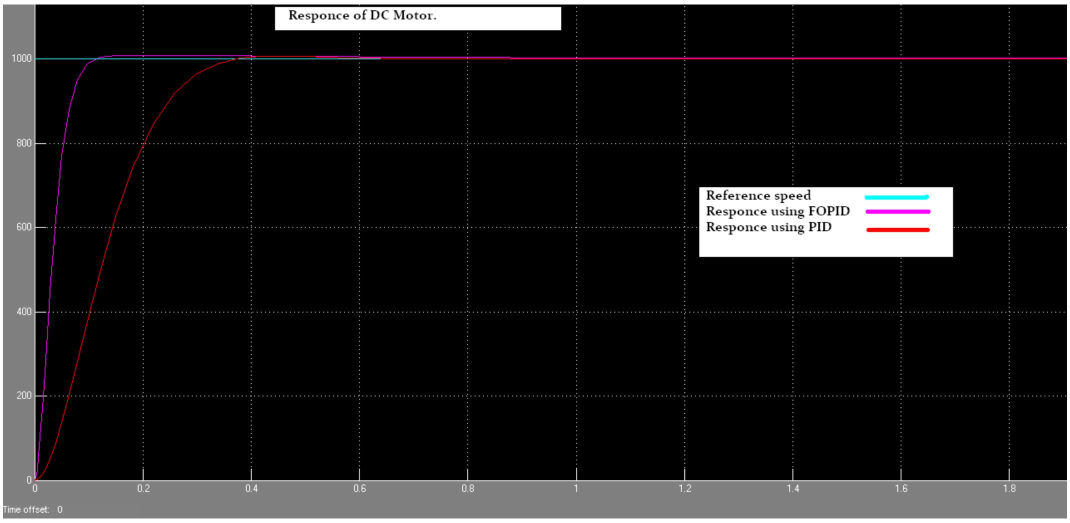


**Fig.9** Comparison of results for conventional PID with FSMC & FOPID with FSMC

## VIII. Conclusion

In present work, performance comparison of PID controller with that of fractional order PID controller is presented. Firstly, a simulation model of DC Motor is constructed with the help of MatLab/Simulink module. Then, performance comparison of PID controller with that of fractional order PID controller are simulated and studied. Comparing the responses with the ones obtained (in simulation) with the PID controller, the better performance of the system with the fractional order PID controller was observed. Fractional order PID controller for integer order plants offer better flexibility in adjusting gain and phase characteristics than the PID controllers, owing to the two extra tuning parameters i.e. order of integration and order of derivative in addition to proportional gain, integral time and derivative time.

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