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Review

A literature review on linear and non-linear controllers: A MATLAB approach

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Abstract: In this article, a review of conventional, optimal, nonlinear and intelligent controllers is presented. High accuracy, reliability, robustness, good range of speed control, compact size, less maintenance and high performance are the primary requirement of an electric drives. A proper controller must be selected in order to bring all of the above-mentioned qualities into an electric drive. In order to have an overall idea of the performance each controller, a common objective is achieved with Direct Current (DC) motor as a plant in closed loop. Proportional integral derivative (PID) controller, model predictive controller (MPC), sliding mode controller (SMC) and fuzzy logic controller (FLC) are used as representative of conventional, optimal, nonlinear and intelligent controller respectively. There is a tradeoff between the desired response and ease of the controller design. Therefore, the selection of controller has drawn increasing attention from research and industry applications. The DC motor mathematical model is used to emphasis the powerful and proper study of the closed loop response with each controller separately. The study has been carried out with the help of MATLAB simulation to bring out more simplicity in result analysis.

Keywords: PID control; model predictive control; sliding mode control; fuzzy logic control

1. Introduction

Due to better dynamic characteristics, DC motors are first choice in the majority of industrial applications over the induction motors. The necessary to implement control algorithms and test its performance in a more realistic way using mathematical models has been of the maximum importance [1]. In [2, 3] closed loop control of DC motor position control is designed with proportional integral derivative (PID) controller and its effect in a closed loop feedback system is presented. Validation of the results is highlighted by calculating the position of a DC motor in a closed-loop system. PID tuner tool in MATLAB is used to improve the performance. In [4-6] the speed control of DC motor is achieved with proportional integral (PI) controller and model predictive controller (MPC). Comparison of both controllers shows that MPC gives zero steady state error, decreases peak overshoot. Accurate performance can be obtained by minimizing cost function. But the implementation of MPC required high computational capability hardware.

In [7-9] the sliding mode controller (SMC) based on variable structure systems for DC motor speed control is designed. The performance of SMC is studied against PI controller and result shows that SMC gives better response against system parameter changes and load disturbances. SMC has advantages of high speed, more accuracy and simple, but it suffers with a drawback chattering phenomenon. In [10-12] the performances of the fuzzy logic controller (FLC) based DC motor speed control was investigated and it is compared with conventional PI controller based drive. PI controller requires tuning parameter values whereas FLC is based on rule-based. The simulation results of fuzzy and conventional controller are compared. FLC gives better transient and steady state performance also it is more robust for speed control applications. In [13] linear, non-linear and intelligent control methods are designed for inverted pendulum on a cart and the performance of various controllers are discussed, but the simulation results are not compared. In this paper, proportional integral derivative controller, model predictive controller, sliding mode controller and fuzzy logic controller are designed for the speed control of DC motor and tuned to set rise time at 2 sec. MATLAB/ Simulink is used to illustrate each controller response and comparison.

This paper is organized as follows: mathematical model of DC motor is given in section 2. PID controller implementation for DC motor and tuning of it is shown in section 3. Model predictive control algorithm and its implementation for the given plant are illustrated in section 4. The robustness of sliding mode controller against uncertainties and external disturbance is explained with simulation in section 5. Implementation of fuzzy logic controller for the speed control of DC motor is done in section 6. Time response of speed control of DC motor using conventional control, model based method, optimal control method and intelligent control method is compared in section 7. Conclusion remarks are made in section 8.

2. DC Motor

The open loop transfer function of armature controlled DC motor is given by the ratio of laplace transform of output speed to the laplace transform of input voltage [14-15]. It is given in Eq(1) and the same is used as plant in the chapters 3 to 6.

$$\frac{\omega(s)}{v_a(s)} = \frac{K_m}{(L_a s+R_a)(Js+B)+K_b K_m} \tag{1}$$

Eq(2) is obtained by substituting R_a = 0.4 (Ω), L_a=2.7 (H), J = 0.0004 (kg-m^2), B = 0.0022 (N-m-s/rad), K_m=0.015 (N-m/A), and K_b=0.05 (V-s) in Eq(1). Eq(2) is implemented in MATLAB as shown in figure 1.

$$\frac{\omega(s)}{v_a(s)} = \frac{15}{1.08s^2+6.1s+1.63} \tag{2}$$

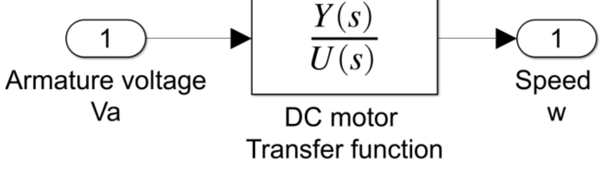

Figure 1. MATLAB implementation of DC motor

3. Proportional-integral-derivative controller

Typical block diagram of closed loop control system is shown in figure 2. Proportional integral derivative (PID) controllers have been playing an important role in control system engineering several decades. PID controller is a sum of proportional of error, integral of error and derivative of error and its block diagram is shown in figure 3. The transfer function of ideal or non-interacting form of PID controller with derivative filter is expressed in Eq(3)[16-20].

$$\frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{sT_i} + \frac{sT_d}{1+\frac{sT_d}{N}}\right) \quad (3)$$

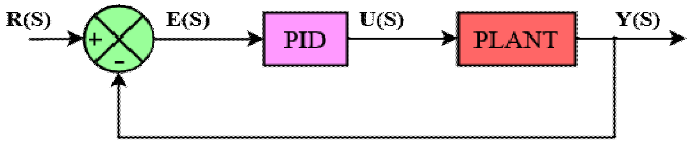

Figure 2. Block diagram of closed loop system

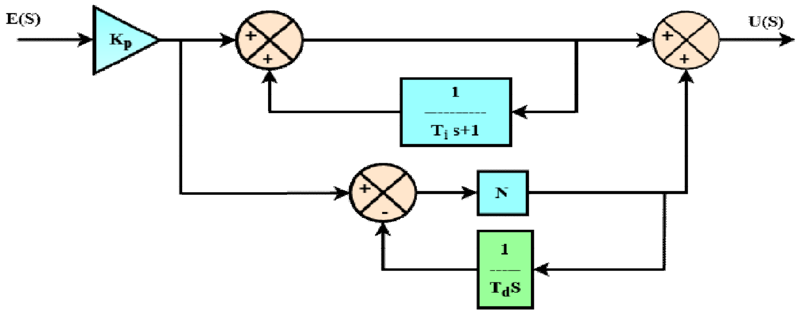

Figure 3. Block diagram of PID controller with filter

3.1 Proportional control action

Proportional controller produces proportional kick directly proportional to the present value of error with proper sign. Proportional term takes care of current error. It reduces error but leaves steady state error.

3.2 Integral control action

Drawback of proportional action is fixed by integral term. Integral action integrates the past error from time t = 0 to t = t_p (present time). It automatically corrects the control variable value and nullifies steady state error. Integral controller is also called as automatic reset. Integral action causes reduction in rise time, makes system oscillatory and reduces system stability.

3.3 Derivative control action

Derivative action exercises the estimation of error and generates appropriate correction prior to actual change. Derivative action also called as anticipatory control. Derivative action amplifies high frequency measurement noise, so derivative term used with low pass filter. Typical value of filter coefficient N varies from 2 to 20.

It is not necessary to consider all the three terms for a given plant. Simple control structure that gives the required performance may be considered. In case of multi- input multi-output (MIMO) system, each loop requires individual and independent PID controller. There is no coordination among loops. For a dynamic system, proper tuning of PID parameters is a challenging task.

3.4 PID controller tuning techniques

Selection of K_p, T_i, T_d and N values is called tuning of PID. One may manually choose the tuning parameter in a trial-and-error method, but the result highly depends on the operator's skill. Tuning rules help to find tuning parameters with less effort[21-23]. List tuning methods are given in figure 4.

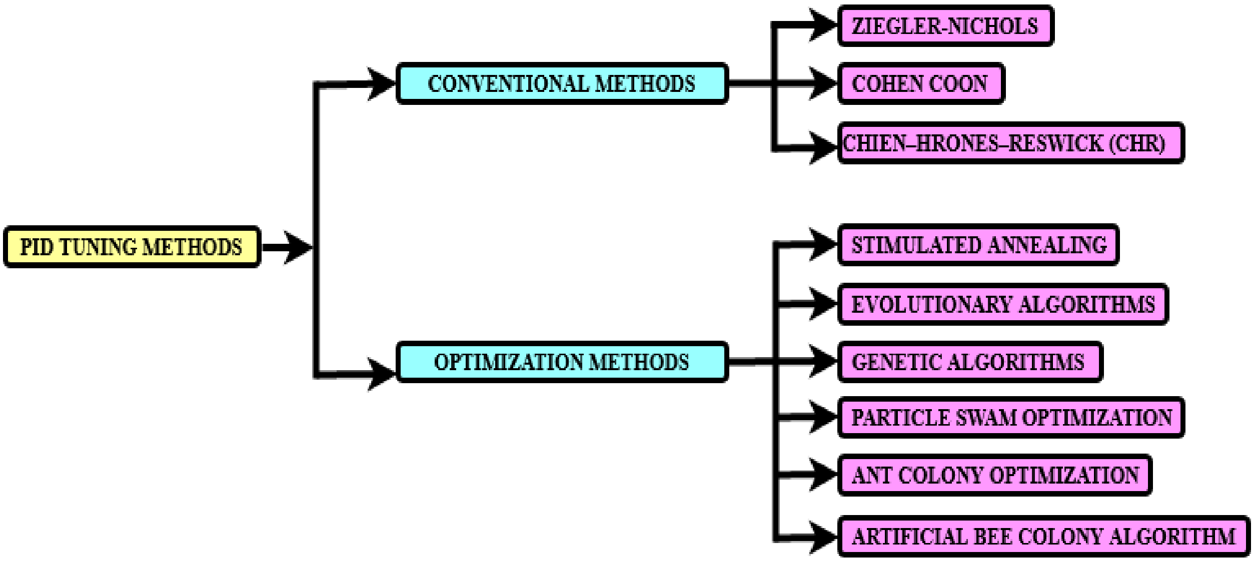

Figure 4. Different tuning methods

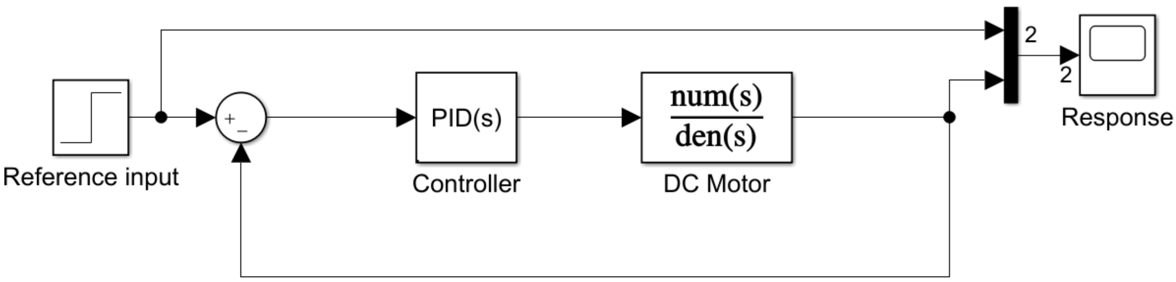

Figure 5. Simulation diagram of speed control of DC motor with PID controller

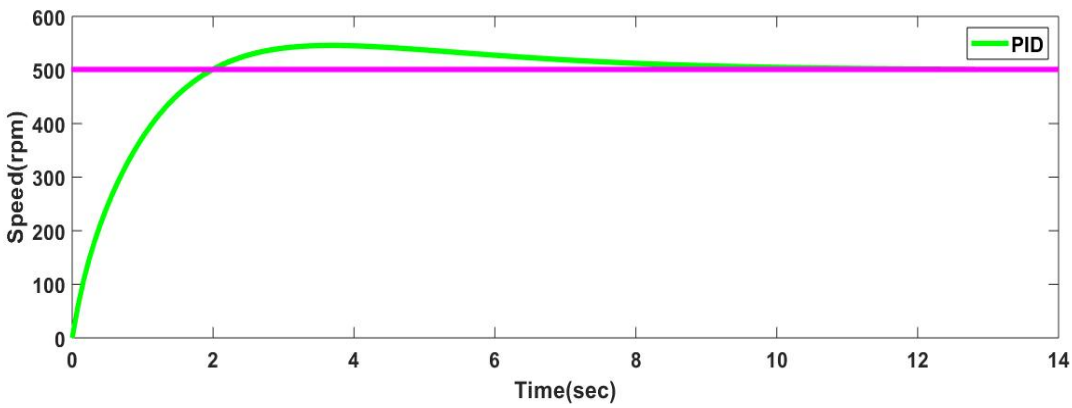

Figure 6. Closed loop response with PID controller

Simulation diagram of speed control of DC motor is shown in figure 5. The step response of the plant is shown in figure 6. The desired value of rise time is 2 sec is achieved. PID controller is designed with PID Tuner command in MATLAB.

4. Model predictive control

MPC algorithm refers to a category of optimal control. It requires mathematical model of the plant, objective function and optimizer as shown in figure 7. It optimizes an objective function, foresees long-term behavior of the plant and can handle constraints on manipulated and controlled variable. Realization of MPC requires hardware with high computational capacity to solve optimization algorithm [24-31].

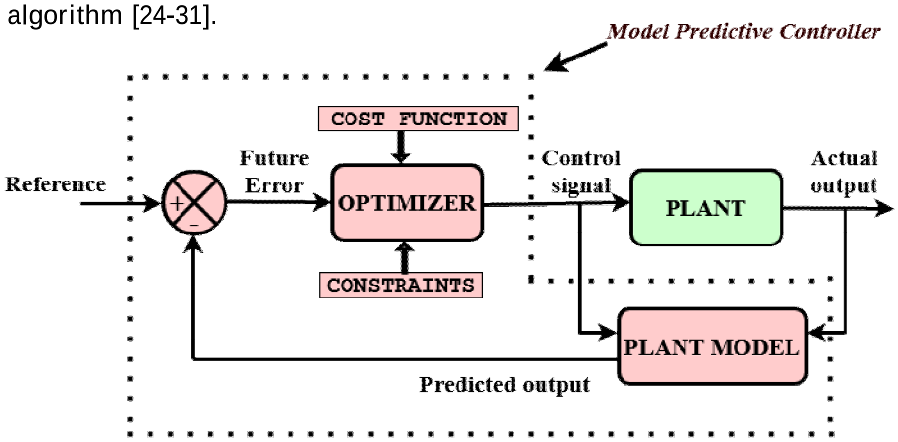

Figure 7: Block diagram of MPC controller

4.1 Receding horizon

The distinguishing feature of MPC is receding horizon strategy as shown in figure 8. The number of predictions P is referred to as the prediction horizon N_p while the number of control moves M is called the control horizon N_u. According to this strategy, at time step $t=kT_s$, optimizer solves cost function to find $(k+N_u-1)$ optimal control sequence over a finite control horizon. Eq (4) gives the cost function J.

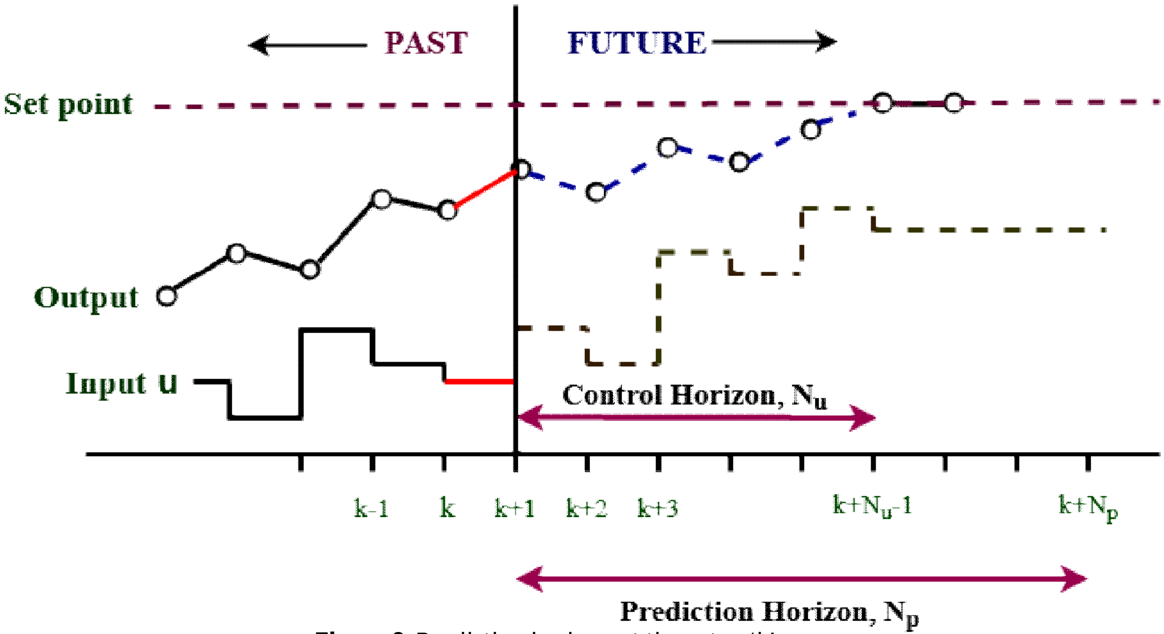

Figure 8. Prediction horizon at time step 'k'

$$J(u) = \sum_{i=N_1}^{N_p} [y(k+i) - y^*(k+i)]^2 + \lambda \sum_{i=1}^{N_u} \Delta u^2 (k+i-1) \quad (4)$$

The control input signal 'u' is subjected with following constraints,

$u_{min} \leq u(k+l|k) \leq u_{max}$

$|\Delta u(k+l|k)| \leq \Delta u_{max},$ $\quad k=0,\ldots\ldots,N_u-1$

$$y_{min} \le \quad y(k+j|k) \le y_{max}, \qquad\qquad j = 1,\ldots\ldots,N_p$$

MPC goal is to find u*(0), u*(1),……..u*(k+N_u-1). This can be achieved by optimizing cost function with constraints optimization algorithm to find the optimal control action. The optimizer provides the control actions. The first control signal in the sequence is applied to the plant and the rest are discarded. The size of the optimization problems depends on the number of variables and the prediction horizon. Controller design is the process of structuring and tuning a controller that meets customer requirements. Design of linear MPC for the plant and its response are shown in figure 9 and 10.

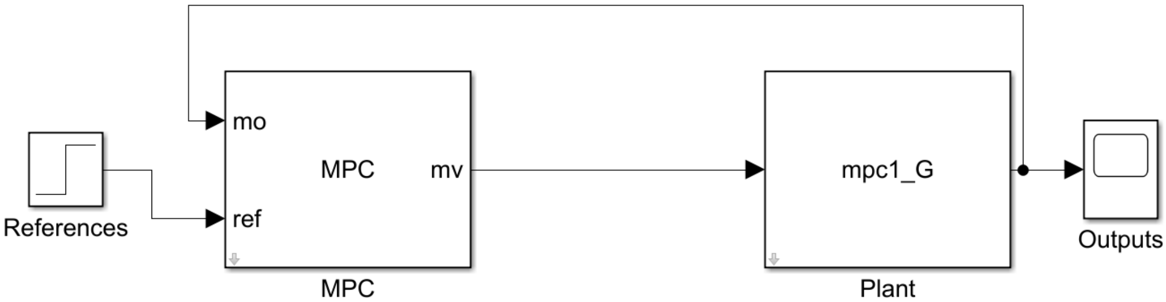

Figure 9. Simulation diagram of speed control of DC motor with MPC

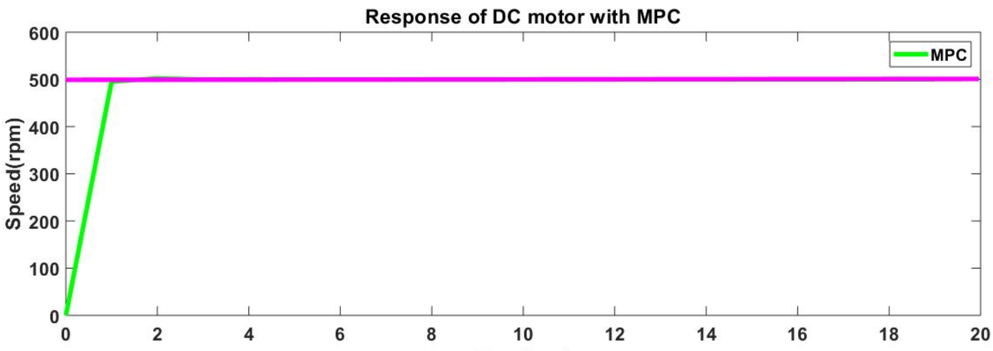

Figure 10. Closed loop response with MPC controller

5. Sliding mode control

SMC has been one of the most popular fields of automatic control research. Its significant feature is that it is absolutely vulnerable to plant parametric instability and sliding mode disturbances. It is the correct option for plants that work in the presence of parametric uncertainties, significant external disruptions and noise. Sliding mode is the motion of a system trajectory along a chosen surface of the state space. SMC is the controller built to achieve the sliding mode [32-44].

5.1 Sliding surface design

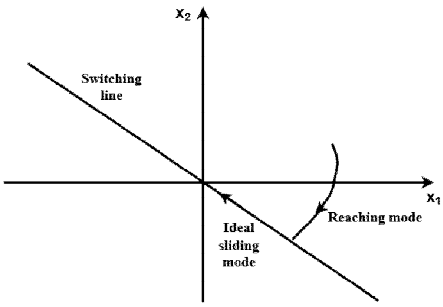

Figure 11. Ideal sliding mode

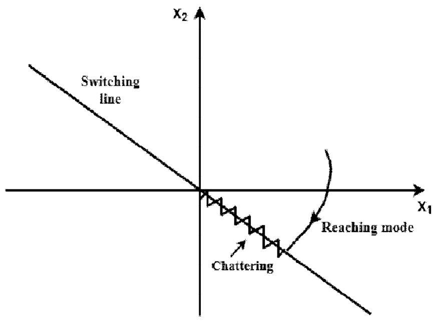

Figure 12. Practical sliding mode

The switching control law steers the state trajectory of the plant onto a predestined and user-chosen surface in state space. This surface is called the sliding or switching surface. For all subsequent periods, the switching control rule preserves the state trajectory of the plant on this surface. If the plant's state trajectory is over the surface control path has one gain, if the trajectory drops under the surface, the surface control path has another gain. A sliding mode controller can stabilize the trajectory of a system. The system states "slides" along the line S=0.

In the SMC design, there are two phases. The first step is to build a sliding surface such that there is a desired system response to the plant confined to the sliding surface. This implies that the plant dynamics states variables are constrained to satisfy another set of equations describing the so called switching surface. The second step is to create the switched feedback gains needed to push the state trajectory of the plant to the sliding surface.

The control signal switches between two structures when the 'S' is very close to zero. Theoretically, zero amplitude oscillations of infinite frequency in x are induced by switching. Practically, at an infinite frequency, actuators do not move and at high frequency non-zero magnitude oscillations occurs. This pattern of undesirability is called chattering. Chattering is the price that the SMC pays for elimination of completely matched disturbances, order-reduction when a system is in sliding mode, systematic design and consistent performances. Ideal and practical sliding with chattering are shown in figure 11 and 12.

5.2 Sliding mode controller

Consider a second order system given in Eq (5)

$$\ddot{x} = f(\dot{x}, x, t) + bu(t) \tag{5}$$

Where,

b-Positive constant

u(t) – System input

If the error is selected as the difference between the desired and the actual angular velocity as given in Eq(6-8)

$$x_1 = e = \omega^* - \omega \tag{6}$$

$$\dot{x}_1 = x_2 = \dot{e} = \dot{\omega}^* - \dot{\omega} \tag{7}$$

$$\dot{x}_2 = \ddot{\omega}^* - \ddot{x}_1 \tag{8}$$

A potential choice of the sliding mode controller structure is given in Eq(9)

$$U = -\varepsilon\, \mathrm{sgn}(S) + u_{eq} \tag{9}$$

Where,

u_{eq} – The equivalent control that makes the derivative of the switching function equal to zero. ε is constant, representing the maximum controller output. 'S' given in Eq (10) is referred to as the switching function since the control operation switches on both sides of the switching surface S=0 depending on control action sign.

$$S = \dot{e} + \lambda e \tag{10}$$

Where,

$e = x - x_d$.

x_d - desired state

λ - Positive constant.

Sign function sgn(S) is defined in Eq(11)

$$\mathrm{sgn}(S) = \begin{cases} -1 & \text{if } S < 0 \\ 1 & \text{if } S > 0 \end{cases} \tag{11}$$

If the condition in Eq(12) matches, the system trajectory shifts towards and remains on the sliding surface S=0 from any initial condition.

$$S\dot{S} \leq -\eta|S| \tag{12}$$

Where,

η is a positive constant that ensures that the trajectories of the device meet the sliding surface in a finite time.

According to equations, (9) and (10) the speed tracking error x_1 decays exponentially after sliding mode occur in the manifold S=0. To enforce the sliding mode, the control gain k should be selected such that $s\dot{s} < 0$. After a finite time interval, the system state will reach the sliding line S=0. Thereafter, the system response depends only on the design parameter λ, after reaching final condition the state is on the sliding line and does not leave the line. Figure 13 shows design of SMC controller for speed control of DC motor with MATLAB software help in understanding overall design of SMC controller. The plant response is illustrated in figure 14.

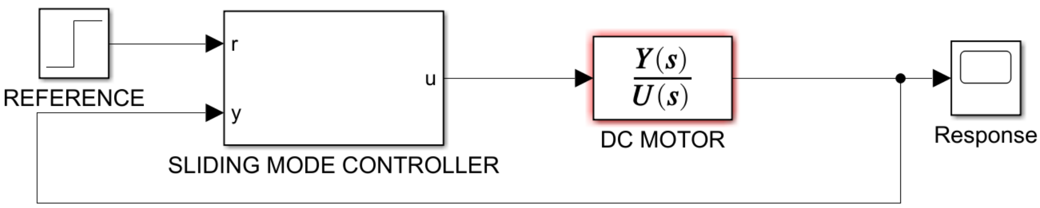

Figure 13. Closed loop control of DC motor with SMC

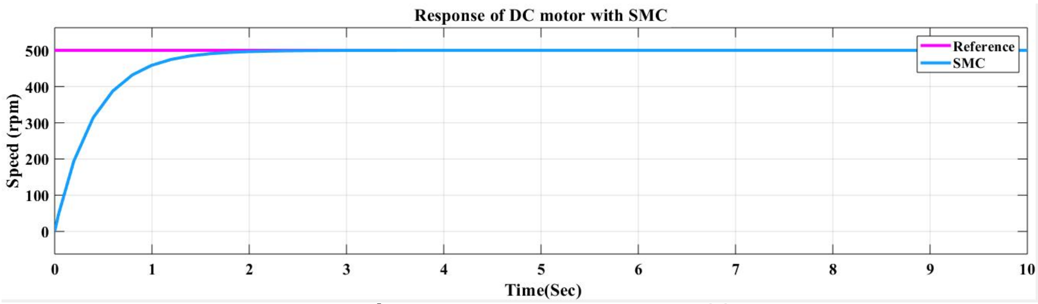

Figure 14. DC motor response with SMC

6. Fuzzy logic controller

FLC provides a formal methodology for representing, manipulating, and implementing a human's heuristic knowledge about how to control a system [45-47]. The fuzzy controller block diagram is given in Figure 15.

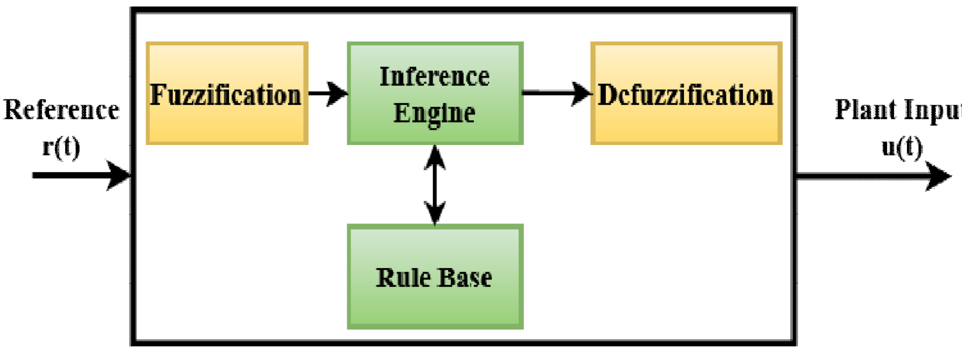

Figure 15. Block diagram of fuzzy controller

6.1 Main components of fuzzy controller

6.1.1 Rule base

The rule base consists of a collection of rules that are typically formulated using the system's expert knowledge. The rules are usually of the "If-then" type form. A simple statement or a compound statement using connectives such as "and" or "or" can be the preceding part of the law. Rules are stated in table 1.

6.1.2 Fuzzification

Fuzzification is the first step in the method of fuzzy inference. Fuzzy requires a transformation of the domain where crisp inputs are translated into fuzzy inputs. The variable which represents system dynamic performance is taken as input variable. In this paper, input error has the range from -4 to 4 and change in error has the range from -2 to 2 as shown in figure 16 and 17 respectively. Triangular fuzzifiers are used for both inputs.

6.1.3 Defuzzification

The method of transposing the fuzzy outputs to crisp outputs is called defuzzification. The defuzzification interface converts the conclusions that the inference mechanism draws into the inputs of the plant. Output membership function is shown in figure 18.

6.1.4 Inference engine

Mamdani-type and Sugeno-type can be applied in two kinds of fuzzy inference systems. Here, data is matched with the condition of the rule and determined how well data is matched with the rule in a specific case. A degree of membership feature is thus established.

6.2 Fuzzy logic controller design

Figure 18 illustrates the power of the fuzzy logic controller in speed control of DC motor. The fuzzy logic approach presents a solution that is easier, faster and more efficient, with strong advantages over traditional techniques. Simulation diagram of plant with FLC and its response are shown in figure 19 and 20.

6.2.1 Overview of FLC

Fuzzy Input	: (i)Error	-7 Membership functions
	: (ii) Change in error	-7 Membership functions
Fuzzy Inference System	: Mamdani	
Defuzzification method	: Centroid	
Fuzzy Output	: Controller output	-7 Membership functions
Total rules	: 49	

6.2.2 Linguistic variables used in table

NB - Negative big

NM - Negative medium

NS - Negative small

ZE - Zero

PS - Positive small

PM - Positive medium

PB - Positive big

Table 1. Rule base for speed control of armature controlled DC motor

E \ CE	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

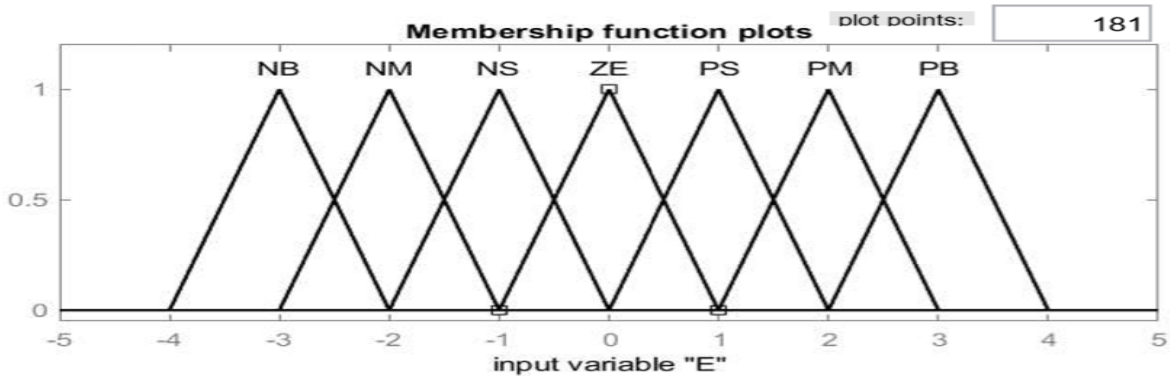

Figure 16. Error variable

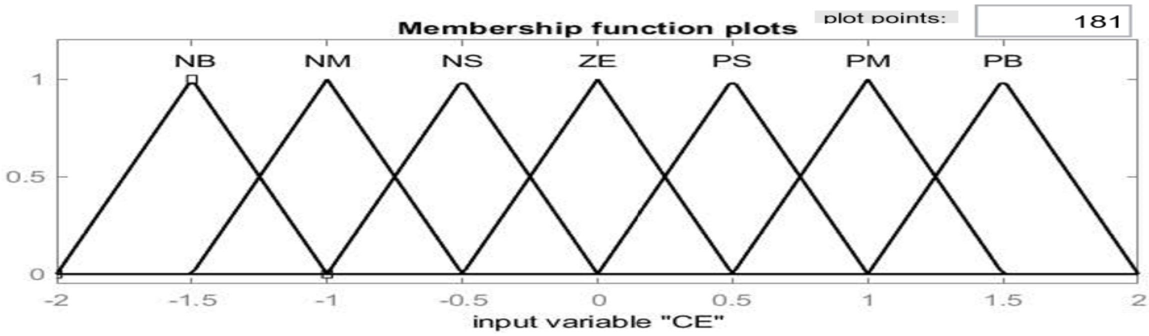

Figure 17. Change in error variable

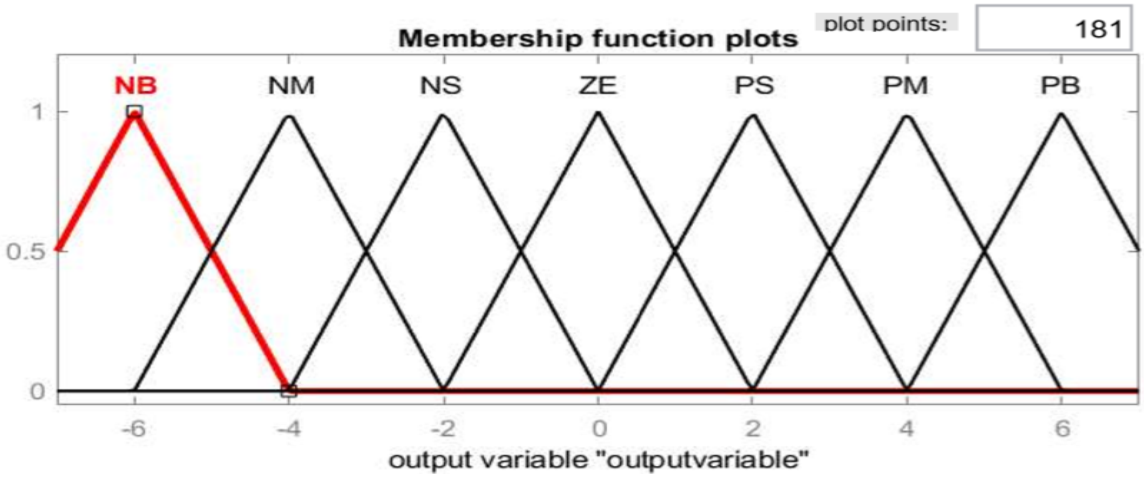

Figure 18. Output variable

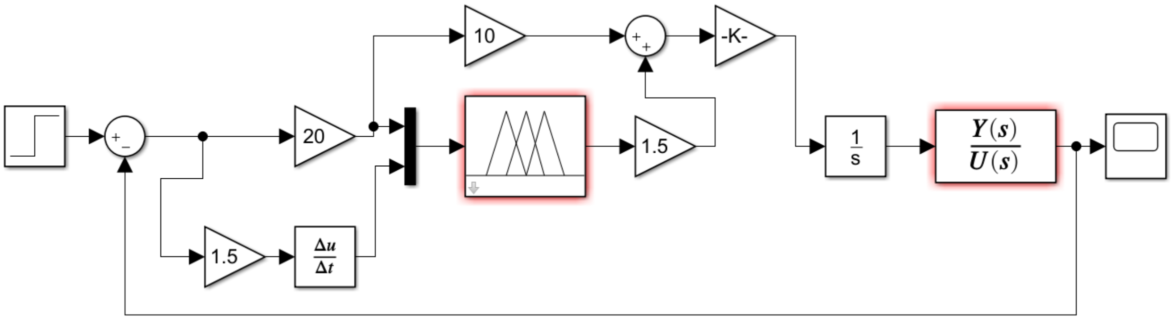

Figure 19. Simulation diagram of closed loop control of DC motor with FLC

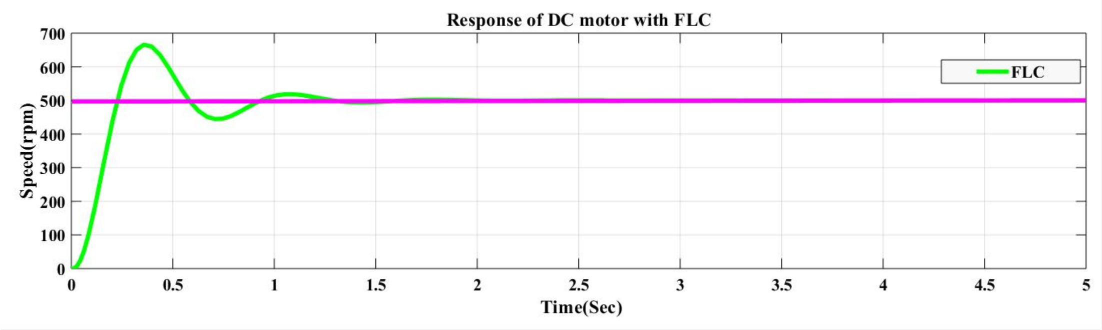

Figure 20. Response with FLC

7. Results and discussion

Comparison of response of speed control of DC motor using PID, MPC, SMC and FLC are shown in table 2.

Table 2. Comparison results of responses with different controllers.

Controller / Time response	PID	MPC	SMC	FLC
Rise Time (Sec)	1.3	0.8	2.0	1.9
%Overshoot	9.4815	0.3759	0	20.5761
Settling time (Sec)	8.1731	0.9886	14.3788	31.0138

Table3. Controller selection

	PID	MPC	SMC	FLC
MIMO system	Each loop requires one PID (one PID is not sufficient)	Can be used	Can be used	Can be used
Adequate Mathematical model dependent	Model free	Model based	Model free	Model free
Requires more computing power	No	Yes	No	Yes
Robustness against uncertainties and external disturbance	No	No	Yes	No
Constraints handling capacity	No	Yes	No	No
Prior input / output knowledge of plant	No need	No need	No need	Need

Table 2 clearly shows that all four controllers are capable to give desired rise time. In term of steady state error, controllers had shown very outstanding performance by giving zero error. Table 3 shows, the choice of controller type depend on the type of plant and control specifications. Conventional, Optimal, Nonlinear and intelligent control are capable of controlling a non-linear system [48-61].

8. Conclusions

There are still great discussions with reference to the usage of classical, conventional, modern and intelligent controllers. On one hand, many proponents of modern and intelligent controller claim that it will reform control engineering, that promises to solve complex engineering problems with little or no effort. On the other hand, many proponents of the conventional control engineering community still proclaim that everything which will be done out of modern and intelligent control is often done with conventional control also. Four simulation results in this context have been put forward in the paper. Accordingly, their limitations and advantages are studied. Simulation of speed control of DC motor with PID controller, MPC, SMC and FLC can give desired rise time is ≤ 2 sec. Therefore, there is no obsolete or ideal controller. Advanced controllers and hybrid controllers are mandatory when preceding controller does not give required performance. Optimization algorithm can be a second-hand to fine-tune the existing controllers.

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