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PERFORMANCE COMPARSON OF P, PI, PID AND MODEL BASED PREDICTIVE CONTROLLERS FOR THE POSITION CONTROL OF BRUSHLESS DC MOTORS

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Abstract: Growing need of industry for higher productivity is placing new demands on mechanisms connected with electrical motors. This is leading to different problems in work operation due to fast dynamics and instability. The stability of the system is essential to work at desired set targets. The non-linear effects caused by a motor frequently reduce stability which reduces the controller's ability to maintain speed or position at set points. Hence number of the industrial process applications requires position control of DC motor. In the present project, various controllers like Proportional (P), Proportional-Integral (PI), Proportional-Integral-Derivative (PID) and Model –Based Predictive Controller (MPC) are used to control the position of a Brushless DC Motor (BLDC). The conventional controllers especially PID is mostly used in industries due to its robust performance in a wide range of operating conditions & simple tuning methods. Here PID controller with Ziegler-Nichols (ZN) technique for controlling the position of the field-controlled with fixed armature current DC motors is designed.

Key words: Model Based Predictive Controller., Proportional, Proportional-Integral, Proportional-Integral-Derivative, Brushless DC Motor.

INTRODUCTION

In most of the industrial process like electrical, mechanical, construction, petroleum industry, iron and steel industry, power sectors, development sites, paper industry, beverages industry the need for higher productivity is placing new demand on mechanisms connected with motors. They lead to different problems in work operation due to fast dynamics and instability. That is why control is needed to achieve stability and to reach desired set targets. The position control of electrical motor is most important due to various non-linear effects like load and disturbances that affect the motor to deviate from its normal operation. The position control of a motor is to be widely implemented in machine automation[1].

The position of the motor is the rotation of motor shaft or the degree of rotation which is to be controlled by giving the feedback to control which rectifies the controlled output to achieve the desired position .The application includes robots (each joint in a robot requires a position servo), computer numerical control machines and laser printers. The common characteristics of all such systems is the variable to be controlled (usually position or velocity) is fed back to modify the command signal. The BLDC Motor employs a dc power supply switched to the stator phase windings of the motor by power devices, the switching sequence being determined from rotor position. The phase current of BLDC Motor in typically rectangular shape is synchronized with back EMF to produce constant torque at a constant speed. The mechanical commutator of the brushed DC motor is replaced by electronic switches, which apply current to the motor windings as a function of the rotor position. To control the position of motor shaft the simplest strategy is to use a proportional controller with gain 'k'. The output is fed back to input and the error signal is the difference between set point and motor actual position acts as command signal for controller.

Torque-Speed Characteristics:

In order to effectively use a D.C. motor for an application, it is necessary to understand its characteristic curves. For every motor, there is a specific Torque/Speed curve and Power curve. The relation between torque and speed is important in choosing a DC motor for a particular application. A separately excited DC motor equivalent circuit is considered. We have two expressions for the induced voltage. Comparing the two:

$$E_b = K\phi\omega_m = V_T - I_a R_a \quad \text{--(1)}$$

The torque developed in the rotor (armature) is given by:

$$T_{dev} = K\,\phi\,I_a \quad \text{---(2)}$$

The current in the armature winding can be found as:

$$I_a = \frac{T_{dev}}{K\phi} \quad \text{--- (3)}$$

Substituting for I_a in equation and rearranging the terms

$$V_T - K\phi\omega_m = R_a\left(\frac{T_{dev}}{K\phi}\right) \quad \text{---(4)}$$

Fig 1 shows the torque developed in the rotor:

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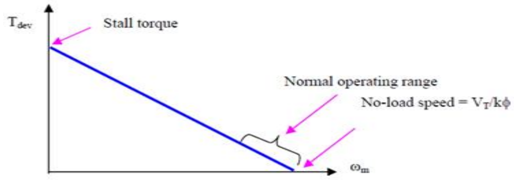

Fig 1: Speed Torque Characteristics

This equation shows the relationship between the torque and speed of a separately excited DC motor. If the terminal voltage V_T and flux Φ are kept constant, the torque-speed relationship is a straight drooping line.

MATHEMATICAL MODEL OF BLDC

Mathematical Modeling of DC motors

The voltages applied to the field and armature sides of the motor are represented by V_f and Va. The resistances and inductances of the field and armature sides of the motor are represented by R_f, L_f, R_a and L_a. The torque generated by the motor is proportional to I_f and I_a the currents in the field and armature sides of the motor.

Field-Current Controlled

In a field-current controlled motor, the armature current I_a is held constant, and the field current is controlled through the field voltage V_f. In this case, the motor torque increases linearly with the field current. We write

$$T_m = K\, i_f\, i_a \quad \text{---(5)}$$

Where I_a will be a constant

A three phase Brushless motor equation can be represented as

$$V_a = R_a I_a + L_a\, dI_a/dt + M_{ab}\,(dI_b/dt) + M_{ac}\,(dI_c/dt) + E_a \quad \text{--(6a)}$$

$$V_b = R_b I_b + L_b\, dI_b/dt + M_{ba}\,(dI_a/dt) + M_{bc}\,(dI_c/dt) + E_b \quad \text{--(6b)}$$

$$V_c = R_c I_c + L_c\, dI_c/dt + M_{ca}\,(dI_a/dt) + M_{cb}\,(dI_b/dt) + E_c \quad \text{-- (6c)}$$

Where

R_a, R_b, R_c - Stator resistance per phase, assumed to be equal for all phases

L_a, L_b, L_c - Stator inductance per phase, assumed to be equal for all phases

M_{ab}, M_{bc}, M_{ac}, M_{ba}, M_{bc}, M_{ca}, M_{cb} - Mutual inductance between phases

V_a, V_b, V_c – respective phase voltage of windings

I_a, I_b, I_c – Stator currents and

E_a, E_b, E_c –Phase back emf

Assuming a balanced system, Phase resistances are equal, self inductances and also mutual inductances

$R_a = R_b = R_c = R$

$L_a = L_b = L_c = L$

$M_{ab} = M_{bc} = M_{ac} = M_{ba} = M_{bc} = M_{ca} = M_{cb} = M$

$$V_a = RI_a + L\, dI_a/dt + M\,(dI_b/dt) + M\,(dI_c/dt) + E_a \quad \text{--(7a)}$$

$$V_b = RI_b + L\, dI_b/dt + M\,(dI_a/dt) + M\,(dI_c/dt) + E_b \quad \text{--(7b)}$$

$$V_c = RI_c + L\, dI_c/dt + M\,(dI_a/dt) + M\,(dI_b/dt) + E_c \quad \text{--(7c)}$$

Neglecting Mutual Inductance

$$V_a = RI_a + L\, dI_a/dt + E_a \quad \text{--(8a)}$$

$$V_b = RI_b + L\, dI_b/dt + E_b \quad \text{--(8b)}$$

$$V_c = RI_c + L\, dI_c/dt + E_c \quad \text{--(8c)}$$

Considering the Field controlled DC motor Torque equation

$$T_m = K_{mf}\, i_f \quad \text{--(9)}$$

Where T_m= torque of the motor

I_f = field Current

By taking Laplace transforms of both sides of this equation gives the transfer function from the input current to the resulting torque

$$\frac{T_m(s)}{I_f(s)} = K_{mf} \quad \text{--(10)}$$

For the field side of the motor the voltage/current relationship is

$$V_f = V_R + V_L = R_f i_f + L_f\left(di_f/dt\right) \quad \text{---(11)}$$

The transfer function from the input voltage to the resulting current is found by taking Laplace transforms of both sides of this equation.

$$\frac{I_f(s)}{V_f(s)} = \frac{(1/L_f)}{s + (R_f/L_f)} \quad \text{--- (12)}$$

(1^{st} order system)

The transfer function from the input voltage to the resulting motor torque is found by combining equations.

$$\frac{T_m(s)}{V_f(s)} = \frac{T_m(s)}{I_f(s)}\,\frac{I_f(s)}{V_f(s)} = \frac{(K_{mf}/L_f)}{s + (R_f/L_f)} \quad \text{-- (13)}$$

So, a step input in field voltage results in an exponential rise in the motor torque. An equation that describes the rotational motion of the inertial load is found by summing moments.

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$$\sum M = T_m - c\omega = J\dot{\omega} \quad \text{---(14)}$$

Thus, the transfer function from the input motor torque to rotational speed changes is

$$\frac{\omega(s)}{T_m(s)} = \frac{(1/J)}{s + (c/J)} \quad \text{-- (15)}$$

Combining equations gives the transfer function from the input field voltage to the resulting speed change

$$\frac{\omega(s)}{V_f(s)} = \frac{\omega(s)}{T_m(s)}\frac{T_m(s)}{V_f(s)} = \frac{(K_{mf}/L_f J)}{(s+c/J)(s+R_f/L_f)} \quad \text{-- (16)}$$

(2 nd order system)

Finally, since $\omega = dq/dt$, the transfer function from input field voltage to the resulting rotational position change is

$$\frac{\theta(s)}{V_f(s)} = \frac{\theta(s)}{\omega(s)}\frac{\omega(s)}{V_f(s)} = \frac{(K_{mf}/L_f J)}{s(s+c/J)(s+R_f/L_f)} \quad \text{---(17)}$$

(3rd order system)

Where

$\omega(s)$ - Rotational speed

$V_f(s)$ - Field Voltage

L_f - Inductance of Field windings

R_f - Resistance of field Windings

(A)PROPORTIONAL CONTROLLER:

Often control systems are designed using Proportional Control. In this control method, the control system acts in a way that the control effort is proportional to the error. The control effort is proportional to the error in a proportional control system, and that's what makes it a proportional control system is shown in Fig 2. In a proportional controller, steady state error tends to depend inversely upon the proportional gain, so if the gain is made larger the error goes down.

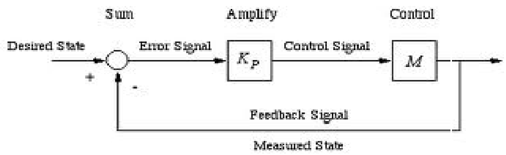

Fig 2: P-Controller

The output equation will be given by

$U(t)= K_p .e(t)+c$ ---(18)

K_p- proportional constant

e-error

c- constant

But the Proportional controller will have more overshoot and offset error to overcome this we use PI Controller.

(B) PI CONTROL:

The combination of proportional and integral terms is important to increase the speed of response and also to eliminate the steady state error. Fig 3 shows the PID controller block is reduced to P and I blocks only.

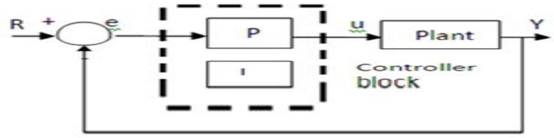

Fig 3: Proportional Integral (PI) Controller

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad \text{---(19)}$$

(C) PID CONTROLLER:

Fig 4 shows the PID controller has proportional, integral as well as derivative so these control actions.

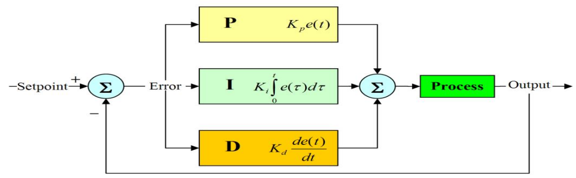

Fig 4: PID Controller

Proportional control:

Proportional action is a mode of controller action in which there is a continuous linear relation between values of deviation and manipulated variable. Thus the action of controlled action is repeated and amplified in the action of control element [2]-[3]. For the purpose of flexibilities, an adjustment of control action is provided and is termed proportional sensitivity.

Proportional control follows the law

$M=k_c e+M$ ---(20)

Where,

M = manipulated variable

K_c=proportional sensitivity

M = constant

E = deviation

Integral control:

Integral action is a mode of controller action in which the value of the manipulated variable "m" is changed at a rate proportional to integral of deviation. Thus if the deviation is doubled over a previous value, the final control element is moved twice as fast. When the control variable is at the set pint, the final control element is remains stationary.

Integral control follows the law

$m=(1/T_i)e$----- (21)

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In integral form

$$m=(1/T_i)\int e\,dt + M \text{ ----(23)}$$

The operational form of the equation is

$$m=(1/T_i s)e \text{---(24)}$$

Proportional-integral-derivative action

The additive combination of proportional action, integral action and derivative action is called as PID action. It is defined by the differential equation

$$M=(k_c/T_i)\int e\,dt+k_c e+k_d[d/dt]e+M \ldots(25)$$

Where

T_i = Integral time,
T_d = Derivative time,
M = manipulated variable,
K_c = proportional sensitivity,
M = constant,
e = error.

Auto Tuning

Astrom and Hagglund described an automatic tuning, called auto tuning method, an alternative to Zeigler-Nichols continuous cycling method. This method has the following features: The auto tuner uses a relay with dead-zone to generate the process oscillation. The period Tu is found simply by measuring the period of the process oscillation. The ultimate gain is given by

$$Kpu=4d/\prod a\ldots (26)$$

Where

D=relay amplitude set by the operator

A=Measured amplitude of the process oscillation

There are various tuning methods proposed to tune the controllers like Ziegler- Nichols method, Cohen Coon method, Oscillatory method etc. Continuous cycling method has some of the disadvantages as the trial and error method. However, the continuous cycling method is less time-consuming than the trial and error method because it requires only one trial and error each.

MODEL-BASED PREDICTIVE CONTROLLER

The models used in MPC are generally intended to represent the behavior of complex dynamical systems. The additional complexity of the MPC control algorithm is not generally needed to provide adequate control of simple systems, which are often controlled well by generic PID controllers. Common dynamic characteristics that are difficult for PID controllers include large time delays and high-order dynamics.

MPC models predict the change in the dependent variables of the modeled system that will be caused by changes in the independent variables. In a chemical process, independent variables that can be adjusted by the controller are often either the set points of regulatory PID controllers (pressure, flow, temperature, etc.) or the final control element (valves, dampers, etc.). Independent variables that cannot be adjusted by the controller are used as disturbances. Dependent variables in these processes are other measurements that represent either control objectives or process constraints.MPC uses the current plant measurements, the current dynamic state of the process, the MPC models, and the process variable targets and limits to calculate future changes in the dependent variables. These changes are calculated to hold the dependent variables close to target while honoring constraints on both independent and dependent variables. The MPC typically sends out only the first change in each independent variable to be implemented, and repeats the calculation when the next change is required.

While many real processes are not linear, they can often be considered to be approximately linear over a small operating range. Linear MPC approaches are used in the majority of applications with the feedback mechanism of the MPC compensating for prediction errors due to structural mismatch between the model and the process. In model predictive controllers that consist only of linear models, the superposition principle of liner algebra enables the effect of changes in multiple independent variables to be added together to predict the response of the dependent variables. This simplifies the control problem to a series of direct matrix algebra calculations that are fast and robust.

Principles of MPC

MPC is a multivariable control algorithm that uses:

- an internal dynamic model of the process
- a history of past control moves and
- an optimization cost function J over the receding prediction horizon,

To calculate the optimum control moves.

The optimization cost function is given by

$$J=\sum_{i=1}^{N} w_{x_i}(r_i-x_i)^2+\sum_{i=1}^{N} w_{u_i}\Delta u_i^{\,2} \quad \text{---(27)}$$

without violating constraints (low/high limits)

With:

x_i= *i* -th controlled variable (e.g. measured temperature)

r_i= *i* -th reference variable (e.g. required temperature)

u_i= *i* -th manipulated variable (e.g. control valve)

w_{x_i}= weighting coefficient reflecting the relative importance of x_i

w_{u_i} = weighting coefficient penalizing relative big changes in u_i

w_{u_i}

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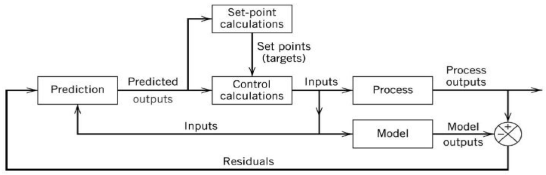

Fig 5: Block diagram of MPC

Fig 5 shows the block diagram of MPC and here the same input is given to both process and the model. Model is the replica of process and the outputs of process and model are compared and the error is fed to the predictor where prediction horizon and control horizon are obtained from the prediction output. Using those parameters the set point will be fixed to reach target.

RECEDING HORIZON:

Fig 6 shows the basic idea of predictive control. In this presentation of the basics, we confine ourselves to discussing the control of a single-input, single-output (SISO) plant

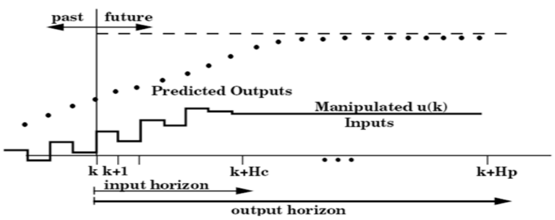

Fig 6: prediction and control horizons

The basic idea of predictive control. In this presentation of the basics, we confine ourselves to discussing the control of a single-input, single-output (SISO) plant. We assume a discrete-time setting, and that the current time is labeled as time step k. At the current time the plant output is y(k), and that the figure shows the previous history of the output trajectory. Also shown is a set point trajectory, which is the trajectory that the output should follow, ideally. The value of the set-point trajectory at any time t is denoted by s(t).

Distinct from the set-point trajectory is the reference trajectory .This starts at the current output y(k), and defines an ideal trajectory along which the plant should return to the set-point trajectory, for instance after a disturbance occurs. The reference trajectory therefore defines an important aspect of the closed-loop behavior of the controlled plant. It is not necessary to insist that the plant should be driven back to the set-point trajectory as fast as possible, although that choice remains open. It is frequently assumed that the reference trajectory as fast as possible, although that choice remains open. It is frequently assumed that the reference trajectory approaches the set point exponentially, which we shall denote T_{ref} , defining the speed of response. That is the current error is

€(k) =s (k)-y(k) ---(28)

Then the reference trajectory is chosen such that the error i steps later, if the output followed it exactly, would be

€(k+i)=exp(-iTs/Tref) *€(k)
= גi *€(k) ----(29)

Where Ts is the sampling interval and ג =exp(-Ts/Tref).(note that 0<ג<1). That is, the reference trajectory is defined to be

r(k+i|k)=s(k+i)-€(k+i)
=s(k+i)- exp(-Ti/Ts) * €(k)---(30)

The notation r(k+i|k) indicates that the reference trajectory depends on the conditions at time k, in general. Alternative definitions of the reference trajectory are possible— For example, a straight line from the current output which meets the set point trajectory after a specified time. A predictive controller has an internal model which is used to predict the behavior depends on the assumed input trajectory u(k+i|k) (i=0,1,…,Hp-1) that is to applied over the prediction horizon, and the idea is to select that input which promises best predicted behaviour. We shall assume that internal model is linear; this makes the calculation of the best input relatively straightforward. The notation u rather than u here indicates that at time step k we only have a prediction of what the input at time k+i may be; the actual input at that time, u(k+i),will probably be different from u(k+i|k).Note that we assume that we have the output measurement y(k) available when deciding, the value of the input u(k).This implies that our internal model must be strictly proper , namely that according to the model y(k) depends on the past inputs u(k-1),u(k-2), …, but not on the input u(k).

In the simplest case we can try to choose the input trajectory such as to bring output at the end of the prediction horizon, namely at time k-Hp, to the required value r(k + Hp). In this case we say, using the terminology of richalet, that we have a single coincidence point at time k+Hp. There are several input trajectories {u(k|k),u(k+1|k),…,u(k+Hp-1|k)} which achieve this , and we could choose one of them , for example the one which requires smallest input energy. But is usually adequate, and in a fact preferable, to impose some simple structure o the input trajectory, parameterized by a smaller number of variables. The figure shows the input assumed to vary over the first three steps of the prediction horizon, but to remain constant thereafter: u(k|k)=u(k+1|k)=…=u(k+Hp-1|k).In this case there is only one equation to be satisfied ---y (k+Hp|k)=r(k+Hp|k)--- there is a unique solution .

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Once a future input trajectory has been chosen, only the first element of that trajectory is applied as the input signal to the plant. That is, we set u(k)=(k|k), where u(k) denotes the actual input signal applied. Then the whole cycle of output measurement is repeated, prediction, and input trajectory determination is repeated., one sampling interval later: a new output measurement y(k+1) is obtained ;a new reference trajectory(k+i|k+1)(i=2,3,…,) is defined ; predictions are made over the horizon k+1+I,with i=1,2,…Hp; a new trajectory u(k+1+i|k+1),with i=0,1,…,Hp-1) is chosen; and finally the next input is applied to the plant: u(k+1)=u(k+1|k+1).Since the horizon prediction remains of the same length as before, but slides along by one sampling interval at each step this way of controlling a plant is often called a receding horizon strategy.

Fig 7 shows that any process with n number of manipulated variables, implementing with both conventional and model predictive controllers with same plant wide optimization, local optimizer and same manipulated variables to be measured. For measuring n number of variables n conventional controllers are required

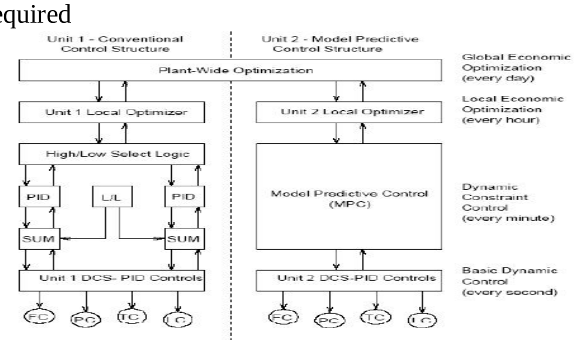

Fig 7: comparison of MPC and conventional controllers

They must be connected in either series or cascade and finally parameters will be measured which is tome consuming process and less reliable and more expenses are involved.

But in case of Model Predictive Controller one controller is enough to measure n number of variables. Hence there will be less time consumption and complexity of the process will be reduced. Fig 8-11 shows the response of dc motor with Rely, P, PI, and PID.

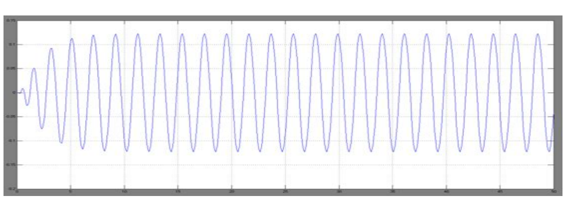

Fig 8: Rely response of a dc motor for Kpu=0.1235 and Tu=2.3064

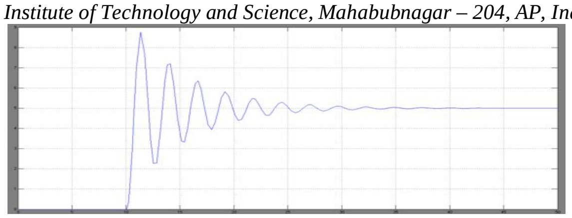

Fig 9: Response of dc motor with P-Controller

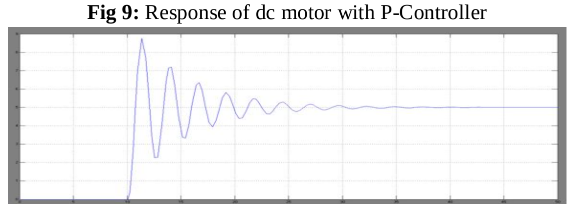

Fig 10: Response of DC motor with PI-Controller

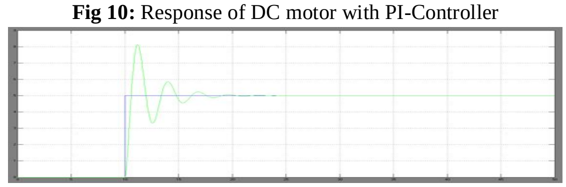

Fig 11: Response of a DC motor with PID Controller

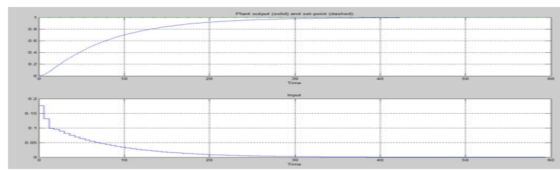

Fig 12: Response of a DC motor with Model based Predictive Controller

The implementation of Model predictive control for DC motor process is implemented in Mat lab. The MPC is implemented by considering the parameters of Prediction Horizon (P) = 20, Control Horizon (M) = 2, Control interval=0.1 and objective function is Quadratic Objective to minimize the error, to track the multi changes in set point and also the change in load disturbance. The multi set point tracking of speed of DC motor process by using MPC controller. The Fig 12 shows that no oscillations occurred in the process and also it takes less time to track the changes occur in the input of the DC motor

CONCLUSION

Electric machines are used to generate electrical power in power plants and provide mechanical work in industries. The dc machine is considered to be a basic machine. The permanent magnet brushless DC motors (PMBLDC) are gaining more and more popularity, due to their high efficiency, good dynamic response and low maintenance. The brushless motors have grown significantly in recent years in the appliance industry and automotive industries. BLDC are systems are very preferable for its compactness, low maintenance, low cost and high reliability system.

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In this paper, a mathematical model of DC motor is developed. The model is represented in block diagram form. The simulation of DC motor is performed using the software package MATLAB/SIMULINK. Effectiveness of the model is predicted over a wide range of operating conditions. The result showed that MATLAB is paired with SIMULINK is a good simulation tool for modeling and analyzing PID and MODEL PREDICTIVE CONTROLLERS for PMBLDC Motor.

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