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Research Article

Design of Advanced Controllers for Speed Control of DC Motor

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Abstract: In this research work, an open loop experimental DC motor from National Instruments is investigated for speed control applications in nuclear industry with higher accuracy. For performance analysis, the DC motor is mathematically modeled and advanced control techniques are established. The two design approaches are therefore hardware in loop which is experimental facility and mathematical in nature which is a simulation model. An adequate mathematical model of DC motor is developed using first principle. The hardware realization is accomplished by DC motor experimental setup. Different advanced control algorithms such as PID, SMC and MPC are developed for both models based and hardware-based DC motor research studies. Model development, control synthesis, simulation and analysis are carried out in Simulink and LabVIEW programming environments. Closed loop performance analyses of nonlinear and predictive controllers are evaluated and found much better, smoother and robust than linear controller for speed control of DC motor under different conditions.

Keywords: DC Motor, Speed Control, Linear Control, Nonlinear Control, Predictive Control.

1. INTRODUCTION

The separately excited DC motors is an electrical machine used for wide range of variable speed control drives in industry and power plants. DC motors are widely used in robotics, control and automation industry for high precision position and speed control drives. Therefore, it is desired to investigate the DC motor drive, conduct speed control experiments and device conventional and advanced control schemes. The linear control systems are generally not so accurate and has poor performance against parametric changes and load changes. Therefore, in order to have the improved performance and better robustness, new control schemes are required to introduce. A detailed literature review is conducted to identify the various modeling techniques with different configuration of DC motor. This survey suggests hardware and model-based approaches for DC motor. Different linear, nonlinear, predictive, optimal and robust controllers are studied for either DC motor or similar electrical or other processes. The nonlinear modeling and system identification-based modeling aspects of the DC motor are discussed by Kara and Eker [1]. A DC motor is modeled and simulated using MATLAB script called in LabVIEW environment is evaluated by Patrascoiu [2]. A model based Proportional Integral Derivative (PID) controller is designed for DC motor in LabVIEW by Kumar *et al.* [3]. This study suggests conventional linear controller design methodology for DC motor. Hardware in loop PID controller is attempted for DC motor in LabVIEW by Pradeepa *et al.* [4]. This study is hardware realization of PID control for DC motor. A Linear Quadratic Regulator (LQR) controller is addressed for DC motor by Saiudha *et al.* [5] which is an optimal control design approach. Hardware based Model Predictive Controller (MPC) is synthesized for QNET VTOL takeoff and landing control by Anoop and Sharma [6]. This is similar National Instruments QNET

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hardware but for different application. A detailed performance comparison is analyzed for DC motor using PID, LQR and MPC by Dani *et al.* [7]. This uses a mix linear, state feedback and predictive controllers for DC motor. Speed control of DC series wound motor is conducted using nonlinear Fuzzy Logic Control (FLC) by Ismail *et al.* [8]. This study is basically an intelligent control scheme for a different configuration of DC series motor. A FLC based PID controller is adopted for DC motor by Bansal *et al.* [9]. This is fuzzy logic based nonlinear tuning of PID controller parameters for DC motor. A model based PID controller and nine rules based FLC are designed and compared for separately excited DC motor by Kushwah *et al.* [10] in MATLAB. This study suggests the performance comparison of intelligent and linear controllers for DC motor. Another complex forty-nine rules based Mamdani type FLC is designed for separately excited DC motor by Usoro *et al.* [11]. This FLC design is more robust and complicated as compared to previous one. Another attempt was made for DC motor speed control using predictive MPC and nonlinear FLC by Jibril *et al.* [12] which provides comparison of predictive and fuzzy control techniques. A comparative study was carried out for separately excited DC motor using PID and Artificial Neural Network (ANN) controllers by Hashmia and Dakheel [13] which is a data drive controller design approach. A second order nonlinear Sliding Mode Controller (SMC) is synthesized for DC motor by Huspeka [14]. An investigation is performed for separately excited DC motor using PID and SMC controller by Hashim and Ahmed [15] in MATLAB. Another similar investigation was performed for separately excited DC motor using PID and SMC controller by Jalalu *et al.* [16] in LabVIEW. In these studies, linear and nonlinear controller design schemes are tested in two different simulation platforms. Research is further expanded for the study of hardware in loop PID and SMC controllers design for DC motor by Dumanay *et al.* [17] in LabVIEW. In this study linear and nonlinear controller are configured on hardware. Sliding mode controller is designed for DC motor and controller gains are optimized using Ant Colony algorithm by Jammousi *et al.* [18]. A model predictive control with mini-max scheme is attempted for bioprocess Ant Colony algorithm by Benattia *et al.* [19].

In this research work, two new advanced controllers are attempted to address poor disturbance rejection problem, poor performance of linear controller under parametric and load changes. Sliding mode and predictive control design schemes are adopted. These schemes are configured in two different ways; one closed loop development using hardware in loop while second closed loop development using two distinct simulation platforms. In the present manuscript we present hardware of DC motor drive, mathematical modeling of DC motor, structure of controllers, problem formulation of various controllers, graphical representation of experimental and simulated results and key investigations are discussed in detail.

2. MATERIALS AND METHODS

2.1. Electrical Machine

The electrical machine under consideration in this research work is a separately excited DC motor which is acquired from National Instruments as shown in Figure 1. DC motor design parameters are motor electrical resistance, motor torque constant and moment of inertia. These parameters are estimated using applied voltage of motor, current the motor armature, speed of motor shaft, motor terminal resistance and motor torque constant using tachometer and current sensor. The linear controller design is accomplished by imposing constraints on

Fig. 1. National Instruments Electrical Machine (DC Motor) Experimental Setup.

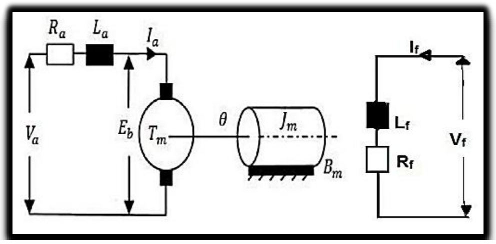


Fig. 2. Schematic Diagram of DC Motor.

the closed loop performance in terms of maximum rise time, overshoot, settling time and steady state error.

2.2. Electrical Machine Modeling

The separately excited DC motor is an electro-mechanical system as shown in Figure 2.

Various parameters/symbols and variables used hereafter in the process of DC motor modeling and controllers are defined in Table 1.

The dynamics of armature current is computed as [7]:

$$\frac{dI_a(t)}{dt} = -\frac{R_a}{L_a} I_a(t) - \frac{K_B}{L_a}\omega(t)\frac{1}{L_a}V_a \qquad (1)$$

The speed of dc motor is computed as [7]:

$$\frac{d\omega(t)}{dt} = -\frac{K_t}{J_m} I_a(t) - \frac{B_m}{J_m}\omega(t) \qquad (2)$$

Table 1. Symbols/parameters of model and controllers.

Parameters	Definitions
V_a	Armature Voltage
E_b	Back emf of Motor
I_a	Armature Current
R_a	Armature Resistance
L_a	Armature Inductance
T_m	Mechanical Torque
J_m	Moment of Inertia
B_m	Friction Coefficient of Motor
ω	Speed of Motor
ω_{ref}	Reference Speed of Motor
K_B	Motor Back emp Constant
K_t	Motor Current Torque Constant
S	Sliding Surface
K_p	Proportional Gain
K_I	Integral Gain = K_p / T_I
a_o	Constant associated with Integral of $e_1$error
a_1	Constant associated with $e_1$error
K	Nonlinear Controller Gain
u(t)	Control Input Signal
PID	Proportional Integral Derivative
SMC	Sliding Mode Control
MPC	Model Predictive Control

Now, equations (1) and (2) are linearized and transformed into standard state-space form as:

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t) \qquad (3)$$

$$y(t) = Cx(t) + Du(t) \qquad (4)$$

2.3. State, Input and Output Vectors

The state vector of state space model of DC motor is given as:

$$x(t) = \begin{bmatrix} \omega(t) & \frac{d\omega(t)}{dt} \end{bmatrix}^T \qquad (5)$$

The input and output variables are defined as:

$$u(t) = V_a(t) \qquad (6)$$

$$y(t) = \omega(t) \qquad (7)$$

2.4. Linear Controller Modeling

The formulation of linear controller is discussed in this section. The linear controller used in the current research work is a Proportional Integral Derivative (PID) controller. This controller configured for DC motor is basically PI controller that can be modeled as [3]:

$$u_{PID}(t) = K_P e(t) + K_I \int e(t)dt \qquad (8)$$

2.5. Nonlinear Controller Modeling

Now, the formulation of nonlinear controller is discussed here. The nonlinear controller used in this research work is a Sliding Mode Controller (SMC). This controller configured for DC motor is basically State Feedback Nonlinear Controller. The error dynamics are defined in equations (9) and (10) while sliding mode surface for the system described in equation (5) is defined in equation (11) and its time domain response is plotted in subsequent section 3.1.

$$e_1(t) = x_1(t) - \omega_{ref} \qquad (9)$$

$$e_2(t) = x_2(t) - \frac{d\omega_{ref}}{dt} \qquad (10)$$

$$s = a_o \int e_1(t)dt + a_1 e_1(t) + e_2(t) \qquad (11)$$

Using the Nonlinear Lyapunov Stability Criteria [17]:

$$s\dot{s} < 0 \qquad (12)$$

The asymptotic stability is guaranteed at the initial state in order to achieve the reachability of the switching plane. A sufficient condition to reach a switching plane is given by Lyapunov function, whose evaluation allows to check the asymptotic stability.

The SMC control law is derived using Lyapunov stability condition mentioned in equation (12) using equation (11) and computed in two parts, one is u_{equ} for speed control and u_{swh} for direction control. The chattering problem is compensated through switching control having a small scaling parameter eta (η) known as tuning parameter. The derived and designed controller model is shown in Figure 4 in the subsequent section. The ultimate control law is given as [17]:

$$u_{SMC}(t)=[f_1(x_1(t)+f_2(x_2(t)-g_1(e_1(t))-g_2(e_2(t)) \\ -g_3(r)]-h(s,\eta) \qquad (13)$$

2.6. Predictive Controller Modeling

In the present section, the formulation of predictive controller is discussed. The predictive controller used in this research work is a Model Predictive Controller (MPC). This controller configured for DC motor is basically nominal MPC, MPC with switching model and Min-Max MPC. Nominal MPC is implemented with fixed model of DC motor. MPC with switching model is implemented with controller that switches between the models according to the DC motor speed.

The Min-Max MPC is implemented using a control input sequence that minimizes cost function with a vector of uncertain parameters in the following form [19]:

$$\hat{u}_k^{k+N_p-1} = \arg\begin{pmatrix}\min\\ u(k)\end{pmatrix}\begin{pmatrix}\max\\ \delta\theta\end{pmatrix}\Pi(x_k,u_k^{k+N_p-1},\delta\theta) \quad (14)$$

Where, $\hat{u}_k^{k+N_p-1}$ is determined to minimize the output and control tracking errors by considering all trajectories over all possible data scenarios while Np is the length of the prediction horizon at the k-th sample interval. The cost function is composed of the control input signal (u) with mini-norm and a vector of uncertain parameters (θ) with max-norm determined by nominal parameters vector (θ_{nom}) additive with parameter uncertainties vector ($\delta\theta$) in the prediction domain.

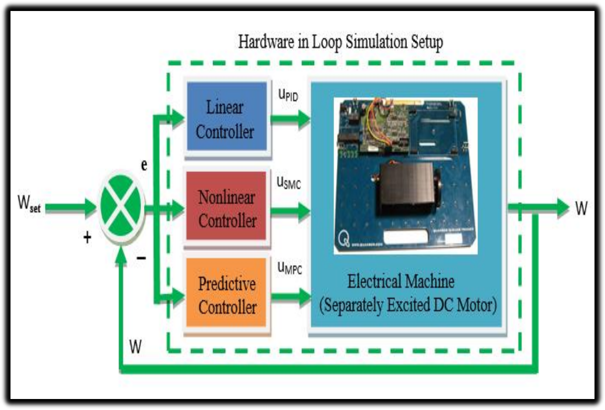


Fig. 3. Block Diagram of DC Motor Speed Control System.

3. RESULTS AND DISCUSSION

The controllers' design, simulation and analysis of DC motor are performed in closed loop framework as shown in Figure 3.

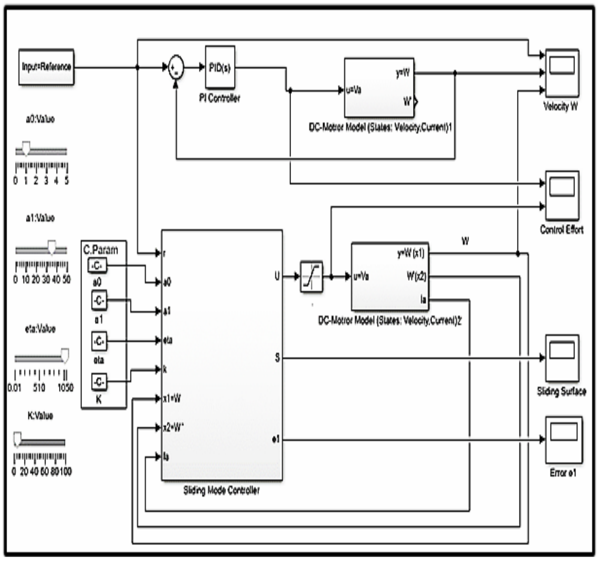


Fig. 4. Simulation Model of Linear and Nonlinear Control of DC motor in Simulink.

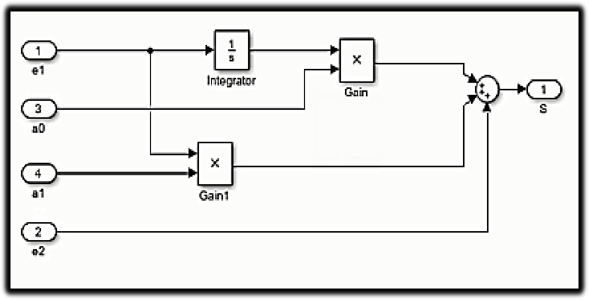


Fig. 5. Simulation Model of Sliding Surface of Nonlinear Controller.

3.1. Performance Analysis of Model based Linear and Nonlinear Electrical Machine Speed Control System in MATLAB Simulink

The PI and SMC controllers modeled in equations (8), (11) and (13) are configured with state space models developed in equations (3) and (4) and programmed in MATLAB Simulink environment as shown in Figures 4 and 5. The control strategy addressed in this research work is designed for the reference tracking mode. Figure 4 shows the design simulation model for tuning of linear and nonlinear controllers and graphical simulations. Figure 5 shows the simulation design model of sliding surface for nonlinear sliding mode controller. The behaviour of the controllers is discussed in Figures 6, 7, 8, 9 and 10.

The response of PI controller in reference tracking mode is shown in Figure 6. The response is fast but it generates a small overshoot in the speed against step reference change. However, the system is stable and no steady state error is observed.

The plot of sliding surface design of nonlinear SMC controller is shown in Figure 7. The response of the sliding surface is quite faster. It minimizes the error dynamics smartly.

The response of nonlinear controller in reference tracking mode is shown in Figure 8. It generates no overshoot in the speed against the step reference change. The closed loop system settles down in around 0.15 second. The system dynamics is quite fast and a very stable output is reached which shows smooth control with SMC.

The closed loop comparison of PI and SMC controllers without parametric variation is shown in Figure 9. The comparison proves that nonlinear controller behavior is better than with linear

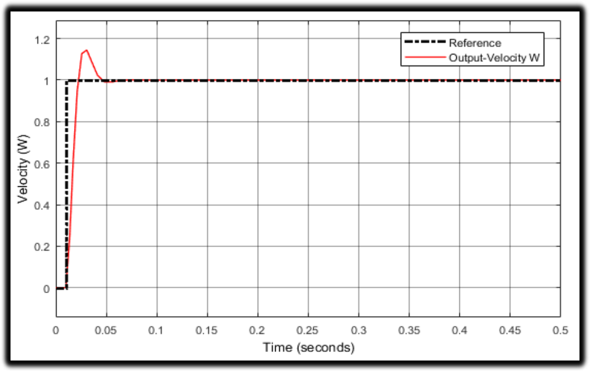


Fig. 6. Reference Tracking Response of DC Motor with Linear Controller

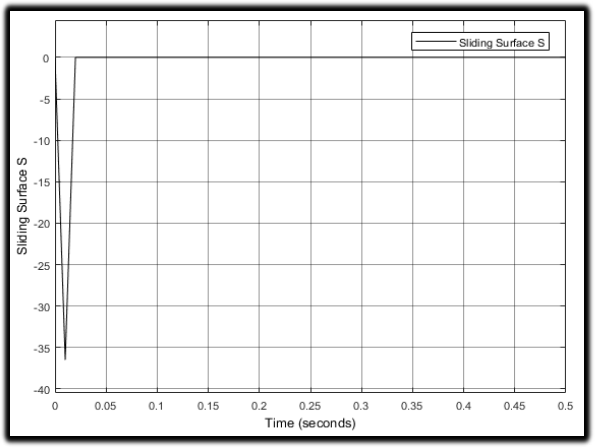


Fig. 7. Response of Sliding Surface of Nonlinear Controller.

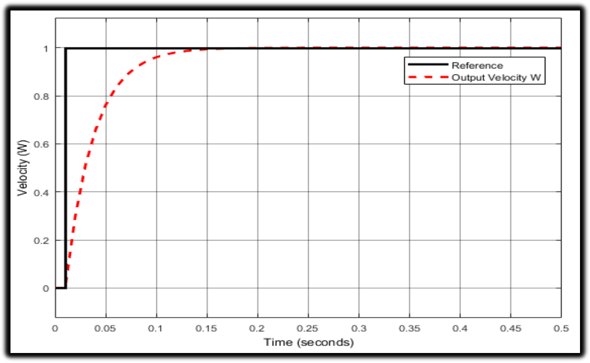


Fig. 8. Reference Tracking Response of DC Motor with Nonlinear Controller.

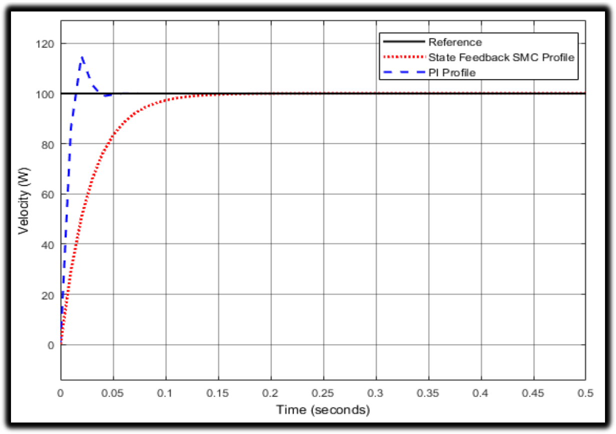


Fig. 9. Closed Loop Simulation of Linear and Nonlinear Control Systems without Parametric Variations.

PID controller. The analysis without parametric variation is basically the closed loop system which is assessed with PI controller and SMC controller with fixed model parameters and there is no role variable structure at all. Such model structure is easier for controllers to handle with.

In this design study, the sliding mode controller is then designed based on variable structure modeling technique using parametric change. This framework is embedded in simulation model as shown Figure 4 and its closed loop performance comparison is graphical represented in Figure 10.

The comparison shows that with parametric change, the PI controller response becomes more oscillatory and takes more time to settle. Therefore, it is obvious that PI controller fails to deal with parametric variation because the controller is not adaptive in nature whereas designed state feedback SMC is insensitive to parametric variations because the controller is nonlinear in nature.

The closed loop gain margin of DC motor speed control system using sliding mode controller is 2 which proves the guaranteed sufficient robustness of the system with remarkable closed loop performance under parametric variations.

3.2. Performance Analysis of Hardware based Linear and Nonlinear Electrical Machine Speed Control System in LabVIEW

The parametric values used in the experimental work are $R_a = 8.7\ \Omega$, $K_t = 0.0334$ N-m, $K_p = 0.0334$ V/(rad/sec), $J_m = 1.8 \times 10^{-6}$ Kg-m^2, $B_m = 1\times10^{-5}$ and $L_a = 8.3\times10^{-3}$ H.

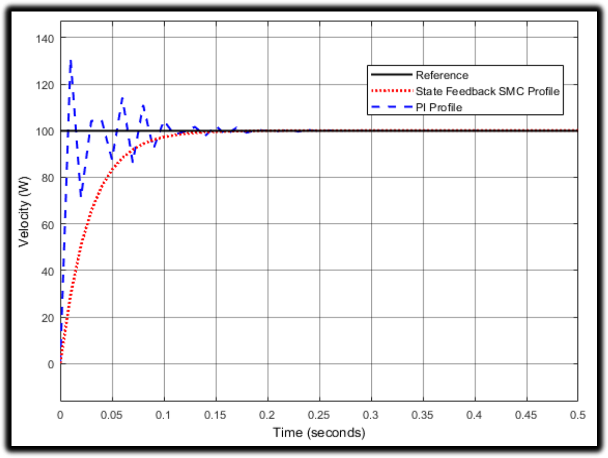
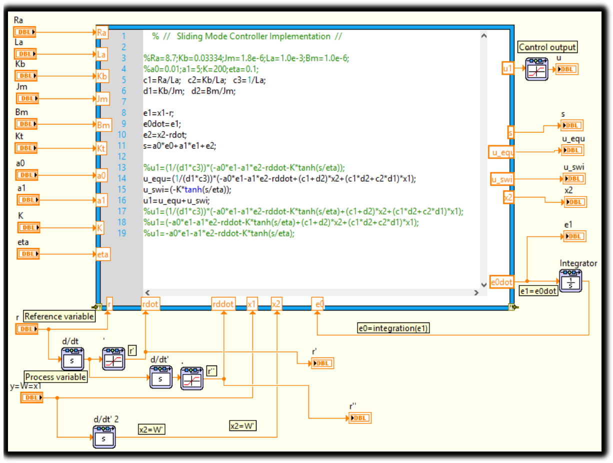


Fig. 10. Closed Loop Simulation of Linear and Nonlinear Control Systems with Parametric Variations.



```
% //  Sliding Mode Controller Implementation  //

%Ra=8.7;Kb=0.03334;Jm=1.8e-6;La=1.0e-3;Bm=1.0e-6;
%a0=0.01;a1=5;K=200;eta=0.1;
c1=Ra/La;   c2=Kb/La;   c3=1/La;
d1=Kb/Jm;   d2=Bm/Jm;

e1=x1-r;
e0dot=e1;
e2=x2-rdot;
s=a0*e0+a1*e1+e2;

%u1=(1/(d1*c3))*(-a0*e1-a1*e2-rddot-K*tanh(s/eta));
u_equ=(1/(d1*c3))*(-a0*e1-a1*e2-rddot+(c1+d2)*x2+(c1*d2+c2*d1)*x1);
u_swi=(-K*tanh(s/eta));
u1=u_equ+u_swi;
%u1=(1/(d1*c3))*(-a0*e1-a1*e2-rddot-K*tanh(s/eta)+(c1+d2)*x2+(c1*d2+c2*d1)*x1);
%u1=(-a0*e1-a1*e2-rddot-K*tanh(s/eta)+(c1+d2)*x2+(c1*d2+c2*d1)*x1);
%u1=-a0*e1-a1*e2-rddot-K*tanh(s/eta);
```

e0=integration(e1)

Fig. 12. Simulation Model of Mathscript based Nonlinear Controller in LabVIEW.

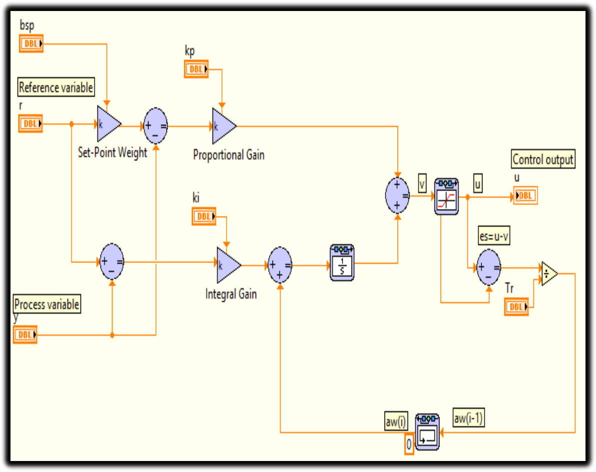


Fig. 11. Simulation Model of Linear Controller in LabVIEW.

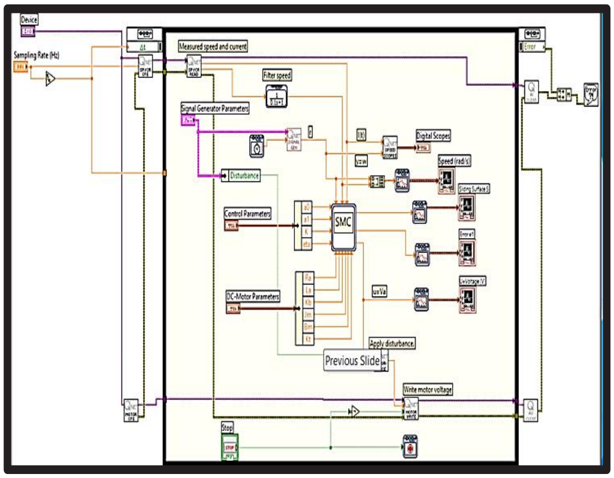


Fig. 13. Hardware in Loop Simulation Model of Linear and Nonlinear Control System in LabVIEW.

The PI and MPC controllers modeled in equations (8), (11) and (13) are configured in hardware in loop framework experimentally and programmed in LabVIEW environment as shown in Figures 11, 12 and 13.

The measured speed of DC motor with linear PID controller experimentally is shown in Figure 14. A sequence of periodic reference behavior is designed and implemented as reference signal and the closed loop system tracks it but with fluctuating dynamics.

The NI instrument-based DC motor speed is measured using nonlinear sliding mode controller as shown in Figure 15. The response reveals that there is very small overshoot with excellent tracking feature, which proves the robust performance of sliding mode controller. The dynamic behavior is much smoother with SMC controller.

It is evident from Figures 14 and 15 that when the linear and nonlinear controllers are implemented on DC motor then its response improves greatly with nonlinear controller and sharp oscillations also decreases.

The measured speed of DC motor is obtained experimentally with linear controller under load disturbance is shown in Figure 16. The fast small fluctuations are the measured values while the sudden dip followed by up spikes are due to motor load torque variations.

The measured speed of DC motor is obtained experimentally with nonlinear sliding mode controller by varying motor load torque as load disturbance. The dynamic response is shown in Figure 17. The sudden fall in motor speed shows the rise in motor load torque.

It is evident from Figure 16 and 17 that when the linear and nonlinear controllers are implemented on DC motor with load disturbances then DC motor speed recovers the desired trajectory quickly. The response with linear PID controller has sharp large overshoots and undershoots while the response with nonlinear sliding mode controller reduces the overshoots and undershoots greatly. Therefore, the state feedback SMC is superior to PI controller in rejecting the external disturbance.

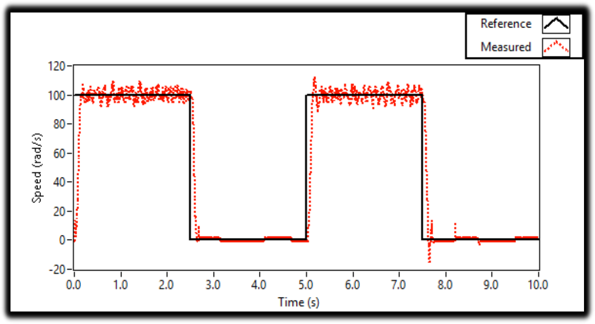


Fig. 14. DC Motor Response with Linear Controller from Hardware.

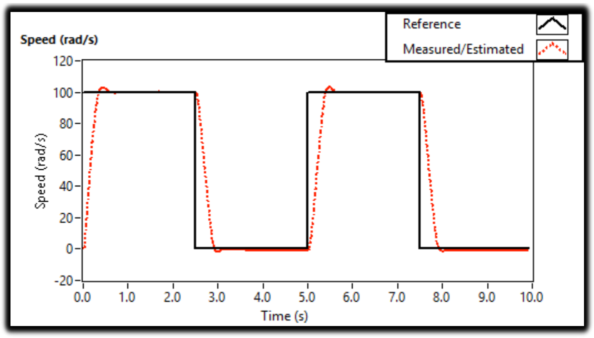


Fig. 15. DC Motor Response with Nonlinear Controller from Hardware.

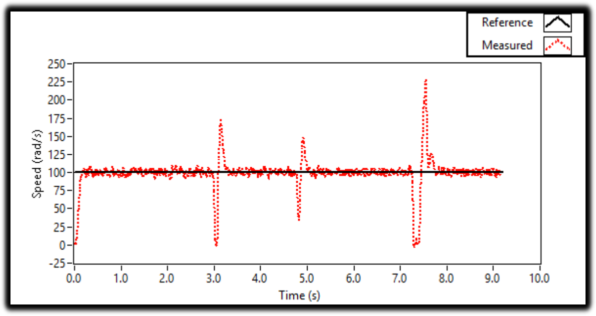


Fig. 16. DC Motor Response with Linear Controller under Disturbance.

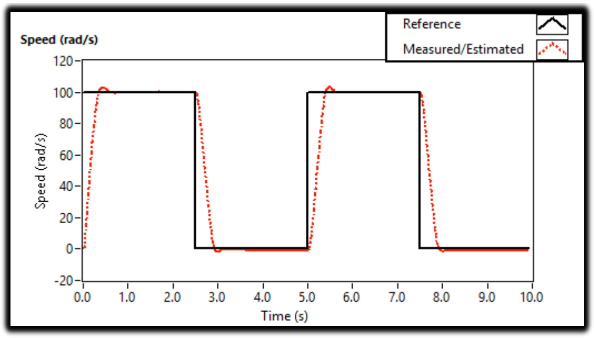


Fig. 17. DC Motor Response with Nonlinear Controller under Disturbance.

3.3. Performance Analysis of Hardware based Linear and Predictive Electrical Machine Speed Control System in LabVIEW

The PI and SMC controllers modeled in equations (8) and (14) are configured in hardware in loop framework experimentally and programmed in LabVIEW environment as shown in Figures 18.

The comparison of predictive behaviors amongst different MPC schemes is shown in Figure 19.

It is evident from Figure 19 that when the MPC with different schemes are implemented on DC motor and tested for reference tracking mode then it is found that MPC with switching model is best in dynamic behavior while the nominal MPC swings around the operating point within a very small steady state error band. Both mini-max MPC and MPC with switching model settles bit quickly in around 1 sec time.

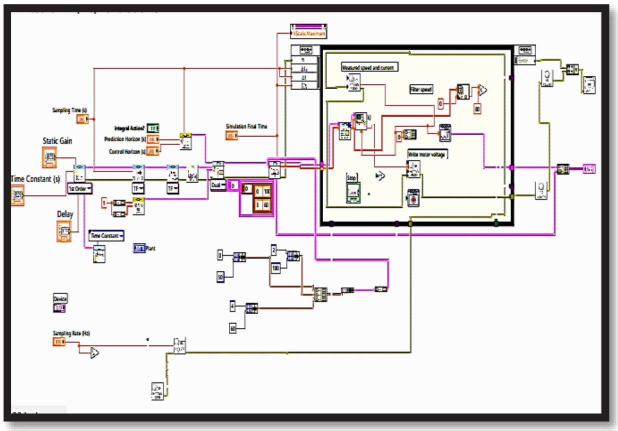


Fig. 18. Simulation Model of Predictive Control System in LabVIEW.

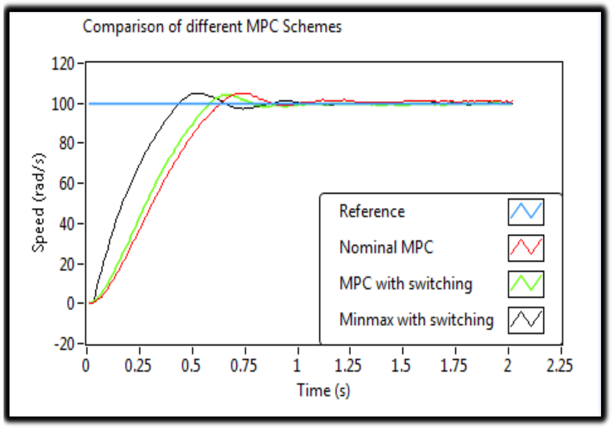


Fig. 19. DC Motor Response with Various Models Predictive Controllers.

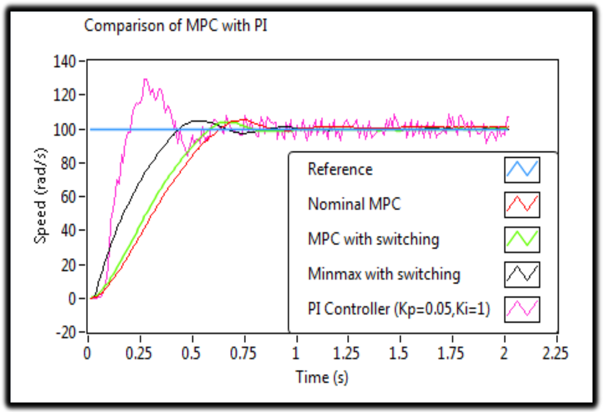


Fig. 20. DC Motor Response with Linear and Various Models Predictive Controllers.

The performance comparison of speed control of DC motor with of PI controller and MPC controller is shown in Figure 20. The comparison shows that the PI controller response becomes fluctuating and more ripples even appear on steady state around the operating point. Therefore, it is obvious that MPC with different schemes are observed with much better performance due to weighted moving average structure.

4. CONCLUSIONS

The separately excited DC motor is formulated in state space form and model parameters are adjusted and fine-tuned in accordance with National Instruments' experimental facility. Simulation experiments are performed to prove the effectiveness of most advanced control design schemes for speed control of DC motor. The designed state feedback SMC has much better performance as compared to PI controller with minimum overshoot and rise time. State feedback SMC is superior in performance as compared to PI controller in rejecting the external disturbances. PI controller fail to deal with parametric variation whereas the designed state feedback SMC is insensitive to parametric variations. MPC with switching scheme is found the best amongst all MPC schemes when compared with PI controller for DC motor. Experimental and simulation experiments proves that successful realization has been achieved for DC motor.

5. ACKNOWLEDGEMENTS

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Technology, Information Support Division of KNPGS is gratefully acknowledged.

6. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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