Speed Control of Dc Motor Using Adaptive Techniques (MRAC)

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Abstract

Speed control is a common requirement in the industrial drives in the presence of varying operating conditions ie .load disturbance, parameter uncertainties and noise. Conventional controllers with fixed parameters are not successful in the real time applications because of the drift in the plants operating conditions. Adaptive control techniques are best suited for these situations. This paper presents a case study on speed control of dc drive using Model Reference Adaptive Control (MRAC). MRAC is one of the main adaptive control schemes. The fluctuation in load is assumed to be an input disturbance on the plant, which causes the deviation in the desired speed. In the literature various adaptive control algorithms have been developed. An adaptive algorithm by Ioannou [8, 9] is applied and simulations have been carried out for different values of load disturbances, parameter uncertainties and output measurement noise. The simulation results reported in this paper demonstrates the effectiveness of the proposed controller against varying operating conditions.
Keywords –dc drives, MRAC, Adaptive control, Lyapunov approach, tracking control.

1. INTRODUCTION

A common actuator in control systems is a dc motor and is obvious choice for implementation of advanced control algorithms in electric drives, due to the stable and linear characteristics associated with it. It is also ideally suited for tracking control applications as shown in references [1, 3, 4, 6,]. From a control system point of view, the dc motor can be considered as a SISO plant eliminating the complexity associated with multi-input drive systems. The speed of a driven load often needs to run at a speed that varies according to the operation it is required to perform. The speed in some cases (such as fluctuating loads like rolling mills) may need to change dynamically to suit the conditions, and in other cases may only change with a change in process. In real time control the parameters are always time variant and are subject to various drifts depending on the operating conditions. It is found that the controllers designed with fixed parameters are not effective in achieving the desired performance and therefore adaptive controllers are best suited. In adaptive control the controller parameters are updated at every instant of time to satisfy the design requirements, unlike the conventional controllers.
This paper describes the rejection of deviation in speed caused by load disturbance for a separately excited dc motor under various load-disturbing situations, parameter uncertainties and measurement noise with an adaptive control approach resulting in an improved performance.

Apart from various conventional control strategies, adaptive control has proved its potential application in tracking/trajectory control problem. **Siri Weerasooriya [2]** developed a modified adaptive controller based on minimum variance self tuning controller. This scheme is effective even in the presence of external disturbances; provided that the system exhibits minimum phase characteristics. **El- Sharkawi (1989) [1 3]** developed the variable structure tracking of dc motor for high performance applications. In his work variable structure system control is used for on-line tracking of dc motor. In **1990, Sharkawi [4]** developed adaptive control strategy based on self tuning control. The purpose of the controller is to force the motor states such as speed, position or armature current to follow prespecified tracks without excessive overshoots and oscillations.

Siri Weerasooriya (1991) [6, 7] used the ability of Artificial Intelligence to identify the system dynamics and for trajectory control, the indirect MRAC is used, which is specifically useful in tracking applications. An attempt has been made to merge the accuracy of MRAC system and calculation speed of ANNs to come up with a trajectory controller for dc motor applications.**El-Samahy (2000)[10]** described the design of robust adaptive discrete variable structure control scheme for high performance dc drives. **Jianguo Zhou (2001) [11]** proposed a global speed controller for the separately excited dc motor. In this work the motor is modeled in two local areas, the first model is a linear one when speed is under the base speed and other is nonlinear when speed is to be obtained using field weakening method. For first part linear robust linear state feedback controller and for nonlinear part adaptive back stepping controller is used. **Crnosiya P. (2002) [12]** presented In [1 5] a fuzzy control has been developed with a fuzzy based MRAC for wide range of speed but the sensing of speed due to load change and corresponding determination of fuzzy control parameters in real time is not included. This may be cause of concern in real time applications. the application of MRAC with signal adaptation to permanent magnet brushless dc motor drives. MRAC with signal adaptation algorithm has been applied to compensate parameter sensitivity and influence of load disturbances In this paper MRAC has been tested for load disturbances as well as for parametric variations using adaptive gain control mechanism explained in sections 3, 4 to achieve zero steady state error. Results of simulation are presented along with comparisons to demonstrate the general applicability .The results are very encouraging compared to earlier studies.

2. MODELING OF DC MOTOR [10, 12]

Control of the motor is achieved by changing the armature voltage as shown in figure 1. The separately excited dc motor drive is characterized in continuous time domain by using following differential equations.

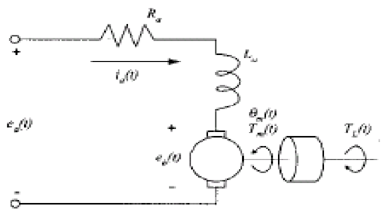


Figure 1 Armature controlled dc motor

The main assumptions for describing the motor dynamics are:
1. The magnetic circuit is linear (because due to saturation of the magnetic core linear relationship does not hold for high values of field current)
2. The mechanical friction including viscous friction and Coulomb friction is linear in the rated speed region.
In the dc motor model the variables and parameters are as given below:

R_a =Armature winding resistance [ohms];

L_a =Armature winding inductance [Henry];

i_a = Armature current [amps];

i_f =Field current [amps]=a constant;

V_a =Applied armature voltage [volts];

E_b = Back emf [volts];

ω_m = Angular velocity of the motor [rad/sec];

T_m =Torque developed by the motor [Newton-m];

J_m =Moment of inertia of the motor rotor [kg-m^2 or Newton-m/(rad/sec^2];

B_m =Viscous friction coefficient of the motor [Newton-m/(rad/sec)];

T_w =Disturbance load torque [Newton-m];

The input voltage **Va** is applied to the armature which has a resistance of **Ra** and inductance of **La**. The field current supplied i_f supplied to the field winding is kept constant and thus the armature voltage controls the motor shaft output. The moment of inertia and the coefficient of viscous friction at the motor shaft bein J_m and f_m respectively. The speed of the motor is being ω_m radian per second. The related dynamics equations are

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + E_b \qquad (2.1)$$

$$E_b = K_b.\omega_m \qquad (2.2)$$

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + K_b \omega_m \qquad (2.3)$$

$$T_m = K_T i_a \qquad (2.4)$$

$$T_m = J_m.\frac{d\omega_m}{dt} + B_m.\omega_m \qquad (2.5)$$

Taking the Laplace transform of equation (3.1)-(3.5), assuming zero initial conditions, we get

$$T_m(s) = K_T I_a(s) \qquad (2.6)$$

$$E_b = K_b \omega(s) \qquad (2.7)$$

$$E_a(s) - E_b(s) = (L_a.s + R_a) I_a(s) \qquad (2.8)$$

$$(J_m.s + B) = T_M(s) - T_L(s) \qquad (2.9)$$

Equation (2.6)-(.9) gives the transfer function between the motor velocity $\omega_m(s)$ and the input voltage $E_a(s)$ is given as below.

$$\frac{\omega(s)}{E_a(s)} = \frac{K_T}{(L_a s + R_a)(J_m s + B_m) + K_T K_b} \qquad (2.10)$$

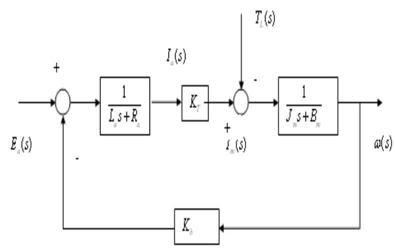


Figure 2 Block diagram of a DC motor (armature controlled) system

3. STATE SPACE REPRESENTATION [5]

Let the armature current ($i_a = x_1$) and angular velocity ($\omega_m = x_2$) be the state variable and the angular velocity be the output variable. Therefore the following state space model can represent the dynamics of dc motor.

$$\frac{di_a}{dt} = -\frac{R_a}{L_a}.i_a - \frac{K_b}{L_a}.\omega_m + \frac{V_a}{L_a} \qquad (3.1)$$

$$\frac{d\omega_m}{dt} = \frac{K_T}{J_m}.i_a - \frac{B_m}{J_m}.\omega_m - \frac{T_w}{J_m} \qquad (3.2)$$

$$\dot{X} = Ax + Bu + Fw \qquad (3.3)$$

$$y = Cx \qquad (3.4)$$

where $x = [x_1 \quad x_2]$; state vector u = Input to the motor (scalar) T_w = Load disturbance, Nm

Matrix A, B and F are given as:

$$A = \begin{bmatrix} -\frac{B_m}{J_m} & \frac{K_T}{J_m} \\ -\frac{K_b}{L_a} & -\frac{R_a}{L_a} \end{bmatrix}; B = \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix}; F = \begin{bmatrix} -\frac{1}{J_m} \\ 0 \end{bmatrix}$$

$$C = [1 \quad 0]$$

For the design of MRAC controller the triple (A, B, C) are assumed to be completely controllable and observable. The load changes are considered as changes in motor rotor inertia and viscous-friction coefficient as practically seen in most control applications. Hence plant parameter changes in the simulation studies reflect abrupt load changes of the system

4. MODEL REFERENCE ADAPTIVE CONTROL

The objective of model reference control is to ensure the output of a controlled system (plant) to track the output of a chosen reference model, in addition to closed-loop stability **[1, 7, 8]**. When the plant parameters are unknown, adaptive laws are designed to update the parameters of a controller to provide the desired output. In this scheme, the objectives of control are specified by the output of the reference model. The design problem involves the adaptation of controller parameters based on past values of controller parameters and the control inputs such that the error between the plant and model outputs approaches zero asymptotically. The tracking error represents the deviation of the plant output from the desired trajectory. The closed-loop plant consists of output feedback, controller (with adjustable parameters) and an adjustment mechanism that adapts the controller parameters online. The main issues are controller parameterization, error model derivation, minimum priori plant knowledge, adaptive law design, and stability analysis **[15]**.The basic structure of this MRAC scheme is shown in figure 3.

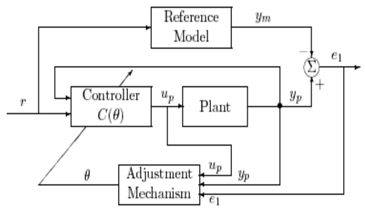


Figure 3: Basic structure of MRAC scheme

4.1 Direct and Indirect Mrac

An adaptive controller is formed by combining a parameter estimator, which provides estimates of unknown parameters at each instant, with a control law that is motivated from the known parameter case. The way the parameter estimator (adaptive law) is combined with the control law give rise to two different approaches. In the first approach, referred to as indirect adaptive control, the plant parameters are estimated on-line and used to calculate the controller parameters. In the second approach, referred to as direct adaptive control, the plant model is parameterized in terms of the controller parameters that are estimated directly without intermediate calculations involving plant parameter estimates. **[2, 9, 10, 11]**

The main differences between indirect and direct adaptive control lies in the following two facts:

- A model of the desired behavior is explicitly used in direct control whereas a model of the plant identified on-line is used in indirect control.
- Identification error in indirect control and the control error in direct control are used to update the controller parameters.

4.2 Design Based On Lyapunov Approach

Stability is an extremely important factor, which must be taken into consideration in the design of MRAC systems because these systems behave like non-linear, time-varying systems. In earlier designs (MRAC) based on MIT rule) instability may arise because of faster adaptations and also for large inputs. Hence, to achieve acceptable design, stability aspect should be incorporated by using the Lyapunov approach. This method of developing adaptive laws is based on direct method of Lyapunov and its relationship with positive real functions. In this approach, the problem of designing adaptive law is formulated as a stability problem where the dynamical equation of the adaptive law is chosen such that certain stability conditions based on Lyapunov theory were satisfied. In this approach, first step is to obtain differential equation that describes the error between the output of the reference model and that of plant. The objective is parameter updation for controller equations, which also assures that the differential equation, which describes the error gradually leads to asymptotic stability. To achieve this, a positive-definite Lyapunov function is formulated for the error equation. The adaptation mechanism is then selected so as to insure the time derivative of the Lyapunov function to be negative definite and result in globally asymptotically stable closed-loop system. Next section describes the design method with above objective **[9, 12].**

5. DESIGN OF MRAC FOR LTI SISO SYSTEM

5.1 Plant Model

Consider an unknown, single input, single output, and linear time-invariant plant in the form of $G_p(s) = k_p \dfrac{Z_p(s)}{R_p(s)}$

(5.1) or in the equivalent state space form as

$$\dot{x}_p = A_p x_p + B_p u_p, x_p(0) = x_0$$
$$y_p = C_p^T x_p \qquad (5.2)$$

where $x_p \in R^n; y_p, u_p \in R^1$ and A_p, B_p, C_p have the appropriate dimensions. Z_p, R_p are the monic polynomials and k_p is a constant referred to as the High Frequency Gain (HFG). In order to meet the MRAC objective plant model satisfy the following assumptions.

P1. $Z_p(s)$ is a monic Hurwitz polynomial of degree m_p.

P2. An upper bound n of the degree n_p of $R_p(s)$.

P3. The relative degree $n^* = n_p - m_p$ of $G_p(s)$, and

P4. The sign of the high frequency gain k_p is known.

5.2 Reference Model

The objective of control system is to find a direct controller that is differentiator free and the output of the plant should follow the output of the pre-specified reference model. The model is chosen in the form of

$$W_m(s) = k_m \frac{Z_m(s)}{R_m(s)} \qquad (5.3)$$

where $Z_m(s), R_m(s)$ are monic polynomials and k_m is constant gain and r is the reference input assumed to be a uniformly bounded and piecewise continuous function of time. The following assumptions regarding reference model are assumed to hold:

M1. $Z_m(s)$, $R_m(s)$ are monic Hurwitz polynomials of degree q_m, p_m respectively, where $p_m <= n$.

M2. The relative degree $n_m^* = p_m - q_m$ of $W_m(s)$ is same as that of $G_p(s)$, i.e., $n_m^* = n^*$.

5.3 Statement of the Problem

The problem statement can be stated as follows:
Given input and output from dc motor as in (5.1) and a reference model described by (5.3), the control input $u(t)$ to the plant is be determined such that

$$\lim_{t\to\infty}|e(t)| = \lim_{t\to\infty} | y_p(t) - y_m(t) | = 0 \qquad (5.4)$$

In the plant considered the occurrence of load on the motor causes disturbance. Due to this load disturbance the speed of the motor fluctuates, so the designed scheme must be able to reject the variation in motor speed and reach the steady desired speed within time by reference model.

5.4 Controller Structure

To meet the above specifications, the controller structure is organized as:

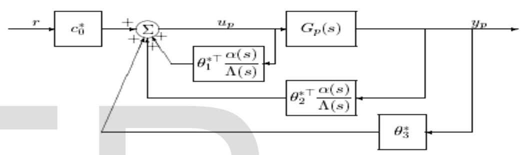


Figure 4: Controller structure

$$u(t) = \theta_1^T(t)\frac{\alpha(s)}{\Lambda(s)}u + \theta_2^T(t)\frac{\alpha(s)}{\Lambda(s)}y_p + \theta_0(t)y_p + c_0 r \qquad (5.5)$$

$$\theta^*(t) = [\theta^{*T}_1(t), \theta^{*T}_2(t), \theta^*_0(t), c_0^*]^T$$

where $\alpha(s) = [s^{n-2}, s^{n-3}, ..., s, 1]^T$; for n>=2

$\alpha(s) = 0$; for n=1

where $\Lambda(s)$ is an arbitrary monic Hurwitz polynomial of degree n-1 that contains $Z_m(s)$ as a factor, i.e.,

$$\Lambda(s) = \Lambda_0(s) Z_m(s) \qquad (5.6)$$

which implies that $\Lambda_0(s)$ is monic, Hurwitz and of degree $n_0 = n-1-q_m$. The controller parameter vector is chosen such that the transfer function from r *to* y_p equals to $W_m(s)$. The I/O properties of the closed loop plant are described by the transfer equation

$$y_p = G_c(s).r \qquad (5.7)$$

we can now meet the control objective if we select the controller parameters ,so that the closed loop poles are stable and the closed loop transfer function $G_c(s) = W_m(s)$ is satisfied.

6. DESIGN OF MRAC FOR RELATIVE DEGREE N=2

The main characteristics of the standard MRAC scheme developed are:
(i)The adaptive laws are driven by the estimation error, which due to the special form of the control law is equal to the tracking error. They are derived using the SPR-Lyapunov approach.
(ii) A Lyapunov function is used to design the adaptive law and establish boundedness for all signals in the closed loop plants. The design of MRAC to meet the control objective control law (5.5) can be written in state space form.

$$\begin{aligned} \dot{\omega}_1 &= F\omega_1 + gu_p, \omega_1(0) = 0 \\ \dot{\omega}_2 &= F\omega_2 + gy_p, \omega_2(0) = 0 \\ u_p &= \theta^{*T}\omega \end{aligned} \quad (6.1)$$

$$\omega = \begin{bmatrix} \omega_1^T & \omega_2^T & y_p & r \end{bmatrix}^T, \omega_1, \omega_2 \in R^{n-1}$$

Where $\theta(t)$ is the estimate of θ^* at time t to be generated by an approximate adaptive law. Obtaining the composite state space representation of the plant and the controller i.e.

$$\begin{aligned} \dot{Y}_c &= A_c Y_c + B_c c^*_0 r, Y_c(0) = Y_0 \\ y_p &= C_c^T Y_c \end{aligned} \quad (6.2)$$

Where $Y_c = [x_p^T, \omega_1^T, \omega_2^T]^T$

$$A_c = \begin{bmatrix} A_p + B_p\theta_3^* C_p^T & B_p\theta_1^{*T} & B_p\theta_2^{*T} \\ g\theta_3^* C_p^T & F + g\theta_1^{*T} & g\theta_2^{*T} \\ gC_p^T & 0 & F \end{bmatrix}, B_c = \begin{bmatrix} B_p \\ g \\ 0 \end{bmatrix}$$

$$C_c^T = \begin{bmatrix} C_p^T & 0 & 0 \end{bmatrix}$$

and Y_0 is the vector with initial conditions. Then adding and subtracting the desired input $B_c\theta^{*T}\omega$ to obtain

$$\dot{Y}_c = A_0 Y_c + B_c\theta^{*T}\omega + B_c(u_p - \theta^{*T}\omega) \quad (6.3)$$

Rewriting the above equation

$$\begin{aligned} \dot{Y}_c &= A_c Y_c + B_c c_0^* r + B_c(u_p - \theta^{*T}\omega), Y_c(0) = X_0 \\ y_p &= C_c^T Y_c \end{aligned}$$

Defining $e = Y_c - Y_m$ and $e_1 = y_p - y_m$ where Y_m is the state of the nonminimal representation of the reference model. Error equation is given by

$$\begin{aligned} \dot{e} &= A_c e + B_c(u_p - \theta^{*T}\omega), e(0) = e_0 \\ e_1 &= C_c^T e \end{aligned} \quad (6.5)$$

The above equation is rewritten as

$$e_1 = W_m(s)\rho^*(u - \theta^{*T}\omega) \quad (6.6)$$

Where $\rho^* = \dfrac{1}{c_0^*}$.

Substituting the control law in equation (6.5), the resultant error equation is given by

$$\begin{aligned} \dot{e} &= A_c e + \bar{B}_c \rho^* \tilde{\theta}^T \omega, e(0) = e_0 \\ e_1 &= C_c^T e \end{aligned} \quad (6.7)$$

Where $\bar{B}_c = B_c c_0^*$ or $e_1 = W_m(s)\rho^*\tilde{\theta}^T\omega$

which relates the parameter error $\tilde{\theta} = \theta(t) - \theta^*$ with the tracking error. Because $W_m(s) = C_c^T(sI - A_c)^{-1}B_c c_0^*$ is SPR and A_c is stable, equation (6.7) is in appropriate form for applying the SPR-Lyapunov approach. With $n^*=2$, $W_m(s)$ is no longer SPR and therefore by using the identity $(s + p_0)(s + p_0)^{-1} = 1$ for some $p_0>0$, rewriting the above equations

$$\begin{aligned} \dot{e} &= A_c e + \bar{B}_c(s + p_0)\rho^*(u_f - \theta^{*T}\phi), e(0) = e_0 \\ e_1 &= C_c^T e \end{aligned} \quad (6.8)$$

i.e.,

$$e_1 = W_m(s)(s + p_0)\rho^*(u_f - \theta^{*T}\phi) \quad (6.9)$$

where $\bar{B}_c = B_c c_0^*$

$$u_f = \frac{1}{(s + p_0)}u, \phi = \frac{1}{(s + p_0)}\omega \quad (6.10)$$

and $W_m(s)$, $p_0>0$ are chosen such that $W_m(s)(s+p_0)$ is *SPR*.

Choosing $u_f = \theta^T\omega$ and rewriting the error equation

$$\begin{aligned} \dot{e} &= A_c e + \bar{B}_c(s + p_0)\rho^*\tilde{\theta}^T\phi, e(0) = e_0 \\ e_1 &= C_c^T e \end{aligned} \quad (6.11)$$

or, in the transfer function form

$$e_1 = W_m(s)(s+p_0)\rho^* \tilde{\theta}^T \phi \qquad (6.12)$$

Transforming the above equation by using the transformation

$$\bar{e} = e - \bar{B}_c \rho^* \tilde{\theta}^T \phi$$

i.e.

$$\dot{\bar{e}} = A_c \bar{e} + B_1 \rho^* \tilde{\theta}^T \phi, \bar{e}(0) = \bar{e}_0$$
$$e_1 = C_c^T \bar{e} \qquad (6.13)$$

where $B_1 = A_c \bar{B}_c + \bar{B}_c p_0$ and

$C_c^T \bar{B}_c = C_p^T B_p c_0^* = 0$ due to n^*=2. With the above error equation adaptive law can be designed as:

$$u = (s+p_0)u_f = (s+p_0)\theta^T \phi \qquad (6.14)$$

which implies

$$u = \theta^T \omega + \dot{\theta}^T \phi \qquad (6.15)$$

$\dot{\theta}$ is available from the adaptive law, the control law given by the above equation can be implemented without the use of differentiators.

Considering the Lyapunov like function as in the previous case for generating adaptive law

$$V(\tilde{\theta}, \bar{e}) = \frac{\bar{e}^T P_c \bar{e}}{2} + \frac{\tilde{\theta}^T \Gamma^{-1} \tilde{\theta}}{2} |\rho^*| \qquad (6.16)$$

where $P_c = P_c > 0$ satisfies the MKY Lemma.

$$\dot{\theta} = -\Gamma e_1 \phi \, \mathrm{sgn}(k_p / k_m) \qquad (6.17)$$

The signal vector ϕ is expressed as

$$\phi = \frac{1}{s+p_0} \begin{bmatrix} (sI-F)^{-1}.g.u_p \\ (sI-F)^{-1}.g.y_p \\ y_p \\ r \end{bmatrix} \qquad (6.18)$$

which implies that $\bar{e}, \tilde{\theta}, e_1 \in L_\infty$ and $\bar{e}, e_1 \in L_2$.

7. SELECTION OF REFERENCE MODEL [7, 10]

The first step in controller design is to select a suitable reference model for the motor to follow. Let us assume that the dc motor is to behave as a second order system whose input is $r(t)$ and the output is $\omega_m(t)$. For a continuous-time system, the reference model can be selected as the ideal second order system transfer function.

$$\frac{\omega_m(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

In this case, speed desired is 57.6 rad/s (550rpm). The damping coefficient (ξ) is taken as one in order to represent critical damping. The above design procedure ensures that the reference model is compatible with the actual motor dynamics. This is an important consideration since an arbitrarily selected reference model can degrade the tracking performance. In case of large and abrupt reference tracks, a bound on the control signal is needed or the control technique must be modified to include the control signal in the performance index. The desired trajectory is as given in figure 5.For the system considered under case study desired specification are given in the following table.

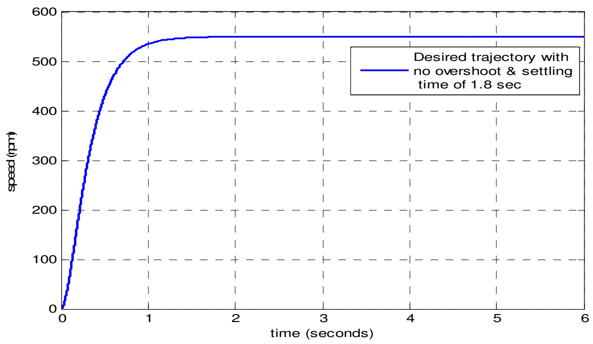
Figure 5. Desired trajectory described by reference model

8. SIMULATION RESULTS

A separately excited dc motor with nameplate ratings of 1 hp, 220 V, 550 rpm is used in all simulations. Following parameter values are associated with it. **[6]**

J_m=0.068 kg-m^2 or Nm/(rad/sec^2).
B_m=0.03475 Nm-sec or Nm/ (rad/sec).
R_a=7.56 ohms.
L_a=0.055 Henry.
K_T=3.475Nm-A$^{-1.}$
K_b=3.475 V/rad/sec.

In this work the adaptive control scheme (MRAC) is simulated for various loading conditions, parameter uncertainties and measurement noise. The performance of the dc motor is studied from no load to full load and open loop to adaptive closed loop. To test the system performance the data of the dc motor are taken from **[6]**.In the design maximum control input limit is kept 250 volts and the maximum motor current is 1.5 times of full load current. The adaptation gain of 0.0008 is selected after number of trials, which suits to the rating of the dc motor.



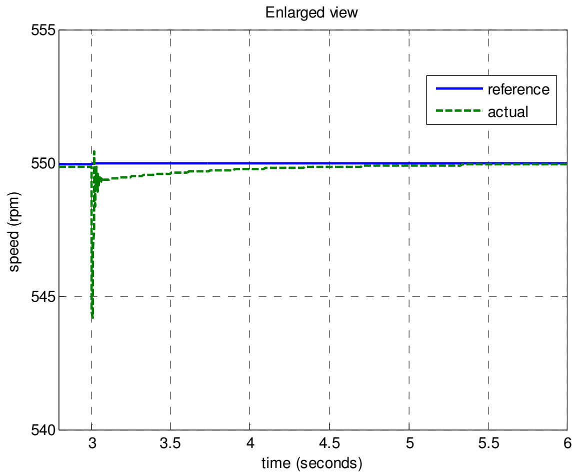


Figure 6. Tracking performance at full load (12.95 Nm) applied at t=3 sec.

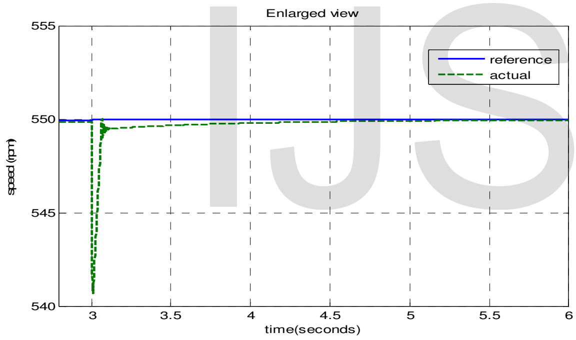


Figure 7. Tracking performance at 125% of full load applied at t=3 sec.

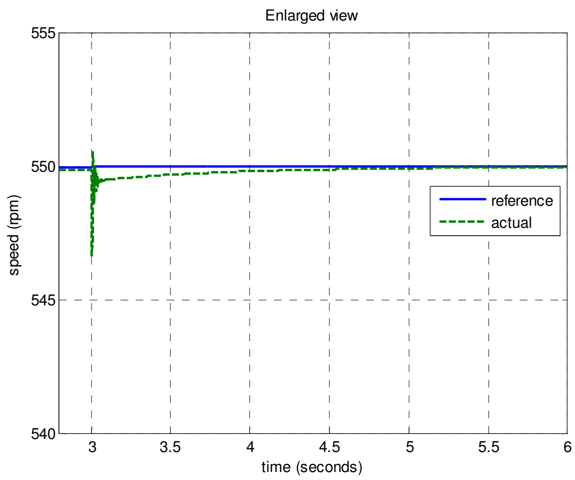


Figure 8. Tracking performance at 75% of full load applied at t=3 sec.

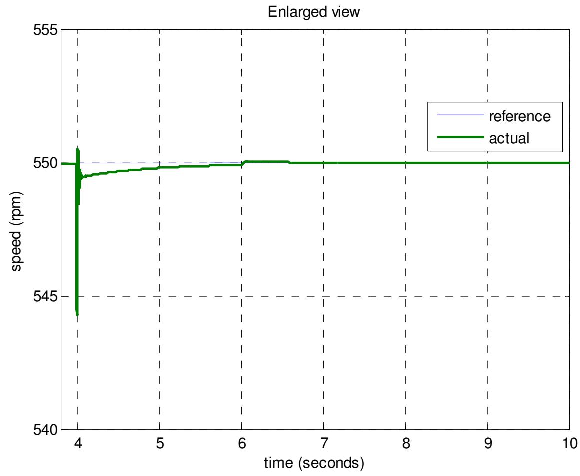


Figure 9. Full load applied at t=4 sec and thrown off at t=6sec

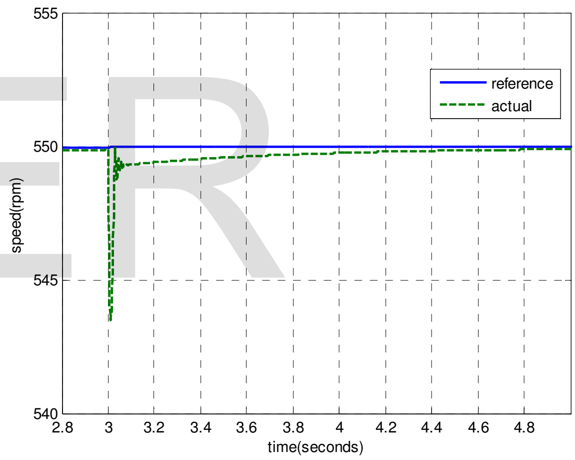


Figure 10. Speed tracking after parameter variation of +20% from nominal value

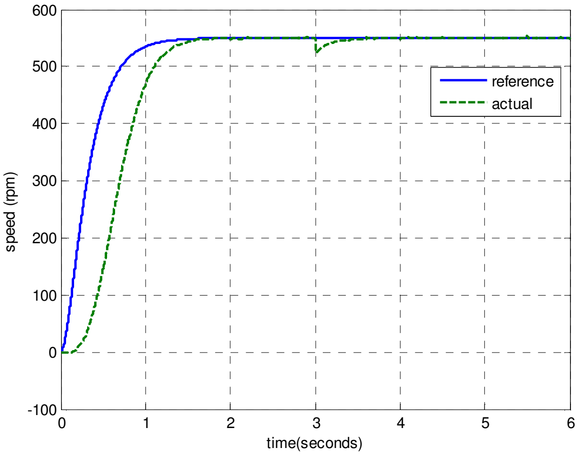


Figure 11. Tracking Responses under measurement noise (±0.1 rad/sec)

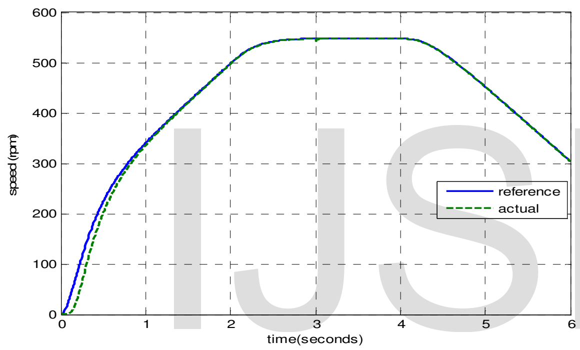


Figure 12. Tracking Responses for trapezoidal trajectory when load is applied at t=3sec

9. DISCUSSIONS AND CONCLUSION

From the simulation results it is inferred that for the limiting value of the control input, the value of adaptation gain can be varied up to certain maximum value. If it is further increased controller parameter does not converge to some constant value. Although as the adaptation gain is increased (within that max value) the adaptation becomes faster on account of becoming control input violently high this may not be compatible to the system. It is also inferred that with the increase in adaptation gain the error becomes smaller .All the results are found for the adaptation gain of 0.0008. All the results show the values of control input (armature voltage), input current (armature current) and speed as per the motor ratings (plots are not shown due to space constraints).

To demonstrate the effectiveness of the MRAC, the system (dc motor) has been simulated under various operating conditions such as load disturbance, parameter uncertainties, and measurement noise and for different shapes of tracks selected. Robustness is of particular importance in most of the control applications. Controllers with the fixed parameters cannot be robust unless unrealistically high gains are used. Hence the fixed controller parameter controllers cannot be considered for high performance applications. Simulation result shows that the robustness is greatly enhanced by this adaptive scheme, by continually adjusting the controller parameters to counteract the change in system operating conditions

The adaptive scheme used for the dc motor also demonstrates the load disturbance rejection capability. So, this capability is important when motor is to be operated at constant speed under varying load perturbations. The oscillatory nature in the control input is due to external load disturbances. .

Simulation study shows some initial oscillations in the control signal are evident because the initial values of controller parameters are obtained by the off-line estimation, which may not be accurate enough. However, once on-line updation begins the controller parameters are more accurate and the control signal is much smoother. In order to get the more smooth control signal, controller parameter estimation can be started from some intermediate values by providing initial values of the controller parameters. The initial parameters can be chosen on the basis of simulations carried for particular operating conditions. It results to the faster adaptation of the reference trajectory.

A dc motor has been successfully controlled using MRAC.The unknown, time variant nonlinear load characteristics have been successfully captured by this adaptive scheme. Particularly the robustness of the controller is of importance because noisy operating conditions are very common in practical applications.

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