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Speed control of DC-DC converter fed DC motor using robust adaptive intelligent controller

Raghupathy Prakash[1] and R Vasanthi[2]

Abstract

DC motors have been extensively used in many industrial applications. The control of the speed of a DC motor is therefore an important issue and has been studied since the early decades of the last century. This paper presents a novel neural network (NN)-based model reference adaptive control (MRAC) to improve the trajectory tracking performance of a DC motor. In this scheme, the controller is designed using a parallel combination of the conventional MRAC scheme and an NN controller. The controller is used to change the duty cycle of the converter and, thereby, the voltage fed to the armature of the separately excited motor to regulate the speed. The operating characteristics of the proposed drive system are compared with MRAC control to verify the effectiveness under various conditions by investigating the transient responses for the step change of the speed command and the load torque. Finally, simulated and experimental results show that on the one hand the proposed controller provides high-performance dynamic characteristics, and on the other hand that this scheme is robust with respect to load disturbances.

Keywords

DC-DC converter, DC motor, model reference adaptive control, neural network

1. Introduction

DC motors used in many applications such as steel rolling mills, electric trains, electric vehicles, electric cranes and robotic manipulators require speed controllers to perform their tasks. The most flexible control is obtained by means of separately excited DC motors in which the armature and field circuits are provided with separate sources. For the armature source a controlled rectifier or chopper is required (Dewan et al., 1984).

The armature voltage control method is used to vary the speed up to the rated speed and the motor operates in the constant torque region (Moleykutty et al., 2010). Conventional controllers such as proportional-integral (PI) and proportional-integral-derivative (PID) controllers have been applied to control the speed of DC motors. The disadvantages of using conventional controllers are that they are sensitive to variation in the motor parameters and load disturbance. In addition, it is difficult to tune PI or PID gains to eliminate and reduce the overshoot and load disturbance. In order to avoid the shortcomings of conventional controllers, researchers have applied adaptive control techniques for DC motor speed control to achieve parameter insensitivity and a fast speed response (Elkeshet, 2009).

Recently, the superior performance of artificial intelligence (AI)-based controllers has encouraged power system and power electronic engineers to replace conventional speed control circuit with intelligent speed controllers (Luiz et al., 1995; Janardan et al., 1996; Rovithakis and Christodoulou, 1996; Minkova et al., 1998; Jui-Hong, 1999; Kukolj et al., 2000; Hussein et al., 2004).

At present, most of the existing industrial speed controllers for DC motor drives are largely based on

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classical approaches which do not guarantee satisfactory performance against machine parameter variations. Hence there is the need for adaptive control and for model reference adaptive control (MRAC). MRAC is a class of adaptive controls and belongs to the modem control theory. In the model reference adaptive system, a reference model specifies the desired control performance and a control input is generated to drive the controlled system to track the response of the reference model (Astrom and Wittenmark, 1995; Ioannou and Jing, 1996).

A common actuator in control systems is a DC motor and is an obvious choice for implementation of advanced control algorithms in electric drives, due to the stable and linear characteristics associated with it. This makes a DC motor controllable over a wide range of speeds by proper adjustments of its terminal voltage. It is also ideally suited for tracking control applications (El-Sharakawi and Huang, 1989; Weerasooriya and El-Sharkawi, 1989). From a control system point of view, the DC motor can be considered as a single input single output (SISO) system, eliminating the complexity associated with multi-input drive systems. The driven load often needs to be run at a speed that varies according to the specific application for which it is being used. The speed in some cases (such as fluctuating loads in the case of rolling mills) may need to change dynamically to suit the conditions, whereas in some other cases may alter with a change in (load) operating conditions. In real-time control, provision is made to consider the controller parameters as time variant and is subject to drift depending on the operating conditions. In an adaptive control strategy, the controller parameters are updated at regular intervals of time to satisfy the design requirements, unlike the conventional controllers. Apart from various conventional control strategies, adaptive control has proved its potential application in tracking/trajectory control problems. Weerasooriya and El-Sharkawi (1989) developed a modified adaptive controller based on minimum variance a self-tuning strategy. This scheme is effective even in the presence of external disturbances, provided that the system exhibits minimum phase characteristics. El-Sharakawi and Huang (1989) and El-Sharkawi and Weerasooriya (1990) discussed the variable structure – tracking, and a self-tuning controller is developed for high performance DC motor applications. El-Sharkawi and Weerasooriya (1991) and Weerasooriya and El-Sharkawi (1993) used the ability of artificial intelligence to identify the system dynamics and used the indirect MRAC for trajectory control, which is specifically useful in tracking applications. An attempt has been made to merge the accuracy of an MRAC system and calculation speed of Artificial Neural Network (ANN) approach, to come up with a trajectory following controller for DC motor applications. EI-Samahy (2000) described the design of a robust adaptive discrete variable structure control scheme for high performance DC drives. Zhou et al. (2001) proposed a global speed controller for the separately excited DC motor, in which the motor is modeled in two regions – the first model is linear when speed is under the base speed and the other is nonlinear when speed is controlled by using a field-weakening method. For the first part a linear robust state-feedback controller is used and for the nonlinear part an adaptive back-stepping controller is used. Crnosija et al. (2002) presented an application of MRAC with signal adaptation to permanent magnet brushless DC motor drives. MRAC with a signal adaptation algorithm has been applied to compensate for the parameter sensitivity and influence of load disturbances. Ban and Crnosiya (2003) applied MRAC with a simplified discrete parameter adaptation algorithm for control of a DC motor, and Cezayirli and Ciliz (2004) developed a multiple model adaptive control (MMAC) for a motor with large and abrupt parameter changes.

The objective of MRAC is to ensure the output of a controlled system to track the output of a given reference model, in addition to closed-loop stability. 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 desired 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 an output feedback controller and an adjustment mechanism that adapts the controller parameters.

Since its first appearance and subsequent intensive research to apply MRAC to speed control, it has not been widely accepted in industrial practice. This is believed to be partly because the MRAC speed control system does not achieve consistent satisfactory performance over a wide range of speed demands, especially at low speed, and there is no defined rule to guide designers to choose the adaptation gains.

The speed control of a DC motor uses an MRAC controller because of simplicity and stability. However, an unexpected change in load conditions or environmental factors would produce overshoot, oscillation of motor speed, oscillation of the torque, or a long settling time and thus causes deterioration of drive performance. To overcome this, a neural-network-based model reference adaptive control (NN-MRAC) scheme can be proposed to control the speed of a

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separately excited DC motor. This paper is organized as follows: the modeling of the DC motor is reviewed in Section 2, the MRAC scheme is described in Section 3, and Section 4 describes the design of the proposed controller. The simulation results, comparison and discussion are presented in Section 5. Section 6 describes the hardware implementation, and Section 7 concludes the work.

2. Mathematical model of DC motor and DC-DC converter

A separately excited DC motor has the simplest decoupled electromagnetic structure. A schematic diagram of the electrical network of the machine is shown in Figure 1.

The DC motor has been modeled with equations (1) and (2).

$$\frac{d^2\theta}{dt^2} = \frac{1}{J}\left[Ki_a - B\frac{d\theta}{dt} - T_L\right] \tag{1}$$

$$\frac{di_o}{dt} = \frac{1}{L}\left[V_0 - Ri_a - K_b\frac{d\theta}{dt}\right] \tag{2}$$

where

J	moment of inertia of the motor (kgm^2)
B	friction coefficient of the motor (Nm/rad/sec)
K_T	torque constant of the motor (Nm/A)
K_b	motor back emf constant (V/rad/sec)
T_L	load torque applied (Nm)
i_a	armature current (A)
V_0	armature voltage applied (V)
R	armature resistance (ohms)
L	armature inductance (mH)

The DC-DC converter is used to change the armature voltage applied to the separately excited DC motor whose speed is to be controlled.

The buck converter was modeled using equations (3) to (6). Mode 1 is when the MOSFET switch is ON and Mode 2 is when the MOSFET switch is OFF.

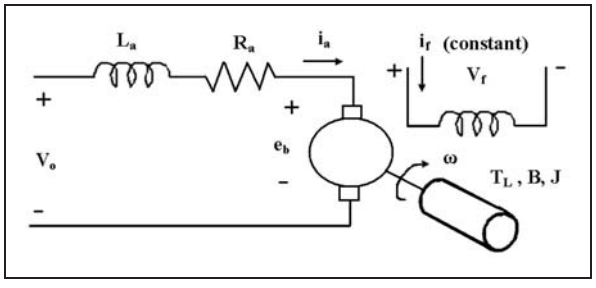


Figure 1. Equivalent circuit of separately excited DC motor.

Mode 1: (Switch ON)

$$V_0 = R_a i_a + L_a\frac{di_a}{dt} + K_b \tag{3}$$

$$K_T i_a = J\frac{d\omega}{dt} + B\omega + T_L \tag{4}$$

Mode 2: (Switch OFF)

$$0 = R_a i_a + L_a\frac{di_a}{dt} + K_b\omega \tag{5}$$

$$K_T i_a = J\frac{d\omega}{dt} + B\omega + T_L \tag{6}$$

The above two states of the converter can be averaged using the fact that the switch is in position 1 for a period of ($d\times$ Ts) over the switching period Ts, where d is the duty cycle. The averaged small signal model is formulated by assuming perturbations in the steady-state values.

The small signal model for the chopper-fed DC drive is given by equations (7) and (8):

$$L_a\frac{d\bar{i}_a}{dt} = D\bar{v}_s + V_s\bar{d} - R_a\bar{i}_a - K_b\bar{\omega} \tag{7}$$

$$J\frac{d\bar{\omega}}{dt} = K_T\bar{i}_a - B\bar{\omega} - T_L \tag{8}$$

Considering duty cycle d(s) as the control signal and speed $\omega(s)$ as the output signal, the motor speed transfer function is

$$\frac{\bar{\omega}(s)}{\bar{d}(s)} = \frac{\bar{\omega}(s)}{\bar{i}_a(s)} \times \frac{\bar{i}_a(s)}{\bar{d}(s)} \tag{9}$$

From these equations, the speed gain is given by equation (10) when the load torque is constant.

$$\frac{\bar{\omega}(s)}{\bar{i}_a(s)} = \frac{K}{Js + B} \tag{10}$$

Similarly, the current gain when the supply voltage is kept constant is given by equation (11):

$$\frac{\bar{i}_a(s)}{\bar{d}(s)} = \frac{V_s(Js + B)}{(L_a s + R_a)(Js + B) + K^2} \tag{11}$$

So, the final transfer function of the chopper-fed DC motor under the assumed conditions is as given in the equation (12):

$$\frac{\bar{\omega}(s)}{\bar{d}(s)} = \frac{KV_s}{(L_a s + R_a)(Js + B) + K^2} \tag{12}$$

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3. Model reference adaptive control

Model reference adaptive control is one of the main approaches of adaptive control schemes. The desired performance is expressed as a reference model, which gives the wished response to an input signal. The adjustment mechanism changes the parameters of the regulator by minimizing the error between the system output and the reference model. In the standard adaptive control scheme, the control U_{mr} is structured as

$$U_{mr} = \theta^T \omega + \dot{\theta}^T \Phi = \theta^T \omega - \theta^T \Gamma \phi e_1 \mathrm{sgn}(K_p/K_m) \quad (13)$$

where K_p is plant gain and K_m is reference model gain, ϕ is signal vector, Γ is a positive gain and $\theta = [\theta_1, \theta_2, \theta_3, C_0]^T$ is a vector of adjustable parameters, and is considered as an estimate of a vector of unknown system parameters θ^*.

The dynamic of tracking error is

$$e = G_m(s)(s + p_0)\, p^* \tilde{\theta}^T \phi \quad (14)$$

where $P^* = \frac{K_p}{K_m}$ and $\tilde{\theta} = \theta(t) - \theta^*$ represent the parameter error. $G_m(s)(s + p_0)$ is strictly proper and strictly positive real (SPR). In this case, because the transfer function between the parameter error $\tilde{\theta}$ and the tracking error e is SPR, and the adaptation rule for the controller gain θ is given

$$\dot{\theta} = \Gamma \phi e_1 \mathrm{sgn}(K_p/K_m) \quad (15)$$

where $e_1 = y_p - y_m$.

The adaptive laws and control schemes developed are based on a plant model that is free from disturbances, noise and unmodeled dynamics. These schemes are to be implemented on actual plants that are most likely to deviate from the plant models on which their design is based. An actual plant may be infinite in dimensions, nonlinear, and its measured input and output may be corrupted by noise and external disturbances. It is shown by using conventional MRAC that an adaptive scheme is designed for a disturbance-free plant model and may be unstable in the presence of small disturbances.

4. Proposed approach

To make the system adapt more quickly and more efficiently than the conventional MRAC system, a neural network-based model reference adaptive control (NN-MRAC) scheme is designed. In this scheme, the controller is designed by using a parallel combination of the conventional MRAC system and an NN controller. The control input of the DC motor is given by the sum of the MRAC output and the NN controller output. The inputs to the NN are the desired system states, its derivatives and the DC motor output. Here the multilayer back propagation NN is used. The block diagram of the proposed NN-MRAC scheme is shown in Figure 2.

The system consists of a buck converter type DC-DC converter or chopper for driving the separately excited DC motor (Krein, 1992; Rashid, 1993;

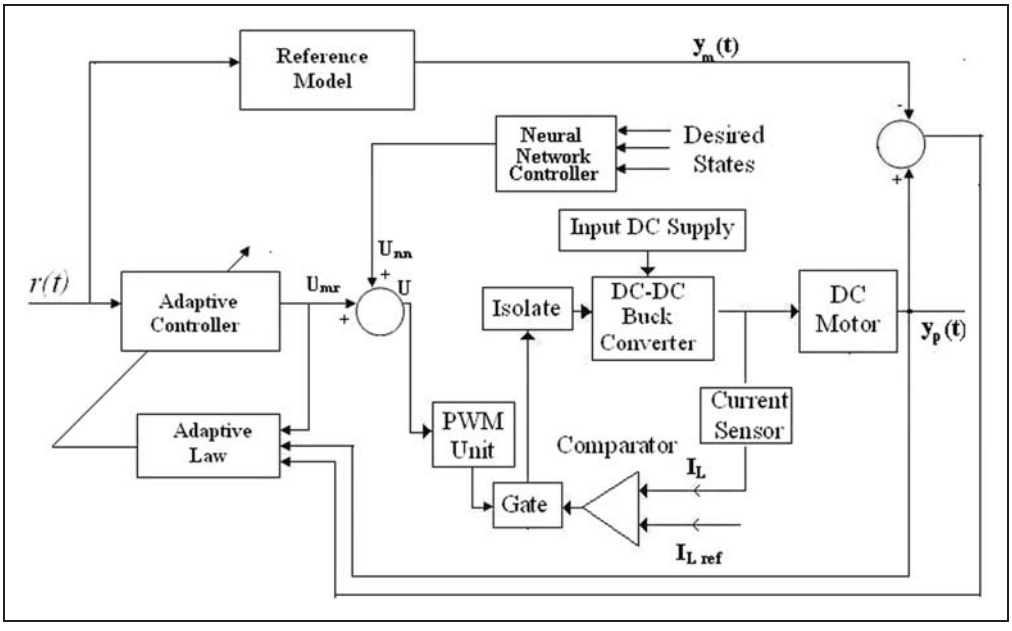


Figure 2. Block diagram of the neural network-based model reference adaptive control (NN-MRAC).

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Erickson, 1997). The proposed NN-MRAC can be used to generate the PWM waveform required to switch the DC-DC converter. The inner current controller is selected as a simple on-off controller.

A gating circuit is used to switch off the PWM signal from the controller whenever the motor current exceeds the reference current I_{Lref}. In the outer speed control loop, the motor speed is sensed by a speed sensor and is fed back to the NN-MRAC. In the controller unit, the speed sensed is compared with the reference speed and an error is given as an input to the controller. The NN-MRAC will attempt to reduce the error to zero by changing the duty cycle of the switching signal. The DC-DC converter is used to change the armature voltage applied to the separately excited DC motor whose speed is to be controlled. The controller is designed to work with a buck converter type DC-DC converter and so the speed can be controlled over a wide range from zero to the rated speed.

The theoretical basis for the designed scheme is as follows, To keep the DC motor output y_p converging to the reference model output y_m, the control input U can be synthesized by equation (16):

$$U = U_{mr} + U_{nn} \tag{16}$$

where U_{mr} is the output of the adaptive controller, U_{nn} is the output of neural network.

The stability of the system and adaptability are then achieved by an adaptive control law U_{mr} tracking the system output to a suitable reference model, such that error $e = y_p - y_m = 0$ is obtained asymptotically. The controller design concept is illustrated using the following state equation of the second-order system, which can be comfortably expanded to a higher-order system.

$$\dot{x}_1 = x_2 \tag{17}$$

$$\dot{x}_2 = ax_1 + bx_2 + cU \tag{18}$$

and let the output, $y_p = x_1$

Differentiating equation (18)

$$\begin{aligned} \ddot{y}_p = \ddot{x}_1 = \dot{x}_2 = ax_1 + bx_2 + cU \\ U = c^{-1}(\dot{x}_2 - ax_1 - bx_2) \end{aligned} \tag{19}$$

Suppose a controller U_d can be established which should track a desired signal, say $\dot{x}_{2d}$, then the controller equation can be written as

$$U_d = c^{-1}(\dot{x}_{2d} - ax_1 - bx_{2d}) \tag{20}$$

which is the same as

$$U_d = D(y_p, x_{2d}, \dot{x}_{2d}) \tag{21}$$

where D is the functional relation between states, control and output. Thus it possible to have a system response that equals the desired value if the controller U_d can effectively inverse the system dynamics. In other words the controller U should track the system such that $\ddot{e} = 0$. However due to system dynamics, the error equation has to be written as

$$e = (x_d - x) = 0$$

Thus the controller U should be written as

$$U = c^{-1}(\dot{x}_{2d} - ax_1 - bx_{2d}) + U_{mr} \tag{22}$$

The NN control law now becomes

$$U_d = D(y_p, x_{2d}, \dot{x}_{2d}) \tag{23}$$

where y_p is the DC motor output. From the above discussion it can be seen that the input to the NN should be

$$X = [y_p, x_{2d}, \dot{x}_{2d}] \tag{24}$$

The design procedure multilayer back propagation NN controller and derivation are discussed next.

4.1. Structure of proposed multilayer back propagation neural network controller design

The inputs of the NN are the desired system states, its derivatives, and the output. The multilayer back propagation NN is used in the present work. The multilayer back propagation NN is especially useful for this purpose, because of its inherent nonlinear mapping capabilities, which can deal effectively with real-time online computer control. The NN of the present work method has three layers: an input layer with n neurons, a hidden layer with n neurons and an output layer with one neuron as shown Figure 3. Let x_i be the input to the i^{th} node in the input layer, z_j be the input to the j^{th} node in the hidden layer, y be the input to the node in the output layers. Furthermore let V_{ij} be the weight between the input layer and the hidden layer W_{j1} is the weight between the hidden layer and the output layer.

4.2. Learning about the neural network

The relations between the inputs and the outputs of NN are expressed as

$$Z_{-inj} = V_{oj} + \sum_{i=1}^{n} x_i V_{ij} \tag{25}$$

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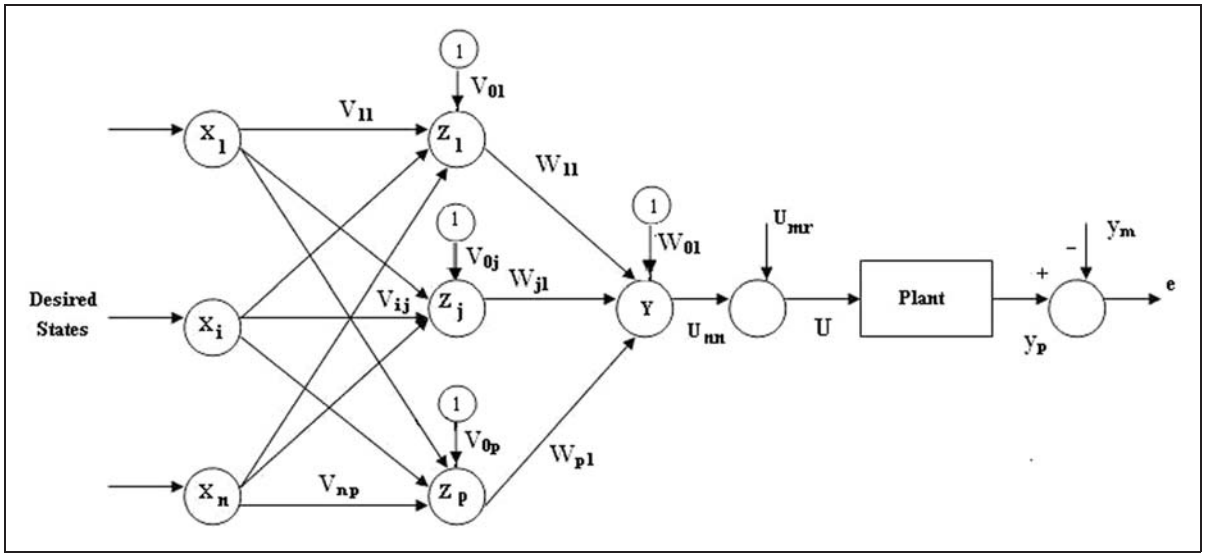


Figure 3. Structure of neural network.

$$Y_{-ink} = W_{01} + \sum_{j=1}^{P} z_j W_{j1} \tag{26}$$

$$Z_j = F(Z_{-inj}) \tag{27}$$

$$Y_k = F(Y_{-ink}) \tag{28}$$

where $F(\cdot)$ is the activation function.

Sigmoid function is chosen for the activation function as follows:

$$F(x) = \frac{2a}{1+\exp(-\mu x)} - a \tag{29}$$

where $\mu > 0$, a is a specified constant such that $a \leq 0$, and $F(x)$ satisfies

$$-a < F(x) < a$$

The aim of training to minimize the sum of square error energy function,

$$E(k) = \frac{1}{2}[y_m - y_p]^2 \tag{30}$$

The weight is updated by using

$$\Delta W_{j1} = -\eta \frac{\partial E}{\partial W_{j1}} \tag{31}$$

$$\Delta W_{01} = -\eta \frac{\partial E}{\partial W_{01}} \tag{32}$$

$$\Delta V_{ij} = -\eta \frac{\partial E}{\partial V_{ij}} \tag{33}$$

$$\Delta V_{0j} = -\eta \frac{\partial E}{\partial V_{0j}} \tag{34}$$

where η is the learning role, $\frac{\partial E}{\partial W_{j1}}$, $\frac{\partial E}{\partial W_{01}}$, $\frac{\partial E}{\partial V_{ij}}$ and $\frac{\partial E}{\partial V_{oj}}$ are derived as follows:

$$\frac{\partial E}{\partial W_{j1}} = \frac{\partial E}{\partial y_p}\frac{\partial y_p}{\partial u_p}\frac{\partial u_p}{F(y_{-ink})}\frac{\partial F(y_{-ink})}{\partial y_{-ink}}\frac{\partial y_{-ink}}{\mathrm{d}W_{j1}} \tag{35}$$

$$\frac{\partial E}{\partial W_{01}} = \frac{\partial E}{\partial y_p}\frac{\partial y_p}{\partial u_p}\frac{\partial u_p}{F(y_{-ink})}\frac{\partial F(y_{-ink})}{\partial y_{-ink}} \tag{36}$$

$$\frac{\partial E}{\partial V_{ij}} = \frac{\partial E}{\partial y_p}\frac{\partial y_p}{\partial u_p}\frac{\partial u_p}{F(y_{-ink})}\frac{\partial f(y_{-ink})}{dy_{-ink}}\frac{dy_{-ink}}{\partial F(Z_{-inj})}\frac{\partial f(z_{-inj})}{z_{-inj}}\frac{\partial z_{-inj}}{\partial V_{ij}} \tag{37}$$

$$\frac{\partial E}{\partial V_{0j}} = \frac{\partial E}{\partial y_p}\frac{\partial y_p}{\partial u_p}\frac{\partial u_p}{F(y_{-ink})}\frac{\partial f(y_{-ink})}{dy_{-ink}}\frac{dy_{-ink}}{\partial F(Z_{-inj})}\frac{\partial f(z_{-inj})}{z_{-inj}} \tag{38}$$

where

$$\frac{\partial E}{\partial y_p} = -(y_m - y_p) \tag{39}$$

$$\frac{\partial u_p}{\partial f(y_{-ink})} = 1 \tag{40}$$

$$\frac{\partial y_{-ink}}{\partial W_{ji}} = F(z_{-inj}) \tag{41}$$

$$\frac{\partial y_{-ink}}{\partial f(z_{-inj})} = W_{j1} \tag{42}$$

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$$\frac{\partial z_{inj}}{\partial Vij} = X_i \tag{43}$$

$$\frac{\partial F(y_{-ink})}{\partial (y_{-ink})} = \frac{\mu}{2a}[(a - F(y_{-ink}))(a + F(y_{-ink}))] \tag{44}$$

$$\frac{\partial F(z_{-inj})}{\partial (Z_{-inj})} = \frac{\mu}{2a}(a - F(z_{-inj}))(a + F(z_{-inj})) \tag{45}$$

$$\frac{\partial y}{\partial U} = \frac{\partial y}{\partial U_{mr}}\frac{\partial U_{mr}}{\partial U} = \frac{\partial y}{\partial U_{mr}} \Big/ \frac{\partial U}{\partial U_{mr}} \tag{46}$$

$$U = U_{mr} + U_{nn} \tag{47}$$

$$\frac{\partial U}{\partial U_{mr}} = 1 + \frac{\partial U_{nn}}{\partial U_{mr}} \tag{48}$$

$$\frac{\partial U_{nn}}{\partial U_{mr}} = \frac{\partial F(y_{-ink})}{\partial y_{-ink}}\frac{\partial y_{-ink}}{\partial F(z_{-inj})}\frac{\partial F(z_{-inj})}{\partial z_{-inj}}\frac{\partial z_{-inj}}{\partial X_i} \tag{49}$$

$$\frac{\partial z_{in-j}}{\partial x_i} = V_{ij} \tag{50}$$

$$W_{j1}(new) = W_{j1}(old) + \Delta W_{j1} \tag{51}$$

$$W_{01}(new) = W_{01}(old) + \Delta W_{01} \tag{52}$$

$$V_{ij}(new) = V_{ij}(old) + \Delta V_{ij} \tag{53}$$

$$V_{0j}(new) = V_{0j}(old) + \Delta V_{0j} \tag{54}$$

5. Results and discussion

Assume that the DC motor is expected to behave as a second-order system whose input is $r(t)$ and output is $y_m(t)$. The reference model can be selected as the ideal second-order system transfer function.

$$W_m(s) = \frac{\omega_m(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{55}$$

where ξ is the damping ratio and ω_n is the undamped natural frequency of oscillation.

The performance of the MRAC and the proposed controller was investigated by simulation for a DC motor whose parameters are listed in Table 1. A series of simulation tests were carried out on a DC motor drive using both the MRAC and the proposed NN-MRAC for various operating conditions. The time response and steady-state errors were analyzed and compared. The robustness of the controller was effectively demonstrated by considering the effects of the variations of the load torque.

Figures 4 and 5 show the speed response for both the MRAC and the NN-MRAC when there is a sudden change in speed reference at three seconds and an applying load torque from 0 to rated load at six seconds. From these figures it can be seen that the NN-MRAC exhibited better speed tracking than MRAC. A change in speed from 900 rpm to 1500 rpm is smoother with NN-MRAC than with MRAC. The starting torque developed in NN-MRAC is much smoother than the MRAC controller. The steady-state operation of NN-MRAC shows negligible speed error and ripple-free behavior. From all points of view, such as variable speed characteristics and speed recovery time, the proposed NN-MRAC is better than MRAC. Especially in full load the MRAC's response has more overshoot and vibration than the proposed NN-MRAC. The proposed NN-MRAC performed better with respect to rising time and steady-state error.

Table 1. Separately excited DC motor specifications.

DC motor parameters	Value
Motor rating	3 HP
DC supply voltage	220 V
Motor rated current	4.3A
Armature resistance R_a	0.6 Ω
Armature inductance L_a	0.008 H
Inertia constant J	0.011 Nm^2
Damping constant B	0.004 Nm/rad/s
Torque constant parameter K_t	0.55
Back emf constant K_b	0.55
Speed	1800 rpm

A comparative study of time domain performances for the controllers under study is shown in Tables 2 and 3. The study was done for 60% and 100% of the rated speed without a load torque and with a full load torque. The proposed NN-MRAC is found to provide low steady-state error and rising time than the MRAC under comparison.

Figures 6 and 7 show the speed response waveforms in the case of moment of inertia variation using the MRAC and the proposed NN-MRAC respectively. The reference speed is 1500 rpm that is increased from zero speed, the moment of inertia J_L is changed to four times the normal value J, and full load is applied at six seconds. It can be observed that the proposed NN-MRAC is more robust than MRAC.

Figures 8 and 9 show the speed response with slow speed operation using the MRAC and proposed NN-MRAC respectively. It can be observed that the proposed NN-MRAC is more robust than the MRAC. In this case, in the NN-MRAC scheme the overshoots and the oscillations are much smaller, yielding a much better performance than the conventional

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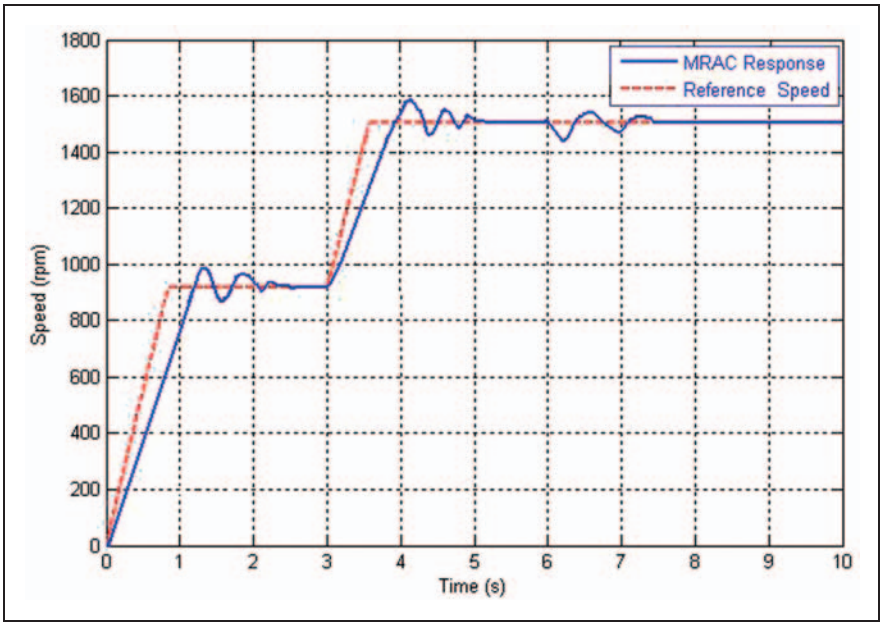


Figure 4. Graph of speed variation for the step change in reference speed from 900 rpm to 1500 rpm at $t = 3$ and for the change in load torque from zero to the rated value applied at $t = 6$ sec with the model reference adaptive control (MRAC).

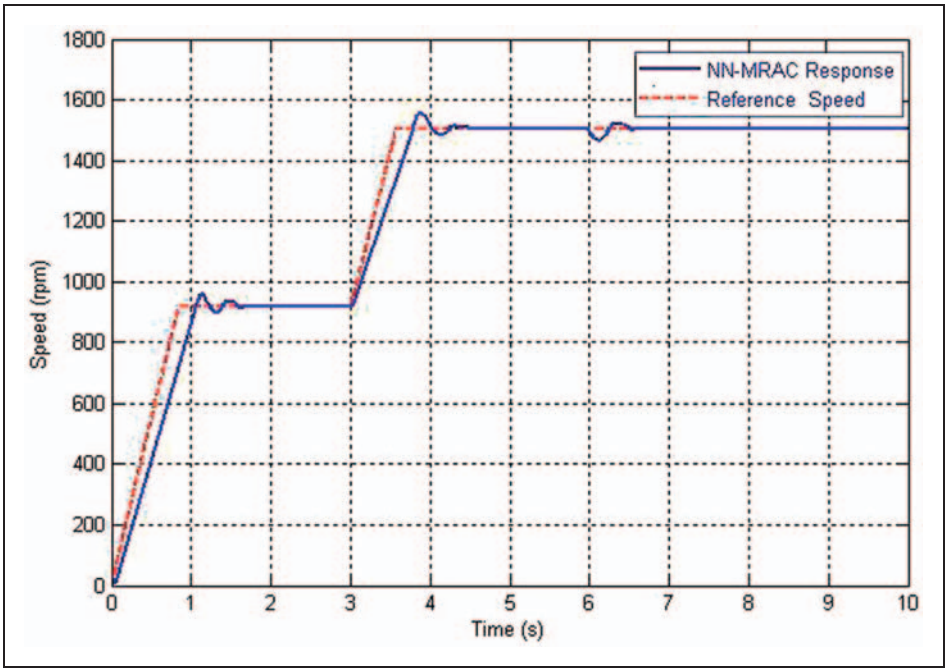


Figure 5. Graph of speed variation for the step change in reference speed from 900 rpm to 1500 rpm at $t = 3$ and for the change in load torque from zero to the rated value applied at $t = 6$ sec with the proposed neural network-based model reference adaptive control (NN-MRAC).

MRAC scheme. In the proposed NN-MRAC scheme, the motor output has tracked with the reference model output within the minimum possible time.

The responses of the control algorithm with only the MRAC are observed to be inferior to those of the control algorithm both with the NN controller and the MRAC. Also, the response of the control algorithm

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with only the MRAC shows large overshoot and oscillation. Further, the response of the output performed by the control algorithm both with the NN controller and the MRAC is more satisfactory for the bounded disturbances with unknown as well as time-varying characteristics than that of the control algorithm with only the MRAC.

From the simulation results, when using the NN controller and the MRAC in coordination where the control law is used to cope with parameter variation and load disturbances, the controlled system can be robustly stabilized all of the time.

Table 2. Comparison of the time domain performances of the conventional MRAC and proposed NN-MRAC under 0% of rated torque.

Time domain performances	Conventional MRAC	NN-MRAC
Rise time	1.2	1
Settling time	2.2 sec	1.2 sec
Max. over shoot	4%	1.4%

MRAC: model reference adaptive control; NN-MRAC: neural network-model reference adaptive control.

Table 3. Comparison of the time domain performances of the conventional MRAC and the proposed NN-MRAC under 100% rated torque and speed $\omega r = 1500$ rpm at $t = 3$ sec.

Time domain performances	Conventional MRAC	NN-MRAC
Settling time	7.5 sec	6.2 sec
Max. over shoot	3%	1%
Recovery time	1.5 sec	0.5 sec

MRAC: model reference adaptive control; NN-MRAC: neural network-model reference adaptive control.

6. Experimental implementation

The designed controllers were implemented by using an NXP 80C51-based processor (P89V51RD2BN). A buck converter was built, and the controllers were tested on the DC motor. A tacho-generator was used to sense the speed and to feed back the speed signal. An LEM current sensor LTS25NP was used to sense the armature current and it is compared with the reference current using the comparator LM 399. The AND gate was used to allow the PWM waveform when the actual current was less than the reference current. This PWM waveform was then level amplified and fed to the DC-DC power converter through an IR2110 isolator chip. The buck converter output was used as a supply to the armature of the DC motor to maintain the speed. The tacho-generator connected to the motor shaft gave a DC voltage proportional to the speed and this DC voltage was fed to the ADC available in the microcontroller. The implemented hardware setup used is shown in Figure 10.

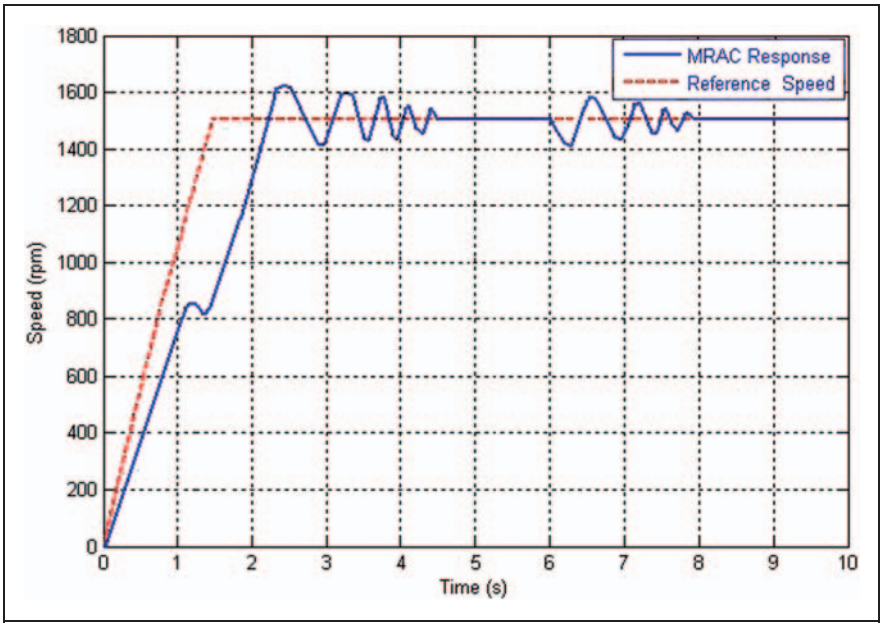


Figure 6. Speed response using model reference adaptive control (MRAC) ($J_L = 4$J).

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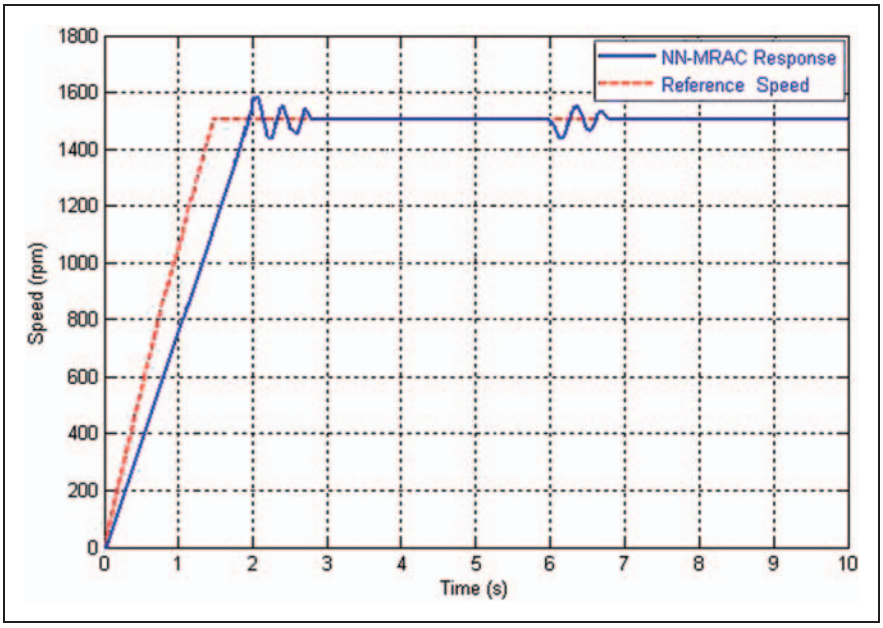


Figure 7. Speed response using neural network-based model reference adaptive control (NN-MRAC) ($J_L = 4J$).

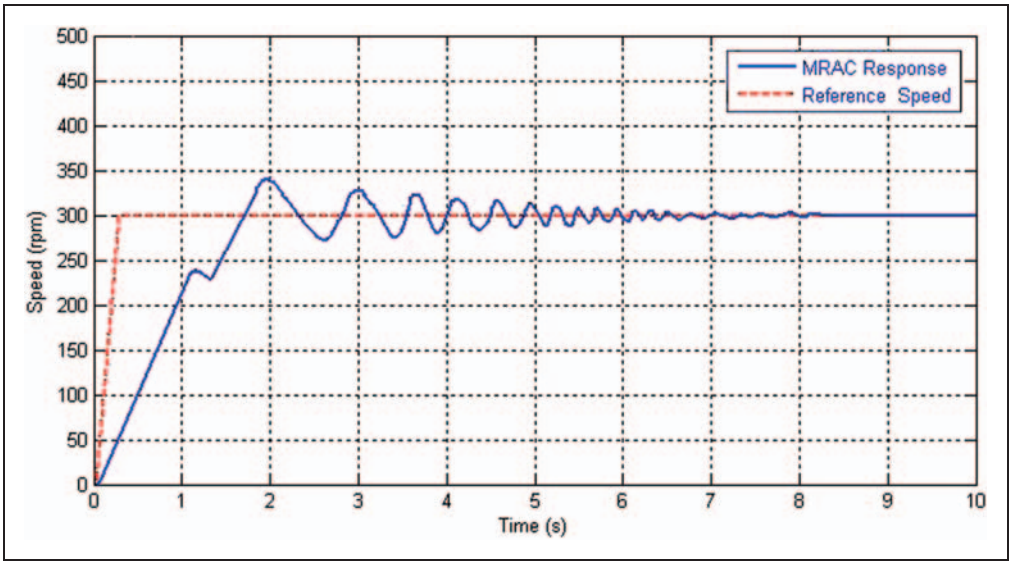


Figure 8. Speed response using model reference adaptive control (MRAC) (slow speed operation).

Figures 11 and 12 show the experimental results of speed variation from standstill to 1500 rpm using MRAC and NN-MRAC respectively. Motor start-up is faster with NN-MRAC compared to MRAC. Steady-state operation of NN-MRAC shows negligible speed error and ripple-free behavior.

A comparison of the hardware performance of the proposed NN-MRAC system and MRAC is given in Table 4.

Figures 13 and 14 show the experimental results of slow speed variation from standstill to 300 rpm using MRAC and NN-MRAC respectively. In the slow speed operation NN-MRAC gives a better performance. The experimental graph agrees with the simulated waveforms and confirms the use of NN-MRAC for the control of motors.

When the set speed is reduced to 300 rpm, it can be seen in Figures 13 and 14 that the MRAC

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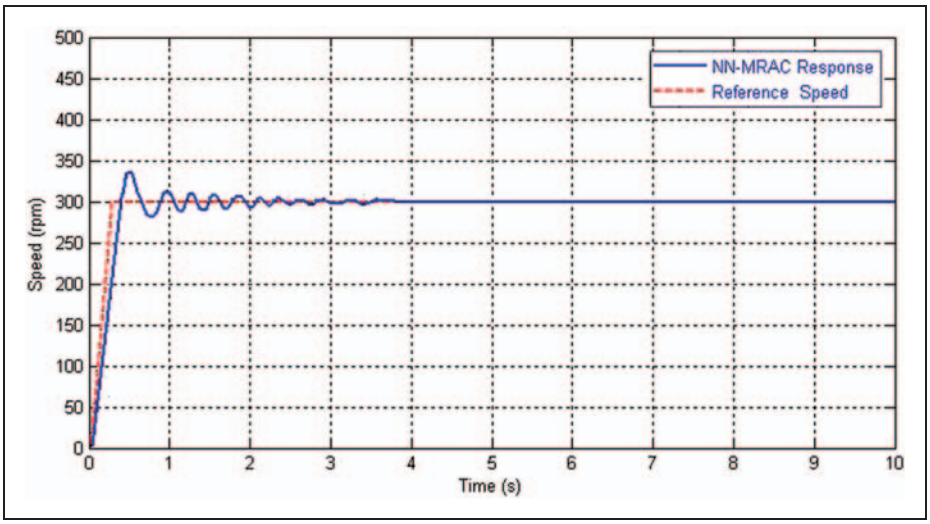


Figure 9. Speed response using neural network-based model reference adaptive control (NN-MRAC) (slow speed operation).

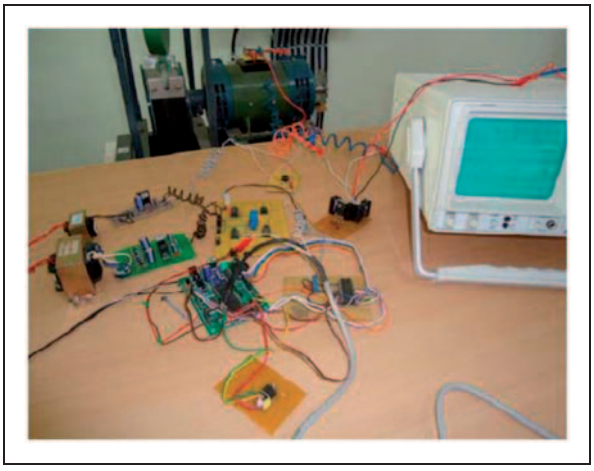


Figure 10. Hardware implementation.

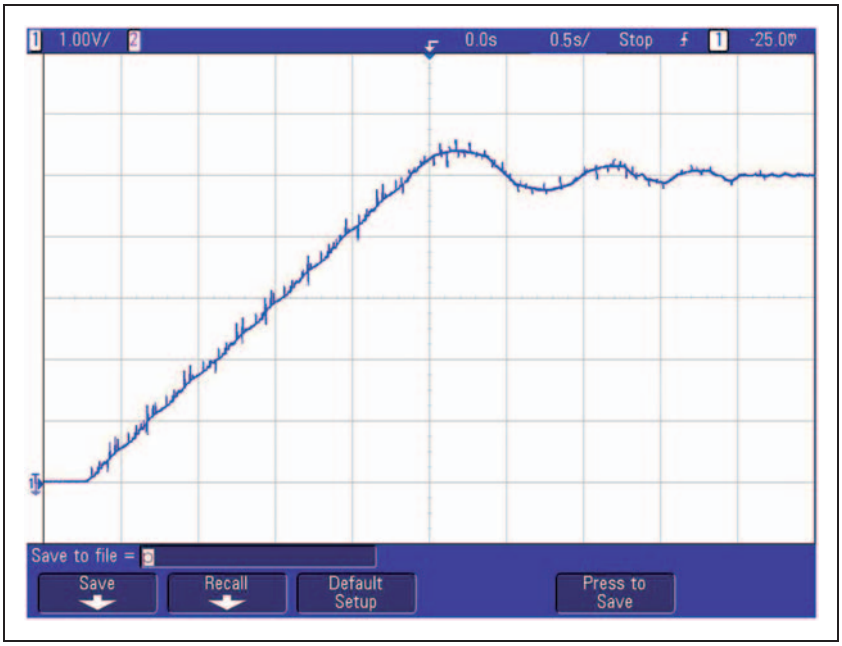


Figure 11. Experimental result of speed response with model reference adaptive control (MRAC).

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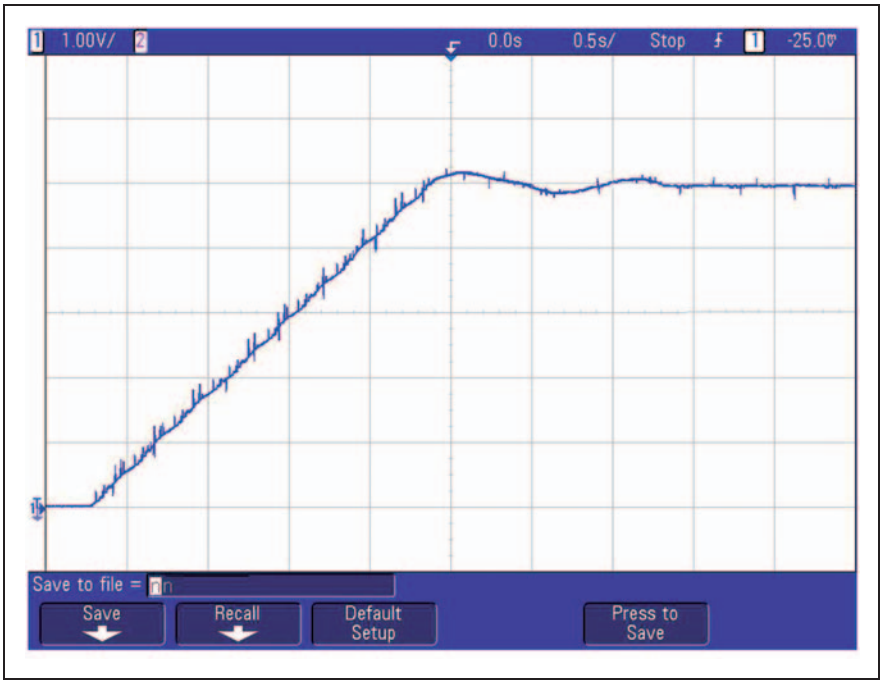


Figure 12. Experimental result of speed response with proposed neural network-based model reference adaptive control (NN-MRAC).

Table 4. Hardware performance comparison of proposed NN-MRAC with MRAC for the speed $\omega_r = 1500$ rpm.

Controller	Settling time in sec	Max. over shoot in %	Steady-state error in rpm
MRAC	4	10	10
NN-MRAC	2.5	2	2

MRAC: model reference adaptive control; NN-MRAC: neural network-model reference adaptive control.

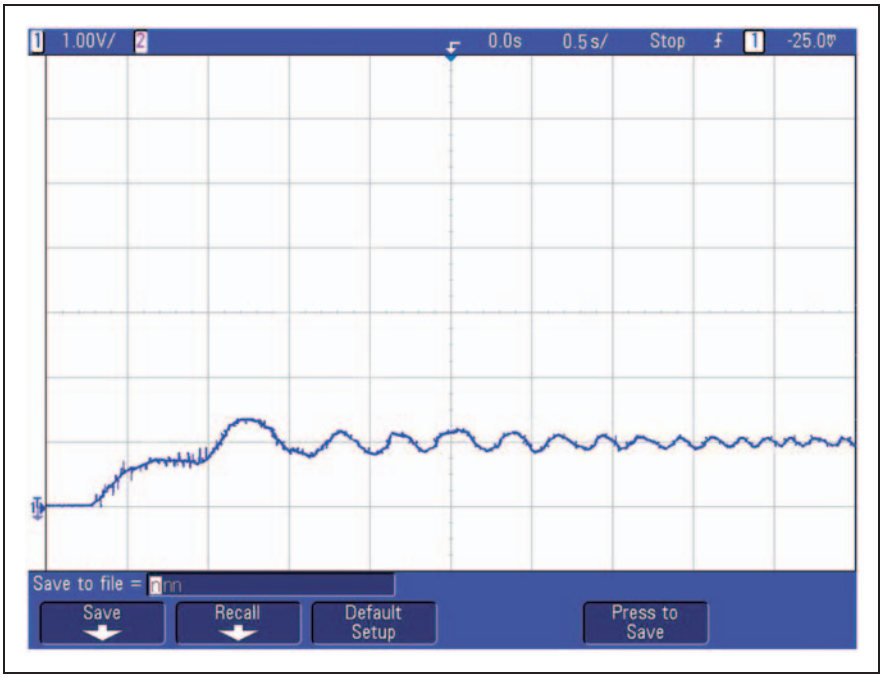


Figure 13. Experimental result of slow speed response with model reference adaptive control (MRAC).

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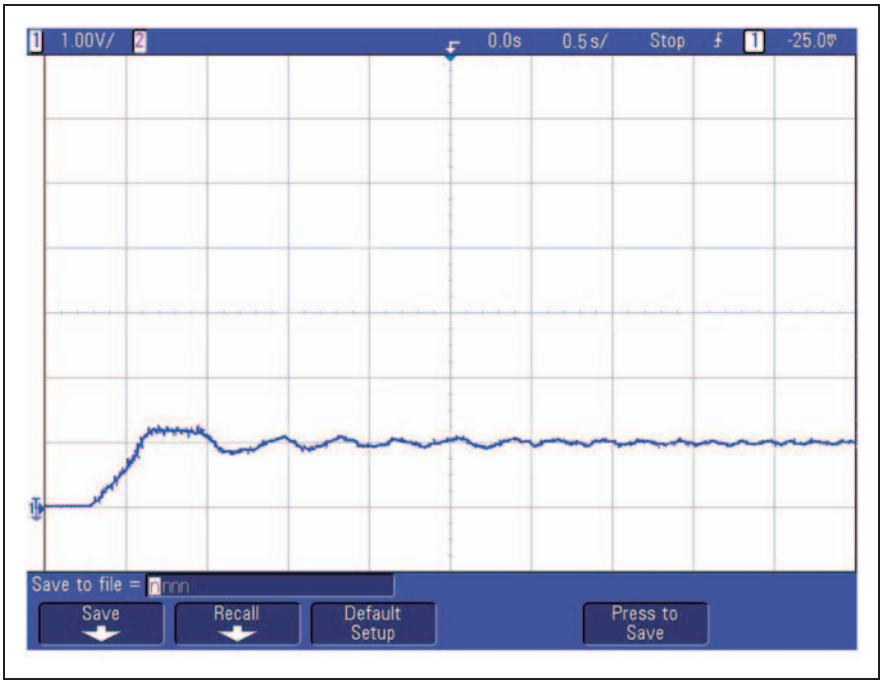


Figure 14. Experimental result of slow speed response with neural network-based model reference adaptive control (NN-MRAC).

performance has degraded with large overshoot and undershoot, slower response and longer settling time. However, the NN-MRAC maintains excellent performance and the plant output closely follows the reference output.

The experimental graph agrees with the simulated waveforms and confirms the use of NN-MRAC for the control of motors.

7. Conclusion

The performance of an NN-MRAC for the speed control of a DC-DC converter fed DC motor drive has been verified and compared with that of a conventional MRAC. The simulation and experimental results obtained have confirmed the very good dynamic performance and robustness of the NN-MRAC during the transient period and during a sudden load change. It is concluded that the performance of the proposed intelligent controller is superior to that of the conventional MRAC and the earlier proposed system. The proposed intelligent controller gives a robust drive performance, the response is not affected by speed variation or load disturbance.

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