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Analysis and Simulation of Speed Control in DC Motor Drive By Using Fuzzy Control Based on Model Reference Adaptive Control

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Abstract. This paper presents the conventional performance of the model reference adaptive control (MRAC) and the model reference fuzzy adaptive control (MRFAC). The aims of this work are: a) increasing in correspondence of motor speed with defined reference model speed of the system, b) decreasing of noises under load changes and disturbances, and c) increasing of system stability. Thus, model reference adaptive control is applied instead of non-adaptive or conventional control. Also fuzzy controller is used in place of classic controllers like PI controller. The operation of non-adaptive control and the model reference of fuzzy and conventional adaptive control are studied for derive and adjustment of dc motor speed. Then they are compared with each other. The model reference and fuzzy controller are designed based on securing of the entire system stability. Simulation is done with constant and variable loads. The result obtained shows that the adaptive control is more favorite than non-adaptive control. Also fuzzy adaptive control is more satisfactory than conventional adaptive control. The simulations are carried out by using Matlab-Simulink.

Keywords: Speed control, PI controller, model reference adaptive control, fuzzy logic controller, DC motor

Model Referans Uyarlanabilir Kontrole Dayalı Bulanık Kontrol Kullanımı ile DC Motor Sürücülerde Hız Kontrolünün Analiz ve Benzetimi

Özet. Bu makalede, model referans uyarlamalı kontrol (MRAC) ve model referans bulanık uyarlanabilir kontrol (MRFAC) için geleneksel performans sunulmuştur. Çalışmanın amaçları: a) sistemin tanımlı referans model hızı ile motor hızının uyumunun arttırılması, b) yükleme değişimi ve bozuklukları durumunda gürültünün azaltılması ve c) sistemin kararlılığının arttırılması. Böylece, model referans uyarlamalı kontrol yerine uyarlanabilir olmayan veya geleneksel kontrol uygulanır. Ayrıca bulanık kontrolör, PI kontrolör gibi klasik kontrolörlerin yerine kullanılmıştır. Uyarlanır olmayan kontrolün işletimi ve model referans bulanık kontrol ve geleneksel uyarlanabilir kontrol, dc motor hızının türetilmesi ve ayarlanmasında çalışılmıştır. Ardından bunlar birbirleriyle karşılaştırılmıştır. Model referans ve bulanık kontrolör, tüm sistemin kararlılık güvencesine dayanarak tasarlanmıştır. Simülasyon, sabit ve değişken yükler ile yapılmıştır. Elde edilen sonuçlara göre, uyarlanabilir kontrol, uyarlanabilir olmayana göre daha gözdedir. Ayrıca bulanık uyarlanabilir kontrol geleneksel uyarlanabilir kontrolden daha tatmin edicidir. Simülasyonlar, Matlab-Simulink kullanılarak yapılmıştır.

Anahtar Kelimeler: Hız kontrolü, PI kontrolörü, model referans uyarlanabilir kontrol, bulanık mantık kontrolörü, DC motor

1. INTRODUCTION

Electric motors convert electrical energy into rotary mechanical energy, which then is further converted to finally provide the needed use-energy. Electric motor systems account for about %60 of global industrial electricity consumption and about %15 percent of final energy use in industry worldwide. Electric motors drive both core industrial processes, like presses or rolls, and auxiliary systems, like compressed air generation, ventilation or water pumping. They are utilized throughout all industrial branches, though the main applications vary. Fig. 1 shows the breakdown of motor uses in an industry [1]. Therefore, the cost of energy to operate motors has become a real concern for industries [2-7].

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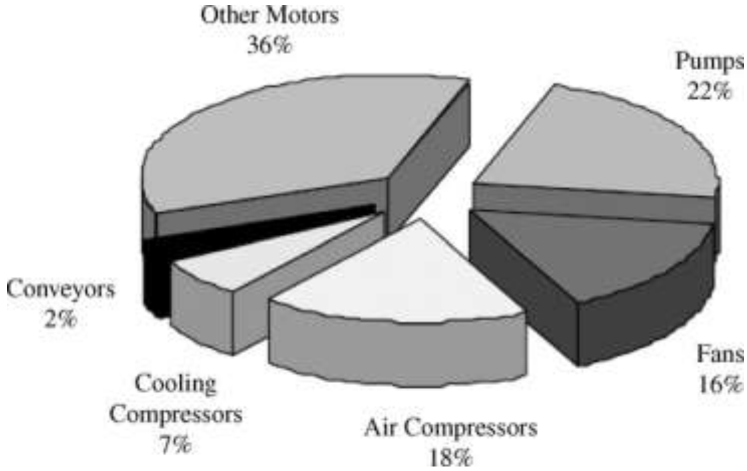

Fig. 1. Share of different motor systems of total electricity use by industrial motor systems

Direct current motors are one of the most applying parts of industrial systems, which are used for applications such as product line, robot control and etc. Thus there is a large tendency and effort to develop the control tool of it [8,9]. In industrial drives and dc motor control, three methods are common [10-20]: 1) a classic method is employment of PI and PID controllers which is not flexible for system parameters change, so it provides many limits and problems. 2) adaptive control methods that are more sophisticated than the classic method, commonly, sudden disturbance and changes in driving motor exist that because we couldn't get a complete and stable design for system. 3) Intelligent methods operate better than the presented previous methods toward disturbance and changes, like fuzzy controllers and neural network.

Several approach of speed control for dc motors have been developed. It can be divided into four categories as shown in Fig. 2 [21-27].

A controller design method for networked DC motor system in the presence of time delays and packet losses is presented in [28], where the estimation of distribution algorithm is used to optimize the control parameters to improve the system control performance. An efficient implementation of neural multi-layer networks on field programmable gate array fabric is described in [29], where the implementation performances were tested using an approximation of some linear and non-linear functions.

Model reference adaptive control is one of the various techniques of solving the control problem when the parameters of the controlled process are poorly known or vary during normal operation [30-32].

A fuzzy logic MRAC is applied to control the speed of a DC motor drive in [33] where the adaptation gains are determined by the aid of fuzzy logic approach to maintain satisfactory response irrespective of the magnitude of the inputs. The optimal PI controller gain is obtained by three algorithms (gradient descent, pattern search and simplex search based optimization algorithm) in a closed loop system with parameter uncertainty in [34]. The conventional MRAC and replaces conventional control technique such as PI control with model reference adaptive control scheme with fuzzy linear adaptation are presented in [35]. In [36] a MRAC method is proposed to regulate the important and main speed loop in the positioning system which was designed with three closed control loop, where a compensatory measure was given so as to counterbalance the friction torque disturbances.

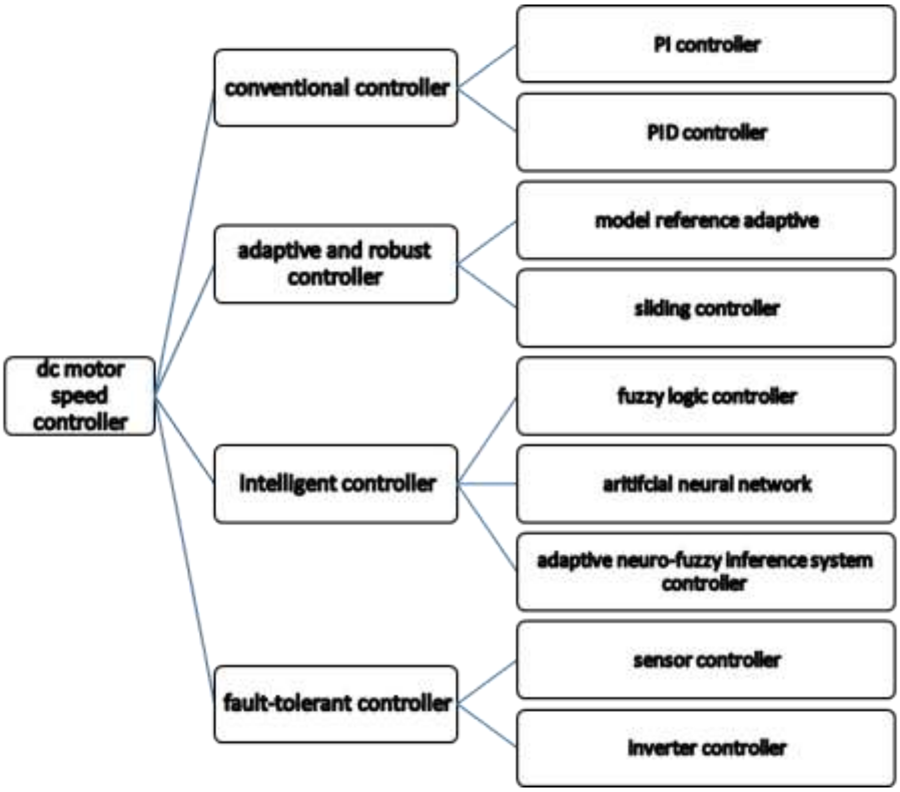

Fig 2. General classification of dc motor speed controller

It is possible to coincidently use fuzzy and classic methods with adaptive controller. In model reference adaptive control method, a reference model is chosen which can work with one of common controllers such as PI or PID. The output of the method is a desired speed that we expect from system. Incorrect choice of reference model makes the system instable, and controller would be unable to control the design. Adaptive controller aim would be an output which cause motor output speed (ω_r) follows desired speed (which is made by reference model (ω_m), and error between output and reference model (e_d) limits to zero.

In this paper, we proposed to simultaneously use fuzzy and adaptive controller method. Reference model fuzzy adaptive control (RMFAC) operates much better in stability and reduction of noises for systems which has unknown designs, than the presented methods.

2. MODEL REFERENCE ADAPTIVE CONTROL

The entire MRAC scheme is shown in Fig. 3. A separately excited dc motor which is supplied through a convertor is shown in the figure. The motor fed through a controller whose gain is K_c. In the figure the network has two inputs, one of the inputs is difference between plant output and model reference output and second input is difference between model output and reference signal. Both plant model and reference model are used to train the network. The dc motor that used is shown in Fig. 4. The excited part is used in model as constant quality and some coefficients. Here J_m and B_m are the moment of inertia and plant friction coefficient, R_a and L_a are the plant armature resistance and inductance. U_a is the adaptive controller output. K_{F1} and K_{F2} are motor parameters. K_{F1} is the torque constant and K_{F2} is electromotive-force constant.

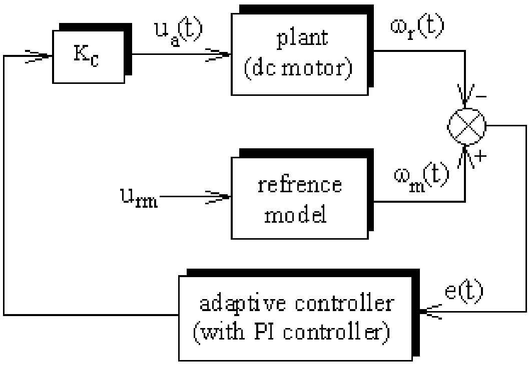

Fig 3. The entire MRAC scheme of DC drive

There are three inputs in the shown scheme in Fig. 2, namely, the input signal to the plant or adaptive controller output U_a, load torque T_L, and output disturbances due to uncertainties T_u. The resultant or ultimate speed of the motor is defined as:

$$\omega_r = \omega_0 + d_1 + d_u = \omega_0 + d \tag{1}$$

$$d = d_1 + d_u \tag{2}$$

where ω_o is the plant output speed with no disturbance and ω_r is the plant output speed with disturbance. d_l and d_u are the effect of load torque on output speed and the effect of uncertainties on output speed, respectively. The dynamics of a separately excited DC motor with negligible load torque and disturbances due to uncertainties is governed by [37,38]:

$$\frac{d\omega_0(t)}{dt} = \dot{\omega}_o(t) = -\frac{B_m}{J_m}\omega_0(t) + \frac{K_{F1}}{J_m} i_a(t) \tag{3}$$

$$T_e = K_{F1} i_a(t) \tag{4}$$

The motor is fed from a convertor, whose input is obtained as the output of adaptive controller U_a and it is expressed as:

$$\frac{di_a(t)}{dt} = \dot{i}_a(t) = -\frac{K_{F2}}{L_a}\omega_0(t) - \frac{R_a}{L_a} i_a + \frac{K_C U_a(t)}{L_a} \tag{5}$$

where K_C is the converter gain. The transfer function of the plant with no load torque and uncertainties ($U_a \neq 0$, $d_1 \equiv 0$, $d_u \equiv 0$) is obtained from as follow as:

$$G_T(s) = \frac{\omega_0(s)}{U_a(s)} = \frac{K_T}{S^2 + a_1 S + a_0} \tag{6}$$

where a_1, a_0 and K_T are given by:

$$\begin{cases} a_1 = \dfrac{B_m}{J_m} + \dfrac{R_a}{L_a} \\ a_0 = \dfrac{B_m R_a + K_F K_{F1}}{J_m L_a} \\ K_T = \dfrac{K_{F1} K_C}{J_m L_a} \end{cases} \tag{7}$$

Let us consider the case with only load disturbances ($T_L \neq 0$):

$$\Delta L(s) = \frac{-T_L(s)(R_{at} + sL_{at})}{s^2 + a_1 s + a_0} \tag{8}$$

where:

$$\begin{cases} R_{at} = \dfrac{R_a}{J_m L_a} \\ L_{at} = \dfrac{1}{J_m} \end{cases} \tag{9}$$

Similarly when load torque and uncertainties in the input supply are present, the resultant speed is obtained by:

$$\omega_r(s) = \frac{U_a(s) - T_L(s)(R_{at} + sL_{at})}{s^2 + a_1 s + a_0} + d_u(s) \tag{10}$$

A reference model is chosen whose pole position decides the stability of the whole system. For an output ω_m, which is the desired speed response of plant, the input of reference model is U_{rm}. The parameters of the reference model are selected such that the poles of transfer function at x_1 and x_2 are placed on the left hand of the s-plane. The transfer function $G_m(s)$ of the reference model is defined as:

$$G_m(s) = \frac{\omega_m(s)}{U_{RM}(s)} = \frac{K_M}{(s + x_1)(s + x_2)} \tag{11}$$

The error signal $e_d(t)$ is derived as follows. The error vector is defined as difference between the plant and the reference model states:

$$e(t) = x_m(t) - x_p(t) \tag{12}$$

where $e_r(t)$ and $e_0(t)$ is defined as error when the disturbance is present ($d \neq 0$) and when the disturbances are absent ($d=0$). That is:

$$e_0(t) = \omega_0(t) - \omega_m(t) \tag{13}$$

When the disturbances are present, the error in the output speed $e_r(t)$ in obtained as:

$$e_r(t) = \omega_r(t) - \omega_m(t) \tag{14}$$

Therefore $e_r(t)$ is given by:

$$e_r(t) = \omega_0(t) + d(t) - \omega_m(t) = e_0(t) + d(t) \tag{15}$$

The adaption process can be explained on the basis of the control laws explained above, When the scalar speed error $e_r(t)$ converges to zero, the controller output also converges to a constant quality and the speed of the motor becomes constant. The adaption process of output speed of motor ω_r can actually verges to the reference speed ω_m those they exactly approaches to a same value. If disturbances or changes in torque and load, input to the model that make ω_r and ω_m different from each other, the adaption process works again till error between ω_r and ω_m converges to zero.

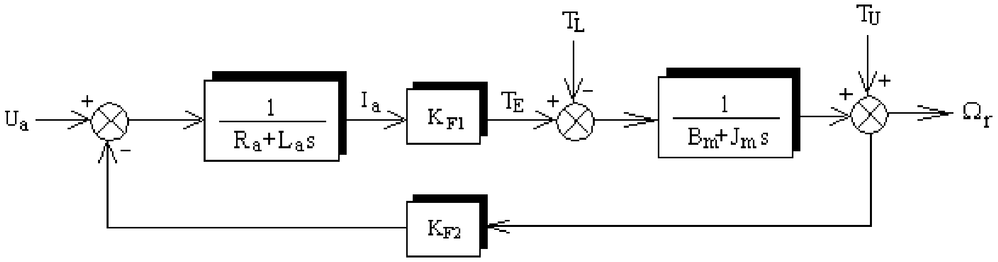

Fig 4. The entire DC Motor scheme

3. MODEL REFERENCE FUZZY ADAPTIVE CONTROL

A schematic representation of MRFAC was shown in Fig. 5. In fuzzy implementation of model reference adaptive control can also use a reference model for increasing function of control process. In this method, the reference model approaches desired speed and direction. The error between the output of the reference model and the plant is used to drive the fuzzy controller. Reference model is designed based on desired speed, control specifications and the speed controller, that appropriate selection of reference model leads to stable the entire system. To design the fuzzy adaptive controller, we can use motor behavior and reference model output. The motor behavior follows input of reference with a primary error as shown in Fig 6. According to the fuzzy implementation of adaptive process, the error approaches zero by laps of time. The error (e) and the error change (ce) are defined as:

$$e(n) = \omega_m(n) - \omega_r(n) \tag{16}$$

$$ce(n) = e(n) - e(n-1) \tag{17}$$

$\omega_m(n)$ is the response of the reference model at x_{th} sampling, $\omega_r(n)$ is the rotor position signal at x_{th} sampling, $e(n)$ is the error signal at x_{th} sampling and $ce(n)$ is the error change signal at x_{th} sampling. The fuzzy if-then rules are provided according to the Table 1. The fuzzy controller input is selected as error (e) (between the output speed of motor DC and the reference model speed) and change of error (ce). According to the error and change of error and the three points marked on Fig.5, three parameters are defined in Table 1 as follows:

If e is ZE and ce is PB then u is PM.
If e is NM and ce is ZE then u is NS.
If e is PS and ce is NS then u is ZE.

Table 1 Linguistic Rule Table

ce e	NVB	NB	NM	NS	ZE	PS	PM	PB	PVB
NVB	NVB	NVB	NB	NB	NM	NM	NS	ZE	ZE
NB	NVB	NB	NB	NM	NM	NS	ZE	ZE	ZE
NM	NB	NB	NM	NM	NS	NS	ZE	ZE	PS
NS	NB	NM	NM	NS	NS	ZE	ZE	PS	PM
ZE	NM	NM	NS	NS	ZE	PS	PS	PM	PM
PS	NM	NS	ZE	ZE	PS	PS	PM	PM	PB
PM	NS	ZE	ZE	PS	PS	PM	PM	PB	PB
PB	ZE	ZE	ZE	PS	PM	PM	PB	PB	PVB
PVB	ZE	ZE	PS	PM	PM	PB	PB	PVB	PVB

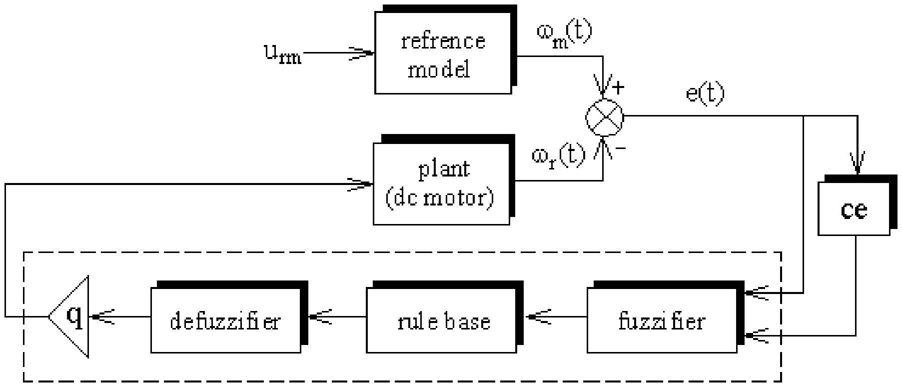

Fig.5. Basic control diagram for model reference fuzzy adaptive control scheme

The membership functions are used chosen triangular for simplicity. The membership functions are used for two inputs of controller in Fig. 7 and for output in Fig. 8. Middle of maximums method (mom) is used as defuzzification method in drive, which gets the best result in all defuzzification methods. For more exact results, it is used 9 language terms which totally result 81 rules, and appropriate scale factors are demonstrated to define desired output. We can see output graphical shape by attention to changes of e (error value) or ce (changes of error) as shown in Fig. 9.

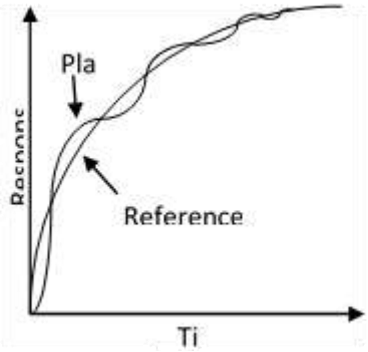

Fig 6. The motor behavior and reference model

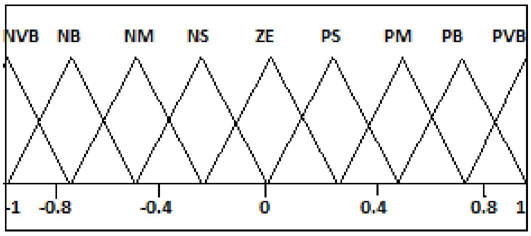

Fig.7. Input membership functions (e and ce)

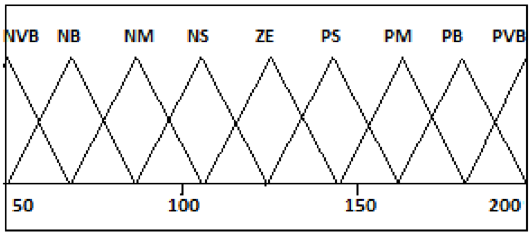

Fig.8. Output graphical shape

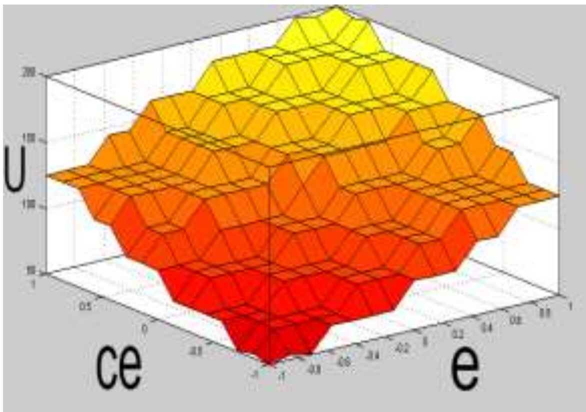

Fig.9. Output graphical shape

4. NON-ADAPTIVE CONTROL

Non-adaptive control means the classic control methods that which uses a constant quantity as the reference quantity instead of using a function as the reference model. In non- adaptive control, controller parameters are constant during process, against adaptive control. At motor drive time by this method, the error is so big, then vibrations amortized and the motor output approaches reference quantity.

5. SIMULATION RESULTS

The simulations have been performed with the help of Simulink software. In this simulation, all the blocks are considered according to the formulas and DC motor model according to the Fig. 3. The model of the system in Simulink-Matlab for simulation is show in Fig. 10. K_{F1} and K_{F2} are two constant qualities for exciter DC motor. The two constant and variable loads are considered for testing implementation of fuzzy controller. The reference model is defined by (11). The U_{rm} which drives reference model can be a constant quantity or a step function with desired start time, which the amplitude of reference model is defined by desired reference speed quantity. Scale factors quantities are defined as getting desired result. Fuzzy controller is loaded by defined rules. A PI controller is used in simulation of conventional model reference adaptive control, instead of fuzzy controller.

In this study, a 3hp, 2400 V, 1500 rpm, separately excited DC motor is considered. The different parameters of the system are show in Table 2. Transfer function of reference model (RM) with poles -6 and -4 is defined as:

$$G_m(s) = \frac{150}{s^2 + 10s + 24} \tag{18}$$

A 1500 constant quantity is used to get the desired speed in simulation of non-adaptive control results. Two constant and variable loads are used for comparing. Variable load affects to the system at 3.5 and 5 seconds.

Table 2 Parameters of the system

Parameters	Value	Unit
K_C	10	
K_{F1}	0.55	
K_{F2}	0.55	
R_a	1	Ω
L_a	0.046	H
J_m	0.093	Kg-m^2
B_m	0.08	Nm/s/rad
K_I	3	
K_P	16	

5.1 Adaptive and Non-adaptive

Driving a system with non-adaptive control was shown in Fig. 10. The results show at driving time, motor's speed is 1000 rpm higher than reference quantity. But conventional and fuzzy adaptive control in Figs. 11-12 shows at driving time that, motor speed is exactly the same as reference speed.

5.2 Fuzzy and Conventional Adaptive

In these two methods, the motor speed is exactly equal to the reference speed at driving time and constant load. But when variable load increases from 7 N.M to 30N.M, conventional adaptive controller has a deviation speed about 20 rpm, and when fuzzy adaptive controller has a deviation speed about 3 rpm. The simulation results are show in Figs. 13-16.

Also the damping time of the oscillations is about 0.5 seconds for the conventional adaptive control while it is 0.15 second for the fuzzy adaptive control. For the heavy load, when the load increases from 7 N.M to 70 N.M, the conventional adaptive control has a speed deviation about 72 rpm while the fuzzy adaptive control has a speed deviation about 11 rpm. Also the damping time of the oscillations for this loading case is 0.9 second for the conventional adaptive control, but it remains the same 0.15 second for the fuzzy adaptive control. The above comparison results are shown in the Table 3.

Table 3 Deviation speed and settling time

		Deviation Speed (rpm)	Settling Time (sec)
MRFAC	7 to 30 N.M	3	0.15
	7 to 70 N.M	11	0.15
MRAC	7 to 30 N.M	20	0.5
	7 to 70 N.M	72	0.9
Non-adaptive		1000	-

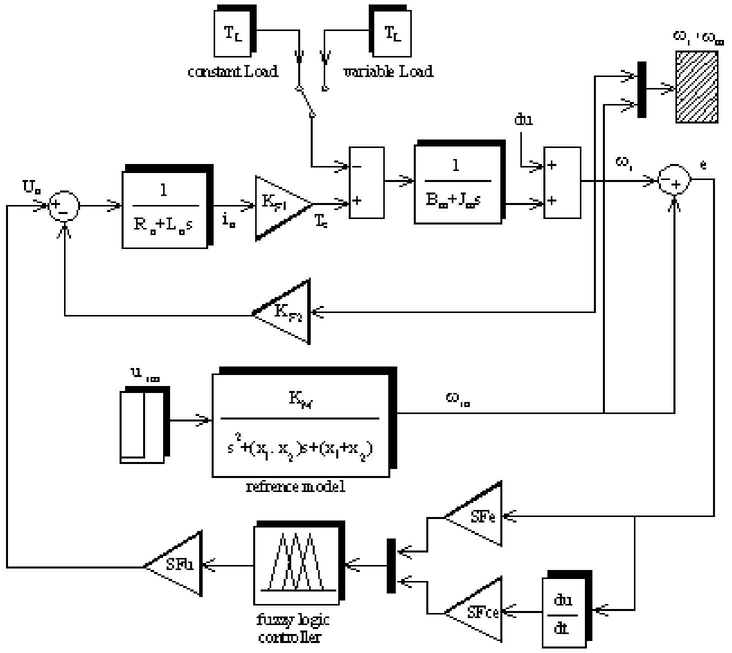

Fig. 10. System model in Simulink/Matlab

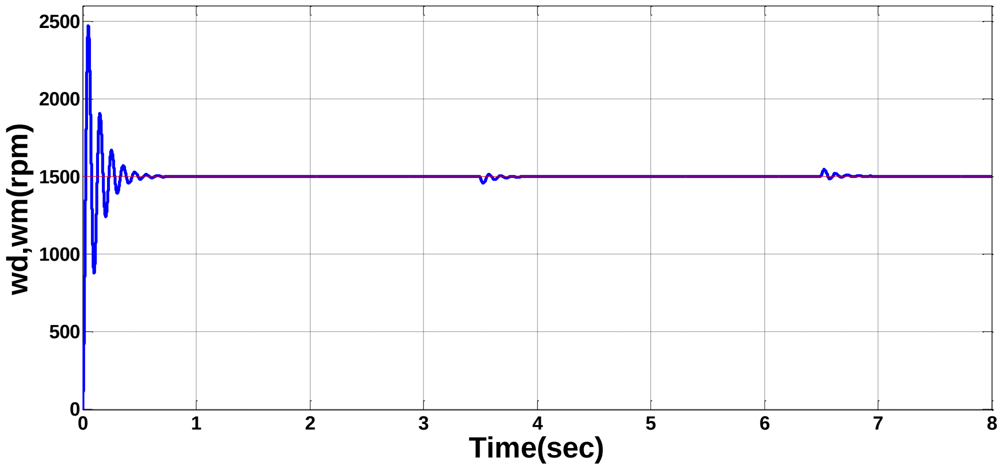

Fig 11. Response of output speed and non-adaptive reference control

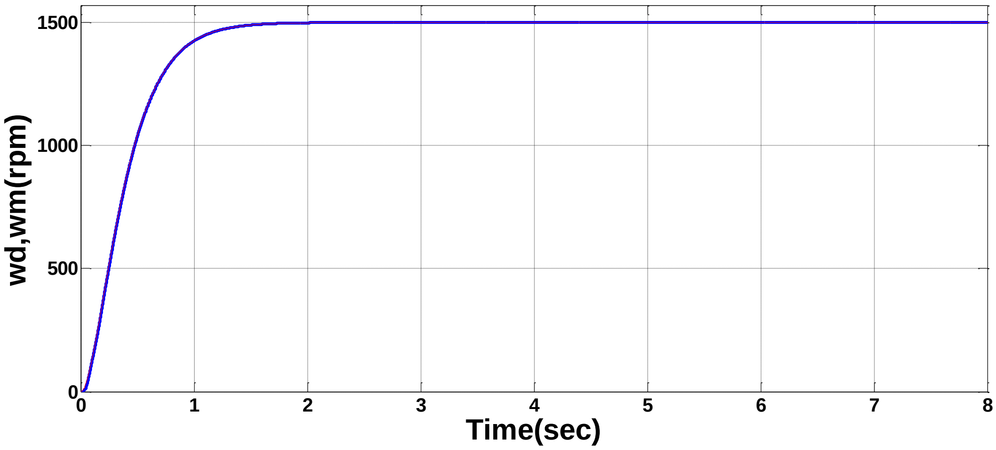

Fig 12. Response of output speed and constant load using conventional MRAC

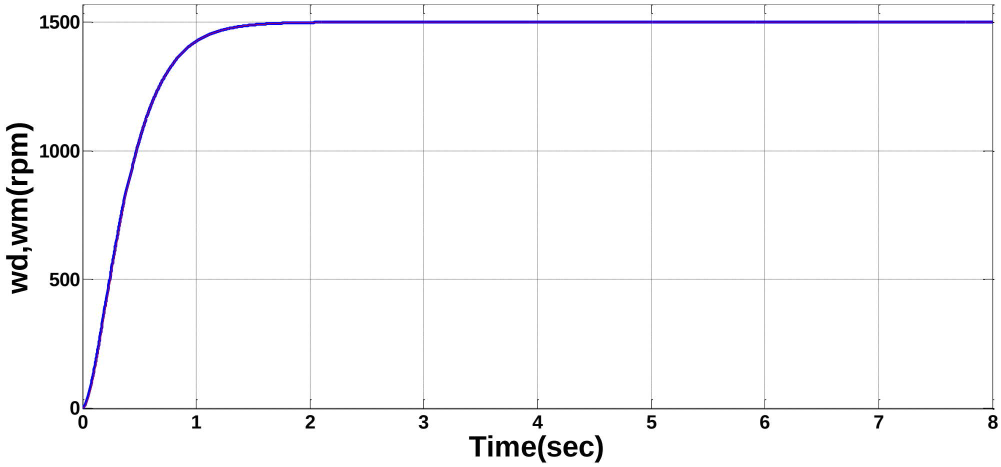

Fig 13. Response of output speed and constant load using MRFAC

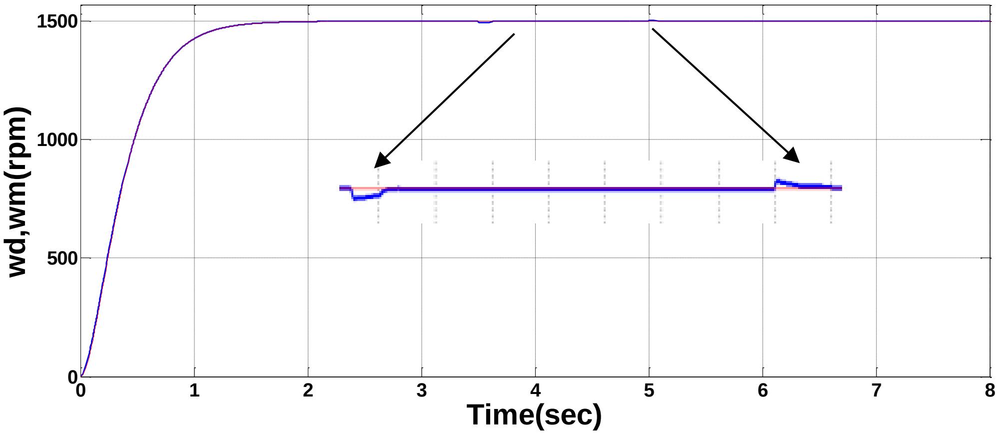

Fig 14. Response of output speed and variable load (7N.M to 30N.M) using MRFAC

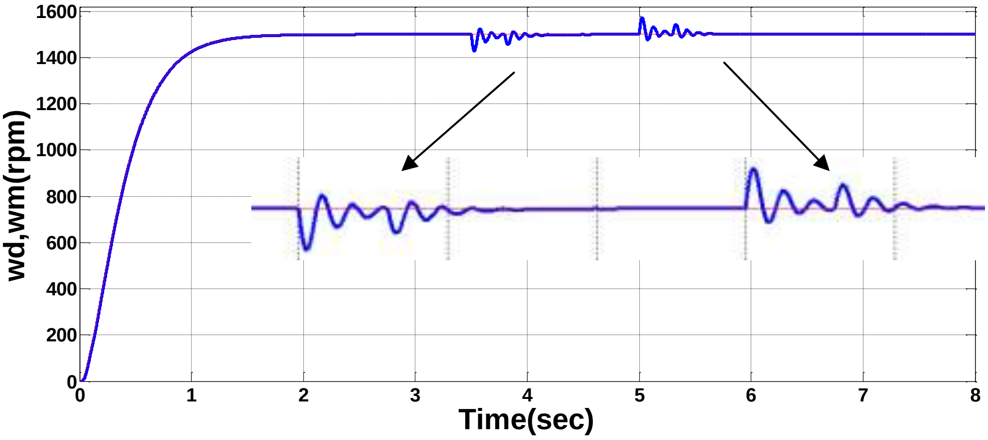

Fig 15. Response of output speed and variable load (7 N.M to 70 N.M) using conventional MRAC.

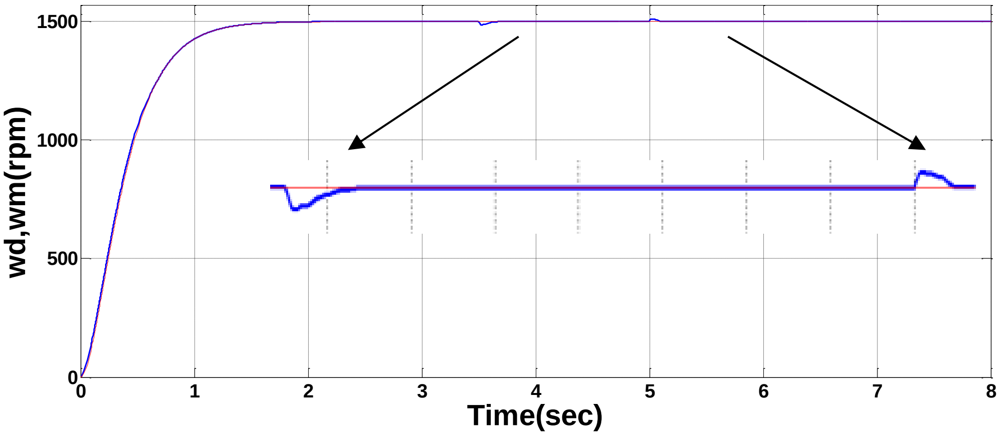

Fig 16. Response of output speed and variable load (7 N.M to 70 N.M) using MRFAC

6. CONCLUSION

This paper basically explains advantage of model reference adaptive control over non-adaptive control and especially model reference fuzzy adaptive control. In the simulation results, dc motor drive by fuzzy adaptive controller results an optimizer and more economical solution. Furthermore MRFAC enhances the performance of driving system because results show, adaptive control is optimizer and safer than non-adaptive control and follows reference quantity without being upper or downer. The work can also be effectively applied higher order systems without any complications. The simulation results show that, whenever a load disturbance or sudden load variation exists, adaptive control works better than non-adaptive control, and fuzzy adaptive control works better than conventional adaptive control and error tends to zero.

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