A SIMPLE FUZZY LOGIC SPEED CONTROLLER FOR A DC MOTOR FED BY SEPIC CONVERTER

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ABSTRACT

This paper presents a closed loop speed control of a separately excited DC motor. A cascade combination of a diode bridge rectifier and single-ended primary inductor converter (SEPIC) is used to feed the DC motor from an AC supply. This circuit combination offers both step-up and step-down characteristics of the motor terminal voltage as well as an approximately sinusoidal supply current with an improved power factor. A fuzzy logic speed controller is used to overcome any system nonlinearity and parameter changes. Also. a wide range of both speed and load changes with satisfactory response is obtained. Two fuzzy membership functions are used reflecting few and simple control rules. Moreover. a genetic algorithm (GA) is used to optimally tune the fuzzy controller parameters. Simulation results of the system are obtained by solving the differential equations in different modes of operation. The system is laboratory implemented and the controller is investigated using a digital signal processing board (DSP1104). The experimental and simulation results are verified and a correlation between both has been found. The results confirm the relevance of the proposed configuration as a useful rectifier that achieves sinusoidal supply current, high power factor and motor speed regulator.

فى هذا البحث تم تصميم حاكم لسرعة محرك التيار المستمر ذى التغذية المنفصـــلة المغــذى بواســـطة محـــول الكترونى من النوع SEPIC . هذا النوع من المحولات الالكترونيه يوفر امكانية الحصول على جهد خرج (على أطراف المحرك) أعلى أو أقل من جهد المنبع ، كذلك يمكن الحصول على تيار منبع جيبى الشكل بمعامل قـــدرة قريب جدا من الوحدة.

تم فى هذا البحث استخدام حاكم منطقى بسيط التكوين للتحكم فى سرعة محرك التيار المستمر وذلك للتغلب علـــى العلاقات غير الخطية للنظام المستخدم ، وأيضا للتغلب على تغير ثوابت النظام وللحصول على مدى واسع لتغيـــر السرعة مع الحفاظ على أداء جيد لتغير السرعة. تم استخدام عدد اثنين فقط من دوال العضوية وبالتالى تم تبســـيط القوانين المستخدمة فى هذا الحاكم. تم كذلك استخدام خوارزمية مورثية (genetic algorithm) لضبط الحاكم المنطقى قبل استخدامه .

تم عمل التمثيل الرياضي للنظام فى كل فترات التشغيل المختلفة واستخدام هذه المعادلات فى الحصول علـــى أداء نظرى للنظام فى ظروف التشغيل المختلفة. كذلك تم بناء النظام معمليا واســـتخدام معـــالج الإشـــارات الرقمـــى DSP1104 فى بناء الحاكم والحصول على نتائج معملية.

أثبتت كل من النتائج العملية والنظرية كفاءة الحاكم المقترح فى الحصول على أداء جيد فـــى ظـــروف التشـــغيل المختلفة ، كما وضح تشابه بين النتائج العملية والنظرية. كما وضح من النتائج إمكانية الحصول على تيار جيبـــى الشكل بمعامل قدرة الوحدة. ونظرا لبساطة تكوين هذا الحاكم فهناك إمكانية لاستخدام الحاكم المتنـــاهى الصـــغر microcontroller فى بناء مثل هذا النظام.

Keywords: SEPIC converter, DC motor, Speed control, Fuzzy logic control.

1-INTRODUCTION

Variable speed DC motor drives are utilized in multitude of applications in steel, paper processing, and mining industries. In such power electronic drives, parameter changes are caused by winding temperature variations, converter switching effects and saturation. Also, significant parameter variations come from load side, for example, in machine tool drives or robotics, the moment of inertia represents a variable parameter dependent on the tool or pay-load. Some research efforts [1-4] have been expended in control application of power electronic equipment and electrical drives. The restriction of such works is the need to dynamic simulation of the system.

Fuzzy logic controllers and neural networks controllers have been used with such systems [5-6]. Interest in these control approaches has intensified due to their potential in circumventing parameter variation effect under dynamic conditions.

In this paper a speed control of a separately excited DC motor fed by single-phase, single-way rectifier is presented. The strategy of AC to DC converter is based on the cascade combination of diode bridge rectifier and SEPIC converter[7-8]. Step-up and step-down characteristics of the output voltage are obtained. The supply current appears to be approximately sinusoidal with a relatively high power factor. A simple fuzzy logic speed controller is applied and a GA [9-10] is used to optimize the fuzzy controller parameters. The modeling and simulation of this system is described in different modes of operation. Also, a laboratory implementation of the proposed system is investigated. The simulation and experimental results predict a high motor speed performance over wide range of reference speed and load changes.

2- SYSTEM DESCRIPTION

The schematic diagram of the proposed system is shown in Fig. 1. The system consists of a cascade combination of a diode bridge rectifier and SEPIC converter supplied from an AC supply. The SEPIC output is connected to a separately excited DC motor loaded by DC generator. The motor speed is fed back through the DSP1104 analog to digital converter and compared with the reference speed. FLC is used to control the motor speed and the controller output is to control the ON period of the MOSFET in the SEPIC converter and, hence, the motor applied voltage can be controlled. All parts inside the dashed line are implemented using the DSP1104 board.

The capacitor C_1 acts as a transfer element. The inductance L_2 and capacitance C_2 are used as a filter to obtain DC voltage with minimum ripples. The switching frequency and the value of C_1 are determined by the value of L_1. The resonance

frequency $f_r = 1/(2\pi\sqrt{L_1C_1})$, and should be sufficiently lower than the switching frequency to prevent any resonance phenomenon in the AC circuit. The system parameters are given in the Appendix.

3- SYSTEM MODELLING

To simulate the detailed operation, the voltage and current equations have to be established for each operating mode.

3.1 -Mode 1:

In this mode the MOSFET is ON and the current i_1 will flow in the loop vs-L_1 – r_1. The capacitor C_1 will discharge and diode D is OFF, as shown in Fig. 2-a. The equations which describe this mode are given as follows:

$$\frac{di_1}{dt} = \frac{v - r_1\ i_1}{L_1} \quad (1)$$

where $v = V_m |\sin \omega t|$

$$\frac{dv_{c1}}{dt} = \frac{-i_2}{C_1} \quad (2)$$

where i_1 and i_2 are the currents of coils 1 and 2, respectively.

$$\frac{di_m}{dt} = \frac{v_m - r_m\ i_m - k_m\ w_m}{L_m} \quad (3)$$

where v_{r1}, i_m, w_m are motor voltage, current and speed respectively. R_m and L_m are motor armature resistance and inductance, respectively. k_m is the motor back emf constant.

$$\frac{dv_m}{dt} = \frac{-i_m}{C_2} \quad (4)$$

where C_2 is the capacitance of the output filter.

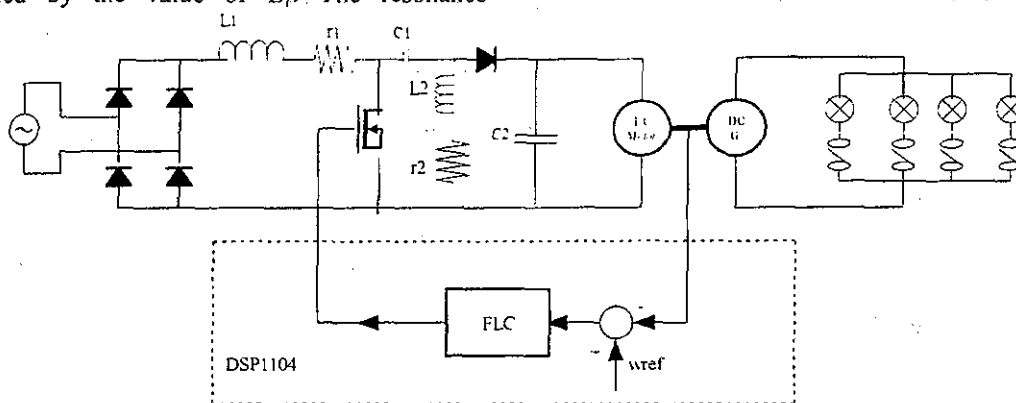$$\frac{di_2}{dt} = \frac{v_{c1} - r_2\ i_2}{L_2} \quad (5)$$

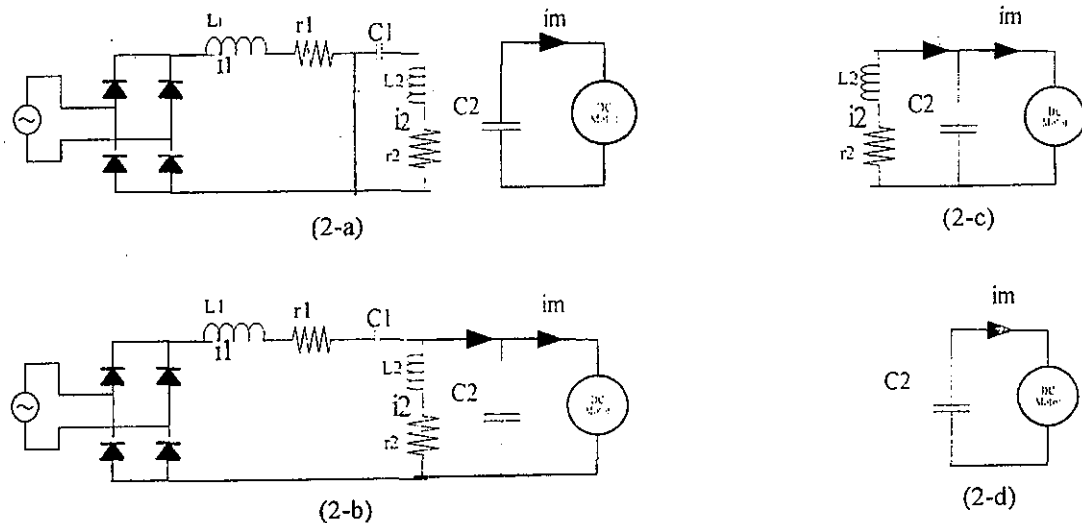Fig. 1 Schematic Diagram of the Proposed System

Fig. 2 System Modes of Operation

3.2 - Mode 2:

In this mode the MOSFET is OFF and diode D is ON, as shown in Fig. 2-b. The current i_1 is greater than zero (positive). The corresponding differential equations which describe this mode are given as follows:

$$\frac{di_1}{dt} = \frac{v - r_1\, i_1 - v_{c1} - v_m}{L_1} \tag{6}$$

$$\frac{dv_{c1}}{dt} = \frac{i_1}{C_1} \tag{7}$$

$$\frac{di_m}{dt} = \frac{v_m - r_m\, i_m - k_m\, w_m}{L_m} \tag{8}$$

$$\frac{dv_m}{dt} = \frac{i_2 - i_m}{C_2} \tag{9}$$

$$\frac{di_2}{dt} = \frac{-r_2\, i_2 - v_m}{L_2} \tag{10}$$

3.3 - Mode 3:

In this mode the MOSFET is OFF, diode D is ON and the current i_1 is equal to zero as shown in Fig. 2-c. The corresponding differential equations which describe this mode are given as follows:

$$\frac{di_m}{dt} = \frac{v_m - r_m\, i_m - k_m\, w_m}{L_m} \tag{11}$$

$$\frac{dv_m}{dt} = \frac{i_2 - i_m}{C_2} \tag{12}$$

$$\frac{di_2}{dt} = \frac{-r_2\, i_2 - v_m}{L_2} \tag{13}$$

3.4 - Mode 4:

In this mode the MOSFET is OFF, diode D is OFF and both currents i_1 and i_2 are equal to zero as shown in Fig. 2-d. The corresponding differential equations which describe this mode are given as follows:

$$\frac{di_m}{dt} = \frac{v_m - r_m\, i_m - k_m\, w_m}{L_m} \tag{14}$$

$$\frac{dv_m}{dt} = \frac{- i_m}{C_2} \tag{15}$$

Beside the above electrical equations which describe the system in the four different modes of operation, there is the motor mechanical motion equation, which is given as:

$$\frac{dw_m}{dt} = \frac{k_m\, i_m - B\, w_m - T_l}{J} \tag{16}$$

4- PROPOSED FUZZY LOGIC SPEED CONTROLLER

Fuzzy logic is the logic underlying modes of reasoning which are approximate rather than exact. Thus it is closer to human reasoning and real world than formal logic. The control objective is to generate a supplementary control signal in order to enhance the motor speed following the reference speed under any disturbances with small settling time, minimum overshoot and no steady state error. At every sampling time, the motor speed deviation and scaled acceleration are denoted as $[e_w(k)\,,\ A*\dot{e}_w(k)]$, where A is a predefined scaling factor. This condition represents a certain point, X , in the acceleration $[e_w(k)\,,\ A*\dot{e}_w(k)]$ phase plane as shown in Fig.3 .
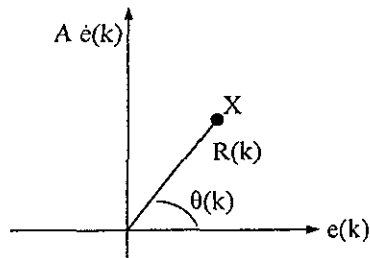
Fig. 3 Phase Plane

The polar displacement R(k) of this point from the origin, and the corresponding angle θ (k) are computed as:

$$R(k) = [(e_w(k))^2 + (A * \dot{e}_w(k))^2]^{0.5} \qquad (17)$$

$$\theta(k) = \tan^{-1}[\frac{A * \dot{e}_w(k)}{e_w(k)}] \qquad (18)$$

$$\dot{e}_w(k) = [\frac{e_w(k) - e_w(k-1)}{T_s}] \qquad (19)$$

where T_s is the sampling interval. In the phase plane the points in the upper half represent the positive acceleration, correspondingly, the points in the lower half represent the negative acceleration, i.e. the deceleration. In addition, the points in the right half plane represent speeds slower than the desired speed, and the points in the left half plane represent speeds faster than the desired one. The origin 0,0 is the desired equilibrium point, and the control efforts should be directed to shift the motor state X(k) towards the origin as soon as possible,

Positive control signal is required when the state X(k) locates in the first quadrant. Negative control signal is required when X(k) locates in the third quadrant. Positive and negative control signals as well are required in the other two quadrants. Two fuzzy membership functions, N(θ), associated with the desired deceleration and P(θ) associated with the desired acceleration, are defined in terms of the polar angle θ(k) to reflect the actions of the control rules. The defining relations for N(θ) and P(θ) are:

$$N(\theta) = \begin{cases} 1 & 0 \le \theta < 90 \\ (180 - \theta)/90 & 90 \le \theta < 180 \\ 0 & 180 \le \theta < 270 \\ (\theta - 270)/90 & 270 \le \theta < 360 \end{cases} \qquad (20)$$

$$P(\theta) = 1 - N(\theta) \quad for \ all \ \theta \qquad (21)$$

The change of the controller output signal ΔU(k) is calculated by:

$$\Delta U(k) = G(k) [N(\theta) - P(\theta)] U_{max} \qquad (22)$$

where G(k) is a gain defined as:

$$G(k) = \begin{cases} R(k)/Dr & for \ R(k) < Dr \\ 1 & for \ R(k) \ge Dr \end{cases} \qquad (23)$$

The parameter Dr is a set value of R(k) at which the gain is fixed at unity and Umax is the maximum value of the control signal which is a prespecified constant parameter.

5- CONTROLLER PARAMETER SELECTION USING GA

In the proposed fuzzy logic control scheme, the two adjustable parameters are A and Dr. An iterative approach is used to determine the fuzzy logic controller parameters. To save time at this stage of the design process, a modified version of GA is utilized to optimally select these parameters. Therefore, the following quadratic performance index, J, is defined by:

$$J = \sum_{k=1}^{M} [t_k \ e_w(k)]^2 \qquad (24)$$

In the above performance equation, the speed error is weighted by the respective time $t_k = KT_s$ and M indicates the total data number. The tuning parameters are coded in a binary string. GA is then used to search for optimal set of parameters that minimizes the performance index. Tournament selection method is used. So, the GA works directly on the given performance index without the explicit definition of a fitness function. The population size is chosen to be 65 strings. The crossover probability is set at 0.75 and the mutation probability at 0.001.
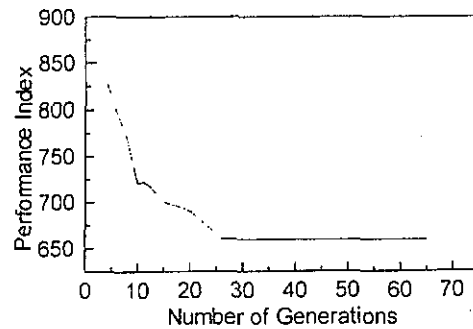

Fig. 4 Convergence of Performance Index

6- EXPERIMENTAL AND SIMULATION RESULTS

Based on the system model in different modes of operation described in this paper and the parameters given in appendix, a computer program is written to simulate the system. The tuning parameters are pre-calculated by making step change in reference speed from 500 rpm to 650 rpm and the performance index is calculated during a time interval equal 0.5 sec. The GA produced optimal tuning parameters (A , Dr) equal to 190.0 and 9.5, respectively. The variation of the performance index J with the number of generation is shown in Fig.4. Also, an experimental circuit has been built to verify the theory and simulation described above. The controller is built by using a DSP1104 digital signal processing board and hence the MOSFET driver pulses are generated.
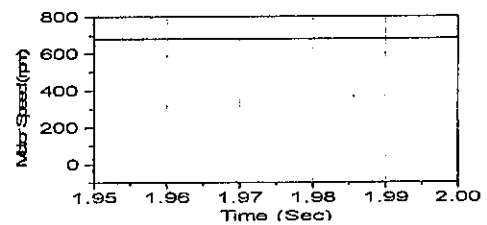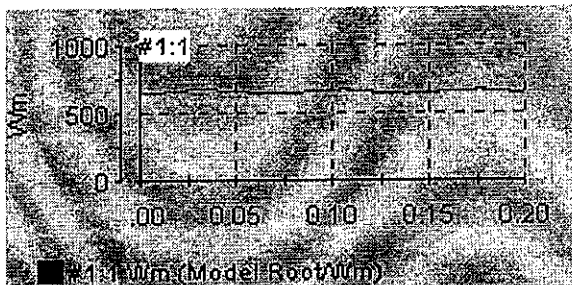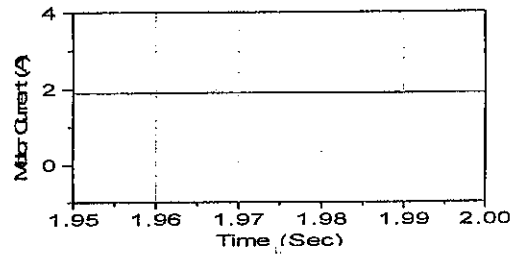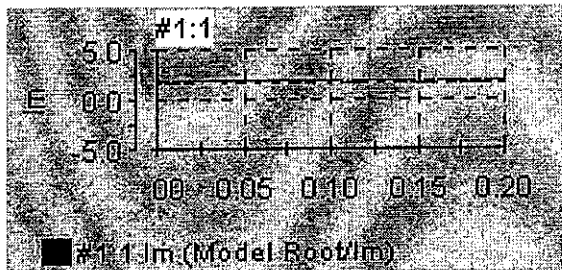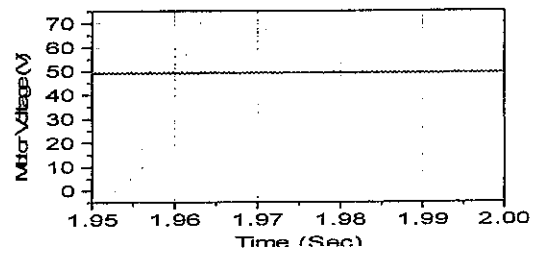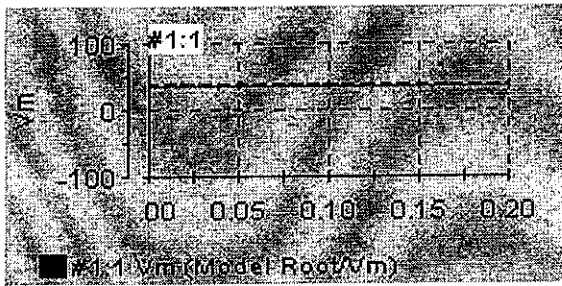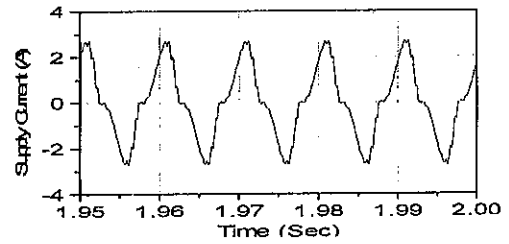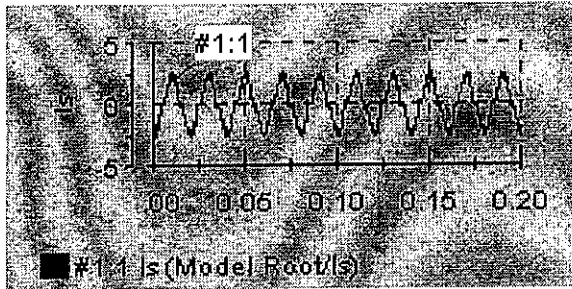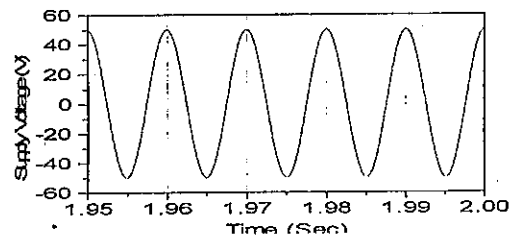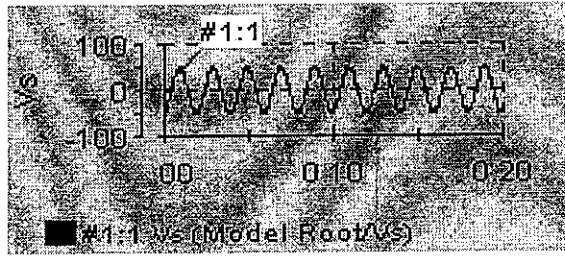
Fig.5 Experimental steady state performance at (Vs)max =50 (V) and Duty cycle =0.5

Fig.6 Simulation steady state performance at (Vs)max =50 (V) and Duty cycle =0.5

The steady state experimental results of the system with peak value of supply voltage equals 50 volts and a duty ratio 0.5 are shown in Fig.5. It can be shown from the figure that the supply current is sinusoidal with near-unity power factor and both the motor voltage and current are pure dc values. The corresponding simulated results are shown in Fig. 6, which were obtained by simulating the previously mentioned differential equations in different modes of operation. A good agreement between both simulation and experimental results is obtained.

A step change in reference speed, from 500 rpm to 650 rpm, under the proposed closed loop speed controller is experimentally shown in Fig.7. Figure 8 indicates the corresponding simulated results. The results indicate the effectiveness of the proposed controller and a good speed response is obtained. Also, the performances of the SEPIC circuit currents and voltages are obtained.

The experimental and simulated system dynamic responses under step changes in motor load are shown in Figs. 9 and 10, respectively. The speed is still following the reference speed with minimum dip at the instants of load changes.

To verify the effectiveness of the proposed controller, Fig. 11 indicates the simulated performance under a wide range of reference speed step changes. The motor speed follows the reference speed with a good performance irrespective of the operating point and the value of the motor load. Also, the performances of the motor terminal voltage and motor current are indicated in Fig. 11. The figure indicates that step-up and step-down characteristics of the motor terminal voltage have been achieved.
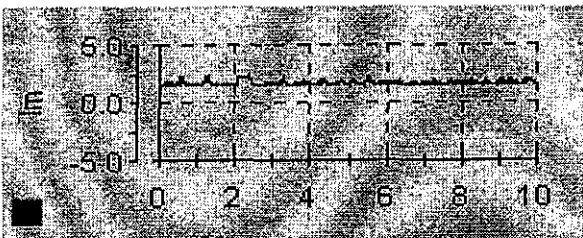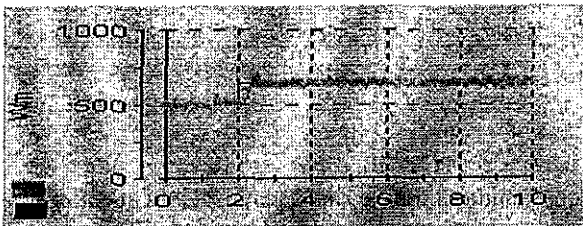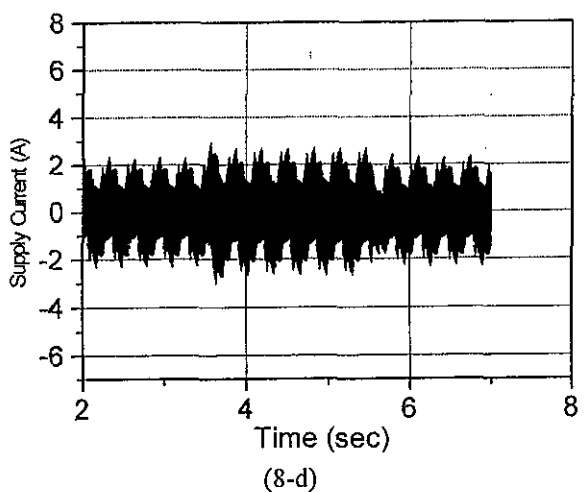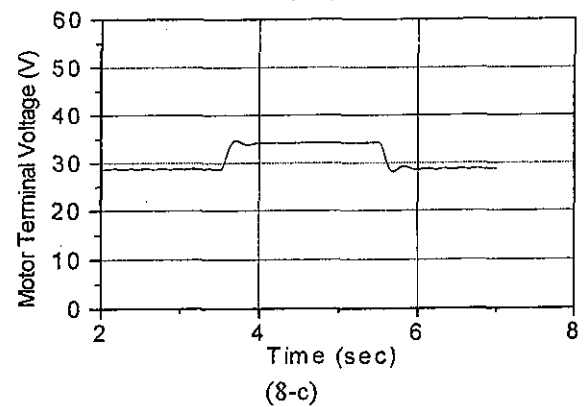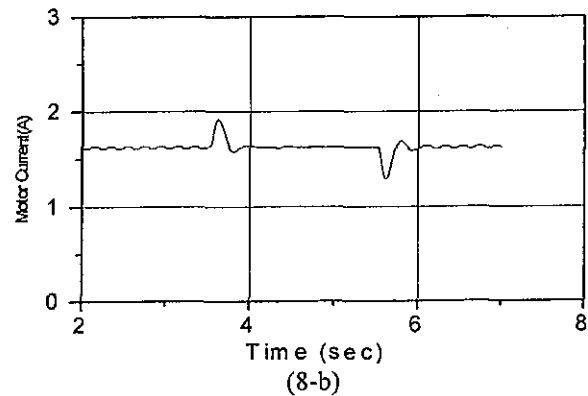

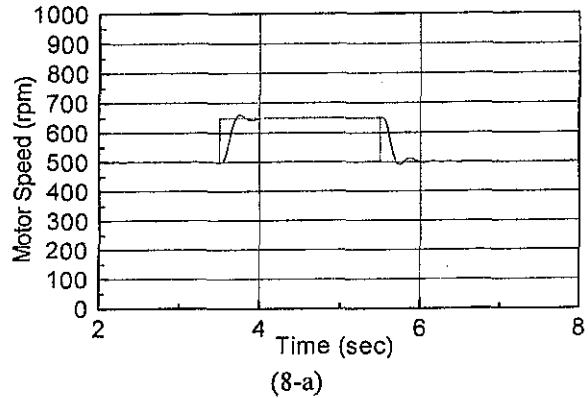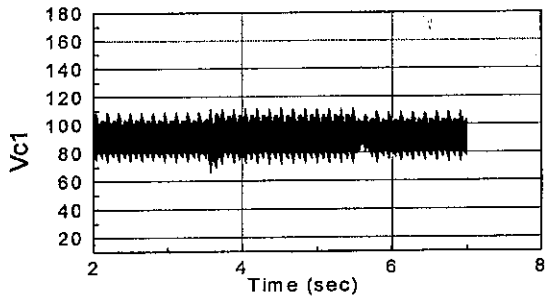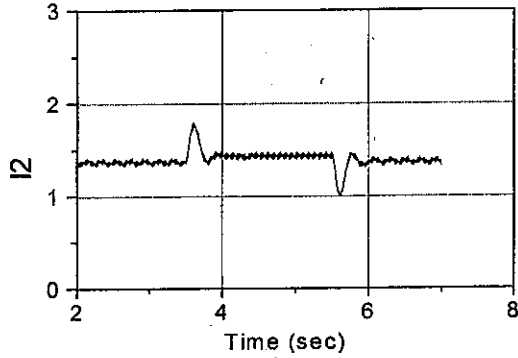Fig. 7 Experimental Performances under step change in reference speed
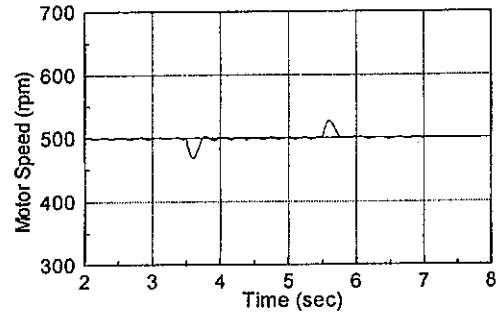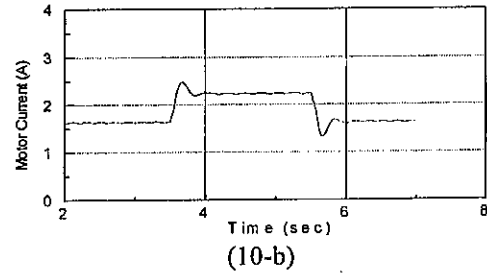

(8-a)

(8-b)

(8-c)

(8-d)

(8-e)

(8-f)

Fig. 8 Simulation Performances under step change in reference speed
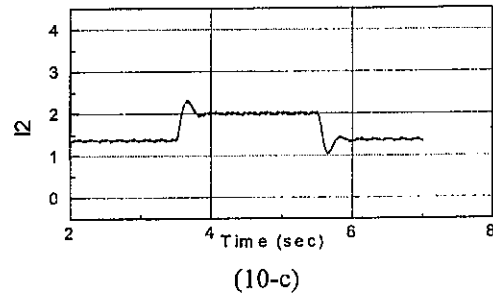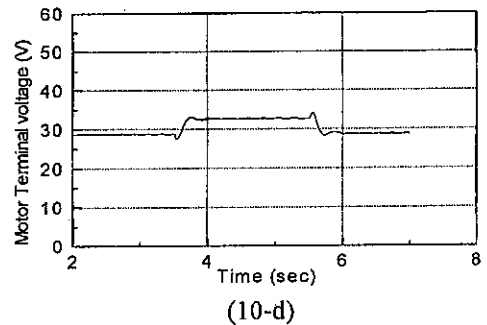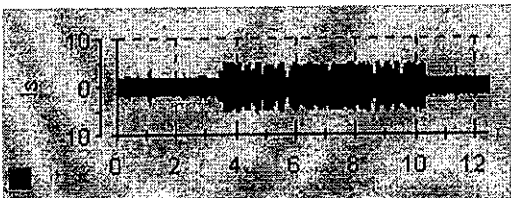
Fig. 9 Experimental Performances under step change in load torque.
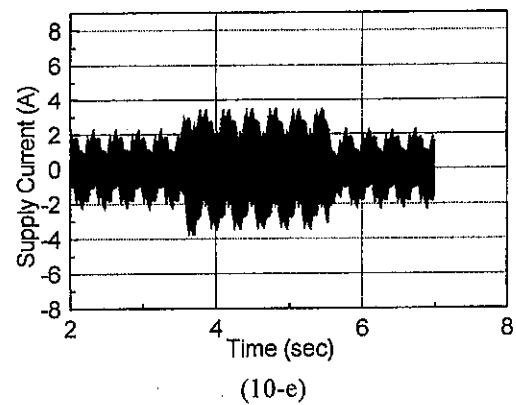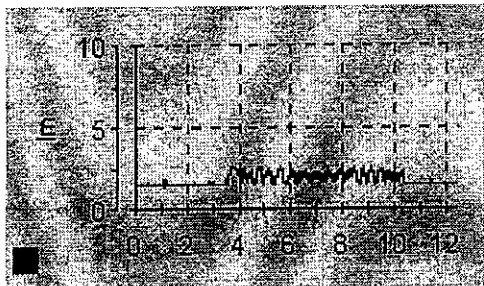

(10-a)

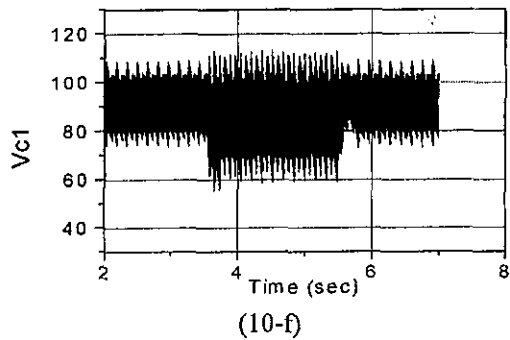
(10-b)

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Fig. 10 Simulation Performances under step change in load torque.
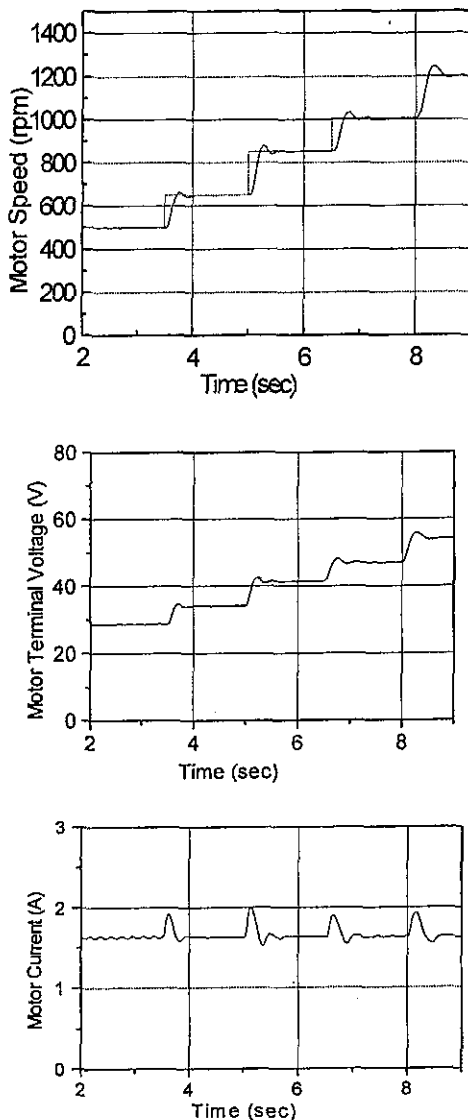

Fig. 11 Simulation Performances under a wide range of step change in reference speed

7- CONCLUSION

The paper has presented a simple FLC to control the speed of a DC motor fed by SEPIC converter. The FLC has only two membership functions and a GA is used to adaptively tune the controller parameters. The exact system parameters are not required in the implementation of the proposed controller. The controller is easy to implement using micro-controller. The results showed that the performance of the motor drive system is robust, stable, and insensitive to both motor parameters and operating point changes.

The use of SEPIC converter offers an approximately sinusoidal supply current with near unity power factor. Furthermore, step-up and step-down characteristics of the motor input voltage have been achieved

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APPENDIX

The DC motor parameters are:
$Ra = 10.5\ \Omega$, $La = 117.83\ mH$,
$Ke = 0.345\ V/red/sec$
And the used SEPIC converter parameters are:
$R1 = 1.5\ \Omega$, $L1 = 0.025\ H$,
$R2 = 1.5\ \Omega$, $L2 = 0.25\ H$,
$C1 = 29\ \mu F$, $C2 = 1200\ \mu F$