IMPROVED PERFORMANCE OF ROLLING MILL DRIVES USING HYBRID FUZZY-PI CONTROLLER

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ABSTRACT:
In this paper, a fuzzy logic control technique is applied to solve the undesired undershoot that gets the process in special steel rolling mill out of control. Because fuzzy logic controller results in steady state error due to load change two control methods are proposed to improve the fuzzy controller performance. The first method uses a fuzzy speed controller with a PI current controller and the other method uses a hybrid fuzzy-PI controller.
The proposed Hybrid fuzzy-PI controller is applied to a rolling mill drives. This technique can solve the common problems associated with rolling mill drives. The entire drive systems are implemented using a high speed digital signal processor (DSP). Experimental results validate the theoretically simulated responses with different operating conditions.

1. INTRODUCTION:
The DC motors have been used in industry as variable speed drives, and provide high starting and torque which is required in some applications such as rolling mills, and traction drives. The methods of control over a wide speed range are simpler and cheaper than those of AC motors. There are different methods for controlling the speed of the DC motor, the most popular methods are armature voltage control and field control [1-4].

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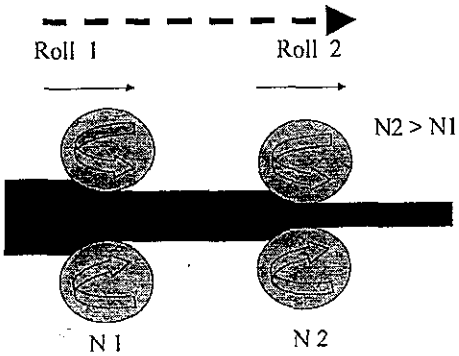
Today, many drive systems employ a conventional controller. This controller works well but only under a specific set of known system parameters and load conditions. However, deviations of the system parameters or load conditions from the known values deteriorate the performance of the closed loop system, resulting in larger overshoots and undershoots, longer rise and settling times, and possibly even, an unstable system [5-6]. It should be noted that the other parameters such as the system inertia and damping ratio might vary over a wide range due to changes in load conditions [7-9]. In Order to achieve a desired performance, a fuzzy logic control is employed [10-15].

In this paper, fuzzy logic controller is used instead of the PI controller to overcome the undesired undershoots coming from load impact at some abnormal conditions. Therefore, the process in special steel rolling mills is disturbed causing save the wasted time and money. As the fuzzy logic controller has a steady state error, two methods are proposed and implemented to recover this steady state error. The first method uses a hybrid Fuzzy-PI control. The second method uses a fuzzy speed controller with PI current controller. A complete circuit for the system under consideration has been constructed. The proposed controllers are implemented using a high speed DSP in order to verify the robustness of these controllers.

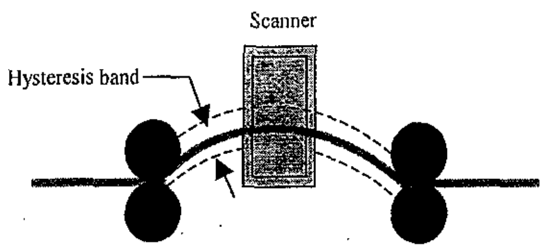
2. ROLLING MILL PRINCIPLES:

The concept of the rolling mill is based on keeping constant quantity of steel material flow independent of the cross section of the steel bar. The process is to reduce the dimension of a bar or billet from high-dimensional cross section to low-dimensional cross section as shown in Fig.(1a) Basically, rolling line consists of several rolling machines working sequentially. Each roll speed is controlled by converter driven motor. All converters are connected together to a common PLC through high-speed communication link to distribute the speed reference individually to each drive. The speed reference to each drive is calculated according to the process control requirements.

The rolling process is controlled by series of converters connected to a common master PLC which is responsible to produce speed reference. The speed of two adjacent motors is controlled so that the tension of the steel bar, which is being rolled, is maintained low and constant within small hysterisis band. To understand this concept, suppose that the steel bar is under the first rolling machine. The torque required to reduce its diameter is memorized. When the steel bar hits the next rolling machine, the torque of the first motor will be reduced and the material will have positive tension and vice versa. The process controller will detect this torque variation and consequently changes the speed of the first motor to return its torque to the memorized value. Then, the torque of the second motor is memorized to control the relative speed with the third motor when the steel bar reaches there. This method is implemented when the steel bar has low speed and high cross section. When the steel bar is processed at high speed with small cross section, the method of regulating the tension is altered to loop position control. The loop position control method is shown in Figure (1b). The loop position control is based on automatic measurements of the excess material formed between two adjacent stands. The excess material is guided to form a loop on a looper table, which is located between each adjacent stands. The loop position provides a direct indication of the tension or the compression content in the steel bar. The process controller calculates the speed reference to the upstream motor to control the loop height according to the required loop height reference. The speed of two adjacent stands motors is thus automatically corrected according to the variation of the measured loop height, so, during load impact, the motor speed will be decreased and therefore, the height of the loop will be increased. At this moment the PI controller will regulate the motor speed by a way that the loop height must be controlled in its hysteresis band. If the load is increased due to any change process conditions such as reduction of the rolled material temperature, the motor speed will be reduced more, and therefore, the loop height will be out of control and the process will be stopped. In this paper, fuzzy logic technique is implemented to solve this problem.



(a) Rolling mill line



(b) Loop position hysteresis band

Fig. (1) Basic of Rolling Mill

3. DESCRIPTION AND MODELING OF THE SYSTEM

To study the problem in special steel rolling mills, the paper investigates the speed control of a separately excited DC motor as it is used in rolling mills, and the load will be a separately excited DC generator. A complete system modeling is developed to study the DC motor performance.

Figure(2) shows the power circuit configuration of the DC drive system under consideration. The circuit comprises two stages. In the first stage, an uncontrolled bridge rectifier is employed to unify the direction of the load voltage and the current. In the second stage a controlled IGBT power switch, operating in the chopping mode, is used to vary the amplitude of the average output voltage. Uniform pulse width modulation (UPWM) control strategy is used for this purpose.

3.1. Modes of operation:

The control of the duty cycle of the chopper leads to the control of the armature voltage and consequently motor speed will be controlled. This duty cycle period is T where ($T = T_{on} + T_{off}$), T_{on} is the switching on period, and T_{off} is the switching off period. Over each duty cycle period, there exist two patterns of conduction: Pattern I and pattern II, corresponding, respectively, to the on and off states of the IGBT power switch as follows:

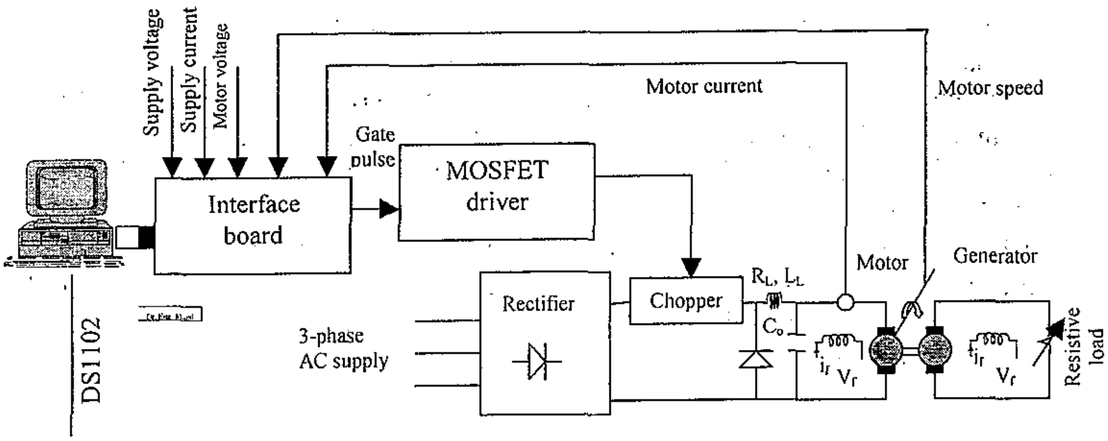


Fig. (2) Schematic diagram for the DSP-based control of DC motor drive

A. Pattern I : Forced Current Transition (Mode 1)

This corresponds to the on-state periods of the chopping switch, where the rectified supply voltage appears across the terminals of the load (armature) circuit through the LC filter circuit and forcing the current to flow from the supply into the armature circuit. The differential equations describing this mode are written as follows:

$$L_L(\frac{di_L}{dt}) = v_S - i_L r_L - V_m \qquad (1)$$

$$L_a(\frac{di_m}{dt}) = v_m - i_m r_a - k_v \omega_m \qquad (2)$$

$$J(\frac{d\omega_m}{dt}) = k_v i_m - B\omega_m - T_L \qquad (3)$$

$$C_o(\frac{dV_m}{dt}) = i_L - i_m \qquad (4)$$

$$i_S = i_L \qquad (5)$$

$$v_S = \sqrt{2}\, V_S \sin(\omega t - (\lambda - 2)\frac{\pi}{3}) \qquad (6)$$

Where L_L, L_a are the filter and motor inductance, i_L, i_m are the filter and the motor current, r_L, r_a are the filter and motor resistance, v_s, v_m are the supply and motor voltage, T_L is the load torque, J is the moment of inertia, k_v is the back emf constant, B is the friction. C_o is the filter capacitance, ω_m is the motor speed in rad/sec, V_s is RMS line supply voltage, and λ is a parameter required to select the appropriate line voltage over the required period $0 \le \omega t \le 2\pi$. It is given as follows:

$$\lambda = \begin{cases} 1 & for\ 0 \le \omega t \le \frac{\pi}{3} & where\ 1 \le m \le N \\ 2 & for\ \frac{\pi}{3} \le \omega t \le \frac{2\pi}{3} & where\ (N+1) \le m \le 2N \\ 3 & for\ \frac{2\pi}{3} \le \omega t \le \pi & where\ (2N+1) \le m \le 3N \\ 4 & for\ \pi \le \omega t \le \frac{4\pi}{3} & where\ (3N+1) \le m \le 4N \\ 5 & for\ \frac{4\pi}{3} \le \omega t \le \frac{5\pi}{3} & where\ (4N+1) \le m \le 5N \\ 6 & for\ \frac{5\pi}{3} \le \omega t \le 2\pi & where\ (5N+1) \le m \le 6N \end{cases} \quad (7)$$

Where m is the m th chopping cycle

B. Pattern I I : Current Freewheeling (Mode 2)

This pattern corresponds to the off-state of the chopping switch, where the load circuit is isolated from the supply, so, the current decays through the freewheeling diode. The differential equations describing this mode are given as follows:

$$L_L(\frac{di_L}{dt}) = -v_m - i_L r_L \quad (8)$$

$$L_a(\frac{di_m}{dt}) = v_m - i_m r_a - k_v \omega_m \quad (9)$$

$$J(\frac{d\omega_m}{dt}) = k_v i_m - B\omega_m - T_L \quad (10)$$

$$C_o(\frac{dV_m}{dt}) = i_L - i_m \quad (11)$$

$$i_s = 0 \quad (12)$$

The motor and filter parameters are given in the Appendix.

4. IMPROVEMENT OF FUZZY LOGIC SPEED CONTROLLER:

The fuzzy controller is able to overcome the disadvantages of conventional PI controller. It is sensitive less to inertia variation and give good results for load excursions[10]. Thus the main problems with classical PI controllers are tuning and robustness in case of changes in system conditions[15].

The disadvantages of fuzzy logic speed control occur under some operating conditions with high load disturbance or high speed reference step changes. Also, there are an oscillatory performance and steady state error. Broadly speaking, conventional fuzzy logic control has a weak point, that it causes steady state error. A number of methods to eliminate the previous disadvantages have been presented. In reference [12], the method which is used to recover the steady state error by regulating the quantization scaling factor and the output scaling factor according to the operating condition, thus the chattering phenomena in the steady state is reduced.

Although, there are several methods of compensation, the lookup table method is suggested [13]. The compensation method might cause instability in the system operation if over compensation occurs or sluggish response if under compensation takes place. In reference (14), an efficient algorithm for representing fuzzy sets in real time implementation is suggested.

In the following paragraph, two proposed methods are designed and implemented in the laboratory to obtain high performance DC motor speed control. Also, gives the solution for the problems of using fuzzy speed control only. These methods are:

1- Using Fuzzy logic speed controller with PI current controller.
2- Hybrid Fuzzy-PI speed controller.

4.1. Fuzzy Logic Speed Controller with PI Current Controller:

The use of fuzzy logic speed controller gives steady state error. The use of a fuzzy logic speed controller with a PI current controller gives a high performance for the system under consideration. The block diagram of the closed loop fuzzy speed controller with PI current controller is shown in Fig. (3).

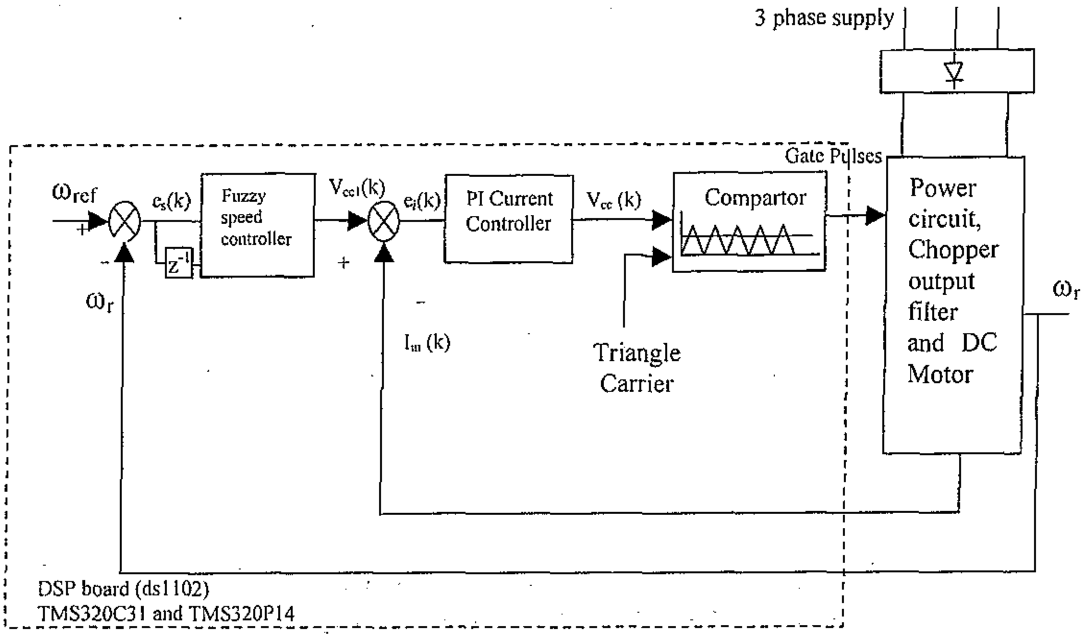
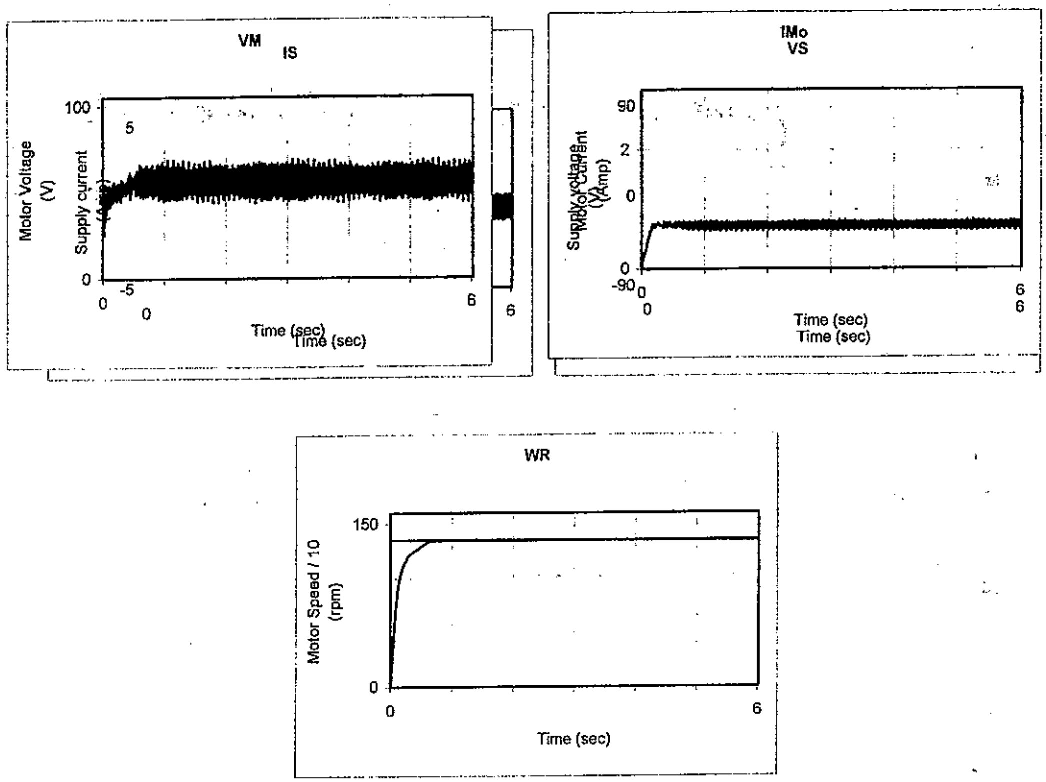


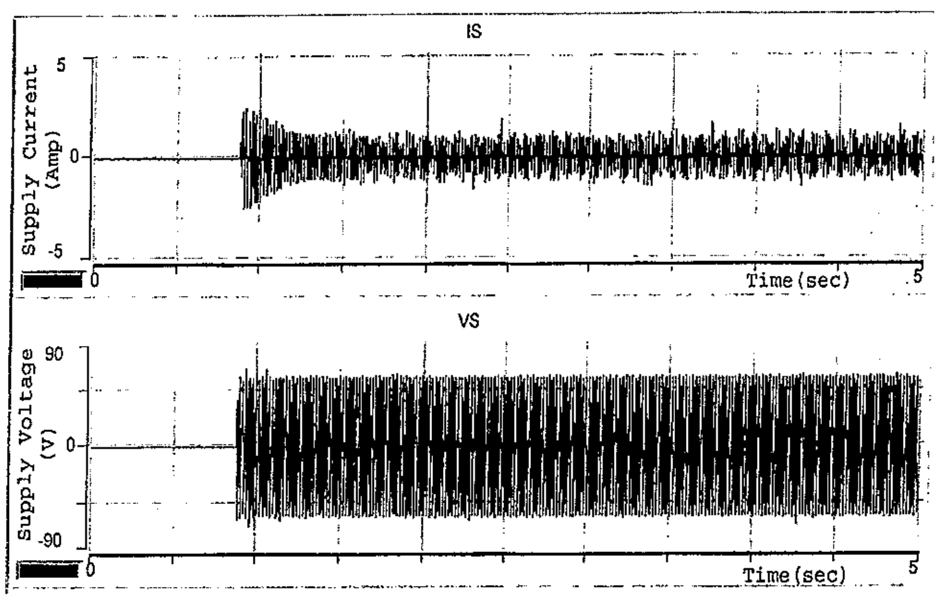
Fig.(3) The Block diagram of the closed loop fuzzy logic speed controller with PI current controller

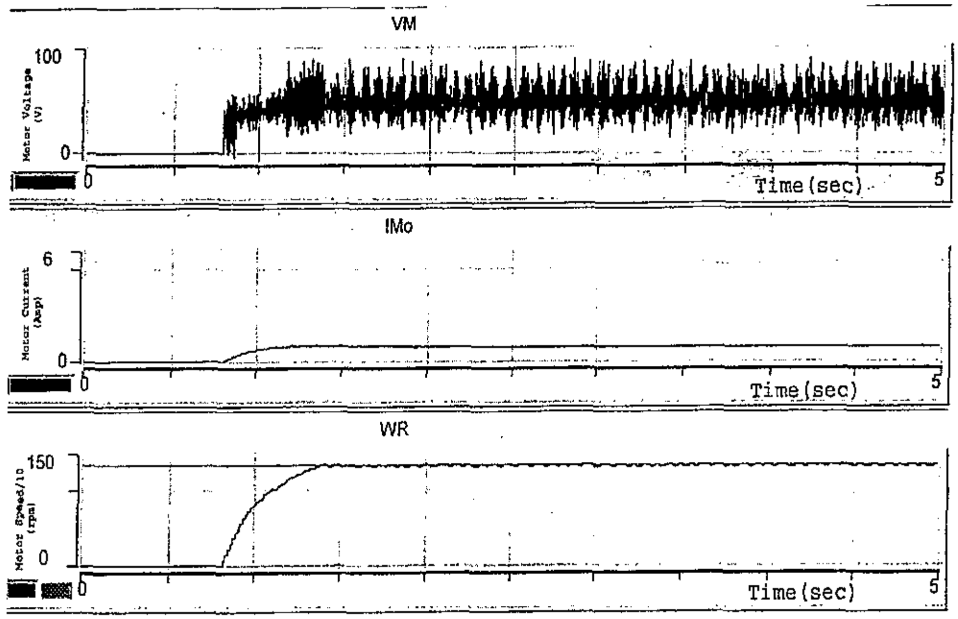
4.1.1. Motor Run up:

Figure (4) shows the simulation and experimental waveforms of the supply current, the supply voltage, the motor current, the motor voltage and the motor speed during run up with 0.4 of rated load torque and ω_{ref} 1350 rpm. The Figure shows that the run up time for the system with fuzzy logic speed controller with PI current controller takes 500 m.sec.



(a) Simulation



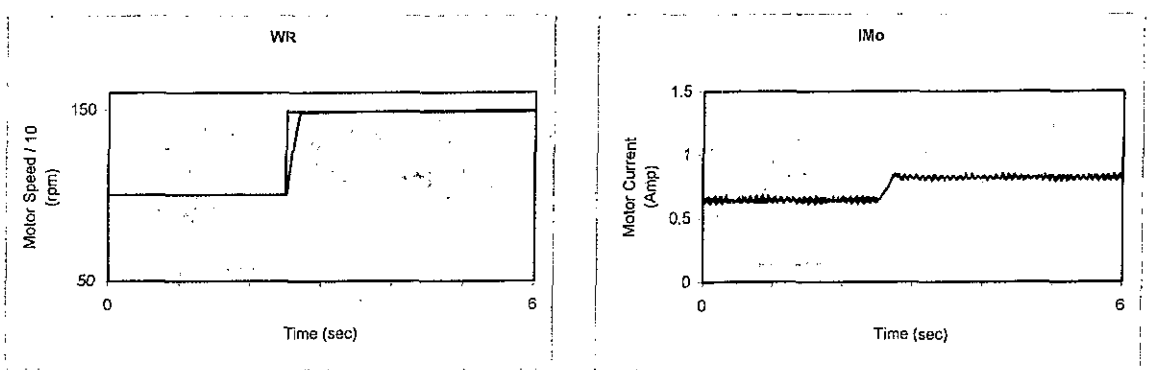


(b) Experimental

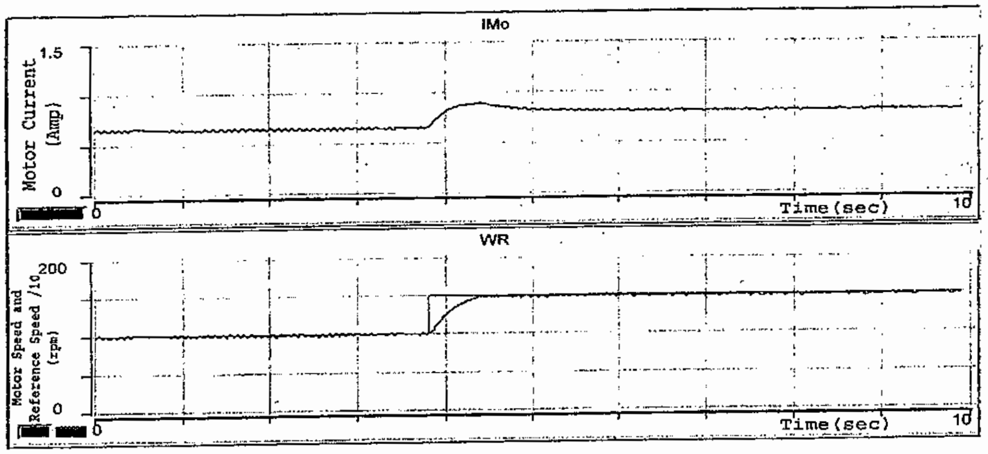
Fig.(4) Simulation and Experimental Results during run up interval for 0.4 of rated load torque and ω_{ref} =1350 rpm

4.1.2. Step Change of speed reference

Figure (5) shows the simulation and experimental responses of the motor speed and the motor current due to step up change in speed reference from 1000 rpm to 1500 rpm with 0.4 of a rated load torque. It is observed that the motor speed can follow the desired speed reference and it is settled after 500 ms with this high step up in speed reference. Figure (6) shows the same responses with a step down change in speed reference from 1500 rpm to 1000 rpm. It is observed that the steady state speed error did not observed.

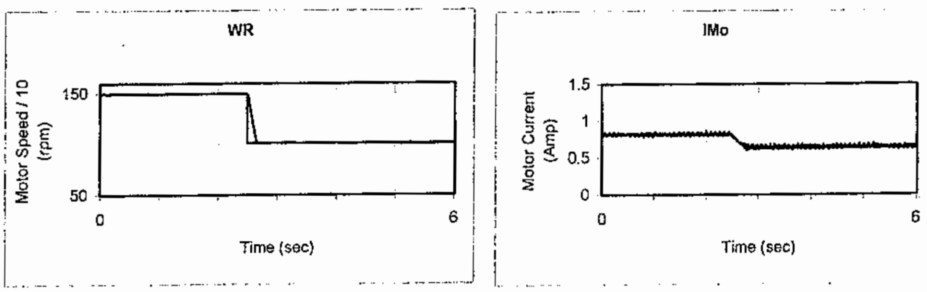


(a) Simulation

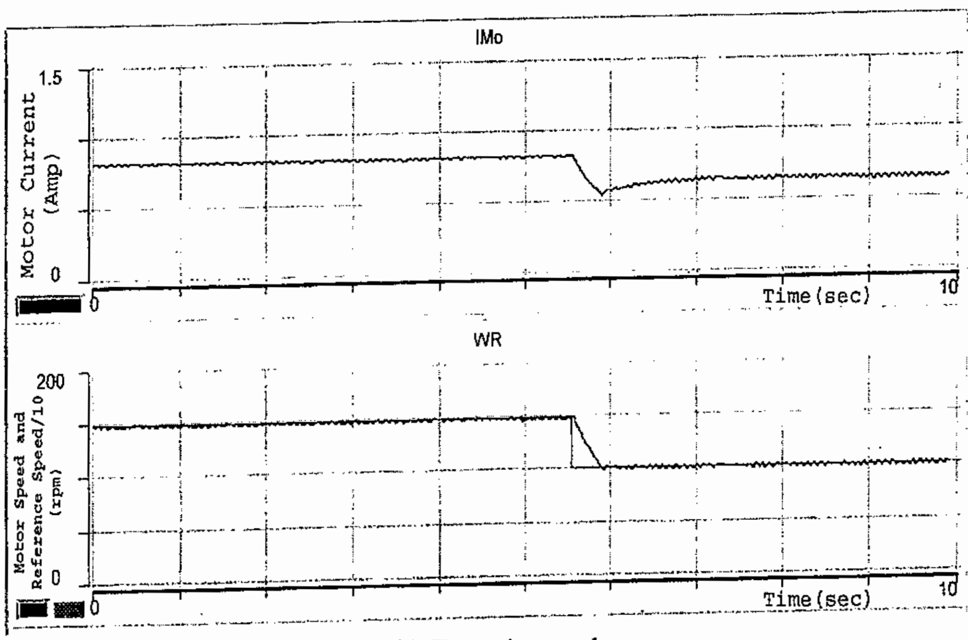


(b) Experimental

Fig. (5) Variation of the motor speed and the current due to step up change in speed reference



(a) Simulation

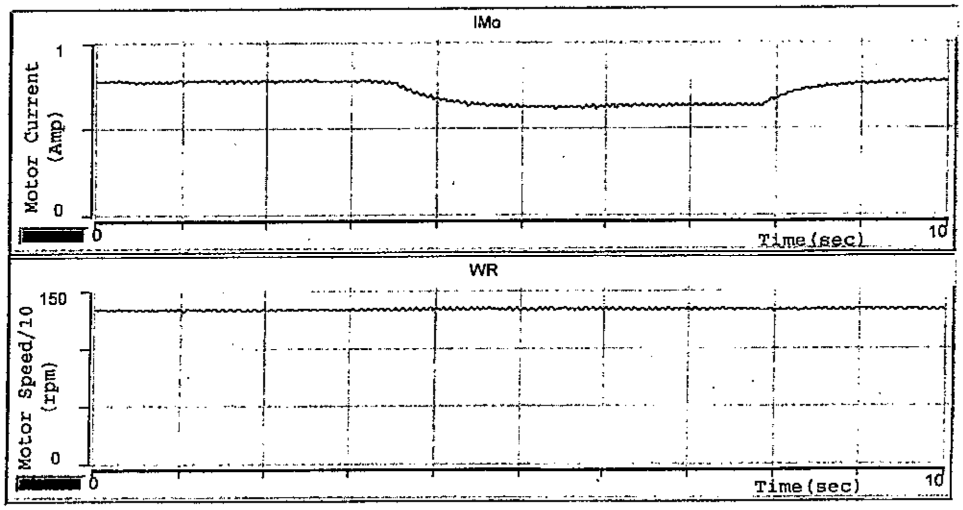


(b) Experimental

Fig. (6) Variation of the motor speed and the current due to step down change in speed reference

4.1.3. Load Change:

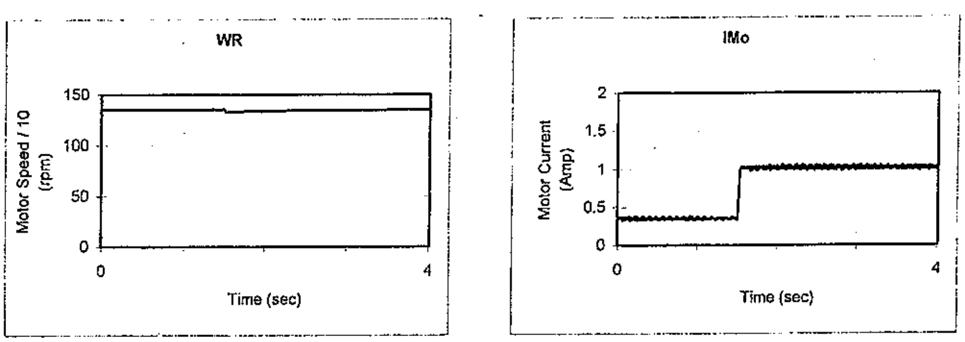
Figure (7) shows the experimental results for the motor speed and the motor current due to the step up and down load change. The load changes are ±25% from the existing load. The Figure shows that the undershoot during applying load is about 3 rpm and the motor speed has returned to its initial value which in turn confirms the validity of the system. Also, the motor speed and the motor current are smooth and the steady state error did not appear due to the presence of the PI current controller.

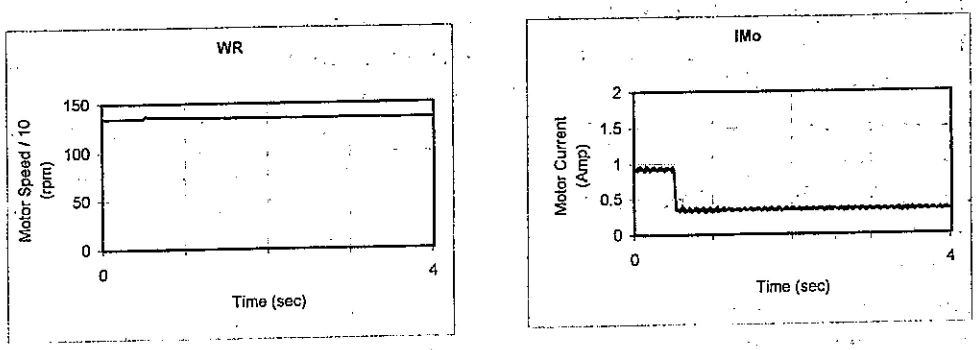


(b) Experimental

Fig. (7) Experimental results for the variation of the motor speed and the current due to step up and down load change

Figure (8) shows the simulation and experimental results for the motor speed and the motor current due to the step up and down load change from light load to a half load. The Figure shows that the undershoot due to this high impact load is about 7 rpm and the motor speed has returned to its initial value, also, the motor speed and current are smooth.





(a) Simulation

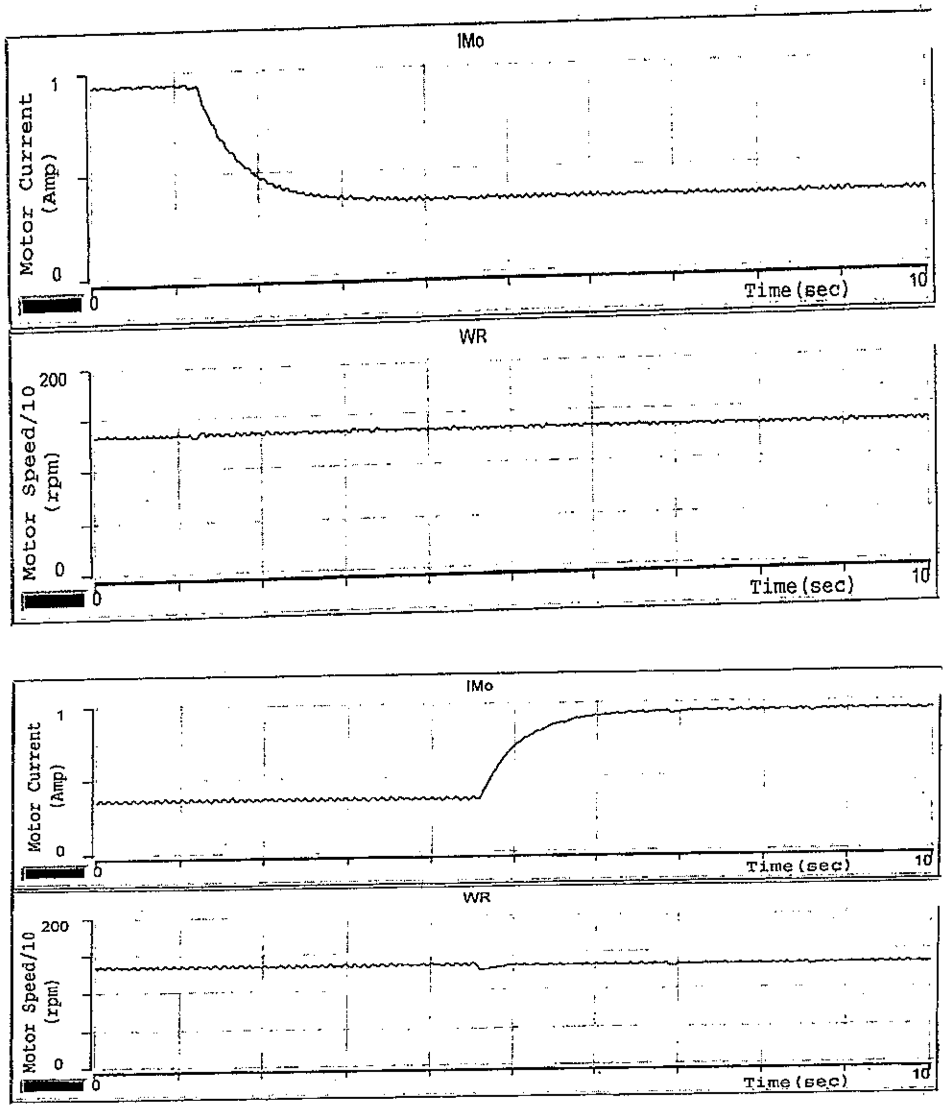


Fig. (8) Variation of the motor speed and the current due to load change from light load to half load and vice versa.

4.2. The Proposed Hybrid Fuzzy Logic-PI Controller:

The design and testing of a hybrid fuzzy control scheme for a high performance separately excited DC motor drive are presented. Both the design of the fuzzy controller and its integration with the PI controller in a global control scheme are proposed. The principle of the proposed control scheme is to use a fuzzy controller, which performs satisfactorily in most operation cases, while keeping in the background, the PI controller, which is ready to take over the fuzzy controller when steady state error occurs. Performance of the hybrid fuzzy-PI controller is evaluated through a laboratory implementation. Simulation and experimental results have shown excellent tracking performance of the hybrid control system and demonstrated the usefulness of the hybrid fuzzy controller in a high performance drive with uncertainties. The schematic diagram for hybrid fuzzy logic control is shown in Fig.(9).

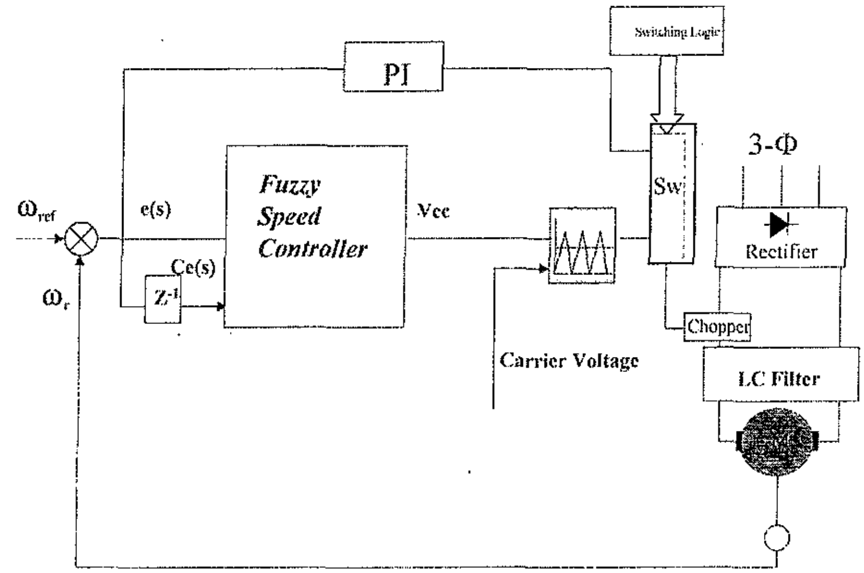


Fig. (9) Hybrid Fuzzy-PI controller scheme

4.2.1. Switching Control Strategy:

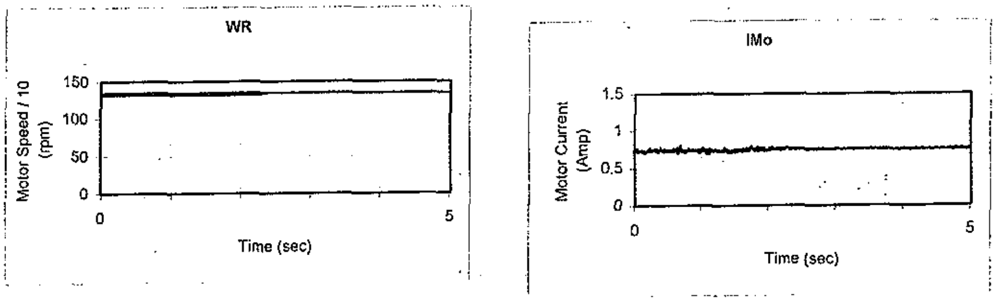
The objective of the hybrid controller is to utilize the best attributes of the PI and fuzzy controllers to provide a controller, which will produce better response than either the PI or the fuzzy controller. The switching between the two controllers needs a reliable basis for determining which controller would be more effective. The answer could be derived by looking at the advantages of each controller. To take the advantages of rapid response of the fuzzy control, one needs to keep the system responding under the fuzzy controller for a majority of the time, and use the PI only at the steady state error. Thus, after designing the best stand-alone PI and fuzzy controllers, one needs to develop a mechanism for switching from the fuzzy to the PI controller, based on the following condition: Switch to PI when steady state error is detected, the switching strategy is then simply based on the following condition:

IF the system has steady state error THEN PI controller is activated, *otherwise fuzzy controller is operated.*

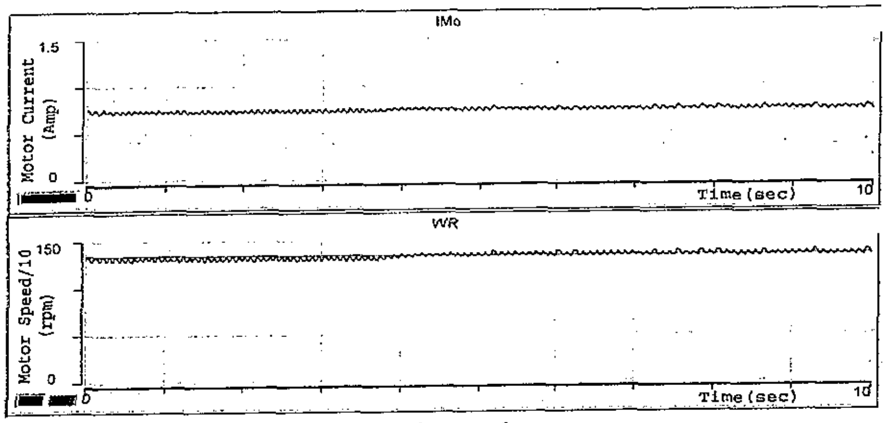
To detect the steady state error one has to observe the system over an extended period of time, which does not lend itself to instantaneous detection. In practice, the error usually fluctuates due to noise and other effects, and therefore, may never remain constant. Consequently, a threshold region is introduced for the error. This reduces undesirable switching between the two controllers. Furthermore, there is no need to smooth the transitions from fuzzy to PI as the error is so small the output of the PI will be small.

4.2.2. Simulation and Experimental Results For The Hybrid Fuzzy-PI *Controller:*

After designing the best stand-alone PI and Fuzzy controllers, the effectiveness of combining the two controllers to produce a hybrid design is demonstrated. The selection of the gains of the PI controller are obtained for different operation regions. To display the capability of the proposed hybrid controller, the performance of both the fuzzy controller and its integration with the PI controller is given using simulation and experimental techniques. Figure (10) shows the speed and current trajectory using the switching control strategy for ω_{ref} = 1350 rpm. The results of the switching control strategy are favorable.



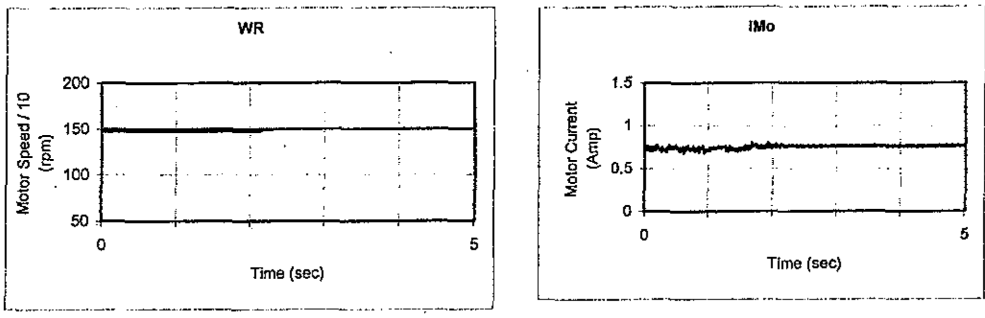
(a) Simulation



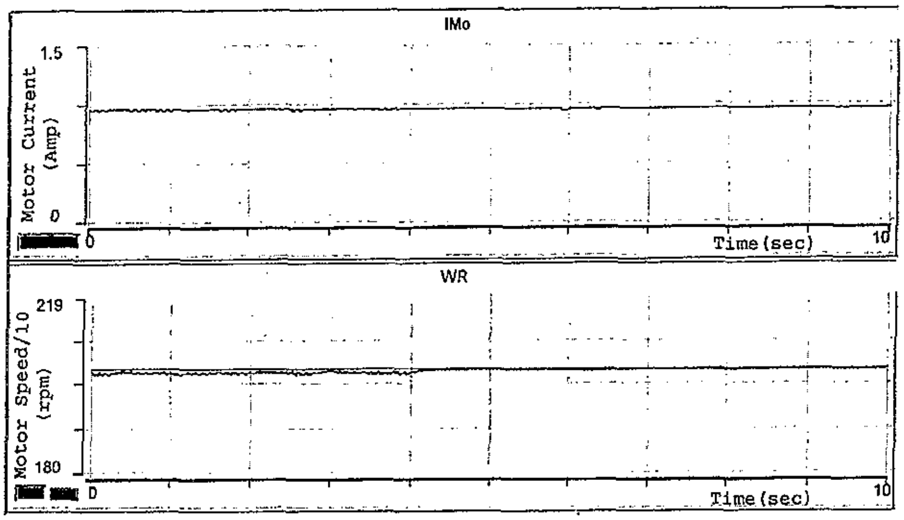
(b) Experimental

Fig. (10) The motor responses for the hybrid control with ω_{ref} =1350 rpm

Figure (11) shows the same results with ω_{ref} = 2050 rpm. It is seen that the hybrid fuzzy-PI controller has shown very good performance as it eliminates the undesired steady state error that can't be accepted by some applications.



(a) Simulation



(b) Experimental

Fig.(11) The motor responses for the hybrid control with $\omega_{ref} = 2050$ rpm

5. CONCLUSION:

The simulation and experimental behavior for dynamic and steady state performance of a separately-exited DC motor fed from an UPWM converter through a power switch and controlled by fuzzy speed controller techniques are presented.

The results show that a steady state error due to load change appears with the fuzzy logic controller. So, the use of fuzzy speed controller with PI current controller or hybrid fuzzy-PI controller can solve this problem. Applying the proposed hybrid fuzzy-PI controller for rolling mill drive enable solving the problem of undershoots during impact loads. The system is using uniform pulse width modulation. A digital signal processor based DS1102 has been successfully used for on-line control of the separately excited DC motor drive. The experimental results ensured the robustness of both the hybrid fuzzy-PI controller and the fuzzy speed controller with PI current controller.

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APPENDIX:

The motor is a separately excited DC motor 220 volt, 1.9 Ampere, 1/3 HP. And has the following parameters:

R_a=10.5 ohm $\quad$ L_a = 0.113 H

K_v = 0.3478 v/rad/sec. $\quad$ B = 0.00012 Nm/rad/sec

J = 0.000625 $Kg.m^2$

Filter parameters:

R_L = 2.0 ohm, $\quad$ L_L = 0.099 H, $\quad$ C_o = 0.00012 Farad.

تحسين الأداء لآلات التسيير المستخدمة فى صناعة الحديد والصلب بإستخدام التحكم المختلط الذى يجمع بين التحكم المبهم بالتبادل مع التحكم التكاملى التناسبى

د./ علوى عيسى الخولى و ا.د/ شكرى سعد شكرالله و ا.د./ أحمد حسانين مرسى
قسم الهندسة الكهربية- كلية الهندسة- جامعة المنوفية

م./ سعيد أحمد العبساوى
مهندس بالشركة العربية للصلب المخصوص

ملخص البحث:

يتضمن هذا البحث إقتراحا للنمذجة والتمثيل العددى وذلك للتحكم فى سرعة محرك تيار مستمر منفصل التغذية وذلك بإستخدام تقنية تعديل عرض النبضة المنتظم وذلك للتحكم فى قيمة الجهد المغذى للمحرك وذلك للتحكم فى سرعته. وقد تم إستخدام حمل عبارة عن مولد تيار مستمر منفصل التغذية وتم إيجاد ثوابت النظام.

يشمل هذا البحث دراسة أداء مثل هذا النظام لكل من حالتى الأستقرار والحالة العابرة وبدء الآله من السكون. وقد تم بناء هذا النظام معمليا بإستخدام معالج الإشارات الرقمية وذلك لمقارنة النتائج العملية بالنظرية والتى أثبت وجود توافق كبير بينهما. وقد أوضحت الدراسة النظرية لهذا النظام أنها أداه قوية للتنبؤ بسلوك مثل هذا النظام ومدى الحصول على تشغيل مستقر وأداء سريع فى الحالات العابرة وذلك بتغير الحمل أو بتغير سرعة الإسناد وقد تم إستخدام التحكم المنطقى المبهم المبنى على أساس التحكم فى السرعة وإستخدام حاكم للتيار من النوع التكاملى التناسبى كمتحكم دائرة مغلقة داخلى. إضافة إلى ذلك فقد تم إستخدام نظام تحكم أخر وهو التحكم المختلط الذى يجمع بين التحكم المبهم بالتبادل مع حاكم للسرعة من النوع التكاملى التناسبى كمتحكم دائرة مغلقة. وقد تم إستخدام نظامى التحكم السابقين للحصول على خواص جيدة للتحكم فى سرعة محرك التيار المستمر.