

PRACTICAL IMPLEMENTATION OF FUZZY CONTROLLER FOR CONTROLLING THE CNC SPINDLE MOTOR USING PLC

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ABSTRACT

The main objective of this paper is to practically design a controller that keeps the performance of CNC spindle speed. The precision of the CNC spindle motor speed affects the quality of the product and machine lifetime. Hereby we apply the PID, fuzzy and fuzzy-PID controller types using the PLC. The controlled parameter is the CNC spindle motor speed. The system performance was evaluated using the three controllers. Results of fuzzy-PID show significant improvement in the performance over a wide range of operating conditions.

Keywords: Computer Numerical Controlled (CNC), Fuzzy Control, Programmable Logic Controller (PLC), PID controller.

1. Introduction

Computer numerical control (CNC) machine tools are now widely used in the manufacturing industry. CNC is one in which the motions and functions of a machine tool are controlled by means of a program containing coded alphanumeric data. CNC can control the motions of the tool or workpiece, the input parameters such as depth of cut, feed and speed, and the functions such as turning coolant on/off, turning the spindle on/off. CNC is widely used for drill press, lathe, milling machine, sheet-metal press working machine, grinding unit, laser, tube-bending machine etc. [1].

Carrying out a high speed of the spindle motor under load is making the motor unstable, so the production is not finished well and the instability of the spindle speed affects the lifetime of the machine and it may cause damage [2]. For that reason, it is very important to control the spindle motor in (CNC) machine [3]. However, the external disturbances are occurred due to the vibration of high speed. These will influence the performance of a spindle motor. To achieve a robust control against the external disturbances and the model uncertainty of the spindle motor, a fuzzy logic controller is implemented.

Fuzzy logic has rapidly become one of the most successful of today's technologies for developing sophisticated control systems. Fuzzy controllers are more robust than conventional PID controllers because they can cover a much wider range of operating conditions than PID can and can operate with noise and disturbances of different nature. Given the dominance of conventional PID control in industrial applications, it is significant both in theory and in practice if a controller can be found that is capable of outperforming the PID controller with comparative ease of use [4]. The simplest and most usual way to implement a fuzzy controller is to realize it as a computer program on a general-purpose computer. However, a large number of fuzzy control applications

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require a real-time operation to interface high-speed constraints[5].In order to show the effectiveness and the power of this new approach, the Fuzzy-PID has been implemented on the Simatic S7 -200 PLC to control CNC machine [6, 7]. The results are compared with the conventional PID and fuzzy controller.

The outline of this paper is organized as follows: The description of the system under study is presented in Section 2. The design controllers (fuzzy, PID, fuzzy-PID) by PLC are given in Section 3. Both the practical results(without load –under load) and analysis are presented in Section 4 followed by the conclusions and the relevant references.

2.System Description

The main parts of the CNC machine are shown in Fig. 1.It includes the following parts:

● The CNC machine axes

The CNC machine includes "X, Y, Z" axes, in which each axis is moving by a stepper motor as shown in Fig.1.

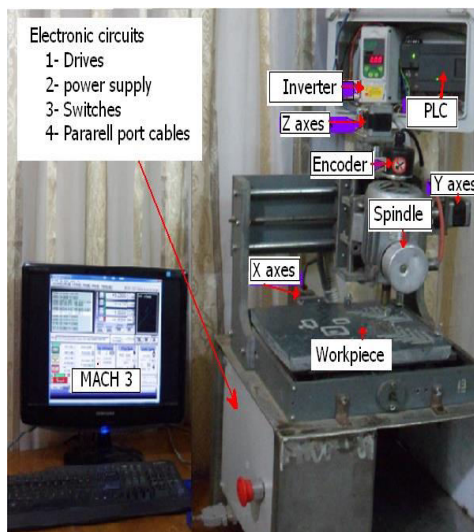


Fig. 1. The CNC machine

● CNC machine interface

The machine is interfaced with the PC and PLC, in which the PC included software as "Mach 3" to supply the stepper motor drives with desired axis motion. The PLC program responsible about controlling the motion based on suggested controller algorithms.

● Machine spindle

The spindle motor is an induction motor with a speed of 3200 rpm and the input supply is 220V AC 3PH, its frequency is 50HZ, and the power is 25 watt, however the speed is changing based on controller of a frequency from 0 to 50HZ as shown in Fig. 2 [8,9].

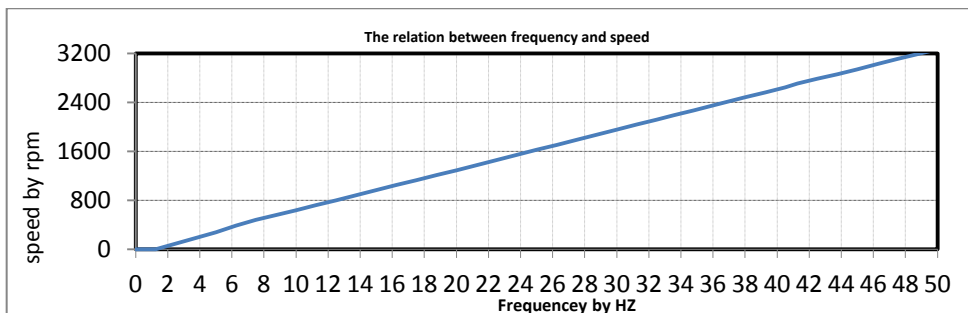


Fig. 2. The calibration curve between frequency and motor

● **The digital encoder**

The digital encoder is a motor speed measurement device, and the changing in output pulses (0~500 "pulse per second") based on motor speed as shown in Fig. 3.

● **The programmable logic controller "PLC"**

The PLC used in this experiment is Siemens S7 200, CPU type is 224XP, 14 inputs / 10 outputs, Boolean execution speed 0.37μs/ instruction, it has digital to analogue converter module in the range (0- 10) VDC [10, 11].

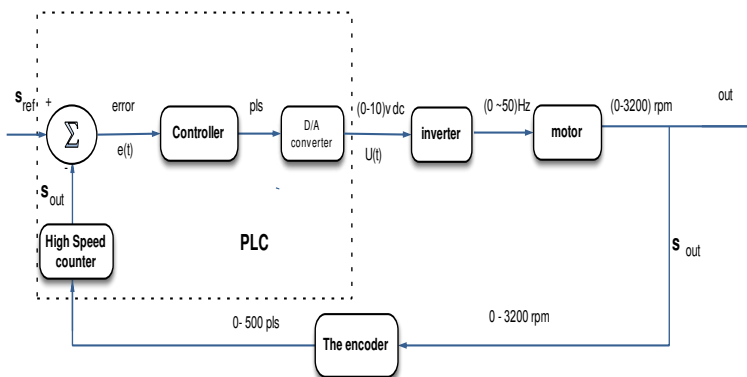


Fig. 3. The control system block diagram.

● **AC inverter**

The AC inverter is a device that converts the output voltage from PLC analogue module (0-10VDC) to frequency (0-50Hz) then the frequency is:

$$F = 5 U(t) \tag{1}$$

where F is the frequency by HZ and U(t) is controller voltage by volt. The input supply is 220V AC 1PH 50Hz the output signal is 220V AC 3PH as shown in Fig.4 [9, 12, 13].

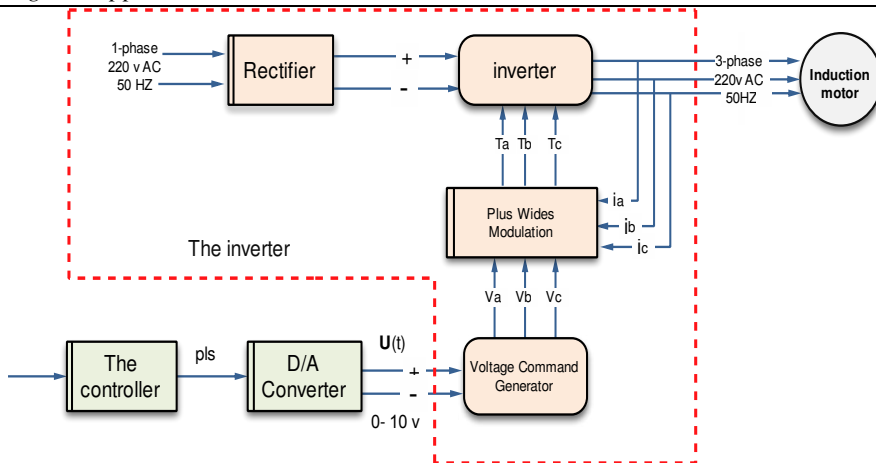


Fig.4.Block diagram for the inverter

3. PID and Fuzzy Controllers Implementation using PLC

3.1 PID controller

The PID controller regulates the value of the output to drive the error $e(t)$ to zero. A measure of the error is given by the difference between the set-point (the desired operating point), and the process variable (the actual operating point) [14]. The principle of PID control is based upon the following equation that expresses the output, $U(t)$ as a function of a proportional term, an integral term, and a differential term as follows:

$$U(t) = U(t)_{\text{initial}} + k_c e(t) + k_c \int_0^t e(t)dt + k_c de(t)/dt \tag{2}$$

where $U(t)$ is the loop output controller PID as a function of time, k_c is the loop gain, $e(t)$ is different between the set-point speed S_{ref} and the actual speed of the induction spindle motor S_{out} , and $U(t)_{\text{initial}}$ is the initial value of the loop output [15].

In order to implement this control function in a digital computer, the continuous function must be quantized into periodic samples of the error value with subsequent calculation of the output. The corresponding equation, which is the basis for the digital computer solution, is:

$$U(k) = U(k-1) + k_c e(k) + k_c T_s / T_I \sum_1^k e(k) + k_c T_D / T_s (e(k) - e(k-1)) \tag{3}$$

where $U(k)$ is the output of the controller of the PID at sample time k , T_s , T_I and T_D are the loop sample time, the integral time, and the derivative time respectively.

Since the digital computer must calculate the output value each time the error is sampled beginning with the first sample, it is only necessary to store the previous value of the error and the previous value of the integral term. Because of the repetitive nature

of the digital computer solution, a simplification in the equation that must be solved at any sample time can be made. The simplified equation is:

$$U(k) = U(k-1) + k_c e(k) + k_i \sum_1^k e(k) + k_d (e(k) - e(k-1)) \tag{4}$$

where $k_i = k_c T_S / T_I$ and $k_d = k_c T_D / T_S$.

3.2. Fuzzy control

In order to establish a proper fuzzy an expert experiences and knowledge is necessary for the membership functions and fuzzy rules [16]. We need to control the speed of the spindle motor by changing the input voltage. When a set-point is defined, if for some reason, the motor runs faster, we need to slow it down by reducing the input voltage. If the motor slows below the set-point, the input voltage must be increased so that the motor speed reaches the set-point, this method is known by fuzzy. The inputs have a set of possible linguistic values {NH, NL, Z, PL, PH}, NH stands for **Negative High**, NL stands for **Negative Low**, Z stands for **Zero**, PL stands for **Positive Low** and PH stands for **Positive High**.

The output changing of voltage is $\delta U(k)$, which is added to the reference value in order to eliminate the deviation between the system output and the desired value. It has a set of possible linguistic values {TSD, SD, NG, SP, TSD,} where TSD stands for **Too Speed Down**, SD stands for **Speed Down**, NG stands for **No Change**, SP stands for **Speed Up** and TSP stands for **Too Speed Up** as shown in Table 1 and Fig. 5.

Table1.

Fuzzy rule table Change of error Δe (k)

$e(k)$	$e \backslash \Delta e$	NH	NL	Z	PL	PH
	NH	<i>TSD</i>	<i>TSD</i>	<i>TSD</i>	<i>SD</i>	<i>NG</i>
	NL	<i>TSD</i>	<i>TSD</i>	<i>SD</i>	<i>NG</i>	<i>SP</i>
	Z	<i>TSD</i>	<i>SD</i>	<i>NG</i>	<i>SP</i>	<i>TSP</i>
	PL	<i>SD</i>	<i>NG</i>	<i>SP</i>	<i>TSP</i>	<i>TSP</i>
	PH	<i>NG</i>	<i>SP</i>	<i>TSP</i>	<i>TSP</i>	<i>TSP</i>

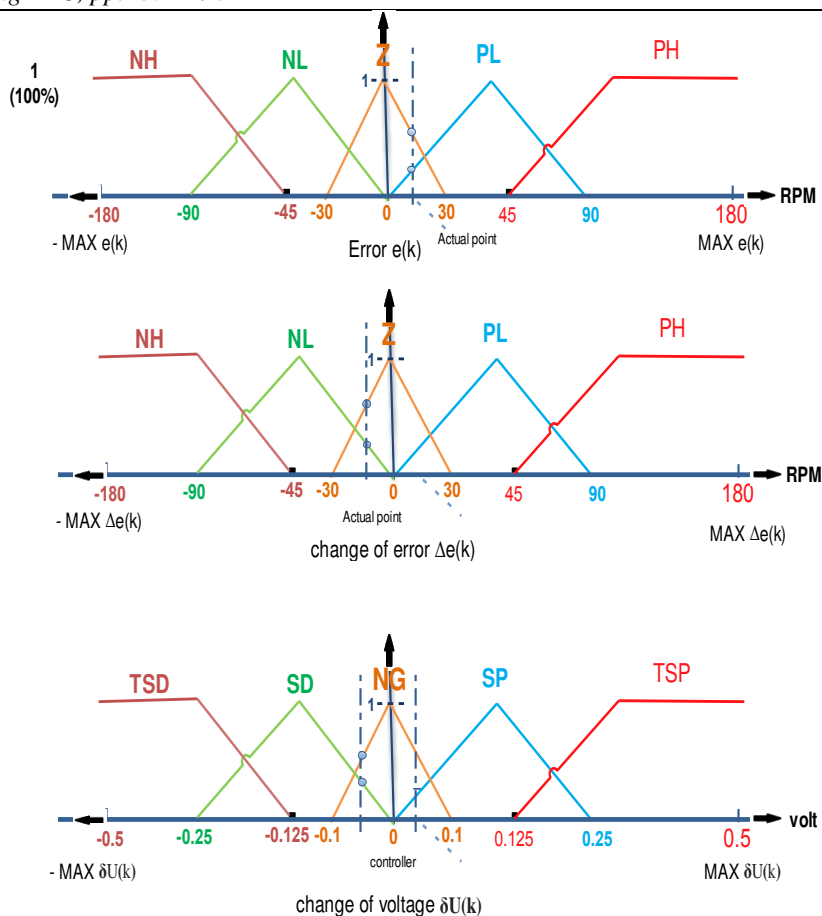


Fig. 5. Membership functions

• Software design

A PC and PLC control system is employed to realize CNC spindle motor motion control, which contains a personal computer (PC). The PC sends initialization commands to the PLC in advance, and sends parameter signals to each individual drivers afterwards, such as operation modes, motor speeds and spindle rotation directions. The spindle is driven by the corresponding driver, and feedback the real-time status to the PLC and the PC. The parameters of the spindle motor display on the PC, and the real-time motion is controlled by the PLC.

The S7-200 of micro-programmable logic controllers (Micro PLCs) is used to control the CNC spindle motor, the programming language is the STEP 7-Micro/WIN 32 Ladder Logic (LAD) editor. The Fig.6 shows the blockdiagram. The print out of the first page of the fuzzy ladderprogram is shown in the appendix.

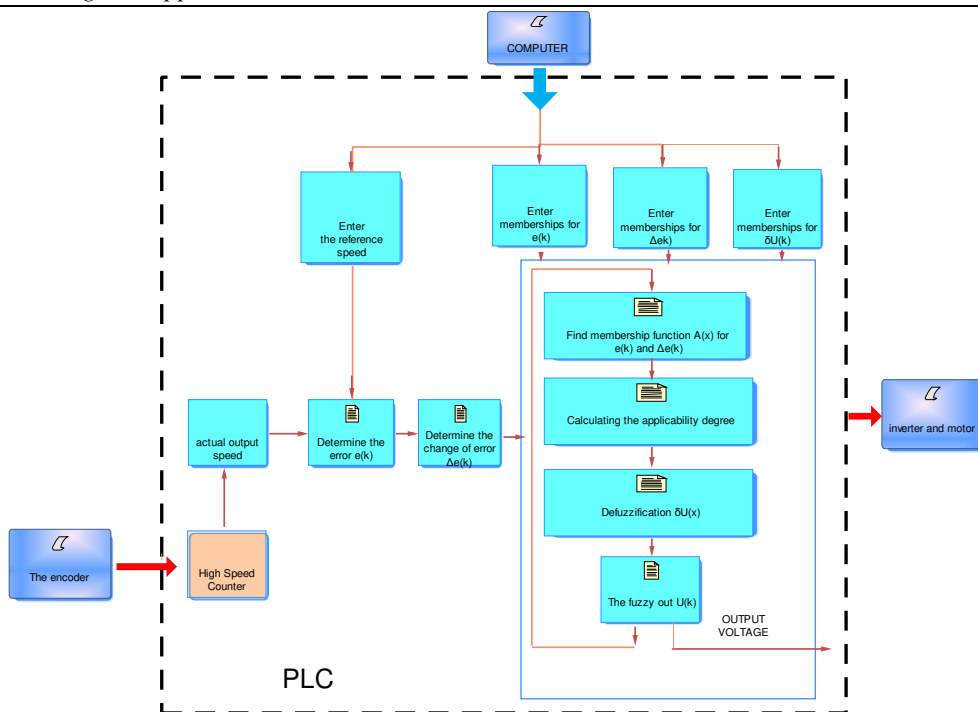


Fig. 6.Block diagram of the ladder program of fuzzy logic controller implementation.

To save the real time reading from PLC to PC (Excel program) by use the Softing S7/S5 OPC Server, The Softing S7 OPC server gives you quick, convenient access to the entire SIMATIC S7 series as well as Siemens WinAC and compatible controllers from other manufactures, the OPC client applications can access the input or output data, flags, timers, counters, etc. of several controllers at once via familiar S7-200.

The following steps show the fuzzy controller designed by PLC:

Step1: Given the reference speed S_{ref} to the program PLC and save in data register.

Step2: The values of memberships for $e(k), \Delta e(k)$ and $\delta U(k)$ given to program PLC.

Step3: The measurement actual out speed of motor S_{out} is save in data register.

Step4: Determine the error $e(k)$ and $\Delta e(k)$ as follows:

$$e(k) = S_{ref} - S_{out} \tag{5}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{6}$$

Step5: Find the intersection of membership function $A(x)$ fore(k) and $\Delta e(k)$

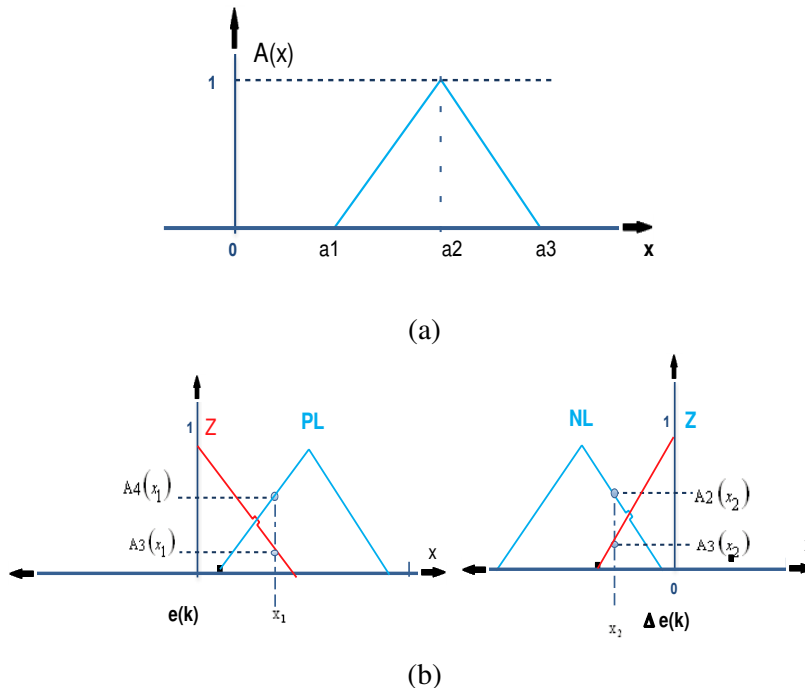


Fig. 7. Membership function (a) Triangular fuzzy member (b) Applicability degree

The grade of triangular membership function is shown Fig.7(a) and defined by [17]:

$$A(x) = \begin{cases} 0, & x < a_1 \\ (x - a_1) / (a_2 - a_1), & a_1 \leq x \leq a_2 \\ (a_3 - x) / (a_3 - a_2), & a_2 \leq x \leq a_3 \\ 0, & x > a_3 \end{cases} \quad (7)$$

Step6: Calculating the applicability degree.

At this stage, the degree to which the whole condition part (all the inputs) satisfies the rule is calculated as showing in Fig.7(b) and the applicability degree here as $\mu_{kj}(x): \mu_{kj}(x) = A_k(x_1) * A_j(x_2) \dots A_n(x_n)$ (8)

Where x_i is the value for the i th crisp input, k and j is the number of membership for $e(k)$, $\Delta e(k)$ respect, $A_n(x_n)$ is the membership function for the corresponding linguistic value for the corresponding input [17].

Step7:Apply fuzzy rules.

Let the measured $e(k)$ and $\Delta e(k)$ be as shown in the figure above. We see that this will fire four rules:

IF $e(k)$ is Z and $\Delta e(k)$ is NL THEN $\delta U(k)$ is SD " μ_{32} ".

IF $e(k)$ is PL and $\Delta e(k)$ is NL THEN $\delta U(k)$ is NG " μ_{42} ".

IF $e(k)$ is Z and $\Delta e(k)$ is Z THEN $\delta U(k)$ is NG " μ_{33} ".

IF $e(k)$ is PL and $\Delta e(k)$ is Z THEN $\delta U(k)$ is SP" μ_{43} ".

Table 2.
Fuzzy rule table

		$\Delta e(k)$				
$e(k)$		NH	NL	Z	PL	PH
$e(k)$	NH	μ_{11}	μ_{12}	μ_{13}	μ_{14}	μ_{15}
	NL	μ_{21}	μ_{22}	μ_{23}	μ_{24}	μ_{25}
	Z	μ_{31}	μ_{32}	μ_{33}	μ_{34}	μ_{35}
	PL	μ_{41}	μ_{42}	μ_{43}	μ_{44}	μ_{45}
	PH	μ_{51}	μ_{52}	μ_{53}	μ_{54}	μ_{55}

From eq. (8) then

$$\mu_{32} = A_3(x_1) * A_2(x_2)$$

$$\mu_{42} = A_4(x_1) * A_2(x_2)$$

$$\mu_{33} = A_3(x_1) * A_3(x_2)$$

$$\mu_{43} = A_4(x_1) * A_3(x_2)$$

Step8:Defuzzification

A defuzzifier compiles the information provided by each of the rules and makes a decision from this basis. The most commonly used method is the Center of Area (COA). It generates the center of gravity of the possibility distribution of $\delta U(x)$ as follows:

$$\delta U(x) = \frac{\sum_{k=1}^n x_k \Pi_{j=1}^n \mu_{kj}(x)}{\sum_{k=1}^n \Pi_{j=1}^n \mu_{kj}(x)} \tag{9}$$

where n is the number of quantization levels of a universe U and x_k is the point in the k^{th} quantization level in a universe U at which $\mu(x)$ is its maximum value $\mu_{kj}(x)$ [17].

From the above formula, then $\delta U(x)$ is:

$$\delta U(x) = \frac{SD*\mu_{32}+NG*\mu_{42}+NG*\mu_{33}+SP*\mu_{43}}{\mu_{32}+\mu_{42}+\mu_{32}+\mu_{33}+\mu_{43}}$$

Step9:The fuzzy out

The control action out U(k) can be determined as:

$$U(k) = U_{cal} + \delta U(x) \tag{10}$$

where U_{cal} is the calibrated voltage of the reference speed S_{ref} .

3.3. Fuzzy-PID controller

In order to achieve high performance under specified operating condition a combination between fuzzy controller and conventional PID controller is proposed as shown as Fig. 8, in which the fuzzy controller achieves improvement in the transient response and the PID controller impress the performance in the steady state [18-22]. The controller that is given in eq. (10) is modified to be:

$$U(k) = U1(k) + \delta U(x) \tag{11}$$

Where $U1(k)$ is the control signal of conventional PID controller and $\delta U(x)$ is defined as in eq. (9).

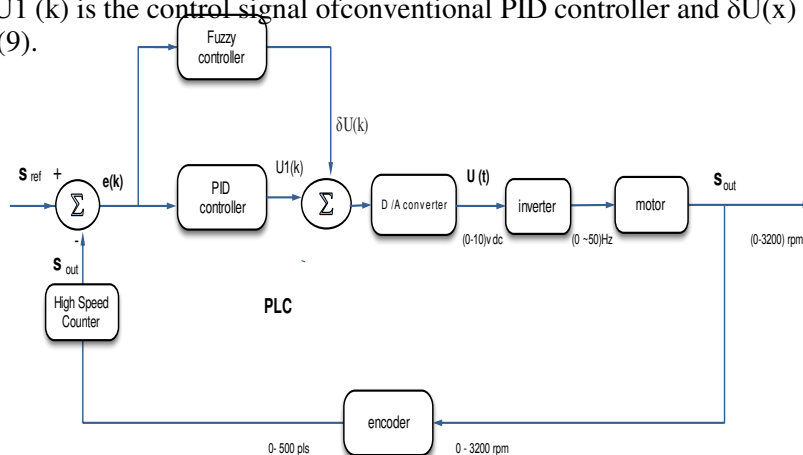


Fig. 8. Fuzzy-PID controller

4. Practical Results

In this section, the controller is tested in two cases: firstly, in case starting without load, secondly in case the controller systems are under load. The RMS error is used as a measure for the controller's performance as:

$$RMS = \sqrt{\frac{1}{N} \sum_{k=1}^N (S_{ref}(k) - S_{out}(k))^2} \tag{12}$$

Where N is the number of the sample points, $S_{ref}(k)$ is the speed set-point and $S_{out}(k)$ is the actual output speed [12].

4.1. System response without load

In the beginning we indicate four references for speed set-point (speed 0 rpm, 1000 rpm, 1700 rpm and 2420 rpm), then we implement the three controller systems PID, fuzzy and fuzzy-PID as shown in Fig. 9.

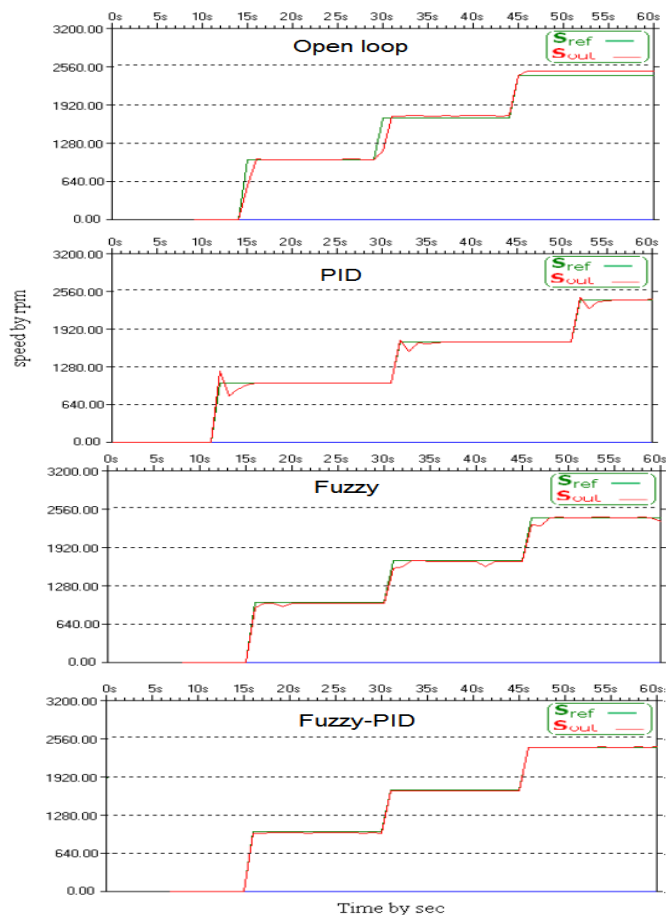


Fig. 9. Controllers results without load between the speed set-point S_{ref} and the actual output speed S_{out} .

Fig. 9 shows the response of the CNC spindle motor without load for the PID, the fuzzy and the fuzzy -PID controllers under reference changes. It is clear that the PID controller has good results in steady state but there is an overshoot occurs when the set-point changes from a step to another. The fuzzy controller has good results in transient state term, there is no overshoot in the output when the set-point changes from a step to the other but there is a steady-state error. The fuzzy -PID controller has good results in the transient and in the steady state in which the output of the system is matched with variable set points.

4.2. Control system under load

The three controller systems are tested using different loads with different depths of cutting at 0mm, 2mm, 4mm and 6mm, the processed material is PVC (PolyVinyl Chloride) material, and the cutting tool's type is Carbide flat with an end mill diameter 6 mm.

Case 1:

The controller systems are tested using four references of speed set-points (speed 0 rpm, 1000 rpm, 1700 rpm and 2420 rpm) with one depth of cutting at 4 mm.

Fig. 10 shows the open loop, PID, fuzzy and fuzzy -PID controller's responses of the CNC spindle motor under change of S_{ref} with fixed cutting depth 4mm. In the case of open loop, the motor is stopped, in which the PID controller causes high overshoot and fuzzy controller causes high error in the steady state, in which the fuzzy-PID controller is better.

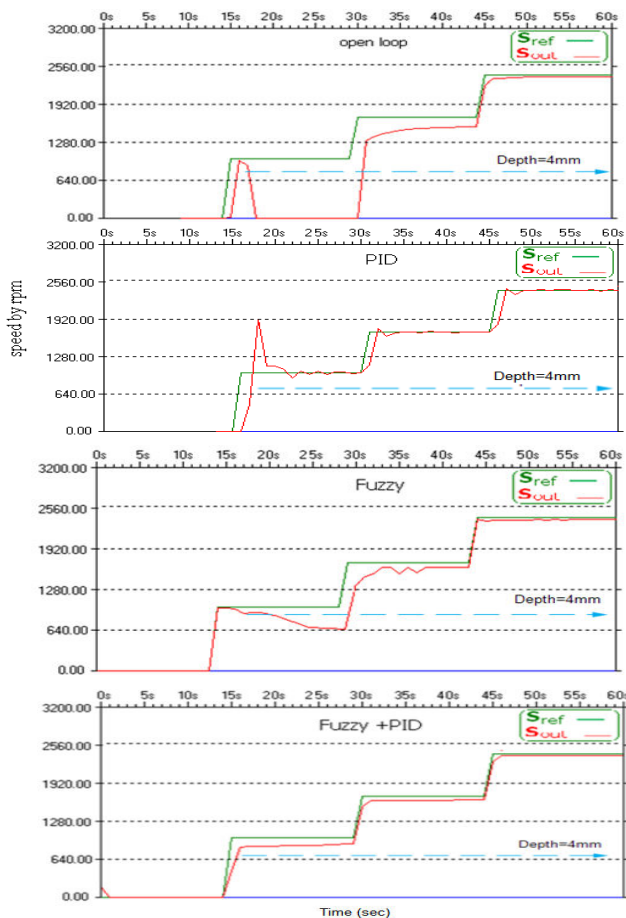


Fig. 10. The controller systems results under load (depth of cutting at 4 mm)

Case 2:

The controller systems are tested using four references of speed set-points (speed 0 rpm, 1000 rpm, 1700 rpm and 2420 rpm) with different depths of cutting at 0mm, 2mm, 4mm and 6mm.

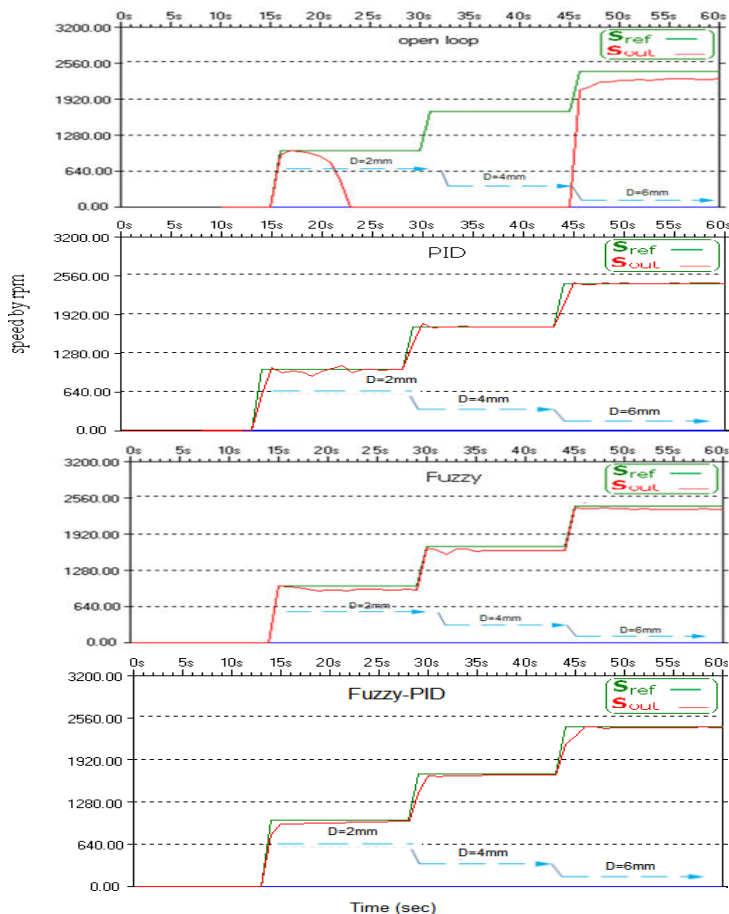
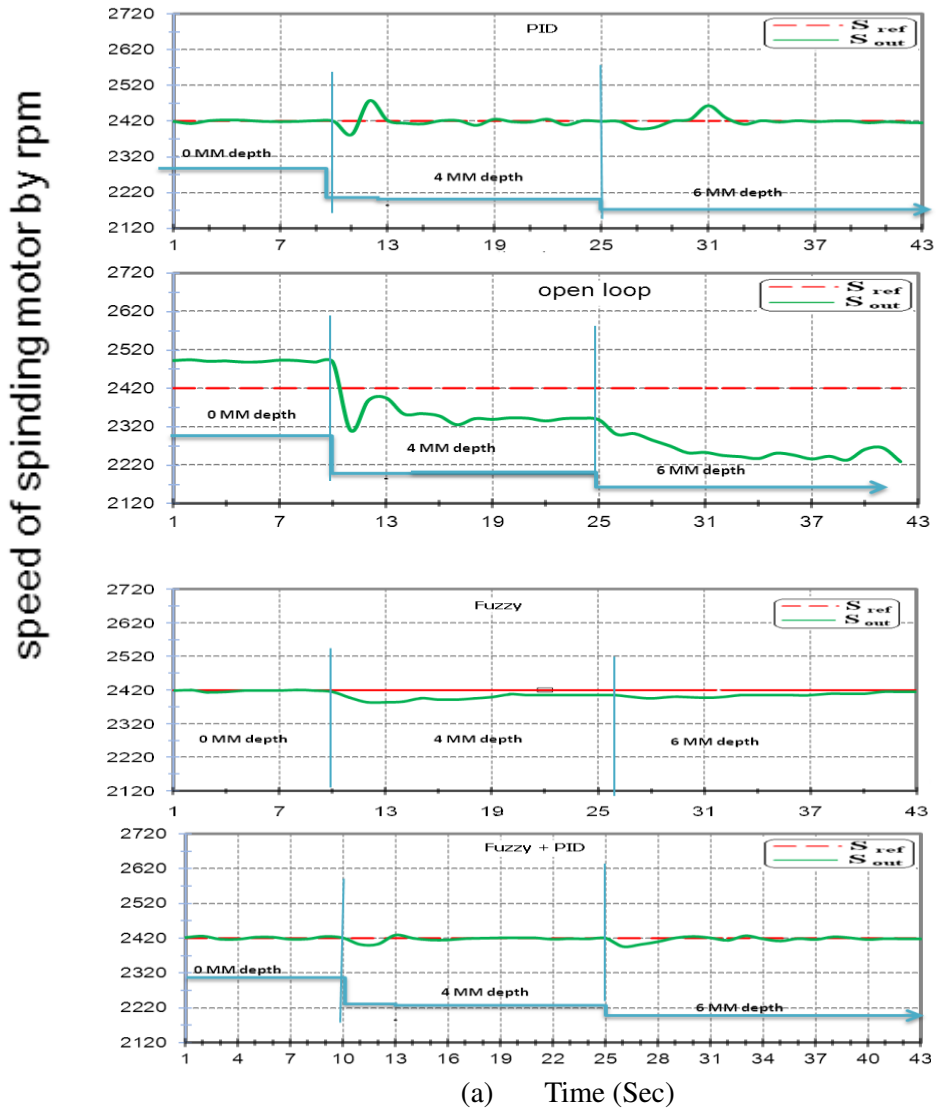


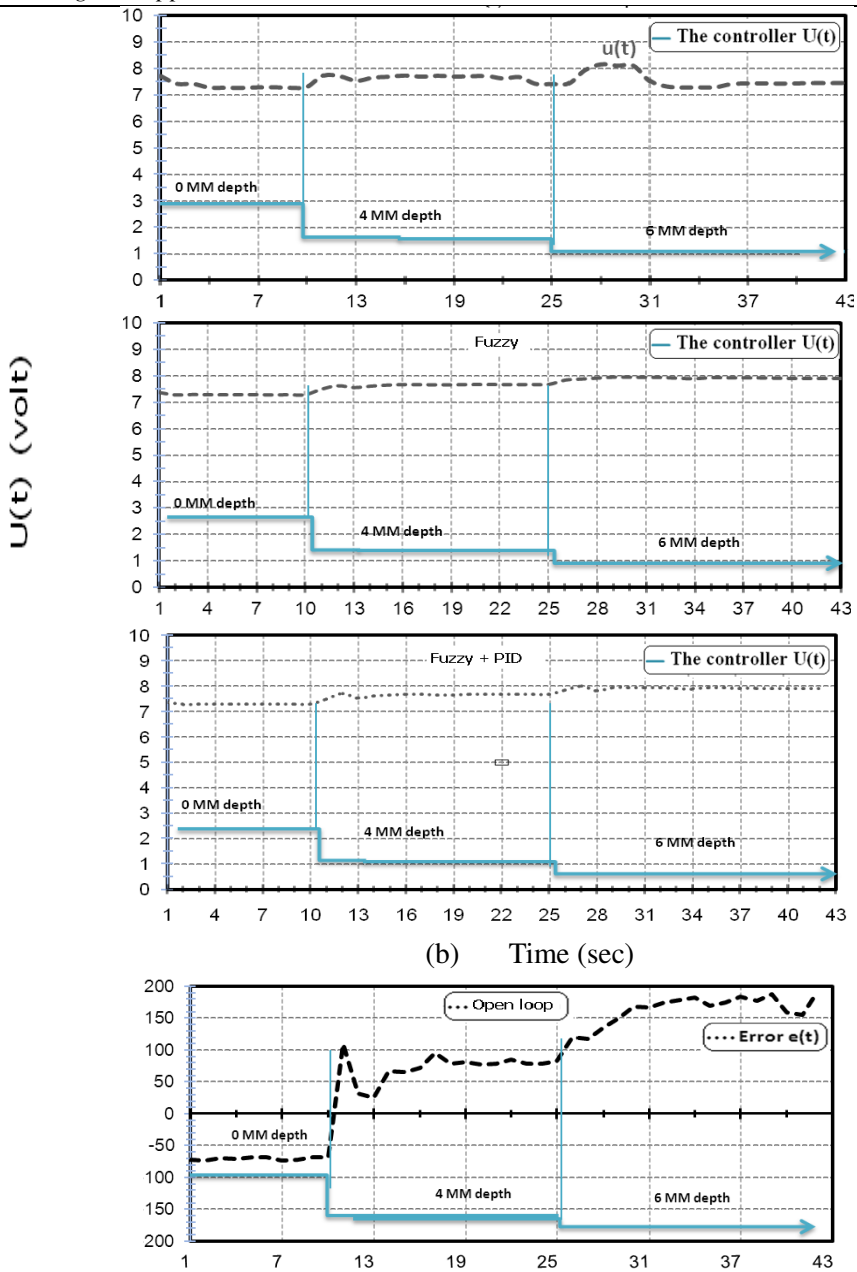
Fig. 11. The controller systems results under load (depths of cutting at 0, 2, 4 and 6mm)

Fig. 11 shows the system controller's responses of the CNC spindle motor under change of S_{ref} with change of cutting depth. Which in the case of the open loop, the motor is stopped at speed is 1000 rpm with cutting depth is 2mm in which the fuzzy – PID solves this problem.

Case 3

The controller systems are tested using one reference of speed set-point (2420 rpm) with different depths of cutting at 0 mm, 4mm and 6 mm.





(b) Time (sec)

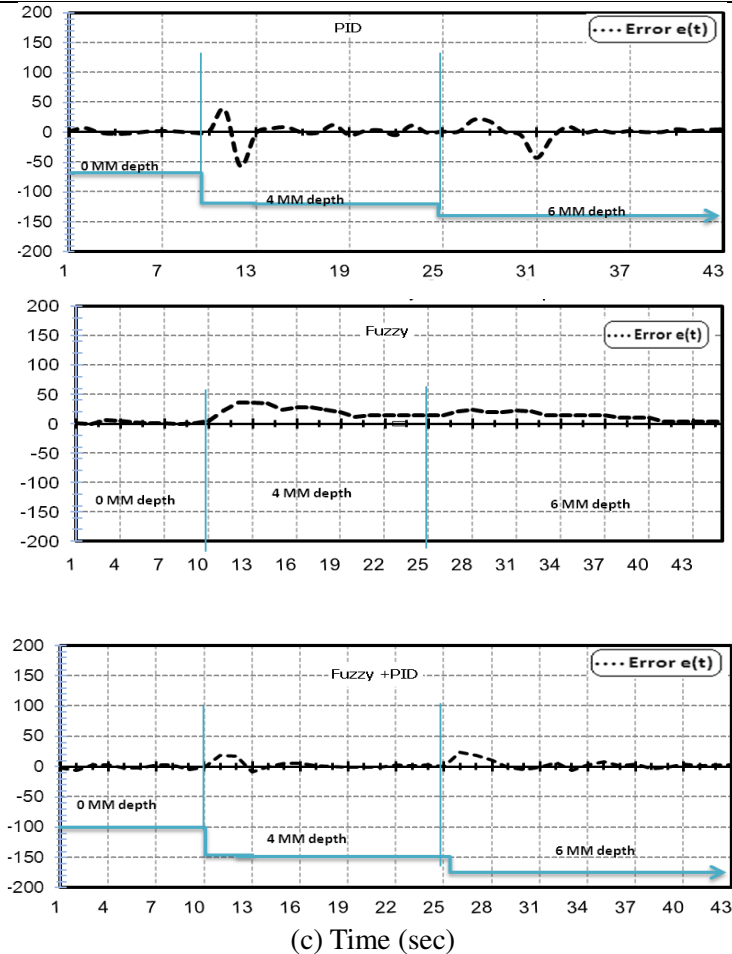


Fig. 12. Controller results under a load at depths 0, 4 and 6 mm (a) the speed set-point S_{ref} and the actual output speed S_{out} (b) The controller signal $U(t)$ (c) The error $e(t)$

Fig. 12 shows the open loop, PID, fuzzy and fuzzy -PID controller's responses of the CNC spindle motor under cutting depth changes. In the case of open loop, the RMS = 165.5 rpm and the E max (MAX error) = (max error/set-point) % is 7.89 %. The PID parameters $k_c=0.9$, $k_i=0.1$ and $k_d=0.001$ are tuned using auto tuning algorithm of PID ladder block s7 200, the details of who using this block is given [15]. The PID controller possesses good results in the steady state, where the actual output close to the desired output but there is an overshoot when the cutting depth changes from a step to another.

It is clear that the fuzzy controller has good results in the transient, and there is no overshoot in the output when the cutting depth changes from a step to another but it

results in a steady state error. The fuzzy - PID controller possess good results in the transient and in the steady state, the output of the system under different cutting depths are almost the same to the desired output which the RMS decrease to 8.3 rpm and MAX error (E max) is 0.99 %, as shown in Fig. 13. The RMS and MAX error (E max) are indicated in Table 3.

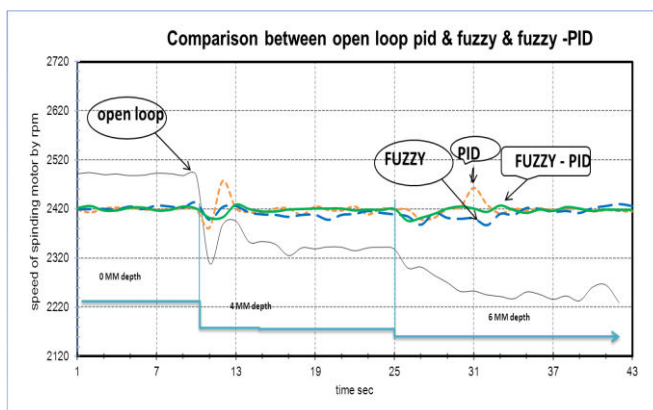


Fig.13. The results of open loop, PID, fuzzy and fuzzy-PID controller under load at depths 0,4 and 6 mm

Table 3.

Comparison between different types of controllers under load.

speed 2420 rpm	Cutting depth= 0 mm				Cutting depth= 4 mm				Cutting depth= 6 mm			
	Open loop	PID	fuzzy	Fuzzy- PID	Open loop	PID	Fuzzy	Fuzzy- PID	Open loop	PID	fuzzy	Fuzzy- PID
RMS (rpm)	70.53	2.68	5.2	3.39	76.76	17.9	12.6	6.76	165.5	13	14.95	8.3
E _{max} %	3.06	0.29	0.29	0.25	4.54	2.36	0.91	0.74	7.89	1.78	1.36	0.99

5. Conclusions

In this paper, the speed of a spindle motor in a CNC machine is controlled experimentally by means of three controllers, PID, fuzzy and fuzzy-PID. The system performance was evaluated using the three controllers under different depths, 0 mm, 4 mm and 6 mm. The results of the fuzzy-PID controller show good and significant improvement in the performance over a wide range of operating conditions.

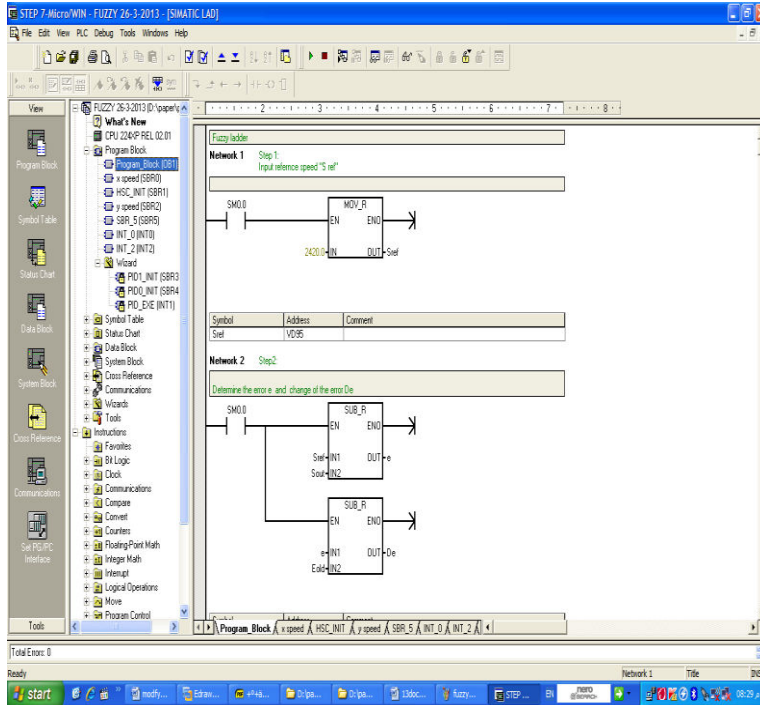
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[1] Appendix

The first page of fuzzy program ladder



تطبيق عملي لحاكم غيمي لتحكم في سرعة ماتور الحفر لمكينة خراطة اتوماتيك (CNC) بأستخدام وحدة التحكم المبرمجة المنطقية

الملخص العربي:

الهدف الرئيسي من هذا البحث هو التنفيذ العملي لحاكم للحفاظ علي سرعة موتور الحفر لمكينة الخراطة (CNC) تم تصميم حاكم غيمي بأستخدام وحدة التحكم المبرمجة المنطقية , وذلك نتجة تعرض موتور لعدم ثبات سرعته اثناء التشغيل وذلك لعدة اسباب منها تغير عمق الحفر او تغير سرعة التغذية او وجود شوائب في الخامة مما يؤثر علي سرعة موتور قد تصل الي ايقافه او تلفه او حرق هذا موتور ومما لاشك فيه يعود بالتأثير السلبي علي جودة المنتج , ففي هذا البحث تم تطبيق ثلاثة انظمة من انظمة التحكم العملية علي هذا موتور وهي (PID, FUZZY, FUZZY-PID) و تم اخذ النتائج العملية علي روتر تم تصميمه وتصنيعه كما هو موضح في البحث واخذت هذه النتائج العملية في حالات:

اولا في حالة عدم تطبيق احمال مع تغير السرعات وثانيا في حالة تطبيق احمال وتم تطبيقها في ثلاث حالات 1- ثبات الاحمال مع تغير السرعات 2- تغير الاحمال مع تغير السرعات 3- تغير الاحمال مع ثبات السرعات وكذلك تم اخذ النتائج في حالة عدم تطبيق اي من انظمة التحكم , وفي النهاية تم عمل مقارنات بينهم جميعا عن طريق الاشكال والحسابات والجداول وفي النهاية تم التوصية بافضل نظام تحكم وهو نظام (FUZZY_PID) تطبقا لافضل النتائج .