Employing Analogue and Digital Solenoid Hydraulic Valves in Position Control System

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Abstract

During the last decades, the rapid advances in hydraulic valves involving their driver electrical circuit have made a physical integration of electro-hydraulic system. Such hardware architecture is widely employed in many industrial applications due to their ability to provide speed, high force and direction control. These procedures have been accomplished with considerably greater power/weight ratio and with the help of some simple components.

Position control system with hydraulic actuators represents one of the most commonly technologies implemented in several industrial applications. The heart of this system is the hydraulic solenoid valve which can be subdivided into two categories, conventional and proportional valve. They are often packaged to provide both direction and flow control of hydraulic and can be classified as digital if the conventional hydraulic valve was implemented or analogue for proportional solenoid valves type.

The objective of this work is to build a prototype electro-hydraulic system constructed from solenoid directional control valves as well as a double acting single ended hydraulic cylinder with limiting position electrical switches to meet the demands of position control system. Simulation has been carried out within the mathematical software package (Matlab / Simulink) to simulate the performance of the electro hydraulic proportional system and the model of the solenoid proportional valve have been introduced to investigate the performance of the employed position control system.

Key word: Solenoid Hydraulic Valves, *Hydraulic cylinder, PID controller*

استخدام ملف الصمام الهيدروليكي (الكمي والرقمي) في منظومة السيطرة على التوقف

ألخلاصة

شهدت العقود الأخيرة حدوث تطورات سريعة وكبيرة في مجال الأنظمة الكهروهيدروليكية بما فيها الأنظمة الكهربائية المتعلقة بها حيث أصبحت ألتطبيقات ألصناعية ألتي تستخدم مثل هذه الأنظمة ضرورية وملائمة من ناحية دقة ألاستجابة ,سرعة ألأداء والحصول على قوة كبيرة.

إن العنصر الرئيسي في مثل هذا النوع من المنظومات الكهروهيدروليكية هو الصمام الكهروهيدروليكي ذو الملف الكهربائي والذي يمكن تقسيمه من ناحية مبدأ العمل في السيطرة على اتجاه وكمية الزيت المار من خلاله إلى نوعين , النوع الأول صمام اتجاهي عادي(يمكن أن يطلق عليه تسمية رقمي) والثاني صمام تناسبي اتجاهي (من النوع الكمي). إن الهدف في هذا العمل هو استخدام نظام كهر وهيدروليكي يعتمد على تقنية الصمام ألاتجاهي الهيدروليكي ذو الملف الكهربائي مع الأسطوانة الهيدروليكية ذات النهاية الواحدة والفعالية المزدوجة وبوجود محددات توقف كهر وميكانيكية لتحقيق نظام السيطرة على الحركة الخطية .

تم استخدام نظام المحاكاة في الحاسبة عن طريق البرنامج الرياضي (Matlab/Simulink) لتمثيل المنظومة الهيدروليكية التناسبية التي نحتوي على صمام تناسبي ذو ملف كهربائي للسيطرة على حركة المكبس للاسطوانة الهيدروليكية.

1. Introduction

The inherent advantages of hydraulic equipment were quickly appreciated by the mining and metallurgical industries, and introduction of hydraulic units proceeded with increasing momentum. They are characterized by their ability to impart large forces at high speeds and are used in many industrial motion systems. The basic part of this technology is the directional spool control valves, with its solenoids, provide the ideal interface for electrical controls. In Such demand close cooperation of electrical components are totally immersed in the hydraulic medium [1].

The general classification of the hydraulic valves may be divided into infinite position valves which can take any position between fully closed and fully open such as proportional valve and finite position valves which generally switches flow of hydraulic oil between different ports and can only be fully open or fully closed such as conventional valve. Consequently, proportional solenoid valves can be considered as analogue devices which provide more functionality and opportunities within the field of electro-hydraulics in contrast with solenoid directional valve which represent a digital type since the flow paths can be in only one of two states either on or off [2,3 and4].

Position control systems require linear movement can be achieved with variety of different technologies. The most commonly used technologies can be grouped into three categories; linear actuators, linear motors and precision positioning tables. Linear actuators can be hydraulic, pneumatic, or electromechanical. Hydraulic actuators provide a rectilinear movement realized by the stroke of a rod connected to a piston sliding inside the cylinder and each type has advantages and drawbacks, so their use depends on the application [5 and 6].

Theoretical and practical researches show that hydraulic control system using switching hydraulic valve can achieve high precision. It is a cheap scheme and can satisfy many purposes [7].

The suggested approach of position control system is based on implementation an electro-hydraulic model contains hydraulic cylinder steering by solenoid valve to realize the effect of utilize the solenoid valves in controller system.

The description of the employed controller system has been introduced in the second section while a detailed of the experimental work and the simulation of the electro-hydraulic proportional system is presented in the third and the fourth sections respectively followed by conclusion.

2. Position Control System

The general description of position control system under consideration can be subdivided into electro-hydraulic subsystem contains solenoid directional control hydraulic valve associated with an electrical controller board specifically designed for this purpose beside hydraulic actuator, in addition to position sensors where electro-mechanical limit switches are used to sense the required position of the rod of hydraulic cylinder as depicted in figure (1).
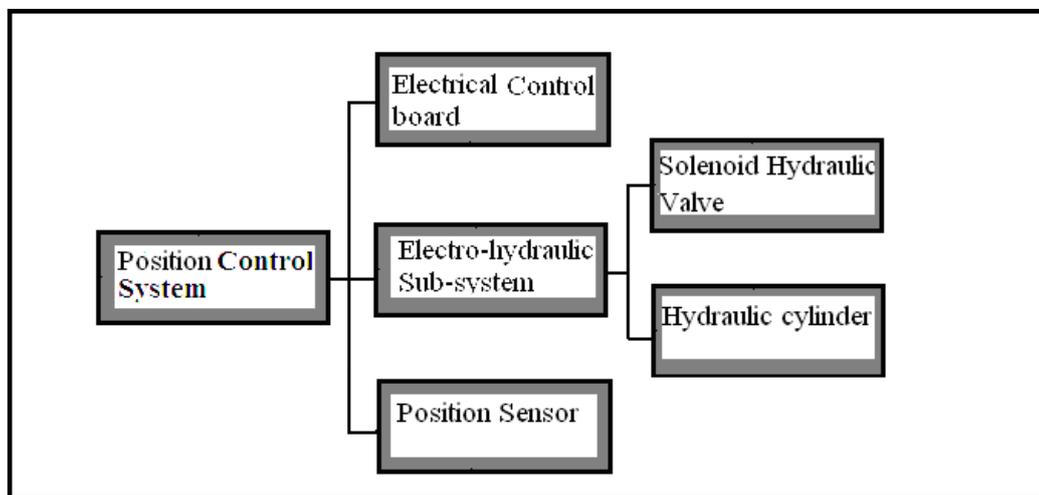
Figure (1) the Schematic Diagram of the Suggested Position Control System.

Solenoids are electro-mechanical interface devices that convert electrical input signal into an applied force [6].As the name indicates, a solenoid consists of a stationary iron frame, a coil, and a ferromagnetic plunger (armature) in the center of the coil as shown in figure (2a).
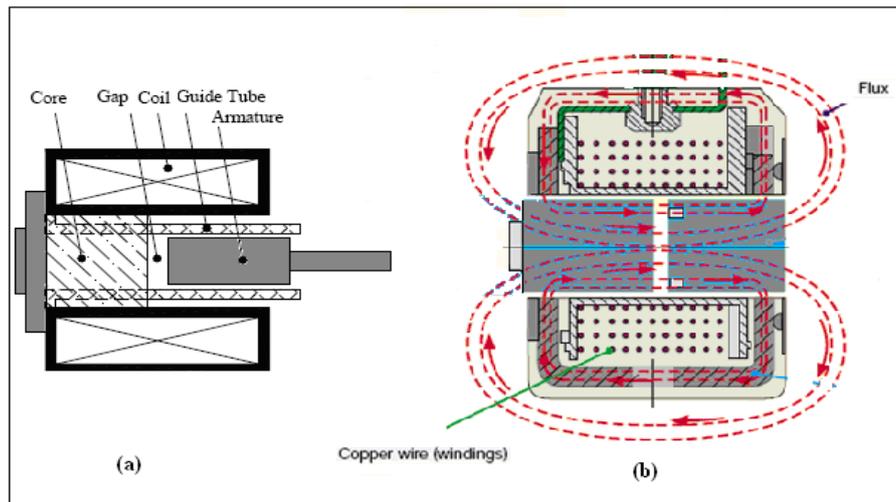
Figure (2) the Basic Solenoid Structure [8].

As the coil is energized, a magnetic field is induced inside the coil. The movable plunger moves to increase the flux linkage by closing the air gap between the plunger and the stationary frame, as shown in figure (2b). The flux density (B) follows the right-hand rule and the magnitude inside the coil is approximately [9].

$$B = \mu H \quad -------------------------------------(1)$$

And

$$H = \frac{NI}{L} \quad -----------------------------------(2)$$

Then

$$B = \mu \frac{NI}{L} \quad ---------------------------------(3)$$

Where

$$\mu = \mu_o \mu_r \quad -------------------------------------(4)$$

In hydraulic operations, electro-hydraulic valves use a solenoid to move the valve spool from one position to another and thereby altering the flow direction of hydraulic oil which moves towards the load. When a voltage is applied to the coil and electrical current flows, the coil builds up a magnetic field that attracts the piston and pulls it into the center of the coil. The voltage applied to the solenoid coil (V) is [9]

$$V = RI + \frac{d\lambda}{dt} \quad -----------------------------------(5)$$

The rate flow of energy can be obtained by multiplying equation (5) with i and can be written as

$$VI \ = \ RI^{\,2} \ + \ \frac{d\lambda}{dt}\, I \ \text{------------------------} (6)$$

Where VI represents the power provided by electric amplifier and RI^2 represents the power dissipated on the resistor (R) of the coil

And

$$R \ = \ \rho \, \frac{L}{A} \ \text{------------------------} (7)$$

The basic components of the solenoid hydraulic valves (conventional and proportional) in addition to the symbol of the solenoid valve are shown in figure (3).
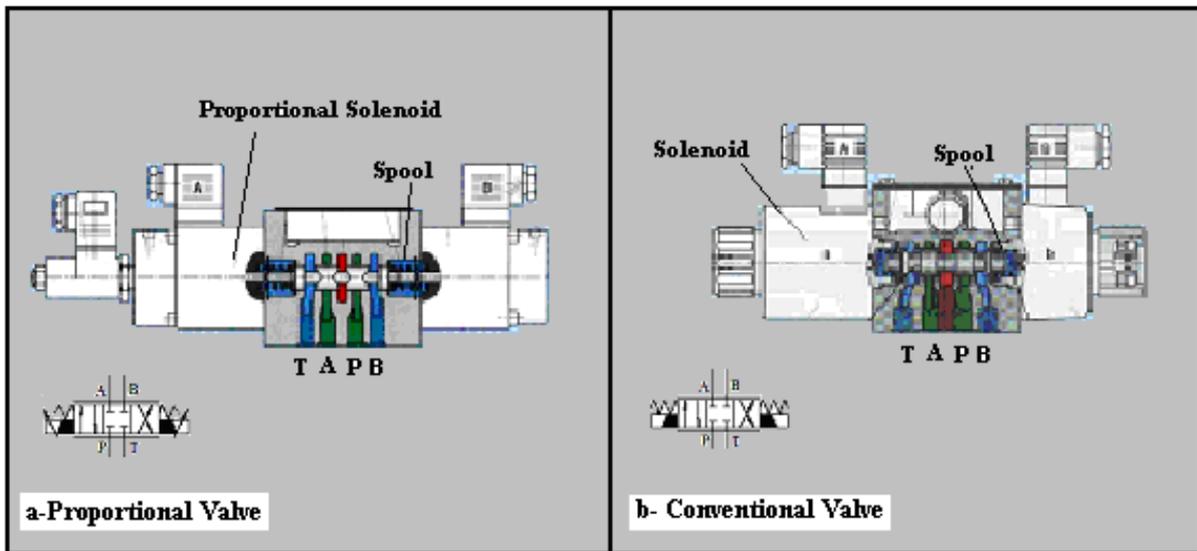
Figure (3) the Basic Component of Solenoid Valve (a-Proportional, b-Conventional) [10].

Where

- P represents the high pressure hydraulic port comes from the pump with the pressure supply line inlet and T the return line to the hydraulic tank.

- A and B represent hydraulic conserving port associated with the actuator connection port.

   As mentioned before the solenoid valve controls the direction of movement of the piston of the hydraulic cylinders throughout changing the direction of the flow of the hydraulic oil that pass from it towards a single ended hydraulic cylinder.

The hydraulic cylinder converts hydraulic energy into mechanical energy in the form of translational motion; it uses pressurized fluid to create a linear motion [6].The hydraulic fluid is pumped into one side of the cylinder under pressure, causing that side of the cylinder to expand, and advancing the piston. The fluid on the other side of the piston must be allowed to escape freely as shown in figure (4).
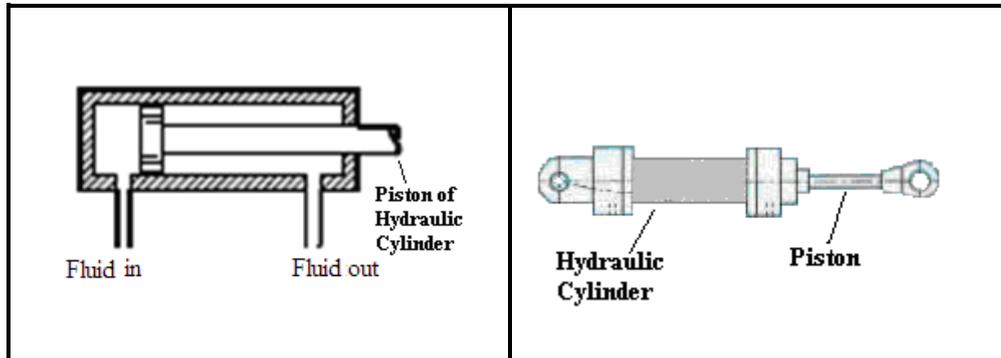

Figure (4) the Schematic Diagram of the Hydraulic Cylinder [7].

Both on/off and proportional solenoids have the same basic construction; a wire coil surrounds a ferromagnetic core with a paramagnetic guide tube and requires an electrical module that provides an electrical current source to the solenoid [8].

The difference between conventional electro hydraulic valves and proportional ones is the type of the input signal they have as an input command .The proportional hydraulic valve converts fluid pressure into motion in response to a signal rather than just electrical switching as shown in figure (5). The advantage of this step is greater flexibility in system design and operation as well as a decrease in fluid-power circuit complexity. Hence the electrical voltage can be infinitely adjusted and they respond to analog signals proportionally to its amplitude, instead of just being (on/off) as in conventional valve [11].
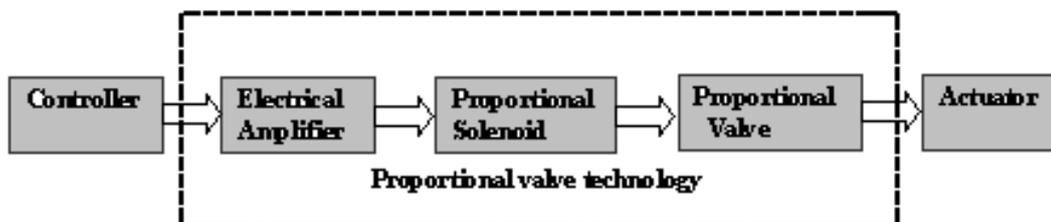

Figure (5) the Schematic Diagram of the Proportional Valve Technology [11].

3. Experimental work

   To realize the suggested position control system, an electro-hydraulic module utilizing solenoid valve and hydraulic actuators was employed as shown in figure (6). Primarily the piston of hydraulic cylinder was actuated by solenoid valve and is shifted either to the right or to the left depending on which solenoid is energized.

   The position sensors which are fixed on the end of the stroke detect the position of the hydraulic rod and send a feedback signal to the electrical control board which indicates that the piston reached the desired point. The valve switching command is coming from the electrical control board.
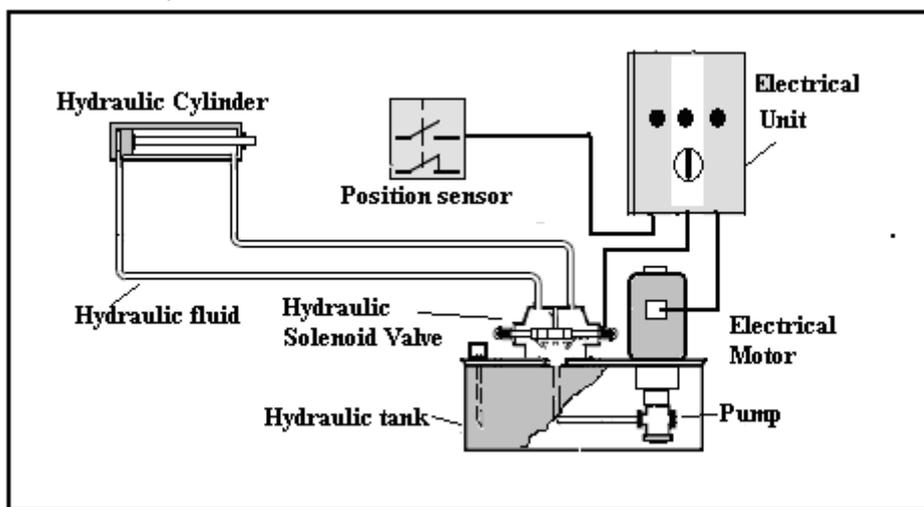
*Figure (6) the Block Diagram of the Employed Position Control System.*

  The heart of the hydraulic control unit under consideration is a single-stage, four-way and three-position, directional spool control valves, either conventional (digital) or proportional (analogue) valve linked to their associated electrical board via electrical solenoids where a DC voltage solenoid valve was selected.

   The hydraulic power unit of the system comprises all the devices for effecting the movements or actions and consists of hydraulic pump, relief valve, pressure gauge, and hydraulic tank in addition to hydraulic cylinder with a 360 mm stroke of the piston as shown in figure(7).
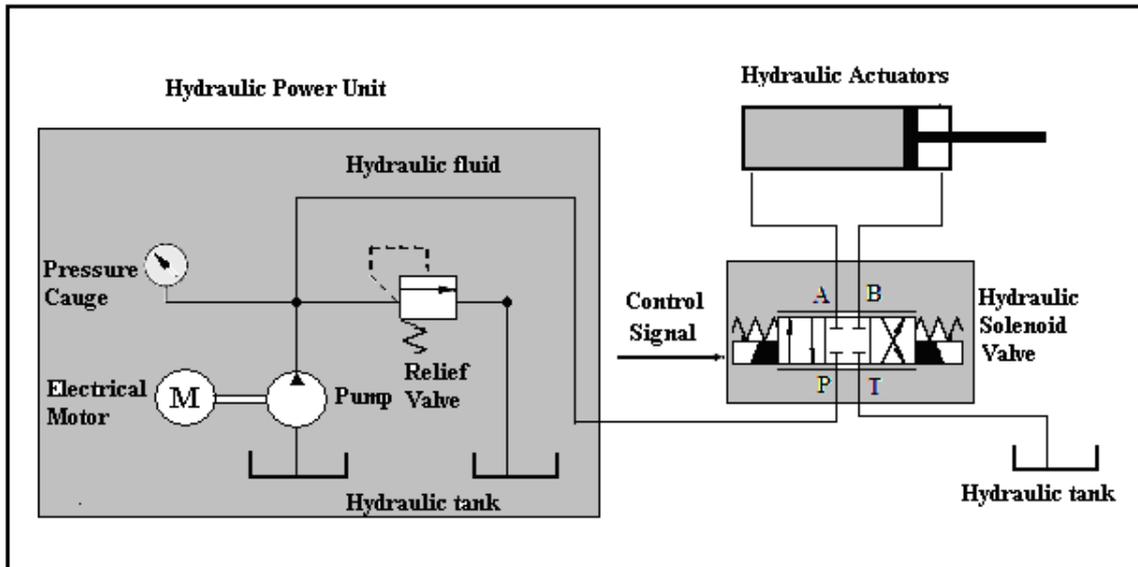
Figure (7) the Electro-hydraulic Circuit of the Position Control System.

The hydraulic valve and cylinder that utilized in position control system are shown in figure (8).
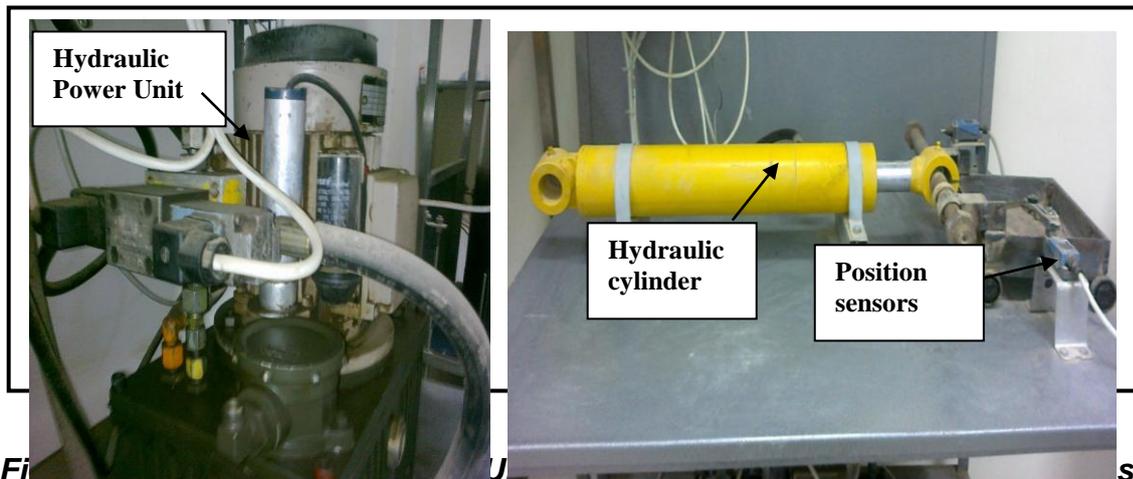
Figure (8) the Hydraulic Power Unit, Hydraulic Cylinder and Position Sensors.

In conventional valve model the spool of the direction valve is either fully opened or fully closed. Hence; two levels of electrical voltage signals are required to supply the solenoid valve. The electrical control unit for the directional valve is shown in figure (9) while the electrical driver circuit for the conventional valve is shown in figure (10).

Figure (9) the Controller Unit of the Solenoid Directional Valve.
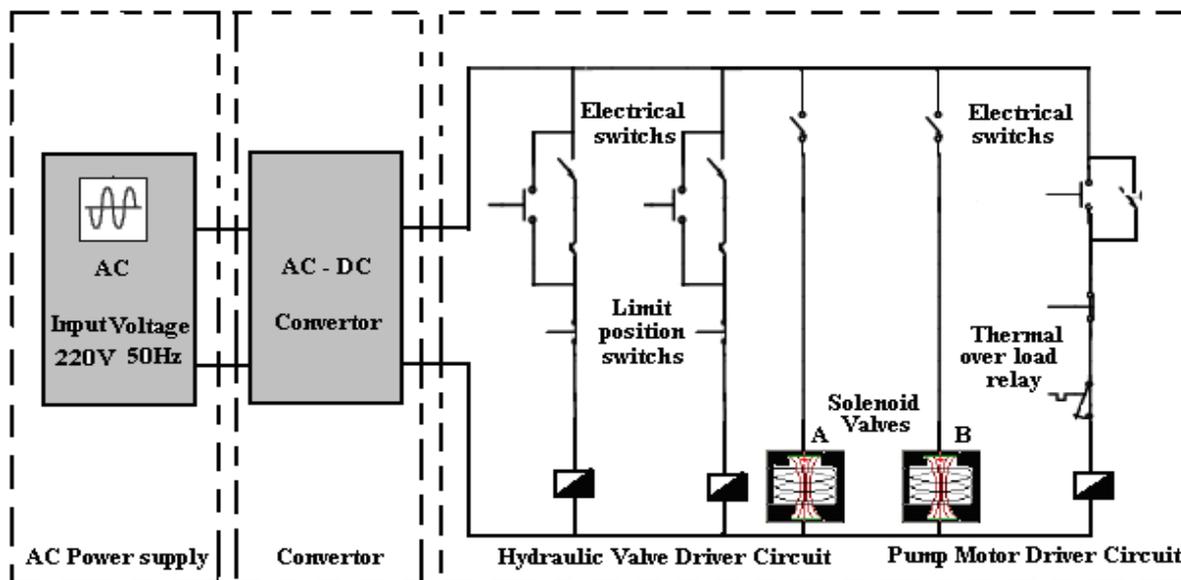
Figure (10) the Electrical Directional Model of the Position Control System.
[Introduced by Researcher]

In case of the proportional solenoid valve the electrical controller module is quite difference to that in directional valve. It consists of a controller unit and an amplifier electronic card specially manufactured for each type of solenoid [11]. Consequentially several modules of controller unit can be utilized to actuate the proportional solenoid valve and to steering the hydraulic cylinder. The suggestion position control system may be subdivided into position sensor, controller unit and proportional electrohydraulic subsystem to acquire the performance of the proportional solenoid valve as shown in figure (11).
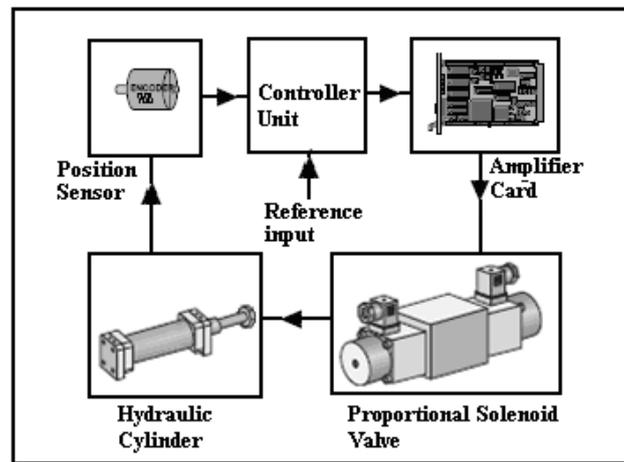
Figure (11) the Controller Model of the Proportional Solenoid Valve.

The controller unit consists of the microcontroller and its interfacing circuit that contains analogue to digital converter(A/D) and digital to analogue converter(D/A) circuits where AD 574 and DA 800 chip set are used as shown in figures (12) and (13) respectively.
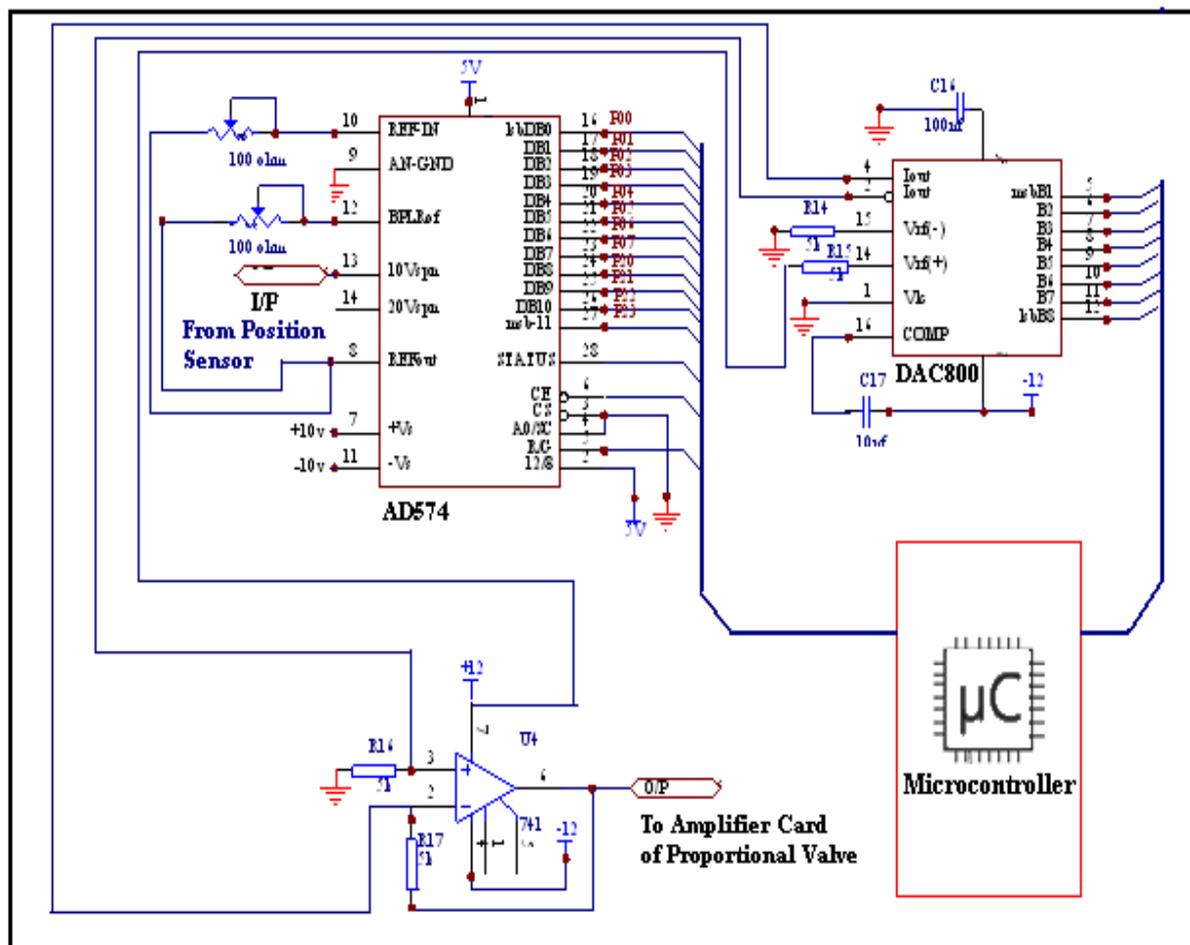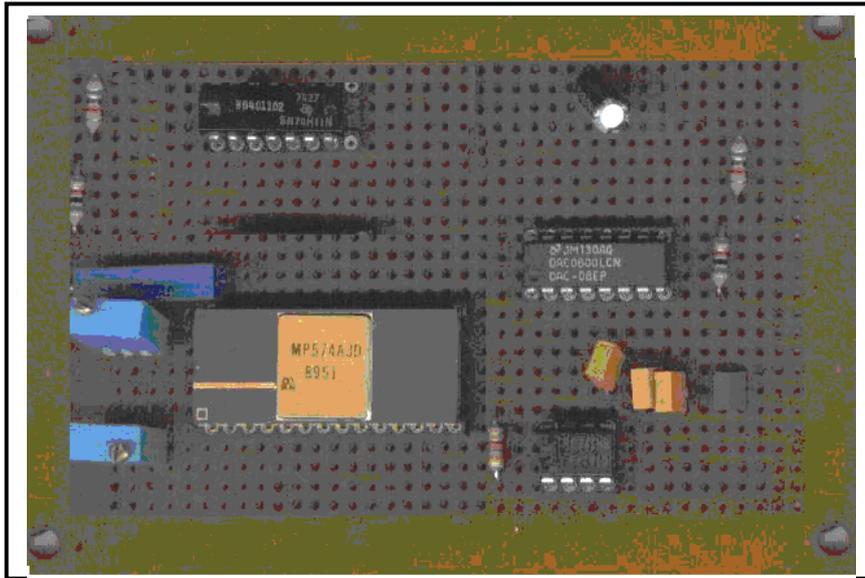

*Figure (12) the Microcontroller and Interfacing Circuit for the Position Control System.*

*Figure (13) the Analogue to Digital (A/D) and Digital to Analogue (D/A) Convertor
Circuit.*
[Introduced by Researcher]

The I/O and memory subsystems contained in microcontroller specializes this device as an entire computer manufactured on a single chip and it can be interfaced with hardware and control functions of the applications. Developing such a system requires building a software part running on the microcontroller as well as a hardware part consisting of mechanical and electronic components [12].

The Position sensors detect the position of the rod of hydraulic cylinder and send a voltage signal to controller unit interfacing circuit .Microcontroller takes in the sensor readings, and supplies the electronic card of the hydraulic proportional valve with appropriate voltage signal.

The varying voltage, which applied to the solenoid of the proportional valve, changes the flow of the hydraulic fluid that passes to the hydraulic cylinders and stop the rod at the required position. The electrical amplifier card of the proportional solenoid valve is used to amplify an analogue input signal and converted into an electrical current. This unit also included Proportional, Integral and Derivative (PID) controller such that the solenoid can be actuated the proportional valves to provide a smooth and continuous variation in flow of hydraulic fluid in response to an electrical input signal as shown in figure(14) [6].
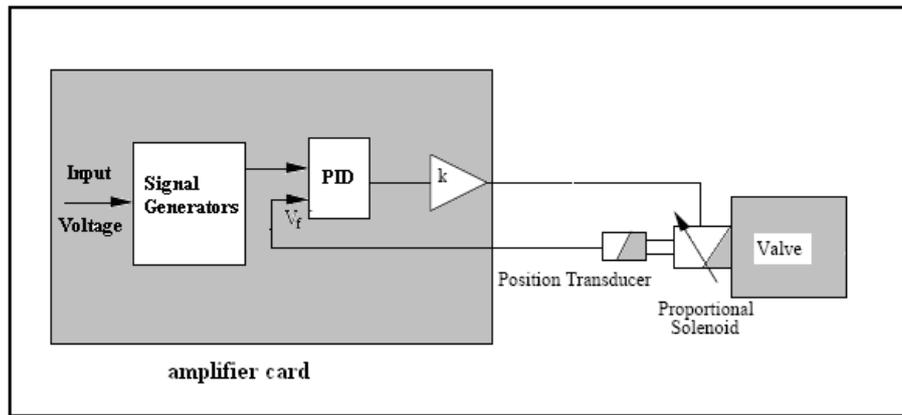
Figure (14) the Schematic Diagram of the Amplifier Card of the Proportional Solenoid Valve [6].

PID controller is one of the earlier control strategies, its implementation was in pneumatic devices, vacuum and solid state analogue electronics before arriving at today's digital implementation of microprocessors.

The PID controller used a simple algorithm as follows [13]:-

$$G(S) = (Kp + \frac{Ki}{s} + Kds) \ - (8)$$

Where (K_P, Ki and K_d) represents respectively the value of proportional, integral and derivative constants of the PID controller.

The experimental works have been done in the hydraulic laboratory of the mechanical department in the engineering college of the Al-Mustansiriyah University and the prototype test rig of the electro-hydraulic model for the position control system utilizing directional control solenoid valve is shown in figure (15).
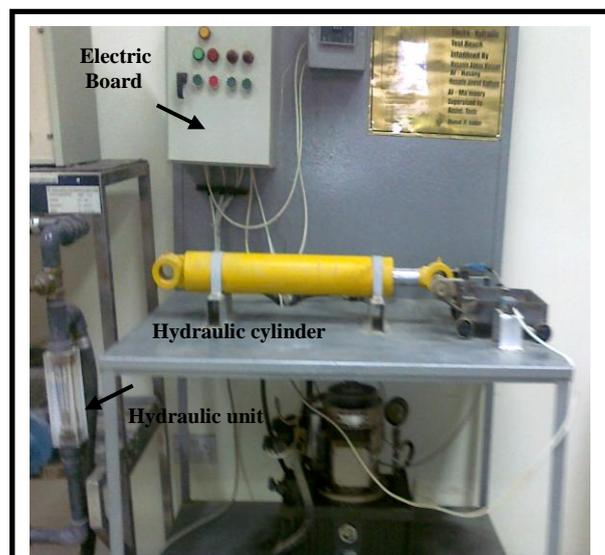
Figure (15) the Employed Electro-Hydraulic Position Control System.

4. Simulation Process

The proposed electro-hydraulic actuating model of position control system consists of proportional control valve and hydraulic cylinder, as well as valve controller unit as shown in figure (16).
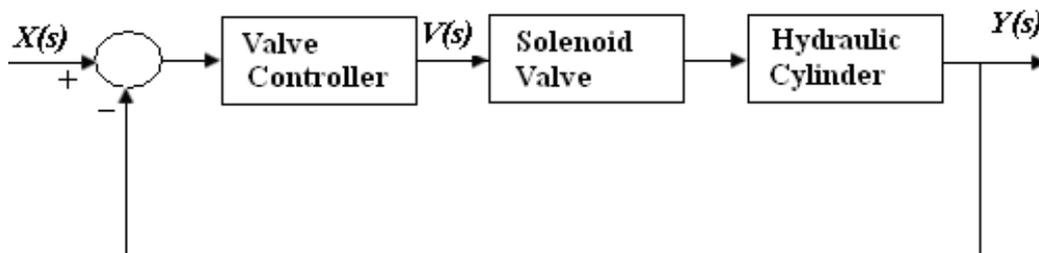

Figure (16) the Block Diagram of the Proportional Actuating System.

Where $X(s)$ represent the desired position of the cylinder, and the output $Y(s)$ may represent the actual position of the cylinder while $V(s)$ is the input voltage signal required to actuate the solenoid proportional valve. Simulation process has been carried out to investigate the performance of the position control system and the electrohydraulic proportional model is introduced within the MATLAB/ SIMULINK as shown in figure (17).

Hydraulic blockset of the Matlab software package provides a collection of hydraulic components beside a graphical user interface for building and analyzing system model and the results can be shown easily and quickly on the display [14].
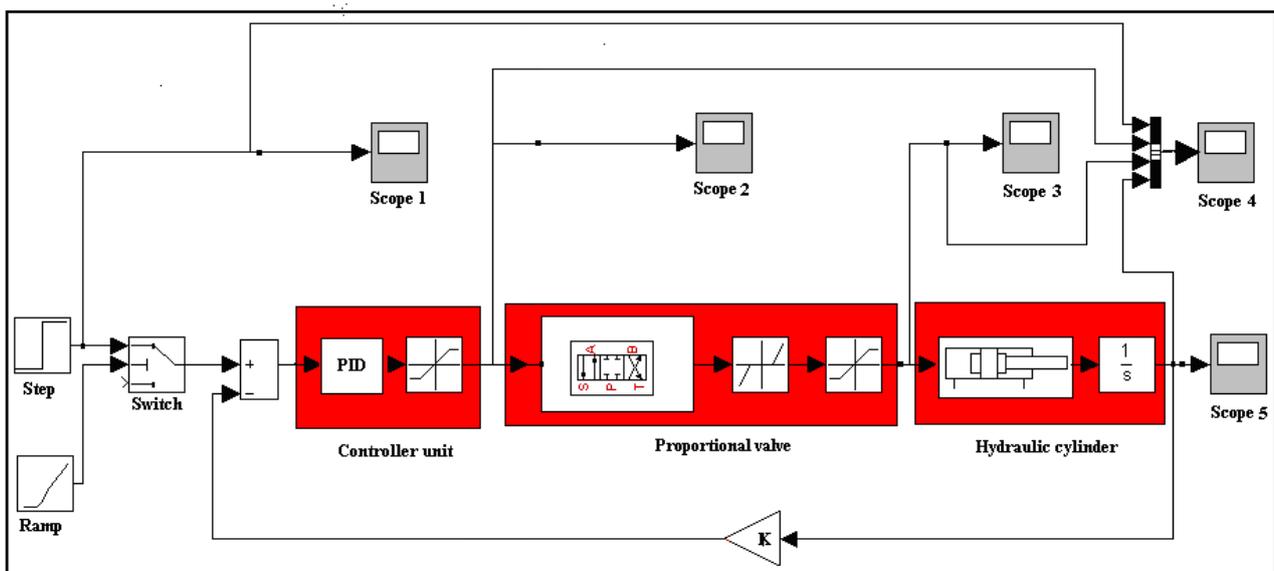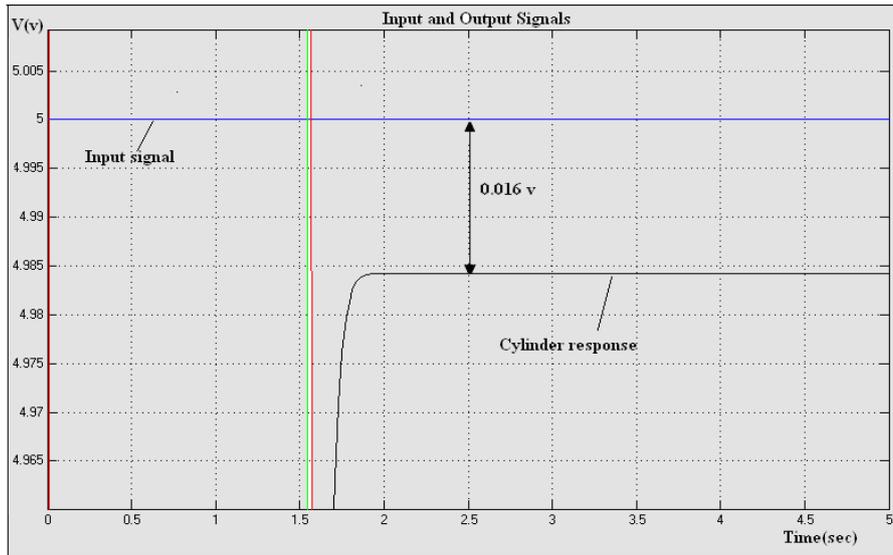

Figure (17) the Electro-Hydraulic Proportional Model [15].

In this model the PID controller was implemented in the valve control unit and the performance of the system such as rise time, overshoot, settling time and steady state error can be improved by tuning the value of *Kp*, *Ki* and *Kd* of the PID controller. The actuators, valve and cylinder were modeled using their parameters provided by the manufacturer and the simulated results for the valve and the cylinder response in the employed model of the position control system are shown in figure (18).
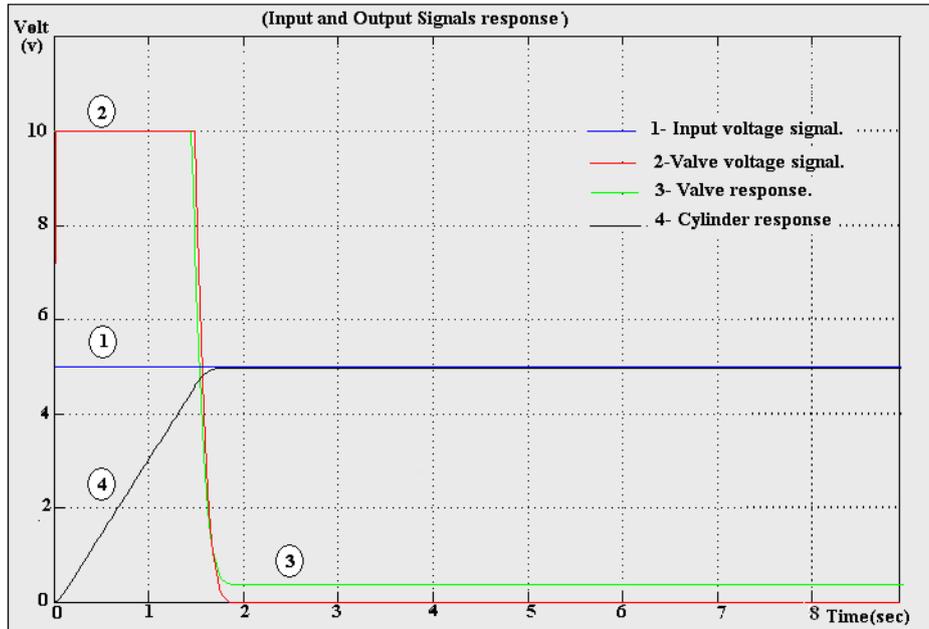

Figure (18) the Response of the Proportional Solenoid Valve and the Hydraulic Cylinder.
(Kp=20, Ki=0.01, Kd =0.1)

The voltage applied to the solenoid valve is being in the range of ±10 volts and it can be noticed that the valve voltage is saturated for about 1.5 seconds. The cylinder reached the desired point with steady state error equal to (0.016 v) with respect to step reference input signal as shown in figure (19).

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Figure (19) the Steady State Error of the Hydraulic Cylinder Response.

The simulation computer program of the electro-hydraulic proportional system could be run at different values of the *Kp*, *Ki* and *Kd* gains to predict the effect of tuning the PID controller on the performance of the hydraulic cylinder. Figure (20) shows that the system is being unstable when (*Kp=Kd*=0) while figure (21) shows that the hydraulic cylinder has no response when derivative controller was implemented only and (*Kp=Ki*=0).
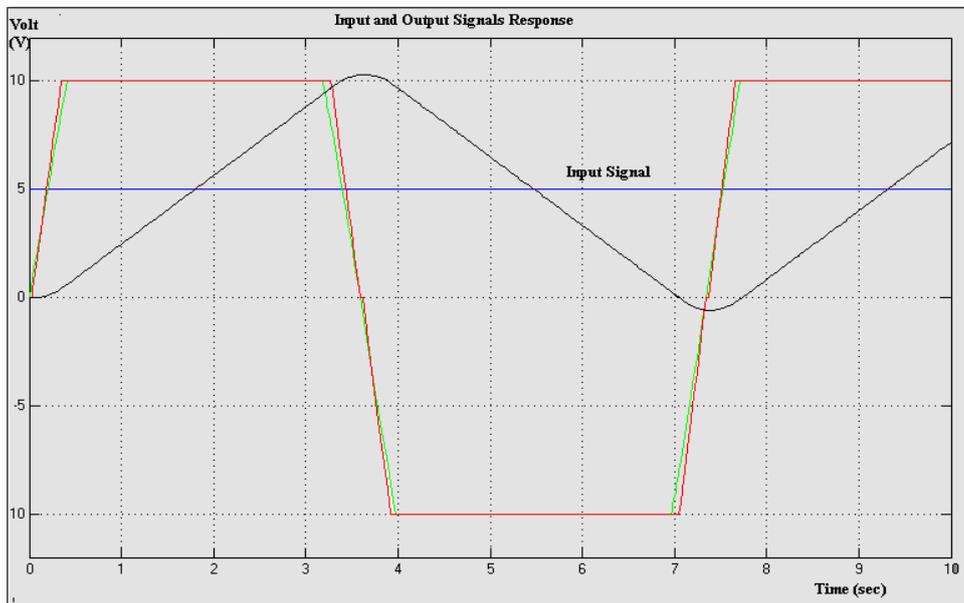
Figure (20) the Hydraulic Cylinder Response (Kp= Kd =0.0).
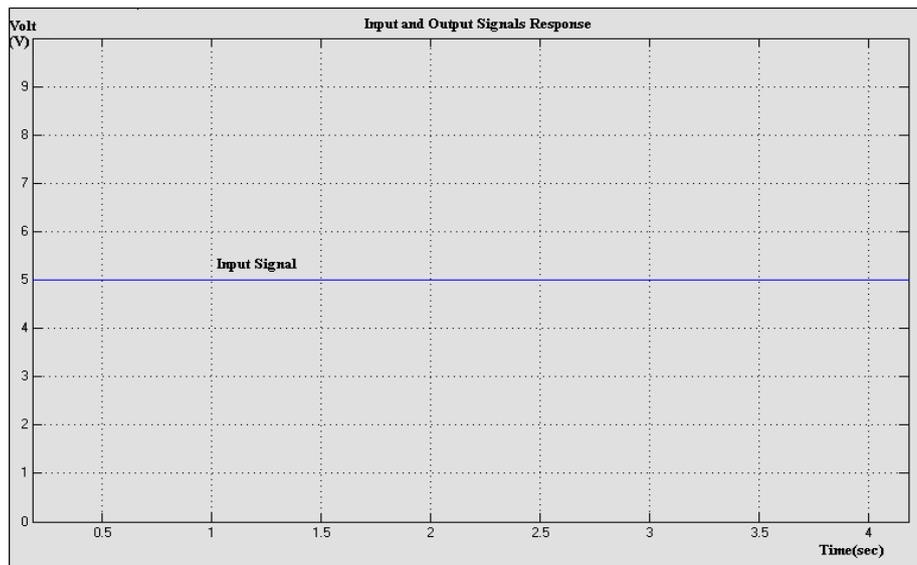
Figure (21) the Hydraulic Cylinder Response (Kp= Ki =0.0).

5. Conclusions

The following remarks can be concluded:-

i. This work is based on implementation an electrically actuating solenoid directional control valve in a position control of hydraulic cylinder and the prototype was built in hydraulic lab. The accuracy of such a system determines the kind of the employed hydraulic valve and according to the required accuracy the hydraulic control valves can be selected.

ii. A simulation process has been performed to investigate the performance of the electrohydraulic proportional system. The best results were obtained involving the proportional, integral and derivative gains of the PID controller.

iii. The proportional solenoid valve provides more functionality and opportunities within the field of electro-hydraulic position control system and it can be selected for fast response and high accuracy. The process is carried out by actuating each solenoid while the position sensors stop the rod of hydraulic cylinder in the set point .The error in results could be due to the backlash of hydraulic shaft and converting analogue signal to binary.

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Notations

A   : the cross sectional area of the solenoid conductor wire (m^2).

B   : the magnetic flux density (in tesla [T] or (Wb/m^2)).

H   : the magnetic flux intensity (AT/m).

I   : the electrical current through the winding of the coil (A).

L   : the length of the coil of the solenoid valve (m).

P   : the specific resistivity of the conductor wire of the solenoid (Ω-m).

R   : the resistance of the solenoid (Ω).

Wb   : the unit of measurement for magnetic flux.

μ : the permeability of the material inside the coil (Wb/Am).

μ_r : the relative permeability.

μ_o : the permeability for free space (Wb/Am).

λ : the flux linkage of the coil (Wb).