Investigation of Energy Efficiency of Servo Motor Drive Hybrid Press Brake System: A Comparative Study with a Traditional Application

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Received 26 October, 2022; Revised 15 November, 2022; Accepted 15 November, 2022
Available online 15 November, 2022 at www.atlas-tjes.org, doi: 10.22545/2022/00214

In this study, an energy consumption comparison of the conventional valve-controlled and variable speed pump-controlled press brake systems was carried out experimentally. The envisaged studies have been applied to the 80-ton press brake. In conventional valve-controlled systems, the flow rate is adjusted with the help of a proportional valve while the required flow in the variable-speed pump-controlled system is provided by changing the pump speed with using of a servo motor. From the results obtained, it has been seen that 54% energy saving can be achieved in 100 cycles, and the amount of oil used has also been reduced.

Keywords: Energy efficiency, hydraulic system, pump control, valve control, press brake.

1 Introduction

Hydraulic systems are used widely in industry because of their high power density, energy storage capability, safe against overloads, shock-free, ability to keep force and torque constant, and at the same time being a closed and protected system [1]. Pressing and cutting presses, plastic injection machines, robots, spacecraft, airplanes, and machine tools are some places where hydraulic systems are used.

The valves used for controlling the hydraulic actuators change the fluid flow areas to provide appropriate control. Due to these area changes during the hydraulic fluid flow in the valves, high-pressure losses and heat generation problems occur. These situations cause energy losses and also heat generation in the system creating the need for cooling, increasing costs, and shortening the service life of the hydraulic fluid due to viscosity changes. Today, due to the difficulties and costs of obtaining energy, it is expected that the systems to be energy efficient and reach high values in terms of performance. For this reason, researchers have done many studies to increase efficiency and reduce costs in hydraulic systems by eliminating the inefficiency caused by energy losses in valve-controlled systems and the need for cooling due to heat generation.

Shang (2004) used a pump-controlled hydraulic circuit with higher efficiency compared to valve-controlled systems to increase the performance of the energy-efficient hydraulic system. PID control algorithm was used as the controller, and the rotational speed overshoot of the pump is reduced by 50%, thus reducing the flow fluctuation [2]. Gao et al. (2005) analyzed the mechanism of the variable displacement pump and the driving force of this swashplate and designed a new variable displacement mechanism with a DC servo motor. With the new design, the displacement change in the pump has been achieved faster, the pump structure has been simplified, and a solution has been provided to the contamination problem encountered in traditional pump systems [3]. Çalışkan et al. (2008) carried out a position control study of the servo-hydraulic system with the variable speed pump. As a result of the study, it has been determined that in valve-controlled systems, there is a loss of 42.3% in the pressure valve and 19.2% in the proportional directional valve. As an alternative, a pump-controlled hydraulic circuit has been suggested. It was stated that the heat loss was reduced, and the position control could be done as precisely as the valve-controlled systems [4]. Çelikayar (2008) carried out a study of servo-driven pump control systems and energy saving. A servo motor and fixed displacement piston hydraulic pump were used. 25% energy saving was achieved by applying the designed system in the plastic injection machine [5]. In the study of Deng (2016), a double-way pump was connected to a single motor for energy saving. At the same time, it is aimed to provide energy to be used again in the supply line, with the pump operating in a hydraulic motor mode in the return line by providing reverse operation in the system. According to the test results, 93% energy efficiency and a 67% increase in volumetric efficiency were achieved [6]. Li et al. (2017) investigated an analysis of the double-actuated energy-saving system for the hydraulic press. The system is modeled in which the return line of one of the actuators is synchronized with the feed line of the second actuator. When the experimental results of the study are analyzed, 20.61% energy savings and 26.09% efficiency increase due to the improvements in the realization time of the processes were obtained [7].

In addition to various studies on the design criteria and efficiency analysis in hydraulic systems, various applications have been made for controlling hydraulic power systems using classical and modern control techniques such as artificial neural networks, fuzzy control, and PID control [8-15]. In addition, different studies examined the effect of valve characteristics on the system dynamics, and the energy flows [16-20]. It can be said that with the increase in energy demand in the world, the concept of energy recovery, energy efficiency, and sustainability has gained importance, and studies on these issues have increased in recent years [22-25].

In this study, the energy efficiency of the hydraulic system used in the press brake system to form sheet metal materials by pressing was discussed. Due to the high energy losses in the study, a pump-controlled system was proposed instead of a valve-controlled system. According to the system requirements, the components of the system were selected, experimental studies were carried out on the bench and the analysis results were evaluated. The position, speed, pressure, energy consumed, and instant hydraulic fluid amount of the piston in the system was investigated. As a result of the study, the efficiency and cost values of the pump-controlled system were compared with the classical valve-controlled system.

2 Methodology

2.1 Experimental Equipment of Press Brake System

Press brakes are machines defined as C-Type presses used for bending sheet metal and composite materials. In Figure 1, a press brake and its main components, in addition to these, the experimental setup is shown schematically. The Control unit, hydraulic actuators, upper jaw, upper mold, lower mold, lower jaw, and side safety devices are the main components of the system. In order to obtain the desired form during the bending process, lower mold and upper mold are used according to the material type and the desired shape.

Controlled movement of the upper jaw is required for the desired bending operations. The one-cycle loop of an example operation is shown in Figure 2.

During the pressing process, the piston, which is the hydraulic actuating element, moves 0.5 m. The amount of hydraulic oil required by the system is 0.24 lt. However, in the classical valve-controlled system,

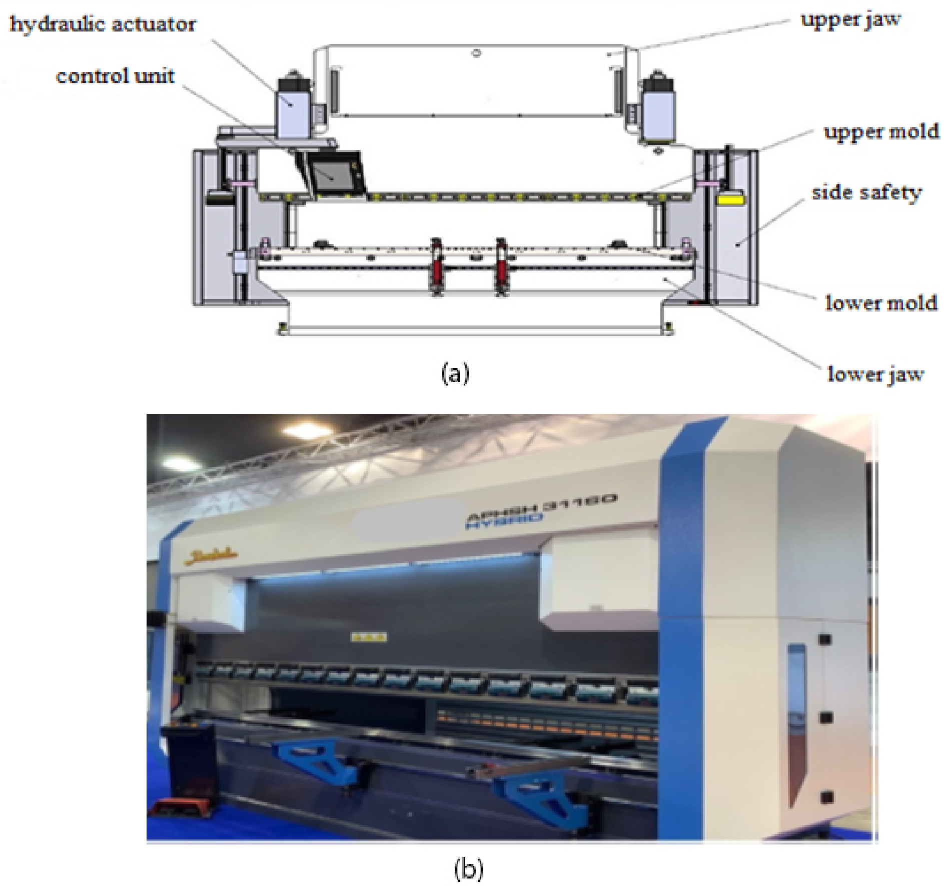

Figure 1: *(a) Schematic representation of the press brake and its main components, (b) Photo of the press brake system.*

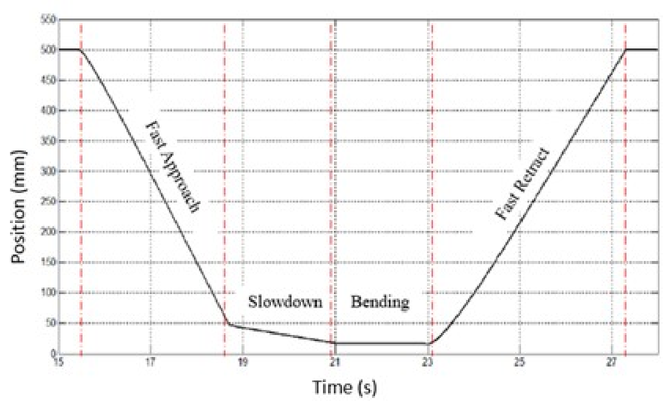

Figure 2: *Working stages of press brake system.*

since the engine rotates at 1500 rpm, there are 34.5 liters of hydraulic oil in the system, and an extra 34.26 liters of oil is sent to the hydraulic tank under pressure. This indicates the amount of heat and the resulting extra wasted energy. In other states, as here, the oil is under pressure and at the same time, the required position control is obtained by reducing the valve flow areas in the proportional valves. In this case, an excessive amount of heat is generated in the system and at the same time, the oil viscosity value changes over time. Therefore, due to the change in the structure of the oil, the service life is reduced. Changing the deteriorated oil in an average of six months according to the catalog values shows how important this situation is for environmental pollution.

Due to these negativities, in this study, the realization of position control with pump control in hydraulic systems has been examined. Basically, with the pump-controlled system, the oil was supplied to the system as much as desired [1]. During this process, a high-efficiency fixed displacement pump and a servo motor were used, which can rotate in both directions. Pressurized oil as much as the system needs were provided by adjusting the speed of the servo motor according to the position of the hydraulic actuator measured with the linear transducer. With the double-way rotational pump, the circulation of extra oil and heat losses in the system were prevented. At the same time, the amount of oil needed was reduced and the service life of the oil was increased. The hydraulic circuit of the proposed system can be seen in Figure 3.

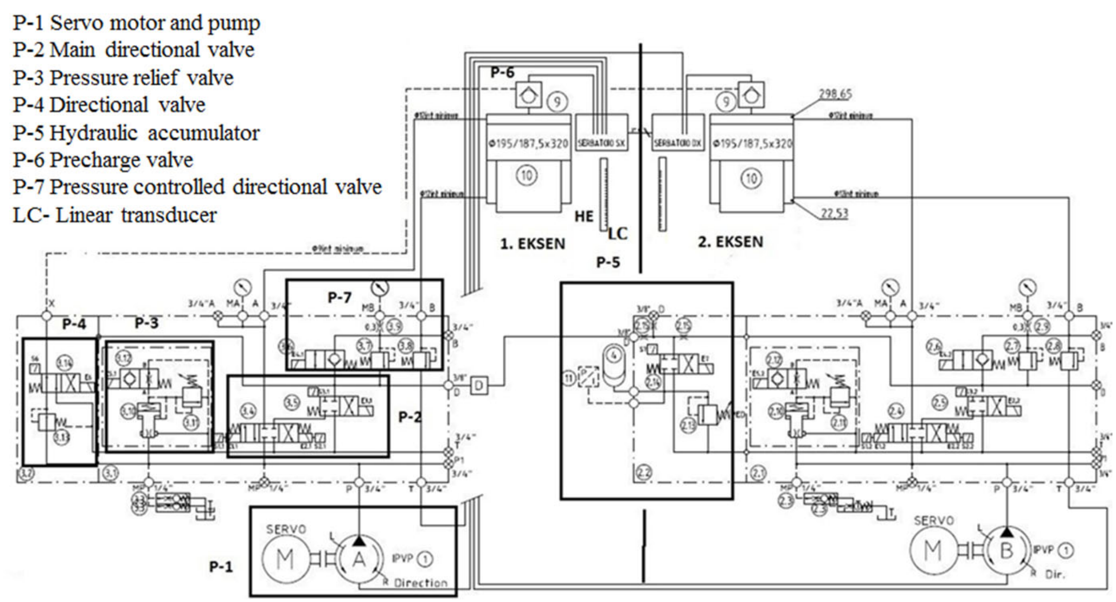

Figure 3: *Hydraulic circuit of proposed pump-controlled system.*

In the designed system, the P-1 component consists of a servo motor and a bidirectional fixed displacement pump. P-2 is the main directional valve, P-3 is the pressure relief valves, P-4 is the directional valve, P-5 is the hydraulic accumulator and pressure relief valve, and finally, P-6 is the pre-charge valve. P-2 is valves that operate as on-off and only used to direct the oil. The amount of oil in the system and the adjustment of the pressure are carried out by the pump. P-4 directional and pressure relief valves are primarily used for pressure relief. P-3 activates in case of overpressure. P-5 hydraulic accumulator and pressure relief valves are used to return the generated energy to the system by accumulating it in the hydraulic accumulator. At the same time, a pressure relief valve is used in this part to prevent damage to the system in case of excessive pressure or excessive oil flow. The P-6 pre-charge valve performs oil suction from the tank by working based on vacuum during the downward movement in the cylinder. The hydraulic cylinder represents the working part of the designed electro-hydraulic system. The P-7 is a directional valve that works with pressure relief valves.

2.2 Sizing of the Pump-Controlled System

As with most processes in the industry, there are certain requirements from a press brake system used for bending sheet metals in order to perform the process appropriately. The requirements related to the process discussed in this study are given in Table 1.

Table 1. Desired requirements in bending process

Requirements	Symbol	Value	Units
Hydraulic actuator force	F_{HA}	80	ton
System pressure	P_{system}	270	bar
Downward velocity of hydraulic actuator	V_{down}	0,15	m/s
Pressing velocity of hydraulic actuator	V_{press}	0,01	m/s
Upward velocity of hydraulic actuator	V_{up}	0,15	m/s
Displacement of hydraulic actuator	L	0,5	m

According to the requirements in Table 1, the hydraulic cylinder cross-sectional area can be found with the formula below depending on the hydraulic actuator force value and the system pressure;

$$F_{HA} = \Delta P_{system} \times A_{cylinder} \tag{1}$$

Based on this equation, the cylinder piston diameter is found as 0,192 (m), but this value is determined as 0,195 (m) in order to choose from standard products. The required flow rate during the up and down movement of the cylinder can be calculated by the following equation;

$$Q_{1,2} = V_{1,2} \times A_{piston} \tag{2}$$

Where $Q_{1,2}$ (lt/min) are flow rate required for up and down movement and $V_{1,2}$ (m/sn) are velocity required for up and down movement. Accordingly, it is found as $Q_{1,2} = 4,48.10^{-3}(m^3/s) = 268,7$ (lt/min). Thus, the required pre-charge valve capacity for the system is determined. The pre-charge valve with a maximum 500 lt/min flow capacity was selected for the pre-charging process. When the flow required during the pressing process is calculated with equation (3) for the desired pressing speed, Q_{press} =17,91 (lt/min) is found. The power of the electric motor, which will provide torque to the pump, can be calculated by the following equation;

$$P = \frac{Q \times \Delta P_{system}}{\eta_v \times 600} \tag{3}$$

Where, P (kW) represents the power of the electric motor, η_v (-) represents the motor efficiency value that usually taken 0,95. Accordingly, the required electric motor power is calculated as 9,6 kW. In this case, the sizing process of the basic elements of a hydraulic power transmission system is completed. The dimensioned basic elements can be seen in Figure 4.

3 Results and Discussion

3.1 Test Results for One Loop (Pressure, Flow Rate and Velocity Variations)

In this section, the proposed pump-controlled system is examined in terms of the flow rate of the fluid circulating in the system and the power values of the process steps. The results of the experimental validation studies that carried out were analyzed. According to the results of the equations given in the

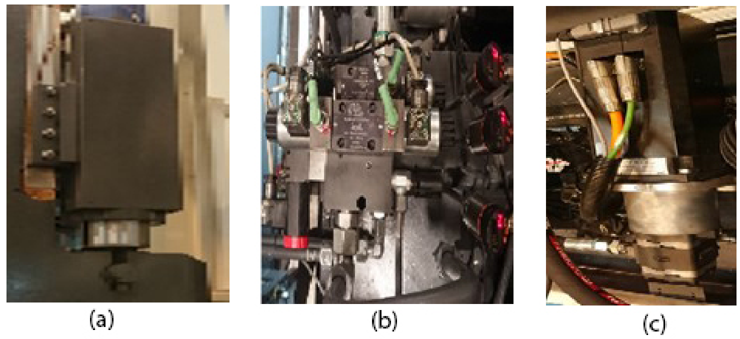

Figure 4: *Basic components of the proposed pump-controlled system: (a) hydraulic actuator (b) directional valve and pressure sensors (c) servo motor and pump.*

previous section, the machine to be used in the experimental studies was dimensioned and the equipment selection was made based on the results obtained from these equations. The general characteristics of the machine are shown in Table 2.

Table 2. General Characteristics of the Experimental Setup

Servo Motor		**Pump**		**Valve**		**Cylinder**	
Maximum Velocity	3000 (rpm)	Maximum Pressure	345 (bar)	Working Pressure	315 (bar)	Maximum Force	80 (ton)
Maximum Torque	40 (Nm)	Maximum Speed	3600 (dev/dk)	Maximum Flow	80 (lt/dk)	Pressing Velocity	1 (cm/s)
Maximum Current	26 (A)	Maximum Flow	74,5 (lt/dk)	Response Speed	40 (ms)	Displacement	50 (cm)

Tests were carried out on thin specimens with a thickness of 1.5 mm and thick specimens with a thickness of 6 mm in the experimental setup composed of the elements in Table 2. The results obtained after the bending tests can be output from the controller result and analysis page. In Figure 5, the pressure, flow, and velocity curves obtained as a result of bending tests on thin parts of the test setup can be seen. According to the results obtained, as expected, the system pressure reached its maximum value of 285 bar at the time of bending, the flow rate provided by the pump remained at the lowest level at the time of bending, and the maximum flow rate was obtained as 24 lt/min during the retraction of the cylinder. In addition, it is seen that the speeds are 15,2 cm/s in the approach movement, 0,85 cm/s in the bending, and 16 cm/s in the retraction movement. Here, the desired maximum flow value during the approach and retraction movement of the cylinder is not provided by the pump alone. Unnecessary high-power pump usage is prevented by obtaining a high flow rate through the pre-charge valve. Thus, the motor adjusted the flow according to how much flow is required during the bending process and significantly preventing the losses in the valve-controlled system and increasing the efficiency.

3.2 Energy Efficiency Analysis

In order to obtain the energy consumption of the tests carried out on the experimental setup, the average energy consumption of the two systems as a result of 100 cycles of bending tests at 9 cm position change is given in Table 3. Dimensions of the bent test piece with St42 material; 1 cm thickness, 20 cm wide, and 300 cm tall.

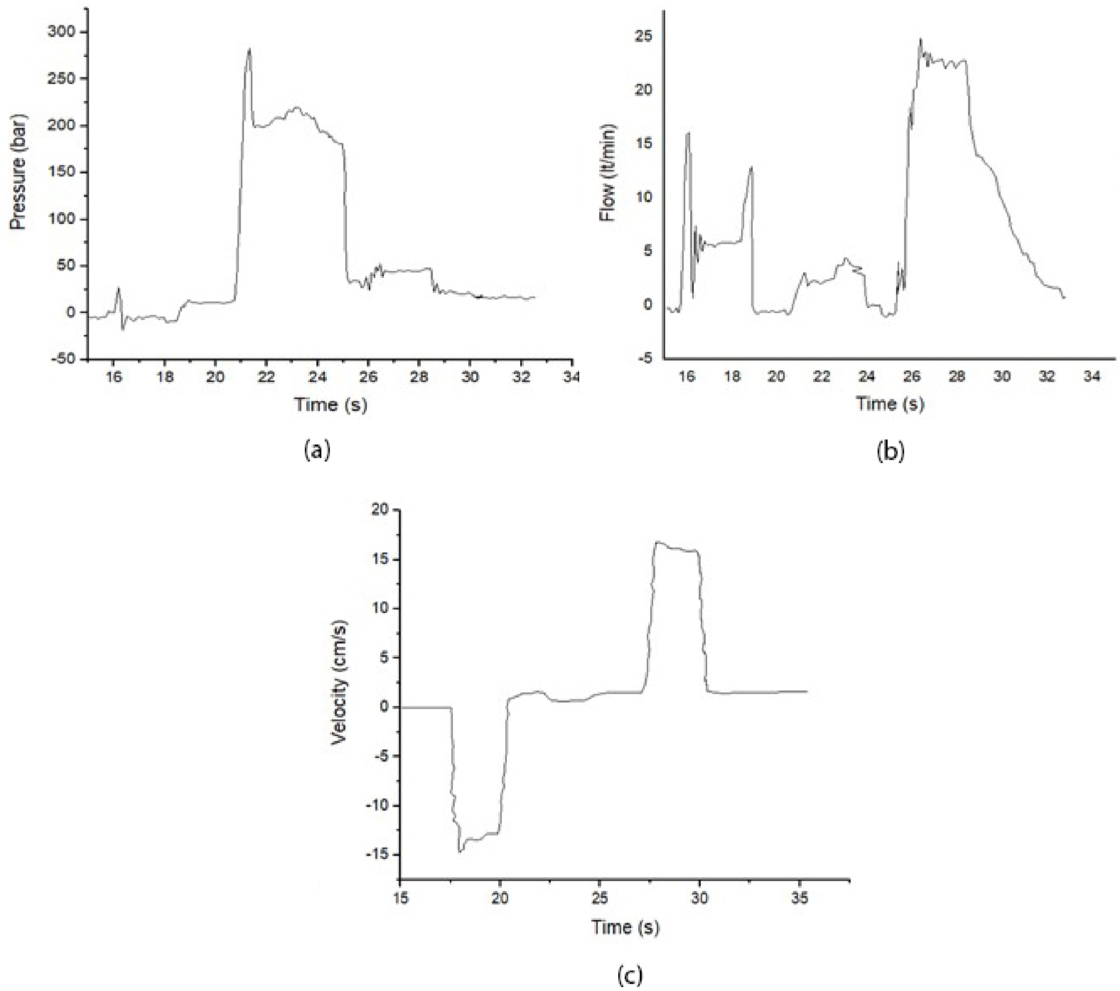

Figure 5: *Results obtained from experimental study: (a) Pressure change (b) Flow change (c) Velocity change.*

Table 3: Energy consumptions of the conventional (valve-controlled) system and the proposed (pump-controlled) system.

	Valve-Controlled System		**Pump-Controlled System**	
Power (kWh)	Thin specimen (1,5 mm)	Thick Specimen (6 mm)	Thin Specimen (1,5 mm)	Thick Specimen (6 mm)
W_0	4,86	6,44	6,44	7,25
W_1	8,23	8,56	7,76	8,45
W_1 - W_0	3,37	2,12	1,32	1,2
Average	**2,74 kWh**		**1,26 kWh**	

The energy consumed at the beginning of bending (W_0) and the energy consumed at the end of the bending process (W_1) were obtained with a measuring device on the experimental panel as in Figure 6. According to the measurement results, when the energy efficiency in the proposed pump-controlled system

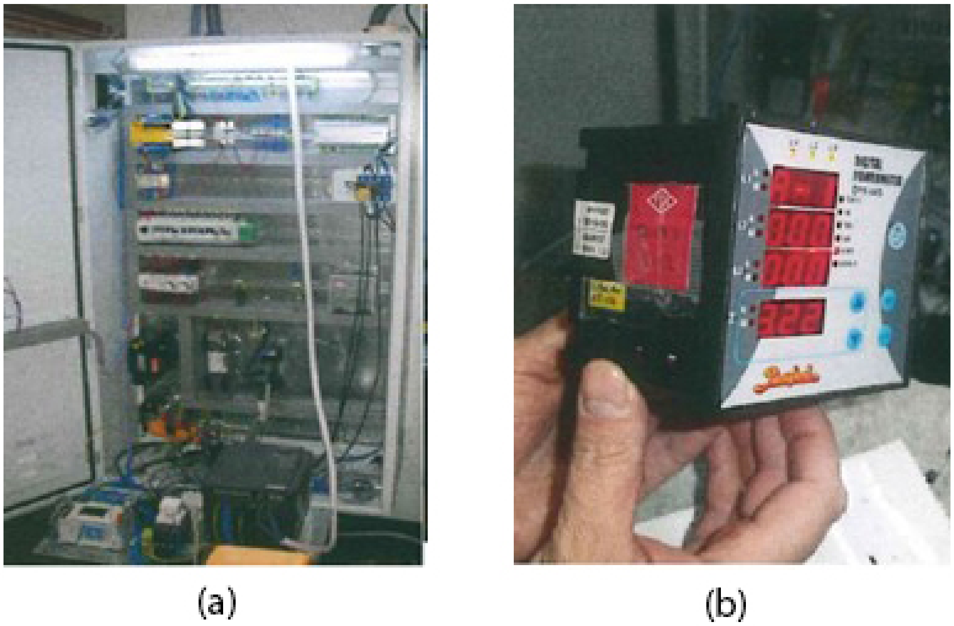

Figure 6: *(a) Experimental measurement panel (b) Power consumption measuring device.*

Table 4: Cost information of the conventional (valve-controlled) system and the proposed (pump-controlled) system

Pump-Controlled System		Valve-Controlled System	
Component	**Cost (€)**	**Component**	**Cost (€)**
IPVP-20 pump	5488	Vane pump	504
Servo motor ESA-142	3920	Asynchronous motor	252
Servo driver ESA-143	2464	Esa graphic unit	504
Main valve group	1232	Main valve group	616
Directional valve group	2691	Directional valve group	1521
Pressure valve group	900,9	Pressure valve group	900,9
Pre-charge valves	643,5	Pre-charge valves	643,5
Other equipments	491,4	Other equipments	491,4
Hydraulic accumulator	409,5		
Total	**18240,3**	Total	**5432,8**

is compared with the energy efficiency in the traditional valve-controlled system, it is concluded that the proposed system is 54% more efficient.

The energy efficiency of the systems used in the industry is important as well as the initial investment costs for the manufacturers. In this context, the cost of pump-controlled and valve-controlled systems used in this study was compared. Due to the energy efficiency of the pump-controlled system, which has a higher initial investment cost, the time to amortize the cost difference between the two systems is discussed. The cost of the main components and the sum of the components used in both systems are given in Table 4.

Two scenarios are set up taking into account the initial investment and the cost of energy consumption for the same pressing conditions, and it is assumed that a press brake machine work for 15 hours/day, and 24 hours/day respectively with one cycle of 15 seconds. According to the information in Table 3 and the

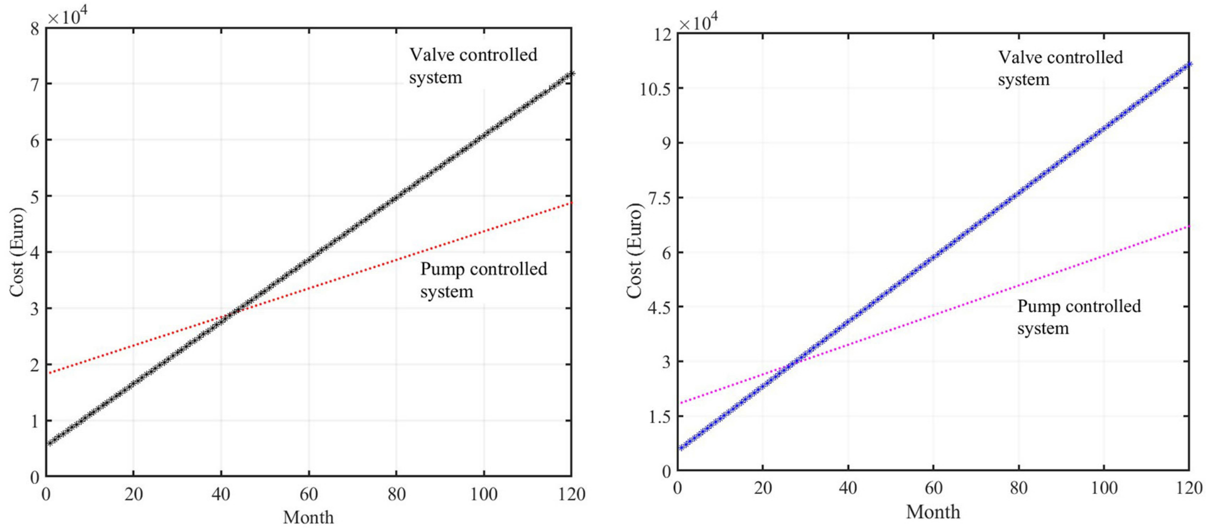

Figure 7: *Amortization period of proposed pump-controlled system.*

current electricity prices of 0.187 €/kWh [21], it is obtained as in Figure 7 that the pump-controlled and the valve-controlled system's costs will be equal approximately 3,5, and 2 years. Maintenance costs are not taken into account when making the calculations, only the costs of the components are calculated.

4 Conclusions

In this study, position control and analysis with pump control of a double-acting actuator are examined. It is aimed to comparatively examine valve-controlled conventional systems and servo motor-controlled pump systems in terms of energy efficiency. In the tests carried out in the experimental setup, the efficiency was found to be 54% higher than the classical valve-controlled system according to the number of 100 cycles of bending. The hydraulic tank capacity used in the traditional system is 135 liters in order not to overheat the oil and due to the extra circulation. In the pump-controlled system, the hydraulic tank for each axis is 34 lt. In total, the volume of the two hydraulic tanks is 68 liters. About half of the hydraulic oil is used in the pump-controlled system. In this case, the pump-controlled system can be accepted as an advantageous system in terms of preventing environmental pollution. In addition to energy efficiency, the amount of oil used in the pump-controlled system is approximately 50% less and it has been seen that it can be recommended as a more environmental solution. Since the oil is not exposed to the throttling in the valves, it heats up less, so it is also advantageous that there is no need to use extra energy for cooling. Based on these results, it has been observed that the double-acting actuator can be precisely controlled with pump control, it can be successfully applied in press brakes used in sensitive bending processes, and the cost difference can be met at the appropriate time with energy efficiency.

In addition to the advantage in electricity consumption of a hybrid press brake system, it also has the features of ease of maintenance and needs less maintenance time. Decreasing energy costs and maintenance easiness provides a competitive advantage to companies in the production and use of products. Considering these results, high-volume system design and efficiency can be studied in the future, where high forces provided by hydraulic systems will be obtained.

Acknowledgments

All authors would like to thank BAYKAL MACHINE for data support and assistance in the preparation of this study Engin Can ÇELİK, who is the bursary of the TUBITAK 2244 Industrial doctorate program (Project code :118C120) presents his appreciation to the supporter institution.

Funding: It was carried out with the project number 1170141 within the scope of TUBITAK 1511 Priority Areas Research, Technology Development and Innovation Projects Support Program carried out by Baykal Machine, and certain parts of it were discussed as thesis topic.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Authors Contributions: Methodology, management of experimental studies, preparing results and analysis has been conducted by Ö.P. Sections of methodology, results & discussion have been conducted by E.E.T. Abstract, introduction, literature review, conclusion, and edit of sections have been prepared by Ö.P. and E.E.T. Literature review and last revisions of the manuscript have been accomplished by E.C.Ç. All authors edited and agreed to the manuscript.

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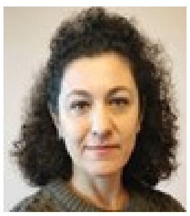

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