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Energy Efficient Hydraulic Clamping System using Variable Frequency Drive in a CNC Machine

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Abstract: In the Computer Numeric Control(CNC) machines, hydraulic clamping system is generally used to hold the work in the locating surface. This is because of the fact that hydraulic clamping system has greater efficiency as compared to the other clamping system and the power consumption is comparatively lesser. The hydraulic clamping system is driven by the hydraulic power pack. The existing hydraulic system is driven by the pump which operates at a constant speed. But during clamping application, the power required is less when it is in clamped position as compared to when the clamp is loaded and unloaded so there is room for reduction in the power consumption which can be achieved by varying the speed of the motor. This can be achieved by introducing a Variable Frequency Drive (VFD). A percentage reduction of 80.65% was found by employing a Variable Frequency Drive. Thus, this paper is presented with a view to illustrate the conservation of energy for hydraulic clamping system with the introduction of Variable Frequency Drive.

Keywords: Hydraulic Clamping System, CNC Machines, VFD, Energy efficiency.

1.Introduction

In the present time, energy consumption is to such an extent that if the same trend goes on then in future at some point of time, the energy sources will be exploited. Thus, saving of energy even in small units is not only advantageous for the future but also benefits manufacturer as well as to the customers. Hence, when it comes about conservation of energy for hydraulic clamping in CNC machine, it is solely in concern with the power consumed in order to hold a work that is to be machined in the machine using hydraulic clamping system.

1.1 Clamping System:

In simple, clamping is a holding or a fastening device. Whether it is to hold any object with hands so that it does not slip away or to attach an animal with a rope against a fixed object, it is clamping. Mechanically, Clamping can be defined as a tool which is used to hold a work piece rigidly against a located surface on the machine so that various operations can be performed on it. In other sense, it is used to overcome the maximum possible forces acting on the work piece. The term clamp is referred to the mechanism used for action [1]. Figure 1 shows schematic of clamping of a work in a CNC machine.



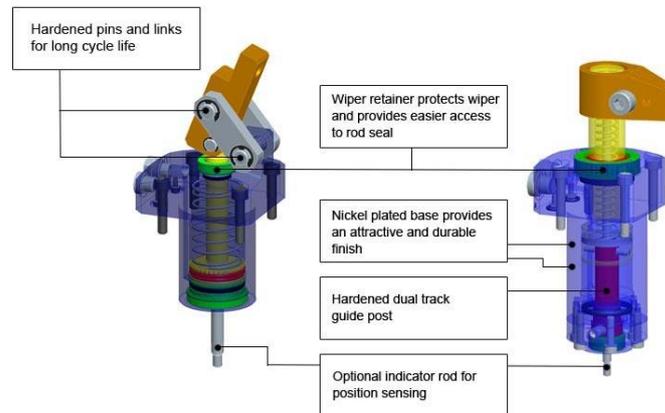


Figure1. Hydraulic Clamping System used for CNC machines

Whenever a clamp is used for holding any kind of work piece, the factor that determines whether it is efficient or not depends upon the action of clamp on the work piece. Some of the main function that an ideal clamp should possess are:

- Reduce the maximum possible stresses acting on the work piece due to various operations with a minimum clamping force.
- Not cause any deformation to the work or change its form due to the clamping force.
- The clamps should not lose its grip on the work piece due to vibrations caused by the tools rather it should get tightened due to the vibrations.

Other basic functions for clamps include ease of operation, easy to handle, cost efficient, provide wide applications, etc.

1.2 Rule of Clamping:

There are many rules for applying clamp on any work piece. The basic rules are discussed below:

- a) The clamping force should always be applied toward the locating surface.
- b) The clamp should be at a safe distance from the tool for safe operation.
- c) Clamps should be arranged in such a way that clamping force acts on strongest part of the work. For example, if an I-section is to be clamped, the clamp should be adjusted in such a way that clamping force acts on the flanges and not on the web of the I-section.
- d) The design of the clamping device should be done based on the work it has to handle.

With the advancement in technology, there are many types of clamping system. Mostly used systems are Mechanical Clamping System and Hydraulic Clamping System. However, due to greater efficiency and ease of application Hydraulic Clamping System has dominated in the rapidly growing industries.

1.3 Six Pin Method (3-2-1)

Before performing any machining operation on a workpiece, the foremost thing that needs to be decided is how the work must be placed in the locating surface. Any work (body) placed in the locating surface has 12 degrees of freedom when it is not fastened. Out of the 12 degrees of freedom, 6 are the translatory degrees of freedom and the remaining 6 are rotational degrees of freedom which is illustrated in the Figure -1 below.

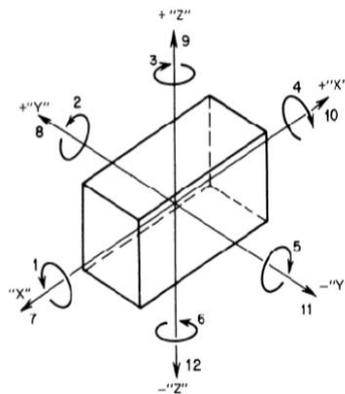


Figure 2: Illustration of degree of freedom of a free body

In the above Figure-2, 1,2,3,4,5 and 6 represents the translation motion along -X, +Y, +Z, +X, -Y and +Z axis and similarly 7,8,9,10,11 and 12 represents rotational motion along these respective axes. In the six-pin method, the pins are located on the work such that 9 out of the 12 motions are restricted. The only permitted motions are translation motion along -X, -Y and -Z. In order to restrict all of the motions during machining operation, six pin method is employed along with the clamps. Figure 3 demonstrates different views of the workpiece with the application of six-pin device.

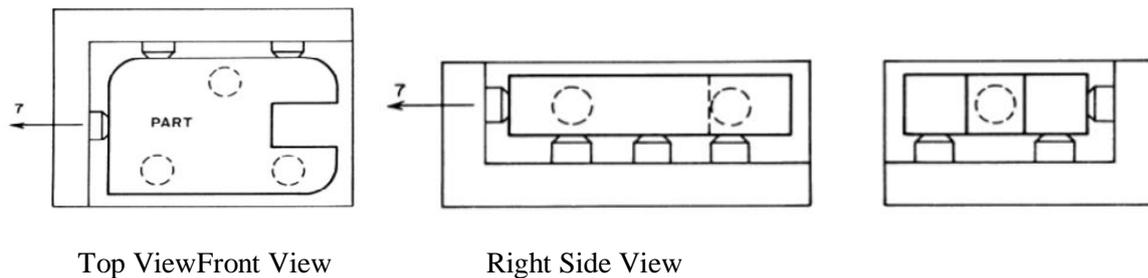


Figure 3: Different views of the workpiece with the six-pin device

The name 3-2-1 for this method is based on the different positions of the pins. There are 3 pins at the bottom (perpendicular to the shop floor), 2 pins at the back and 1 pin at the left side (parallel to the shop floor), hence the name 3-2-1 method. Such arrangement of pins permits only translation motion of the work in the negative axis directions restricting all the other motion. These permitted translatory motion of the work are then restricted using a clamp. This method is widely applied for the 4-faced work such as square, rectangle, etc. Since, the contact area is small, accuracy is more. Also, the pins perpendicular to the shop floor helps to raise the work, hence the chips formed doesn't obstruct the machining operation.

1.3 Hydraulic Clamping System:

Hydraulic Clamping System is the clamping system which makes the utilization of pressurized liquid like oil, water, etc. to hold a work against the finding surface. It has a more prominent proficiency than other clamping system in view of less friction surfaces which increases the life of the tool. Hydraulic system generally consists of single or double acting cylinder with a piston. On the blank side of the piston, there is a port for the stream of pressurized liquid. On the other side i.e. the rod end side there is a clamp like swing clamp, vertical clamp, link clamped, etc. which exerts force on the work to accomplish the clamping action. Figure 4 illustrates the working of Hydraulic Clamping System.

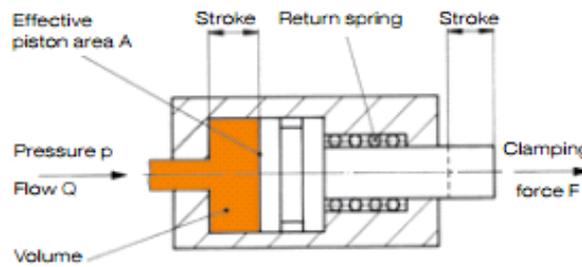


Figure 4. Illustration of Hydraulic Clamping System (Courtesy. www.amf.de)

Hydraulic clamping system is a motor driven device. Generally, the power house for the hydraulic clamping is Hydraulic Power Pack. Its major part constitutes of Oil Reservoir, Pump, Motor, Pressure Relief Valve, Pressure Gauge, etc. A schematic circuit of a Hydraulic Power Pack is shown in Figure 5. Similarly, Figure 6 shows a typical Hydraulic Power Pack manufactured in **Bosch-Rexroth India Ltd, Bangalore.**

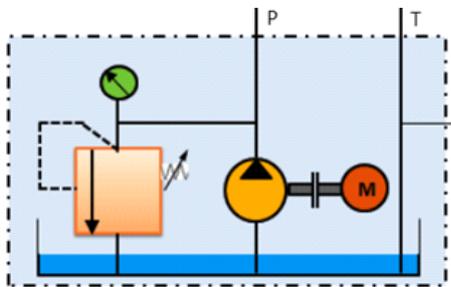


Figure 5. Hydraulic Power Pack Circuit



Figure 6. Hydraulic Power Pack

1.4CNC Machine:

CNC abbreviates to Computer Numerical Control. If it is required to manufacture a product from a work, it is needed to be undergone through different operations. Those operations are performed one by one by Programmable Logic Controller in CNC machine which means some theoretically programmed commands are prearranged in a storage medium. When those programs are executed the operations are performed one by one [2]. These machines are differentiated based on the machining centers as:

- i) Horizontal Machining Center
- ii) Vertical Machining Center

In CNC system a computer is used to perform all the basic functions once all the instructions are given by the programmer and the program is stored in the computer memory. The system commands several units to perform its required task such as; to servo drives, it commands to drive the servo motor & other output devices like relays, solenoids etc. to start the operations such as starting and stopping of the motor, coolant, etc., changing of tools, pallets, etc., and other important functions. Once the system gives the required instructions through the program, it is necessary to check whether the particular function has been completed or not. This is done by feedback devices like linear scale, encoder, resolver etc. Some sensors like proximity switch, limit switch, pressure switch, flow switch and float switch are also used as feedback devices to monitor the miscellaneous operations. Thus, all operations of CNC machine are checked continuously with the help of the feedback devices. Thus, a CNC machine system is called as Closed Loop system. If any failure feedback is obtained, the system generates a fault message. Figure 8 illustrates the working of a CNC machine.

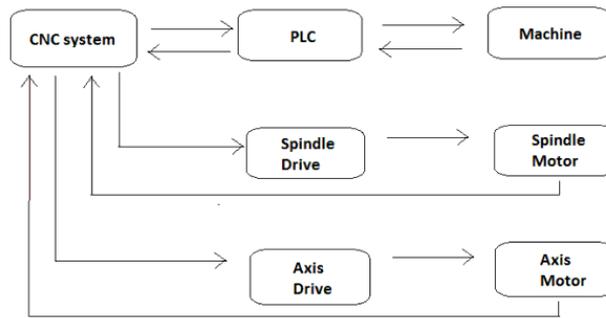


Figure 7: Working of a CNC Machine (Courtesy. www.trendingtop5.com)

2. Application of Hydraulic System in CNC Machine

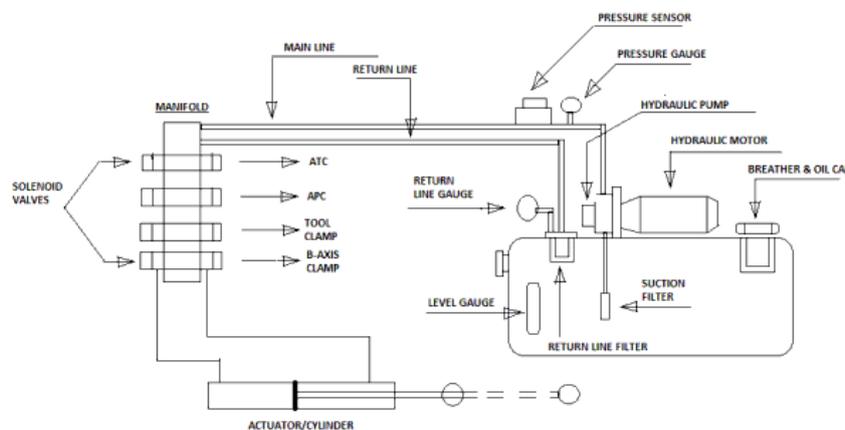


Figure 8. Illustration of Application of Hydraulic System in CNC machine (Courtesy www.trendingtop5.com)

Hydraulic system is a system which is operated by hydraulic oil. At the point when there is a need of high pressure in a small volumetric area, hydraulic system is used. CNC machine is such type of machine which is used in manufacturing industries in which the parts of the machine are controlled by the computers. In such situation, hydraulic systems plays a major role to execute different operations. The pressure required in CNC machine is developed by hydraulic power pack which consists of several hydraulic components. It is a close circuit as it sends a feedback after each working cycle. A hydraulic pump is consolidated to raise the pressure up to required system pressure and this system pressure is utilized at different locations in the machine through solenoid valves and controlled through hydraulic pressure regulators [3]. The major applications of hydraulic system are discussed below:

- Tool clamp/declamp operation;
- Pallet clamp/declamp operation;
- Hydro-motor for arm rotation or turret rotation;
- Hydraulic hammer for hot and cold swaging;
- Rotational axis clamp/declamp;

3. Energy conservation for a Hydraulic Clamping in CNC Machine using VFD:

Figure 10 demonstrates the existing Hydraulic circuit used for the clamping application in the CNC machine. It comprises of a double acting cylinder as it can be incited in both the direction by the pressurized liquid. At the point when the solenoid is activated to one side (say right), liquid streams

from port P into port A. This causes the retraction of the piston to the blank end of the cylinder. Similarly, when the solenoid is activated to the other side i. left, the cross setup to the right is achieved. This activity extends the cylinder to the inverse end of the cylinder [4]. A 4/3-way solenoid operated, spring controlled direction control valve (DCV) is employed for controlling the course of liquid stream in the hydraulic system. A reservoir present consists of a working fluid (oil). [5]

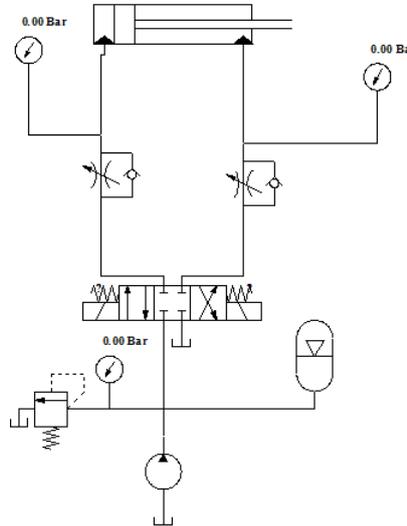


Figure 9. Schematic circuit of a motor driven hydraulic system for clamping application

Once the cylinder reaches either of the Dead-end positions i.e. blank side or rod end side, the pressure in the system increases to the maximum pre-set pressure which is set in the Pressure Relief Valve. When the pressure in the system reaches the maximum pre-set pressure, in order to safeguard the components, present in the system, the Pressure Relief Valve opens and the oil flows back into the reservoir. A certain percentage of this pumped oil maintains the required pressure in the system and the excess oil flows through Pressure Relief Valve into the reservoir [6]. Similarly, the current hydraulic circuit is an open loop system as there is no feedback signal about the pressure changes due to the variation in load condition. Thus, there will be no adjustments in the pump flow during the machining process time. Also, the accumulator which is installed close to the cylinder might make up for smaller pressure variation but if pressure is largely reduced, the pump needs to supply liquid. Hence, the pump works for the entire cycle time, despite the fact that the stream prerequisite is very less during the clamping period. This unnecessary pumping of oil due to the constant rpm of the motor leads to excess usage of power.

To reduce the power consumption of present hydraulic circuit, these changes can be made:

- Installation of Variable Frequency Drive (VFD) and Pressure switch;
- Changing the position of accumulator position;
- Removing the Flow Control Valve (FCV)

A Variable Frequency Device by Bosch Rexroth India Ltd. as shown in figure 10(a) is a device that controls the motor by varying its frequency and the voltage. Frequency is directly proportional to the revolution per minutes (RPM) of the motor i.e. higher the frequency, higher is the speed of the motor and vice-versa. This mechanism can be very useful in order to conserve the energy for a Hydraulic Clamping System. This is because during clamping application it is not required for the motor to run at full speed every time. Hence, the speed can be slowed down when it is not required to run at full speed

[6]. VFD brings its application at this time by varying the frequency and the voltage and thus, lowering the speed of the motor. At the same time, when the speed needs to be increased, VFD increases the frequency and the voltage. A drastic variation in power consumption can be found by employing a VFD in a hydraulic circuit as it saves a lot of energy when motor is not required to run at full speed. Figure 10(b) demonstrates a schematic circuit of the hydraulic system with a VFD. [7]

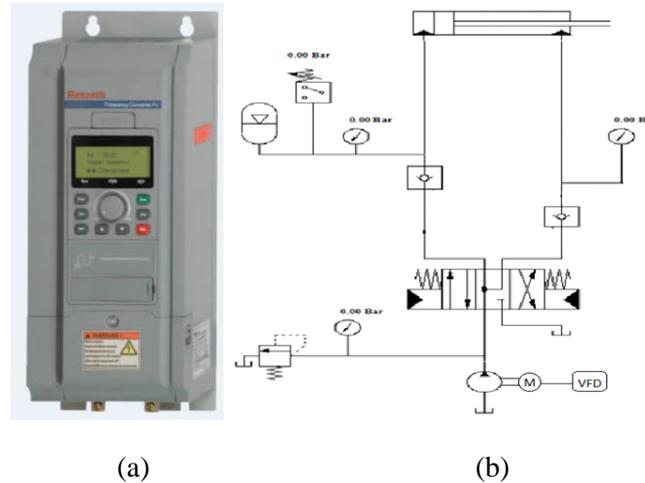


Figure 10. (a) Variable Frequency Device (Courtesy. Bosch Rexroth Ltd.), (b) Schematic circuit of a motor driven hydraulic system with VFD for clamping application

3.1 Laws of Affinity

Energy conservation by a VFD is derived from the Laws of Affinity. There are 3 affinity laws which are stated below:

Law-I: Flow is proportional to the Shaft Speed i.e. $Q_1/Q_2 = N_1/N_2$

Law-II: Pressure is Proportional to the Square of Shaft Speed i.e. $H_1/H_2 = (N_1/N_2)^2$

Law-III: Power is Proportional to the Cube of Shaft Speed i.e. $P_1/P_2 = (N_1/N_2)^3$

Where, Q = Volumetric flow rate in LPM

N = Shaft Rotational Speed in rpm

H = Pressure in Bars

P = Power in kW

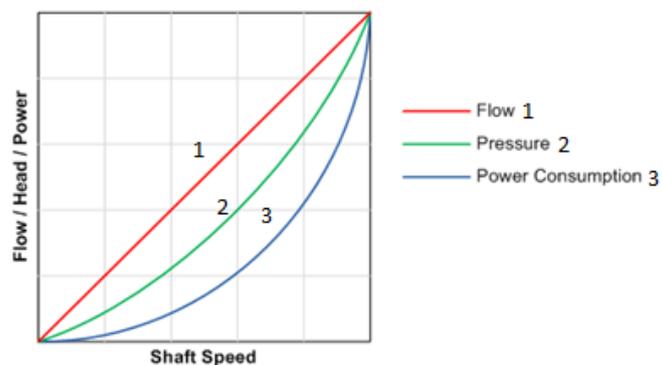


Figure 11. Curve Illustrating Affinity Law

From the affinity laws, it can be seen that the speed variations changes the flow rate, pressure head and power consumption of the hydraulic system which is illustrated by figure 12. Based on experiments the results can be analyzed using the affinity laws and are shown below by the characteristic curves:

i) Law-I: Flow is proportional to the Shaft Speed i.e. $Q_1/Q_2 = N_1/N_2$

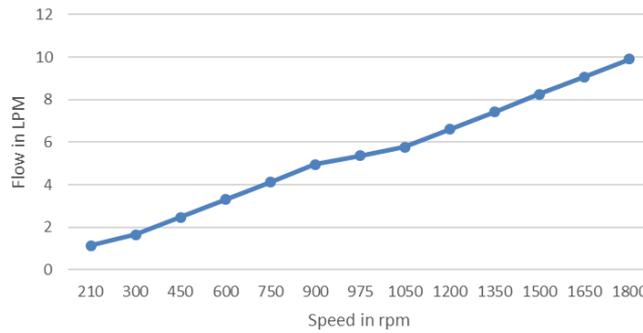


Figure 12. Flow v/s Shaft Speed

It is observed that the increase in frequency increases of the electric motor by large magnitude. Hence, the increase in speed of electric motor, increases the flow rate of the pump. Therefore, there is an increasing trend for the flow rate of the pump for increase in speed of the electric motor as shown by curve in Figure 12.

ii) Law-II: Pressure is Proportional to the Square of Shaft Speed i.e. $H_1/H_2 = (N_1/N_2)^2$

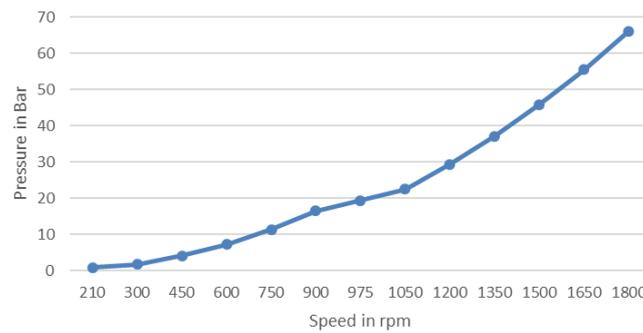


Figure 13. Pressure v/s Shaft Speed

Similar to that of the flow rate with the increase in the operating speed, the pressure head in the hydraulic unit increases which is explained by the curve in Figure 13.

iii) Law-III: Power is Proportional to the Cube of Shaft Speed i.e. $P_1/P_2 = (N_1/N_2)^3$

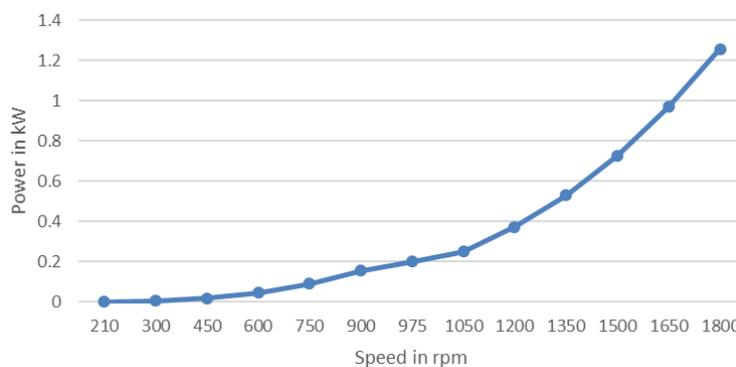


Figure 14 Power v/s Shaft Speed

The power consumption also increases with the increase in the operating speed. This can be understood with the help of the curve in the Figure 14.

4. Calculations for Hydraulic Clamping System in CNC

4.1 Without VFD:

Extension time = Extension volume/Discharge = 6.94 minutes

Retraction time = Retraction volume/Discharge = 4.16 minutes

Total clamping time = 11.10 minutes

Assuming machining time for 1 hour,

Total Loading Time = 48.89 minutes

Power consumed = $(P_w) = (P \times Q) / (612 \times \eta) = 1.107 \text{ KW}$

Where P - Pressure in bar

Q - Discharge in lpm

η - Efficiency 0.85

4.2 With VFD:

For minimum speed,

Frequency (f) = 10 hertz when pressure (≥ 40 bar)

Number of poles (p) = 4

Displacement of the pump (v) = 5.5 cc/rev = 5.5×10^{-3} liters/ revs

Efficiency of the pump (η) = 85% = 0.85

Speed (N) = $(120 \times f) / p = 300$ rpm

Discharge by the Pump (Q) = $v \times N = 1.65$ lpm

Power consumed by the pump (P_{w1}) = $(P \times Q) / (612 \times \eta) = 0.1268 \text{ KW}$

For maximum speed,

Frequency (f) = 50 hertz when pressure (< 40 bar), P = 35 bar

Number of poles (p) = 4

Displacement of the pump (v) = 5.5 cc/rev = 5.5×10^{-3} liters/ revs

Efficiency of the pump (η) = 85% = 0.85

Speed (N) = $(120 \times f) / p = 1500$ rpm

Discharge by the Pump (Q) = $v \times N = 8.25$ lpm

Power consumed by the pump (P_{w2}) = $(P \times Q) / (612 \times \eta) = 0.456 \text{ KW}$

Total Power Consumed (P_w),

Considering for 1 hour; such that it is 45 minutes clamped and 15 minutes for loading:

$P_w = [(P_{w1} \times 45) + (P_{w2} \times 15)] \times 60 \text{ KJ / hour} = 770.76 \text{ KJ / hour} = 0.2141 \text{ KW}$

The total power consumer by the hydraulic circuit without VFD was found to be **1.107 KW**

Percentage of energy saving = $(1.107 - 0.2141) \times 100 / 1.107 = 80.65\%$

5. Conclusion:

This paper presents a strategy for the conservation of energy using a VFD for hydraulic clamping system in a CNC machine. Different characteristics of the hydraulic system without VFD and with VFD were compared and the results are presented. From the results obtained in the experiment, it was observed that the hydraulic system with VFD works at the lower flow rate for achieving the pressure of 40 bar which is required for the clamping application and hence the power consumption is less. Effect of speed variations on the pump characteristic was studied using affinity law and plotted. It was observed that using a VFD in the hydraulic circuit for clamping in a CNC machine saves of 80.65% of energy every hour. Incorporating a VFD, the speed of the pump can be varied by varying the frequency. It can be observed that varying the frequency by 1 hertz varies the speed of the motor by 30rpm. Increasing the frequency increase the speed and hence, the flow rate and vice-versa. During the cycle when the lower pump speed is sufficient, VFD lowers the speed and thus the power consumption is lowered.

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