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An Energy Conservation Strategy Using Variable Frequency Drive for a Hydraulic Clamping System in a CNC Machine

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Abstract

Electric motor driven hydraulic clamping systems are commonly employed in Computer Numerically Control (CNC) machine tools for fixing work pieces on the machine table. The flow requirements for a typical hydraulic clamping system varies during machining of components, however, the existing electric motor drives operates at the constant speed and it leads to increased electrical power consumption. This paper presents an energy conservation strategy by retrofitting a variable frequency drive (VFD) in the motor drive of the hydraulic clamping system in a CNC machine for varying the speed of the motor at different load conditions and minimizing the power consumption of an electric motor. Flow characteristics and electric power consumption of proposed VFD based hydraulic pumping system was compared with the existing hydraulic pumping circuit and the results were presented. It was found that the proposed hydraulic pumping system operates at low follow rate after implementation of VFD and it consumes less power compared to existing hydraulic clamping system.

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Keywords: Energy efficiency, Hydraulic Circuit, CNC machines, Variable frequency drives

1. Introduction

In today's modern era, energy efficiency of machine tools is a topical issue for the machine tool users and builders as the industrial electrical consumption contributes to 42.6 % of the universal electricity consumption [1]. Former studies have shown that the most important negative environmental impact of machine tools is the electrical energy utilization during the use phase [2]. The large use of electrical energy for industrial operations is responsible for significant CO2 emissions and thus climate changes [3]. In a typical CNC machine, various auxiliary operations

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such as clamping, coolant spray, machine table movements and they consume large amount of electrical energy during the machining process [4]. Clamping of large work piece is commonly carried out using hydraulic system driven by the electrical drives. Figure 1 shows the typical hydraulic clamping system used for holding the work piece in the machine table using swing clamps.

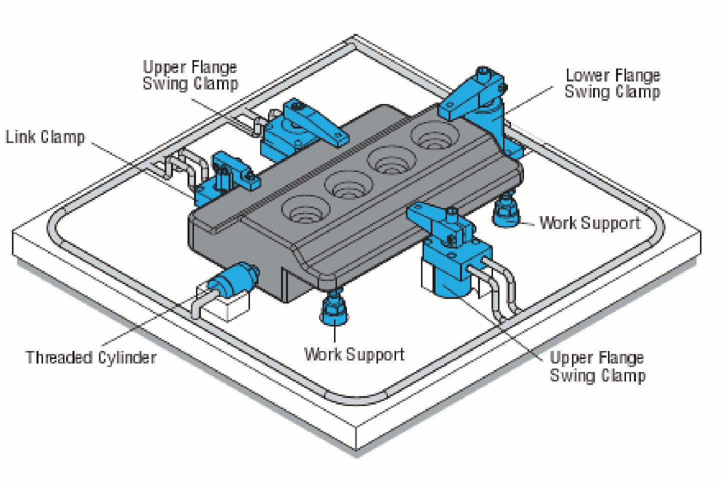

Fig.1Typical hydraulic clamping system [5]

Mainly electrical, hydraulic, and pneumatic drives perform at rated power during roughing cycle, whereas consumption of power is comparatively low during finishing cycle. The mismatch of functionalities typically causes waste of resources and energy, over dimensioning, high development reliability limits, poor combination into the production environment and wasteful operation. At the same time, the global manufacturing industries, energy saving potential is projected by 20% until 2050 [6]. In order to maintain competitiveness and lower costs, there is a need for developing energy conservation strategies to decrease the energy consumed during manufacturing for a given product.

Several studies have been proposed by various researchers for increasing the energy efficiency for machine tool. R. Neugebauer et. al., have focused on the system level events for energy efficient increase of machine tools and production system that can roughly be divided into direct efficiency increase on component level by optimized interface of the components on the higher system level [7]. M. Mori et.al., have emphasized on energy consumption reduction can be obtained by modifying cutting conditions, this aspect for either regular drilling, face/end milling and various machining operations [8]. The overall influence of light weight design methods on energy efficiency in machine tools and limitations on the maximum mass reduction for structural components and light weight machine tools were designed by L. Kroll et. al., [9]. Active interactions of various processes and along with the auxiliary equipment's need also considered when planning and controlling manufacturing systems. This concept has been discussed by C. Herrmann et. al., on their work on energy oriented simulations of manufacturing systems [10]. Vijayaraghavan et. al., have developed an automated energy monitoring machine of machine tools to improve the environmental performance of manufacturing systems [11].

2. Description of the existing hydraulic clamping system under study

In the present work, an experimental study has been carried out for the electrical energy consumption of a hydraulic clamping system in a CNC machine developed by ACE Manufacturing System Limited, Bengaluru.

Figure 2 shows the photograph of the hydraulic pumping system in the CNC machine. The existing hydraulic system is used for meeting the demands of clamping operations of work piece in a CNC machine during machining and it consists of AC synchronous electric motor driven pump, control valves, reservoir and fittings as shown in Figure 3.

Fig.2. Photograph of the hydraulic clamping system used in CNC machine considered in the present study

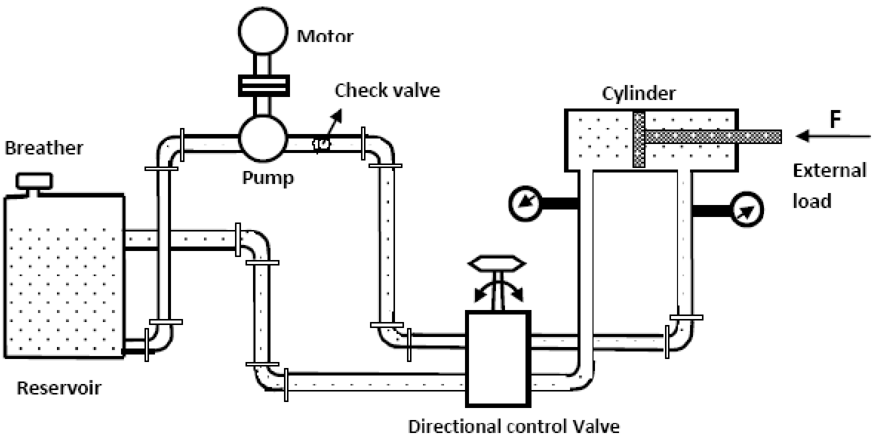

Fig.3. Schematic diagram of electric motor driven hydraulic pumping system

The hydraulic clamping system needs to provide a pressure of 40 bar for clamping operation and it uses 0.75kW power pack electric motor drive. A gear-type power pump which consists of two meshed gears that revolve in housing is used to supply the hydraulic oil with the specified pressure. The general specifications of the hydraulic pumping system are shown in Table.1.

Table 1 Specification of the existing hydraulic pumping system

S. No	Description	Values
1	Make	Bosch-Rexroth
2	Motor capacity	0.75kW
3	Motor type	Crompton Greaves induction motor
4	Rated motor speed	200-2000rpm
5	Pump type	1Gearpump
6	Pump displacement	16 cc/rev
7	Maximum pressure	50 bar
8	Maximum flow	16 lpm
10	Clamping pressure	40 bar
11	Standard cylinder size	25/16-200 cm
12	Oil used	Hydraulic oil of grade 68

This section presents the hydraulic circuit details and the operation of the hydraulic clamping system along with its flow characteristics.

3. Operation of the existing hydraulic clamping system

Figure 4 shows the complete hydraulic circuit used for the clamping operations in the CNC machine. It consists of a double acting cylinder as it can be actuated in both directions by the pressurized fluid. When the solenoid is triggered to the right, fluid flows from port P into port A. This action retracts the piston to the end of the cylinder. When the solenoid is activated to the left, the cross configuration to the right is enabled. This action extends the piston to the opposite end of the cylinder. A direction control valve (DCV) 4 /3 way is used for controlling the speed and/or direction of fluid flow in the hydraulic system. A reservoir is used to store and adequately supply of fluid for the system.

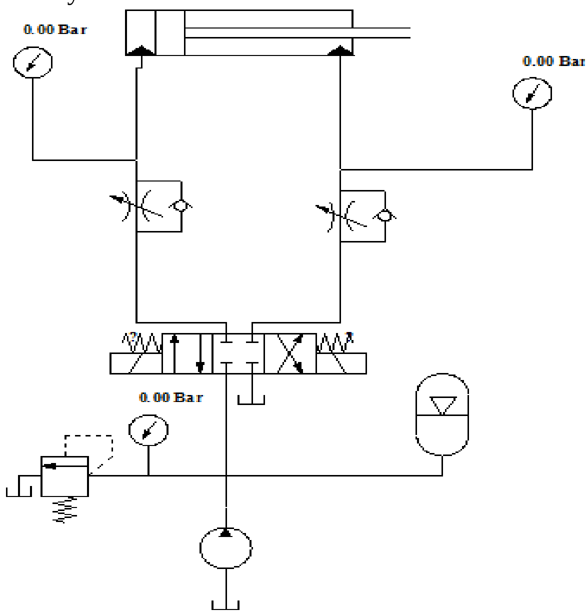

Fig.4.Existing Hydraulic circuit for the electric motor driven clamping system

The existing hydraulic circuit is found to be an open loop system as there is no feedback signal about the pressure variations due to load conditions. Hence, there are no changes in the pump flow through pressure relief valve during the machining cycle time. The accumulator installed near the cylinder may compensate for smaller pressure change, but for the maximum pressure reduction, the pump has to supply fluid. Hence the pump operates throughout the cycle time, even though the flow requirement is minimum during clamping period.

3.1. Calculation of power consumption of existing hydraulic system

As the existing hydraulic system uses gear driven pump the energy consumption tends to be directly proportional to the volume pumped and savings are readily quantified. Equation (1) shows the electric power consumption for the given pressure and discharge.

Power consumed $E = (P \times Q) / (612 \times \eta)$ kW (1)

Where P - Pressure in bar

Q - Discharge in lpm

η - Efficiency

The discharge of hydraulic fluid by the existing system depends on the speed of rotation of the electric motor and it is calculated using equation 2 and equation 3.

Discharge (Q): $v \times N$ lpm (2)

Synchronous speed of a motor (N) $N = (120 \times f) / p$ rpm (3)

Where p - no. of poles in the motor, f – Frequency in Hz

It can be noted that the existing hydraulic system uses the constant speed electric motor which operated at the speed of 1800 rpm. Consequently, there is an opportunity to reduce the electric power consumption of the electric motor by motor speed variations during low flow demand which can achieve significant energy savings.

4. Proposed energy conservation strategy using VFD in the hydraulic circuit

Figure 5 shows the modified hydraulic clamping involving VFD of variable frequency drive the input to the motor can be altered so the motor speed can be altered. This section highlights the strategies implemented in the proposed hydraulic circuit for conserving electrical energy [13]. It includes the implementation of variable frequency drive for providing variable speed to the motor which leads to elimination of flow control valves in the existing hydraulic circuit [14].

4.1. Modified hydraulic clamping circuit using VFD for speed variations

Figure.5 shows the modified hydraulic circuit with the implementation of VFD along with the electrical motor. The most common form of VFD is the voltage-source, pulse-width modulated (PWM) frequency converter (often incorrectly referred to as an inverter). The variable frequency drive (VFD) changes the supply frequency and voltage to the desired frequency and voltage to drive a motor. In its simplest form, the converter progresses a voltage directly proportional to the frequency, which produces a constant magnetic flux in the motor. Since motor depends on the speed of the rotating field and the supply frequency, speed control can be affected by changing the frequency of the AC power supplied to the motor.

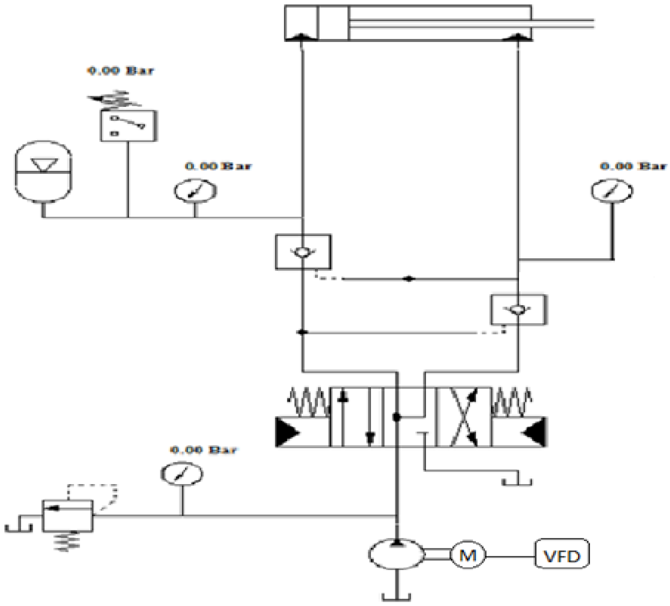

Fig.5. Proposed hydraulic clamping circuit using VFD

As the speed of the motor is controlled by the supply voltage using VFD, the general hydraulic characteristics of the pump such as Pressure, Flow rate, Power, and Speed is also varies with respect to the change in speed of the electric motor. The effect of speed variations on the pump characteristic can be explained using the affinity Laws in Hydraulics as given by the following equations: [16].

Law-I Flow is Proportional to Shaft Speed

$$\frac{Q1}{Q2} = \frac{N1}{N2} \tag{4}$$

Law-II Pressure is Proportional to the square root of Shaft speed:

$$\frac{H1}{H2} = \left(\frac{N1}{N2}\right)^2 \tag{5}$$

Law-III power is Proportional to the Cube of Shaft Speed

$$\frac{P1}{P2} = \left(\frac{N1}{N2}\right)^3 \tag{6}$$

Where Q is Volumetric flow rate in LPM
N in Shaft Rotational Speed in rpm
H is Pressure in Bar
P is power in kW

From the above equations, it can be noticed the speed variations modifies the flow rate, pressure head and power requirements of the hydraulic system. Experimental results for the effect of speed variations on the pump characteristics are analysed using the affinity laws and discussed in Section.5.2. The speed varying capacity of the proposed hydraulic system using VFD eliminates a number of costly and energy inefficient ancillaries, such as throttle valves or bypass systems [15].

4.2. Elimination of Control Valves

Commonly, control valves are used to alter the pump output to costume varying system requirements. Generally, a constant-speed pump is pumping against a control valve, which is moderately closed for most of the time. Hence, a considerable frictional resistance is applied. Energy is therefore wasted overcoming the added frictional loss through the valve. As the proposed VFD based hydraulic system, flow variations are achieved by controlling the speed of the motor, the existing flow control valves used in the existing circuit are eliminated.

4.3. Closed loop feedback system using Pressure switch.

As the existing hydraulic circuit is found to be an open loop system with no feedback on pressure variations due to varying load conditions during clamping, a feedback system using a pressure switch is implemented in the proposed hydraulic system. Pressure switch acts as sensor and sends signal to the VFD about the pressure variations. If the pressure in the clamping cylinder reaches pre-set value of the pressure switch, it sends signal to VFD, accordingly the VFD changes the frequency input to the motor. This approach provides a closed loop control for modifying the speed of the motor as per load requirements. It leads to lesser power consumption as compared to the existing hydraulic circuit as the motor speed is less during the part load conditions.

4.4. Change in accumulator position and Pair of Pressure Control Valves (PCV).

The accumulator installed in the existing circuit is before the DCV, it leads to leakage of accumulator fluid through DCV. Hence the accumulator fluid is not available completely to compensate the change in clamping pressure. To minimize this effect, the position of accumulator is fixed near the cylinder with pair of PCVs for ensuring zero leakage.

5. Results and discussion

Proposed energy conservation strategies were implemented in the VFD based hydraulic circuit for reducing the electrical energy consumption during the clamping operation in the CNC machine. Experimental results for flow characteristics of the existing hydraulic circuit driven by the electric motor and the proposed VFD based hydraulic circuit were presented and analysed in this section.

5.1. Flow characteristics of the existing and proposed hydraulic system

Figure 6 shows the flow rate and pressure variations of the proposed and existing hydraulic circuits during the clamping operations. There is a decreasing trend for the flow rate with the increase in pressure as the frictional losses in the hydraulic circuit increases with the increase in pressure.

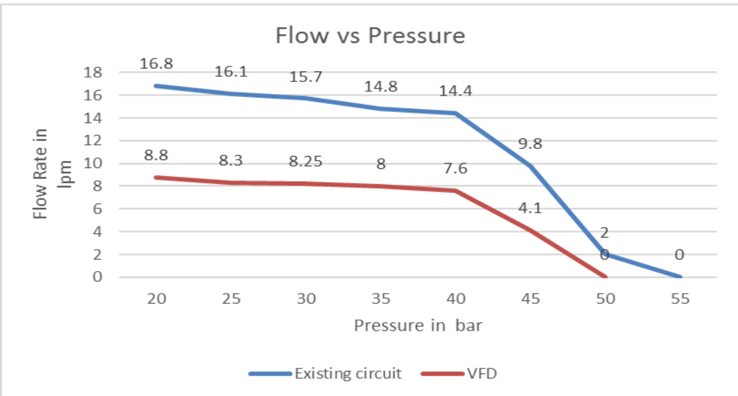

Fig.6 Pressure-Flow characteristic curve for the pump used for clamping operation

It is observed that flow rate decreases sharply around 14.4 lpm at 40 bar pressure for the existing circuit. However, the proposed VFD based hydraulic system uses a lesser flow rate of 7.6 lpm for achieving the pressure of 40 bar due to the reduced speed of the motor for the given increase in the pressure. Hence, the flow rate of 7.6 lpm and 40 bar pressure are identified as the optimal operating conditions for the proposed VFD based hydraulic clamping system. These results prove that the proposed system operates at low flow rate and low speed as compared to the existing hydraulic system, it leads to lesser electrical energy consumption of the motor and it is highlighted in Table.2 for different operating frequencies of VFD.

5.2. Analysis of effect of speed variations on pump characteristics using VFD

In the proposed VFD based hydraulic system, the speed variations of the motor are achieved by varying the frequency of supply voltage to motor according to the load variations during clamping operation. Effect of speed variations on the pump characteristics is analyzed using the affinity laws and the results are listed in Table.2. It can be noted that the increase in 5 Hz of supply frequency correspondingly increases 150 rpm of the electric motor. The increase in speed of the electric motor increases the flow rate of the pump; hence there is an increasing trend for the flow rate of the pump for increase in speed of the electric motor as shown in Fig.7 (a). As the flow rate increases in the hydraulic circuit, the pressure head also increases linearly with respect to the increase in speed of the motor and it shown graphically in Fig.7 (b).

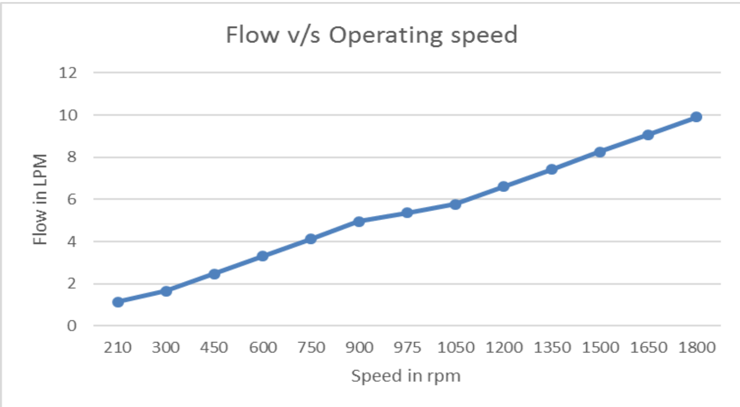

Fig. 7. (a) Flow rate

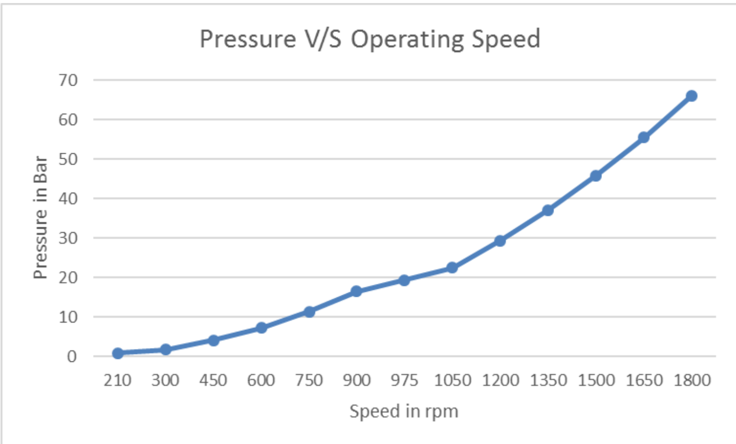

Fig. 7. (b) Pressure

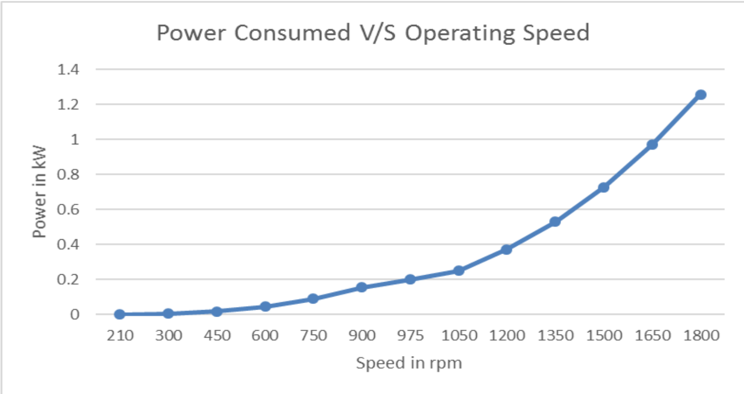

Fig. 7. (c) Power consumption

Fig.7. Effect of speed variations on the characteristics of the proposed hydraulic system

Increase in flow rate and pressure head in the hydraulic circuit for the given increase in speed of the motor increases the power consumption of the motor also. Hence, the power consumption increases with the increase in speed of the motor and it is graphically indicated in Fig.7(c). These results prove the speed dependent behaviour of the proposed hydraulic circuit.

5.3. Energy conservation of the proposed hydraulic system using VFD

In order to highlight the energy savings by the proposed hydraulic circuit using VFD, the cost of electrical energy consumption is calculated and given in Table.2. It can be noticed that the existing the hydraulic circuit operates at the constant speed of 1500 rpm for the supply frequency of 50 Hz and the energy consumption is found to be 7970.4 kW h/year. However, the proposed hydraulic circuit the energy consumption varies from 7.2 kW h/year to 5241.6 kW h/year for change in supply frequency of 5 Hz-50 Hz.

Table:2 Effect of speed variations on the characteristics of proposed VFD based hydraulic system and Energy conservation of proposed hydraulic system

Frequency (Hz)	**Pump Operating Speed (rpm)**	**Pressure in Bar**	**Discharge in Lpm**	**Power Without VFD In kW**	**Power With VFD In kW**	**Energy consumption without VFD In kW h/year**	**Energy consumption with VFD In kW h/year**	**Energy saving in kWh/year**
Existing Circuit (50 Hz)	1500	40	14.4	1.107		7970.4	----	----
10	300	1.836	1.65	1.107	0.005	7970.4	36	7934.4
15	450	4.132	2.475	1.107	0.019	7970.4	136.8	7833.6
20	600	7.346	3.3	1.107	0.046	7970.4	331.2	7639.2
25	750	11.479	4.125	1.107	0.091	7970.4	655.2	7315.2
30	900	16.530	4.95	1.107	0.157	7970.4	1130.4	6840
35	1050	22.5	5.775	1.107	0.249	7970.4	1792.8	6177.6
40	1200	29.387	6.6	1.107	0.372	7970.4	2678.4	5292
45	1350	37.193	7.425	1.107	0.530	7970.4	3816	4154.4
50	1500	45.918	8.25	1.107	0.728	7970.4	5241.6	2728.8

These calculated were made based on the following working hours and cost. Assuming the total working hours per year = 7200 Hours (24 hours shift / day *300days) and the system works for 24 hours a day for 300 days a year at Rs. 5.16 / kWh (Source KPTCL). These energy savings using the proposed VFD based hydraulic circuit leads to significant annual cost savings.

6. Conclusions

This paper presented an energy conservation strategy using a VFD based hydraulic clamping system in a CNC machine. The pressure – flow characteristics of the existing hydraulic system and the proposed system are compared and the results are presented. From the experimental results, it is observed that the proposed VFD based hydraulic system works at the lower flow rate for achieving the pressure of 40 bar required for the clamping operations due to the variable speed capability as compared to the existing hydraulic system. Effect of speed variations on the pump characteristics is analysed using the affinity laws and it proves the speed dependent behaviour of the proposed hydraulic system. It is also found that the irrespective of the load variations during the clamping operations, the existing hydraulic circuit uses a constant speed motor which operates at 1500 rpm for the given supply frequency of 50 Hz, its energy consumption is found to be 7970.4 kW h/year. Implementation of VFD in the existing hydraulic clamping system resulted in speed variation of 150 rpm for the given change in supply frequency of 5 Hz for the electric motor and these it resulted in reduced energy consumption for the CNC machine.

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