OPERATION ANALYSIS OF A INDUSTRIAL COOLING SYSTEMS WITH VARIABLE SPEED AIMING THE EFFICIENCY ENERGY

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***Abstract* – The paper relates the simulation and analysis of the behavior efficiency industrial cooling system's in a constant speed compared with a variable speed system from inverter PWM sinusoidal, aiding to control fluid volumetric flow rate and pressure and consequently save energy.**

***Index Terms*— Cooling system, efficiency, motor, energy, PWM inverter, save.**

I. INTRODUÇÃO

The scarcity of natural resources, the economic picture of stagnation and a competitive process for which were the society in the last times, have reduced costs for better applying capital, it results save energy in the sectors industrial, commercial and residential. In the industry, it this comes being done from reducing energy losses in the productive process, specifying the equipments with maximum efficiency and operating them next to this condition. The fans and the hydraulical pumps are used more at the industry in some applications. They are used about 65 % of the industry electric energy is consumed by electric [2]. The fans are common in industrial processes, such as: blast furnaces in the siderurgical ones, installations of boilers, sprays of coal, burners and in many other applications [1].

This work is one of activities released by LAMOTRIZ (Laboratório de Eficiência Energética em Sistemas Motrizes) with objective in energy efficiency of systems's force motor in industrial consumers. The main objective of this work is to analyze the operation the variable speed of a system of industrial cooling, shaping since the hydraulical part until the electric part, aiming at the efficiency in the consumption of the electric energy for the diverse situations of demand of an installation.

II. COOLING SYSTEM

The industrial cooling system is composed for the installation of cooling and the group motor-fan, each one have a characteristic curve of load versus flow rate that, when it crossed, they determine the point of system operation. Some elements in the industrial cooling installation of the LAMOTRIZ are: suppressors of noise, expansion, reduction, curve, damper and centrifugal fan.

A. Group of benches of cooling

The centrifugal fan has an excellent point of operation that it determines flow rate, pressure and rotation, where its losses to flow are minimum. In the work the operation of a radial centrifugal fan analyzed, it is the most used in the industry, in Figure 1. The fan has an electric motor 2 hp, static pressure of 784 Pa and outflow of 1,67 m^3/s and an inverter.

Fig. 1. Photograph of experimental setup - LAMOTRIZ – UFC.

Fig. 2. Photograph of experimental setup - LAMOTRIZ – UFC.

In Figure 2, it is observed suction (the right) and the air discharge of the radial fan (left).

The cooling system has acquisition of electric data and mechanical, amongst them: voltage, current, rotation of the motor, temperature of the motor and environment, pressure in the input and output of the fan and flow rate.

In Figure 3, it is observed place of the sensors in the plant of used cooling.

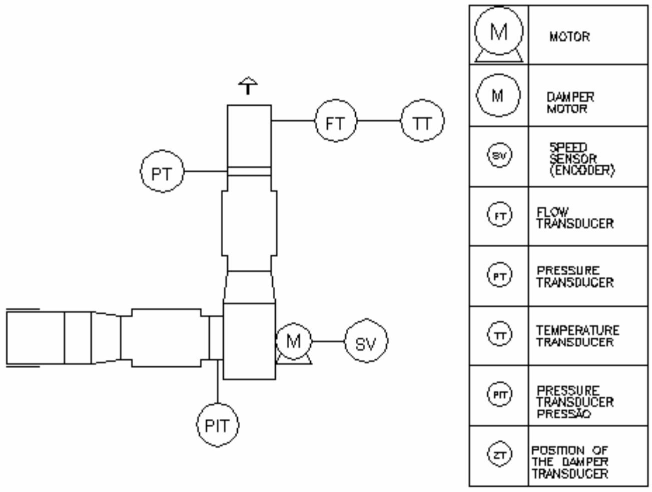

Fig. 3. Position of the sensors in the cooling plant.

At moment some electric data can be collected, while that others are being programmed.

1) Fan's Model - some equations for the mathematical model was used, to the constant speed. This modeling is modified for the operation in variable speed, with aiming in energy efficiency. An equation (1) describes the fan load curve, considering the number of infinite blades, or either, an ideal flow of the fluid. The fan characteristic curve involves the losses of load to been successful and the resultant flow rate of the energy supplied to the fluid, in the case air [11].

$$P_{\infty} = \frac{\gamma u_2}{g}\left(u_2 - \frac{Q.\cot(\beta_2)}{\pi.b_2.d_2}\right) \quad (1)$$

Where:

- γ - Specific weight of the fluid.
- g - Acceleration of the gravity.
- υ_2 - Peripheral speed of exit of the rotor.
- Q - Volumetric flow.
- P_{∞} - Ideal static pressure.
- b_2 - Height of the rotor.
- d_2 - External diameter of the rotor. r.
- β_2 - Angle of bending of the shovels.

The hydraulical losses are in the fan, amongst these, they are losses in the canals of the rotor and losses for shocks [11]. So, the real pressure developed by the fan, P_{real}, is the theoretical pressure deducted from the hydraulical losses (2):

$$P_{real} = P_c - \sum P_{loss} \quad (2)$$

B. Installation of Cooling

Considering the fan and system characteristics curve, it determines the point of operation through crossing of the curves. Figure 2 shows to the centrifugal fan and an installation curve, defining the point of operation of the fan to constant speed. In this point, the fan produces energy to the fluid to win one given pressure to an flow rate [3].

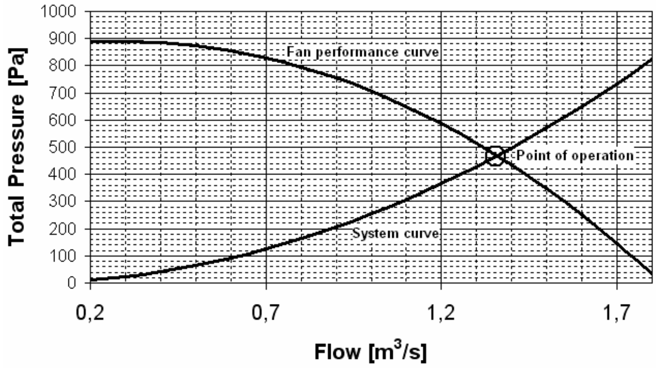

Fig. 4. Fan performance and an installation curve determining the operation point.

III. FLOW RATE CONTROL

Some industrial processes, such as: exhaustion of subway, tunnels, mines, tobacco refrigeration and climatization, and anothers, use cooling system to vary the fluid flow rate, or either, it works with the modification of the point of operation of the system [4]-[6]. The alteration of this point can be carried through from variation of the fan curve or the installation.

A. Modification of the Curve of the Installation

A common method to vary flow rate is to change the position of an outlet damper downstream of the fan [7]. Closing an outlet damper increases system pressure drop, reduces flow, and causes the operating point on the fan curve to move to the left [8].

This airflow control is used in majority of the industrial installations because it is simple and low cost. Damper is a device that varies section area of the duct, controlling the airflow. It operates manually or automatic in saw clockwise or the counter-clockwise. In Figure 3, it is showed variation of the position of damper, defining new points of operation for the new curves of installation.

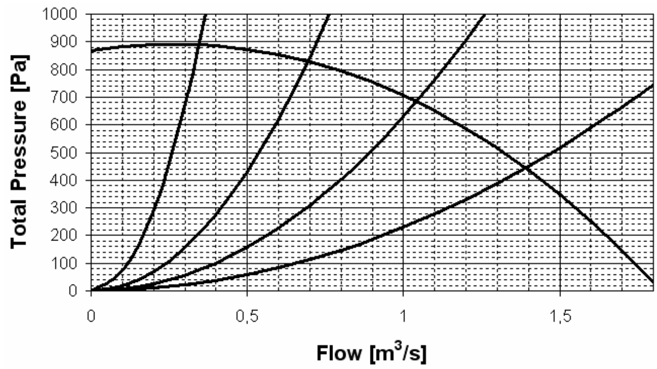

Fig. 5. Variation of the installation curve by damper.

B. Modification of the Curve of the Fan

The most energy efficient method of flow control is to vary the rotational speed of the fan. If flow rate varies continuously, fan speed can be varied by installing a variable speed drive (VSD) in the power supply to the fan motor.

So, it varies rotational speed of the fan, as show the characteristic curves in Figure 4. Variable speed is made by VSD and doing use of the fan affinity laws [8]:

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \tag{3}$$

$$\frac{P_1}{P_2} = \frac{n_1}{n_2} \tag{4}$$

Where:

n_n - Speed of rotation.
Q_n - Flow for the speed n_n.
P_n - Pressure for the speed n_n.

From (3) and (4) and of the load curve of the fan for nominal rotation, it is gotten Figure 6.

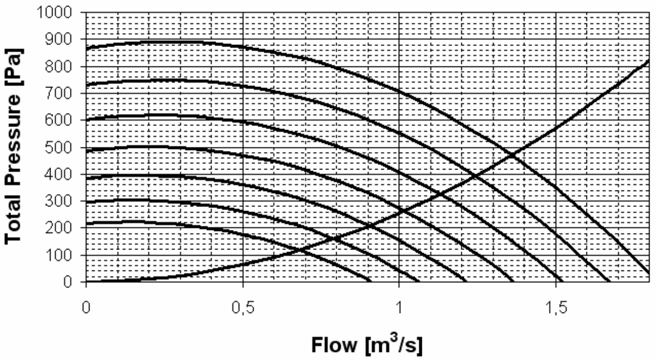

Fig. 6. Variation of the fan curve by control variable speed.

IV. ANALYSIS OF THE METHODS OF FLOW RATE CONTROL

In this section, the two methods described above are compared. In Figure 5, it observes useful power curves of the cooling system used for each method. It control can be through traditional drive for flow control the constant speed (damper) or via drive technique the variable speed by inverter. The useful power curve required for fluid to damper is shown in Figure 5 (continuum curve), while the power required for fluid to inverter is shown hatched curve in the same picture.

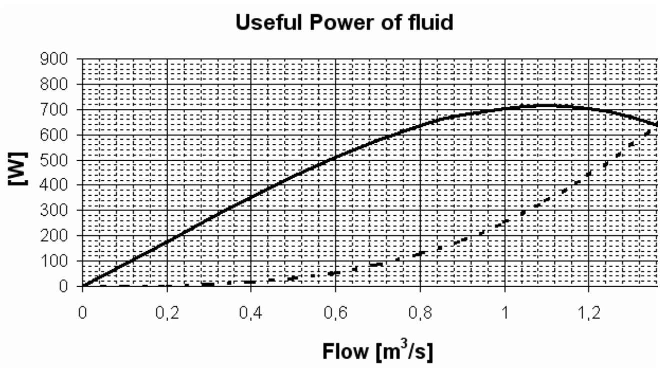

Fig. 7. Useful power required for fluid.

V. THREE-PHASE INDUCTION MOTOR

The induction motor's model implemented was carried through in the domain of the frequency, therefore it has as objective the analysis in the permanent regimen. The circuit of Figure 8, is shown with the objective to analyze the behavior of the motor for the non-sinusoidal power.

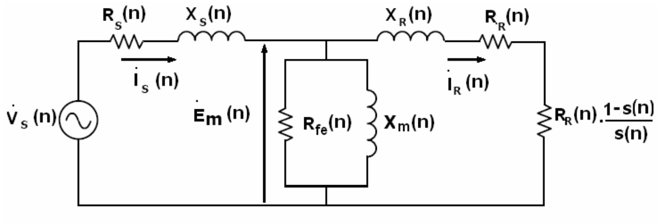

Fig.8 Circuit equivalent, for phase, for one given harmonic frequency.

Where:

R_S – Resistance of the stator.
R_R - Resistance of the rotor.
X_S - Reactance of dispersion of the stator.
X_R - Reactance of dispersion of the rotor.
X_m - Reactance of magnetization.
E_m - Induced voltage in the rotor.

Table I shows the parameters of the motor used in the computational simulation.

TABLE I
Parameters of the motor

Parameters	[Ω]
R_S	3.2116
R_R	2.2771
X_S	3.8144
X_R	5.7538
X_m	124.9945

In this circuit the adjustment of the parameters for one each frequency becomes, after that the overlapping theorem's is applied. The resistance of the stator, for small e average electric motor, in which the rolling up of the stator is constituted by conductors small-diameter, the pelicular effect does not exert significant influence in the resistance in function of the frequency. So, the resistance can be considered constant. However, for the rotor it does not occur the same, thus is calculated in (5):

$$R_R = \frac{R_R(1) \cdot K_{RR}(n)}{K_{RR}(1)} \tag{5}$$

Where:

$K_{RR}(n)$ – factor of correction of the bars of the rotor for harmonic order n.
$K_{RR}(1)$ – factor of correction of the bars of the rotor to the fundamental frequency.
$R_R(1)$ – resistance of the bars of the rotor to the fundamental frequency.
$R_R(n)$ – resistance of the bars of the rotor for harmonic order n.

The value of $K_{RR}(n)$ is calculated in agreement the work [12].

The representative resistance of the losses in the iron with the frequency is given as shown in the equation (6):

$$R_{fe}(n)=\frac{\left|E_m(n)\right|^2}{P_{fe}(n)}, \qquad (6)$$

where $P_{fe}(n)$ it is the loss in the iron in function of the frequency, gotten in function of the nominal losses for hysteresis (PH_{nom}) and Foucault current's (PF_{nom}) as the equation (7):

$$\begin{aligned} P_{fe}(n) &= n\cdot PH_{nom}\cdot\left(\frac{E_m(n)}{n\cdot E_m(1)}\right)^{KS}+ \\ &+PF_{nom}\cdot\left(\frac{E_m(n)}{E_m(1)}\right)^2\cdot K_{fe}(n) \end{aligned}, \qquad (7)$$

where KS is the constant of Steinmetz of the material and $K_{fe}(n)$ is a factor of exponential reduction of losses, similar to the factor $K_{LR}(n)$.

Thus, due to complexity of the calculations the effect of the magnetic saturation is not considered, as presented in [12], the magnetization impedance can be adjusted for a wide band of powers of the machines of in agreement induction the equation (8):

$$X_m(n)=n\cdot 0,25\cdot X_m(1) \qquad (8)$$

VI. VOLTAGE INVERTER

In the diagram of block, as shows Figure 6, the basic configuration of the inverter. In the first section, it is rectifier, where the three-phase voltage ca is converted in voltage dc, after that it comes the bank of capacitors, where the voltage is filtered and finally the inverter, where the voltage and the frequency are variable [9].

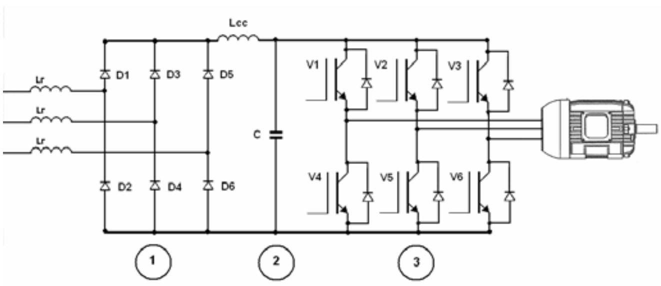

Fig. 8. Basic structure of an inverter.

Currently, the voltage inverter operating to one of commutation above of 20 commercially meets kHz. The inverter of sine voltage PWM is the employee in the study due the ample use in 10 industrial applications [10]. The control is of the V/f type, to keep the constant magnetic flow. This presents losses for commutation and conduction that influence in its income. The output voltage applied to the load, is constituted by a succession of rectangular pulses of equal amplitude to the voltage of feeding CC of input [10], as it shows Figure 9.

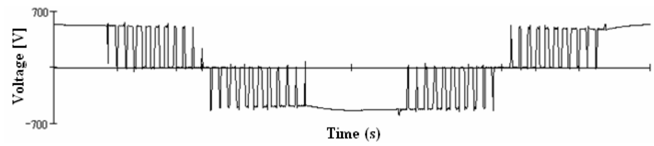

Fig. 9. Output voltage of the three-phase inverter.

VII. COMPUTATIONAL RESULTS

A. Sine power

Initially, the engine was simulated fed for sine tensions with frequency and efficient value varying according to 220 V/f relation = V/60 Hz. Considered the resistências and constant indutâncias and of the reatâncias of dispersion of the stator and the rotor, as well as the reactance of magnetization, varied proportionally with the frequency.

Figure 10 shows to the total load the one that the motor system fan is submitted, it varying flow rate for the adjustment of damper and for variable speed. It Observes in Figure 10, for one given to flow rate the use of damper it requires greater pressure of the system of that to use the method of variable speed.

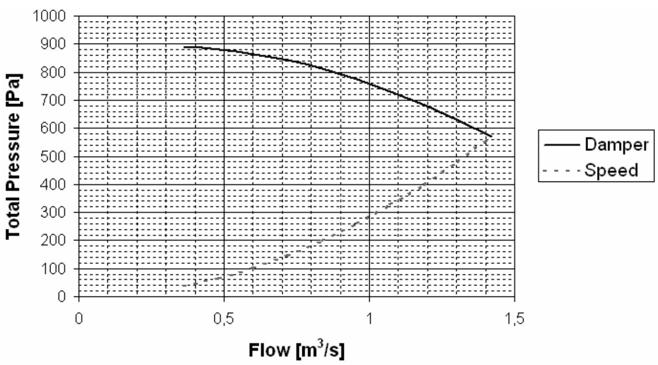

Fig. 10. Comparative of the total pressure of the system using to damper and variable speed.

Figure 11 shows power demanded for the two methods of flow control.

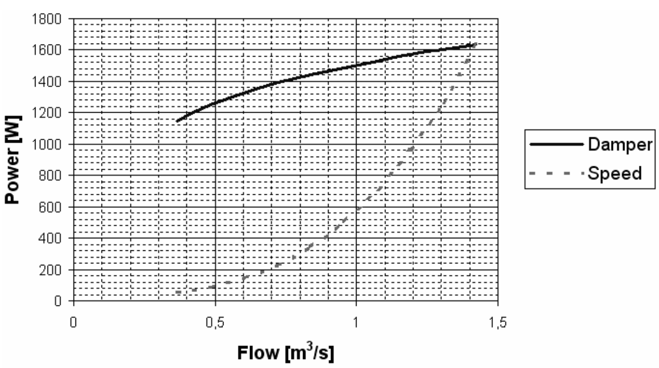

Fig. 11. Comparative of the power for the system using to damper and variable speed.

Table II shows to the demand reduction using the flow control variable speed, in relation to the power required through the flow control by damper for the same flow rate.

TABLE II
Reduction of the demand of the system

f [Hz]	Flow rate [m^3/s]	Reduction [%]
15	0.36341	95.17
20	0.48334	92.87
25	0.60265	89.09
30	0.72135	83.55
35	0.83942	75.98
40	0.95686	66.14
45	1.07366	53.84
50	1.18979	38.91
55	1.30525	21.10

As it shows to Figure 12, the total efficiency of the system is better for the use of variable speed. Being that in some few points of flow the total efficiency of the system is better for the flow control by damper.

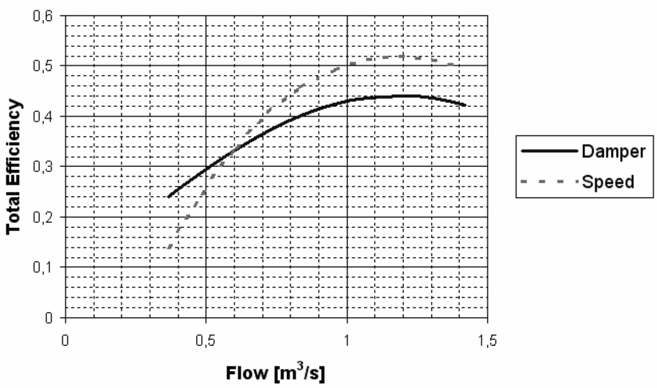

Fig. 12. Comparative degree of the income of the system using to damper and variable speed.

In table III the total efficiency of the system gotten in two distinct situations is observed. The first one mentions variable speed, while that second position of damper for attainment of the same flow is mentioned to it.

TABLE III
Total efficiency of the system

f [Hz]	Flow rate [m^3/s]	Efficiency with varible speed	Efficiency (Damper) to same flow rate
15	0.36341	0.2397	0.13989
20	0.48334	0.28984	0.24639
25	0.60265	0.33387	0.33782
30	0.72135	0.37153	0.40832
35	0.83942	0.40186	0.4595
40	0.95686	0.42387	0.49371
45	1.07366	0.43685	0.5129
50	1.18979	0.44059	0.5187
55	1.30525	0.43541	0.51265

For frequency f=15 hz, as shows table III, the efficiency of the system is better with the use of damper.

B. Power non-sinusoidal

From the modeling of the presented motor, it is determined of the losses in the motor happened of the non-sinusoidal power. To compare the experimental values, it was become fullfilled simulation for the frequency of 60 Hz. Table IV shows to the comparison between the electric variable and internal losses of the motor for a sinusoidal power and a non-sinusoidal power.

TABELA IV
Comparison between the methods of flow control

Active Power		Reactive Power		Power Factor		Efficiency	
[W]	[%]	[VAr]	[%]	-	[%]	[%]	[%]
7,548	0,557	61.957	8,683	-0,016	-1,78	-0,011	-0,014
P_joule_stator		P_joule_rotor		P_iron		P_add	
[W]	[%]	[W]	[%]	[W]	[%]	[W]	[%]
0,433	0,535	2,398	3,481	0,266	0,82	4,44	65,588

It considers the constant rotational losses, data to the rotation speed to be practically the same one. Still, the determination of the values of the add losses is based on [12], where these are equal 0.5% and 8% of the active power of the motor, respectively for the cases of sinusoidal and non-sinusoidal power (specifically a wave form of voltage of a voltage inverter with sine modulation PWM). This justifies the high increase of these losses.

VIII. EXPERIMENTAIS RESULTS

The experimental data had been collected in the LAMOTRIZ, after to reach it thermal estalibility of the motor. The temperature measured in the carcass of the engine was of 47,5 ^{0}C. Amongst the assays daily pay-to eliminate, became fullfilled the assay of close damper and the assay of speed variable speed via inverter.

In table V, it is verified power for some positions of damper.

TABLE V
Power required for position of damper

Damper	Power [W]
Close	722
Open (50%)	911
Open (100%)	972

Figure 14 shows the power required by system from the inverter.

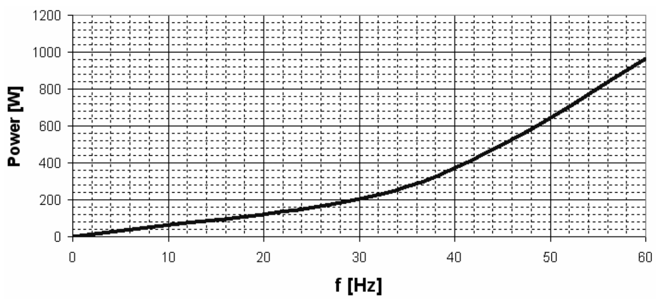

Fig. 14. Power required for the motor.

In table VI, it is verified power required for some frequencies for the motor gotten from the inverter.

TABLE VI
Power required measuringfor some frequencies

Frequency [Hz]	Power [W]
30	206.5
45	497.8
50	917.6
60	965

IX. CONCLUSION

The group of benches of industrial cooling of the LAMOTRIZ intends to simulate the different systems of installed in an industry, aiming at to the energy efficiency and considering solutions that contribute for the reduction in the consumption of electric energy. The study it analyzes the operation of the industrial fans in constant speed, in general used in the park manufacter, comparing it with the use of the system of variable speed by inverter, aiming at to the variation of the flow rate and pressure of the fluid and consequently the energy economy.

It concludes that from the data shown in Figure 5, it exists potential of reduction in the consumption of electric energy. By means of simulation still verifies the best efficiency of the system as shows Figure 12 and it table III. However, more measurements are necessary for better analysis of the energy efficiency of this system.

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