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OPTIMAL U/f CONTROL FOR INDUCTION MOTORS

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Abstract: This article presents a methodology to find an optimal U/f curve that minimizes the energy consumption in induction motors that drive loads where the torque is proportional to the square of the speed, such as centrifugal pumps and fans; the experimental results presented here validate this methodology. *Copyright © 2002 IFAC*

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1. INTRODUCTION

In industrial induction motors applications, around the 65% of them drive pumps and fans; in most of these applications, the motors operate under their nominal operating point; the applied stator voltage creates a rotating magnetic field that induces rotor currents, generating torque in the shaft; if the nominal torque is not required, the nominal magnetic field won't be required and the currents produced by the additional magnetic field increases losses, decreasing the motor efficiency.

In many industries, the induction motors are controlled by variable frequency drives with the Volts/Hertz (U/f) control; this strategy intends to keep a constant flux, imposing a constant volts/hertz ratio. These drives have flexible configuration in order to be adapted to different loads, and the users can specify the desired U/f curve. However, most of the times, the practical criterion to choice the U/f curve are unknown, so that is not possible to obtain high drive performance.

In current literature, several methods intending to maximize motor efficiency have been proposed (Ramirez, 1998); in variable frequency drives for pumps and fans, Jarc and Robechek (1982) show that the use of a variable speed drive to control flow, instead of constant speed drive and throttle valve, increases the pump efficiency, reducing the global energy consumption; to improve motor efficiency in steady state, several authors have searched the optimal operation points; Kirschen *et. al. (*1985) proposed a heuristic method that change the flux online, seeking decrease the total input power; Famouri *et. al*. (1991) use the Kirschen's ideas in order to get the optimal slip frequency for an U/f control strategy; Park and Sul (1984) obtain experimentally the optimal slips for several operation points in U/f controls; other authors have attacked the problem by analytic methods; Kusko and Galler (1983) calculated the optimal slip that minimizes the Joule losses; Seleme and Canudas (1992) consider additionally the magnetic energy stored in the inductances; García *et. al.* (1992) considered the core losses.

The most part of the proposed algorithms were relatively complexes for their application in industrial commercial drives with U/f control; on the other hand, some of the theoretical results are simple to implement, however, at the most of our knowledge, there are not applications of these analytical results in industrial commercial U/f drives.

In this paper a simple result is introduced that allows to calculate an optimal U/f curve that improves the motor efficiency, when the motor drives centrifugal pumps or fans; in the next section, the U/f control technique is briefly revised; then, the optimal flux condition given by Seleme and Canudas (1992), is applied to pumps and fans loads; in section 4, the experimental results carried out in the Electrical Drives Laboratory of the Universidad del Valle are presented; finally, the conclusions of this work will be introduced.

2. THE VOLTS HERTZ CONTROL STRATEGY

The U/f control strategy is obtained from the stationary motor model, assuming sinusoidal and symmetrical stator voltages, and negleting the drop voltage in the stator resistance R_s.

When the induction motor is part of a variable speed drive, the RMS stator voltage magnitude U_s and his frequency w_a could differ from their rated values U_{s0}, w_{a0}; the normalized steady state torque is given by (Leonhard, 1996):

$$y = y_{p0}\left(\frac{U_s / w_a}{U_{s0} / w_{a0}}\right)^2 \frac{2}{S/S_p + S_p/S} \qquad (1)$$

where y_{p0} is the maximal torque at nominal voltage and frequency; S/S_p is the normalized slip (S_p is the slip for maximum torque), given as:

$$\frac{S}{S_p} = \frac{\sigma \cdot w_s \cdot L_r}{R_r} \qquad (2)$$

where σ is the leakage factor of the motor, L_r is the rotor inductance, R_r is the rotor resistance and w_s is the rotor frequency or slip frequency.

Assuming negligible the drop voltage in the stator resistance R_s, the stator flux magnitude can be written as (Vas, 1992):

$$\| \Phi_S \| = k \frac{U_S}{w_a} \qquad (3)$$

where k is a constant; substituting the equation (3) in (1), the torque can be expressed by:

$$y = k_1 \|\Phi_S\|^2 \left(\frac{1}{k_2 w_s + \left(1/k_2 w_s\right)}\right) \qquad (4)$$

where k_1 and k_2 are constants.

In the classical U/f control, the flux is maintained constant while the slip is changed in order to vary torque, see equation (4). On the other hand, it is possible to keep constant the slip, and to use the flux to vary torque; this permits to adequate the magnetic state of the machine to the operating value of torque, improving efficiency; this strategy will be presented in more detail in the following section.

Additionally, in the U/f control, it must be considered other restrictions, in fact, at low speed, it should be compensated the tension drop in R_s in order to maintain the desired flux (the stator resistance become dominant with rapport to the magnetization reactance); on the other hand, flux should be reduced at high speed to avoid inverter saturation. The figure 1 shows a scheme of the U/f control; in the function $f_u(w_a)$, the mentioned restrictions are considered. The function $f_f(w_{ref})$ calcules the stator frequency in order to obtain the desired speed w_{ref}, by:

$$w_a = u w_{ref} + w_s \qquad (5)$$

where u the number of pole pairs.

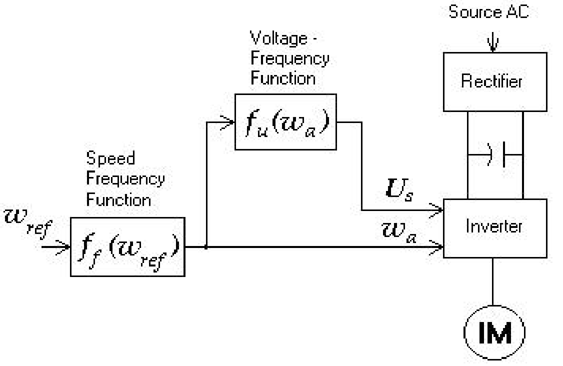

Fig. 1. Scheme of the U/f Control.

Then, the basic idea of this strategy is to impose the flux level via the tension magnitude U_s and the desired speed via the stator frequency w_a.

The Volts/Hertz control has poor dynamic performances but is useful in applications where the torque is constant for long time intervals, such that pumps and fans; on the other hand, is a simple technique easy to implement; taking advantage of this feature, in the following section it will be find the relationship between voltage and frequency that improve the efficiency of motors driving centrifugal pumps or fans.

3. THE OPTIMAL U/f CURVE

Seleme and Canudas (1992) obtained the magnitude of the rotor flux, for the minimal energy operation condition:

$$\left\|\Phi_r^*\right\| = \beta \cdot \sqrt{|y|} \qquad (6)$$

Here, β is a constant; note that this condition demands to vary the flux magnitude with the generated torque; considering negligible the drop voltage in the stator resistance R_s and the magnetizing reactance bigger than the leakage reactance, the stator flux could be approached to:

$$\left\|\Phi_S\right\| \approx \frac{L_m}{L_r}\left\|\Phi_r\right\| \tag{7}$$

From (6) and (7), the torque varies cuadratically with the stator flux; this implies (see equation 4) a constant slip frequency w_s at diferent torque levels:

$$\left\|\Phi_S^*\right\| = k_3\sqrt{w^2} = k_3\left|w\right| \tag{8}$$

Therefore, the stator flux should vary proportionally with the speed magnitude, from (3), the stator voltage that should be applied to the motor in order to get the optimal flux is:

$$U_S^* = k_4 \cdot \left|w\right| \cdot w_a \tag{9}$$

from (5):

$$u \cdot w = w_a - w_s \tag{10}$$

then:

$$U_S^* = k_5 \left|f_a - f_s\right| \cdot f_a \tag{11}$$

The frequencies f_a and f_s are in Hertz in this equation, where the slip frequency f_s remains constant at its nominal value f_{s0} in the whole speed range.
In general, the induction motor presents its maximum efficiency between 75% and 100% of the nominal torque; therefore, is possible to specify k_5 in order to match the rated voltage U_{s0} at the rated frequency f_{a0}:

$$k_5 = \frac{U_{s0}}{f_{a0}^2 - f_{s0} \cdot f_{a0}} \tag{12}$$

Equations (11) and (12) define a new curve that optimize the energy consumption in the motor; note that the parameters of the curve can be obtained from the nameplate datas.

This curve can be easily implemented in an industrial drive as it will show in the next section.

4. EXPERIMENTAL VALIDATION

4.1 Testbed Description.

The figures 2 and 3 show the block diagram and the testbed used for the experimental evaluation; it consists of the following equipment:

-An industrial variable frequency drive of 6 HP that provides a three-phase voltage with variable magnitude and frequency in agreement with a linear or parabolic U/f characteristic.

-A three-phase squirrel-cage induction motor, with the following nameplate datas: 1/4 HP, 2870 r.p.m., 220V., 50Hz., connected in star with isolated neutral, $R_s = 9.88\Omega$, $R_r = 8.78\Omega$, $L_s = 0.898H$, $L_r = 0.917H$, $L_m = 0.860H$.

-A DC generator independent excited, of 1/4 HP, 3000 r.p.m., 220 V D.C.

-A Mechanics Loads Emulator (MLU 188, of the Feedback), that varies the generator current, and then the mechanical load torque in the shaft; load torque and speed are measured in this unit.

Finally, a taco-generator of 2Volts_d.c./1000 rpm., installed in the shaft of the DC generator.

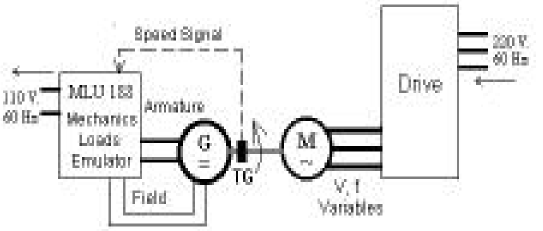

Fig. 2. Block Diagram of the Testbed.

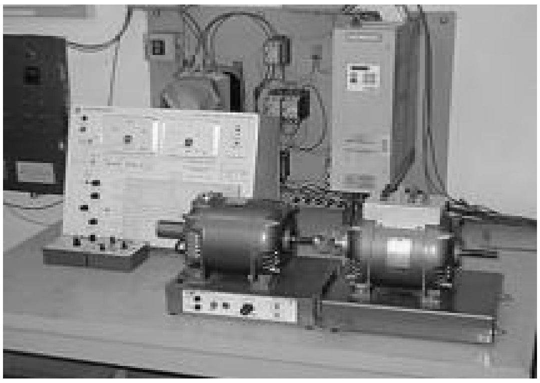

Fig. 3. The experimental Drive System

4.2 Experiment description

For the experimental evaluation, a parabolic load was used with nominal point equal to the rated operation point of the motor. Some points of the torque-speed emulated load are shown in the following table:

Table 1. Points of the Torque vs. Speed Emulated Load

TORQUE –Nm	SPEED –r.p.m
0,650	2870
0.450	2391
0.290	1913
0.175	1489

The objective of the experiment is to compare the energy consumption given by the optimal U/f curve (CME), the parabolic curve (PF) given by the manufacturer for this kind of loads, and the linear or classic U/f curve (LF); these curves are given by the following relationships:

CME: $U_s = 0.092\,(f_a^2 - 2.16\,f_a)$
(Obtained according to the procedure described in the previous section).

PF: $U_s = 0.0499\,f_a^2 + 1.9162\,f_a$
(Obtained from a two-order Polynomial Regression of measured data).

LF: $U_s = 4.4\,f_a$
(Obtained from a Linear Regression of measured data).

Where U_s is the line to line RMS magnitude of the voltage in Volts and f_a is the applied frequency in Hertz. The curves are illustrated in the figure4.

It can be observed that the smaller losses correspond to the CME curve; at 80% of the nominal speed, 2296 rpm, the CME wins 2 watts with rapport to the PF, a little more than one point of efficiency; with regard to the LF curve, CME wins 6 watts, which correspond to four points of efficiency, like is illustrated in the figure 6. It can also be noted that at low speed, when the motor operates very far from its nominal operation point, the losses decrease in 24%, which gives improvements of 6 points in efficiency.

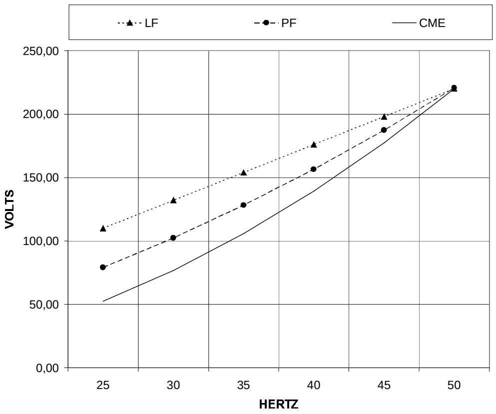

Fig. 4. Voltage vs. frequency curves.

Note that for very low and high frequency values are not considered here, this comes from the fact that in these operation regions, the curve would be defined by the constraints given for the classical U/f control, i.e. the R_s voltage-drop compensation and flux weakening to avoid the inverter saturation.

4.3 Experimental Results

The figure 5 shows the losses obtained in the three cases, for different speeds; the losses were calculated from the difference of the electrical power consumed by the motor and the mechanical power in the shaft which was calculated from the speed and torque measured in the MLU.

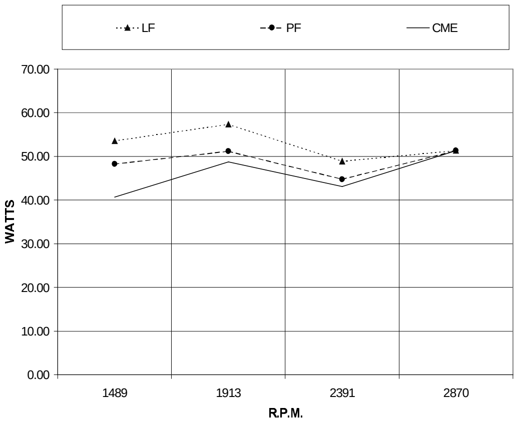

Fig. 5. Losses vs. Speed

The CME strategy also contributes to improve the power factor, such as it can be observed in the figure 7. Note that among the 70% to 80% of the nominal speed, the power factor obtained with the CME is better than the nominal one, and it is always above the other control strategies.

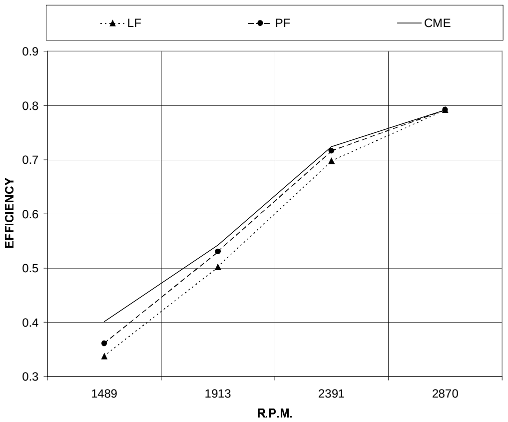

Fig. 6. Efficiency vs. Speed

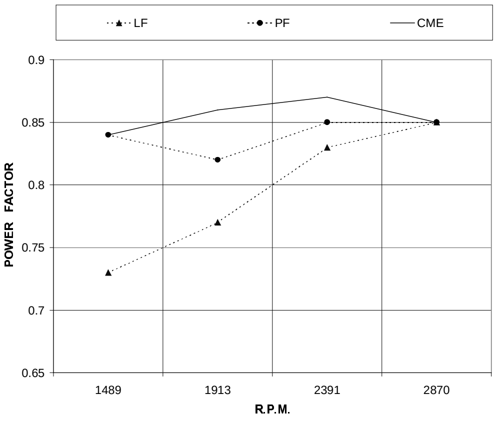

Fig. 7. Power Factor vs. Speed

5. CONCLUSIONS

A methodology has been presented to calculate U/f curves that improve the efficiency in an electrical drives for pumps and fans; the curves can be directly parametriced from nameplate datas; then it is easy to apply in industrial commercial drives without doing extensive or costly experiments.

Energy savings were achieved up to 12 watts (24% of the total losses), with improvement of the power factor up to 10 percentage points.

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