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The Study and Evaluation of the 3phase Induction Motor Controlled by an Inverter to Identify Power Losses and Energy Saving

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Abstract

The control of induction motors through an inverter has many advantages. By changing the frequency and size of the supply voltage, a better efficiency at load conditions can be achieved outside the rated operation. In this study, tests were conducted on a laboratory device for a three-phase induction motor of 1Hp capacity that was driven by an inverter. The induction machine loading was done via a magnetic brakes machine, while all the necessary measuring devices were used in order to record the necessary electrical magnitudes with accuracy and detail. Through specific tests, the components of the detailed electrical equivalent circuit were determined. The vector control technique was used on inverter operation. Through this study, the authors concluded that a drive system can be driven on different frequency levels without a great loss of torque. Furthermore, energy can be saved by operating in lower frequencies for smaller loading, having an equally satisfactory level of performance. It is also worth to mention the friendliness of the inverter to control the motor speed, the smooth (soft) starting and the high degree of efficiency in all frequency ranges.

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Keywords

Induction motor drives; electrical machines; efficient operation of electrical machines

I. Introduction

Three-phase squirrel-cage induction motors are widely used in industrial drives because they are rugged, reliable and economical. Although traditionally used in fixed-speed service, induction motors are increasingly being used with variable-frequency drives (VFDs) in variable-speed service.

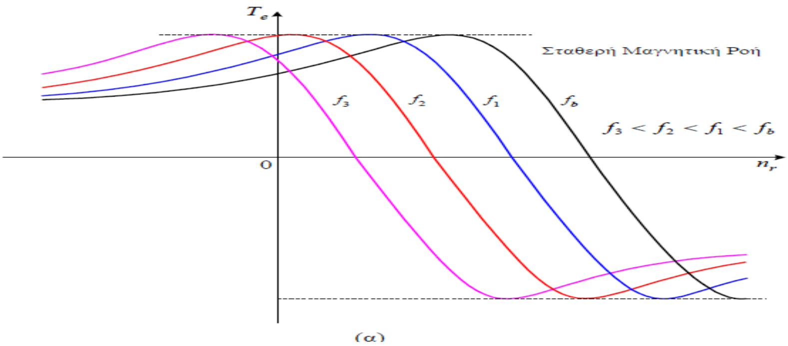

Fig. 1. Torque to frequency

VFDs offer especially important energy-saving opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications. Squirrel cage induction motors are widely used in both fixed-speed and variable-frequency drive (VFD) applications. Variable voltage and variable frequency drives are also used in variable-speed service.

It is estimated that more than 50% of the world electric power is consumed by induction motors. Improving the efficiency in electric drives is very important, both for economic saving and for the reduction of environmental pollution [1,2]. Even though induction motors have a high efficiency at rated speed and torque, at low loading motor efficiency decreases dramatically due to an imbalance between the copper and the core losses. Hence, energy saving can be achieved by controlling the flux level in the motor [3,4]. The main induction motor losses are usually split into: stator copper losses, rotor copper losses, core (iron) losses, mechanical and stray losses. To improve the motor efficiency, the flux must be reduced, obtaining a balance between copper and core losses. Induction motor drive can be controlled according to a number of performance functions, such as input power, speed, torque, airgap flux, power factor, stator current, stator voltage, and overall efficiency [5].

Full load motor efficiency varies from about 85% to 97%, related motor losses being broken down roughly as follows:

- Friction and windage, 5% – 15%
- Iron or core losses, 15% – 25%
- Stator losses, 25% – 40%
- Rotor losses, 15% – 25%
- Stray load losses, 10% – 20%.

II. Method

A small industrial three-phase induction motor was tested in the laboratory. The topology of the electric circuit is shown below:

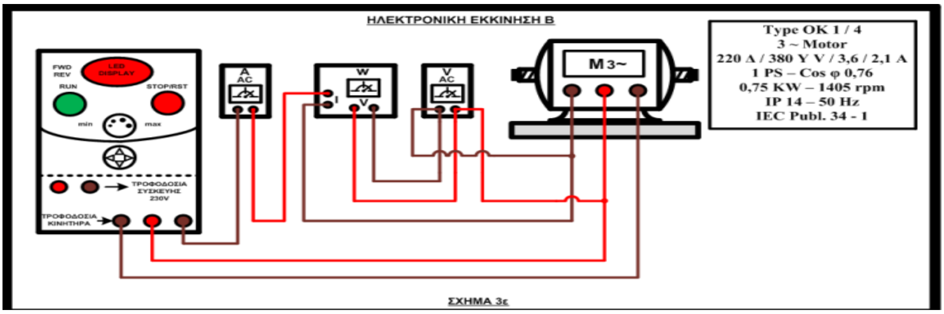

Fig. 2. Equivalent connection diagram for the experimental setup

In order to test the motor in loading, an electromagnetic breaking system on the axle was used, as shown in the picture below.

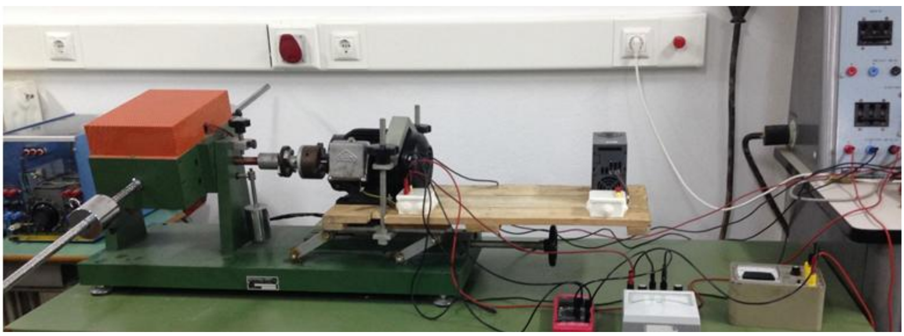

Fig. 3. Experimental setup. In this assembly, it is very helpful that also the torque can be calculated with a satisfying accuracy

III. Mathematical modeling

For the analysis of the operation of the ac motor the well known single-phase equivalent electric circuit was used [6].

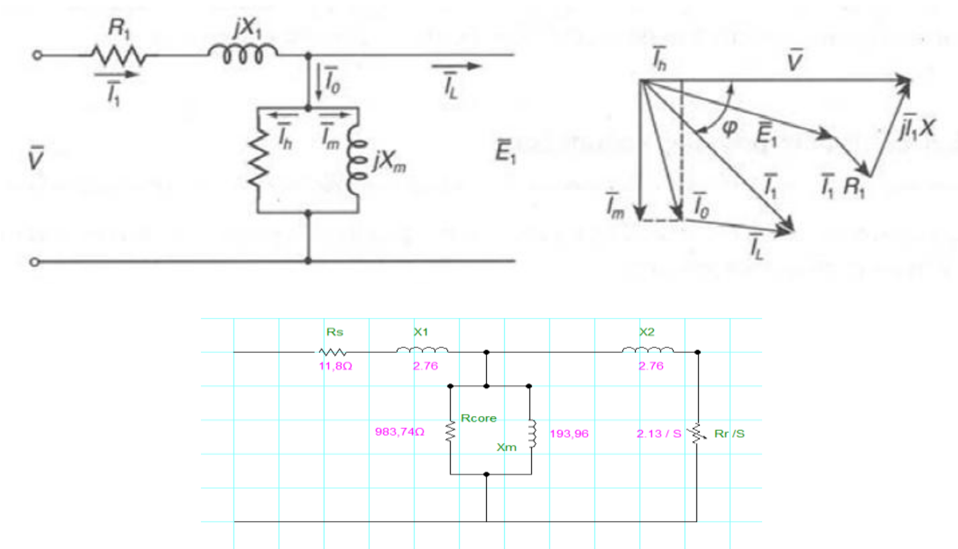

Fig. 4. Equivalent single-phase electrical circuit for the induction motor of out tests

The parameters of the circuit were calculated through the locked rotor and open no load test of the motor.

$$Rs = 11.8\Omega$$
$$R_r = 2.13\,\Omega$$
$$X = Xs = Xr$$
$$L = \frac{x}{2\,\pi\,f} = 0.0088\text{ H}$$
$$Rcore = 983{,}74\Omega$$
$$X_m = 193{,}96$$
$$V_1 = I_1(R_1 + jX_1) + E_1 \;\; <=>$$
$$V_1 = (I_0 + I_L)(R_1 + jX_1) + E_1$$

Where:

I_1 : rms value of phase current (A)
R_1: resistant of phase stator winding Rs(Ω)
X_1= $2\pi f 1 L_1$: inductance of phase stator winding (Ω)
I_L: load current (A)
E_1 : induced EMF per phase in stator winding

Also

$$I_0 = I_m + I_h$$

where:

I_m : magnitude current (A)
I_h : hysteresis and dynes current (A)

In rotor:

$$E_{2s} = 4.44 K_2 f_2 N_2 \Phi_{\delta\iota\alpha\kappa}$$

$$E_{2s} = I_2(r_2 + j2\pi f_2 L_2) = I_2(r_2 + jsx_2)$$

where:
I_2: per phase rotor current (A)
r_2 : per phase resistance (Ω)
$L_{2,}$ x_2: inductance of phase in rotor winding (H, Ω)
sx_2 : inductance on rotor frequency (Ω)

Also:

$$n_s = 120\frac{f_1}{P}$$

$$\omega_s = 2\pi\frac{n_s}{60} = \frac{2}{P}2\pi f_1 = \frac{2}{P}\omega_1$$

$$S = \frac{n_s - n_r}{n_s} \text{ or } S(\%) = \frac{n_s - n_r}{n_s} \times 100 \text{ or , } S = \frac{\omega_s - \omega_r}{\omega_r}$$

$$f_2 = \frac{P}{2}\frac{(n_s - n_r)}{60} = \frac{P}{2}S\frac{n_s}{60} = Sf_1$$

Power loss in ac induction motors:

There are electrical (Cu), magnetic (iron) and mechanical power losses:

$$\text{Stator: } P_{iron\,(s)} = k_e \omega^2{}_e \Phi^2{}_m + k_h \omega_e \Phi^n{}_m$$

$$Roror: P_{iron\,(r)} = k_e (s\omega_e)^2 {\Phi_m}^2 + k_h s\omega_e \Phi^n{}_m$$

$where\ Ke = machine\ constant,$
$\Phi_m \quad = magnetic\ flow$
ω_e=radial speed

$$P_{iron\,(s+r)} = [\,k_e(1+s^2){\omega_e}^2 + k_h(1+s)\omega_e]{\Phi_m}^2$$

Correspondingly:

$$P_{cu_s} = 3R_s I^2{}_s$$

$$P_{cu\_r} = 3R'_r I'^2_r$$
$$\mathrm{P_{cu}} = \mathrm{P_{cu\_r}} + \mathrm{P_{cu\_s}}$$
$$P_{fw} = C_{fw} n_r^2$$

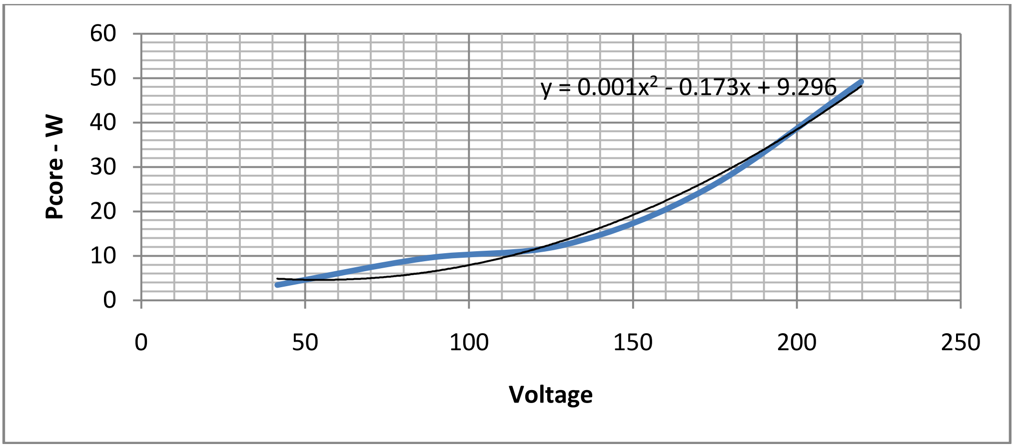

Fig. 5. In figure above the core (iron) power losses can be related to the voltage level.

IV. Inverter Drive Technique

A commercial inverter drive for ac motor control was used. The drive is connected to the network (single phase). The is a simple rectifier that provides a dc bus at 320V (=230*sqrt(2)). The inverter used the vector control technique in order to produce the desired Voltage and frequency on the three phase output.
The various strategies for controlling induction motors provide good steady state response but low dynamic response [8-9].

The reason why the dynamic response is low is that the magnetic gap flow coupling deviates from the specified value. Variations in the magnetic flow must be controlled by the size and frequency of the phase currents of the stator and the rotor, and by their instantaneous phase to be as small as possible deviation of the phase and magnitude of the flow in the gap.

The oscillations of the gap flow causes vibrations in the electromagnetic torque and, if not controlled, causing oscillations in the speed, which is undesirable in many demanding applications.

As in dc motors, and so on ac, it is possible to control both the flow of power and torque. The stator current vector may be analyzed along the rotor flux. The component parallel to the rotor flux corresponding to the current producing the field. This requires, however the position of the rotor flux at any time. If possible, control of ac motors is much like the corresponding control in dc separately excited motors.

- measure of the stator current vector: $i_s = \sqrt{(i_{qs}^e)^2 + (i_{ds}^e)^2}$
- Angle of the vector of the stator current : $\theta_s = tan^{-1}\{\frac{i_{qs}^e}{i_{ds}^e}\}$
- i_{qs}^e και i_{ds}^e are the currents in the d and q axes of the synchronous rotating reference system resulting from the projection of the stator current vector in the d and q axes .

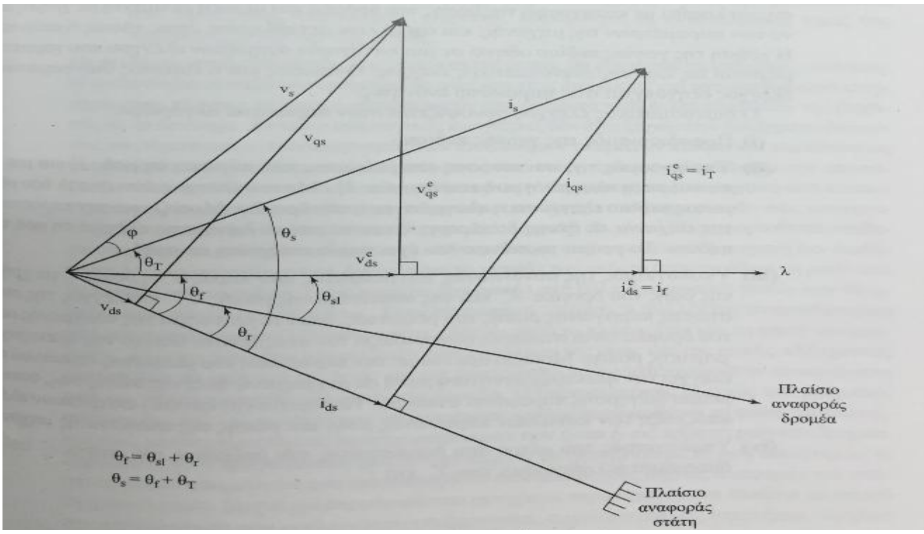

Fig. 6. Vectors for vector control technique

The figure above shows that the magnitude of the stator current vector remains constant regardless of the choice of the reference system. The illustration is the power producing flow lr and torque Te of the rotor. The current component that produces the flow of the rotor must be in phase with lr. The if component is generating the field and the transverse component iT produces torque. The if and iT have only components dc in the stationary state because the relative speed relative to that of the rotor field is zero: the vector of braided rotor flow has a velocity equal to the sum of the rotor speed and the slip and is equal to synchronous speed. The orientation of the vector of braided flow cursor lr dictates to θf = θr + θsl

We assume that the current components that produce flux and torque are components dc. Therefore it is ideal to be used as control variables.

Prerequisite for the implementation of vector control is to record the instantaneous position of the vector of the rotor flux thf, with

$$\theta_f = \int (\omega_r + \omega_{sl})dt = \int \omega_s dt$$

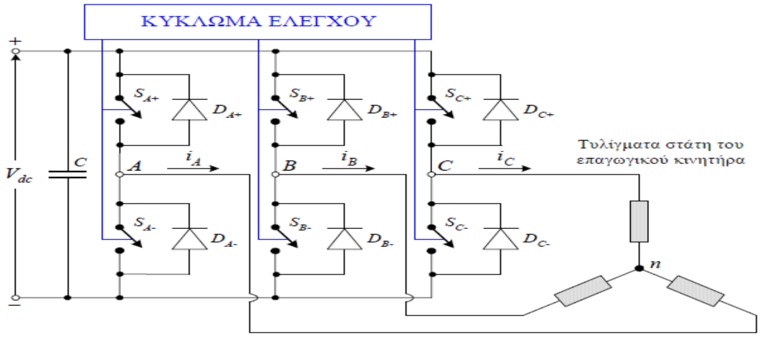

Fig. 7. Inverter equivalent circuit

The whole idea of the well known vector control technique is to drive the 3-phase ac motor as dc motor by the use of the feedback control. PWM technique is used for firing the power switching components in the appropriate timing.

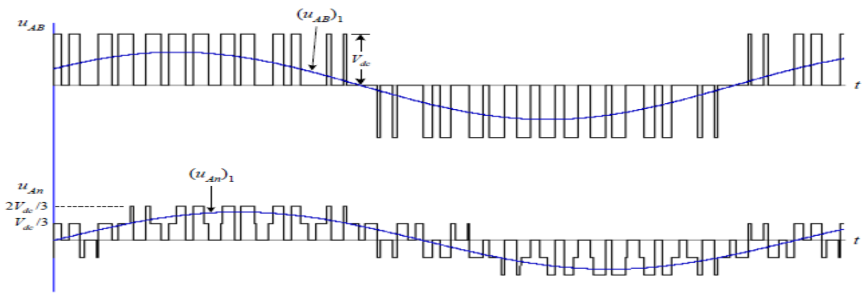

Fig. 8. PWM technique for an harmonic signal production

V. Testing scenarios – Results

Specific scenarios of loading the motor were investigated. At first there was a load test without inverter drive, just connected to the network with nominal voltage and frequency. This scenario was the base one.

n(rpm)	Pin (W)	I (A)	Vπολ(V)	Vφασ(V)	kgm	T (Nm)	cosΦ	Pout (W)	%synt_apo
1498	130	2,1	234,6	135,450	0,027	0,265	0,152	41,547	31,959
1458	550	2,5	227,2	131,178	0,272	2,670	0,559	407,612	74,111
1445	620	2,75	224,4	129,561	0,350	3,433	0,580	519,400	83,774
1429	820	3	220,8	127,483	0,418	4,100	0,715	613,525	74,820
1415	900	3,25	219,8	126,905	0,457	4,482	0,727	664,028	73,781
1400	1000	3,5	217,3	125,462	0,525	5,149	0,759	754,838	75,484

Pcus (W)	Pcore(W)	Prot(W)	s	Pag(W)	Pcure(W)	Pconv(W)	out_th(W	a%_th	T_th
52,038	50,100	23,569	0,001	27,862	0,037	27,825	4,256	3,274	0,027
73,750	50,100	22,939	0,028	426,150	11,932	414,218	391,279	71,142	2,563
89,238	50,100	22,735	0,037	480,663	17,624	463,038	440,304	71,017	2,910
106,200	50,100	22,483	0,047	663,700	31,415	632,285	609,802	74,366	4,075
124,638	50,100	22,263	0,057	725,263	41,098	684,164	661,902	73,545	4,467
144,550	50,100	22,027	0,067	805,350	53,690	751,660	729,633	72,963	4,977

Fig. 9. Measurements for base scenario

The next scenarios that were applied on the test system were by use of an inverter drive, with V/F ratio constant, in different varying frequencies from 20Hz to 60Hz.

The basic idea was to measure the power loss and to investigate its variation. For low loading conditions, it is preferable to run in lower speed, with low frequency and low Voltage correspondingly. Lower speed means low mechanical losses, and lower Voltage means less magnetic - iron losses.

Below several measurements are presented:

A. 40Hz

n(rpm)	Pin (W)	I (A)	Vπολ(V)	Vφασ(V)	kgm	T (Nm)	cosΦ	Pout (W)	%synt_ap
1197	110	1,9	201,5	116,339	0,027	0,265	0,166	33,393	30,357
1151	470	2,5	193	111,432	0,233	2,288	0,562	275,815	58,684
1140	600	2,75	192,5	111,143	0,330	3,242	0,654	387,004	64,501
1133	680	3	191,8	110,739	0,379	3,719	0,682	441,191	64,881
1118	780	3,25	191,2	110,393	0,447	4,386	0,725	513,489	65,832
1107	840	3,5	190,9	110,219	0,476	4,672	0,726	541,596	64,476

Pcus (W)	Pcore(W)	Prot(W)	s	Pag(W)	Pcure(W)	Pconv(W)	out_th(W	a%_th	T_th
42,598	35,470	18,833	0,003	31,932	0,080	31,852	13,019	11,836	0,104
73,750	35,470	18,109	0,041	360,780	14,732	346,048	327,939	69,774	2,721
89,238	35,470	17,936	0,050	475,293	23,765	451,528	433,592	72,265	3,632
106,200	35,470	17,826	0,056	538,330	30,057	508,273	490,447	72,125	4,134
124,638	35,470	17,590	0,068	619,893	42,359	577,533	559,943	71,788	4,783
144,550	35,470	17,417	0,078	659,980	51,148	608,832	591,415	70,407	5,102

Fig. 10. Measurements for 40Hz tests

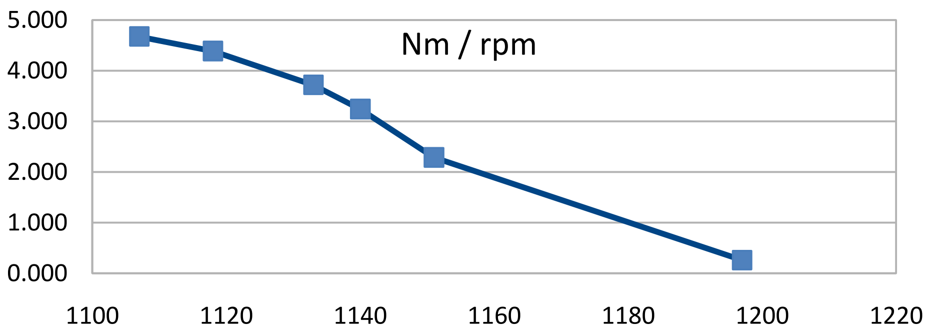

Fig. 11. Torque to rpm

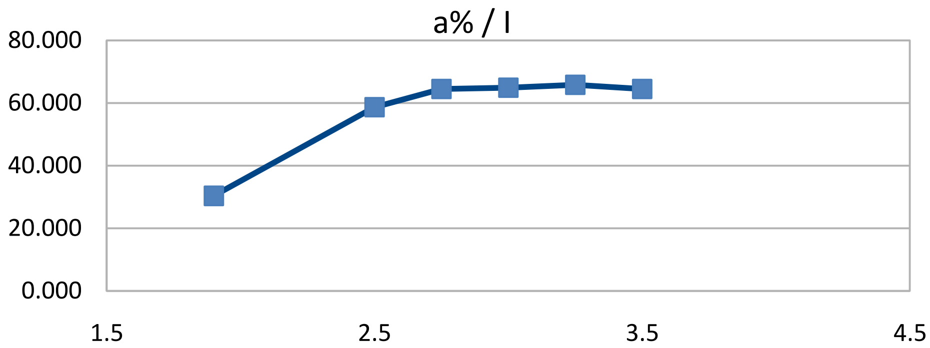

Fig. 12. Performance to current

B. 60Hz

n(rpm)	Pin (W)	I (A)	Vπολ(V)	Vφασ(V)	kgm	T (Nm)	cosΦ	Pout (W)	%synt_ap
1796	150	1,6	237,0	136,836	0,025	0,245	0,228	46,122	30,748
1755	450	2,0	227,1	131,120	0,194	1,907	0,572	350,460	77,880
1727	680	2,5	222,8	128,637	0,301	2,956	0,705	534,547	78,610
1710	790	2,8	220,8	127,483	0,360	3,528	0,751	631,727	79,965
1698	860	3,0	219,9	126,963	0,399	3,909	0,753	695,110	80,827
1681	970	3,3	218,2	125,982	0,428	4,196	0,790	738,503	76,134
1669	1030	3,5	217,5	125,577	0,457	4,482	0,781	783,224	76,041

Pcus (W)	Pcore(W)	Prot(W)	s	Pag(W)	Pcure(W)	Pconv(W)	'out_th(W	a%_th	T_th
30,208	52,430	28,257	0,002	67,362	0,150	67,212	38,955	25,970	0,207
47,200	52,430	27,612	0,025	350,370	8,759	341,611	313,999	69,778	1,709
73,750	52,430	27,171	0,041	553,820	22,460	531,360	504,188	74,145	2,788
89,238	52,430	26,904	0,050	648,333	32,417	615,916	589,012	74,558	3,290
106,200	52,430	26,715	0,057	701,370	39,744	661,626	634,911	73,827	3,571
124,638	52,430	26,448	0,066	792,933	52,422	740,511	714,063	73,615	4,057
144,550	52,430	26,259	0,073	833,020	60,625	772,395	746,136	72,440	4,269

Fig. 13. Measurements for 60Hz tests

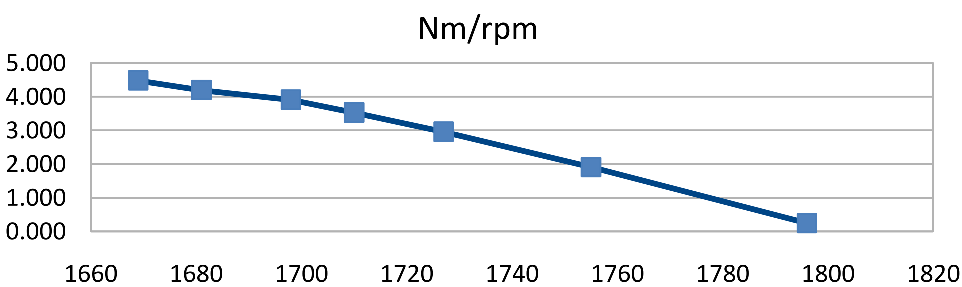

Fig. 14. Torque to rpm

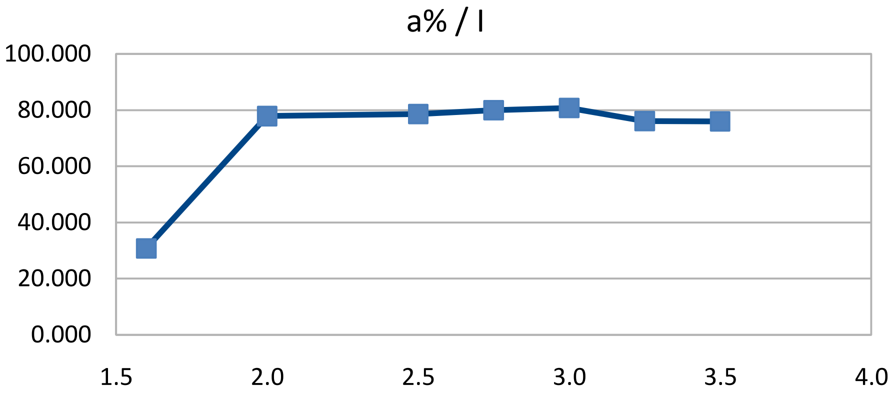

Fig. 15. Performance to current

Y: Torque – X: rpm

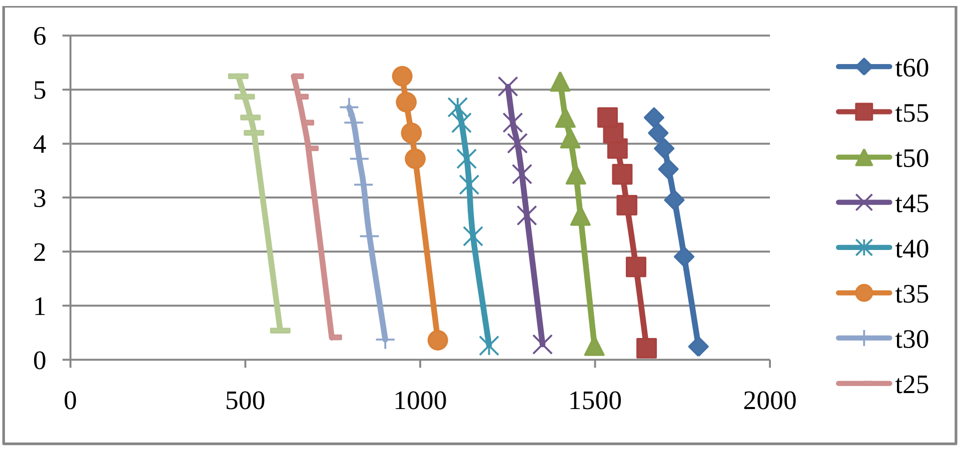

Fig. 15. Torque to rpm

In the above graph it is obvious that practically in all the frequency levels of the motor, the torque response is quite satisfactory. So in applications where high torque is necessary, the motor can operate also in lower levels of frequency and hence less power consumption.

Y: Efficiency – X: rpm for different frequencies

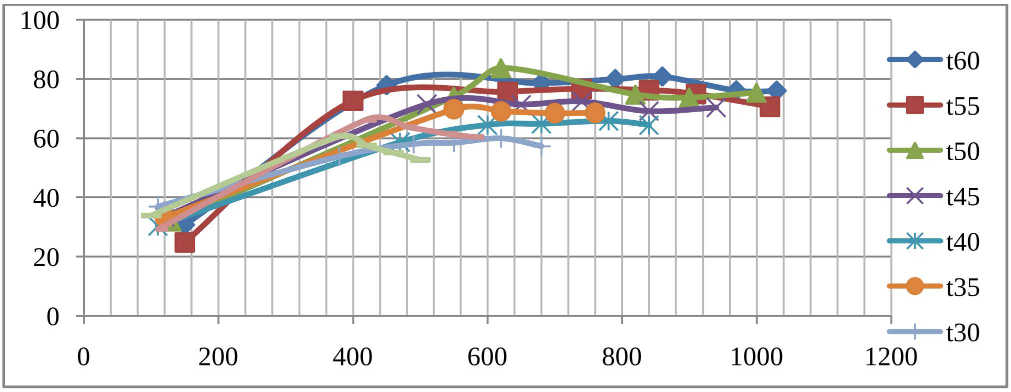

Fig. 16. Performance to rpm

From the above chart we see that the motor efficiency at frequencies 45Hz to 60Hz is quite satisfactory. We also note that the performance at different frequencies of operation is relatively stable, at a high level, while the motor power consumption range descends. So we understand that driving the engine at these frequencies, we can have high efficiency and low power consumption.

Y: cosφ – X: rpm

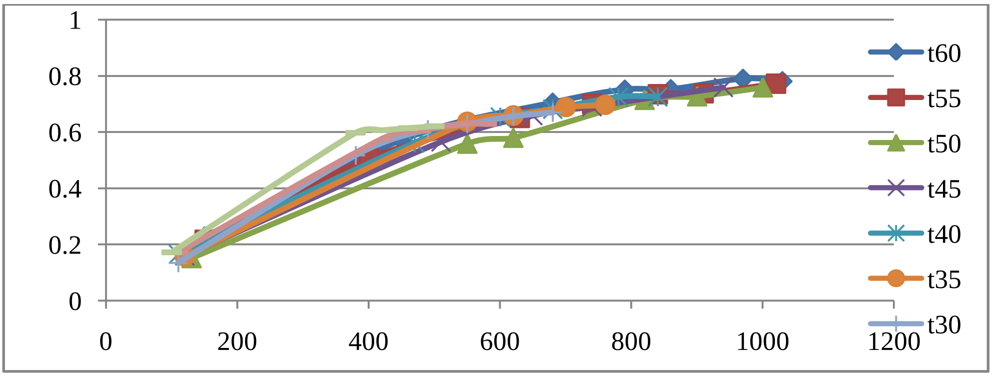

Fig. 17. Cosφ to rpm

Observing the graph above, we see that it is possible to have a drive system of a power factor of about 0.70, driving the motor at all frequency levels in our tests. Thus, in applications where control of motor speed is necessary, on one hand we control the speed and on the other hand we ensure a good level in power factor.

VI. Discussion and Conclusions

The work described in this paper helped significantly to understand the general operation of the three-phase induction motors driven by frequency converter. We found that we can drive a system at different frequency levels without greatly lost torque. We can also save energy by operating the lower frequencies where but we equally satisfy the nominal level of performance.

It is also worth to mention about the user friendly character of the inverter to control the motor speed, the smooth starting and the high-efficiency in all frequency ranges.

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