Experimental Determination Of Mechanical Losses In The Mechanical Equation Of The High-speed Asynchronous Motor

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***Abstract* — In this paper experimentally is determined parameters of the mechanical equation of asynchronous motor with cage rotor at speeds up to 30000rpm. Data is used from experiment at idle. As a result of the research is proposed a more accurate mechanical equation for the model of induction motor valid at high speed.**

Keywords* — *Asynchronous motor model; Mechanical losses; Mechanical equation.

I. Introduction

For proper functioning of the model of the motor at high speed in Matlab/Simulink environment, losses in the motor should be given correctly. In the available motor models in Matlab/Simulink, the coefficient of own losses F_r is a constant. There it is stated that the resistive torque created in the motor itself increases linearly with the speed. This is almost true for speeds up to about 4000 rpm. When modeling an electric motor that is being researched in this speed range this assumption gives satisfactory results when compared to the experimental, but at high rotation speeds the own resistive torque significantly exceeds the maximum possible moment of electric drive. Therefore, it is necessary to make a more precise modeling of the mechanical equation of the electric motor in the study of high-speed electric drive.

With the researched motor (ATF 80 E4 IM B3 4kW of ELPROM-Harmanly JSCo) a high-speed inverter, speeds up to 30 000 rpm can be achieved.

Losses in the motor can be determined using slip data when the motor is running without load. In this way, losses in the motor are from friction and ventilation losses in the air gap (the motor is without a fan).

II. Determination of parameters in mechanical equation

The mechanical equation of the electric motor is

$$J\frac{d\Omega}{dt} = M_e - M_m - M_L. \qquad (1)$$

Parameters are the moment of inertia J, which is set by the motor manufacturer and the torque of its own mechanical losses M_m, consisting mainly of the friction moment in the two bearings and the moment of the ventilation losses in the air gap ($M_m = 2M_{fr} + M_w$). We can find this moment when idling and steady state. Then the motor works without load and $M_L=0$. When running in established mode, the acceleration is $d\omega_{rmec}/dt=0$. Then the all power consumed, generating the rotor's electromagnetic torque is used up to overcome mechanical losses and from (1) comes out $0=M_e-M_m-0$ i.e. $M_e=M_m$. Thus, in established mode and idling, the motor's own mechanical resistance torque is equal to the rotor's electromagnetic torque.

In static mode, the active electromagnetic power [1] transmitted through the air gap from the stator to the rotor of motor can be written

$$P_r = 3I_r^2 R_r / s = \frac{3U_s^2 R_r / s}{\left(R_s + R_r / s\right)^2 + x_k^2}, \qquad (2)$$

where $I_r = \dfrac{U_s}{\sqrt{\left(R_s + R_r / s\right)^2 + x_k^2}}$, U_s is the effective value of the stator phase voltage, x_k is the impedance at short circuit $x_k=x_s+x_r=\omega_s(L_{sl}+L_{rl})$, as ω_s is the electrical angular velocity of the stator.

On the other hand, by expressing the electromagnetic torque M_e trough the power P_r and the angular velocity of the stator field Ω_s, it comes out

$$M_e = \frac{P_r}{\Omega_s}. \qquad (3)$$

After replacing (2) in (3), for the electromagnetic torque the equation [1] is obtained

$$M_e = \frac{3U_s^2 R_r}{s.\Omega_s.\left[\left(R_s + R_r / s\right)^2 + \Omega_s^2.p^2\left(L_{sl} + L_{rl}\right)^2\right]} \qquad (4)$$

where $\Omega_s=\omega_s/p$, ω_s is the electrical angular velocity of stator current, p is the number of pole pairs. The examined motor has two pairs of poles $p = 2$.

We received the electromagnetic torque in static mode as a function of voltage, slip, frequency of the stator field and motor parameters.

Slipping is calculated as a relative difference between the rotation speeds of the stator field Ω_s and the rotor Ω.

$$s = \frac{(\Omega_s - \Omega)}{\Omega_s} \tag{5}$$

The experimentally obtained slip data, when idling in an established mode of operation, are listed in table1 and graphically represented in fig.1 and fig.2.

TABLE I. EXPERIMENTALLY OBTAINED SLIP DATA, WHEN IDLING IN ESTABLISHED MODE OF OPERATION

n_s, [rpm]	*n, [rpm]*	*s*
10	9.95	0.005000
50	49.75	0.005000
100	99.5	0.005000
300	298	0.006667
500	496.5	0.007000
1000	992.3	0.007700
1500	1488	0.008000
3000	2976	0.008000
5000	4960	0.008000
10000	9916	0.008400
15000	14863	0.009133
20000	19796	0.010200
25000	24634	0.014640
26000	25587	0.015885
27000	26532	0.017333
28000	27399	0.021464

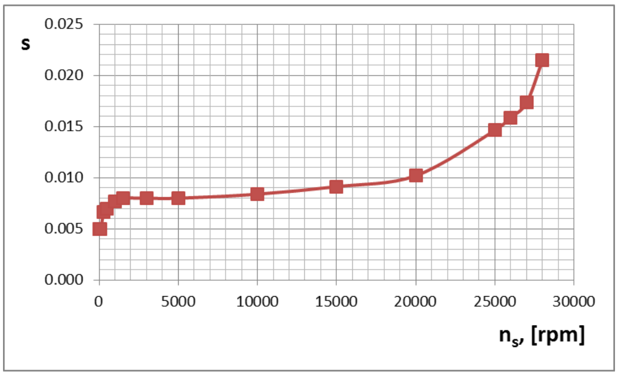

Fig. 1. Slip at idle speed from 10 rpm to 28 000 rpm of asynchronous motor with 4 poles.

Using the high speed inverter, connected to the asynchronous motor, the rotation speed of the stator field is set to $n_s = \Omega_s.30/\pi$,[rpm]. The mechanical rotation speed of rotor *n*[rpm] is measured by a photo tachometer for speeds up to 30000rpm. Speeds up to 3000rpm are measured using the instrument shaft and speeds up to 28000rpm are measured in a stroboscopic way.

The remaining data is collected at motor identification. They are obtained in an established mode at different frequencies of the stator field ns,[rpm] and are given in table 2.

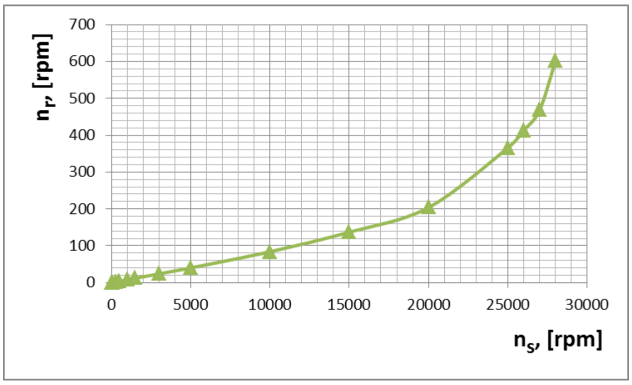

Fig. 2. Rotor field speed n_r[rpm] at idle speed of 0÷28000rpm of asynchronous motor with 4 poles.

The experimentally obtained data for the R_s, R_r, L_{sl}, L_{rl}, U_s and slip *s*, used in equation (4) are given in table 2 and the results of calculation are given in table 3 and are graphically shown in fig. 3.

It can be seen that at 3000rpm a maximum is obtained for the resistance torque M_m at 0.22Nm. After this speed, the torque starts decreasing to about 12000rpm and stays constant (0.06Nm) to 25000rpm and then starts increasing.

Mechanical power losses increase steeper to 5000rpm (100W), then they decrease slightly and grow smoothly again, so they reach 280W at 28000rpm (fig.3)

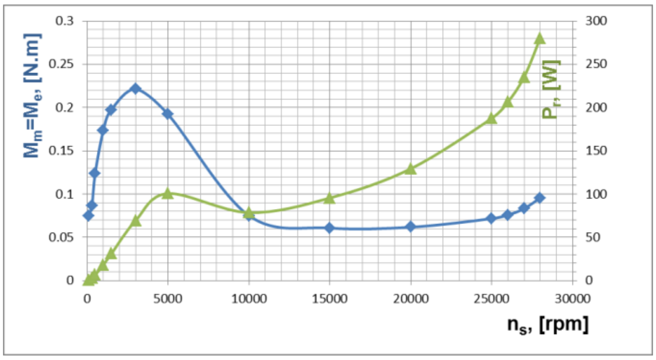

Fig. 3. Dependence of the resistance moment and power of mechanical losses due to friction in bearings and ventilation losses in the air gap, from the speed of rotation of the motor.

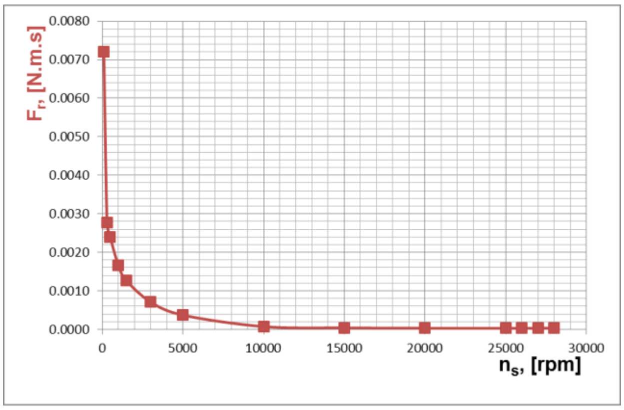

Fig. 4. Dependence of Fr coefficient associated with friction in bearings and ventilation losses in the air gap, from the speed of rotation of the motor.

TABLE II. EXPERIMENTALLY RECEIVED INPUT DATA FOR EQUATION (4)

N_s, [rpm]	Ω_s,[rad/s]	s	U_s, [V]	R_s, [Ω]	R_r, [Ω]	L_{sl},[mH]	L_{rl}, [mH]
100	10.472	0.005	6.35	1.015	0.76	4.05	4.05
300	31.416	0.0067	10.39	1.017	0.78	4	4
500	52.36	0.007	16.16	1.05	0.83	3.8	3.8
1000	104.72	0.0077	27.71	1.1	0.91	3.6	3.5
1500	157.08	0.0079	37.52	1.231	1.11	3.5	2.85
3000	314.16	0.008	62.35	1.36	1.32	3.25	2.6
5000	523.6	0.008	82.56	1.5	1.6	3.15	2.4
10000	1047.2	0.0084	88.91	1.847	2.5	3.6	1.5
15000	1570.8	0.0091	94.11	1.847	2.5	3.9	0.9
20000	2094.4	0.01	103.92	1.847	2.5	3.5	1.4
25000	2618	0.01464	105.65	1.847	2.5	3.5	1.5
26000	2722.72	0.01588	106.81	1.847	2.5	3.5	1.5
27000	2827.44	0.017	109.69	1.847	2.5	3.5	1.5
28000	2932.16	0.0215	109.12	1.847	2.5	3.5	1.5

To keep the traditional mechanical equation record in the asynchronous motor model in SIMULINK, we are using the coefficient F_r to reflect its own mechanical losses:

$$F_r = M_m/\Omega \ [N.m.s], \qquad (6)$$

where Ω[rad/s] is the mechanical speed of the rotor.

Figure 4 shows the dependence of F_r coefficient associated with friction in bearings and ventilation losses in the air gap, depending on the speed of rotation of the motor. The coefficient F_r drops rapidly as the speed increases and at high speeds it becomes small and changes slightly.

TABLE III. RESULTS OBTAINED FROM THE CALCULATIONS OF EQUATIONS (2), (4) AND (6).

n_s,rpm	P_r, W	M_m, Nm	F_r, Nms
100	0.785525723	0.075012006	0.0071990976
300	2.735031998	0.087058569	0.0027761125
500	6.496193039	0.124067858	0.0023862195
1000	18.14120829	0.173235373	0.0016671088
1500	30.63742587	0.195043455	0.0012672492
3000	69.50590009	0.221243634	0.0007099181
5000	100.6446769	0.192216725	0.0003700666
10000	78.62534465	0.075081498	0.0000723047
15000	95.14092789	0.060568454	0.0000390542
20000	126.8634201	0.060572680	0.0000297871
25000	187.6211579	0.071665836	0.0000277810
26000	206.3546163	0.075789878	0.0000282930
27000	231.0958703	0.081733253	0.0000299385
28000	280.3927335	0.095626683	0.0000332811

III. CONCLUSION

The proposed mechanical equation of the system at high speed of rotation is

$$\frac{d\Omega}{dt} = \frac{1}{J}\left(M_e - F_r(\Omega).\Omega - M_L\right), \qquad (7)$$

where the coefficient, reflecting the mechanical losses, F_r is a function of the rotor shaft speed.

The results of the experimental studies can be used to create a high-speed asynchronous motor model in a Matlab/Simulink environment. When modeling the mechanical equation, the coefficient F_r representing the mechanical losses can be set by a tabular function dependent on the rotor speed.

Figure 6 shows a developed converter for controlling three-phase high-speed asynchronous motors with output frequency of the main harmonic from 0Hz to 1000Hz. Figure 7 shows the examined four-pole asynchronous electric motor, in which all components are normally used in regular production (bearings, blades, stator and rotor bundle, conductors).

Fig. 5. Inverter for high-speed asynchronous motors control.

Fig. 6. Four-pole asynchronous motor ATF80E4IMB3 for speed up to 30000 rpm.

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