

Analysing Torque-slip Characteristic of a Small Power Induction Motor Operating under Geophysical Conditions

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Abstract—The article analyses the torque-slip characteristic of a small power induction motor up to 50 W used in mechatronic system drives of a borehole investigation devices, that works at a wide range of temperature (from -20 °C to +150 °C) and is supplied through a long geophysical cable with complex impedance which changes from $\underline{Z}_c = (127.5 - j1.8)$ to $\underline{Z}_c = (165 - j2.9)$. The external diameter of the induction motor is up to 36 mm, the number of stator teeth is 8. The torque-slip characteristics have been calculated for different cases, when the stator winding is single-layer, two-layer short-pitch and sinusoidal, motor rotor is solid and copper-cage solid. The calculated torque-slip characteristics at environment temperature +20 °C were compared with the tested performed experiments.

Index Terms—Cage solid rotor induction motor, stator winding, torque-slip characteristic.

I. INTRODUCTION

Considering the requirements for the special purpose small power induction motors (high mechanical and thermal resistance; motor working medium – dielectric fluid or air; high quality of starting characteristic; motor operation under a wide slip range as it does not have a fixed operating point and other specific requirements), the optimal criteria may be the corresponding functional characteristic. In this case, torque-slip characteristic considered as a functional characteristic. Therefore, the satisfaction of the requirements contradicts the energy parameters, which are set for traditional induction motors.

Special purpose induction motors operating under geophysical conditions were analysed in [1], [2]. At the beginning, induction motors (up to 150 W) with solid rotor and supplied by single-core cable were designed for geophysical borehole research equipment, where the environment temperature rises up to +250 °C, and hydrostatic pressure happens up to 210 MPa in [3]. More powerful cage-solid rotor induction motors were analysed in

[4], [5].

The development of geophysical equipment and its functions increase the requirements for the operation of electric motors used in various mechatronic system electric drives, when motors are supplied by limited power sources through long multi-core geophysical cables, their complex impedance reaches up to $165-j5$, and environment temperature - up to +150 °C. The insulating high temperature resistant materials based on polyimide and polytetrafluorethylene are used.

High environment temperature or other factors, *e.g.* contact loss between the ring and rods, may cause an accident. In case of a contact loss, the motor the copper-cage solid rotor will work almost as a solid rotor. Therefore, traditional induction motors with cage rotors are unacceptable due to insufficient rotor reliability.



Fig. 1. The main components of the copper-cage solid rotor induction motor.

The goal of the work is to perform analysis of a torque-slip characteristics and to test experimentally of small power induction motor when it is made with solid rotor and cage solid rotor, the stator windings are made as two-layer short-pitch, sinusoidal and single-layer. The research is focused on a limited external diameter small power two-phase symmetrical induction motor, which has main parameters as: 36 mm external diameter, 50 mm active length, the number of stator slots ‘8’, 17 mm internal stator diameter, 0.2 mm air gap and made by solid and copper-cage solid rotors. The one of motor with copper-cage solid rotor is shown in Fig. 1.

II. STATOR WINDING

Single-layer winding is simpler manufactured, the slot is exploited more efficiently, but superior harmonics are highly expressed ($\epsilon = 3, 5, 7, 9$ here 7 and 9 are teeth harmonics of the first order). Two-layer winding is more complex in manufacturing, the slot is exploited worse, but the winding pitch may be shortened [6].

Sinusoidal two-phase winding ($2p = 2$, $Z_s = 8$) with concentric coil groups has to be produced two-layer, because one coil group corresponds to one pole. On the other hand, the slots of this sinusoidal winding will be filled equally, as well as the two-layer preformed short-pitch windings.

The harmonic factor $k_{w\epsilon}$ of sinusoidal winding is given in [7]. The equations below show a procedure to calculate the ν -th harmonic factor of sinusoidal two-phase winding

$$k_{w\epsilon} = \sum_{i=1}^q N_{si} \sin\left(\epsilon y_i \frac{r}{2}\right), \quad (1)$$

where q – number of slots per pole per phase; N_{si} – turn number of i section; y_i – pitch of i section; $r = \frac{\tau}{\tau}$ – slot pitch expressed by the electrical degrees of the main space harmonic.

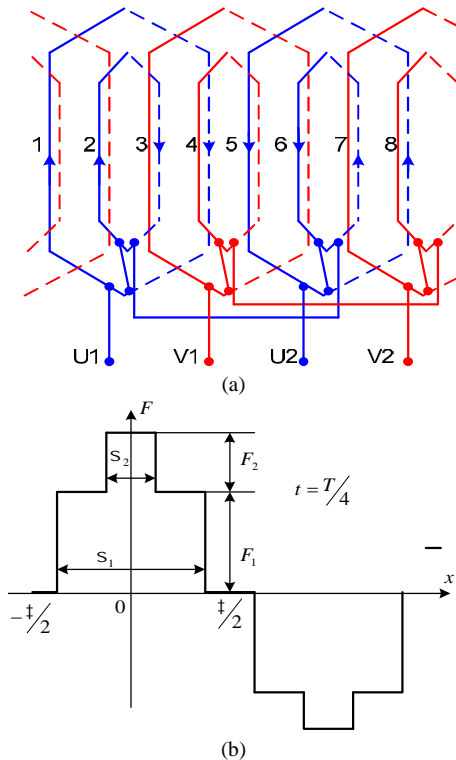


Fig. 2. Electric diagram of sinusoidal winding and space distribution of magnetomotive force developed by sinusoidal winding.

Because these windings $q=2$, so $N_{s1}^* = \frac{1}{2}$, and

$$N_{s2}^* = \frac{1}{2}, \text{ here } \frac{1}{2} = \sin\frac{S_1}{2}, \frac{1}{2} = \sin\frac{S_2}{2}, \frac{1}{2} = \frac{1}{2} + \frac{1}{2}$$

(Fig. 2). Therefore the first harmonic ($\epsilon = 1$) of sinusoidal winding harmonic factor is

$$k_{w1} = 0.707 \sin\frac{3}{8} + 0.293 \sin\frac{3}{8} = 0.7653, \quad (2)$$

and for higher harmonics $k_{w3} = -0.001395$, $k_{w5} = 0.0001395$, $k_{w7} = -0.7653$, $k_{w9} = -0.7653$. While for two-layer windings accordingly $k_{w1} = 0.8534$, $k_{w3} = -0.1464$, $k_{w5} = 0.1464$, $k_{w7} = -0.8534$, $k_{w9} = 0.8534$.

III. ANALYSING OF TORQUE-SLIP CHARACTERISTIC

The calculating of torque-slip characteristic performed for small power induction motor considering the temperature change of borehole medium and its effect to the motor and geophysical cable parameters by algorithm in [8]. The algorithm also evaluated the compatibility of motor and feed circuit parameters, saturation of motor magnetic circuit, rotor end effect, hysteresis losses and the higher space harmonics of the magnetic field. The main parameter of geophysical cable is complex impedance \underline{Z}_C . Therefore, the geophysical cable is replaced by quadripole one, connected between the supply source and electric motor. Torque-slip characteristic was calculated as evaluating as 1, 3, 5, 7, 9 space harmonics.

The supply voltage of these motors in slip range $1 - s_0$ changes approximately from 175 V to 200 V when rotor is cage solid and from 190 V to 215 V when rotor is solid (s_0 is the no-load slip). Power supply voltage was chosen 240 V (it depends on the complex impedance of the supply circuit) because the motor operates under different environment temperatures from -20°C to $+150^\circ\text{C}$ and its torque-slip characteristics also changes even changing form a little. In order to avoid high changes of torque-slip characteristic, it is foreseen to change power supply voltage every 10 V, and for capacitor motor – every 20 V.

Usually the complex impedance \underline{Z}_C is set; it depends on the cable length, which is put into *e.g.* borehole, and on the environment temperature at the measurement point. The traditional design methods of the conventional cage rotor induction motors directly unfit for use of the borehole motors, because the fixed nominal operation point is not characteristic for them due to complicated specific working environment [1]. The factor $k_M = \frac{P_M}{P_{M\max}}$ shows how

effectively the supply circuit is exploited (here P_M – input active motor power, $P_{M\max}$ – maximum transmitted active power to motor) [9]. $P_{M\max}$ would be maximum, if motor input impedance \underline{Z}_M is equal to conjugate value of cable output impedance \underline{Z}_C^* . Difference $1 - k_M$ indicates the biggest part of electric loss that is lost in feed circuit.

Electromagnetic efficiency factor k_{ef} indicates what part of the first harmonic relative rotational magnetomotive force remains after the compensation of negative effect of its higher harmonics [7]. For the sinusoidal winding, it is 0.775

and is only 1.42 % higher than of two-layer winding.

Table I presents the results of the analysed induction motor torque-slip characteristic: when power supply voltage is 240 V; number of rotor teeth is $Z_R = 13$; slot dimensions are $h \times b = 2,8 \times 1,8$ mm; *the dimensions of this rotor slot are $h \times b = 2,0 \times 0,8$ mm.

It is convenient to evaluate torque-slip characteristics according to the electromagnetic torque average value $T_{em.av}$ (Table I) in the working slip range $1 - s_0$ [9]

$$T_{em.av} = \frac{1}{1-s_0} \int_{s_0}^1 T_{em}(s) ds. \quad (3)$$

In motors with two-layer and sinusoidal windings (Table I, Table II and Fig. 3, Fig. 4), when rotor is cage solid (power supply is two-phase symmetrical) torque-slip characteristics do not differ more than 5 %. The electromagnetic torques created by the first harmonics differs up to 7 %. Torque-slip characteristic is more advantageous when stator winding is sinusoidal, because the electromagnetic torques created by higher harmonics is much smaller than stator winding is two-layer. (Table I, Fig. 4). Winding factors affect the rotor's active resistance, inductive reactance and reactance of mutual induction values.

TABLE I. COMPUTED PARAMETERS.

Two-phase symmetrical power supply						
Stator winding	Rotor type	$T_{em,av}$ N·m	$T_{em}(s_c)$ N·m	s_c	s_o	k_M
Two-layer former short pitch $y = 3$	Cage solid rotor	0.131	0.154	0.353	0.024	0.743
		0.091	0.109	1.140	0.029	0.703
Two-layer former short pitch $y = 3$	Solid rotor	0.078	0.122	1.142	0.038	0.765
		0.041	0.066	1.145	0.032	0.703
Sinusoidal $y = 3, y = 1$	Cage solid rotor	0.132	0.159	0.321	0.013	0.363
		0.090	0.103	0.475	0.017	0.390
Sinusoidal $y = 3, y = 1$	Solid rotor	0.079	0.123	1.143	0.002	0.412
		0.039	0.065	1.142	0.0017	0.452
Single-phase power supply, $C_w = 4 \mu F$						
Two-layer former short pitch $y = 3$	*Cage solid rotor	0.089	0.099	0.450	0.051	0.798
		0.078	0.091	0.672	0.052	0.777
Sinusoidal $y = 3, y = 1$	Cage solid rotor	0.0698	0.0955	0.225	0.0141	0.838
		0.0595	0.0718	0.329	0.0164	0.828
Single-layer concentric $y = 4$	Cage solid rotor	0.067	0.083	0.268	0.043	0.790
		0.065	0.074	1,111	0.048	0.795

Note: in numerator – when environment temperature is $+20^\circ C$; cable complex impedance $Z_C = (127.5 - j1.8)$; in denominator – when environment temperature is $+150^\circ C$; cable complex impedance $Z_C = (165 - j2.9)$.

If the motor rotor is solid, the torque-slip characteristics are similar when environment temperature is either $+20^\circ C$ or $+150^\circ C$ according to the computed results (Table I) and according to their form (Fig. 5). When power is supplied from a single-phase network, the most rational

torque-slip characteristic according to the form and parameters (Table I) is of motor with two-layer winding (*cage solid rotor slot measurements are $h \times b = 2,0 \times 0,8$ mm).

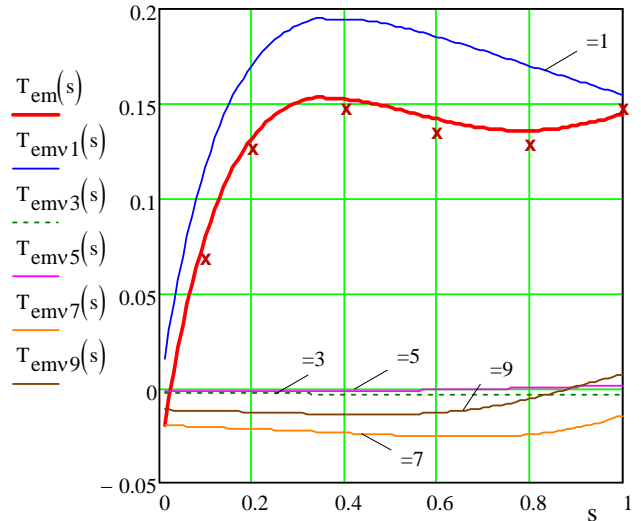


Fig. 3. Calculated and measured torque versus slip characteristics: (computed, solid lines; measurement, dots; see TABLE II).

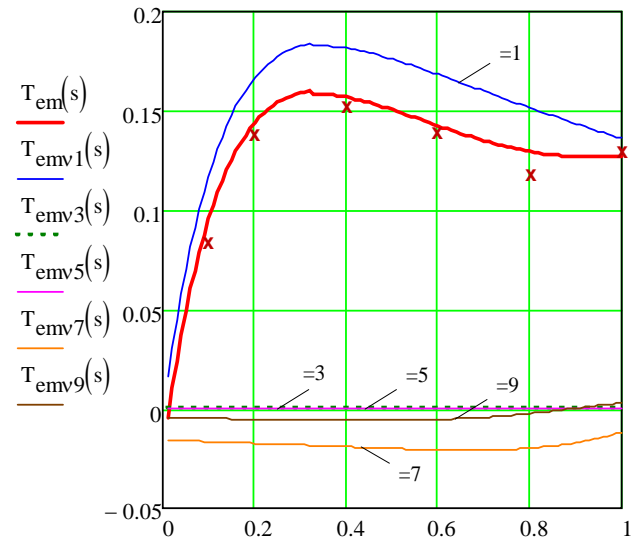


Fig. 4. Calculated and measured torque versus slip characteristics: (computed, solid lines; measurement, dots; see TABLE II).

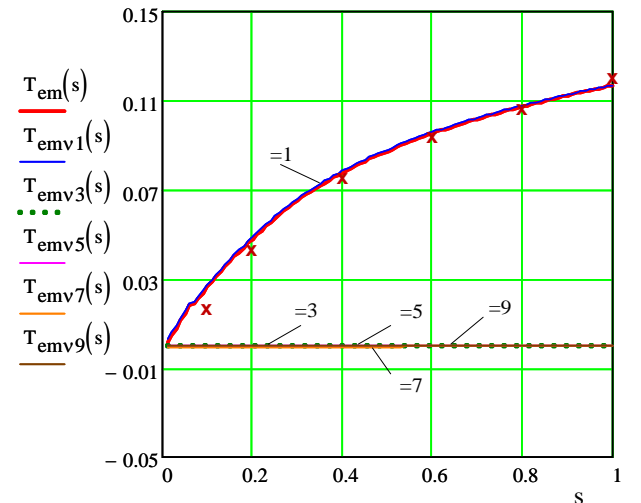


Fig. 5. Calculated and measured torque versus slip characteristics: (computed, solid lines; measurement, dots; see TABLE II).

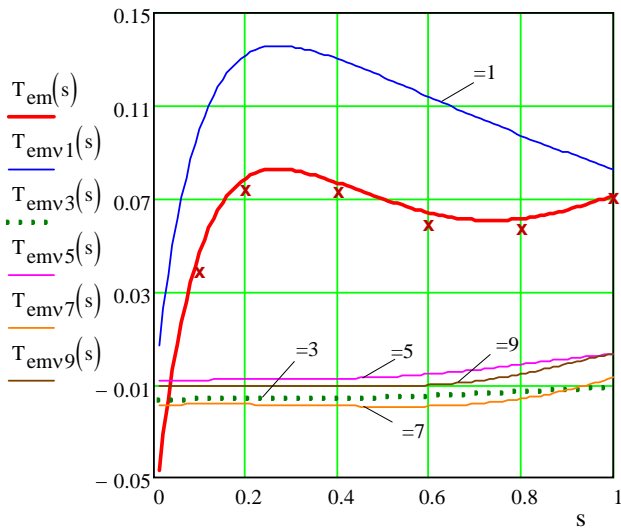


Fig. 6. Calculated and measured torque versus slip characteristics: (computed, solid lines; measurement, dots (see TABLE II)).

The torque-slip characteristic form of capacitor motor with cage-solid rotor is unacceptable (Fig. 6), because the starting torque is low, and electrical loss is high. When the cage winding resistance is increased, then torque-slip characteristic becomes more rational, starting torque is higher and $T_{em,av}$ is bigger. The biggest $T_{em,av}$ value is when the running capacitor's capacity is 4 μF . This is valid for motor stator with winding of the analysed type. If the running capacitor's capacity is 3 μF , $T_{em,av}$ decreases to 8 %, when it is 5 μF – to 2 %.

IV. EXPERIMENTAL RESEARCH

Active resistance of stator winding phase: two-layer windings – 225 Ω , sinusoidal – 232 Ω , single-layer – 258 Ω . Turn numbers of stator winding phase – two-layer and sinusoidal – 1100, single-layer 1200. Numbers of rotor teeth are 13, slots are rectangular. The cable was replaced by equivalent scheme (which was formed of resistances and capacitors) so that 1 km corresponds to 25.5 Ω , and the capacity between cable core and armor or between the cores is 0.25 μF (when cable is multi-core, three-core cable was simulated). The experiment carried out under the temperature +20°C. Resistance of power supply scheme was $Z_C = (127 - j1.8) \Omega$. Two perpendicular voltages (two-phase symmetrical) were made applying Scott-connected transformer, voltage values were regulated by single-phase laboratory autotransformers. Torque measurement points were fixed and deduced corresponding slip values 1.0, 0.8, 0.6, 0.4, 0.2, 0.1 (Table II).

The tested motor was vertically fixed between the rotating torquemeter centres. The lower centre was connected to the rotating drive motor, which rotation speed was smoothly controlled from $n=0$ to $n=3500\text{min}^{-1}$. The motor's frame is its external diameter too. A central ring was attached to the frame; the ring was reinforced with the torque (force) pick-up. Force was measured with strain-gauge transducer. The rotation speed was measured with "testo 465".

During the test, the stator winding temperature (at each slip point) was maintained +20°C. After every deduction, the voltage was turned off; motor was cooled with an additional ventilator. The temperature was controlled by measuring the stator winding's active resistance.

TABLE II. CALCULATED AND MEASURED TORQUE VALUES AT SLIP VALUES AS ENVIRONMENT TEMPERATURE +20°C.

$T_{em}(1)$ N.m	$T_{em}(0.8)$ N.m	$T_{em}(0.6)$ N.m	$T_{em}(0.4)$ N.m	$T_{em}(0.2)$ N.m	$T_{em}(0.1)$ N.m	s_o
Two-layer short pitch winding, cage solid rotor, two-phase symmetrical power supply (Fig. 3)						
0.147	0.136	0.142	0.152	0.132	0.079	0.024
0.145	0.134	0.139	0.147	0.126	0.071	0.030
Sinusoidal winding, cage solid rotor, two-phase symmetrical power supply (Fig. 4)						
0.128	0.130	0.143	0.157	0.144	0.096	0.013
0.129	0.120	0.140	0.152	0.139	0.089	0.017
Two-layer short pitch winding, solid rotor, two-phase symmetrical power supply (Fig.5)						
0.117	0.108	0.096	0.079	0.048	0.027	0.044
0.118	0.106	0.094	0.076	0.043	0.020	0.009
Single-layer concentric winding, cage solid rotor, single-phase power supply (Fig.6)						
0.072	0.062	0.064	0.077	0.079	0.047	0.043
0.071	0.58	0.060	0.072	0.073	0.041	0.051

Note: Upper row – computed values; lower row – measured values.

V. CONCLUSIONS

According to the presented analysis results of torque-slip characteristic, it is possible to choose the induction motor for the special purpose drives operating under geophysical conditions considering the supply circuit parameters. The analysis of the torque-slip characteristic of the investigated motor was performed in different cases i.e. replacing one-by-one the laid out stator winding, when the made rotor was copper-cage solid and solid (Table I).

When the motor is supplied from single-phase power source, and the stator winding is sinusoidal, the best results are obtained. But, in order to synchronize the total rotor active resistance with the power cable circuit active resistance, the rotor slots are reduced (slot diameter up to 3 times). The use of single-layer winding is not purposeful because of the significant effect of the third harmonic. As the environment temperature increases the torque-slip characteristic's form changes due to relatively small influence of higher harmonic. The torque-slip characteristic is more advantageous when stator winding is sinusoidal and rotor is copper-cage solid.

Torque-slip characteristic's electromagnetic torque values that are computed by the motor and are experimentally set do not vary more than 10 % in the slip range $s = 1 - 0.25$, but when slip range values are smaller $s < 0.25$, then torque values differ more than 10 %.

The analysis of characteristics in much the same way can be put in practice for other size motors with smaller external diameters (e.c. 31 mm, 25 mm) and different parameters of the supply circuit.

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