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An Influence of Operating Medium Temperature Change on Characteristics of Electric Motor for Borehole Investigating Devices

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Introduction

A borehole investigating device is used for geophysical investigations of the Earth Crust or sea ground and prospecting works for oil, gas, ores, etc. The borehole depth reaches up to 10000 m or more and the induction motor is supplied through the long geophysical cable with distributed parameters as well as the motor operates under extraordinary conditions: wide operating medium temperature change interval is from – 20°C up to +250°C or more; hydrostatic pressure changes from atmospheric up to 210 MPa or more; operating medium – dielectric liquid; non-constant load during the operating cycle; non-constant the supply voltage of motor through all range of slip. These extraordinary conditions have an influence on the reliable work of motor, maximum power transmission and change of characteristics taking into account the wide operating borehole medium temperature interval. The diameter of the motor is strictly limited and it directly depends on the investigating device diameter which in its turn depends on the purpose of the borehole but the length is not limited. There is lack of information in scientific and technical literature about investigating or design and also operating peculiarities of electrical motors under these conditions.

The conventional induction motors are unfit for use to operate with the specific scheme of the supply circuit through very high thermal resistance, limiting transmitted electrical power to motor, etc. [1, 2]. The maximum phase active power which can be transmitted to the motor in real three–phase supply circuit did not exceed 75 W at supply voltage 300 V and phase active resistance of the geophysical cable reaches up to 300 Ω [1]. The optimal torque-slip characteristic of borehole motor should be the one which would guarantee maximum torque in all range of slip [3].

The geophysical cable is of the fixed length for the concrete investigating device as a rule. One part of the cable is at the environment temperature and the second is in the borehole at the medium temperature which is distributed depending on the ground locality properties and it's temperature gradient.

For the boreholes which operating medium temperature exceeds +200°C it is expedient to use three-phase c with solid ferromagnetic rotors. The solid ferromagnetic rotor in it's simplest form, for the rotor of three–phase induction motor offers the advantage in case of manufacture, offering high torque per ampere at standstill, and operation in unusual environments [4]. Usually for the boreholes investigation self-contained supply is used, so the power-supply source has limited power because the measuring of a borehole ground parameters and remote control need less electric power than for the supply of electric motor. For the deeper borehole the longer geophysical cable is necessary, so the active resistance of the cable and the voltage drop in the cable will be bigger.

Critical slip and maximum electromagnetic power of borehole induction motor

The torque-slip characteristic of an induction motor easily described if are known critical slip s_C and maximum value of the electromagnetic torque $M_{em,\max}$. Usually the parameters s_C and $M_{em,\max}$ are determined taking into account L equivalent circuit for phase. But this L equivalent circuit does not evaluate the parameters of supply circuit as well as the known expression of critical slip [5] is unfit for use, when the induction motor with solid ferromagnetic rotor is supplied through long geophysical cable with distributed parameters. We deduce a formula of critical slip do not taking into account concrete electrical power-supply source of induction motor with solid ferromagnetic rotor. For this purpose we use the condition of transmitted maximum power in electrical circuits. Applying this condition for electrical circuit represented in Fig.1 is given as

$$\frac{Z_2'}{\sqrt{s}} = \left(\mathrm{abs}\left(\underline{Z}_T\right)\right) = Z_T ; \qquad (1)$$

where $\underline{Z}_T$ is the input complex impedance with respect to terminals $2\text{-}2'$ of the equivalent complex impedance $\frac{\underline{Z}_2'}{\sqrt{s}}$ when the terminals 1-1' of power-supply source are short connected; Z_T is the input impedance; s is the slip; Z_2' is the equivalent rotor impedance.

From equation (1) the critical slip s_C is obtained

$$s_C = \pm\left(\frac{Z_2'}{Z_\mathrm{T}}\right)^2 . \qquad (2)$$

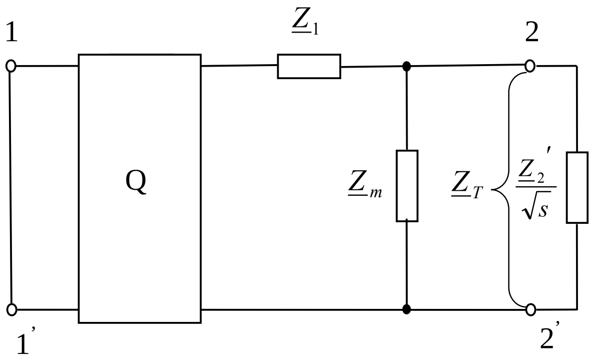

Fig.1. Calculation scheme of the input impedance Z_T : Q is the four-pole

Suppose that the parameters of calculation scheme Fig.1 are known then the input impedance Z_T can be expressed as follows:

$$Z_T = \mathrm{abs}\left(\frac{\underline{Z}_m\left(\underline{A}_{11}\underline{Z}_1 + \underline{A}_{12}\right)}{\underline{A}_{11}\left(\underline{Z}_1 + \underline{Z}_m\right) + \underline{A}_{12}}\right); \qquad (3)$$

where $\underline{Z}_1 = R_1 + jX_1$; $\underline{Z}_m = R_m + jX_m$;
$\underline{A}_{11}, \underline{A}_{12}$ are the four-pole complex coefficients.

Applying the calculation rule of four-pole to scheme Fig.1, the complex of equivalent rotor current can be expressed as follows

$$\underline{I}_2'(s) = \frac{\underline{U}_S}{\underline{A}_{11}\underline{Z}_M(s) + \underline{A}_{12}} \cdot \frac{\underline{Z}_m}{\underline{Z}_m + \underline{Z}_2'(s)} ; \qquad (4)$$

where $\underline{Z}_2'(s) = \frac{R_2'}{\sqrt{s}} + j\frac{X_2'}{\sqrt{s}}$; $\underline{Z}_M(s) = \underline{Z}_1 + \frac{\underline{Z}_m \cdot \underline{Z}_2'(s)}{\underline{Z}_m + \underline{Z}_2'(s)}$;
$\underline{U}_S$ is the supply complex voltage of power-supply source.

Then the electromagnetic power of the induction motor is expressed as

$$P_{em}(s) = m\left(\mathrm{abs}\left(I_2'(s)\right)\right)^2 \frac{R_2'}{\sqrt{s}} ; \qquad (5)$$

where m is the number of motor phase.

Substituting the expression of critical slip s_C equation (2) in place s into equation (5) the maximum electromagnetic power is given as

$$P_{em,\max} = m\left(\mathrm{abs}\left(\frac{\underline{U}_S}{\underline{A}_{11}\underline{Z}_{Mm} + \underline{A}_{12}} \cdot \frac{\underline{Z}_m}{\underline{Z}_m + \underline{Z}_{2m}'}\right)\right)^2 \times$$
$$\times \frac{R_2'}{Z_2'} Z_T ; \qquad (6)$$

where $\underline{Z}_{2m}' = \frac{R_2'}{\sqrt{s_C}} + j\frac{X_2'}{\sqrt{s_C}}$; $\underline{Z}_{Mm} = \underline{Z}_1 + \frac{\underline{Z}_m \cdot \underline{Z}_{2m}'}{\underline{Z}_m + \underline{Z}_{2m}'}$.

If the expression of critical slip evaluating the power-supply circuit is known then the expression of maximum electromagnetic power is not complicated to obtain.

The electromagnetic torque of the motor can be expressed as follows:

$$M_{em}(s) = pP_{em}(s)/\omega_1 ; \qquad (7)$$

here $\omega_1 = 2\pi f_1$; f_1 is the frequency of the power–supply source current.

Parameters of equivalent and supply circuits taking into account borehole medium temperature

The operating medium temperature of the motor depends on the borehole depth and changes the resistances of the motor and geophysical cable. The stator phase active resistance is directly proportional to the specific conductance of the copper wire at the borehole depth temperature. The rotor equivalent active resistance is proportional to the square root of the specific conductance of the material of solid ferromagnetic rotor at the borehole depth temperature. The rotor equivalent inductive reactance is related with rotor equivalent active resistance X_2'=0,6 R_2' [6, 7]. The geophysical cable resistance depends on average specific resistance and temperatures of borehole surface and of the let down device in borehole depth. It is assumed that the dependence of the operating medium temperature as the function of the borehole depth is linear.

The four-pole complex coefficients taking into account the operating medium temperature of the borehole can be expressed as follows:

$$\underline{A}_{11} = \mathrm{ch}\,(\underline{\gamma}\left(\ell_1\frac{r_{0\Theta_0}}{r_{0\Theta_V}} + \ell_2\right)); \qquad (8)$$

$$\underline{A}_{12} = \underline{Z}_0 \text{sh}\,(\underline{\gamma}\left(\ell_1 \frac{r_{0\Theta_0}}{r_{0\Theta_V}} + \ell_2\right)); \tag{9}$$

where

$$\underline{\gamma} = \sqrt{(r_{o\Theta v} + \text{j}\omega_1 L_o)(g_o + \text{j}\omega_1 C_o)}\,; \tag{10}$$

$$\underline{Z}_0 = \sqrt{\frac{r_{0\Theta v} + \text{j}\omega_1 L_0}{g_0 + \text{j}\omega_1 C_0}}\,; \tag{11}$$

$$r_{0\Theta_V} = \frac{r_{0\Theta_0} + r_{0\Theta\ell_2}}{2}; \tag{12}$$

$$r_{0\Theta_0} = r_{0\Theta_{0K}}\left(1 + \alpha_T\left(\Theta_0 - \Theta_{0K}\right)\right); \tag{13}$$

$$r_{0\Theta\ell_2} = r_{0\Theta 0}\left(1 + \alpha_T\left(\Theta_{\ell_2} - \Theta_0\right)\right); \tag{14}$$

$r_{0\Theta_v}$ is the average specific resistance; $r_{0\Theta_{0K}}$ is the specific resistance of the cable according to catalog data at temperature Θ_{0K}; Θ_0 is the temperature at the borehole surface; Θ_{ℓ_2} is the temperature of the borehole depth ℓ_2; α_T is the temperature coefficient of the conductor resistance; ℓ_1 is the cable length on the ground surface; ℓ_2 is the let down in borehole cable length; $\ell = \ell_1 + \ell_2$.

Then the active resistance of the core of geophysical cable at temperature Θ is expressed as:

$$R_{C\Theta} = r_{0\Theta_V}\left(\ell_1 \frac{r_{0\Theta_0}}{r_{0\Theta_V}} + \ell_2\right). \tag{15}$$

Results and discussion

From the equation (6) it is seen that maximum electromagnetic power of the induction motor with solid ferromagnetic rotor depends on the parameters of the long geophysical cable as well as on borehole motor parameters.

According to the equations (2), (4), (5), (6), (7) the characteristics of the borehole motor with solid ferromagnetic rotor can be calculated for any parameters of the equivalent and the supply circuits.

At the different borehole depth the borehole medium temperature as well as the viscosity of dielectric liquid changes, so the motor load torque will changes in wide range. Then the motor working point at every moment also changes and to discuss about the motor rated parameters is inexpedient.

For the effective evaluation of torque-slip characteristic more comfortable to use the coefficient k_M which directly proportional to average electromagnetic torque:

$$k_M = \frac{1}{1 - s_0}\int_{s_0}^{1} M(s)\,\text{d}s\,. \tag{16}$$

The formation of the necessary characteristics of the motor for borehole investigating devices taking into account only equivalent circuit parameters is possible in the case when the parameters of the supply circuit are very much small or unlimitedly large in comparison with the special demands should be designed for the concrete supply circuit taking into account the impedance accordance of the motor and the supply circuit.

The borehole motor supplying from the limited power-supply source and through the long geophysical cable should be investigated inseparably from the whole system.

The increasing of the equivalent circuit parameters X_m and R_1 at design stage decrease s_C also and $P_{em,\max}$. The magnetic permeability μ_r and specific resistance of the rotor material have a big influence on the value of the critical slip.

The characteristics of the three-phase two pole borehole motor ($\underline{U}_S$=230 V, f_1=50 Hz, , $\underline{Z}_1$=(46+j48) Ω, $\underline{Z}_m$=(0+j612) Ω, $\underline{Z}_2' = (390+\text{j}234)$ Ω – rotor material Ст 3, $\underline{Z}_2' = (135+\text{j}81)$ Ω – rotor material CM–25, ℓ=8 km, $r_{0\Theta_{0K}}$=25,5 Ω/km, the parameters are given at 20 ^{0}C) are calculated (results are indicated in table).

Better results are obtained using the iron–copper alloy CM–25 ($\mu_r = 30 - 50$, $\rho_2 = (1 - 2)10^{-6}\Omega\cdot\text{m}$) $s_C < 1$ if $Z_2' < Z_T$. If the rotor is manufactured from iron then $s_C >> 1$.

When the borehole motor operates at the lower medium temperature the supply voltage will decrease so much that torque-slip characteristic will be the same as at the higher medium temperature. In this way the supply voltage can be adjusted in stage.

Table. Computed results

Θ, °C	s_c	k_M	M_{em}, (s=1) N·m	$P_{\text{em,max}}$ W	P_{em}, (s=1) W	U_M, V
Iron Ст 3 (in Russian)						
–20	4,31	0,316	0,39	141	124	169
+20	4,22	0,264	0,33	117	103	165
+200	4,87	0,171	0,224	78,7	68	162
+250	4,94	0,155	0,195	71,5	62	159
Iron – copper CM–25 (in Russian)						
-20	0,52	0,425	0,44	141	134	129
+20	0,51	0,354	0,37	118	116	123
+200	0,55	0,237	0,24	78,8	77,1	122
+250	0,56	0,215	0,22	71,6	70	121

So the borehole motor with set peculiarities and characteristics can be designed solely for the set supply circuit while the accordance of the motor and circuit parameters is one of the main factor determining the motor power and characteristics.

Conclusions

The critical slip and the maximum electromagnetic power expressions of the induction motor with solid ferromagnetic rotor supplied through the long geophysical cable with distributed parameters taking into account the transmission condition of maximum electrical power in the electrical circuits has been deduced.

The algorithm and program for study of the borehole motor characteristics taking into account the wide temperature change interval of operating medium and it influence to the geophysical cable parameters while the cable lengths on the ground surface and let down in borehole are different has been developed.

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S. Gečys. Darbo terpės temperatūros pokyčių įtaka gręžinių tyrimo įtaisų elektros variklio charakteristikoms // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2006. – Nr. 1(65) . – P.64 – 67.

Gręžinių variklio ekstremalios darbo sąlygos yra tokios: platus darbo terpės temperatūros kitimo intervalas nuo – 20°C iki +250°C ir daugiau; hidrostatinis slėgis – nuo atmosferinio iki 210 MPa; darbo terpė – dielektrinis skystis; ribotos galios maitinimo šaltinis; ilgas maitinimo kabelis (iki 10000 m) ir nepastovi variklio apkrova per darbo ciklą. Šios sąlygos turi įtakos variklio patikimam darbui, maksimaliosios galios perdavimui, charakteristikų pasikeitimui. Pateiktos asinchroninio variklio su vientisuoju feromagnetiniu rotoriumi kritinio slydimo ir maksimaliosios elektromagnetinės galios išraiškos, atsižvelgiant į variklio ir maitinimo grandinės parametrus. Sudarytas variklio charakteristikų skaičiavimo algoritmas ir programa, atsižvelgiant į gręžinio terpės temperatūros kitimą ir jo įtaką variklio bei kabelio parametrams, kai kabelio ilgiai žemės paviršiuje ir gręžinyje yra skirtingi. Il.1, bibl. 7 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

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The extraordinary conditions for borehole motors are following: the operating medium temperature changing interval is from –20°C up to +250°C; the hydrostatic pressure changes from atmospheric up to 210 MPa; the operating medium – dielectric liquid; an energy source is of limited power; the length of geophysical cable is up to 10000 m; the load during the operating cycle is non-constant. These conditions have influence on the motor reliable operating, maximum power transmission, changing of characteristics. The critical slip and maximum electromagnetic power of the induction motor with solid ferromagnetic rotor supplied through the long geophysical cable taking into account the parameters of the motor and supply circuit have been derived. The algorithm and program for study of the borehole motor characteristics taking into account the wide temperature change interval of the borehole operating medium and it's influence to the parameters of motor and geophysical cable while the cable lengths on the ground surface and let down in borehole are different has been developed. Ill.1, bibl. 7 (in English; summaries in Lithuanian, English and Russian).

С. Гячис. Влияние изменения рабочей температуры среды на характеристики электродвигателя для геофизических скважинных устройств // Электроника и электротехника. Каунас: Технология, 2006. – № 1 (65). – С. 64-67.

Экстремальные рабочие условия двигателя для геофизических скважинных устройств такие как: широкий интервал изменения температуры рабочей среды от – 20 °C до +250 °C и более; гидростатическое давление – от атмосферного до 210 МПа; рабочая среда – жидкий диэлектрик; источник питания предельной мощности; длинный геофизический грузонесущий кабель питания (до 10000 м) и непостоянная нагрузка двигателя влияют на его надёжную работоспособность, передачу максимальной мощности, изменению характеристик. Представлены выражения для критического скольжения и максимальной электромагнитной мощности асинхронного двигателя с массивным ротором питаемого через длинный геофизический кабель учитывая параметры двигателя и схемы питания. Учитывая широкий диапазон изменения рабочей температуры среды и её влияние на параметры двигателя и кабеля при различных его длин на поверхности земли и в скважине составлен алгоритм и программа для расчёта характеристик скважинного двигателя. Ил.1, библ. 7 (на английском языке; рефераты на литовском, английском и русском яз.).

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