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Design Aspects of Electric Motors for Borehole Investigating Mechatronic System

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Introduction

All the growing demand of a mineral-source of raw materials demands to increase prospecting works with expansion of geography and increase in depth of boreholes. The increase in depth of boreholes causes serious problems connected in particular to temperature and hydrostatic pressure of an environment. Drilling of deep and super-deep boreholes becomes the utmost important problem of creation of the geophysical equipment calculated for work at temperature +250 $^{\circ}$C or more and hydrostatic pressure up to 210 MPa. On the other hand greater depths draw attention to themselves not only with commercial but also from the scientific point of view.

It is necessary to note, that some questions, concerning development of the heat-pressure-resistant electric motor for mechatronic systems of geophysical researches are already partially solved. The single-phase capacitor asynchronous electric motors with outer diameter 58 mm, are efficiently developed and introduced at an ambient temperature up to +200 $^{\circ}$C and hydrostatic pressure up to 150 MPa [1, 2]. Such electric motors cannot be attributed to a class, where the electric motors are supplied from a voltage source as properties and characteristics of the electric motors supplied both from a current source and from a voltage source can prevail.

So it is necessary to discuss some design aspects and peculiarities of the borehole motor as an unconventional motor with the specific non-standard demands, which depend on the complicated operating conditions of the borehole investigating and prospecting reserves of the raw materials.

Some design aspects of borehole motors

The choice of the main dimensions of a conventional induction motors and also servomotors is related to power characteristics. In most cases, as a rule, it starts from Arnold's constant [3]. The peculiarities and operating conditions of the borehole motors are very specific and characteristic only to the concrete purpose equipment, operating at the extraordinary conditions [1, 4]. The outer diameter of the borehole motor is strictly limited (the scale of a borehole devices diameters is standardized), but the length L_1 is unlimited. In order to achieve the design motor power (or torque), it is necessary to increase the active motor length. When the ratio L_1/D_i is more than three, the problem is to lay the winding into slots (D_i is the inner diameter of stator). This ratio of the conventional induction motors does not exceed L_1/D_i<1.

The same design problem is for the electric drills for borehole and immersion depth water pump motors. The active part of the motor is assembled from the sections into the common indivisible frame.

It is important to remark that borehole motors have not the concrete fixed rated operation point and just so the rated parameters, because the operation point depends on many factors such as: the operating medium temperature (up to +275^{0}C); the viscosity of dielectric liquid; hydrodynamic losses (the main part of the mechanical losses); non-constant load during the operating cycle; non-constant supply voltage of motor through all range of slip; non-constant transmitted active power to motor, etc. In this case it is significant to change the usual rated parameters to a certain integral parameters, which will characterized the borehole motors at slip range from 0 up to 1. The number of these parameters may be minimum, but enough in order to synonymously characterize the borehole motor. Then for the borehole motor it is expedient to use the average electromagnetic power at motor operation slip range:

$$P_{ema} = \int_0^1 P_{em}(s)ds\,, \tag{1}$$

for the two-phase and three-phase motors, and

$$P_{em,a} = \frac{1}{1-s_0} \int_{s_0}^{1} P_{em}(s) ds \,, \tag{2}$$

for the single-phase motors.

For the borehole motors (outer diameter 36mm) it is expedient rationally to use the inner volume of the electromechanical unit of a mechatronic system.

When the motor, chassis, transit wires are placed into the inner volume of the electromechanical unit, the space factor of the transit wires can be expressed as:

$$k_{tw} = \frac{\sum_{i=1}^{k} S_{itw}}{S_i - (S_M + S_S)} \,, \tag{3}$$

where S_{itw} is the cross-section area of the i-th transit wire; S_i is the inner cross-section area of the housing of electromechanical unit; S_M is the cross-section area of the motor; S_S is the cross-section area of the chassis; k is the number of transit wires.

The space factor of the transit wires can be increased: the transit wires can be laid in the four slots, which are on the outer motor surface. This will be taken into account when calculating the slot form of the stator core lamination; the transit wires can be laid into the slots of motor.

The borehole motor construction is frameless. The stator core at four places along to core is welded using ozone gaseous medium. The outer diameter of stator core is the motor outer diameter. In this case it is possible to achieve the shortening of the active motor length till 20%, leaving the same average electromagnetic power. Therefore the construction of motor becomes stronger and the possibility to deform itself stator welded core due to wide temperature change interval disappears.

The motor operates in dielectric liquid, that is why hydrodynamic losses increase, but on the other hand the cooling of motor becomes better. The superheat temperature of the station winding is (2-3)^{0}C (test have been made in autoclave), therefore it is possible to choose the higher current load, but it is impossible to forget the motor reliability one of the main demand's. The rotor type of borehole motor usually is solid ferromagnetic or double-layer and also solid ferromagnetic with copper cage winding.

As a rule if the motor diameters decrease, the motor input complex impedance Z_M increase and sometimes it can be rather bigger than the complex impedance of the supply circuit Z_C. It is important to remark that impedances Z_M and Z_C change differently due to the medium temperature change. So at the design stage the calculating algorithm of the motor characteristics must evaluate the change parameter of the motor and the complex supply circuit depending on the specific and non-stable peculiarities and characteristics of the borehole logging problems.

The principal methods of the borehole motor design can be: a) the parameters of the motor are known and it is necessary to choose the suitable power-supply circuit with favourable parameters; b) the power-supply circuit and its parameters are known, it is necessary to design borehole motor with demanded characteristics; c) the borehole motor and the power-supply circuit are designed together.

The third method is the most general, while the first and the second methods are the partial cases. The operating standard borehole logging equipment can be successfully used.

The parametric method of synthesis with the setting peculiarities of the borehole motors in design stage is useful and desirable. The individual stages of the motor optimization (geometric dimension of magnetic circuit, winding data, synthesis of equivalent parameter) can be done according to methods presented in [5].

Electromagnetic estimation of stator winding

Because the outer diameter of the borehole motor is strictly limited (do not exceed 60 mm), therefore the number of teeth on the station Z_1 is small. The borehole motors are two-pole two-phase or three-phase induction motors supplied from the single-phase, symmetrical two-phase (Scott connected transformer) or three-phase limited power-sources. Let us investigate and compare all the possible two-phase and three-phase station winding variants (Z_1=8, Z_1=12 the number of slots per pole per phase q in whole). The main demands for the windings of the borehole motors are: high reliability, simple and reliable manufacturing technology.

The amplitude of the ν-th two-phase and three-phase stage-form rotating magnetomotive force (mmf), symmetrical with respect to coordinates axis, harmonic can be calculated from the following equation:

$$F_{m\nu} = \frac{4}{\pi \nu} \sum_{i=1}^{n} F_i \sin\left(\nu \frac{\beta_i}{2}\right); \tag{4}$$

where F_i is the i-th rectangle height of the stage-form mmf spatial distribution; n is the number of rectangles making semi period of the stage–form mmf spatial distribution; ν is the order number of the positive and negative sequence spartial harmonic, β_i is the rectangle width of the stage-form mmf spatial distribution expressed in degrees of the fundamental harmonic period.

The analysis was carried out by using graphical picture which have been obtained on the basis of the examined winding mmf waves consisting of the certain height rectangles [6]. Let us suppose that the conditional number of turns in the phase of the invest examined winding types is the same and the conditional unit currents flow in it. The spatial distributions of the phase mmf wave of the investigate winding were extended according to (4) equation. One of the main factors for choosing the most suitable winding type may be the quality index. This quality index would be one of a few of the complex quality index, which characterizes the functional and technical effectiveness of the winding.

Then this quality index relatively would evaluate the weight of the higher mmf harmonics in the mmf spatial distribution and it can be expressed as:

$$k_{Q_i} = 1 - k_\nu \,; \tag{5}$$

where $k_\nu = \sqrt{\sum_{\nu=1}^{\infty} f_\nu - 1}$ is the harmonic coefficient of the phase mmf spatial distribution; $f_\nu = F_\nu / F_1$ is the relative mmf ν -th harmonic value.

Table 1. The comparison of the quality indexes and winding factors of the two-pole two-phase and three-phase all the possible types of the stator windings

Variant number	Parameters	Winding type	Quality index k_{Qi}	Winding factor k_{W1}
1	Z_1=8; m_1=2; y=4	Single-layer former	0,715	0,900
2	Z_1=8; m_1=2; y=4	Single-layer concentric	0,715	0,900
3	Z_1=8; m_1=2; y=3	Single-layer former with short sections	0,715	0,900
4	Z_1=8; m_1=2; y=3	Single-layer concentric with short sections	0,715	0,900
5	Z_1=8; m_1=2; y=3	Two-layer former short-pitch	0,764	0,855
6	Z_1=8; m_1=2; y_a=2	Sinusoidal	0,775	0,766
7	Z_1=12; m_1=2; y=6	Single-layer former full-pitch	0,788	0,911
8	Z_1=12; m_1=2; =6	Single-layer concentric	0,788	0,911
9	Z_1=12; m_1=2; y=4	Two-layer former short-pitch	0,837	0,789
10	Z_1=12; m_1=2; y_a=3	Sinusoidal	0,853	0,694
11	Z_1=12; m_1=3; y=6	Single-layer former full-pitch	0,837	0,966
12	Z_1=12; m_1=3; y_a=6	Single-layer concentric	0,837	0,966
13	Z_1=12; m_1=3; y=5	Two-layer former short-pitch	0,852	0,933
14	Z_1=12; m_1=3; y_a=5	Two-layer concentric	0,853	0,933
15	Z_1=12; m_1=3; y_a=5	Sinusoidal	0,854	0,928
16	Z_1=12; m_1=3; y_a=4	Sinusoidal	0,853	0,897

The computed quality indexes (evaluating up to 99th harmonic) and winding factors of the single-layer and two-layer of the various types two-phase windings laid into 8 stator slots as well as appropriately the two-phase and three-phase windings laid into 12 stator slots are presented in Table 1 and relative values of the higher mmf harmonics $f_\nu = F_\nu / F_1$ of the same windings are given in Table 2.

The laying into stator slots of the two-layer winding is more complicated than of the single–layer winding, and therefore it can decrease the reliability of it. For the same windings the mmf space higher harmonic relative values are just the same, while of others are different (see table 2). The sinusoidal three-phase winding with maximum average pitch can be made from simple two-layers concentric three-phase winding, because it completely satisfies structural requiments for sinusoidal winding [7].

Since the rotor impedance of the borehole motor is sufficiently big (solid ferromagnetic rotor and it is necessary to combine the complex impedances of the motor and supply circuit), that the influence of the higher harmonics to motor operating is not great, meanwhile when the losses of the motor increase. On the other hand the single-layer concentric winding may be suitable for the borehole motors.

Conclusions

The traditional design method of the conventional induction motors directly unfit for the use of the borehole motors, because the rated operation point is not characteristic for them.

At the design stage of the borehole motor it is necessary to match the complex impedances between the motor and the supply circuit as well as to endeavour maximum use the all possible reserves of the transmitted active power.

The choice of the borehole motor winding is linked with the simple and high quality manufacturing as well as the high relialibity, while the harmonic composition substantially is not principal. The single-layer concentric windings can be used for the borehole motors.

Table 2. Computed relative values of higher mmf harmonics

ν	Z_1=8; m_1=2			Z_1=12; m_1=2			Z_1=12; m_1=3		
	Variant number of winding according to table 1								
	1-4	5	6	7-8	9	10	11-12	13	16
1	1	1	1	1	1	1	1	1	1
3	-0,13807	-0,05719	0,00006	-0,12201	0,00000	0,00000	0,00000	0,00000	0,00000
5	-0,08284	0,03431	0,00004	-0,05359	0,05359	0,00000	-0,05359	-0,01436	0,00001
7	0,14286	-0,14286	0,14286	0,03828	-0,03828	0,00000	-0,03828	0,01026	0,00001
9	-0,11111	0,11111	-0,11111	0,04067	0,00000	0,00000	0,00000	0,00000	0,00000
11	0,03766	-0,01560	-0,00002	-0,09091	-0,09091	0,09091	0,09091	-0,09091	0,09091
13	0,03186	0,01320	-0,00001	0,07692	0,07692	-0,07692	-0,07692	0,07692	-0,07692
15	-0,06667	-0,06667	-0,06667	-0,02440	0,00000	0,00000	0,00000	0,00000	0,00000
17	0,05882	0,05882	0,05882	-0,01576	0,01576	0,00000	0,01576	-0,00422	0,00000
19	-0,02180	-0,00903	0,00001	0,01410	-0,01410	0,00000	0,01410	0,00378	0,00000
21	-0,01972	0,00817	0,00001	0,01743	0,00000	0,00000	0,00000	0,00000	0,00000
23	0,04348	-0,04348	0,04348	-0,04348	-0,04348	-0,04348	-0,04348	-0,04348	-0,04348
25	-0,04000	0,04000	-0,04000	0,04000	0,04000	0,04000	0,04000	0,04000	0,04000
27	0,01534	-0,00635	-0,00001	-0,01356	0,00000	0,00000	0,00000	0,00000	0,00000

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The design aspects and peculiarities of the electric motor for borehole investigating mechatronic system which are related to the specific operating conditions of these motors are presented. Such borehole motors have not the concrete fixed rated operation point, which is characteristic for the traditional electrics motors, therefore the usual rated parameters can be changed into the integral parameter, which characterize the borehole motor in entire slip range from 0 up to 1. The electromagnetic estimation of the main possible two-pole two-phase and three-phase stator windings for the borehole motors, of which the slot number of the stator is 8 or 12, is presented. The stator windings from the electromagnetic point of view are evaluated considering the winding factor and quality index, which characterize the weight of the relative magnetomotive force higher harmonic of the stator winding. The increased main demands for the stator windings of the borehole motors are discussed. Bibl. 7 (in English; summaries in English, Russian and Lithuanian).

С. Гячис, П. Смольскас. Аспекты проектирования электрических двигателей для геофизических скважинных мехатронных систем // Электроника и электротехника. Каунас: Технология, 2007. – № 2(74). С. 75–78.

Предложены аспекты и особенности проектирования электрических двигателей для геофизических скважинных мехатронных систем, которые связаны с специфическими условиями работы этих двигателей. Такие скважинные двигатели не имеют конкретной фиксированной рабочей точки, которая характерна для обычных стандартных электрических двигателяй, поэтому обычные номинальные параметры могут быть заменены интегральным параметром, характеризующим скважинный двигатель во всём диапазоне его скольжения. Предсталенна электромагнитная оценка, скважинных двигателей в статоре которых имеется 8 или 12 пазов, со всевозможными основными вариантами двухполюсных двухфазных и трехфазных обмоток статора. Статорные обмотки с электромагнитной стороны, оцениваются коэффициентом обмотки и показателем качества, характеризующим относительный вес высших гармоник магнетодвижущей силы. Оговорены основные предъявляемые требования к обмоткам статора скважинных двигателей. Библ.7 (на английском языке; рефераты на английском, русском и литовском яз.).

S. Gečys, P. Smolskas. Geofizinių gręžinių mechatroninių sistemų elektros variklių projektavimo aspektai // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. Nr. 2(74). P. 75–78.

Pateikta gręžinių tyrimo mechatroninių sistemų elektros variklių projektavimo aspektai ir ypatumai, kurie siejami su šių variklių specifinėmis darbo sąlygomis. Tokie gręžinių varikliai neturi konkretaus fiksuoto darbo taško, kuris būdingas tradiciniams elektros varikliams, todėl įprastiniai vardiniai parametrai gali būti pakeičiami integriniu parametru, apibūdinančiu gręžinių variklį visame jo slydimo diapazone. Pateikta gręžinių variklių, kurių statoriaus griovelių skaičius yra 8 ar 12, pagrindinių galimų dvipolių dvifazių ir trifazių statoriaus apvijų tipų, elektromagnetinis įvertinimas. Statoriaus apvijos elektromagnetiniu požiūriu vertinamos apvijos koeficientu ir kokybės rodikliu, apibūdinančiu statoriaus apvijos santykinį magnetovaros aukštesniųjų harmonikų svorį. Aptarti gręžinių variklių statoriaus apvijoms keliami pagrindiniai reikalavimai. Bibl.7 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).