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Application of Parametrical Method Synthesis for Borehole Motors Design

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Introduction

The parametrical method of synthesis first was elaborated in detail for the design of induction control motors [1]. Later it was applied (created algorithms and software for verifying and optimization calculations) for the other types of conventional motors, such as stepping motors, gyroscopic motors, and special purpose motors.

The main requirements for borehole motors are to guarantee the maximum reliability in all slip range of the borehole investigation device under geophysical operating conditions, such as wide operating medium temperature change interval from –20ºC up to +150ºC; operating medium – dielectric liquid; length till 6000 m geophysical cable; changing of hydrostatic pressure from atmospheric up to 120 MPa; non-regular short-time and reverse duty-type; non-constant load due to operating cycle [2, 3].

It is necessary to seek forming the torque-slip characteristic of the borehole motor, which could be reliably started up and could reach maximum rotational speed, while the load distribution is large, i.e. the integral opening time of the spring system is minimal. So, the borehole motors usually are two-pole two-phase asynchronous motors supplied from the single-phase or two-phase (supply from symmetrical and controlled two-phase power source) limited power-sources.

Generally the power-supply circuit network, its parameters, the maximum borehole medium temperature are known in advance and the motor with demanded characteristics is necessary to design.

Methodology of parametrical method synthesis

The torque-slip characteristic of the borehole motor could be reliable starting up and reaching maximum rotational speed; while the load distribution is large, i.e. the integral opening time of the spring system is minimal. In most cases, the motor operation time is short, therefore the motor efficiency and power factor are not very important indexes. In this case the design of borehole motors differs from conventional motors. The conventional induction motors are designed according to these primary data: rated voltage and frequency; rated power; rated rotational speed.

The calculation of the designed borehole induction motor is started by orientationally and expediently choosing the related equivalent circuit parameters.

The above mentioned related parameter system can be changed by integral parameter which will characterize induction motor in the entire slip range. Such parameter can be average electromagnetic power $P_{\mathrm{em.av}}$ or its mathematical analogue – criterion k_{P}:

$$k_{\mathrm{P}} = P_{\mathrm{em.av}}(s) = \frac{1}{1-s_0}\int_{s_0}^{1} P_{\mathrm{em}}(s)\mathrm{d}s\,; \qquad (1)$$

here s_0 – the no-load slip.

On the other hand, the electromagnetic power characterizes the form of torque-slip characteristics and it is also possible to find out in what scale the supply circuit is exploited [2]. When the borehole motor operates under geophysical conditions, the rated rotational speed and rated torque (or power) cannot be foreknown. It follows, that neither of the rated parameters, mentioned above, could be practically used to describe the borehole motor characteristics.

As the borehole motor has enough limiting factors

(D_y, $\rho_2' \Rightarrow R_C$, motor has no rated operating point, k_P or $T_{em.av}$), it is more expedient to discuss the rational parameters of the equivalent circuit, but not the optimal ones, because the concrete rated operating point is not fixed due to specific operation peculiarities.

Naturally, the same factors are valid for the efficiency, power factor and other parameters, which characterize the motor operation at the concrete fixed load and rotational speed. The established techniques of electrical machines design do not evaluate those peculiarities and their application for borehole motors confront with some difficulties. Surely, the motor can be designed, but differently in conventional motor case, it is implied, that the designed motor successfully operates under geophysical conditions.

Application of the method

The primary data for the design of borehole investigating motors should be as follows: power supply source phase voltage U_s; power supply source current frequency f_1; supply circuit network and parameters of its elements ($r_{o\Theta_k}$, C_0, g_0, L_0); maximum active resistance of supply circuit R_C; the number of motor pole pairs (or synchronous rotation speed of the motor); average electromagnetic power k_P or average electromagnetic torque $T_{em.av}$, when s changes $1-s_0$. Generally $f_1 = 50$ Hz, $2p = 2$.

From the equation

$$T_{em.av} = k_P \frac{U_s^2}{R_C \Omega_1} \tag{2}$$

we calculate $T_{em.av}$ or k_P (here $\Omega_1 = \frac{2\pi f_1}{p}$).

From the calculated dependence $k_P = f(\rho_1)$ [2] we find ρ_1, considering that $\rho_2' = 1$, taking into account the electromagnetic calculations and experimental data with investigated borehole motors for copper-cage solid rotor induction motors ($k_m = 1{,}20 - 1{,}40$) and for solid rotor induction motors ($k_m = 1{,}40 - 1{,}60$). The maximum electromagnetic power is expressed as follows

$$P_{em.max} = k_m k_P \frac{U_s^2}{R_C} \tag{3}$$

and maximum electromagnetic torque

$$T_{em.max} = P_{em.max} \frac{1}{\Omega_1}. \tag{4}$$

The calculations of magnetic circuit were performed changing the number of stator phase turns and the cross-section of winding wire, supposing that the supply source was of limited power. Beforehand the determination of the equivalent circuit parameters is important at the initial design stage and later on to use the parametrical design synthesis.

The outer diameter D_y of borehole motors is limited (the scale of borehole devices is standardized), but the length l_1 is unlimited (the length is limited due to the stator winding technological laying problems). One of the limiting factors is the transit wires which can be laid in four slots on the outer motor surface. The motor electromagnetic power is proportional to its active volume, while the equivalent circuit parameters R_1, X_1, X_m directly depend on motor length l_1. Taking into account the accumulated design experience of a small power conventional induction motors, the factor for the first approach can be accepted as $k_D = \frac{D_i}{D_y} = 0{,}45 - 0{,}55$. The factor $\lambda = \frac{l_1}{D_i} = 2{,}50 - 3{,}50$ for borehole motors exceed $\lambda = 0{,}22 \div 1{,}60$ for conventional small power motors. Relative stator slot area [1]:

$$k_{ZS} = \frac{4 Z_S S_s}{\pi D_i^2 \left(\frac{1}{k_D^2} - 1 \right)} = 0{,}30 - 0{,}40, \tag{5}$$

here S_s – the stator slot cross-section area; Z_S – the stator teeth number; D_i – the stator bore diameter.

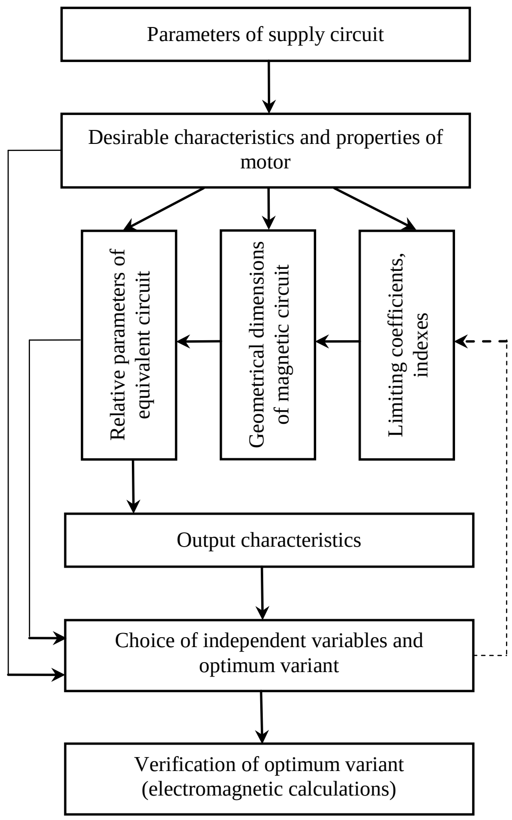

Fig. 1. Structure diagram of active part synthesis of borehole motor taking into account parametrical method

Relative rotor slot area is

$$k_{ZR} = \frac{4 Z_{\mathrm{R}} S_{\mathrm{r}}}{\pi D_{\mathrm{i}}^2} = 0{,}20 - 0{,}30\,, \qquad (6)$$

here S_{r} – the rotor slot cross-section area; Z_{R} – the rotor teeth number. Taking into account the stator tooth width, technological limits of the slot lay out on the stator surface for the transit wires, semi-oval stator slot shape is more suitable.

Results and considerations

The basic geometrical dimensions of the three studied two-phase and two-pole motors are: outer diameters – 36 mm; 31 mm; 25 mm (outer diameter of the stator core is also the outer diameter of the motor); active length of the stator and also of the rotor – 50 mm; 50 mm; 45 mm; inner diameter of the stator core – 17 mm; 15 mm; 13 mm; air gap – 0.15 mm. The number of stator slots – 8, the stator winding is double-layer former short-pitch; the number of the rotor slots – 14.

The ratio of stator core length l_1 and stator inner diameter D_{i} for the borehole motors depends on the stator core length, as the stator core outer diameter is strictly limited.

When the motor values k_{P} and $P_{\mathrm{em.max}}$ are known, the approximate specific active volume of motor can be calculated according to [1] considering that $P_{2\mathrm{N}} = k_{\mathrm{P}}$ average electromagnetic power is equal to rated motor power.

So, the relative parameters, used for the calculations of motor characteristics, would be as follows:

$$\begin{cases} \rho_1 = \dfrac{R_1}{R_{\mathrm{C}}}; \quad \xi_1 = \dfrac{X_1}{R_{\mathrm{C}}}; \quad \xi_{\mathrm{m}} = \dfrac{X_{\mathrm{m}}}{R_{\mathrm{C}}}; \\ \rho_2' = \dfrac{R_2'}{R_{\mathrm{C}}}; \quad \xi_2' = \dfrac{X_2'}{R_{\mathrm{C}}}; \end{cases} \qquad (7)$$

here ρ_1, ξ_1 – the relative stator resistance and reactance values; ξ_{m} – the relative magnetizing reactance value; ρ_2', ξ_2' – the relative rotor resistance and reactance values, referred to stator parameters.

Table 1. Construction coefficients of small power investigated borehole motors when the maximum active resistance of the supply circuit is $R_{\mathrm{C}} = 165\,\Omega$

Motor type	D_{j}, mm	k_{D}	λ	k_{ZS}	k_{ZR}
Solid rotor induction motor	36	0,472	2,94	0,335	-
	31	0,484	3,33	0,352	-
	25	0,480	2,92	0,340	-
Copper-cage solid rotor induction motor	36	0,472	2,94	0,335	0,222
	31	0,484	3,33	0,352	0,239
	25	0,480	2,92	0,340	0,248

In order to realize $R_2' = R_{\mathrm{C}}$, the optimization copper-cage solid rotor teeth zone is necessary. The rational parameters of equivalent circuit, when R_{C} is known, can be calculated according to [2].

The calculations, according to active part synthesis structure diagram of borehole motor, taking into account parametrical method (fig.1) are carried out for three motor types with different rotors (solid rotor and copper-cage solid rotor) and the results are presented in tables 1 and 2.

Table 2. Real relative equivalent circuit parameters of small power borehole induction motors operating at $R_{\mathrm{C}} = 165\,\Omega$ and $\Theta = +20$ °C (parameter change limit for solid rotor induction motor is in the numerator and for copper-cage solid rotor induction motors is in the denominator)

Relative parameter	Main factors influences on relative parameters	Change limit
ρ_1	ρ_{Cu}, l_1, w_1, S_{Cu}, slot form and dimensions	1,40–1,50
ξ_1	w_1, l_1, p, q, $\Sigma\lambda$, k_β, slot form and dimensions	0,50–0,70
ξ_{m}	m_1, f_1, δ, p, w_1, k_{w_1}, τ, l_1, k_μ, k_δ	$\frac{5{,}00 - 6{,}50}{4{,}00 - 6{,}00}$
ρ_2'	ρ_{Cu}, l_2, τ, S_{Cu}, p, m_1, Z_{S}, w_1, k_{w_1}, $\Sigma\lambda$, q_2, ρ_2, μ_2, k_β, χ, γ_{o}, ξ_{r}, slot form and dimensions	$\frac{5{,}50 - 7{,}50}{0{,}90 - 1{,}20}$
ξ_2'	ω_1, μ_{o}, l_2, p, w_1, k_{w_1}, k_{w_2}, m_1, Z_{R}, $\Sigma\lambda$, q_2, σ_2, τ, k_x, ξ_x, μ_2, γ_{o}	$\frac{3{,}00 - 4{,}50}{0{,}25 - 0{,}36}$

Preliminarily calculations of stator core length further are made more exact, taking into account the stator winding technological laying process. The individual stage of the motor optimization, such as stator winding data, is made according to the parametrical method synthesis presented in [1]. Electromagnetic properties of the two-phase windings can be evaluated by performing harmonic analysis of the rotating magnetomotive force, created by them and by calculating electromagnetic efficiency factors, based on the results of this analysis [4].

Preliminarily the determined relative equivalent circuit parameters are further analyzed by the realization of real parameters. Parametrical method synthesis at the initial design stage successfully can be applied for the devices such as [5, 6] which operates without concrete stabile rated operating point. The seventh and ninth spatial harmonics are the first order of tooth–ripple harmonics and they should be taken into account. Since the solid ferromagnetic rotor complex impedance is sufficiently larger (the factor $\lambda = 2{,}50 - 3{,}50$, while the rotor outer diameter is small), the influence of the higher harmonics to motor operating is rather small, but, in this case, the rotor referred resistance to stator parameters is more than six times bigger than resistance of the supply circuit. In this case the most suitable rotor type, corresponding to mechanical, electrical and reliability characteristics, is copper-cage solid rotor. The complex impedance of this type rotor can be changed in various ranges at design stage.

There is no problem to calculate and to manufacture cage rotor induction motor, but at worst, if the rotor is defective (the contact between rotor bars and end rings, etc.), the motor could not start. In this case, the copper-cage solid rotor induction motor will be employable and will carry out the foreseen functions. On the other hand at all points the main thing is the reliability of the borehole motor.

Conclusions

The parametrical method synthesis for small power borehole motor design is developed, taking into account the specific operating peculiarities and limiting factors.

The main construction coefficients and change limit related parameters of the equivalent circuit for design of the borehole motors, applying the parametrical synthesis principles, are determined considering the maximum transmitted active power through the supply circuit to the motor.

The calculations of equivalent circuit parameters, characteristics applying the proposed parametrical method synthesis and tests are carried out. It confirms reliable operation in the concrete supply circuit.

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The design methodology of conventional induction motors is not suitable for the borehole motors due to specific and extraordinary operating conditions. The parametrical method synthesis for small power solid rotor and copper-cage solid rotor induction motors is developed, taking into account the specific operating peculiarities and limiting factors. The main construction coefficients and change limit related parameters of the equivalent circuit for the design of the borehole motors, applying the parametrical synthesis principles, are determined, considering the maximum transmitted active power through the supply circuit to the motor. The calculations of equivalent circuit parameters, characteristics, applying the proposed parametrical method synthesis and tests, are carried out. This confirms reliable operation in the concrete supply circuit. Ill. 1, bibl. 6, tabl. 2 (in English; abstracts in English, Russian and Lithuanian).

С. Гячис, П. Смольскас, М. Жмуйда. Применение параметрического метода синтеза при проектировании двигателей геофизических скважинных приборов // Электроника и электротехника. – Каунас: Технология, 2010. – № 5(101). – С. 9–12.

Методология проектирования традиционных двигателей неприемлема для двигателей геофизических скважинных приборов из-за специфических и экстремальных условий работы. Далее развит параметрический метод синтеза для проектирования маломощных асинхронных двигателей с массивными и массивными с коротко замкнутой клеткой роторами, применяемых для работы в геофизических условиях. Применив принцип параметрического синтеза, удалось установить пределы изменения основных конструктивных коэффициентов и относительных параметров схемы замещения для проектирования двигателей геофизических скважинных приборов, учитывая передачу максимальной активной мощности цепи питания двигателю. Применив предлагаемый параметрический метод синтеза, выполнены расчёты параметров схемы замещения, характеристик и проведены испытания двигателей подтвердили, что они могут надёжно работать в данной цепи питания. Ил. 1, библ. 6, табл. 2 (на английском языке; рефераты на английском, русском и литовском яз.).

S. Gečys, P. Smolskas, M. Žmuida. Parametrinės sintezės metodo taikymas gręžinių tyrimo įtaisų varikliams projektuoti // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 5(101). – P. 9–12.

Tradicinių kintamosios srovės asinchroninių variklių projektavimo metodologija netinka gręžinių tyrimo įtaisų varikliams projektuoti dėl specifinių ir ekstremaliųjų darbo sąlygų. Išplėtotas parametrinės sintezės metodas darbui geofizinėmis sąlygomis skirtiems mažos galios asinchroniniams varikliams su vientisaisiais ir vientisaisiais narveliniais rotoriais projektuoti. Pritaikius parametrinės sintezės principus, nustatytos pagrindinių konstrukcinių koeficientų ir ekvivalentinės schemos santykinių parametrų kitimo ribos, atsižvelgiant į maitinimo grandinės didžiausios galios perdavimą varikliui. Siūlomuoju parametrinės sintezės metodu, atlikti gręžinių tyrimo įtaisų variklių ekvivalentinės schemos parametrų ir charakteristikų skaičiavimai ir bandymai patvirtino, kad šie varikliai gali patikimai dirbti nurodytoje maitinimo grandinėje. Il. 1, bibl. 6, lent. 2 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).