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Methods for rotational speed reduction for alternating current electric motors

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Abstract. The analysis of rotational speed reduction methods for alternating current electric motors are given, assigned to low-speed electric drives of various power levels. The integrated classification of electric machines of well-known types is given, the rotational speed reduction method being used as the basis. The main advantages and disadvantages, defining perspectives for the application in various low-speed electric drives, are explained. The approximate bounds of engineering expediency of the applications of the motors are given for obtaining certain assessments in selection of a type of the drive motor.

1. Introduction

Growing demands for low-speed electric motor drives of various power levels, intended for various applications in machinery, have drawn special attention to up-to-date low speed a.c. machines. Although a great number of investigations have been devoted to research and development of the abovementioned machines, the working-out of recommendations on high-torque low-speed electric machine application were not considered in a proper way. So we will first consider the classification of the above-mentioned class of machines, as well as the prospects of application in the high-torque electric drive.

2.Classification

It has been found expedient to apply the principle of obtaining a reduced rotational speed of the output shaft as the basis for classification of low-speed high-torque a.c. machines (Figure 1).

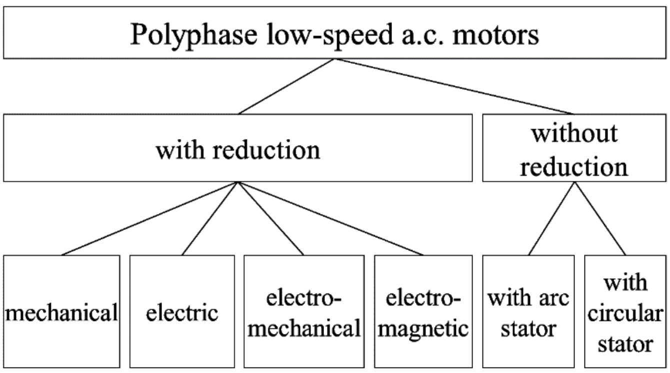

Figure 1. The classification diagram of low-speed high-torque electric motors.

In accordance with the given integrated classification, all the polyphase low-speed machines can be divided into two groups: geared motors and gearless motors.

Geared motors are specified by reduced angular velocity ω_2 of the output shaft, compared to angular velocity ω_1 of the main harmonic term of the magnetic field, the power being a source of conventional frequency. In connection with this, the reduction factor is $k = \omega_2 / \omega_1 > 1$.

Based upon the rotational speed reduction principle, geared electric machines are divided into motors with mechanical reduction, motors with electric reduction, motors with electromechanical reduction and motors with electromagnetic reduction.

Gearless low-speed electric machines ($k = 1$) are divided into circular stator motors and arc-stator motors [1], both types being fed from conventional frequency sources. The rotational speed reduction in arc-stator motors is achieved not through an increase of pole quantity but through the lay-out of the stator winding over a part of a circle. Hence, the power of the above-mentioned motors is substantially lower than the power of circular-stator motors, their low rotational speeds being equal. Therefore, arc-stator motors are basically designed for relatively low torques, and the application of the latter is effective in electric drives of the machines wherein the connection of the electric machine with its actuator is considered to be expedient. Hence, we consider exclusively arc-stator gearless motors as the most general case for multipolar electric machines.

It should be noted that the consideration of the above-mentioned low-speed electromechanical systems as cascaded ones, as well as the application of the multi-rotor motors, etc., presents a definite problem because of the variety of the effectiveness estimate criteria.

We will analyze the potentialities for classification principles of achieving the low rotational speed of the a.c motor output shaft (from the point of view of the potential use in high-torque motor drives).

3. Motors with reduction

A mechanical reduction gear extensively applied in a.c electric drives [2, 3] is the simplest way of achieving a low rotational speed for the actuator. In so doing, a reduction gear is built in the electric machine body or is located outside, the reduction factor of the above-mentioned motor being equal to reduction gear ratio i ($k = i$) and being varied within certain limits depending on a reduction gear type used.

The rotational speed reduction principle consists in feeding an electric machine from a certain dedicated electric power source with frequency f_0 (the latter being a connector between the motor and the power network), but not from a conventional frequency source. The necessity of a special source is a factor associated with the main disadvantage of a motors of the above-mentioned group and limiting their application.

Low frequency (in comparison to conventional frequency f) motors are excited by the reduced frequency current and have reduction factor $k = f / f_0$. The frequency converter transmits the required full power to the above-stated electric machine.

Well-known «double-powered» motors (slip-ring motors) are defined by reduction factor $k = f_1 / (f_1 – f_2)$ where f_1 and f_2– voltage frequencies feeding the stator and the rotor. Besides, contactless motor drives with slip rings are well known [4], two separate windings of different poles p_1 and p_2 being dropped in stator slots. The above motor reduction factor is defined by $k = f_1(p_1+p_2) / p_1(f_1–f_2)$.

The principle of electromechanical reduction of the rotational speed is based on the integration of a mechanical reduction gear box with the electromagnetic portion of the motor [5, 6]. The maximum reduction factor for the above-mentioned machines is estimated roughly as 100-5000. As we know, there are two main types of motors based on the above-mentioned principle.

In the rolling rotor machine, the rotor axis rotates about the stator axis of symmetry in synchrony with the field. The reduction factor is $k = D_2/(D_1–D_2)$, where D_1 and D_2 are the stator bore diameter and the rotor bore diameter, respectively.

The wave-rotor motor (where a wave drive is physically integral with the electric machine) features reduction factor $k = z_2 / (z_2–z_1)$, where z_1, and z_2– teeth numbers (teeth quantities) of rigid and flexible gear rings in the stator and the rotor. In spite of certain advantages, the above-mentioned motors are currently not produced (with a relatively low torque), that is caused by design complexities and difficulties in manufacturing of an elastic rotor of the required core thickness.

The motors with electromagnetic reduction operate by the principle of magnetic flux amplitude modulation [7, 8]. Taken together, they are divided into excitation winding (active) motors and motors without the excitation winding (reactive motors).

The reduction factor for an active motor is $k = z_2 / p_1$, where z_2–the number of rotor teeth, p_1– the number of stator winding pole pairs.

The reduction factor for a reactive motor is defined by $k = z_2 / (z_2–z_1)$, where z_1 and z_2 – the number of stator and rotor teeth, respectively.

The Megatorque high-torque a.c. machines with actuators produced by Motornetics (USA) are included into the above-mentioned class of low-speed electric machines. The above-mentioned motors comprise inner and outer stators with open poles (salient pole stators), the teeth being located over the pole pieces, and a thin ring rotor — with a low moment of inertia. Other designs are known as well, e.g. a low-speed machine [9].

The maximum reduction factor of motors with electromagnetic reduction is estimated roughly as 50-100. The motors based on two of the above-mentioned reduction principles are also available.

4. Gearless motors

The low rotational speed can be obtained at the expense of multipolar winding arranged over the stator. The versions of winding arrangements are thought to be the most practical in providing a maximum permissible low-speed: with slot numbers for a pole and for phase $q \le 1$.

It is a fact that value q (according to the rules of symmetrical stator winding arrangement) cannot assume value $q \le m–1$, where m – the number of phases. When$m–1 < q < 1$, the MMF winding curves include a wide range of relatively practically expressed harmonic components, the majority of the latter are of prohibitively high value, as research indicates. The above-stated fact causes a rise of differential dissipation, an increase of the complementary losses level, and thereby an efficiency decrease; it causes parasitic electromagnetic moments as well as noise and the vibration rise.

Our analysis shows that when $m–1 < q \le 1$, the machine with stator windings at $q = 1$ and with slot skewing features the best properties. Yet the diameter of the machine is rather large, which is impossible to tolerate according to operating conditions. Thus, if the traditional design motor is unrealizable, it isadvantageous to direct attention to a polystator machine offering a certain advantage of raising its low-speed level at the required diameter. The design of the gearless multipolar machines demonstrates certain characteristic properties [10], which will be considered in the part given below.

5. Dimension relationships in multipolar machines

We will first consider the main overall dimensions in the multipolar motors. As theoretical investigations show, the Esson constant in multipolar motors is two times lower in comparison to high-speed electric machines and can be approximatly estimated by value $C \approx 2.5$ kVA·min/m^3, because of a relatively low induction value for a slot in a multipolar motor ($B_\delta < 0.55T$) and more complicated cooling conditions in comparison to high-speed electric machines. We proceed from the fact that the outer diameter is defined as $D_a = (1.1\text{-}1.25)D$, where D – the inner diameter of the core. Then the design length of the motor is determined by the following relationship:

$$l_\delta = \frac{(5.2–6.2)\cdot 10^{-4}}{D_a^2}\frac{S}{n} , \tag{1}$$

where S– the design power; n– the rotational speed.

The third main dimension-air gap ofδ is taken on the basis of providing an allowable dissipation in a multipolar motor as well as by manufacturing standards.

As it does so, δ satisfies the following relationship:

$$10^{-3}D < \delta < 1.3(D/p)^2, \tag{2}$$

where p – the number of pole pairs.

In certain cases of preliminary assessment, we need to define the maximum obtainable number of poles for the maximum allowable design outer diameter of the armature in a low-speed motor. That is done by means of relationship:

$$p \leq (3.2\text{–}3.7)\cdot 10^{-3}\sqrt{D_a}. \quad (3)$$

The multipolar machine with a restricted diameter is characterized by relatively low pole pitch τ. In this situation, the core altitude of poles is to be extended for providing the required power level as well as design power factor $\cos\varphi$ in the synchronous electric motor. The required number of exitation winding turns is to be reduced in core slots, the conductor cross-sections being of a definite value. In this event, pole altitude h becomes objectionably high, the latter results in impermissible pole dissipation. Thus, the relative pole altitude should be restricted according to:

$$\frac{h}{\tau} \leq 0.3p\Big/\left(1+\frac{p^2}{100}\right). \quad (4)$$

Relationships (1)-(4) have been approved by the practice of design and development of multipolar machines (p = 12-60) with certain limited cross-sectional dimensions ($D_a < 4m$), the power range being S = 100-1000 kVA, and the required quantity estimates can be done.

6. Conclusion

The diagram roughly estimating the bounds of engineering expediency of low-speed a.c. electric motors is presented, based on the torque developed and the rotational speed of the output shaft (Figure 2), and on the strength of the analysis of the given design relationships and statistical processing of research data. The given diagram provides obtaining assessments essential for a choice of a low-speed gear electric motor type. In the diagram, a point located in areas *a-e* (or outside these areas) corresponds to each pair of required torque values T and rotational speed n. The location of the above-mentioned point outside the areas marked by dashed lines (by shading) is evidence that in developing the motor with a combination of these parametres, there are certain engineering problems. In search of alternatives, the area (that is the reduction type), located at a lower level, is preferable. Thus, if we are to provide rotational speed n = 100 r/min at torque T = 10 kN·m, we get to the point overlapped with the *c*, *d*, *e* areas, simultaneously. Consequently, there is a scope for developing either an electric machine with mechanical reduction or an electric machine with electric reduction or a gearless multipolar machine. However, the principle of rotational speed mechanical reduction is more preferable from the point of view of maximum engineering and economical effectiveness in decision-making.

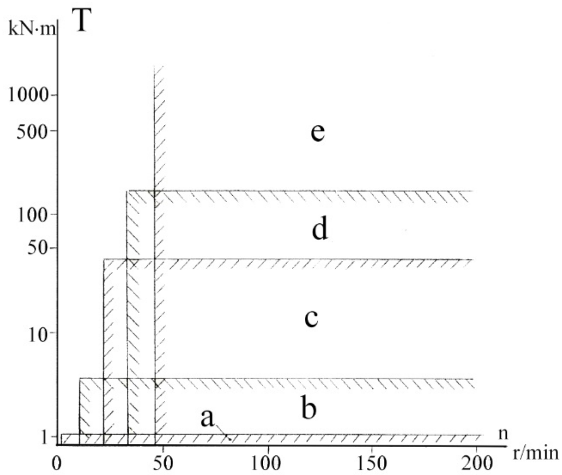

Figure 2. Statistically averaged fields of application for various types of low-speed electric machines: a – motors with electromechanical reductions; b – motors with electromagnetic reduction; c – motors with mechanical reduction; d – motors with electric reduction; f – gearless multipolar electric motors.

The data presented are averaged, but the allowance is made for the development of a low-speed electric drive on the basis of a high-torque motor, the limiting values of parameters lying outside the above-mentioned areas.

References

[1] Voldec A I and Popov V V 2007 *Electric Machines, Alternating Current Machines* (Saint-Petersburg: Piter)
[2] Bekeshev R F and Dementiev U N 2016 *Electrical drives* (Moscow: Urait)
[3] Kagan A V 2012 Construction of electrical machines (Saint-Petersburg: Saint-Petersburg Mining University)
[4] Broadway A and Burbridge L 2010 *Proc. IEEE (Piscataway)* vol 117 (Stevenage: IET) p 2160
[5] Borzyak Yu G, Zaikov M A and Nanii V P 2002 *Electric Motors with Rolling Motor* (Kiev: Technika)
[6] Green G W and Paul K J 2010 *Proc. IEEE (Piscataway)* vol 118 (Stevenage: IET) p1413
[7] Harris M, Finch J, Mallick J and Miller T 2008 *IEEE Trans. on Ind. Appl. (Greenfield)* vol IA-22 (Piscataway: IEEE) p 716
[8] Andrienko P D and Zhulovyan V V 2001 *Russian J. Electrotechnics* **11** 23-25
[9] Hashimoto I, Ishizaki K, Hayashida H, Miyashida K 1989 *Low-Speed High-Torque Motor* Patent US 4890024 A
[10] Kagan A V and Ryabukha V I 1988 *Russian J. Electromechanics* **6** 48-52