Journal of Engineering and Applied Sciences 10 (5): 102-106, 2015
ISSN: 1816-949X

Increasing the Field Reliability of Traction Switched Reluctance Motor Drive of Railway Rolling Stock

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Abstract: Calculation and the analysis of forces of a one-way electromagnetic attraction operating on bearing unit in the traction drive of switched reluctance type taking into account eccentricity of a rotor are given. It is proved that effective use of the switched reluctance motor on a rolling stock of the serious problem consisting available of significant forces of a one-way electromagnetic attraction, exceeding maximum permissible values. The methods of solution of this problem consist in tightening of manufacturing tolerances of SRM parts and assemblies or artificially introduced asymmetry of magnetizing forces.

Key words: Switched reluctance motor, forces of a one-way electromagnetic attraction, eccentricity, bearing unit, analysis, traction

INTRODUCTION

Transport process security to a large extent depends on the reliability and durability of the basic installations, units and parts of rolling stock. Durability in turn besides the intelligent exploitation, servicing and timely repair of high-quality should be provided at an early stage with the right design, calculation with precise manufacturing and assembly.

One of the main structural elements of the rolling stock, limiting its operational reliability is a traction drive. Therefore, traction motor drive reliability largely determines the reliability of the rolling stock. And the problem of increasing reliability of traction drive is relevant.

Good perspective of application among electrical machines capable of operating in the traction drive has Switched Reluctance Motor (SRM). This is due to its simple construction, reliability, high energy performance which is especially important for electric traction machines as well as low-cost manufacturing and operating costs.

However, SRM has some disadvantages. One of the most essential lacks is the presence of large periodic forces acting on the Bearing Unit (BU). This reduces the operating life drive motor, generates vibrations and as a result, noise.

MAIN PART

Usually SRM, like any other electric motor has an air gap eccentricity e due to reasons of technological and operational as shown in the block diagram of a traction drive (Fig. 1). So, the cause of the former eccentricity are: objectively existing manufacturing tolerances of SRM parts, possible errors of machines assembly, bending the shaft of the rotor, the BU wear during exploitation and others.

Because of the SRM air gap eccentricity give rise to forces of various physical natures. These include One-Way Electromagnetic Attraction Force (OWEA), disbalancement force, rotor weighload forces. Consider the action of the OWEA forces and the disbalancement forces more detail.

In eccentric disposition of the rotor relative to the stator bore and assuming that the magnetic field of the machine is symmetrical in the SRM air gap a force mutual attraction of the rotor and the stator of electromagnetic origin. Thus, the resultant of the electromagnetic forces

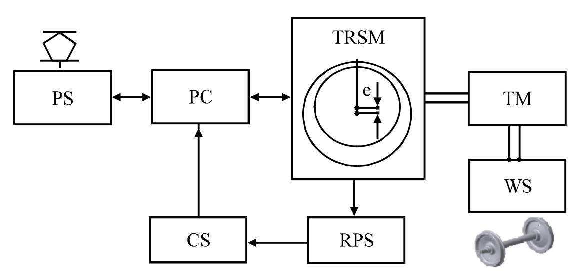

Fig. 1: Structural scheme of traction SRM drive. PS: Power Supply; PC: Power Converter; TSRM: Traction SRM; RPS: Rotor Position Sensor; CS: Control System; TM: Transfer Mechanism and WS: Wheel Set

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exerted on the rotor has a component which is directed along the displacement line in the direction of a smaller air gap. This component is OWEA force between the rotor and the stator. This force tends to increase the eccentricity and significantly reduce the critical speed of rotation and more importantly, leads to oscillations of the rotor and the generation of dynamic loads on the bearings.

The critical speed of rotation is reduced for the following reason. OWEA force increases bending deflection of the shaft, i.e., to increase the magnitude of the eccentricity defined by the elastic reaction of the curved shaft. Steady state shaft bending deflection from OWEA force determined from the equation:

$$\delta_m = \frac{\delta_0}{1\text{-}k},\ k = \frac{\delta_0}{e_0}$$

Where:
δ_0 = Proportional deflection
e_0 = Initial eccentricity

Total deflection:

$$\delta = \delta_{st} + \delta_m$$

where, δ_{st} static deflection. Then the first critical speed, taking into account the OWEA forces is reduced which follows from the equation:

$$n_{crm} = 300\sqrt{\frac{1\text{-}k}{\delta_{st}}} = n_{cr}\sqrt{1\text{-}k}$$

By the fact as SRM still has a limited area of application the impact of OWEA forces on BU reliability now is underexplored and is rare in scientific and technical literature (Colby *et al*., 1996; Pillay and Cai, 1999; Husain *et al*., 2000). Things are quite different in the field of OWEA forces acting in induction motors. A lot of research studies and publications are devoted to this subject. For example when operating asynchronous motors with increased eccentricity OWEA forces increased to 400-600% of calculated values.

At the same time with the OWEA forces when eccentricity of the rotor occur the forces of disbalancement also applied to the BU. These forces are undesirable and dangerous for many reasons. For one of these reasons include the high dynamic loads in bearings which are superimposed on the static forces and cause accelerated wear and a decrease in service life of bearings.

According to numerous studies, it is almost impossible to eliminate the disbalance of the rotor but can only reduce it to a certain value. In this regard, it has developed a number of standards, the latter of which is

Table 1: Geometric sizes of traction SRM

Size	Numerical value (mm)
External stator diameter	500
Internal stator diameter	340
Air gap (one side)	1.0
Length of core stack	360

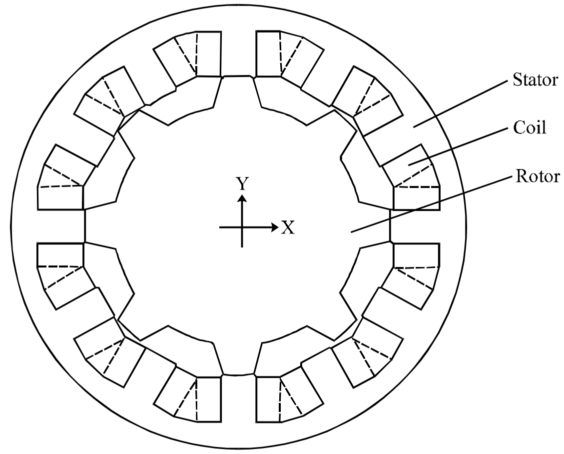

Fig. 2: Cross-section of traction SRM core stack

GOST ISO 1940-1-2007 quality requirements for balancing rigid rotors. Defining an acceptable disbalance. From this, it follows that the main purpose of balancing is to limit the impact of the forces caused by an disbalance on the bearings. However, developing the GOST ISO 1940-1-2007 it was practically difficult to isolate and study the effect of the imbalance of OWEA forces and forces of disbalancement on the BU wear separately because the forces acting at the same time and it is to fundamentally impossible to exclude OWEA forces from the process. We conclude that it is necessary to limit the magnitude of OWEA forces of not more than the amplitude of the force acting on the bearing at a residual imbalance.

To determine the values of OWEA force and to make recommendations for their reduction the magnetic system of three-phase traction SRM of the railway track machines was calculated.

Basic geometric sizes of the SRM are given in Table 1. Configuration of SRM magnetic system without shaft is shown schematically in Fig. 2.

The two most typical SRM modes when the three-phase operation were examined: nominal one-pulse mode and work with current limiting (current corridor). Calculations were conducted at the rotor shift along the X and the Y by 0.2 mm in the following sequence:

- The dependence of phase flux linkage from phase current and rotor position angle is determined solving the field problem by finite element method. Material properties and winding data were set before hand

- The dependences of phase current from rotor position angle under different operation modes were determined in MATLAB/Simulink
- The dependences of phase current from rotor position angle were used for the magnetic field calculations by finite element method in FEMM 4.2. As a result of "field" calculations dependences of OWEA force acting on the rotor from rotor position angle were received

In nominal one-pulse operation mode it was accepted: nominal torque T_n = 781 Nm, rotation speed n_n = 1700 rpm, effective current I_d = 159 A, maximum current I_{max} = 327 A. In current corridor operation mode: T_n = 782 Nm, rotation speed n_n = 850 rpm, effective current I_d = 150 A, maximum current I_{max} = 235 A.

Results of OWEA force calculations are shown on Fig. 3-6. The graphs show that the electromagnetic torque has a pulsating character and OWEA force has significant value when eccentricity of the rotor reaches. Component of force along the axis X on going from the unaligned rotor position to aligned decreases and becomes zero with the full rotor teeth with stator teeth coincides. The largest value of the resultant of forces in X and Y reaches in the end of the phase switching cycle. This is due to the fact that the tail current in the coil falls on the most unfavorable area in which the maximum OWEA force (Petrushin *et al*., 2015). The first peak of force is accounted for tail current winding phase C, the second phase A, the third phase B.

Then, the maximum allowable value of OWEA force acting on SRM BU in one-phase operation mode is determined (mass of the rotor m = 200 kg, nominal rotation frequency ω = 178 rad sec^{-1}).

According to GOST ISO 1940-1-2007 described traction SRM is referred to motors with spindle height >80 mm and nominal rotation speed >950 rpm. So, balancing accuracy class index is $e_{reg}\cdot\omega$ = 2.5 mm sec^{-1}. Allowable residual disbalancement:

$$U_{reg} = 1000\cdot\frac{(e_{reg}\cdot\omega)\cdot m}{\omega}$$

$$U_{reg} = 1000\cdot\frac{2.5\cdot 200}{178} = 2.8\cdot 10^{-3}\,kg\cdot m$$

The force acting on the bear under allowable residual disbalancement:

$$F = U_{reg}\cdot\omega^2$$

$$F = 2.8\cdot 10^{-3}\cdot 178^2 = 88.7\,N$$

From Fig. 3-6, it follows that the maximum value of the resulting force reaches 6325 N and significantly exceeds allowable disbalancement force 88.7 N calculating for rotation speed 1700 rpm.

A similar calculation was performed for the current limit operation mode. Maximum permissible force acting on the bearing at a residual imbalance amounted to 44.5 N at rotor speed of 850 rpm and the estimated resultant force of OWEA 5600 N (Fig. 5 and 6).

As the calculation of the effective use of SRM on rolling stock is facing a significant problem in the presence of significant OWEA forces exceeding the maximum permissible value. The interaction of these forces and forces caused by rotor imbalance, vibrations and environmental influences lead to a deterioration of the bearings and the bearing seats in the end shields. The problem is complex and requires a comprehensive approach. Two ways of solving it seems to be reasonable.

In the first case, it is necessary to eliminate the reasons of increased eccentricity origin. This may be

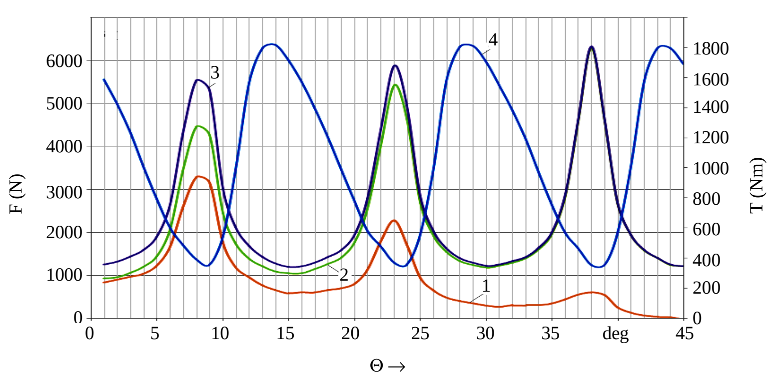

Fig. 3: Calculated SRM parameters in one-pulse operating mode; 1: X-axis OWEA force; 2: Y-axis OWEA force; 3: magnitude of OWEA force and 4: electromagnetic torque

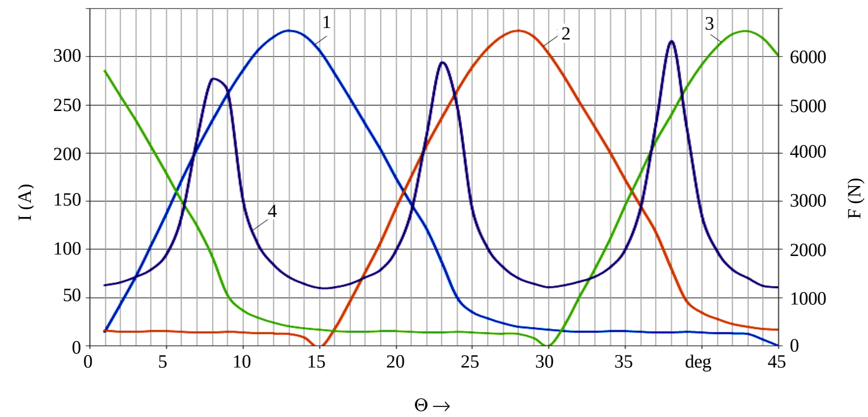

Fig. 4: Calculated SRM parameters in one-pulse operating mode; 1: A phase current; 2: B phase current; 3: C phase current and 4: magnitude of OWEA force

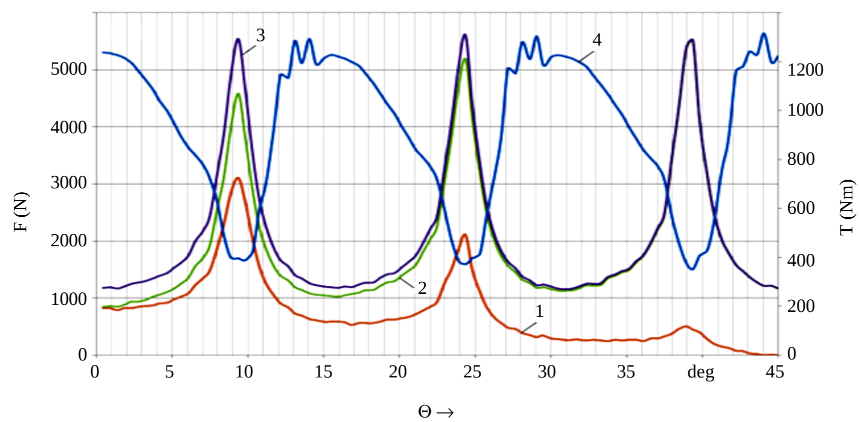

Fig. 5: Calculated SRM parameters in current limiting operating mode; 1: X-axis OWEA force; 2: Y-axis OWEA force; 3: magnitude of OWEA force and 4: electromagnetic torque

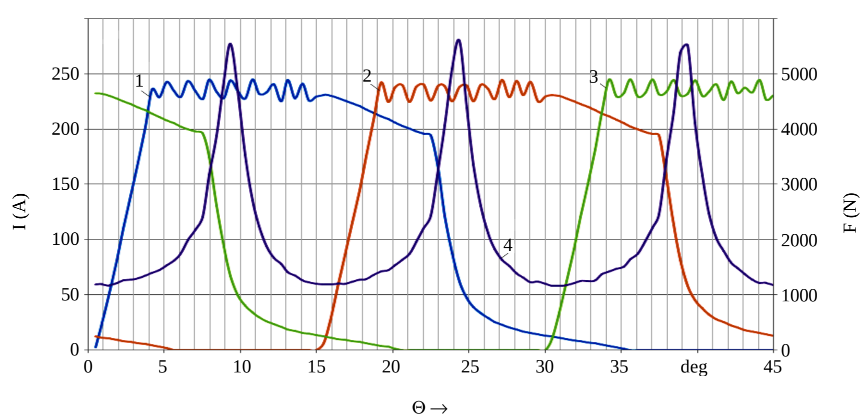

Fig. 6: Calculated SRM parameters in current-limiting operating mode; 1: A phase current; 2: B phase current; 3: C phase current and 4: magnitude of OWEA force

accomplished by the appointment of such tolerances of SRM elements design, giving a total allowable operation eccentricity and importantly, the opportunity to achieve on the present equipment manufacturers without additional investments for the purchase of a new close control equipment.

In the next case may reduce the impact of OWEA forces by artificially introduced asymmetry magnetizing forces by adjusting the current in the individual coils. For example when feeding the coils of one phase of the individual semiconductor switches can be compensated by the unilateral power of attraction is almost completely the same way as is done in active magnetic bearings with magnetic suspension.

CONCLUSION

Creating the conditions for discharge bearings from the OWEA forces is especially true for large electric machines, working in difficult operation conditions such as traction electric machines of the railway rolling stock.

From the calculations it is seen that the OWEA force considerably exceeds the force resulting from the imbalance and therefore will have a negative impact on the wear of the bearing assemblies, vibration, noise and ultimately, on the operational reliability of the traction rolling stock.

The essence of the proposed methods of OWEA forces reduction is tightening of manufacturing tolerances of SRM parts and assemblies and if this is not enough by compensating OWEA forces by artificially introduced asymmetry magnetizing forces.

ACKNOWLEDGEMENTS

The presented research has been developed with support of Russian Ministry of Education, grant RFMEFI60414X0040.

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