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Coil short-circuit in the stator winding of Line-Start Permanent Magnet Synchronous Motor

Streszczenie. *Celem tego artykułu jest wykazanie, czy silnik synchroniczny wzbudzany magnesami trwałymi o rozruchu bezpośrednim może pracować ze zwartą cewką uzwojenia stojana. Analizie poddano silnik elektryczny o mocy 3150 kW mogący napędzać wentylator głównego przewietrzania kopalni lub młyn cementowni. Za pomocą modelu polowo-obwodowego zbadano wpływ zwartej cewki uzwojenia stojana na właściwości rozruchowe oraz eksploatacyjne badanego silnika. Wskazano najbardziej narażone na uszkodzenia elementy konstrukcyjne oraz podano rekomendacje, czy praca badanego typu silnika jest możliwa w analizowanym stanie pracy.*

***Abstract**. The purpose of this article is to show whether line-start permanent magnet synchronous motor (LSPMSM) can operate with a stator coil short-circuit. Analyzed motor has a power of 3150 kW and could drive the main mine ventilation fan or the mill of the cement plant. Utilization the field-circuit model, the influence of a stator coil short circuit on the starting and operating properties is investigated. The most vulnerable construction elements are indicated and recommendations are given as to whether the operation of investigated machine type is possible in the analyzed operating condition. (**Zwarcie cewki uzwojenia stojana w silniku synchronicznym wzbudzanym magnesami trwałymi o rozruchu bezpośrednim**).*

Słowa kluczowe: silnik synchroniczny, magnesy trwałe, zwarta cewka, metoda elementów skończonych,
Keywords: synchronous motor, permanent magnet, stator coil short-circuit, finite-element method.

Introduction

The development of high power line-start permanent magnet synchronous motor (LSPMSM) has been going to on several years. The capacity barrier of 1 MW has been exceeded. In industry, this type of motor works in the drive of pumps, fans and mills [1, 2]. These machines have been working continuously for that time, collecting positive reviews. The introduction of high-power machines was preceded by the development of low-power motor. Thanks to this treatment, design patterns were verified and start-up problems were solved.

Long-term operation of LSPMSM is exposed to similar negative phenomena as induction motors. Failures can occur as a result of short circuits, surges, bearing failures [3]. Surges of the main insulation of the stator winding are quite likely to occur. They can occur as a result of moisture in the insulation, dust and pollution, frequent motor starts, the aging effect of insulating materials, transient states and operation with increased supply voltage.

Another reason for the risk of insulation damage is the disconnection of the power supply to the stator terminals. In the first moment after disconnection of the power supply, the permanent magnets placed in the rotating rotor induce a voltage at the opened terminals of the stator exceeding the rated voltage. LSPMSM in generating operation with opened stator terminals can induce a voltage of 1.2 U_N. Frequent motor starts and stops contribute significantly to the service life of the main stator insulation. Therefore, dimensions and electrical strength of main insulation should be adapted to these conditions.

Surges are one of the main causes of failure of high-power and high-voltage electrical machines (above 1 MW and above 6 kV). During this abnormal operating state, the main insulation of the stator winding fails. In the past for induction motors, surges have damaged the main insulation of a single stator winding coil. In the case where the drive was essential for the operation of an industrial plant, the defective coil was cut out and the adjacent two coils were connected together. This was practiced especially in the case of not having a replacement motor for a given workplace or when the overhaul period was too long. The repair involves pulling out the entire stator winding, building new coils, installing the coils inside the stator slots and connecting them according to the winding diagram. After the stator is wound, all the coils are saturated with resin. The above scope of repair is time consuming. In addition, repair companies often do not have drawings of the overhauled motors, and the coils are reconstructed after measuring the coils and slots. Design work can only begin after the coils have been pulled out of the slots for proper measurement. Therefore, some industrial plants take the risk and allow the motor to run with a shorted coil for a short time at a fairly limited power on the shaft until the motor was replaced with a new one.

Coil short circuit in the stator winding of induction motor can cause the asymmetric distribution of the magnetic field. As result, there will be an increase in additional losses due to the induction of eddy currents in conductive construction parts [4]. High-power induction motor are built in the following cooling system: open-circuit ventilated (IC 01), air-to-air heat exchanger (IC 611) and air-to-water heat exchanger (IC 81W). Thank to utilization of radial ventilation ducts, induction motor is obtained better blow-off and better heat pick-up. By controlling the temperature of the winding, exhaust air and coolant, it can be possible to operate the induction motor with a short-circuited coil. During this state the measured temperature cannot exceed the temperature class of the insulating materials.

High-power induction motor and LSPMSM have the same type of stator winding: loop winding. Therefore after appearance of surge it is possible to short stator coil in case of LSPMSM. Unfortunately this type of machine possess the permanent magnets inside the rotor and usage of radial ventilation ducts inside this part is not possible. Utilization of radial ducts only in stator is not effective. Therefore LSPMSM are surface-cooled (IC 411) or external surface cooled (IC 416). Significant reduction of losses in the rotor by the use of permanent magnets allowed for surface cooling from the LSPMSM motor using a fan on the shaft or with an external fan.

The purpose of this article is to investigate the impact of coil short-circuit in the stator winding on the starting and operating properties of LSPMSM. The scope includes building a field-circuit model of LSPMSM and simulating the mentioned abnormal operating state. Based on the obtained results, the most vulnerable construction elements to damage will be indicated and recommendations whether it is possible to work in investigated abnormal state.

Field-circuit model of investigated LSPMSM

In order to study the influence of the coil short-circuit on the operational properties of LSPMSM, field-circuit model was built. Investigations of turn-to-turn short-circuit and short-circuit of the stator winding coil on a small physical model showed that the numerical model correctly reflected the phenomena occurring in the electric motor [4, 5]. The measurement verification of the LSPMSM motor showed a high convergence of physical quantities [10]. Many positive implementations in industry, including high-power motors, were based on field-circuit calculations [1,2]. Therefore, an attempt was made to build a numerical model of motor with a power of more than 1 MW.

Rated power on the motor shaft and speed equal 3150 kW and 500 rpm respectively. Such motor data was assumed because there are many machines with these data in the industry, which can be replaced by high-efficiency LSPMSM. The motor types that can be replaced by tested machine type are the following: squirrel cage and slip ring induction motor, synchronous motor and synchronized asynchronous motor [6]. The rest rated data of investigated motor are shown in table 1.

Table 1. Main rated data of investigated LSPMSM

Data name	Symbol	Unit	Value
power on the shaft	P_N	kW	3150
terminal voltage	U_N	V	6000
stator current	I_{SN}	A	310
frequency	f_N	Hz	50
speed	n_N	rpm	500
power factor	$\cos\varphi_N$	-	0.99
efficiency	η_N	%	98.6
torque	T_N	kNm	60.2
start-up current	I_S / I_{SN}	p.u.	7.0
initial start-up torque	$T_{start\ max} / T_N$	p.u.	2.2
minimum start-up torque	T_{min} / T_N	p.u.	1.1
overload	T_{max} / T_N	p.u.	1.85

The field model of investigated motor is shown in figure 1. The two-dimensional model of LSPMSM was created in ANSYS software dedicated to finite element analysis of electromagnetic field distribution. The stator and rotor cores are laminated. The rotor possess two damper cages. The first is made of bronze and the second is made of copper. The ring-shaped segments are made of copper. The permanent magnets are put inside the rotor.

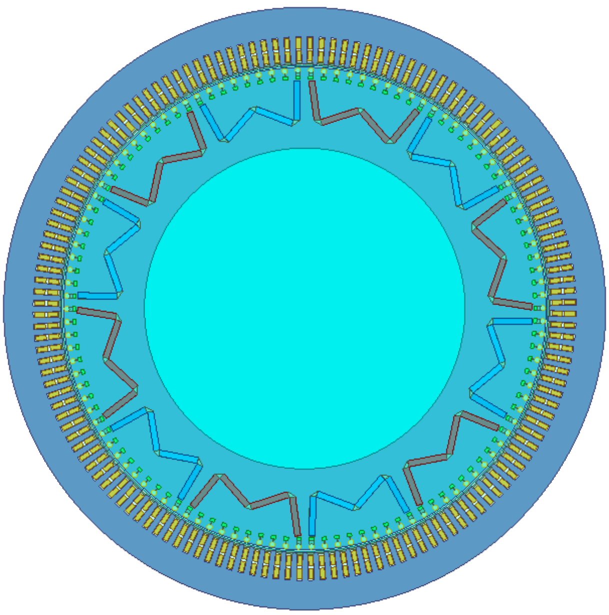

Fig. 1. View of field model of investigated LSPMSM

The field model is coupled with the circuit model, which includes passive elements (winding resistances and end-winding inductances), power source and elements representing rotor cages. Using this model, a short-circuit of a single stator winding coil was simulated. Top coil side is located in slot no. 11, whereas bottom coil side is in slot no. 1 (figure 2). A stator coil pitch equals to 10 and number of stator slot is 144.

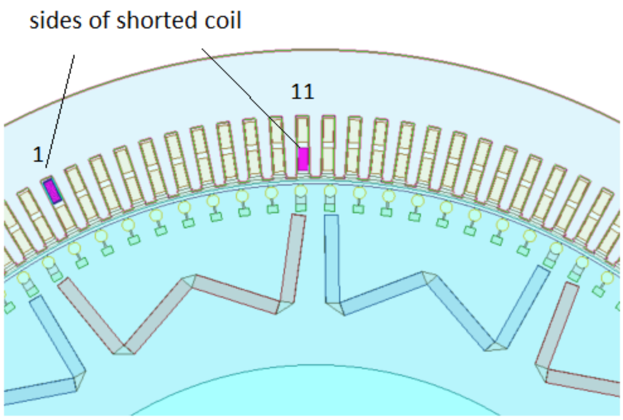

Fig. 2. View of coil short circuit in the stator winding of LSPMSM

The field-circuit model of investigated motor reflects the nonlinear magnetizing curves of rotor and stator cores, possibilities of inducing current in rotor bars, rotor movement, and external electrical circuit with voltage sources. However, the skin effects in stator coils and eddy currents in the stator and rotor laminations are neglected.

Described model has been optimized in terms of obtaining the highest possible efficiency, overload capacity and limiting the starting stator currents. This motor was designed to drive pumps, fans and mills. In this research work, it will be used to examine the impact of the stator winding coil short-circuit on the operating and starting properties of LSPMSM.

Calculation results of stator coil short-circuit in the stator winding

The short circuit of the stator coil in phase A was simulated. One coil is cut. the resistance of the section connecting two adjacent coils is 1E-9 Ω. The transient state analysis of a Line-Start Permanent Magnet Synchronous Motor is studied. The short-circuit of the stator coil contributed to the creation of an unsymmetrical magnetic field inside the motor. Lower number of turn in phase A causes lower inducted back-EMF on the armature terminals (fig. 3).

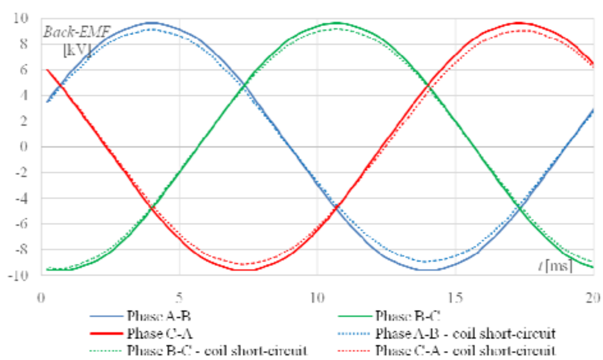

Fig. 3. View of electromotive forces induced on the stator terminals

Based on harmonic distribution of induced voltage (between phase A and B) on the stator terminals during generating operation (fig. 4) it can be noticed that first harmonic of back-EMF is reduced from 1.13 into 1.08 U_N. The value of the induced voltage is higher than the rated value (U_N) to obtain high power factor over the entire load range. Therefore, it should be expected that the occurrence of the analyzed failure state will contribute to the deterioration of power factor. Unsymmetrical magnetic field has a huge impact on the waveform of induced back-EMF. Total harmonic distortion (THD) increases from 0,5 % (without failure) to 1,0 % (during coil short-circuit).

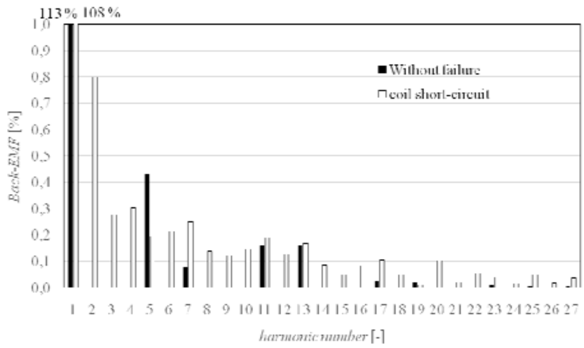

Fig. 4. Back-EMF harmonic distribution between phases A and B

The single coil short-circuit does not significantly affect the cogging torque. Figure 5 shows a comparison of the cogging torques as a function of the rotor position for two stator slot pitches for normal and failure condition.

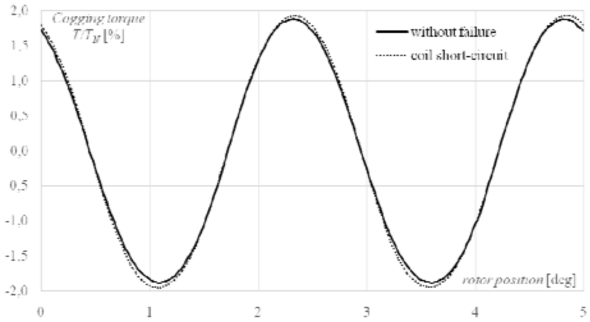

Fig. 5. Cogging torque in function of rotor position

The next investigated operating state is motor operation with rated load. The single coil short-circuit causes the ripple of stator currents and electromagnetic torque. The waveforms of stator currents during failure and normal operating work are presented in figures 6 and 7. The highest current occurs in phase A where the coil short-circuited. Ripple of electromagnetic torque are visible (fig. 8) and can cause vibration. This can lead to shortened machine lifetime or damage the bearings.

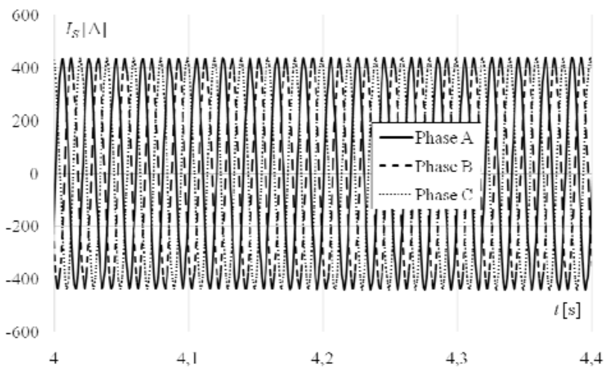

Fig. 6. Waveform of stator current during rated load (without failure)

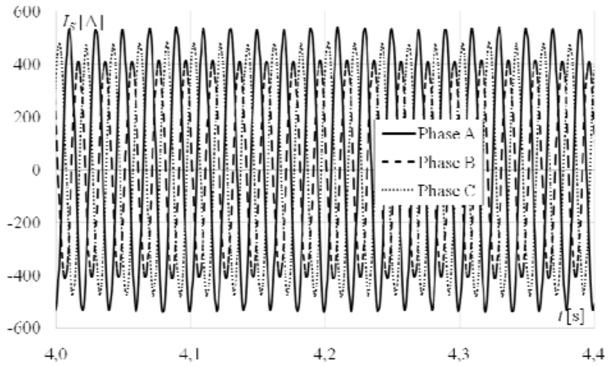

Fig. 7. Waveform of stator current during rated load with coil short-circuit

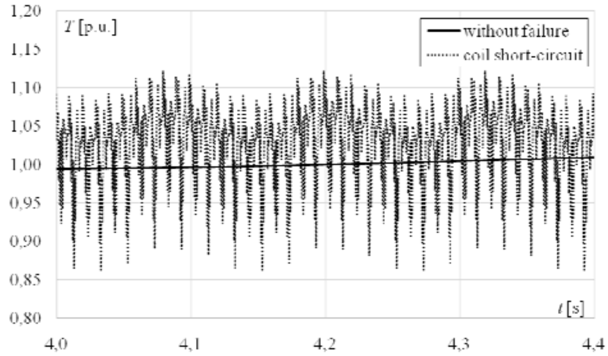

Fig. 8. Waveform of electromagnetic torque during rated load without failure and with coil short-circuit

The single coil short-circuit does not impact significantly on motor overload capacity (fig. 9). During the fault condition, the overload capacity decreases slightly.

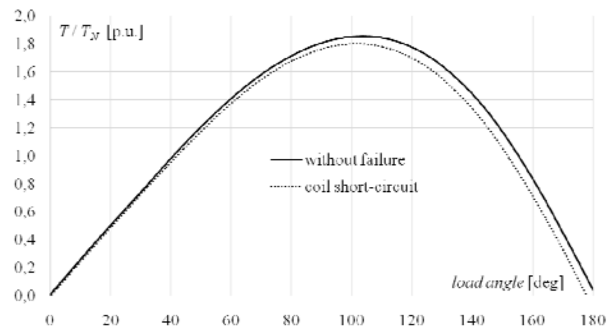

Fig. 9. Motor overload capacity in function of load angle

Efficiency of LSPMSM (fig. 10) is constant at almost full load range (from 0,3 to 1 T_N). Whereas occurrence of stator coil short-circuit reduces efficiency by 2.0 % (from 98.6 to 96.6 %) at rated load. Beside this it drops down significantly after reducing the power on the shaft. The efficiency graph resembles the graph of the efficiency of an induction motor.

Unsymmetrical magnetic field has a huge impact on increase of additional losses, especially in rotor cages. For healthy stator winding the losses in rotor cages are in range from 1.6 to 2.4 kW depending on the load. Whereas losses in rotor cages after occurrence of coil short-circuit equals to 68 kW and do not depends on the load. The statement of this losses for normal and failure conditions are presented in figure 11. Only the losses in the rotor cages account for as much as 155% of the total losses of a healthy motor. Therefore the motor work is not recommended with coil short-circuit because of huge temperature of rotor cages which can enormous impact on the permanent magnets properties and their temperatures. This temperature can be above class temperature and magnets will be demagnetized [9].

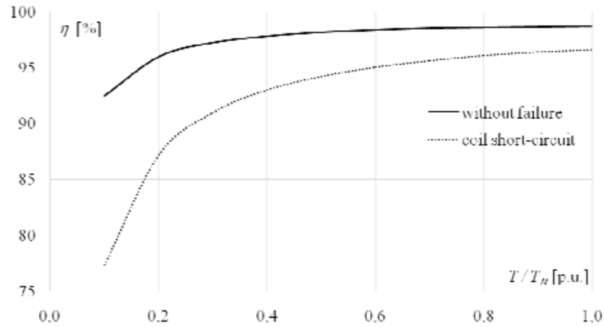

Fig. 10. Efficiency in function of load

Lower number of turns (after coil short-circuit) contributes to a reduction of back-EMF and thus a reduced power factor (fig. 12). Power factor is reduced from 0.99 to 0.94 at rated load. This trend is maintained in load range from 0.5 to 1 T_N. Lower power factor contributes to an increase of the stator current and thus to an increase of the losses in the stator winding. The core and mechanical losses are at the same level regardless of the analyzed operating states.

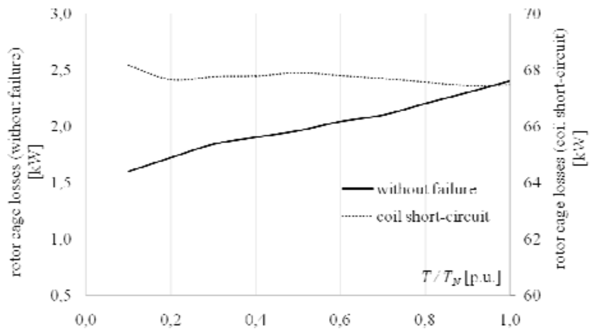

Fig. 11. Rotor cage losses in function of load

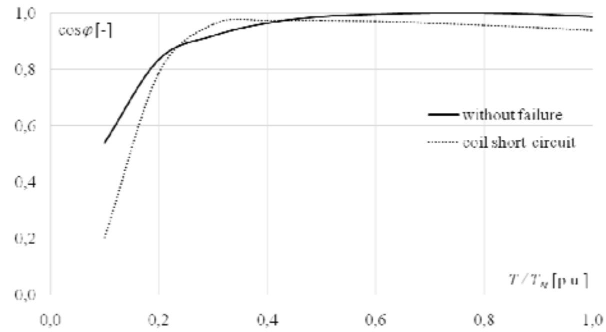

Fig. 12. Power factor in function of load

A graphical comparison of the values of the currents induced in the rotor bars is shown in figures 13 and 14. The highest values of current densities exist in the bars located in close of magnets with different polarization.

The maximum current density during rated load equals to 0.35 A/mm^2. Whereas during coil short-circuit is 80 A/mm^2. It means analyzed abnormal state increases the eddy currents 228 times.

The last years of research on LSPMSM has been concerned to obtaining the starting torque exceeding the load torque and the braking torque coming from the rotor magnets. therefore it is important to check that this motor starts with a shorted stator coil. Figure 15 presents the mechanical characteristic. The starting torque of healthy motor is almost constant in speed range from 0 to 400 rpm and equals to ca. 2.15 T_N. There is no risk of the motor not starting, even taking into account the braking torque (fig. 16). The maximum value of breaking torque is 1.1 T_N.

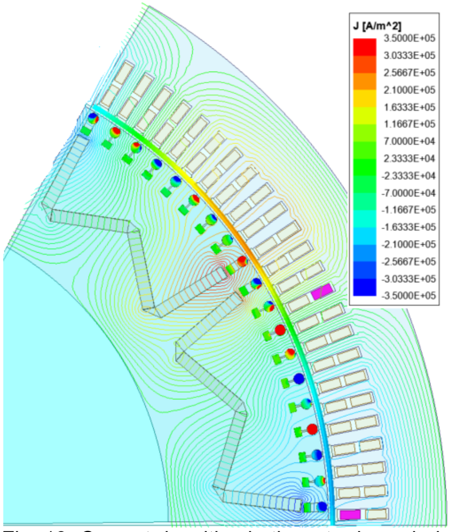

Fig. 13. Current densities in the rotor bars during rated load without failure

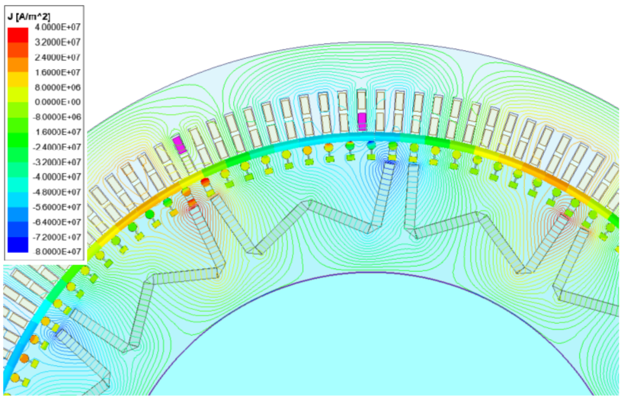

Fig. 14. Current densities in the rotor bars during rated load and with coil short-circuit

A smaller number of turns in one stator phase contributes to an increase in the starting torque for n=0 rpm. Starting torque increases from 2.15 to 2.6 T_N. unfortunately, with the increase in rotational speed in the first phase of starting, the starting torque decreases. After reaching the speed of 90 rpm, this torque increases. The resulting torque saddle increases the starting time and can lead to motor stalling. Too long start-up time contributes to an increase in the temperature of construction elements, in particular the stator winding and rotor cages. If the start-up is too long, the high temperature coming from the rotor starting cage may lead to exceeding the temperature class of the magnets, and consequently to the irreversible loss of their properties.

The computed braking torques coming from the permanent magnets for investigating cases are similar. The coil short-circuit does not impact on that (fig. 16). The maximum braking torque is computed for speed of 4 rpm.

The starting current is slightly higher for a motor with a shorted stator coil (fig. 17). This current for the healthy motor equals to 7.0 I_{SN}, whereas for coil short-circuited motor is 7.4 I_{SN}. The curves of starting currents in function of speed for investigated cases are very similar.

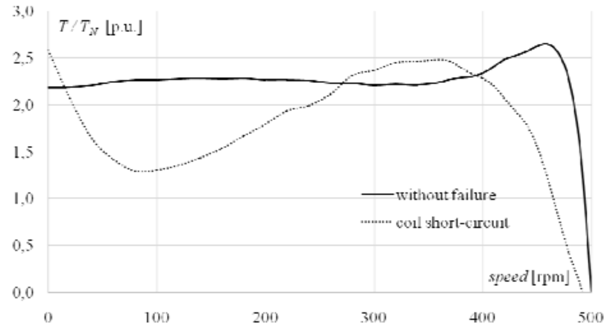

Fig. 15. Electromagnetic torque coming from the rotor cage

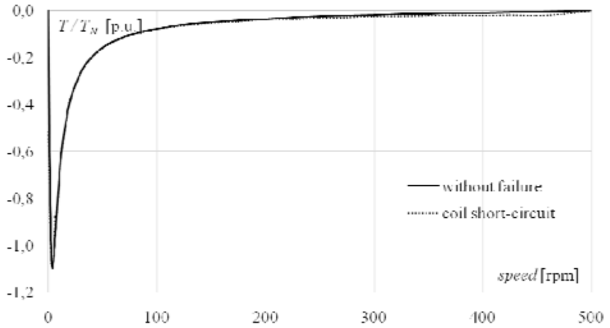

Fig. 16. Braking torque coming from the permanent magnet mounted in the rotor in function of speed

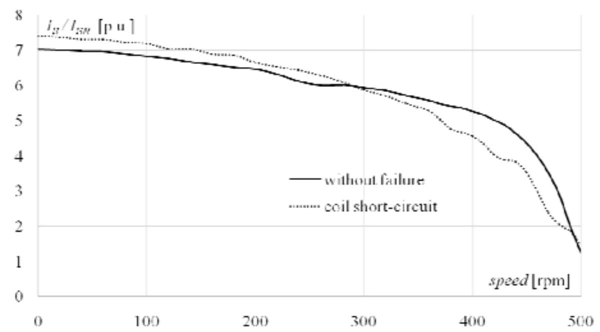

Fig. 17. Starting current in function of speed

Conclusion

The stator coil short-circuit decrease the number of turns in one phase, thus reducing the electromotive force induced at the armature terminals. Therefore power factor is lower and thus higher value of reactive power must be absorbed from the power system in order to magnetize the motor cores. In this way the stator current increases in the stator winding.

During this abnormal condition, additional losses in the rotor cage bars increase, so that the efficiency of the motor decreases significantly. The increase of eddy currents in the rotor cages contributes to the increase in their temperature. It can lead to heating of permanent magnets above their temperature class, and consequently lead to irreversible loss of their properties. LSPMSM has a ribbed hull and cooling system of IC 411 or IC 416 and therefore heat removal from the rotor is difficult. Thus, the removal of heat from the heated construction elements of the rotor is difficult.

Current and electromagnetic torque ripple can cause the machine to vibrate excessively. This can lead to excessive noise and accelerated aging of the bearings.

A visible saddle in the starting torque curve contributes to an extended motor starting time. This can lead to overheating of the rotor cage, stalling of the motor, and in the worst case, desoldering of the rotor cages or demagnetization of the permanent magnets.

Cutting the coil requires appropriate insulation of the places connecting two adjacent coils. If these connections are not made correctly, the insulation may be punctured at this point or the turn-to-turn insulation may be damaged, and thus turn-to-turn short circuits. The risk of surge of the main insulation is greater the higher the stator voltage, because it requires, apart from a sufficiently thickness insulation, outer corona protection and an appropriate distance between the coils in the stator end-winding. Incorrect repair of the main insulation may lead to another surge.

Based on the obtained results, it is not recommended to operate the LSPMSM with a short-circuited stator coil.

It is recommended to repair the place of insulation where the surge occurred, if it is the stator end-winding, or to rewind the entire winding with a new one.

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