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A new approach to design line start permanent magnet synchronous motors

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ABSTRACT

The article describes a new approach to line start permanent magnet synchronous motors (LSPMSM) design process. This different, novel approach is based on the modification of mass-produced induction motors. The presented method facilitates and expedites the electrical motor design process. A field-circuit model of the motor has been created to expound the methodology of the process. Then, the machine's geometry was changed to apply permanent magnets. The problems and benefits associated with the use of permanent magnets were described. The created model was tested. The authors examined the operation of the LSPMSM motor in different states, such as starting, no-load, and blocked-rotor tests. Electromechanical characteristics have been plotted. The simulation results were compared with the parameters and characteristics of the induction motor. The conducted tests proved the correctness of the design process. The operational properties of the motor have been improved. Moreover, the validity of using LSPMSM motors instead of induction motors has also been demonstrated.

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1. INTRODUCTION

In the era of technological development and automation of the industry, an increase in electricity consumption is forecasted in the following years [1], [2]. A large number of new factories and industrial plants are being built in the world. Electric drives are currently the dominant electrical energy receivers in the industry. The current research and analysis on electricity use with a division by receivers show that electric motors installed in the network consume up to 50% of the electricity produced in the system [3], [4]. Therefore, due to concern for the environment, energy-saving solutions are sought. The savings can also be found in the field of electric drives and machines.

The latest standards introduce ever higher requirements for the efficiency of electric motors. The IEC 60034-30-1: 2014 standard [5] describes the efficiency classes of alternating current (AC) motors supplied directly from the grid. Classic induction machines may struggle to achieve the IE5 class. This rating corresponds to the highest efficiency of the motor. The solution to this problem may be using modern synchronous motors with permanent magnets (PMSM) in electric drives. Motors of this type are increasingly used in heavy mining drives. The motors with permanent magnets drive fans [6], pumps [7], and ball mills [8]. In addition, they find their application in precise drives of computerized numerical control (CNC) machine tools [9] and robotic manipulators [10]. Furthermore, permanent magnet synchronous motors are increasingly used in traction vehicles as electric drives in high-speed railways [11], [12]. The advantages of the motors with permanent magnets have also been noticed by manufacturers of electric and hybrid cars, which contributed to the development of zero-emission vehicles [13]–[16].

The topicality of the topic is evidenced by numerous publications prepared by many research centers. Scientists worldwide conduct intensive research in this field to create modern solutions for such motors to be implemented in modern electrical devices or electric cars. In papers [4], [17]–[19] the influence of the arrangement of the permanent magnets in the rotor of PMSM motors on the electromechanical characteristics and operational properties is discussed. The authors also included an analysis of the material from which the permanent magnets were made. In [20]–[22] the influence of the rotor design on the starting properties of synchronous motors with permanent magnets was emphasized. Work is also carried out on modifying the machine geometry, for example: changing the number and shape of slots and stator teeth to reduce the cogging torque, negatively affecting the operation of the machine in various states [23]–[25].

The authors of this article proposed a different approach to the design of PMSM motors. This approach consists of the modification of the induction motor. Hence, the design process is relatively swifter and more straightforward than the standard design process. The construction of the stator remains unchanged. The interference concerns only the rotor's construction. Practically every electrical motor installed at a given factory may be subject to such modifications. The authors proved that the optimal modification of commonly used induction motors provides measurable benefits, both operational and financial. These modifications include the appropriate parameterization of the machine, its geometry, and the arrangement of permanent magnets, which is an aspect of the novelty. For this purpose, appropriate computer-aided design (CAD) computer programs can be used. The most popular of them in the described field are flux and Ansys Maxwell [4], [13], [18], [26].

2. MODEL

The construction of PMSM and induction motors are similar. Especially the structure of the mechanical systems (bearings, cooling), the stator core, and stator windings are almost identical. The three-phase, three-layers winding in the stator is the same type as in an induction motor. However, due to the necessity to place permanent magnets, there are differences between the rotor of the induction motor and the rotor of the PMSM. There are two main constructions of rotors: with magnets stuck on the rotor and recessed magnets. The choice of rotor structure also affects the operational properties of the motor, such as load characteristics, mechanical characteristics, induction distribution along the air gap, and the shape of the voltage induced in the stator [4], [22], [27]. The rotor of the line start permanent magnet synchronous motors (LSPMSM) is also equipped with a starting squirrel cage. The starting squirrel cage has a structure similar to that of an induction motor.

For the purposes of the paper, the field-circuit model of the LSPMSM motor was created in the commercial finite element method (FEM) program, the flux product of the French Company Cedrat. This model is based on a modification of the mass-produced induction motor. It is a 1.5 kW, 4 pole induction motor with a 90 mm shaft rise. The rated data of the motor are presented in Table 1.

Table 1. Nominal parameters of based induction motor

Symbol	Quantity	Value
P_n	Rated power	1.5 kW
n_n	Rated speed	1415 rpm
M_n	Rated torque	10.13 Nm
V_n	Rated voltage	400 V
I_n	Rated current	3.6 A
f_n	Rated frequency	50 Hz
PF	Rated power factor	0.76
η	Rated efficiency	79 %

The construction of the stator of the modified motor remained unchanged. However, the rotor and the motor shaft were modified. The number of slots and their shape in the rotor have been changed. The shaft diameters have also been reduced to have more space for neodymium permanent magnets. The change in the shaft construction has not adversely affected its mechanical properties. Permanent magnets with a sufficiently large volume used in the LSPMSM motor provide a large magnetic flux hence the motor's power factor will improve. However, permanent magnets have a negative impact on the starting properties of motors due to reducing the surface of the starting squirrel cage and high cogging torque. The geometry of the tested model of the LSPMSM motor is shown in Figure 1. The geometry consists of two main parts: outer–stator and inner–rotor.

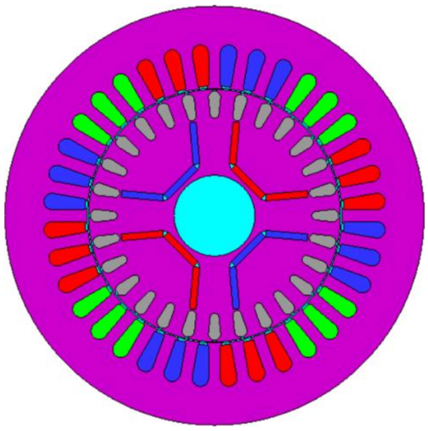

Figure 1. The geometry of the field-circuit LSPMSM model

The motor has 36 slots in the stator and 28 slots in the rotor. The colors of the stator slots reflect the phases of the stator winding and correspond to the three phases of the supply voltage. This motor is made as a four-pole motor. The south pole is marked in red, and the north in blue. Permanent magnets used in the model are arranged in the shape of the letter "U". Each pole consists of 3 segments of rectangular bars of magnets with dimensions of 13.5×2.15 mm. The stator's outer diameter is 135 mm, and the inner diameter is 82 mm. The outer diameter of the rotor is 81.2 mm, while the inner diameter is 26 mm. The thickness of the air gap is 0.4 mm.

The most significant difference in the construction of induction and LSPMSM motors is the application of permanent magnets. Permanent magnets N30SH type were used in the tested model. They are made of the NdFeB (an alloy of neodymium, iron, and boron) alloy. The magnetic properties of the material used in the production of magnets are presented in Table 2.

Table 2. Properties of NdFeB permanent magnets

Symbol	Quantity	Value
B_r	Remanence	1.22 T
H_c	Coercivity	860 kA/m
$(BH)_{max}$	Max energy density	239 kJ/m3
T_{max}	Max operating temperature	150 °C

The stator and rotor of the modelled LSPMSM motor are made of M600-50A type steel sheet. The loss of this sheet is 5.17 W/kg with induction of B=1.5 T and 2.34 W/kg with B=1.0 T. The stator and rotor windings were made of copper and aluminum, respectively. An important issue concerning the field part of the field-circuit model is its discretization. Appropriate discretization ensures correct calculations and their high accuracy. The fragment of the mesh used in the tested model is presented in Figure 2.

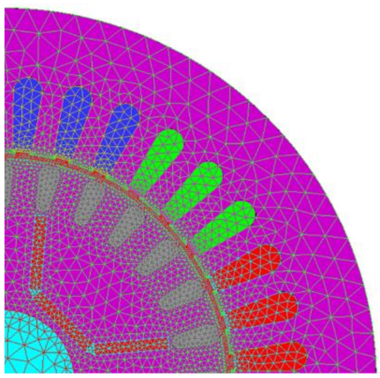

Figure 2. Cross-section of the model with mesh

The circuit part of the model reflects the electrical connections used in the motor's model. It also shows the phenomena occurring in them. Moreover, it is coupled to the field part of the model by assigning some circuit elements to particular regions. For example, the circuit elements representing the stator winding and rotor cage are mapped to their equivalent in the field part.

3. SIMULATION RESULTS

The starting process of permanent magnet synchronous motors is one of the most interesting and problematic aspects of their operation [6]. LSPMSM motors are adapted to direct starting. During the start, the motor is directly connected to the network without using devices limiting inrush current. LSPMSM motors' starting properties compared to standard induction motors are worse [6]. The reason is the utilization of permanent magnets. They generate a negative braking torque, which reduces the resultant torque of the machine. Its value is lower than the asynchronous torque of a standard induction motor [6], [28]. Exemplary waveforms of the individual components of the electromagnetic torque of the LSPMSM motor are shown in Figure 3 [6].

Another important phenomenon that should be considered during the analysis of the starting of permanent magnet synchronous motors is the flow of high currents. In some cases, the inrush current values during starting exceed ten times the motor's rated current. The heating of the rotor cage due to the flow of such a large current is a big problem. The heating problem is especially dangerous for permanent magnets in the rotor, in the immediate vicinity of the starting cage. Even a short-term flow of the inrush current may heat the rotor cage to a value of about 200 °C, which is slightly less than the Curie temperature of some magnetic materials used to produce permanent magnets. In extreme cases, these magnets may even be demagnetized. The results of simulations of the LSPMSM motor starting with the rated load are presented below. The diagram in Figure 4 shows that the starting time was about 0.3 seconds. The rotational speed was fixed at the level of synchronous speed, i.e., 1,500 rpm.

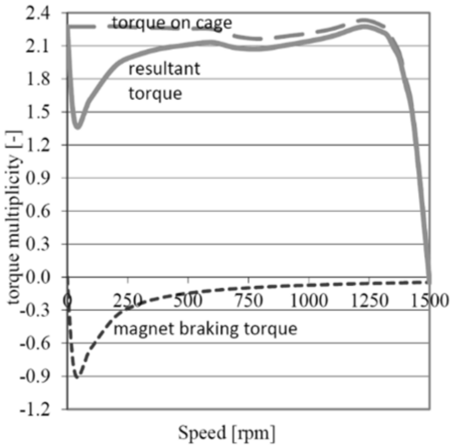

Figure 3. LSPMSM total electromagnetic torque and its components [6]

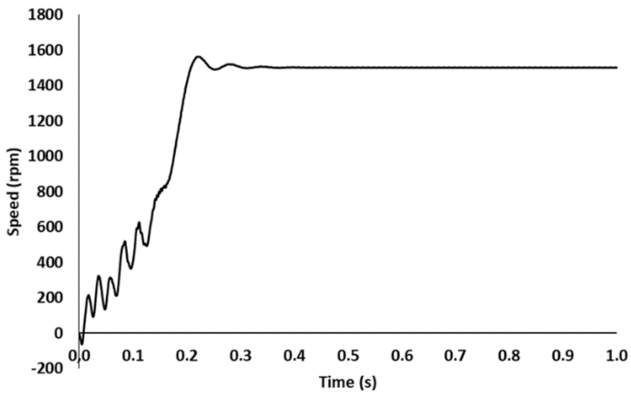

Figure 4. LSPMSM speed during starting with the nominal load

Analyzing the stator current waveform during the starting with rated load as shown in Figure 5, the maximum instantaneous values of the inrush current are about 35 A. The current with high-value flows through the windings for about 0.15 seconds, which is too short to damage permanent magnets. After about 0.25 seconds, the current stabilized at a value of 3.4 A RMS. Figure 6 shows the waveform of the electromagnetic torque of the LSPMSM motor. The maximum instantaneous value is 67 Nm. In a steady-state, it has a value of approximately 12.73 Nm.

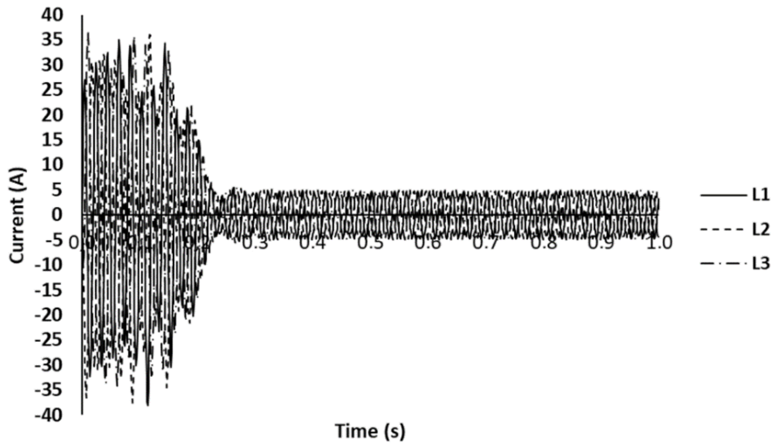

Figure 5. LSPMSM stator current during starting with a nominal load

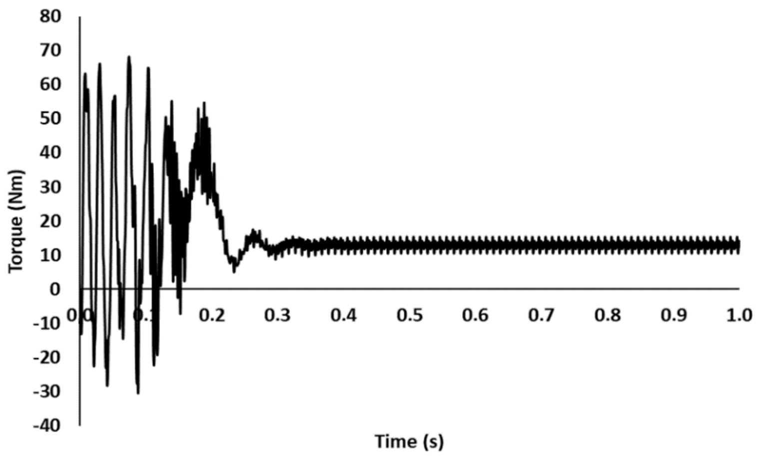

Figure 6. LSPMSM torque during starting with a nominal load

An undesirable phenomenon in permanent magnet synchronous motors is the presence of cogging torque. It is related to slots design in the stator and permanent magnets placed in the rotor. The reason for the cogging torque generation is a change in the magnetic energy caused by the rotation of the permanent magnet rotor relating to the grooved core of the stator. The disadvantage of the cogging torque occurrence is a deterioration of the motor's starting process. Additionally, it causes torque pulsations, noise, and vibration in a steady-state. The value of cogging torque is proportional to the induction in the air gap. Furthermore, it depends on the design parameters of the motor, such as the number of poles, the slot opening width, the thickness of the air gap, and the length and diameter of the motor. Hence, during the design stage, it is necessary to minimize this parameter [19], [21], [24], [25], [29]. The cogging torque as a function of the rotor's angle is shown in Figure 7. Its measurement was performed in an idle state.

The maximum value of the cogging torque is 1.1 Nm, which is about 8.6% of the rated motor torque. It can be observed that the average value of the cogging torque is 0, and it proves that the modelled LSPMSM motor is symmetrical. To minimize the cogging torque, modifications to the motor geometry can be made at the design stage. For example, skew stator slots or skew permanent magnets or the appropriate selection of the number of stator slots and the number of poles can be used.

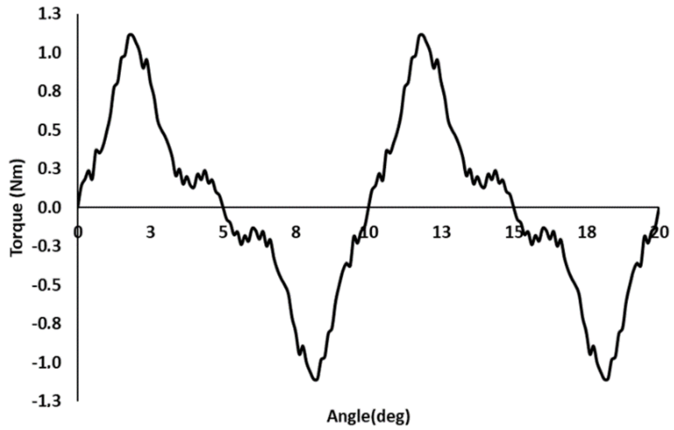

Figure 7. LSPMSM cogging torque

Electromechanical characteristics as shown in Figure 8, also known as operating characteristics, are the dependencies of motor parameters such as stator current, efficiency, and power factor on the mechanical power on the shaft. The characteristics describe the essential operating properties of the motors. The first obtained electromechanical characteristic is the dependence of the stator current of the LSPMSM motor on the power on the shaft. The motor's current while working with a different load can be estimated. The shape of the characteristic in the range of about 750 W is rectilinear. Another important relationship describing the performance of the LSPMSM motor is the graph of efficiency as a function of the output power. The maximum efficiency of the tested LSPMSM motor is 92.1% and is achieved in the rated operation condition. An interesting feature of permanent magnet motors is that they maintain a practically constant, high efficiency over a wide range of load changes. Only the heavily underloaded motor is characterized by low efficiency and unfavorable operating properties. The last obtained characteristic describing the operation of the tested LSPMSM motor is the dependence of the power factor on the output power. An important feature of permanent magnet motors is the high-power factor, which has a maximum value is 0.995. The high-power factor value means that LSPMSM motors practically do not absorb reactive power from the network in a wide range of load changes.

Based on the conducted research, the rated parameters of the tested LSPMSM model were obtained are shown in Table 3. Moreover, basic characteristics describing the behavior of the motors in various operating states were achieved. The obtained information enables the assessment of the correctness of the created model. The information was also used to compare the LSPMSM motor with the induction motor.

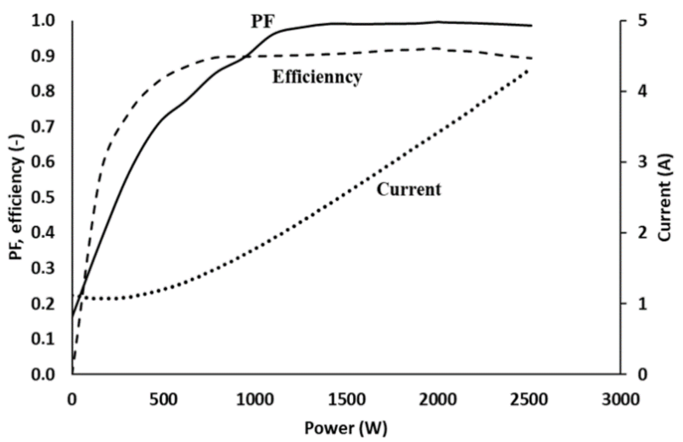

Figure 8. Electromechanical characteristics of LSPMSM motor

Table 3. Nominal parameters of tested PMSM motor

Symbol	Quantity	Value
P_n	Rated power	2.1 kW
n_n	Rated speed	1500 rpm
M_n	Rated torque	12.73 Nm
V_n	Rated voltage	400 V
I_n	Rated current	3.4 A
f_n	Rated frequency	50 Hz
PF	Rated power factor	0.99
η	Rated efficiency	92 %

4. DISCUSSION

The aim of the paper was to justify the use of line start permanent magnet synchronous motors in modern electric drives. Based on the research, it can be concluded that the operational properties of LSPMSM motors are more favorable than those of induction motors. The created LSPMSM motor model was a modification of the mass-produced induction motor. Table 4 compares the rated parameters of both machines.

Table 4. Comparison of motors' nominal parameters

Symbol	Quantity	Induction motor	PMSM motor
P_n	Rated power	1.5 kW	2.1 kW
n_n	Rated speed	1415 rpm	1500 rpm
M_n	Rated torque	10.13 Nm	12.73 Nm
V_n	Rated voltage	400 V	400 V
I_n	Rated current	3.6 A	3.4 A
f_n	Rated frequency	50 Hz	50 Hz
PF	Rated power factor	0.76	0.99
η	Rated efficiency	79 %	92 %

The use of permanent magnets in the rotor had a positive effect on the rated parameters of the machine. From the same motor volume, higher power and torque have been obtained. As a result, the power factor and efficiency have been significantly improved. In addition, the value of the current in the steady-state has decreased. The comparison of both types of motors can also be made based on their electromechanical characteristics. Figure 9 shows the electromechanical characteristics of the tested induction motor. The electromechanical characteristics of the tested LSPMSM motor are presented in the previous chapter as shown in Figure 8. Comparison of Figures 8 and 9 shows that the induction motor consumes more current than the LSPMSM motor for each value of the load on the shaft. Moreover, its power factor is not constant during load changes and is much lower. The efficiency of an induction motor has a similar character as an LSPMSM motor; however, it also takes lower values.

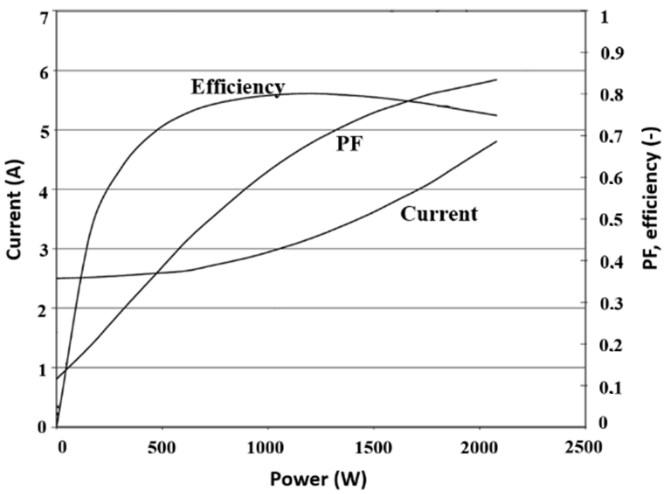

Figure 9. Electromechanical characteristics of tested induction motor

5. CONCLUSION

Based on the conducted research, it can be concluded that a presented approach to the design of permanent magnets synchronous motors profits measurably. This different approach consists of the modification of the induction motor. The process is relatively swifter and more straightforward than the standard design process. The construction of the stator remains unchanged. The interference concerns only the rotor's construction. This change in the rotor's structure and the use of permanent magnets significantly improve the motor's operational properties. However, it also causes difficulties. The use of permanent magnet motors requires higher initial financial assets due to the high price of permanent magnets and the innovative solutions used in this type of motor. Nevertheless, it is profitable, owing to the very high efficiency of the LSPMSM motors, which is especially evident in high power drives. In summary, modern line start permanent magnet synchronous motors are an alternative solution to currently used electric motors due to their good operational properties and economic aspects.

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