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Analysis of a new concept of Line Start Permanent Magnet Synchronous Motor

***Abstract**. The new concept of the Permanent Magnet Synchronous Motor (PMSM) was presented and described in detail. Machine was created as a motor dedicated for operation from the direct start from the grid or from the inverter (open control loop). The basic operational properties of a prototype 0.75 kW motor was tested. The PMSM was equipped with a cage enabling asynchronous starting, so this machine can be named Line Start Permanent Magnet Synchronous Motor (LSPMSM). The construction of the prototype of LSPMSM was based on an unusual stator design created from the electrical sheets cutting by laser machine. Additionally, the prototype of LSPMSM was equipped with induced poles. The starting properties and operating conditions were analysed for different conditions. The model and analysis of the novel LSPMSM created in the Maxwell software was presented and described. The tests were carried out on a specially adapted measuring stand. Machine was tested in three phase and single phase conception.*

***Streszczenie.** Przedstawiono nową koncepcję silnika synchronicznego z magnesami trwałymi o rozruchu bezpośrednim i szczegółowo opisano. Maszynę wykonano jako silnik dedykowany do rozruchu bezpośredniego i zasilania z przemiennika częstotliwości pracującego w pętli otwartej. Prototyp silnika o mocy znamionowej 0,75 kW poddano testom. Zbudowany silnik synchroniczny z magnesami trwałymi posiada klatkę w wirniku umożliwiającą rozruch asynchroniczny, dlatego można go nazwać silnikiem typu LSPMSM. Konstrukcję silnika oparto na niestandardowym wykonaniu w postaci wykrojów z blachy elektrotechnicznej ciętej laserowo. Poza tym, prototyp silnika wykorzystuje indukowane bieguny magnetyczne. Zbadano właściwości rozruchowe i eksploatacyjne w różnych warunkach. Przedstawiono i opisano model polowo-obwodowy wykonany w oprogramowaniu Maxwell. Badania eksperymentalne wykonano na profesjonalnym stanowisku pomiarowym. Maszynę przebadano jako zarówno jako silnik trójfazowy jak i silnik jednofazowy. (**Analiza silnika synchronicznego z magnesami trwałymi o rozruchu bezpośrednim nowej koncepcji**)*

Keywords: LSPMSM, line start, induced pole, enclosure-less motor
Słowa kluczowe: LSPMSM, rozruch bezpośredni, indukowane bieguny, silnik bezkadłubowy

Introduction

Three-phase line start permanent magnet synchronous motors (LSPMSM) are being increasingly popular due to their extremely high efficiency and power factor. LSPMSM were earlier mainly used in the high power applications [1, 2, 3]. LSPMSM, unlike classic permanent magnet synchronous motor (PMSM), have a copper starting cage. This allows an asynchronous start up [1, 3, 4]. LSPMSM has magnets recessed in the rotor. They are usually arranged in the shape of the letters VV or W. The concept of this type of motor is presented in the paper [4]. The paper [5] submits a LSPMSM with magnets arranged in the letter L, T, I and U. Classical synchronous motors have inferior starting properties than induction motors. The application of a starting cage in the rotor, reduces this problem and simplifies the starting process. During start-up operation, the motor exhibits the characteristics of an induction drive, then goes into synchronous operation. Thanks to this, it is possible to self-start and good working parameters under load. These types of drives are perfect for use in pumps or fans [1, 2, 3, 6, 7, 8].

Machines of this type are characterized by a much higher energy efficiency compared to induction drives. They achieve the efficiency class IE5. Additionally, with the same size, the LSPMSM achieves much bigger power [9, 10, 11]. These properties allow us to conclude that LSPMSM can be an alternative to the currently most popular induction motors. Single-phase LSPMSM are less popular instead of the difference of the efficiencies of single-phase LSPMSM and single-phase induction motor can be significantly higher than in case of three-phase LSPMSM and IM with the same rated power P_n and level of rated voltage U_n [1, 2, 3, 4].

Performance improvement techniques of a LSPMSM are divided in two main categories: 1- design methodologies, 2-optimization algorithms [10, 11]. Construction process of LSPMSM demand considering many parameters. For example in [6] the power factor and efficiency were taken into account. In article [2] construction, which improves synchronization capabilities was presented. Far less research are carried out on multi-criteria design [10, 11]. During process of designing many performance features are conflicted to each other. For example high magnetizing inductance improve start-up performance but worsen synchronization capability. Another example is pole-changing, which may cause oscillations occurring and dynamics problems during switching [12]. The literature describes many ways to streamline the construction. In [7] non-symmetrical squirrel cage winding was compared with symmetrical one. Another solution was presented in paper [1]. Authors describe LSPMSM with hybrid salient rotor. Experimental results showed it allows reduce cogging torque and steady-state losses. In [2] different shapes of magnets were considered to get maximum efficiency. Author appoints that shape of magnets has huge impact on motor performance and V-shape gives highest efficiency. In the experiment author used I-shape, which minimalizes cost of production. The paper [13] presents a novel dual stator line-start permanent magnet synchronous motor, which can remove the conflict between the starting torque and the synchronization capability existing in the conventional LSPMSM by minimalizing the braking torque during start-up. In [14] motor performance is improved by using composite solid rotor. Rotor construction mainly based on solid steel allows to obtain higher start-up torque. Starting performance was validated by using 2-D finite-element method. The slotted solid rotor owns much deeper flux penetration than the smooth one. It allows obtain a larger energy conversion area in the rotor. In [2] a 6/8 pole changing LSPMSM is designed based on the novel 6/8 pole changing stator winding. Due to different pole numbers between stator winding and rotor's permanent magnets during 6-pole starting process, the inherent braking torque and pulsating torque for conventional LSPMSM can be reduced, and the starting capability can be improved.

Installation of permanent magnets into PMSM is drawback of these type of motors. This is quite difficult and time-demanding process. One effective solution of reducing this problem is induced pole PMSM [4]. For these motors type the number of permanent magnets is double less but mass of the magnets is the same due to demagnetization endurance.

Example of four-pole induced pole LSPMSM is presented in Figure 1. Two combinations of permanent magnets are set on the opposite pole pitch in the rotor. Another magnetic pole are produced on the pole pitches without permanent magnets due to their closing magnetic field lines.

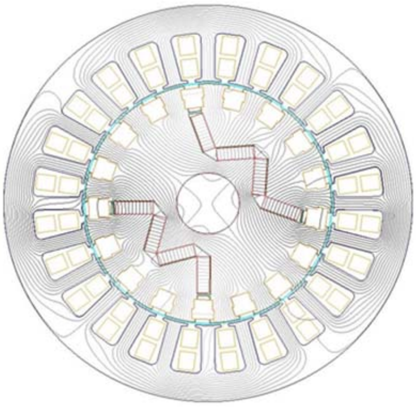

Fig.1. Four-pole induced pole LSPMSM

There are three main types of methods for optimizing structure of LSPMSM: analytical methods, numerical and empirical. Analytical methods is simplest but inaccurate, numerical is most accurate but time consuming and empirical is fastest but less accurate [10]. One of the most popular method is Finite Element Method (FEM). It allows optimize construction of motor and receive more accurate result evaluations [3, 4]. In paper [15] non-deterministic algorithm based on observations of the natural environment - grey wolf for optimization was presented. Low power LSPMSM with adopted stator from induction motor and surface mounted permanent magnets were used. Grey wolf method was used to determine the dimensions of permanent magnets. Into account parameters like motor efficiency, power factor and starting capability was taken. Prototype LSPMSM was compared with traditional induction motor obtaining better properties. In paper [14] analytical calculations based on multidamping-circuit model (MDCM) was shown. This method is used to consider spatial harmonic components of LSPMSM. In first step MDCM of damping bar in the rotor is established, then from a group of differential equations eleven-order system of LSPMSM was deduced. Starting process with the proposed method was simulated under different value of input phase voltage, moment of inertia, and load torque. In [15] Bat Algorithm (BA) was shown to optimize LSPMSM. BA is inspired by the echolocation behaviour of small species of bats looking for food. Used software consist of two independent modules: a module containing mathematical model of the device and an optimization solver. The algorithm has been applied in the optimization procedure. The results of test calculations were encouraging.

In this paper starting and performance features of induced pole prototype LSPMSM are presented. Results are presented for single phase and three phase versions of motor. The article consists of 5 sections. In first chapter literature review of designing process of LSPMSM is presented. Second part contents general model and equivalent circuit of research type of motor. Next parts include carried out design process and physical motor model in single phase version. In the 4[th] section basic features of three phase motor are presented. Last part contains summary of obtaining results.

Design process of research motor

The main problem during LSPMSM designing is arrangement of permanent magnets inside the rotor. It is also connected with the number of rotor slots. The goal of this designing step is limitation of Total Harmonic Distortion coefficient of back Electromotive Force THD_{back} *EMF* and magnetic induction in the air gap THD_{B}, cogging torque T_{cogging}, and simultaneously maximization of back EMF and the first harmonic of magnetic induction in the air gap B_1. For the number of stator slots $Q_s = 24$ the following numbers of rotor slots were considered $Q_r = 16, 17, 18, 19, 20$. Circuit-field models of single-phase induced pole LSPMSM were built in Ansys software. The models are shown in Figures 2a-e. The rotor construction was simultaneously verified due to mechanical stress. Example of mechanical investigation for speed $n = n_n$ and load torque $T_{\text{load}} = 10T_n$ is presented in Figure 2f. There is quite high margin taking into account obtained maximum mechanical stress 28 MPa with rotor sheet yield strength $R_e = 250$ MPa.

For cogging torque investigation mesh in the motor model air gap was concentrated to obtain more accurate results. Difference between standard motor model mesh and cogging torque model computation mesh is shown in Figure 3.

Results of the computation of the influence of the number of rotor slots on the motor properties is presented in Table 1. For easier verification of the obtained results another table (Tab. 2) was made which shows scores for the each investigated motor property with adequate colour (5-green for the best solution, 1-red for the worst one). Due to the summary score the best solution for the designed single-phase induced pole LSPMSM is the number of rotor slots $Q_r = 17$.

Next step in designing process of single-phase induced pole LSPMSM is stator winding optimization, especially auxiliary winding with running capacitor. The main goal was reducing electromagnetic torque pulsation for load power $P_{\text{load}} \approx 0.8P_n$.

The final of the presented work will be physical model of the investigated single-phase induced pole LSPMSM. The concept of the motor without enclosure is shown in Figure 4. Lack of the enclosure ensures more place in the stator yoke and better motor thermal performance.

Table 1. The parameters of the sensor

Q_r [-]	*back EMF [V]*	$THD_{\text{back EMF}}$ [%]	B_1 [T]	THD_{B} [%]	T_{cogging} [%]
16	235,1	12,76	0,674	55,1	2,84
17	231,8	7,43	0,677	56,6	0,46
18	233,7	8,65	0,672	58,1	1,05
19	230,6	8,33	0,673	57,2	0,22
20	236,2	18,52	0,669	57,4	0,92

Table 2. Results of the influence of the number of rotor slots on the motor properties comparison

Q_r	*back EMF*	$THD_{\text{back EMF}}$	B_1	THD_{B}	T_{cogging}	Σ
16	4	2	4	5	1	12
17	2	5	5	4	4	18
18	3	3	2	1	2	8
19	1	4	3	3	5	15
20	5	1	1	2	3	7

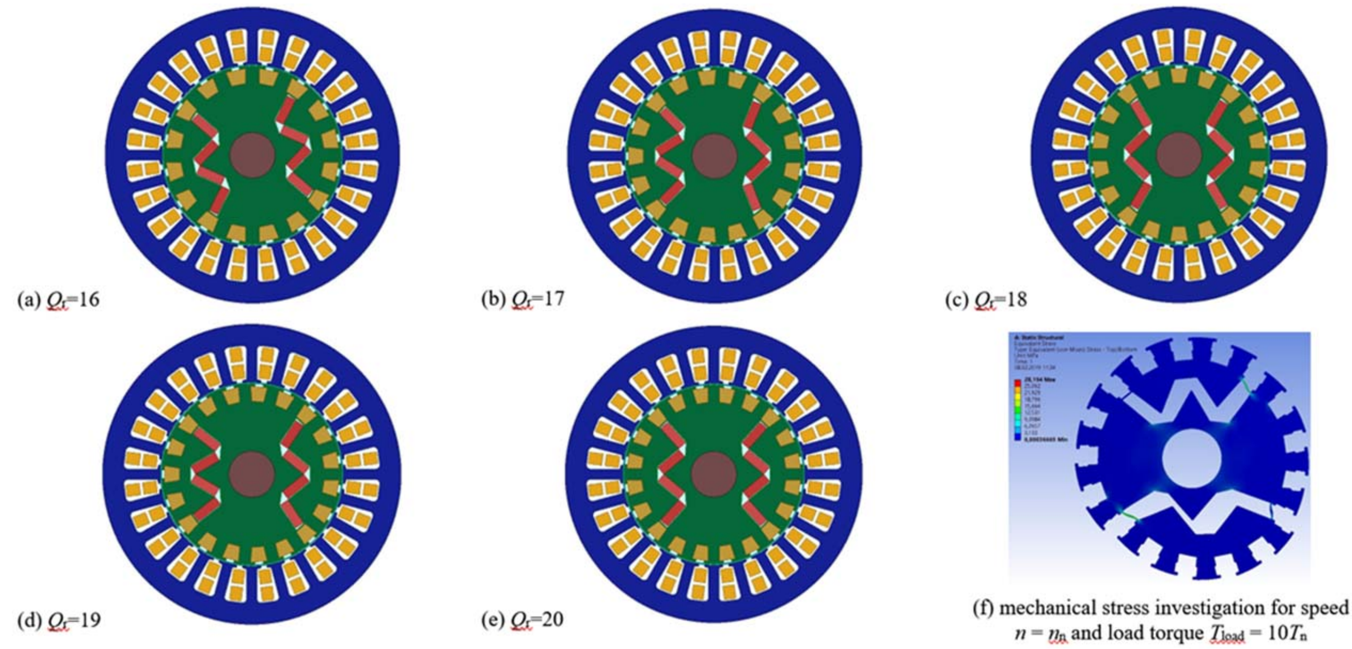

Fig.2. Investigated motor with various number of the rotor slots and mechanical stress investigation of the rotor

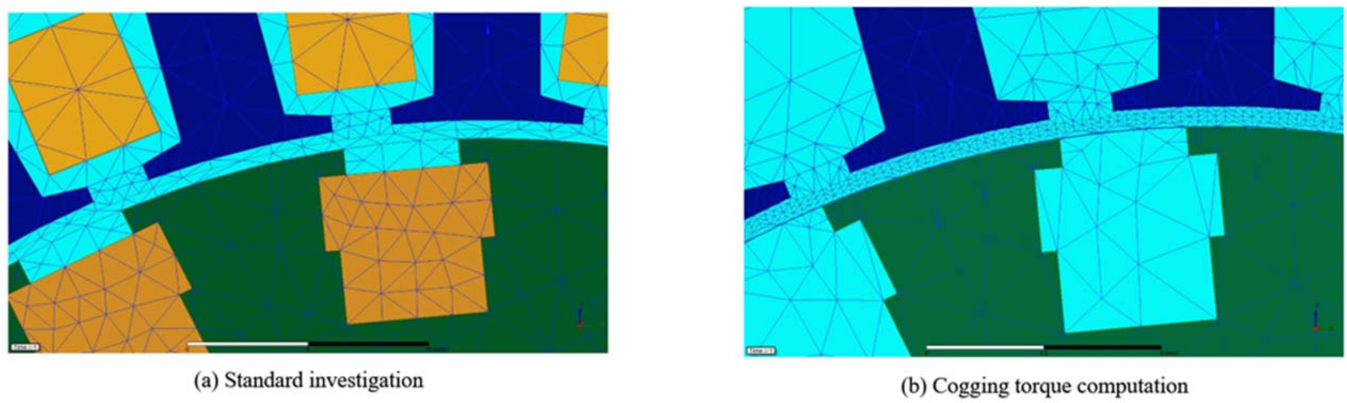

Fig.3. Mesh of the field-circuit motor model

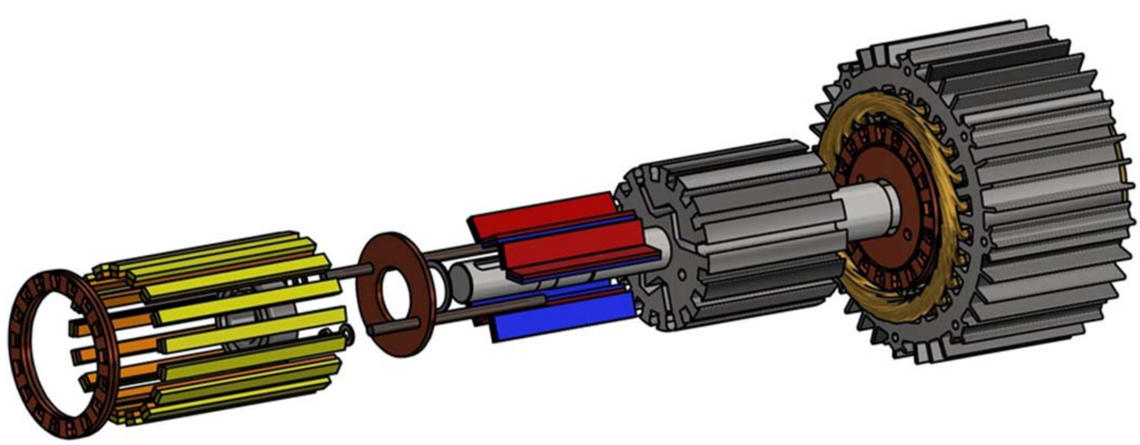

Fig.4. Concept of the enclosure-less induced pole single-phase PMSM

Physical motor model

Single-phase induced pole LSPMSM was built as enclosure-less construction. The built model was made from steel and copper sheets cut by laser. Rotor shaft, bearing plates, fan and fan enclosure were machined. Bearings 6205 C3 type are standard. Stator and rotor magnetic core sheets are shown in Figure 5. Stator sheets have ribs to improve cooling conditions. Stator and rotor sheets have holes for rods which keep the whole construction and ensure stiffness of the motor. Stator winding (Fig. 6) consists of main and auxiliary winding. Main winding is connected in series, auxiliary wining can be connected either in series or in parallel. It is standard copper winding made from enamelled wire.

The rotor (Fig. 7) has quasi-trapezoidal bars made from copper rectangular rods cut by laser. The bars are connected with copper rings (also cut by laser) by soldering. Permanent magnets N42SH type were installed into rotor before installation it into stator. The stator with its winding (Fig. 8) was immersed in liquid insulation bath. Process of rotor installation into stator is presented in Figure 9.

Built physical model of single-phase induced pole LSPMSM was measured in Laboratory of Electric Machines at Wroclaw University of Science and Technology (Fig. 10).

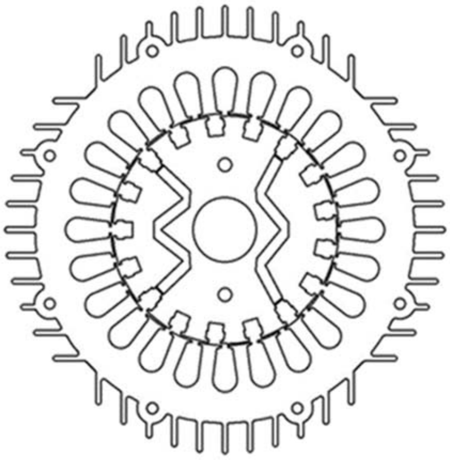

Fig.5. Stator and rotor sheets

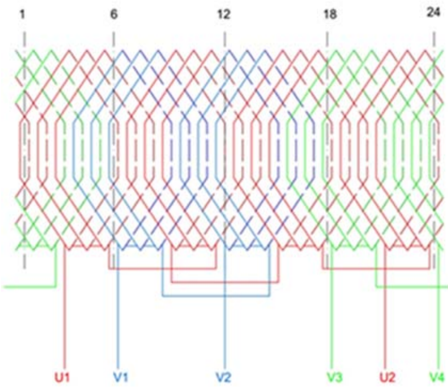

Fig.6. Stator winding schema

Fig.7. Rotor after permanent magnets installation

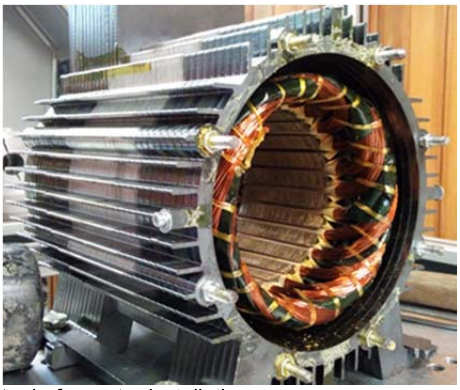

Fig.8. Stator before rotor installation

Fig.9. Installation rotor into stator

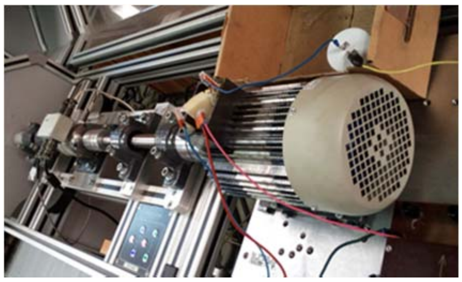

Fig.10. Motor on the measurement test stand

After finished measurements obtained results were compared with computation results of FEM motor model. Shapes of back EMF and current of physical and FEM motor models in time domain are quite convergent (Fig. 11 and 12). Verifications results presented in Table 3 show that FEM model is proper and can be sufficient tool for this electric motor type designing.

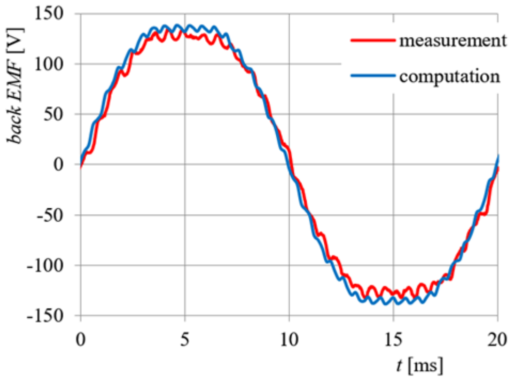

Fig.11. Motor back EMF in time domain of physical and FEM motor model for idle-running state stator

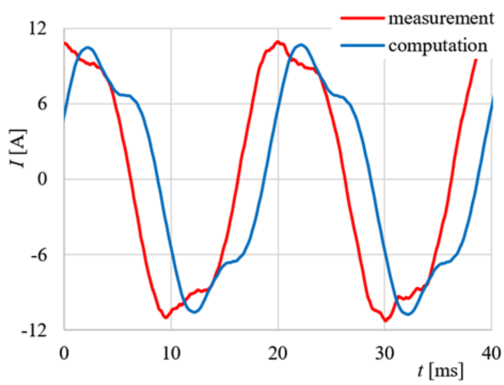

Fig.12. Motor current in time domain of physical and FEM motor model for rated load state stator

Table 3. Verification of single-phase induced pole line start permanent magnet synchronous motor model

parameter	unit	FEM model	physical model
P_n	W	750	
U_n	V	120	
n_n	rpm	1200	
back EMF	V	100	98
I_n	A	8,1	8,2
η_n	%	80	79

Concept of three-phase LSPMSM

After first experiments, construction was improved to a three-phase LSPMSM. In this section motor performance during start-up is presented. Research was carried out with use of the same measurement test stand. At first maximal electromagnetic torque was appointed. Value about 11.4 N·m was obtained (Fig. 13). In Figure 14 motor electromagnetic torque under variable supply frequency is presented.

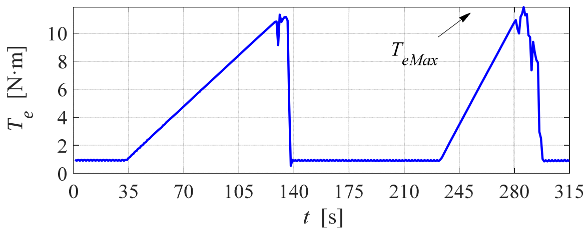

Fig.13. Motor current in time domain of physical and FEM motor model for rated load state stator

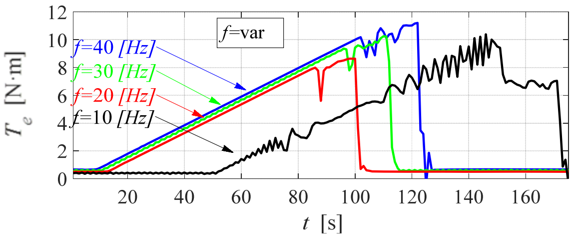

Fig.14. Electromagnetic torque under variable supply frequency

In the next step basics properties of tested motor was analysed. Power factor even during condition without load is close to unity. It is because of permanent magnets induced voltage in stator windings. Motor does not require much reactive power to demagnetize the core (Fig. 15).

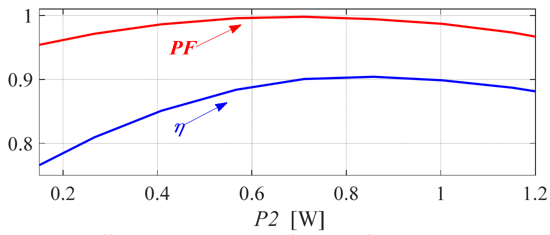

Fig.15. Motor efficiency and power factor VS load power

Then the properties of motor under variable conditions were analyzed (Fig. 16-18).

In Figure 19 braking torque produced by magnets is shown. This effect is an undesirable component of this type of motor. Occurrence of cogging torque worsen properties of start-up and hamper to come into synchronism. Because of this effect LSPMSM got minor start up torque then IM, which achieve the same power.

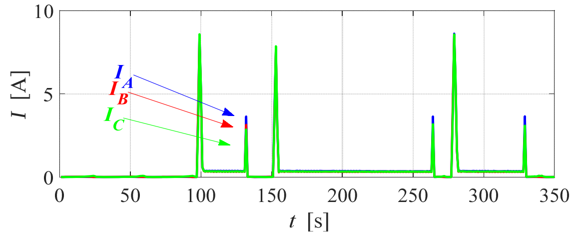

Fig.16. Start-up motor current in time domain

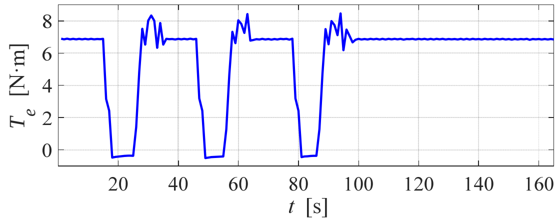

Fig.17. Electromagnetic torque under full load conditions in time domain

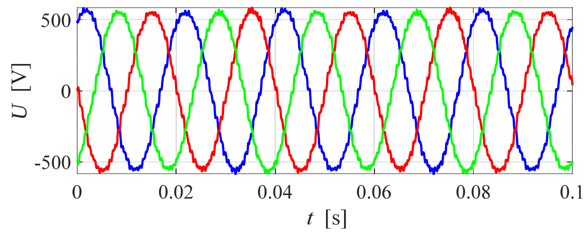

Fig.18. Motor back EMF in thermal steady-state

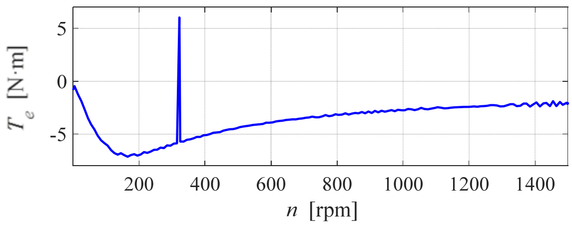

Fig.19. Braking torque VS speed

Conclusions

Single-phase induced pole LSPMSM can reduce time and work recruitments connected with permanent magnets assembly in the rotor. For presented solution magnets are two times thicker in comparison with standard LSPMSM. Due to that magnets are much higher resistant to break during their installation in the rotor slots. Additionally, two times thicker permanent magnets can be two times longer taking into account their braking resistance during installation into PMSM rotor. According to that it allows the possibility to decrease the number of permanent magnets in induced pole PMSM four times what significantly limits time of the motor manufacturing.

Proposed methodology of PMSM designing using colorful table with scores adequate to the obtained results of the investigated motor parameters can be convenient tool in machine designing. This applies especially to the number of LSPMSM rotor slots assortment taking into account such parameters like back Electromotive Force, magnetic induction in the air gap and cogging torque.

Three phase version of research motor allows obtain power factor close to unity and good performance properties.

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