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Sizing by optimization of line-start synchronous motor

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Abstract

Purpose – The purpose of this paper is to develop an algorithm and software for determining the size of a line-start permanent magnet synchronous motor (LSPMSMs) based on its optimization.

Design/methodology/approach – The software consists of an optimization procedure that cooperates with a FEM model to provide the desired behavior of the motor under consideration. The proposed improved version of the genetic algorithm has modifications enabling efficient optimization of LSPMSMs. The objective function consists of three important functional parameters describing the designed machine. The 2-D field-circuit mathematical model of the dynamics operation of the LSPMSMs consists of transient electromagnetic field equations, equations describing electric windings and mechanical motion equations. The model has been developed in the ANSYS Maxwell environment.

Findings – In this proposed approach, the set of design variables contains the variables describing the stator and rotor structure. The improved procedure of the optimization algorithm makes it possible to find an optimal motor structure with correct synchronization properties. The proposed modifications make the optimization procedure faster and more

Originality/value – This proposed approach can be successfully applied to solve the design problems of LSPMSMs.

Keywords Electrical machine, Optimal design, Shape optimization, Finite element analysis, Multiobjective optimization, Line-start permanent magnet synchronous motor, Improved genetic algorithm

Paper type Research paper

1. Introduction

In the contemporary process of electrical machine design, computer simulations have become an essential tool. Computer simulations enable the application of models of phenomena with a varied degree of computational complexity. In the process of designing electromagnetic

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devices, finite element models of phenomena are the most accurate (Carbonieri and Bianchi, 2021; Młynarek *et al.*, 2018; Mutluer *et al.*, 2020; Arnoux *et al.*, 2015; Zawilak, 2020). These models take into account: electromagnetic field equations, equations for external power circuits, mechanical motion equation and equations, which describe thermal processes in the designed device (Barański, 2019; Dupré *et al.*, 2014; Knypiński and Nowak, 2013; Nageswara Rao *et al.*, 2020). Such models of phenomena in designed devices are computationally complex, and the optimization processes are very time-consuming.

Currently, the design process is often supported by optimization procedures. The design process automation consists of the application of the "master" optimization procedure, whose task is to search for "optimal" values of decision variables. The structure of the optimal device is searched in consecutive iterations of the optimization procedure, called generations, in the case of a genetic algorithm. The result of the optimization is the optimal solution that fulfills all requirements set by the designer.

The article presents the software used to support the design of the line-start permanent magnet synchronous motors (LSPMSMs). The optimization task, which consists of the determination of structural parameters of the rotor and stator, was solved. The developed optimization procedure involves the application of the modified genetic algorithm. The software consists of two independent modules optimization module and module consist the mathematical model of the LSPMSM. The optimization algorithm has been elaborated in the Delphi 7.0 programming environment. The mathematical model includes two submodels (steady-state operation model and transient operation model) and has been developed in Maxwell. These two modules were linked by an additional script allowing the exchange of information.

The novelty of our work consists of the following: development of a modification of the classical genetic algorithm for the optimization of LSPMSMs and taking into account the design variables describing stator and rotor parameters in the optimization procedure.

To test the performance of the developed software, the sizing process of an LSPMSM for the crane's application was performed. At present, induction motors are commonly used as a drive to cranes. Research about the application of permanent magnet (PM) synchronous motors has been recently done (Krupiński and Knypiński, 2021). So far, the usefulness of LSPMSMs for such applications has not been analyzed.

2. Permanent magnet synchronous motors

Nowadays, manufacturers and users of electric machines pay special attention to the energy efficiency of the manufactured equipment, which is associated with natural environment protection. For this reason, an increased interest in designs of PM motors can now be observed. The most popular is PM synchronous motors (PMSMs). PMSM motors are subject to research in many research centers all over the world (Sorgdrager *et al.*, 2018; Haifeng, *et al.*, 2017; Da-Chen Pang *et al.*, 2020; Jędryczka *et al.*, 2020).

PM motors are characterized by many advantages: high efficiency, high torque to mass ratio, high torque overload capability, higher power factor and low failure rate.

Most frequently, the PMSM machines are low- and medium-power motors. Synchronous machine stators do not differ from induction machine stators, whereas PMs are placed on the rotor. In general, in PM motors, the magnets are mounted on the external surface of the rotor or inside its core. Therefore, in the case of PMSM machine designs, the following methods are used most frequently to mount magnets: surface-mounted PMs, magnets inserted in the rotor and buried interior PMs (Kolehmainen and IkAheimo, 2008; Dong *et al.*, 2016; Komeza *et al.*, 2019; Elistratova *et al.*, 2013).

It is worth noting that drive motors for cranes application most often work under hard work conditions, especially the hoist winch motor. In such applications, it is much better to use motors with PMs buried in the rotor (Baek and Lee, 2020). Figure 1 presents the selected structure of the PM synchronous machines with buried magnets.

The synchronous machines are powered using inverters provided with systems that allow for frequency adjustment. The application of an inverter system increases the total cost of the propulsion system. In recent years, an interesting alternative for PMSMs has been PM motors with self-starting ability, so-called LSPMSMs. The main advantage of this type of motor is the ability to direct start-up after connecting to a three-phase grid (Zöhra, *et al.*, 2018; Knypiński, 2021); because of the application of PMs in the rotor, it is possible to achieve better efficiency and power factor of the devices. LSPMSMs are very good replacements for induction motors, which are now commonly used in crane drive systems.

3. Magnetic materials in construction of permanent magnets motors

As a result of the rapid development of material engineering, PMs with high energy densities, better magnetic, thermal and mechanical parameters are currently manufactured. Despite significant changes in prices caused by an increase in the costs of mining rare earth elements in China, the sale of magnets manufactured on the basis of these elements has been increasing on a continuous basis.

Usually, magnetic materials with admixtures of elements, which belong to the lanthanide group, are used in the process of manufacturing PM electric machines (Yogal and Lehrmann, 2014; Gundogdu and Komurgoz, 2013). At present, the two most popular types of magnets are samarium-cobalt ($SmCo_5$ and Sm_2Co_{17}) and neodymium-iron-boron (NdFeB). Samarium magnets have better thermal properties; the maximum operating temperature ranges between 250 and 300 °C. However, the price of such magnets is relatively high. The most popular neodymium magnets ($Nd_2Fe_{14}B$) are characterized by a high density of magnetic energy and high repeatability of magnetic properties. The biggest drawback of these magnets is their low resistance to corrosion. Despite good magnetic properties, the neodymium magnets have worse performance parameters; for economic reasons (lower price), they are used most frequently for the construction of PM motors.

4. Structure and design parameters of the line-start permanent magnet synchronous motor

To elaborate the numerical model of LSPMSM, the data of series-produced induction motor about type MS112M-4 were partially used. The main dimensions (outer diameter and stack length) of the optimized motor were selected on the basis of power and size of the induction motor, which is used as a motor for slewing drive in tower crane with symbol KR 90–5 flat top. The crane 90–5 has the following parameters: maximum capacity equal 5 tons and maximum jib equal 50 m. The selected stator dimensions are shown in Figure 2.

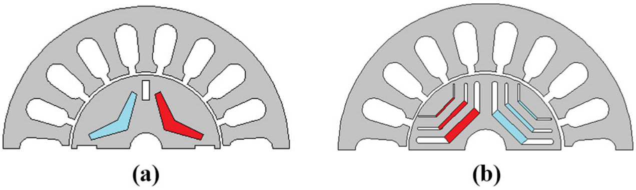

Figure 1.
Selected structures of PM synchronous motors

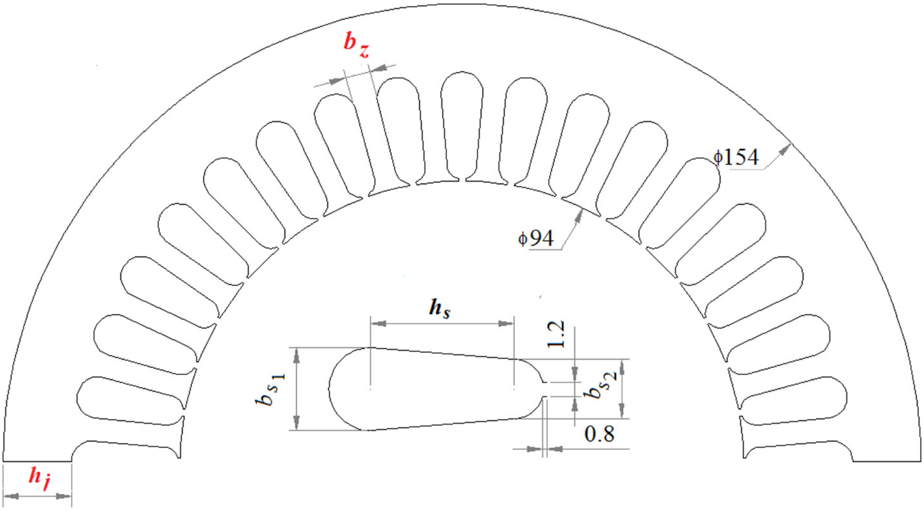

Figure 2. The dimensions of stator from studied LSPMSM, h_s is the height of the stator slot, b_{s1} and b_{s2} are the upper and down slot diameters.

The stator height yoke h_j and stator tooth width b_z are design variables and are marked in red color. The value of h_s, b_{s1}, b_{s2} and b_z are calculated on the basis of the slot pitch t_s. The slot pitch is calculated according to the given formula:

$$t_s = \frac{\pi\left(D_w + \frac{(D_z - D_w)}{2} - h_j\right)}{N_s} \tag{1}$$

where D_z is the outer diameter of the stator, D_w is the inner diameter of the stator, N_s is the number of slots in the stator, h_j is the stator yoke height.

The stator has 36 slots. The three-phase single-layer overlapping half-coiled winding has been applied. The winding is wye-connected. The coils distributions are presented in Figure 3.

The structure of the rotor is presented in Figure 4. The five selected design variables in the rotor are marked in red color.

The studied LSPMSM is described by nine design variables. The five design variables describe the structure of the rotor (Figure 4): $s_1 = r$ – the distance between poles, $s_2 = g$ – the

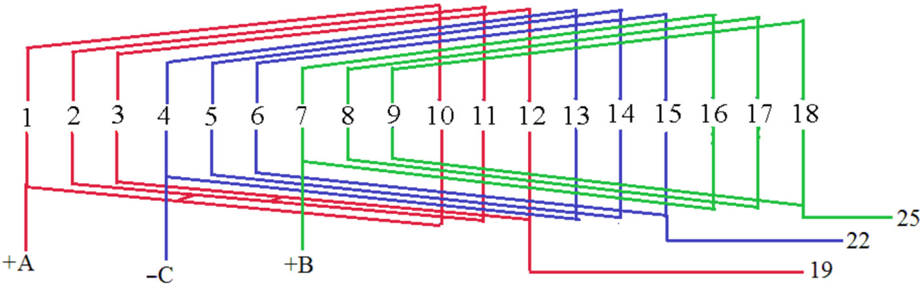

Figure 3. The stator winding distribution

thickness of PM, $s_3 = l$ – the width of the PM, $s_4 = O_1$ and $s_5 = O_2$ – the parameters defined position of W type magnets. The next three design variables describe stator and winding parameters: $s_6 = N$ – the number of conductors in the slot, $s_7 = h_j$ – the stator yoke width and $s_8 = b_z/t_s$ – relative depth of the stator slot. Additionally, the air gap length is chosen as a last design variable $s_9 = \delta$. The ranges of design variables are presented in Table 1.

5. Optimization algorithm

The algorithm and software are developed to support the process of designing LSPMSMs. To test the performance of the developed software, the sizing process of an LSPMSM for crane's application was performed. The designed motor will be applied to a slewing drive system in a tower crane of type 90–5 flat top. The device should be characterized by rated power equal to 4 kW and rated supply voltage equal to 400 V.

The proposed compromise objective function contains three components: efficiency η, power factor PF and the total mass m of PM material. The objective function has the following form:

$$f_i = \lambda_1\left(\frac{\eta_i}{\eta_0}\right) + \lambda_2\left(\frac{\mathrm{PF}_i}{\mathrm{PF}_0}\right) + \lambda_3\left(\frac{m_i}{m_0}\right) \tag{2}$$

where i is the number of individuals, λ_1, λ_2 and λ_3 are the weighting factors, η_i, PF_i and m_i are the efficiency, power factor and total PM mass for the ith individual, η_0, PF_0 and m_0 are

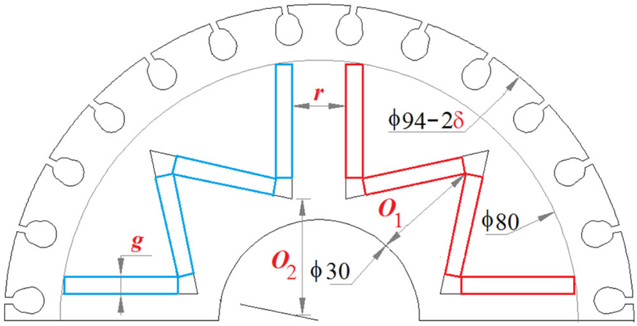

Figure 4.
The rotor from LSPMSM

Table 1.
The ranges of design variables

Variable	Design parameter	Down	Up
s_1	r	1 mm	8 mm
s_2	g	1 mm	4.5 mm
s_3	l	20 mm	45 mm
s_4	O_1	16 mm	22 mm
s_5	O_2	6 mm	18 mm
s_6	N	32	40
s_7	h_j	8 mm	20 mm
s_8	b_z/t_s	0.3	0.8
s_9	δ	0.6 mm	1.0 mm

the average values of efficiency, power factor and total mass of the magnetic material obtained during the initiation procedure, respectively.

It is also necessary to point out the self-starting ability of the optimized LSPMSM. Sometimes the designed LSPMSM can not fall into a synchronous state during its start-up process. In the world literature, researchers have proposed various solutions to this problem. Most often, the additive component responsible for the correct synchronization of the LSPMSM is added to the objective function (Jędryczka *et al.*, 2018; Knypiński *et al.*, 2020).

5.1. The improved algorithm for optimization of line-start permanent magnet synchronous motors

The genetic algorithm was used as an optimization procedure. The optimization procedure has been specially prepared to optimize LSPMSMs. The pseudo-code of the optimization procedure is presented in Algorithm 1.

The most important property during the start-up process of the LSPMSM is the self-synchronization capability. This ability is necessary to pull the motor into synchronous operation. Synchronization ability and starting torque are the two most important parameters during start-up (Palangar *et al.*, 2021). At the same time, the ability to self-synchronize is crucial for the proper operation of the LSPMSM, and it must absolutely be achieved for the optimal machine. Therefore, the authors propose modifications of the classical algorithm that provides the desired feature.

```
BEGIN { of Optimization Procedure}
// indication of the location for the files with the partial results
getdir(0,path);
getdir(0,dir);
//save the initial parameters
assign(plik1,path+'\individuals.dyf');
assign(plik2,path+'\generations.dyf');
Input_Data;
Randomize;
//proposed improved initiation procedure
Initiation;
Transformation_Bin_Real;
//calculation of objective function for initial population
Adaptation;
//declaration of the generation number after initiation
npok:=1;
//data recording for the initial generation
append(file1);
writeln(file1);
close(file1)
append(file2);
writeln(file2);
close(file2)
//the main loop of the optimization procedure
{Start_of_Genetic_Evolution}
for npok:=1 to l_pokol do
begin
    Reproduction;
    Crossover;
    Mutation;
    //data recording for the current generation
    append(file1);
    writeln(file1);
    close(file1)
    append(file2);
    writeln(file2);
    close(file2);
// end of main loop of optimization procedure
end;
// printout data for the optimal structure
Final_optimization_result;
END. {of Optimization Procedure}
```

Algorithm 1. The proposed optimization procedure.

In the optimization procedure, all operations are performed with the use of a binary, 32-bit representation of chromosomes (design parameters). The initial population is generated randomly. During the *Initiation* procedure, the simulation of a start-up process is executed for each randomly generated machine. If a "drawn" individual does not fall into synchronization; a new individual is generated. After obtaining half of the initial generation with individuals having proper start-up properties, the remaining individuals are selected without start-up control. The linear-ranking selection is applied to *Reproduction*. The one-point crossover is used. Both the selection of a pair of parents and a cut-point are random. The new genetic generation is formed by half of the best parents and half of the best children. The *Mutation* is performed with a constant probability of mutation p_m. The p_m value should be chosen very carefully and should be a compromise between the convergence and total computation time. The authors recommend selecting a maximum value of $p_m = 0.02$. The best individual can be lost in the procedures of crossing and mutation. Thus, an *Elitism strategy* is applied (Rani *et al.*, 2019). In each genetic generation, all three operations are performed: reproduction, crossover and mutation.

The time and frequency of calculating functional parameters determine the program execution time. To minimalize the number of objective function calls (total time of the optimization process), only the functional parameters for new individuals during crossover and mutation are calculated. In the case of obtaining an individual with a better value of the objective function than the best individual in the same generation so far, a start-up analysis is performed. If the start-up process is positive, this individual is accepted. Otherwise, its objective function is decreased by 30%.

Additionally, the optimization procedure includes procedures for saving partial optimization results. Such procedures enable the division of the optimization process into stages, which are necessary due to the very long computation time resulting from the use of the field model.

The optimization procedure cooperates with the mathematical model of the optimized LSPMSM. The diagram of the data flow in the optimization software is shown in Figure 5.

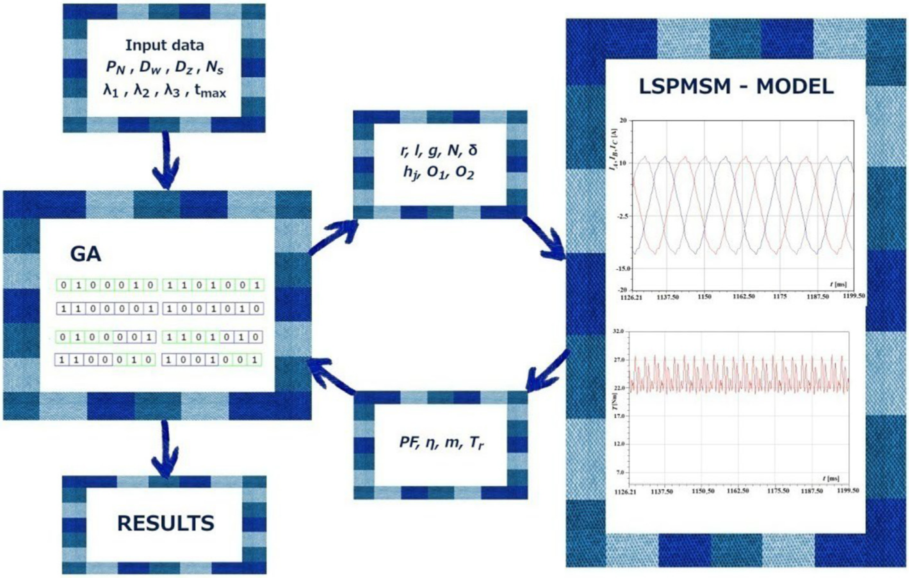

Figure 5.
The block diagram of the developed optimization software

The optimization software consists of two modules: optimization procedure and mathematical model of the motor. All design variables are coded binary systems. All real values of design variables are sent to the Maxwell environment using special computer scripts. The mathematical model executes calculations and determines the values of the functional parameters of the device. The values of functional parameters are returned to the optimization module by the use of additional scripts.

6. Simulation results

The optimization process has been performed for the following parameters of the optimization procedure: the number of individuals in the population was 32, the probability of mutation was $p_m = 0.02$. The maximum number of genetic generations ($n_{\max} = 25$) was adopted as the stop criteria. The values of weighting coefficients were: $\lambda_1 = 0.54$, $\lambda_2 = 0.35$ and $\lambda_3 = 0.12$, respectively. The values of the weighting coefficients were determined with the use of a spreadsheet for several starting generations during a random initiation process. The value of the objective function is very sensitive to the initial total mass of the PM material (m_0); therefore, the values of the weighting factor (λ_3) related to the mass should be selected very carefully. The values of the weighting factors must be carefully selected. Incorrect selection of the coefficients may lead to a wrong solution. Weighting coefficients were selected based on many trial calculations using Excel by analyzing the initial populations.

The optimization process was performed for the LSPMSM with the dimensions presented in Section 4.

The results for the best individual in each generation are shown in Table 2, where n is the number of generations. The values of all design variables, parameters (power factor – PF, efficiency – η, the total mass of PM – m and starting torque – T_r) of the motor and values of the objective function are displayed in the successive columns.

It is worth noting that the optimal solution was determined after 10 genetic generations. Additionally, it is to point out here a good value of the starting torque than the rated torque of the LSPMSM. On the basis of the obtained results, it can be observed that during the optimization process, the efficiency was improved by only 6%. The value of the power factor was improved significantly, by around 17%.

The induction motor applied in the tower crane of type 90–5 has the following parameters in rated conditions: $\eta_N = 86.8\%$, $\text{PF}_N = 0.82$, $I_N = 8.23$, $T_r = 62$ Nm. The proposed optimal LSPMSM has better steady-state parameters. The efficiency is bigger by

Table 2. The parameters for the best individuals for selected generations

n	r [mm]	l [mm]	g [mm]	N [–]	δ [mm]	b_z/t_s [–]	h_j [mm]	O_1 [mm]	O_2 [mm]	PF [–]	η [%]	m [kg]	T_r [Nm]	f [–]
1	1.48	26.13	2.65	34	0.75	0.47	15.37	16.82	10.27	0.808	84.31	0.257	52.7	1.02441
2	1.39	30.73	2.51	33	0.69	0.63	12.34	19.38	6.12	0.861	86.45	0.285	54.2	1.06379
3	2.63	29.89	3.58	36	0.82	0.41	16.16	17.13	15.29	0.984	88.35	0.396	46.4	1.07338
4	3.19	36.42	3.78	37	0.90	0.41	14.30	19.25	12.36	0.999	88.36	0.509	45.7	1.07340
5	3.09	29.89	3.58	36	0.82	0.41	16.14	17.01	15.29	0.985	88.37	0.396	46.3	1.07396
7	2.64	29.89	3.44	36	0.82	0.41	16.14	17.13	15.20	0.981	89.19	0.381	46.4	1.07499
10	3.01	29.89	3.39	36	0.82	0.41	15.16	17.13	15.29	0.981	89.29	0.376	46.5	1.07632
15	3.01	29.89	3.39	36	0.82	0.41	15.66	17.13	16.79	0.985	89.39	0.375	46.3	1.08447
20	3.01	29.89	3.39	36	0.82	0.41	16.16	17.13	16.79	0.985	89.39	0.375	46.3	1.08447
25	3.01	29.89	3.39	36	0.82	0.41	16.16	17.13	16.79	0.985	89.39	0.375	46.3	1.08447

about 3%, whereas the power factor is significantly improved by 20% than the induction motor. Unfortunately, the starting torque for optimal LSPMSM is smaller.

Then, simulation calculations were performed for the optimal LSPMSM structure using the more accurate FEM model than the model used during the optimization process. The waveforms of the phase currents (Figure 6) and the waveform of the electromagnetic torque (Figure 7) for the optimal LSPMSM in the synchronous operation state were determined. The calculation was performed using a 2-D field model of an LSPMSM in the ANSYS Maxwell environment.

Next, the simulation of the start-up process for the optimal motor structure under rated torque load was analyzed. The waveform of the rotational speed is shown in Figure 8. It can be concluded that the optimal motor is able to synchronize.

The analysis of the rated torque load during the start-up process shows that the optimal motor was pulled into synchronism. It is worth noting that the motor started to work at a synchronous speed of about 1 s after its stator winding was supplied. After a large number of computer simulations, it can be concluded that the objective function with a component that guarantees proper synchronization is a critical factor in the design of crane motors.

7. Conclusions

In the article, the optimization algorithm for optimization of LSPMSMs was developed. The designed motor structure is defined by nine design variables described stator and rotor structure. To improve the efficiency of the optimization process and take into account the synchronization properties of the line-start motor, a modified genetic algorithm was proposed. Special attention was paid to initiation, crossover and mutation procedures.

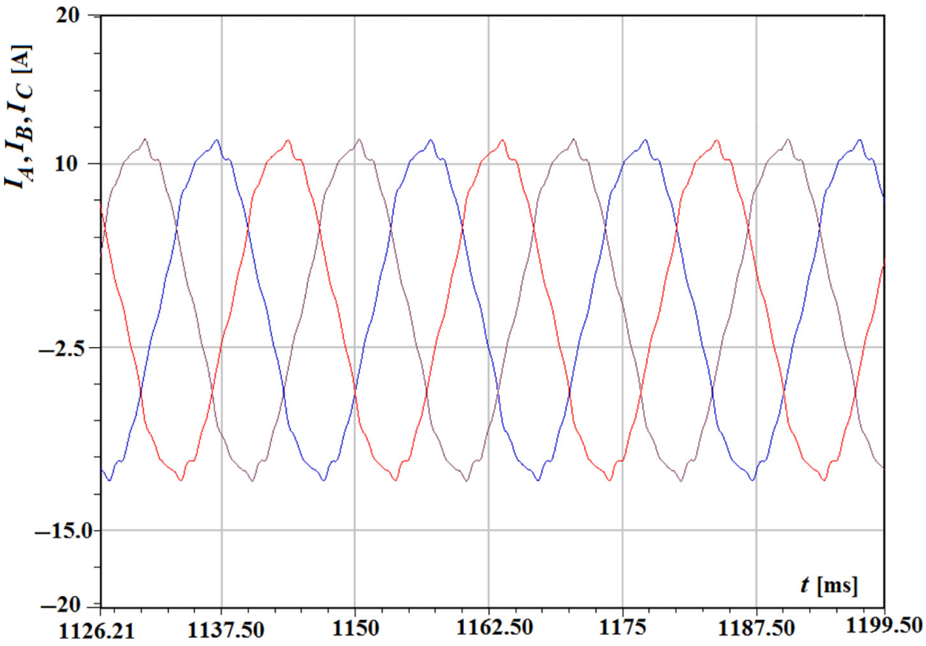

Figure 6.
The waveforms of phase currents in the synchronous operation state

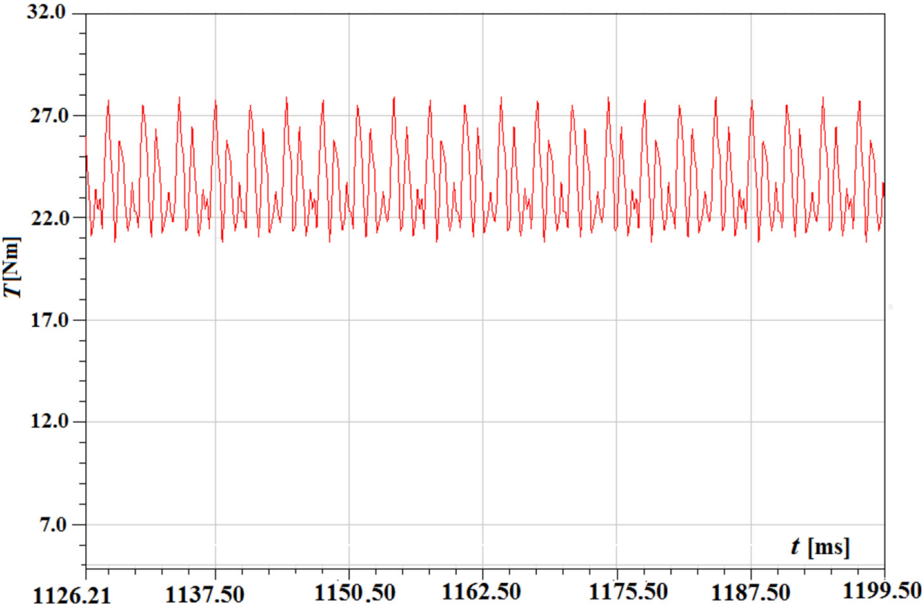

Figure 7.
The waveform of the electromagnetic torque in the synchronous operation state

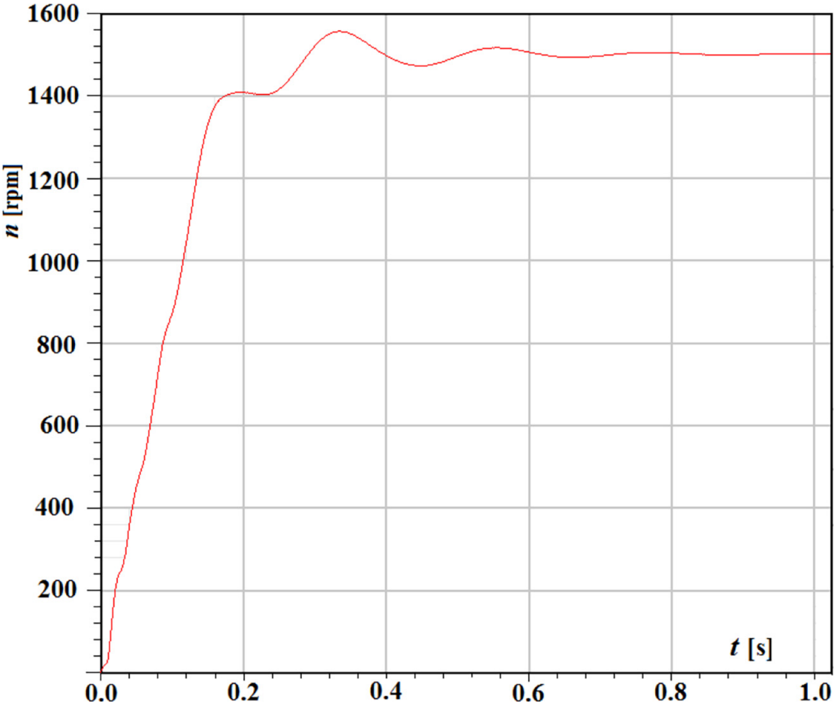

Figure 8.
The waveform of rotational speed during start-up process

Special modifications in selected genetic operators make it possible to resign from analyzing the start-up state for each individual in the generation. The start-up process is analyzed only for selected individuals during the optimization process.

The software was applied to the designing of LSPMSM for the slewing drive in the tower crane. The obtained results encourage future research. The optimized motor has better parameters than the induction motor previously used for series production.

Further research will focus on adopting a new form of the objective function, which will include the parameter responsible for starting and synchronization properties.

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