ELECTROMAGNETIC ANALYSIS OF LINE-START SYNCHRONOUS RELUCTANCE MACHINES OPTIMIZED BY MEANS OF TOPOLOGY OPTIMIZATION

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Abstract: This paper deals with the electromagnetic analysis of a line-start synchronous reluctance motor optimized by means of topology optimization based on the normalized Gaussian network. Topology optimization using the normalized Gaussian network represents the novel approach for electrical machines improvements. This article evaluates this approach as promising due to the electromagnetic analysis results of selected individual of the Pareto front. The main contribution of this article is a comprehensive electromagnetic analysis of line-start synchronous reluctance machine optimized by the above mention method.

Keywords: Ansys Maxwell, electromagnetic analysis, FEM, line-start synchronous reluctance motor, the normalized Gaussian network, topology optimization, transient analysis

1 INRODUCTION

There are worldwide efforts for a reduction in energy consumption within the framework of sustainable development. The electrical rotating machines are one of the biggest consumers of electricity. Thus, the efficiency requirements for electrical rotating machines is raised considerably by the efficiency classification standard IEC 60034-30. Presented research deals with the line-start synchronous reluctance machines (LSSynRM) due to the promising performances of this type of machine [3]. Although LSSynRM can reach the high-efficiency requirements of the efficiency classification standard, there is a demand for further improvements. The improvements of LSSynRM are done by the means of topology optimization (TO) based on the normalized Gaussian network (NGnet). Comprehensive electromagnetic analysis of LSSynRM optimized through the described methodology is the main goal of this paper and it can be found in the following sections.

The paper is organized as follows: Section 2 presents the TO based on NGnet in the general and developed method for its application to LSSynRM. Moreover, it contains the results of TO performed in [2] and it presents one individual geometry selected from the Pareto front for the more extensive electromagnetic analysis because the electromagnetic analysis was not the main goal of [2]. So the electromagnetic analysis is presented in Section 3. The analysis is divided into three parts: 3.1 Starting performances, 3.2 Steady-state analysis and 3.3 Synchronization capability. Section 4 concludes the paper.

2 TOPOLOGY OPTIMIZATION BASED ON THE NGNET OF LINE-START SYNCHRONOUS MACHINES

TO is an approach when the geometry of the optimized part of an electrical machine is changed directly without any previous expectations or limitations for topology. This is the main advantage of TO compared to parametric optimization, which works with predefined geometry such as number of flux barriers, bars etc. The authors of [1] explains this matter in more detail. They also discuss the disadvantages of TO such as a high number of optimized parameters and the possibility of achieving unfeasible geometries. These disadvantages can be partly solved by TO based on NGnet, which is described in [2] and [3] in more detail. The principle of the TO is shown in Fig. 1. The geometry of the rotor is fully determined by the assignment of pixels in the rotor to the predefined material such as iron or aluminum depending on the values of NGnet.

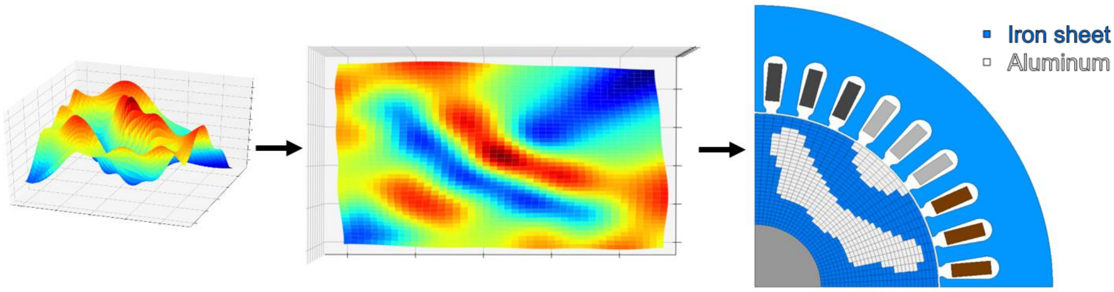

Figure 1: The NGnet defines geometry of LSSynRM rotor.

The TO considering NGnet was firstly presented by authors in [4]-[6] and it was used for permanent magnet and reluctance synchronous machines optimization. Although there are notable complications of application TO to line-start synchronous machines, the author of this paper developed the methodology for TO. The methodology includes a developed algorithm for the evaluation of a single individual, which leads to a significant reduction of the computational part. The comprehensive description of this algorithm can be found in [2] and [3] as it is out of the scope of this paper. The software tools used for TO are SyMSpace [7], Ansys Maxwell Electronics Desktop and Python.

The LSSynRM was selected as the type of machine for the optimization. LSSynRM is based on a conventional induction motor with a rated power of 2.2 kW and a rated speed of 1500 rpm. The main objectives of the optimization were: efficiency, power factor and torque ripple in the steady-state. The running time of TO was approximately one and half month and nearly 15 000 individuals were evaluated. The obtained Pareto front with roughly forty individuals is shown in Fig. 2. Although the results of the Pareto front were already presented in [2], this paper deals with the more extensive electromagnetic analysis of the selected individual. The individual selected for comprehensive electromagnetic analysis is highlighted in Fig. 2 and its topology is shown in Fig. 3, where a grey part is an iron sheet and orange parts are aluminum. The electromagnetic analysis is performed in the software Ansys Maxwell Electronics Desktop and it is presented in the following section.

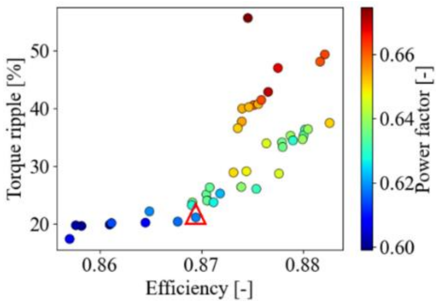

Figure 2: Pareto front [2].

Figure 3: The selected geometry for comprehensive analysis.

3 COMPREHENSIVE ELECTROMAGNETIS ANALYSIS OF SELECTED INDIVIUAL

The geometry of the selected individual strongly depends on the shape of NGnet, which is changed by the genetic algorithm DECMO2 [8] in SyMSpace during TO. It can be seen in Fig. 3, that the main flux barrier and main flux guide are rather thick. The thickness is caused by the low number of Gaussian functions used in NGnet. The low number of Gaussian functions, and thus a small number of optimized parameters, was necessary to ensure the reasonable time of optimization. This produces not ideal geometry with only one main flux barrier. Three bars are located near to surface of the rotor. Their functionality is the same as in an induction motor. Besides, two more bars are located in the inner area of the rotor, which do not serve as squirrel cage due to their location too far from the surface of the rotor. Also, the whole geometry seems insufficient from the mechanical point of view because of the thin iron bridge between the shaft and the main flux barrier. Even though the mentioned deficiencies in geometry, an electromagnetic analysis was performed to evaluate the performance of obtained LSSynRM as well as the performed topological optimization.

3.1 STARTING PERFORMANCES

The analyzed machine is a line-start synchronous reluctance machine. Thus, the supply source is set as a voltage source with a nominal voltage of 230 V. The stator winding connection is a star. The step time of transient analysis is set to 0.1 ms and the final time is 300 ms. The fan load with nominal load torque 14 Nm at 1500 rpm is connected to the shaft and the load moment of inertia is equal to the moment of inertia of the rotor. The starting process of the motor is quite dynamic and it is shown in Fig. 4. The speed gradually rises and it stabilizes at 1500 rpm in 180 ms. The torque during the starting process is shown in Fig. 5. The torque dependency on the speed is shown in Fig. 6, where the point of synchronization can be seen. The starting current is ten-times bigger compared to the nominal rated current at steady-state and it is shown in Fig. 7.

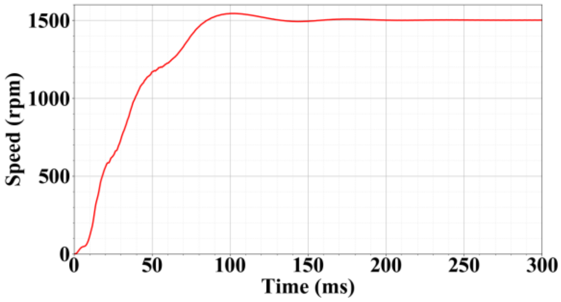

Figure 4: The speed during the starting process.

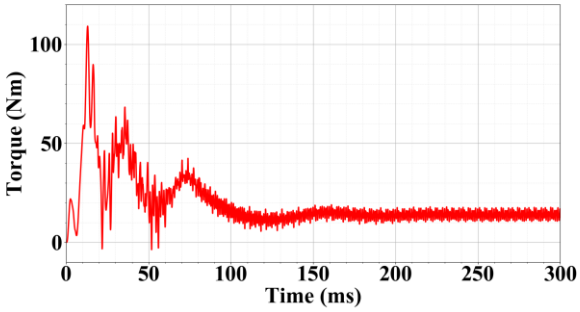

Figure 5: The torque during the starting process.

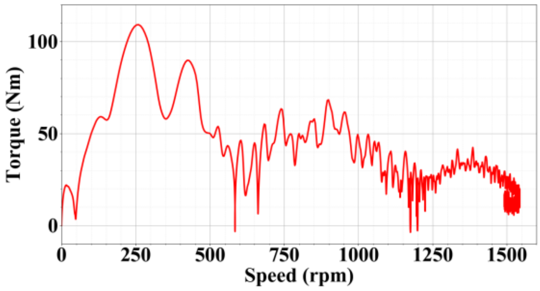

Figure 6: The torque dependency on the speed.

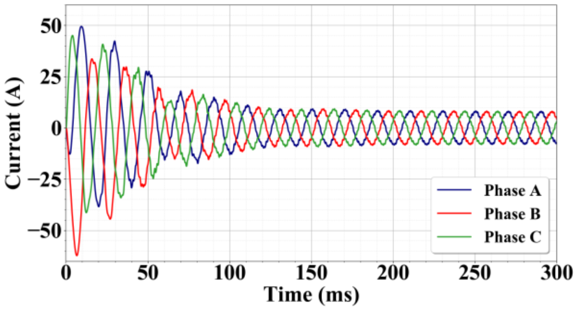

Figure 7: The currents during the starting process.

Rated power	kW	2.2
Rated speed	rpm	1500
Rated torque	Nm	14.1
Rated line-to-line voltage	V	400
Rated phase current	A	5.52
Efficiency	-	0.862
Power factor	-	0.629
Fundamental harmonic of flux density	T	0.761
Torque ripple	%	25.45

Table 1: Main parameters of selected individual at steady-state.

3.2 STEADY-STATE ANALYSIS

The last two periods of the starting process analysis described before are used for steady-state analysis. The main parameters of steady-state analysis are shown in Tab. 1. The motor has a power factor 0.629 and an efficiency of 86.2 %, thus this machine, unfortunately, does not reach even IE3. The magnetic flux density distribution is shown in Fig. 8 and the magnetic flux density in the middle of the air-gap is shown in Fig. 9. It can be seen that flux is forced to go also through the inner area of the rotor and the shaft. The flux density in this area is almost 2 T. On the one hand, the saturation in this area can be lowered if there were not two inner bars that decrease permeance in this area. On the other hand, the saliency ratio could also decrease due to the absence of these inner bars.

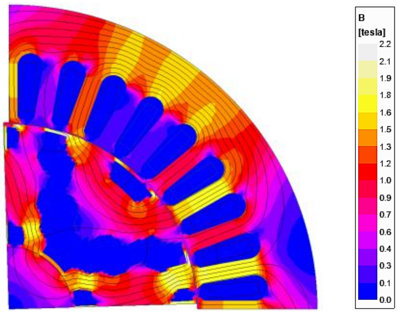

Figure 8: Flux density distribution in steady-state.

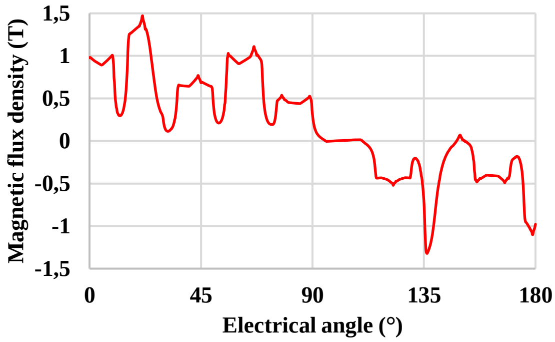

Figure 9: Magnetic flux density in the middle of the air-gap.

The torque ripple is shown in Fig. 10 and its value is 25. 6 % of the nominal torque. Fig. 11 shows the distribution of the losses in the motor at the steady-state. The resistive losses in stator represent almost 60 % of all losses. It is caused by a quite low power factor. The core losses are multiplied by the correction coefficient which considers the manufacturing effect on the material. The waveform of the current is shown in Fig. 12. The torque dependency on the load angle is shown in Fig. 13, but as this machine is supplied from the grid it stabilizes at a load angle of 21° corresponding to 14.1 Nm. The nominal load torque on the grid voltage supply is highlighted in Fig. 13.

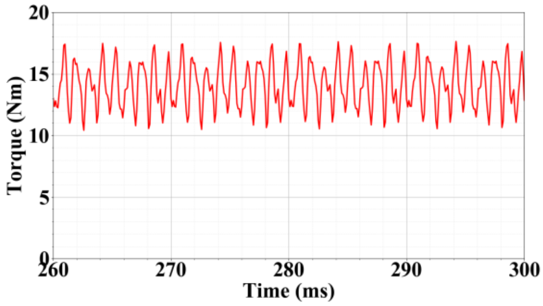

Figure 10: The torque behaviour in steady-state.

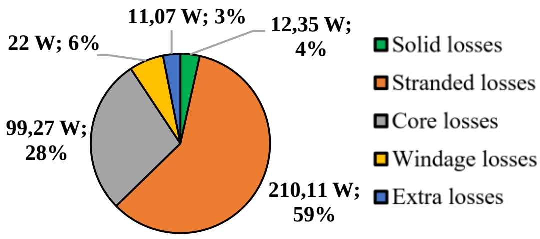

Figure 11: The distribution of the losses in steady-state.

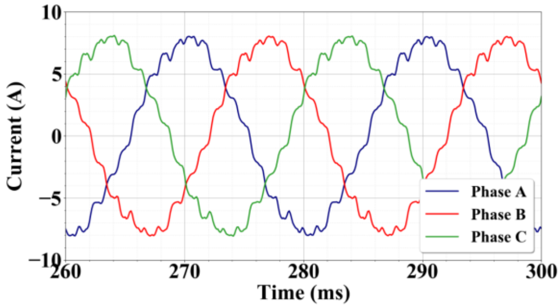

Figure 12: The currents behaviour in steady-state.

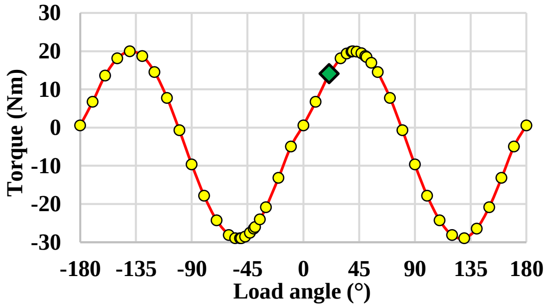

Figure 13: The torque dependency on the load angle.

3.3 SYNCHRONIZATION CAPABILITY

The synchronization capability is crucial for the application of LSSynRM. It is determined by critical inertia, which can be synchronized corresponding to the given statical load torque. The critical inertia decreases with bigger load torque. The synchronization capability of selected individual is shown in Fig. 14.

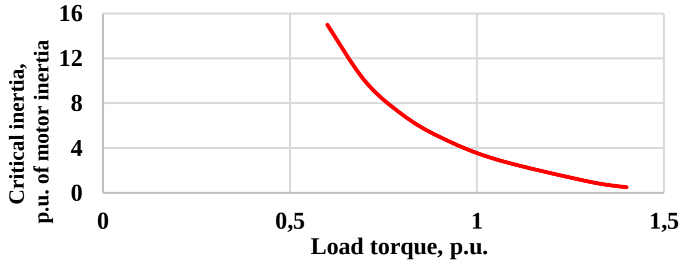

Figure 14: The synchronization capability.

4 CONCLUSION

The presented paper deals with the electromagnetic analysis of LSSynRM optimized by means of TO based on NGnet. The result of the analysis shows that the LSSynRM optimized by such an approach has the potential to reach considerably good performance. Thus, the TO based on NGnet is suitable for the improvement of LSSynRM, but there have to be done further development of this methodology for achieving the best results.

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