DESIGN AND PROTOTYPING OF DIRECTLY DRIVEN OUTER ROTOR PERMANENT MAGNET GENERATOR FOR SMALL SCALE WIND TURBINES

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Abstract. *The paper is about the design and prototyping of directly driven outer rotor permanent magnet generator for small scale wind turbine. In the paper, the initial design of the generator is given. Main issues and phenomena affecting the generator design, such as cogging torque and its reduction possibilities, selection and demagnetization risk assessment of permanent magnets, machine losses and thermal analysis, are described. Test results of prototype generator construction and final parameters are also presented. The necessity of further study is pointed out.*

Keywords

Electric machines, finite element analysis, generators, permanent magnet machines, wind energy.

1. Introduction

The world market for small wind turbines (1 to 300 kW) has stabilized after the fall in 2013, in terms of units and installed capacity [1]. The three biggest markets (China, USA and UK) showed stable growth and 945 000 small wind turbines were installed in 2014 worldwide.

In the traditional gearbox-operated wind turbines, the blades spin the shaft, which is connected through a gearbox to the generator [2]. The multiple wheels and bearings in the gearbox suffer tremendous stress because of wind turbulence and any defect in a single component can bring the turbine to a halt [2]. For this reason, the gearbox requires maintenance. The overall reliability of a wind turbine is reduced by the use of a gearbox in wind energy systems. However, on the other hand, direct-drive brings some significant drawbacks: cost and weight. Nevertheless, over the last two years, direct-drive machines have been demonstrated to not necessarily be heavier or more expensive than geared systems [2]. This fluctuation has been caused by two technological advancements: the cost of the permanent magnets used in direct drives has declined significantly and the arrangement of the generator has become more streamlined [2].

Gearless wind systems mostly use direct-driven low-speed generators with a large number of poles and an outer diameter larger than conventional generators. This kind of design makes the construction of a turbine more convenient due to the simple installation of the wind rotor directly to the generator surface. The blades can be put straight into the nests of the outer rotor frame. For outer rotor construction, the installation of magnets is easier compared to the inner rotor design. On the other hand, the construction with inner stator blocks the heat transfer from the stator windings [3].

In the last few decades, reduced magnet price has made synchronous generators with permanent magnet excitation an attractive alternative. In comparison to the electrical excitation, the permanent magnet excitation favours reduced active weight and decreased copper losses, yet the energy yield is higher [4]. Due to this fact, such applications have the highest efficiency and additionally, they are the most reliable [5].

2. Design Criteria

Before starting the generator design process, it is important to define in which way the generator will be utilized. In this paper, the generator suitable for the wind turbine equipped with a converter for battery charging, which is required for maintaining the required DC voltage on the battery terminals, is taken under investigation. This application also defines the design criteria for the design of the machine. The wind turbine defines the rated mechanical power and rotational speed, and the converter defines the required output voltage. In the current application, the wind turbine consists of a combination of Darrieus and Savonius type blades, the characteristic of which is given in Fig. 1.

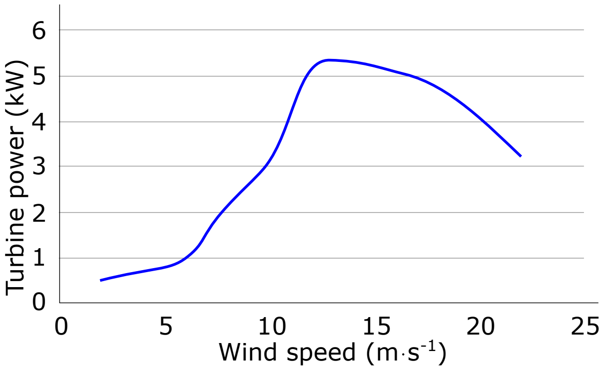

Fig. 1: The combined wind turbine characteristic.

The turbine achieves its maximum power when the wind speed is about 12 m·s^{-1} and corresponding rotational speed is 200 rpm. The batteries are charged through the converter with its nominal three-phase input of 400 V. Based on the wind turbine input and output parameters and requirements from the customer, outer rotor directly driven permanent magnet generator concept was chosen for investigation, with given construction in Fig. 2. The initial design parameters are given in Tab. 1.

Tab. 1: The required parameters of the generator specified by the customer.

Parameter	Symbol	Value	Unit
Total power	S_n	5000	VA
Rotational speed	N	200	rpm
Line voltage under load	U_{ll}	400	V
Temperature rise class		F	

3. Generator Design

At the beginning of the design process, the generator main dimensions were determined. The core length of the generator was found according to the relation of core length versus copper losses, iron losses, total losses, stator tooth flux density and current density in the stator winding. The given losses with relation to the core length are given in Fig. 3, where it can be seen that the minimum amount of total losses is present when the core length is equal to 90 mm. The prototype was built using the core length of 100 mm, with the air-gap diameter of 448.8 mm. The length was chosen due to the companies' choice, as ready-made 50 mm magnets were available on the spot.

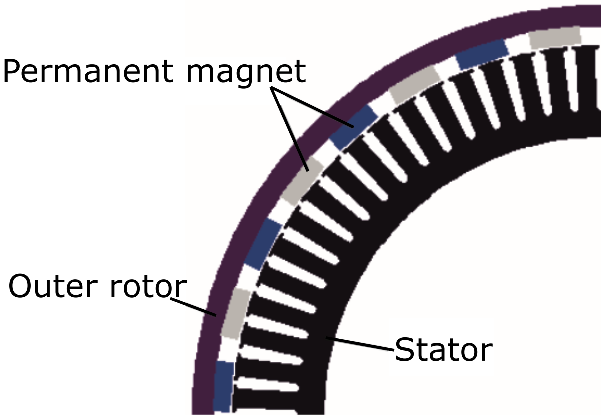

Fig. 2: Cross section of the designed PM generator with outer rotor.

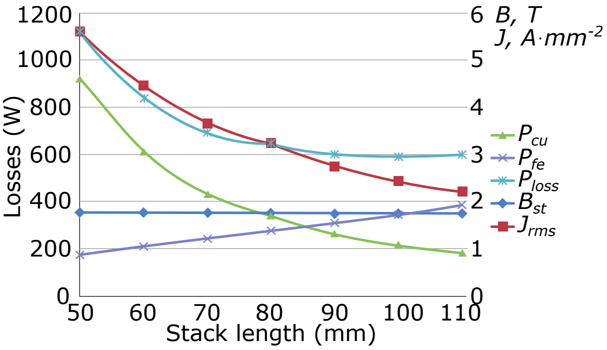

Fig. 3: Current density J_{rms}, magnetic flux density B_{st} and loss values (copper losses P_{Cu}, iron losses P_{Fe}, total losses P_{loss}) according to different lengths of the stator stack. These curves have been used to define the most efficient combination of losses in the generator.

The selection of the magnetic core dimensions is based on the saturation curves of the electrical steel, shown in Fig. 4. For the manufacturing of the machine, type M800-65A steel was used, as the material was available on the spot. This was considered to be a cost-effective solution, especially, as the machine operates on low frequencies and there is no special need for magnetic material with lower losses.

In Fig. 5, the distribution of flux density along the radius to the direction from outer rotor core to inner stator core is shown. As it can be seen from the curve, the maximum flux density is present in stator teeth.

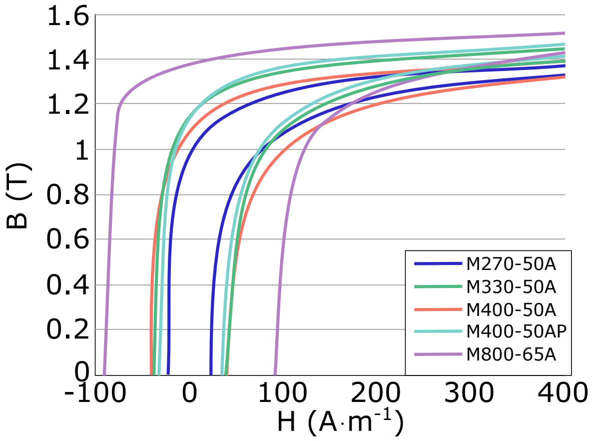

Fig. 4: Saturation curves for different steel materials, including M800-65A steel.

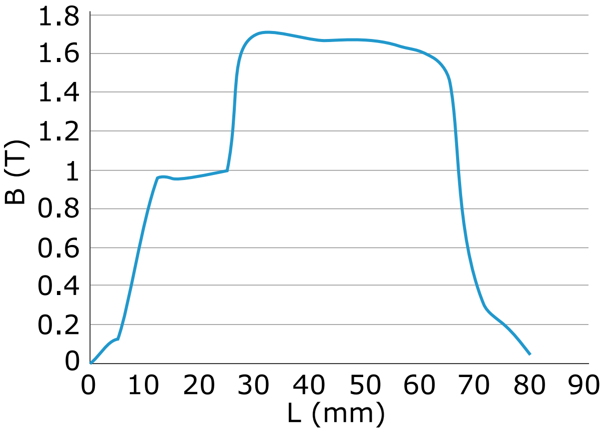

Fig. 5: Distribution of flux density along the radius to the direction from outer rotor core to inner stator core.

Figure 6 presents the finite element method (FEM model of flux density distribution along the radius of the machine. SPEED software was used for magnetic field simulations.

3.1. Cogging Torque Reduction

Cogging torque is created by different factors like slots per pole per phase, magnetic field distribution in the air gap, slot opening, slot filling factor, pole pitch and form of magnetic field. Cogging torque has an influence on the PM generator starting torque. Too high starting torque can have a significant influence on the generator operation.

There are different cogging torque estimation methods. The most widely used methods for cogging torque estimation are the virtual torque method and Maxwell stress calculation method [6].

There are different methods and possibilities, how to reduce the undesired cogging torque phenomenon in the designed electric machines. Mostly, the used methods are minimizing the slot opening of the machine and slot skewing method. The winding process limits minimizing the slot opening of the machine and in case of the slot skewing method, the manufacturing process of the stator stack must be very accurate and precise.

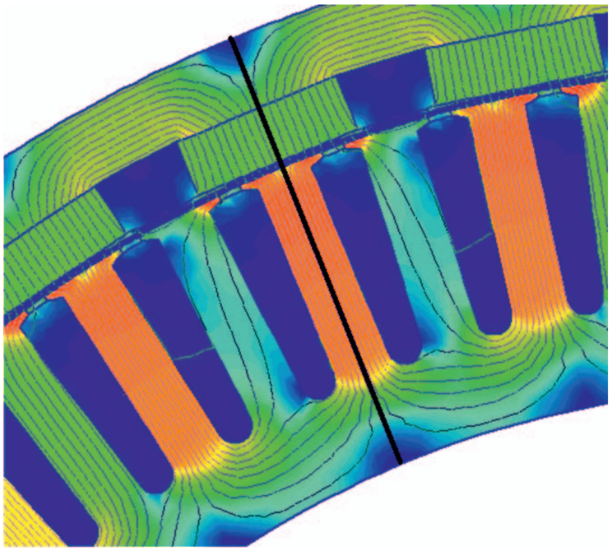

Fig. 6: FEM model of flux density distribution along the radius of the machine.

The mounting position of the magnets plays its role in cogging torque reduction. According to the simulations, the machine with surface mounted magnets has more than two times lower cogging torque than the machine with embedded magnets.

Nowadays, the slotless design of permanent magnet machines [7] is widely used for cogging torque reduction. In such design, coreless windings are used, which offers lower inductance and no cogging torque. The problem is in the rising price of manufacturing, as the amount of magnetic material needed for the construction is higher [8].

In case of the prototyped generator, all of the described options were taken into account. An in-depth analysis of the simulations and effect of one or the other method on machine parameters is presented in [6].

For the prototype generator reduction of cogging torque through slot skewing was selected. The possibilities of the amount of cogging torque reduction depending on the level of skewing were analysed and the results are shown in Tab. 2.

Minimum amount of cogging torque was found to be in case of one pole pitch skew (100 %). Further increase of the skewing angle started increasing the cogging torque amplitude again. On the ground of this analysis, the generator prototype was designed and manufactured using the one pole pitch skew of stator slots [3].

Tab. 2: Cogging torque values with different slot skewing levels.

Slot skew from slot pitch (%)	Cogging torque (Nm)
0	15.30
20	3.73
40	3.06
60	2.18
80	1.55
100	0.23
120	1.32

3.2. Permanent Magnet Selection

To choose the appropriate permanent magnet types and grades, FEM analysis of the designed generator was performed in order to investigate the magnetic flux density distribution in the air-gap. NdFeB magnets were chosen out from NdFeB - N42H; Alnico - AC900; Sm2Co17 - S3018; Ferrite - HF083. The magnet type N42H was selected, as it yields the best energy density compared to the other options described; also this magnet type was available on the spot and was the cost-effective solution for the manufacturing company. The distribution itself is presented in Fig. 7. The simulation of other magnetic materials was performed in order to see if there are other economically feasible possibilities of permanent magnet selection suitable for the selected design. Full permanent magnet material simulation results for the designed generator are presented in [9].

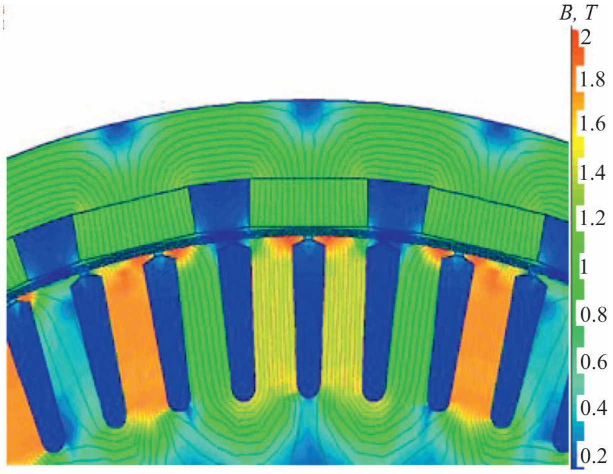

Fig. 7: Magnetic flux density distribution in the generator in case of NdFeB magnets.

3.3. Demagnetization Analysis

Permanent magnets themselves are one of the most critical parts in permanent magnet machines. One of the most important values that has to be considered in case of magnetic materials is the operating temperature of the selected permanent magnets. This is due to the risk of permanent magnet demagnetization when the operating temperature is exceeded. For the prototype generator, NdFeB magnets, grade N42H, were chosen to be used. This grade has the maximum operating temperature of 180 °C.

Most severe conditions that the magnets are likely to meet must be taken into account when assessing the risks of demagnetization. These are the maximum load conditions, which mean short-circuit situation, and maximum temperature.

High temperature is also the result of short-circuit due to armature reaction influence and significant decrease of flux density in such situation. To minimize the risk of demagnetization, the construction of the machine is vital. Permanent magnets must be mounted to well-cooled regions of the machine. Simulated flux density distribution during short-circuit in the designed machine can be seen in Fig. 8.

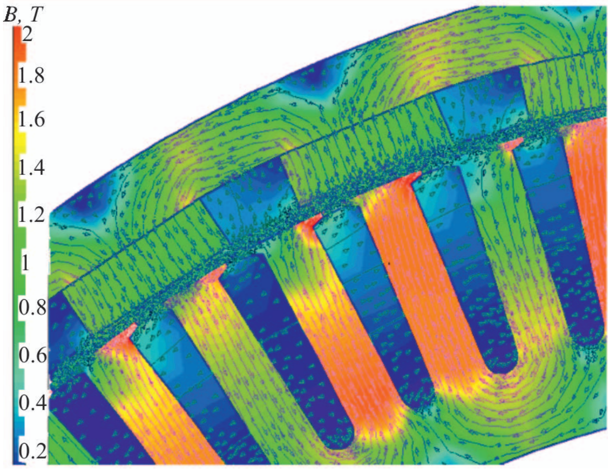

Fig. 8: Magnetic flux density distribution in the generator during short-circuit situation.

Calculation of the designed machine showed that the armature reaction is quite weak and does not pose a demagnetization threat to the chosen permanent magnets. The simulated lowest flux density in case of a short-circuit was found to be 0.7 T at 100 °C. As the designed machine has an outer rotor, the magnets are also well cooled by the air flow through the ribs on the rotor surface.

3.4. Machine Losses

There are different losses present in electrical machines. These are the copper losses, the iron losses and the mechanical losses. In case of permanent magnet machines, copper losses are the major losses.

Calculated losses for the prototyped generator as well as current density and magnetic flux density according to different stator stack lengths are presented in Fig. 3. The mechanical or rotational losses have not been taken into account in the calculations during the design process of the given generator. These losses make usually up to 10 % of total losses and consist of bearing friction and air-friction or windage loss. As the percentage of mechanical losses in relation to total losses is small, they can be discarded.

In addition, due to the relatively low frequency of the machine, and since the higher order time harmonics in the stator current waveform and space harmonics in the winding distribution are relatively small, the permanent magnet losses are neglected.

3.5. Thermal Analysis

The heat extraction of the generator can be described by three modes: conduction, convection and radiation. Conduction heat transfer mode is created by the molecule vibrations in a certain material. Aluminium, copper and steel have quite high thermal conductivity due to their structure [10]. On the other hand, rare earth NdFeB permanent magnets have a hundred times higher thermal resistivity than copper. Convection heat transfer mode appears between a surface and a fluid. Two types of convection can be distinguished: natural and forced. Radiation depends on emissivity and the view factor of the surface.

The thermal calculations have been performed using thermal lumped- circuit analysis. Motor-CAD software was used for the simulations. The necessary radiation and convection coefficients were determined using knowledge obtained from the design of other similar machines manufactured in the company. The cross-section of the simulated machine with the main temperatures is shown in Fig. 9. For different parts of the machine, transient temperature rise versus time relations are presented in Fig. 10.

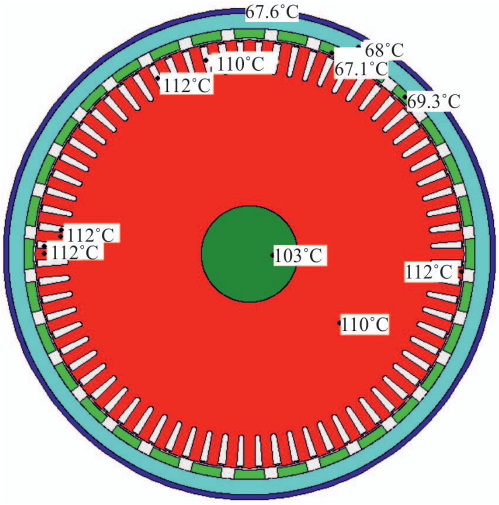

Fig. 9: The cross section of the calculated design, on which temperature rise values are marked for different parts of machine.

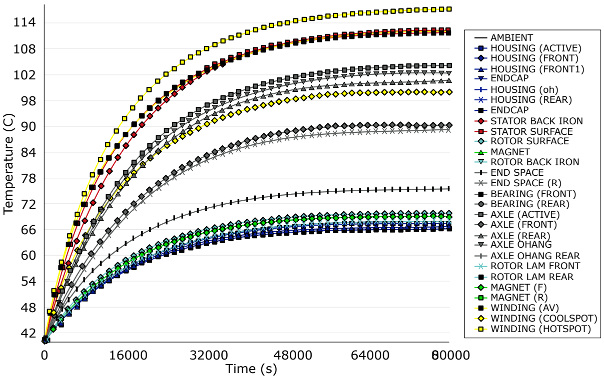

Fig. 10: Temperature rise vs time thermal transient curves. The yellow curve indicates the maximum temperature rise (hot spot) that appears in the stator winding.

4. Prototype and Testing

The prototype generator was manufactured, as well as tested, in the Konesko AS motor factory. The prototype generator is presented in Fig. 11 and Fig. 12.

To rotate the prototype, an induction machine was used. Loading of the machine was done using a special load bank, equipped with twenty-six steps of different active resistances. This was done to ensure smoother loading of the prototype generator.

Fig. 11: Prototype generator with outer rotor.

4.1. No-Load Test

No-load test results showed that the predicted and calculated no-load voltage was 1.6 % lower than the measured one. It was expected to be 435 V, and it turned

Fig. 12: Assembled prototype generator.

out to be 442 V. Possible reason for such deviation could be the higher power of the used magnets, than it was expected at the calculation stage. Temperature rise of the magnets did not reduce the strength of the magnets as the calculations predicted. Total harmonic distortion of the generator turned out to be less than 1 %. This was achieved by the combination of selected windings, stator slots and permanent magnets. No-load characteristics of the prototype generator are presented in Fig. 13.

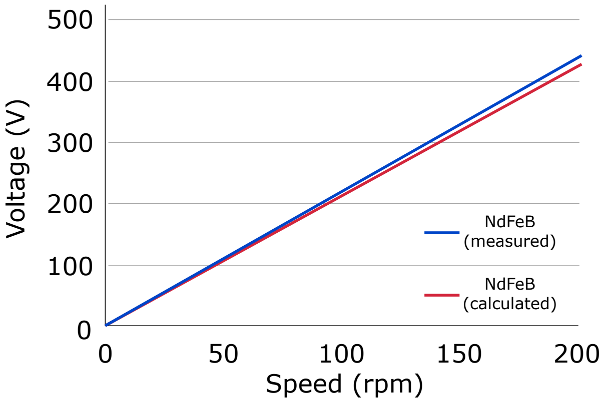

Fig. 13: No-load characteristic of the prototype generator. Red line shows voltage measured during the test and blue line shows the calculated voltage.

4.2. Load Test

Load test of the generator was performed using a rated active load of 5 kVA during 4.5 hours until temperature of the generator stabilized. Load characteristic of the prototype generator is presented in Fig. 14. From the figure, it can be seen, that the line voltage drop on the nominal load is around 5 %. This can be considered relatively small.

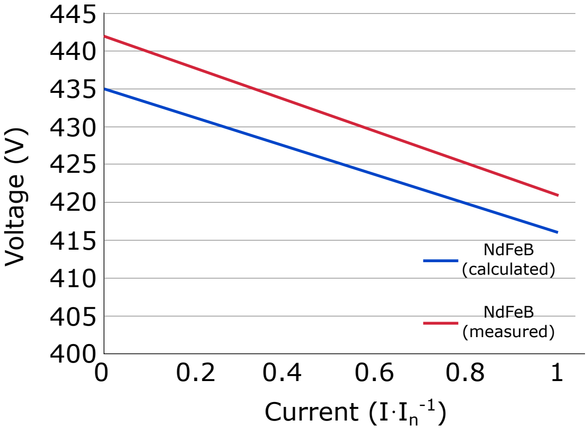

Fig. 14: Load characteristic of the prototype generator. Red line shows voltage measured during the test and blue line shows the calculated voltage.

The temperature test was carried out in natural cooling environment. The machine temperature was measured by PT100 sensors, placed in the stator slot between the winding and the wedge. Without using any additional cooling, the temperature of the generator stabilized when reaching 115 °C. Due to the totally closed rotor and shaft, the cooling of the prototype generator is quite poor. To improve the cooling condition, making of aeration holes between stator and shaft could be considered. This would also reduce the generator size.

The measured results differ slightly from the calculated values. On the other hand, as the machine is meant to be used in wind applications, mounted in an outside natural environment, having better natural cooling properties as the laboratory setup, the results can be considered sufficient, and there is no danger of overheating the machine.

Cogging torque of the generator was expected to be less than 1 Nm, but it turned out to be 5 Nm. Still, it did not affect the operation of the generator. Final main parameters of the prototype generator are presented in Tab. 3.

Tab. 3: Final parameters of the generator.

Parameter	**Symbol**	**Value**	**Unit**
Total power	S_n	5057	VA
Rotational speed	N	200	rpm
No-load voltage	E_1	255	V
Phase voltage under load	U_{ph}	242	V
Current density in winding	J	II.56	$A \cdot mm^{-2}$
Cogging torque	T_{cog}	5	Nm
Efficiency	η	89.2	%

4.3. Prototype Generator

The test results showed that the designed and manufactured generator was working as predicted by the design and calculations. The prototype of the generator is currently installed in Tallinn University of Technology campus. It is working in a 5 kVA vertical axis wind turbine, as a part of the local microgrid test facility. Photo of the installed generator with the wind turbine is presented in Fig. 15.

Fig. 15: Prototype generator installed into vertical axis wind turbine.

5. Conclusion

The generator for small scale wind turbine application has been designed, constructed and tested. The calculation and test results showed good agreement. During the design process, some important topics like cogging torque reduction, permanent magnet characteristic variability, permanent magnets demagnetization, and thermal analysis have been studied in-depth. As the result of the studies, the most efficient and safe design has been chosen.

Further study of the prototype generator should be conducted in order to study the behaviour of the machine in different fault situations like permanent magnet damage, eccentricity in rotor, stator winding faults. Regarding thermal analysis and cooling, further study is also needed.

Thermal analysis could be performed using finite element methods. More precise cooling circuit modelling should be taken into account by considering the air movement inside the machine, which is created by rotor movement. Also, the movement of outside cooling air should be taken into account.

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