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Study on the Thermal State of a Transverse-Flux Motor

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ABSTRACT Based on the analysis of transverse flux machine designs, it was established that they exhibit a relative simplicity of design and demonstrate high specific power indices. This paper seeks to explore the influence of design features on the heating of the stator coil, identified as the most temperature-sensitive element in the system. Additionally, the study aims to characterize the temperature distribution pattern within the stator. To achieve this goal, experiments were conducted using a 3D model of a low-speed transverse flux motor. Thermal analysis was carried out using modern software, enabling the determination of temperature patterns in the coil, cores, and stator body. Graphs illustrating the temperature rise over time for each motor component were generated. The obtained results include corresponding graphs and dependencies, revealing that the average coil temperature reached 92°C, deviating by 3.3% from the experimental value. A significant finding is that the stator coil in a transverse flux motor experiences non-uniform heating, with temperature variations in areas lacking circulated air. Introducing thermal paste in the region enclosed by the U-shaped cores, coil, and body was found to equalize and reduce the stator coil temperature by 10%. These modeling results were subsequently validated through experimentation on the operational prototype of the TFM-200/32 transverse flux motor.

INDEX TERMS transverse flux motor, permanent magnet, transient thermal processes, temperature field pattern.

I. INTRODUCTION

Despite the extensive history of electric machine development with permanent magnet excitation, their widespread adoption is a relatively recent phenomenon. The catalyst for the rapid integration of such machines across various fields lies in the advent of high-coercivity rare earth magnets based on NdFeB. These magnets boast high specific magnetic energy, enabling the production of machines with superior mass and dimensional characteristics under equivalent conditions. The utilization of permanent magnets for electric machine excitation eliminates electrical losses associated with excitation, positively impacting overall efficiency [1, 2].

Advancements in semiconductor and microprocessor technology played a pivotal role in the widespread acceptance of permanent magnet machines. These machines find prominent application in regulated electric drive systems, and the emergence of MOSFET and IGBT transistors, contributing to increased speed and power of control systems, further expanded their application into new domains [3].

Many low-speed electrical machines are now permanent magnet AC synchronous motors, known for their durability and performance in challenging conditions. Their high torque at low speeds makes them suitable for various applications, including driving printing machines in the paper industry, serving as a drive for extruders or drawing machines in the polymer industry, and commonly being utilized in robotics and direct drive mechanisms [4–7].

A distinct subclass of electric machines is represented by transverse flux machines (TFM). This type allows for the application of simple stator windings, and the availability of high-specific-energy permanent magnets in the global market positively influences operational, technical, and economic characteristics. Electric transverse flux machines are implemented in multi-pole designs with external, internal, or disk rotor arrangements [8–12].

Similar to most electrical machines, permanent magnet transverse flux machines are fully reversible, functioning effectively in both motor and generator modes [13, 14]. The study of motor operation in these machines commenced in the mid-eighties of the last century, with existing research primarily limited to electromagnetic calculations, and thermal considerations seldom taken into account [15, 16].

Transient thermal processes occur during the operation of electrical machines, encompassing start-up, load and speed changes, braking, and tripping modes. Influencing factors include overcurrent, frequent and prolonged motor starts, and short-circuit operations [17]. Notably, the inertia of transient thermal processes in electric machines results in a significant lag between temperature changes and electromechanical transients. This property allows electric machines to endure overloads, short-circuit currents, and other transient modes for extended periods. Considering thermal inertia in transient calculations is imperative for result reliability [17].

Theoretical studies of heat conduction processes heavily rely on numerical modeling using computer programs. Progress in analytical methods, computational techniques for solving partial differential equations, and the increased computing power of modern machines have facilitated this approach. Numerical modeling of heat conduction processes has become crucial for predicting these processes, especially when experimental study proves difficult, expensive, or impractical, making it an integral part of modern mechanical engineering [18].

Accurate thermal calculation methods for electrical machines often involve solving differential equations of heat conduction, particularly when obtaining a continuous temperature distribution in space or time is crucial. Alternatively, equivalent thermal schemes for stationary problems and assumptions of body homogeneity in non-stationary problems are applied based on simplified equations. Synthetic methods that leverage both complex and simplified solutions also exist [19].

Solving a 3D field poses significant challenges of a fundamental nature. Consequently, many contemporary methods for the thermal calculation of electrical machines rely on simplifying assumptions. The reduction of the actual 3D heat conduction process to a conditional one-dimensional process, coupled with the quest for solutions closely resembling the authentic temperature distribution, constitutes a crucial aspect of these assumptions [20].

In recent decades, the utilization of computational methods has expanded rapidly, owing to advancements in computer engineering. Among these methods, the finite element method (FEM) has taken a prominent position. Initially developed for addressing durability issues, FEM is increasingly applied to various research areas, particularly in solving problems related to the distribution of temperature fields in diverse environments. Modeling the heating of electric machines of different types falls within this category of problems [21].

Numerous software environments exist for calculating thermal fields through numerical modeling. Some simpler programs, such as ELCUT, QuickField, FEMM, etc., are relatively easy to master. On the other hand, there are more advanced professional programs like ANSYS, Flux 3D, Femap, COMSOL, etc., which offer enhanced capabilities but demand a greater effort to become proficient in their usage.

The ELCUT software package stands out for its highly user-friendly interface, making it a potent tool for engineering modeling of electromagnetic, thermal, and mechanical problems through the finite element method. Its intuitive interface, straightforward description of even complex models, extensive analytical capabilities, and a high degree of automation in operations allow developers to fully concentrate on their tasks [22].

On the other hand, the COMSOL Multiphysics software environment offers a powerful and interactive platform for modeling and calculating a wide range of scientific and engineering problems. It is based on differential equations with partial derivatives, utilizing the finite element method. The software facilitates extending standard models to incorporate multiple physics, eliminating the need for in-depth knowledge of mathematical physics and the finite element method. This is achieved through built-in physics modes, where coefficients are set as understandable physical properties such as thermal conductivity, thermal capacity, heat transfer coefficient, volumetric power, etc. The program interaction occurs through a user-friendly graphical interface [23].

In the context of electromagnetic processes, research indicates that the discussed motor type holds significant potential in terms of energy performance, specifically specific torque, while maintaining favorable mass and size indices.

The mass of an electric machine is known to be influenced by the adopted values of electromagnetic loads, with admissibility determined through thermal calculations. Typically, these values rely on recommendations from design experience. However, applying such an approach may not always be justified, especially when considering new design schemes with improved heat dissipation conditions. Therefore, thermal calculations play a crucial role beyond mere validation, as they can significantly impact the design of the machine itself, especially when exploring novel electrical machine types. This aspect has not been adequately addressed in the previously discussed works, making it relevant for reducing maximum stator winding temperatures resulting from these losses.

Despite successful experiences in modeling thermal and electromagnetic processes in classical electrical machines, specific challenges arise in transverse flux motors due to their pronounced stator cogging. These challenges, particularly related to heat flux distribution and motor heating, have not been explored in the existing literature and constitute the focus of this research article.

The primary objective of this paper is to investigate how the design features of a transverse flux motor influence the heating of the stator coil, recognizing it as the most temperature-sensitive element in the motor design. Additionally, the study aims to determine the pattern of temperature field distribution within the stator.

The importance of this study lies in the fact that low-speed gearless motors, such as TFM, have not been widely researched. It is clear that there is a global trend towards improving the reliability of electric drives. One way to achieve this is by eliminating the gearbox and directly connecting the motor to the drive mechanism. However, there are not enough studies that focus on the thermal processes in hermetic machines with direct drives.

While non-uniform heat distribution in stator coils is a known phenomenon, the study uniquely focuses on its specific manifestation in transverse flux motors (TFMs), which differ significantly from conventional designs due to their distinct geometry and operational constraints. By employing detailed 3D modeling and experimental validation, the research identifies and quantifies previously undocumented thermal behaviors in TFMs, such as the differential heating caused by limited contact with U-shaped cores. The innovative application of thermal paste to mitigate these effects represents a practical and cost-effective solution, advancing the thermal optimization of TFMs in sealed, low-speed, high-torque applications.

II. OBJECT, SUBJECT, AND METHODS FOR RESEARCH

Ensuring thermal homogeneity in electric machines is critical for their reliability and operational longevity, particularly in practical applications where consistent performance is paramount. In transverse flux motors (TFMs), uneven heating of stator coils leads to localized hotspots, which accelerate the degradation of insulation materials, reduce motor efficiency, and increase the risk of failure under sustained load conditions. This is especially problematic in low-speed gearless motors used in sealed environments, such as marine or industrial applications, where external cooling options are limited. By addressing thermal non-uniformity, the study not only aims to enhance the durability of TFMs but also provides a framework for improving thermal management in other compact and high-torque motor designs. The insights gained contribute to reducing maintenance costs, extending service life, and ensuring consistent performance in challenging operating conditions, underscoring the practical significance of achieving thermal homogeneity.

The design of the TFM-200/32 transverse flux motor stands out for its simplicity when compared to classical machines such as asynchronous, synchronous, and DC machines. The primary distinction lies in the rotor's configuration, which takes the form of a disk rather than the cylindrical shape characteristic of other machines.

In the vast majority of cases, electric machines with a disk-shaped rotor design exhibit a higher specific torque compared to machines with a traditional cylindrical rotor. The increase in specific torque is due to the fact that the outer diameter of the rotor is comparable to the outer diameter of the stator. As a result, these machines demonstrate a significantly higher specific torque compared to cylindrical designs, where the rotor's outer diameter matches the stator's inner diameter. The electromagnetic torque is generated in the air gap, and disk rotor machines benefit from the larger radius at which this torque is produced.

Figure 1 illustrates the bench with the TFM-200/32 motor on the left, captured during its laboratory testing phase.

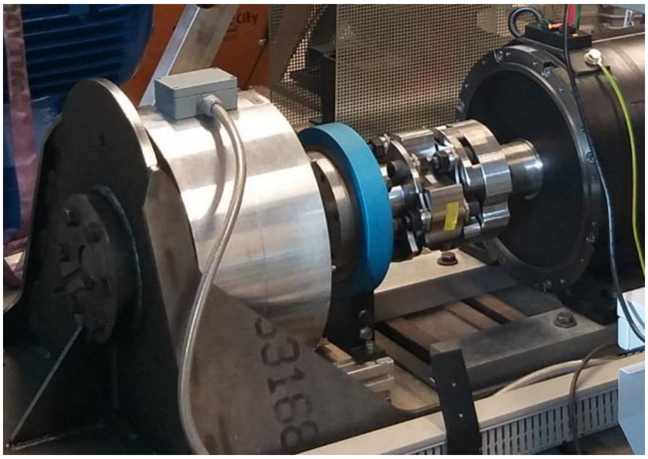

FIGURE 1. TFM-200/32 motor on the laboratory bench.

As shown in Fig. 1, the motor is sealed, meaning there is no option for air cooling. The housing consists of two parts, each made from solid aluminum. This design is necessary for the intended hermetically sealed application of the motor as a direct drive for steering mechanisms on boats, turbine blades in mini hydroelectric stations, and other similar uses.

The utilization of the TFM-200/32 transverse flux motor differs from classical machines as it requires operation through a specialized frequency converter that supplies AC voltage to the stator coils. This configuration enables precise control of the motor speed by adjusting the frequency of the current flowing through its coils. The control system also monitors the current supplied to the motor's coils. This motor has two phases and is an experimental prototype with 0.5 kW of nominal power.

The nominal operating mode for the TFM-200/32 motor is considered to be at a current frequency of 50 Hz, resulting in a rotor speed of 94 rpm and a nominal voltage of 24 V.

Notably, the machine body is not integral to the magnetic circuit, allowing it to be constructed from non-magnetic materials, akin to induction motors. Furthermore, being a low-speed machine, the body of the TFM-200/32 motor does not bear substantial mechanical loads, enabling it to be crafted from an aluminum alloy. The disassembled appearance of two-phase the TFM-200/32 motor is depicted in Figure 2, and relevant design parameters are detailed in Table I.

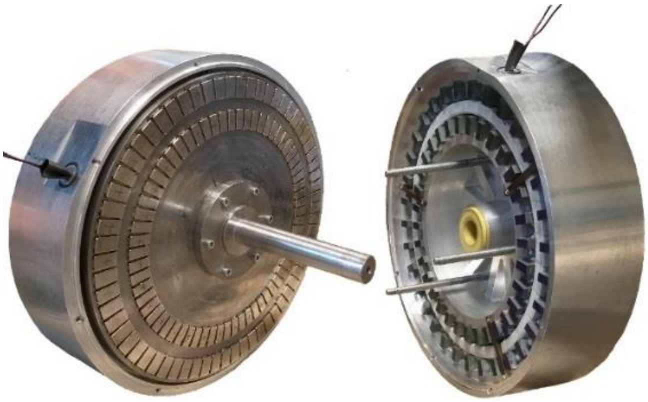

FIGURE 2. **TFM-200/32 motor in a disassembled state.**

TABLE I
DESIGN PARAMETERS OF THE TFM-200/32

Parameter	Value
Outer diameter, mm	400
Inner diameter, mm	210
Length, mm	180
Air-gap, mm	1
Number of phases	2
Number of poles per phase	32
Number of PM per phase	64
Permanent magnets	N38M
Stator poles material	Electric steel M19
Stator poles thickness, mm	0.23

The detailed design of the TFM-200/32 motor is shown in Fig. 3 in the form of a disassembled 3D model. The motor experiences heat generation from two primary sources – the stator coil (pos. 5) and the magnetic core consisting of the U-shaped (pos. 3) and the I-shaped (pos. 4) cores. Given that each stator phase (pos. 2) is separated by air gaps and the disk rotor (pos. 6), it is possible to evaluate the thermal state of each phase independently. The disk rotor, having direct contact with the stator only through the bearing unit in the body (pos. 1) and being separated from the active stator part by an air gap, can be disregarded in the modeling process. Its gear structure, characterized by the presence of permanent magnets (pos. 7) extending beyond the rotor disk's plane, only influences the heat transfer coefficient from the inner surface of the stator.

To streamline the modeling process, it is feasible to consider only a portion of the stator, implementing symmetry conditions on the side faces (i.e., zero heat flow), thereby reducing calculation time without necessitating extensive computer resources. Additionally, certain assumptions, while not significantly impacting the results, are accepted to simplify the model:

- Radii of roundings are replaced by right angles.
- There are no air gaps between contacting surfaces.
- Cylindrical surfaces are approximated as multifaceted ones.

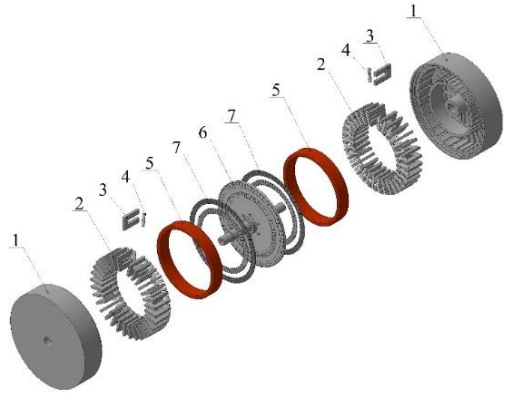

FIGURE 3. **Disassembled 3D model of TFM-200/32 motor.**

The stator coil, comprising 150 turns of round enameled PET-155 wire (insulation heat resistance class F with 155°C) with a diameter (d_{scis}) of 1.2 mm, is wound on a special winding machine, where each turn closely abuts its neighboring turn. However, due to the round shape of the winding wire cross-section, air gaps exist between turns (partially filled with insulating varnish after impregnation). Consequently, there is a notable thermal anisotropy in the thermal conductivity of the area occupied by the coil along and across the wires, and this difference is significant [24].

To increase the thermal conductivity of the stator coil, it is impregnated by a compound with a certain impregnation coefficient value. This factor characterizes the degree of air displacement from the gaps between the conductors themselves, as well as between the conductors and the groove insulation. This is a purely empirical value. It varies between 0 and 1 and depends on both the impregnation method and the amount of solids in the impregnating varnish. In the case of vacuum impregnation, the impregnation coefficient, $k_p = 0.9$.

The equivalent thermal conductivity of the area occupied by the coil across the wires is affected by the thermal conductivity of the insulation, which consists of two elements – the enamel wire coating and the impregnating varnish. For the most commonly used materials of heat resistance class F, the thermal conductivity of enamel and varnish can be assumed respectively equal to $\lambda_{em} = 0.165$ W/(m·°C) and $\lambda_{km} = 0.20$ W/(m·°C). It is essential to use the empirical relation to solve the problem of the value of the equivalent transverse thermal conductivity [24]

$$\lambda_{Cu} = 0{,}17 \cdot \left(1 + 0{,}18 \cdot d_{scis}^2 + d_{scis} \cdot \left(1 - 1{,}15 \cdot \left(1 - k_p\right)^2\right)\right). \quad (2)$$

Heat-engineering parameters of the TFM-200/32 motor design elements and volumetric densities of heat sources are shown in Table II. Thermal conductivity coefficients for calculating the thermal conductivity of the coil across the conductors are calculated using formula 2, and for other materials they are taken from the COMSOL database and scientific articles on calculating the thermal state of electrical machines [23, 25]

TABLE II
HEAT-ENGINEERING PARAMETERS OF MOTOR DESIGN ELEMENTS

Motor design element	Volume density of heat flux, W/m^3	Thermal conductivity coefficient, W/(m·°C)
Coil	263290	Across the conductor 0.43 Along the conductor 400
U-core	34720	34
I-core	0	34
Permanent magnets		9
Isolation	0	0.24
Body	0	900

The motor is designed to operate in damp, confined spaces without heating or ventilation, where water or condensation may be present, such as mines, ship holds, or basements. The operating ambient temperature ranges from -10°C to +35°C, with relative humidity from 90% at +15°C to 100% at +25°C. Cooling of the motor is carried out by natural convection from the outer surface of the stator and the action of the gear structure of the disk rotor located inside the machine. Thus, the heat transfer coefficients on different structural elements will not have the same values.

III. THERMAL ANALYSIS OF THE TFM MODEL AND THE METHODOLOGY OF ITS RESEARCH

The transient thermal analysis the 3D model for the TFM-200/32 motor was conducted using the finite element method using the COMSOL Multiphysics software. The model itself was created in a specialized CAD program and then imported into COMSOL Multiphysics. The selection of design properties and their corresponding parameters was set from the program's built-in material database: heat capacity at constant pressure, density, thermal conductivity [23].

Simulating the heating of the entire motor requires significant computational power. Therefore, to simplify the calculation model, only 1/8 of the motor model can be used, as the stator is symmetrical. To apply this simplification, a symmetry condition is set in the planes of the cut, assuming no heat flow across the plane of symmetry. Heat transfer coefficients are assigned to all surfaces of the structural elements [23–26].

After specifying the materials and inputting the thermal parameters of the motor design elements and limit requirements, the automatic division of the calculation model into tetrahedral elements was carried out. This process is illustrated in Figure 4. The program itself addressed the problem of transient thermal processes for the stator segment of the TFM-200/32 motor.

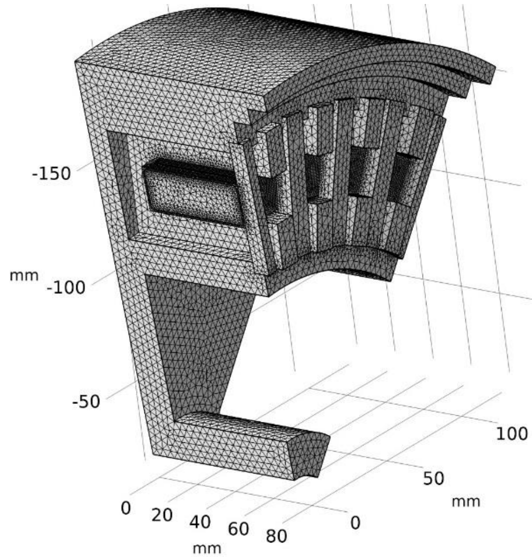

FIGURE 4. **Calculation model with generated mesh (rotor is hidden).**

The results of the calculation of the temperature field of 1/8 part of the stator of the TFM-200/32 motor for the operating mode S1 are shown in Fig. 5. The main source of heat generation in the TFM-200/32 is the coil, which consequently reaches the highest temperature of 93°C. This statement is supported by both simulation results and experimental data. According to the simulation, the average temperature of the permanent magnets does not exceed 78°C. However, during the experiment conducted on the operating motor, temperature measurements on the surface of the magnets were not taken, as they are located on the rotating rotor, making it difficult to measure their temperature.

Non-stationary thermal calculation allows for obtaining temperature rise diagrams of each motor design element over time. Thus Fig. 5 shows the temperature rise of the stator coil in different parts of the coil.

To validate the obtained results, an experimental study of the motor's heating was conducted. The TFM-200/32 was connected through the control system and operated under load for an extended period, with the current in the coil maintained consistently at 11 A. Temperature measurements were taken using a thermal camera. In addition to capturing the overall temperature distribution, the thermal camera allows up to three specific points for direct temperature measurement. Numerous temperature measurements were carried out. Figure 6 shows the experimental results with measurement points placed at different locations along the coil. The figure clearly illustrates the uneven temperature distribution along the coil.

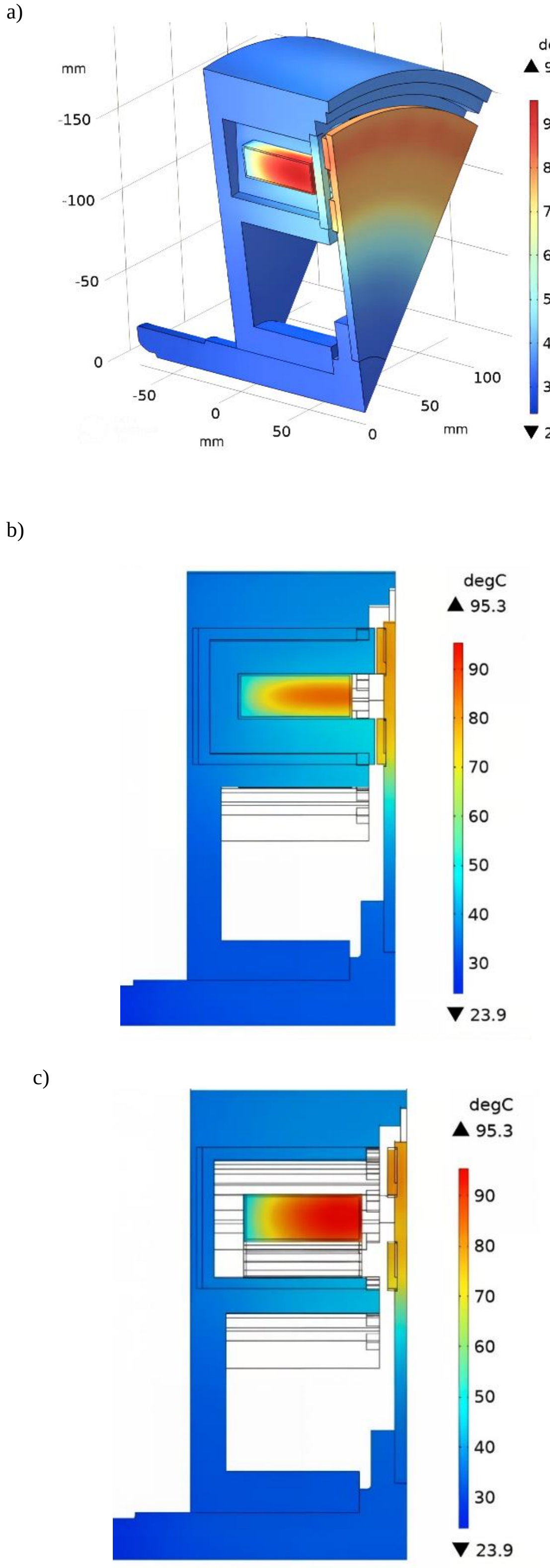

FIGURE 5. **Pattern of TFM-200/32 motor temperature field:**
a) – 3D model view;
b) – cross section in the middle of the U-shaped core;
c) – cross section between U-shaped cores.

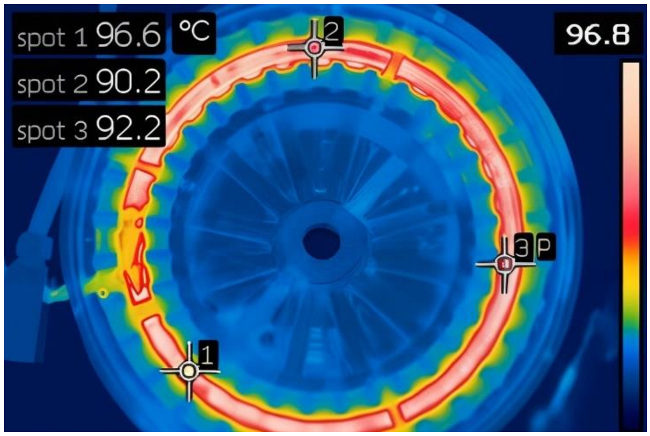

FIGURE 6. **Temperature distribution of the stator coil in TFM-200/32.**

Average temperature values of each element of the structure and comparison with experimental data are summarized in Table III.

TABLE III
RESULTS OF CALCULATION

Motor part	Average temperature, °C		Relative error, %
	Modeling	Experiment	
Coil	92	93	1
U-core	50	47	6
I-core	52	48	8
Body	48	43	9
Permanent magnets	78	–	–

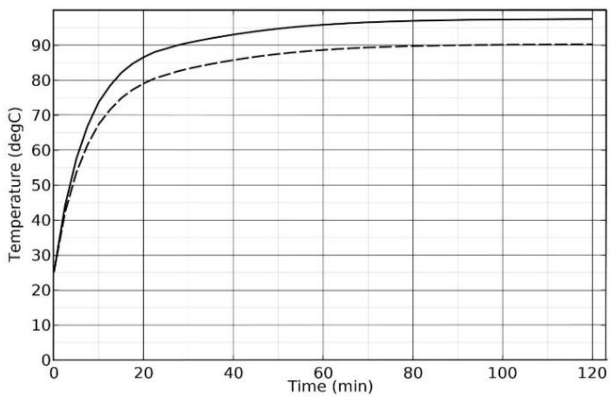

FIGURE 7. **Stator coil heating diagram:**
– part of the coil between U-shaped cores;
- - part of the coil under U-shaped cores.

The obtained values for the heating of the stator coil and the outer surface of the body were compared with experimental data, and the relative error was calculated based on these comparisons. As indicated in Table 4, the relative error in modeling the thermal state of the TFM-200/32 motor is no

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more than 9%. This falls within an acceptable range for the engineering design of electrical machines.

Upon analyzing the data presented in Figure 5, it is evident that the stator coil experiences differential heating. This temperature variation is further illustrated by the temperature field pattern plotted in a plane running along its mean diameter parallel to the rotor, as depicted in Figure 7. For comparison of the obtained results, Figure 8 shows the temperature distribution captured using a thermal camera. Figure 9 highlights that the section of the coil situated between the U-shaped cores exhibits higher temperatures and more intense heating, with the temperature maximum covering a larger area in the cross-section of the coil compared to the section beneath the U-shaped core.

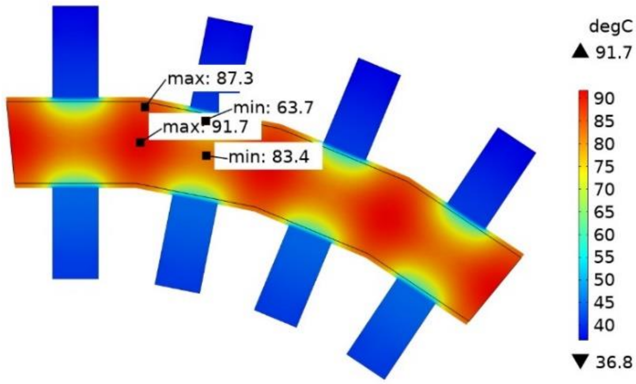

FIGURE 8. Temperature field pattern along the center line of the coil (body not shown).

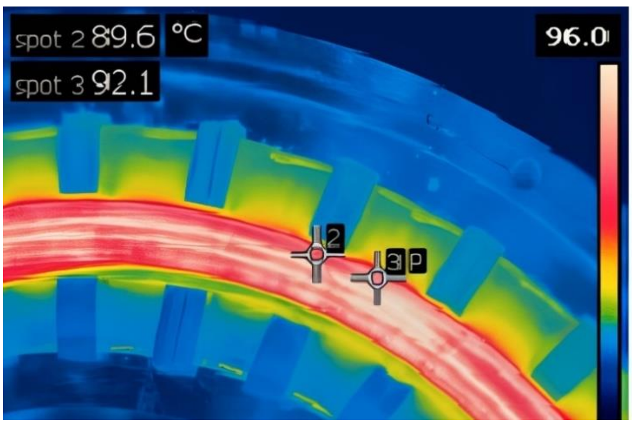

FIGURE 9. Temperature distribution of the stator coil in TFM-200/32.

3D modeling revealed that the part of the stator coil that is situated between the U-shaped cores overheats 7% more than the part directly encompassed by the U-shaped cores. Contact on one side only is not sufficient for complete heat dissipation.

IV. STATOR COIL TEMPERATURE EQUALIZATION

The results of modeling the thermal state of TFM-200/32 motor found that the non-uniformity of the coil contact with the stator cores leads to the formation of local overheating, which negatively affects the dielectric properties of the coil insulation.

The danger of overheating the insulation lies in irreversible thermal aging, which accelerates the degradation of the polymer insulation structure. This, in turn, leads to a deterioration of electrical and mechanical properties, ultimately reducing the service life. It is well known that for every 8–10°C increase in insulation temperature, its lifespan is halved [25]. The motor's insulation system uses F insulation class winding, where a reduction in service life due to operation below 100°C is not a significant issue in practice. The temperature inside the machine is largely determined by the most heated component – the coil. The primary source of heat in the motor is the coil, with the core and magnets contributing to a lesser extent. These power losses contribute to heating the air inside the motor.

It is important to note that the operating conditions of the motor do not allow direct contact between the internal air and the external environment, as the machine is sealed and not ventilated. Eddy currents generated in the permanent magnets are a source of power losses as well, leading to their heating. However, when analyzing the thermal state of the permanent magnets, the temperature of the surrounding environment, in this case, the air inside the sealed machine, must also be considered.

As a result, the heating of the permanent magnets occurs not only due to their own power losses but also due to the additional heat transferred from adjacent structural elements. These elements, in turn, also heat up, creating a complex, interconnected system of heat transfer.

Thermal calculations showed that the permanent magnets heat up to 78°C, which is close to the maximum allowable operating temperature (80°C) for this type of magnet used. Thus, reducing the temperature of the coil directly impacts the overall temperature inside the machine, which, in turn, leads to a decrease in the heating of the permanent magnets. Ultimately, controlling the coil temperature becomes a key factor in managing the temperature of the entire machine and preventing excessive heating of the permanent magnets, which could negatively affect their performance and service life.

The TFM-200/32 features a unique design, where magnetic shunts are placed between the poles. However, due to the internal layout of the machine, a significant amount of free space is created, limited by the poles and shunts. As a result, the coil only makes contact with the U-shaped cores on 30% of its surface, creating a problem of insufficient heat dissipation to the motor housing. The increase in temperature inside the machine is inevitable, which is especially critical when using permanent magnets of type N38, which are limited to an operating temperature of 80°C.

Using more heat-resistant PMs could solve the problem, but it would significantly increase the cost of the motor. Therefore, the optimal solution is to keep the PMs N38 type while using thermal paste to improve heat dissipation and prevent PMs and machine overheating in general.

The motor design contains elements made out of materials with significantly different thermal conductivity and thermal capacity. It is especially manifested in coils that are made out of copper and have poor heat dissipation due to the need to insulate them. Non-circulating layers of air that form air pockets are the worst heat conductor.

The area with non-circulating air can be allocated to the space bounded by the U-shaped cores, coil and body. In Fig. 10 it is shown in green.

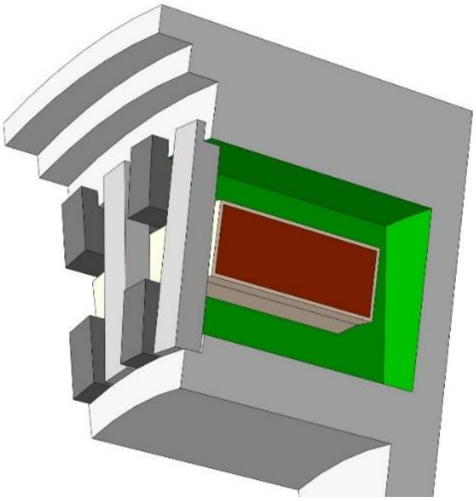

FIGURE 10. Area with non-circulating air.

Thermal conductivity in these areas can be increased in two ways:

– at the design stage provide for a body structure that directly contacts with the coil in the space between the U-shaped cores;

– fill this area with a material with a thermal conductivity coefficient close to the active or structural elements of the motor, e.g. thermal paste.

The first option is the most preferable. However, it causes difficulties in stator assembly.

The advantage of the second option is the possibility of upgrading already finished motors and greater "maneuverability" when assembling new ones.

There are many brands of thermal paste available for both domestic and industrial applications. They all differ in the value of thermal conductivity coefficient, which ranges from 0.5 W/(m·°C) to 80 W/(m·°C), consistency and, most importantly, price. This factor directly affects the cooling efficiency and, naturally, the cost of the material. The higher the thermal conductivity of the thermal paste, the more expensive it is.

A thermal conductive paste KPT-8 [27], which is a heat-resistant white mass with a thermal conductivity coefficient of at least 0.7 W/(m·°C) at 20°C, was used for modeling and analyzing the effect of filling the area with non-circulating air. The paste has a density of 2.6–3.0 g/cm^3. It is inferior in performance to almost all of its competitors but has more than 30 times the thermal conductivity of air.

Additionally, the price of this thermal paste is up to 15 euros per kilogram, making it a very cost-effective option. We need approximately 3.5 kg of material to fill all the cavities between the poles and the motor windings. Therefore, the total cost of the thermal paste is negligible compared to the cost of more heat-resistant PMs and motor itself. Choosing the KPT-8 thermal paste with a thermal conductivity of 0.7 W/(m·K) is the optimal solution, offering a balance between economic efficiency and high performance. We expect this thermal paste to achieve the desired results at minimal cost, making it an ideal solution for our needs.

The selection of KPT-8 thermal paste was based on a balance between economic feasibility and performance requirements. While the paste's thermal conductivity of 0.7 W/(m·°C) is lower than that of premium alternatives, it is substantially higher than that of air (approximately 0.03 W/(m·°C)), making it effective in addressing the specific issue of non-circulating air pockets within the stator. The paste's low cost (15 euros per kilogram) ensures scalability for practical applications without significantly increasing production costs. Furthermore, the material demonstrated sufficient durability and stability under operational conditions during experimental validation, confirming its adequacy for achieving a 10% reduction in coil temperature. The choice reflects a deliberate trade-off, prioritizing cost-effectiveness while meeting the thermal management requirements of the motor design.

The result of modeling of 1/8 part of stator of TFM-200/32 motor for continuous operation with areas with non-circulating air filled with thermal paste is shown in Fig. 11 (for clarity the cross sections in the 3D model are shown, and the body is not shown).

As can be seen from the modeling results, the use of thermal paste in the area bounded by the U-shaped cores, coil, and body, allows for equalizing the temperature of the stator coil. In addition, due to better heat dissipation, there was a decrease in the maximum value by almost 10%. This results in the elimination of local overheating and increased coil reliability for the selected insulation heat resistance class.

The simulation results showed that the temperature of the permanent magnet decreased by 8°C due to the reduction in the maximum temperature of the winding. This decrease in winding temperature was made possible by the equalization of thermal distribution achieved with the application of thermal paste in areas with no air circulation. Thus, the thermal paste played a key role in optimizing the thermal conditions, promoting a more even temperature distribution and, consequently, reducing the maximum temperature of the permanent magnets, preventing it from reaching critical levels.

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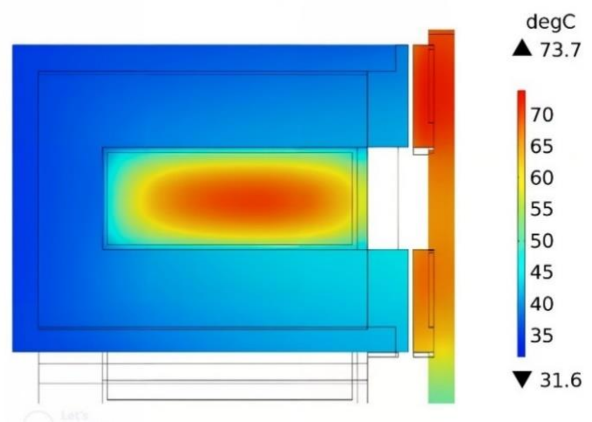
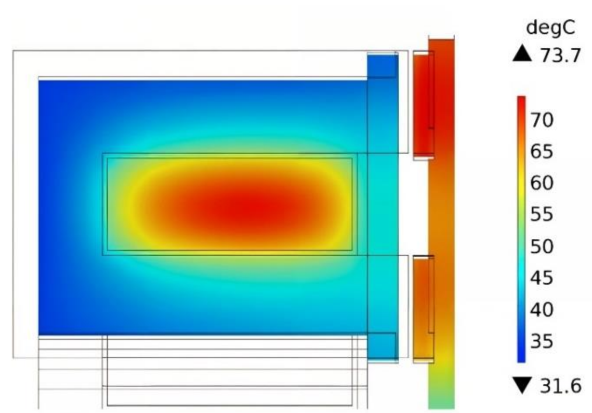
a)



b)



c)

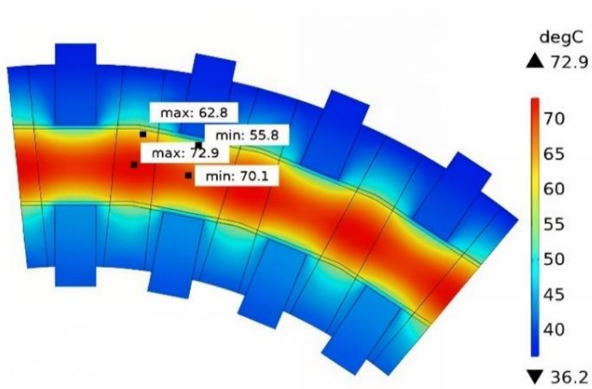


FIGURE 11. **Temperature field pattern of TFM-200/32 motor with thermal paste:**
a) – cross section in the middle of the U-shaped core;
b) – cross section between U-shaped cores;
c) – centerline cross section of the coil.

V. CONCLUSION

The modeling results of the thermal condition of the transverse flux motor reveal non-uniform heating of the stator coil. This non-uniformity arises because only a part of the coil is in direct contact with the cores. Having contact on just one side is insufficient for complete heat dissipation, leading to a 7% higher overheating in the segment of the coil between the U-shaped cores compared to the part directly encompassed by the U-shaped core.

The study highlights that local overheating can degrade key dielectric properties of the coil insulation, including its dielectric strength, volume resistivity, and permittivity. Dielectric strength, critical for preventing breakdown under high voltage, diminishes as thermal aging accelerates the deterioration of polymer chains within the insulation. Volume resistivity, which impacts the insulation's ability to prevent leakage currents, decreases due to microstructural changes caused by sustained high temperatures. Additionally, permittivity fluctuations can alter the insulation's capacitance, adversely affecting the motor's electromagnetic behavior. The observed uneven heating, with a 7% higher temperature in regions between U-shaped cores, underscores the need to equalize thermal distribution to preserve these properties. By reducing maximum coil temperatures by 10% with thermal paste, the proposed solution significantly mitigates risks associated with insulation degradation, enhancing long-term reliability.

Thus, the use of thermal paste proved to be an effective method for reducing the temperature in the winding and, consequently, the maximum temperature of the permanent magnet. The application of thermal paste helped equalize the thermal distribution, especially in areas with no air circulation, allowing for the optimization of the motor's thermal condition and preventing the permanent magnets from reaching critical temperature levels.

While the study focuses on low-speed gearless transverse flux motors (TFMs), the insights into managing non-uniform heating and optimizing thermal performance have broader implications. The proposed approach of thermal modeling and the use of thermal paste to mitigate localized overheating can be adapted to other electric machine designs with similar challenges, such as high-torque motors in robotics, renewable energy systems, and direct-drive mechanisms. These machines also encounter thermal inefficiencies due to constrained cooling paths or geometric limitations. Furthermore, the cost-effective thermal paste solution demonstrates potential for scalability in various industrial applications where high-performance, low-cost thermal management is a priority. Future research will explore how these methods can be customized for other machine types, broadening the applicability of the findings to diverse electric drive systems.

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