MJSAT

Malaysian Journal of Science and Advanced Technology

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Influence of Insulating Materials in Switched Reluctance Machine

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KEYWORDS

Thermal propagation
Switched reluctance machine
Insulated and non-insulated coils,
FEMM Software

ARTICLE HISTORY

Received 29 September 2025
Received in revised form 25 February 2025
Accepted 9 March 2026
Available online 27 March 2026

ABSTRACT

Switched Reluctance Machines (SRMs) are increasingly used in industrial and automotive systems due to their simple design, robustness, and cost-effectiveness. Their performance and reliability, however, are strongly affected by thermal behavior, which can limit efficiency and service life. This paper investigates the role of insulating materials in thermal management of SRMs through modelling and numerical simulation. A thermal model was developed to represent heat transfer by conduction, convection, and radiation, considering the geometry and material properties of the machine. The approach was validated using FEMM 4.2 under steady-state operating conditions. Three cases were examined: without insulation, with polystyrene, and with plaster. The results indicate that the windings experience the highest thermal stress and represent the most critical region of heat accumulation. Introducing polystyrene as an insulating material significantly reduces winding and stator temperatures, leading to a more uniform thermal distribution across the machine. In contrast, plaster has little to no effect on the thermal behavior. These findings highlight the key role of insulation in improving heat dissipation and reducing hot spots in SRMs. Optimized thermal design through appropriate material selection can enhance energy efficiency, extend service life, and improve reliability in demanding industrial environments.

1. INTRODUCTION

Switched reluctance machines (SRMs) are attracting increasing interest in engineering and industry. They have gained popularity, particularly thanks to their use in sectors such as electric automobiles, renewable energy, and automated systems. This machine consists of the following components (see Figure 1):

- The stator: consists of a rolled steel core organized into poles, and windings inserted into the slots of the core [1].
- The rotor: is generally made of soft iron and has specially designed projections (or poles) to create a variation in reluctance in the magnetic circuit.
- The air gap: This is the air space separating the rotor from the stator [2].
- Electronic commutation system: To control the machine, an electronic system is used to manage the power supply to the windings based on the rotor position.
- Enclosure and supports: The mechanical structure includes the casing.

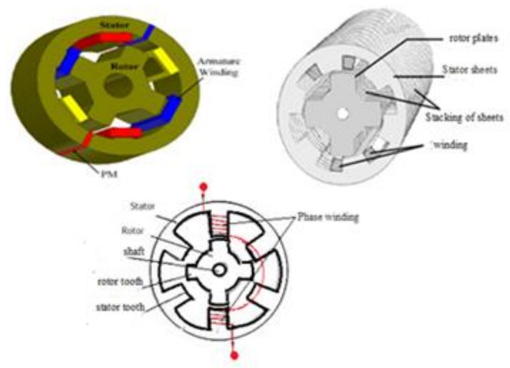

Fig. 1. Stacking of the magnetic circuit sheets and distribution of the winding of a phase

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https://doi.org/10.56532/mjsat.v6i1.626
2785-8901/

SRMs are known for their robustness, manufacturing simplicity, and competitive cost. As such, they are increasingly used in a wide range of industrial applications. However, their overall performance is highly dependent on thermal management, which affects not only energy efficiency but also reliability and operational lifespan [3–7].

2. ORIGINS AND EFFECTS OF HEAT IN SRRMS

Heat generation is an unavoidable consequence of converting electrical energy into mechanical motion. In switched reluctance machines (SRMs), this thermal dissipation stems from various sources:

- Mechanical losses, due to friction in the bearings and airflow interactions,
- Electrical losses, primarily from Joule effect in the conductors, slots, and coil heads,
- Ferromagnetic losses, including eddy currents, hysteresis, and other parasitic effects.

These energy losses are not just inevitable they have a direct and tangible impact on the machine's overall performance, reliability, and service life. The main consequences include:

- Degradation of insulating materials,
- An increase in resistive (Joule) losses,
- Diminished efficiency of permanent magnets,
- Heightened mechanical stress and wear .
- Accelerated aging of the system, as even a 10 °C temperature rise can drastically shorten its expected lifetime.

Faced with these challenges, engineers must design effective thermal management strategies. Selecting the right insulating materials suited to the machine's thermal and electrical constraints becomes essential. Poor heat dissipation can limit the allowable current, reduce the available torque, and significantly increase the risk of critical failure [8].

3. MODELING HEAT TRANSFER IN SRMS

Modeling heat transfer in Switched Reluctance Machines (SRMs) involves several key components:

- The mechanism of conduction, convection and radiation, each mechanism is governed by fundamental physical laws such as Fourier's law.
- Thermal capacity, which characterizes how quickly materials respond to changes in temperature.

The modeling technique presented uses advanced numerical approaches (finite elements FEM), allowing to accurately simulate the thermal behavior of SRMs under varied operational conditions.

This theoretical framework is applied practically through simulations performed using FEMM 4.2 software, which allows for the resolution of heat flow problems and a detailed analysis of the thermal performance of the SRMs 6/4 machine.

In this modelling process, each zone of the machine's structure is defined according to its specific heat sources and physical and thermal properties. The machine is divided into distinct regions, integrated into the "structure" or "geometry" modules.

Next comes the meshing process, which involves defining discretization nodes. Regions affected by contact thermal resistance or located near the air gap require finer meshing to ensure greater accuracy in the calculations. Because the geometry must be approximated, an approximation space for the solution is defined based on the mesh.

Once the solution is computed, it can be further analyzed to extract other quantities or performance indicators, depending on the objectives of the study. [9,10]

4. PRESENTATION OF THE MACHINE UNDER STUDY

Our study focused on a double-saliency variable reluctance machine (MRVDS) or more simply 6/4, which means that it has six teeth on the stator (Ns = 6) and four teeth on the rotor (Nr = 4), figure 2. [11, 12].

The double-saliency structure of the DSVM has the advantage of being suitable for high-speed applications, due to the absence of active elements on the rotor, but also for low-speed applications, where an increase in the number of teeth allows for a reduction in rotational speed without requiring additional windings.

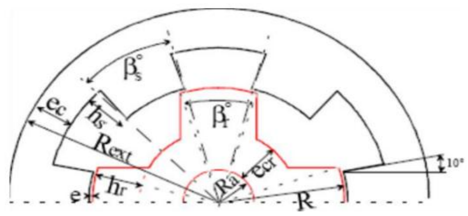

Fig. 2. Definition of the dimensional parameters of the prototype.

The geometric parameters of the machine are shown in the following table:

Table 1. Geometric parameters of the machine

Title	Notation	Dimensions
Number of stator teeth	***Ns***	***6***
Number of rotor teeth	***Nr***	4
Length	***L***	100mm
Outer stator radius	R_{ext}	90mm
Rotor radius	***Rr***	57mm
Air gap	***e***	3mm
Stator tooth height	***hs***	10mm
Rotor tooth height	***hr***	12mm
Shaft radius	***Ra***	15mm
Stator yoke thickness	***ec***	20mm
Stator pole arc	***βs***	14.425°
Rotor pole arc	***βr***	16.13°

5. SRMs Modeling

In the first step, we created the equivalent model of the machine. We then defined the materials for each part, as shown in the figure below (Figure 3), which represents the cross-section of a type 6/4 variable reluctance machine

Fig. 2.Section of a type 6/4 switched reluctance machine

This model cut into finite elements, which we see in the figure below (Figure 4)

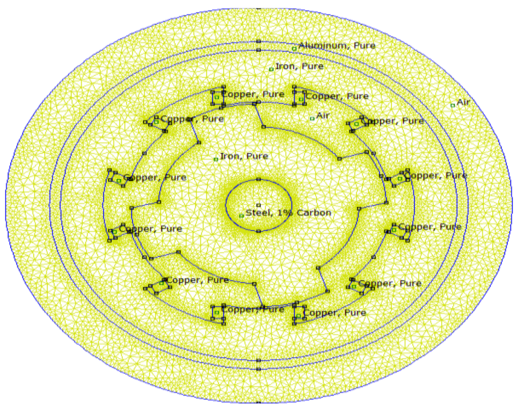

Fig. 4. Cross section of the MRV type 6/4

6. Results and Discussion

First, we consider uninsulated coils to observe their thermal behavior without the influence of an insulating material. This preliminary step will allow us to establish a baseline for later evaluating the impact of insulation on heat dissipation and conductor temperature stability. The objective is to identify the critical parameters influencing winding heating and to optimize the choice of insulation for improved system reliability [13].

6.1 Non-insulated winding

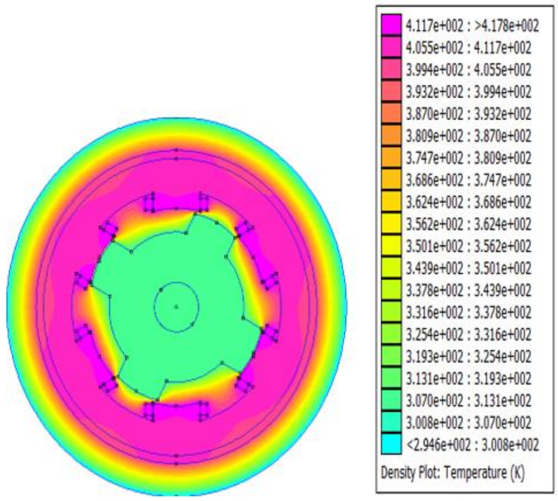

Fig. 5. Temperature propagation in an MRV (without insulation).

Table2 illustrates the evolution of the average temperature in steady state for a winding without insulation, in the different elements of the machines, according to the results obtained using the FEMM 4.2 software

Table 2 The evolution of the average temperature in steady state (without insulation)

Number	Region	Temperature (K)
1	Windings	417.8
2	Stator Teeth	411.7
3	Stator Yoke	405.5
4	Case	401.4
5	Air Gap	395.7
6	Rotor Teeth	325.4
7	Rotor Yoke	319.3
8	Shaft	313.1

These values in Table 2 show a decreasing thermal gradient from the winding to the outside of the machine. The windings naturally have the highest temperature, being the main source of Joule losses. The thermal proximity of the stator teeth (411.7 K) and the stator yoke (405.5 K) indicates good thermal conduction to the ferromagnetic structure of the stator. The air gap, although a poorly thermally conductive medium, partially transmits heat to the rotor, as evidenced by the temperatures measured in the teeth and the rotor yoke (325.4K and 319.3K respectively). The lower shaft temperature (313.1 K) suggests a gradual dissipation of heat to the peripheral areas of the machine [15].

6.2 Insulated Winding

In this second experiment, specific insulating materials are incorporated around the windings. This step aims to evaluate the impact of the insulators on thermal management and temperature distribution within the machine, by comparing the results obtained with those of the first phase without insulation.

First, plaster was chosen as the insulating material due to its advantageous thermal and electrical properties. Polystyrene was then used as a second insulator to further this comparative study because it has high electrical resistivity, essential for ensuring effective insulation of the coils under high electrical stress [16].

1) Use of plaster as an insulator:

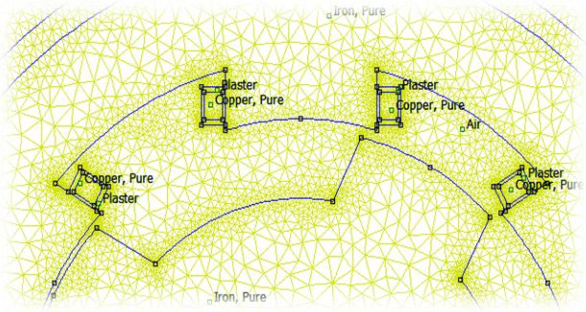

Fig. 6. Cross section of the MRV with insulated windings (plaster).

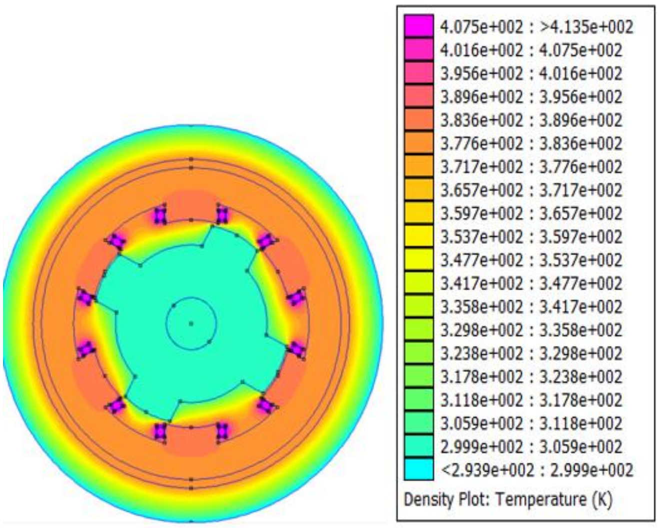

Fig .8. Cross section of the MRV with insulated windings polystyrene)

Table 3 illustrates the evolution of the average temperature in steady state for an insulated winding, in the different elements of the machines, according to the results obtained using the FEMM 4.2 software

Table .3. The evolution of the average temperature in steady state (with plaster).

Number	Region	Temperature (K)
1	Windings	413.5
2	Stator Teeth	383.6
3	Stator Yoke	380.6
4	Case	377.6
5	Air Gap	371.7
6	Rotor Teeth	310
7	Rotor Yoke	305.9
8	Shaft	300.1

Adding a layer of plaster results in a slight decrease in the winding temperature, from 417 K (without insulation) to 413K. This reduction, on the order of 4 K (≈ 0.96 %), remains relatively small. It is explained by the thermal conductivity of the plaster (0.3 to 0.5 $W \cdot m^{-1} \cdot K^{-1}$), which remains sufficiently high to allow heat transfer.

Thus, although the plaster introduces additional thermal resistance, this is insufficient to significantly alter the overall thermal behavior of the system, which is dominated by other heat dissipation pathways.

Plaster has adequate insulating capacity, reducing heat dissipation to the outside, but its thermal conductivity remains sufficient to allow some heat evacuation from the windings.

2) Use of Polystyrene as an Insulator.

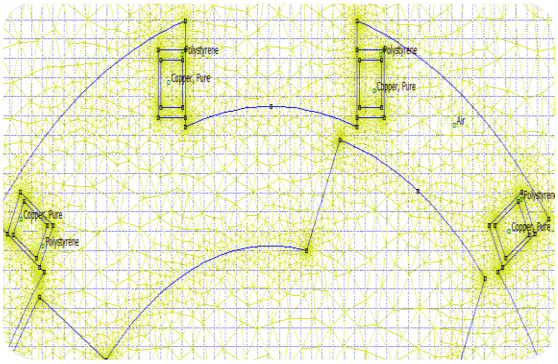

Fig. 7. Temperature propagation in an MRV with insulation (plaster).

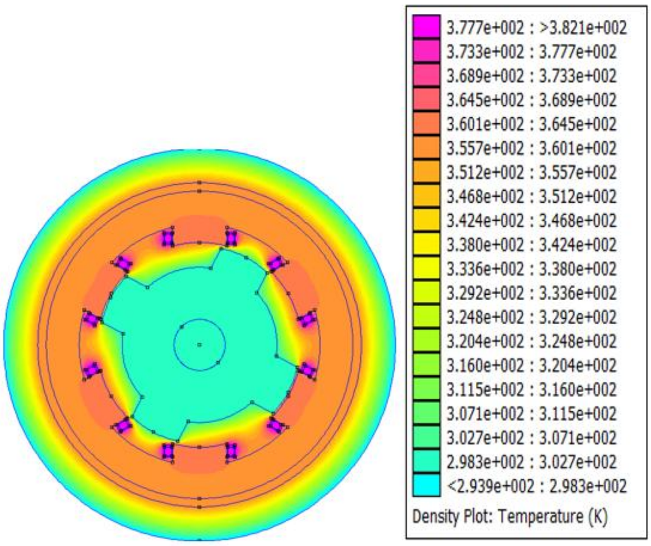

Table4 illustrates the evolution of the average temperature in steady state for an insulated winding, in the different elements of the machines, according to the results obtained using the FEMM 4.2 software.

Table 4. the evolution of the average temperature in steady state (with polystyrene)

Number	Region	Temperature (K)
1	Windings	382.1
2	Stator Teeth	364
3	Stator Yoke	360
4	Case	355.7
5	Air Gap	351.2
6	Rotor Teeth	302.7
7	Rotor Yoke	300
8	Shaft	298.3

7. Conclusion

This study highlights the need to develop a reliable thermal model for predicting and controlling overheating risks in switched reluctance machines, which may affect their performance and durability. The results show that the insulating properties of materials directly influence the overall thermal resistance and, consequently, the efficiency of heat dissipation, emphasizing the importance of careful material selection in machine design. Steady-state simulations enabled the quantification of heat flux distribution across the different components, while transient analysis provided insight into the time evolution of temperature under various load conditions. Future work will focus on improving meshing strategies, experimental validation of the model, and the investigation of advanced insulating materials to further enhance thermal management. Moreover, in a 6/4 switched reluctance machine, polystyrene, due to its very high electrical resistivity compatible with high insulation classes (F or H), effectively limits leakage currents, maintains the dielectric integrity of the windings, and reduces the risk of partial discharges in critical stator regions, thereby improving overall reliability under severe operating conditions.

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