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Thermal Investigation of a Switched Reluctance Motor

A. Pavan
School of Mechanical and Building Sciences VIT University Chennai, India

Sathyanarayanan N
School of Electrical Engineering VIT University Chennai, India

Rajesh Kumar R
Research Department CD-Adapco Bengaluru, India

N.C. Lenin
School of Electrical Engineering VIT University Chennai, India

Sivakumar R
School of Mechanical and Building Sciences VIT University Chennai, India

Abstract

The purpose of this paper is to observe the heat distribution inside the Switched Reluctance Machine (SRM) through Computational Fluid Dynamics (CFD). Electromagnetic losses such as copper and core losses are considered as the heat sources in the machine. Initially, a three dimensional (3-D) steady state thermal analysis is carried out to determine the film coefficient of machine parts. Further, a transient thermal analysis is performed to predict the temperature rise. From the transient analysis, heat distribution for the given speed and time taken to reach the steady state are observed.

Keywords— computational fluid dynamics; switched reluctance motor; thermal analysis; flow analysis; core loss; copper loss

I. INTRODUCTION

Nowadays the attention towards the energy saving electrical machines has increased. Switched reluctance machines are most popular and have been generating attention of electrical researchers due to its robustness, simplicity and low cost manufacturing for the past 3 decades [1]. The losses in SRM originates mainly due to two things; electrical and mechanical. The friction in machine parts and electric currents are the beginnings of heat propagation. Hence the temperature rise in different components of the machine could cause deterioration of insulation in the windings, thermal stress, efficiency reduction and this may contribute to motor failure [2]. Also under high loads, temperature rise influences the motor's electrical and magnetic parameters. It is thus necessary to keep the temperature of the machine components within permissible bounds for safety performance. Due to this, thermal analysis plays prominent role in the analyses of electrical machines [3]. There are two basic types of thermal analysis of electric machines: Analytical lumped-circuit and numerical methods. To design energy saving electrical machine, numerical methods are the most prominent technique. There are several packages of numerical methods to perform thermal analysis such as Finite element analysis (FEA), Motor-CAD, CFD etc. Among these CFD is a virtual modeling technique with powerful visualization capabilities which can be used to evaluate the performance of a wide range of applications [4]. This paper presents the CFD based thermal analysis of SRM with steady and transient conditions.

II. DESIGN SPECIFICATION

In SRM, the stator and rotor have salient poles. The machine has six stator poles and four rotor poles which are uniformly placed. The windings are present only in the stator which is wounded around the stator teeth. A 3 phase, 6/4 3-D SRM model is shown in Fig. 1 and the geometric dimensions of the corresponding model is presented in Table I.

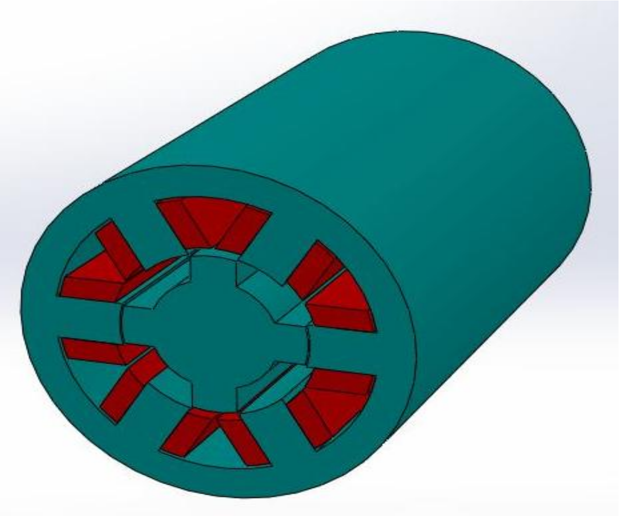

Fig. 1. 3-D Geometric model of SRM

TABLE I. DIMENSIONS OF 6/4 SRM

No of stator Poles	6
No of rotor poles	4
Stator outer diameter (m)	0.055
Rotor outer diameter (m)	0.026
Stack length (m)	0.08522
Air gap length (m)	0.00025

III. NEED FOR FLOW ANALYSIS

The fluid that flows inside the SRM is air. Heat transfer inside the SRM mainly depends on the air velocity. When the rotor begins its rotation, the air inside the SRM is highly turbulent. To investigate the air flow inside the SRM, the air region is split into two areas i.e. the area near to the rotor is taken as rotor air region and the region close to the stator is taken as stator air region. An interface was created in the middle of air gap to interpolate the above two regions. The air gap and the air pockets of SRM is shown in Fig. 2. Air gap means the gap in between the stator and rotor poles. For the given SRM, the rotor is rotating at a speed of 1000 rpm and it is assigned to rotor air regions. To find the air velocity, the flow analysis is carried out for both stator and rotor air regions. The fluid properties shown in Table II are attributed to both stator as well as rotor air regions and a steady state analysis is carried out using STAR-CCM+.

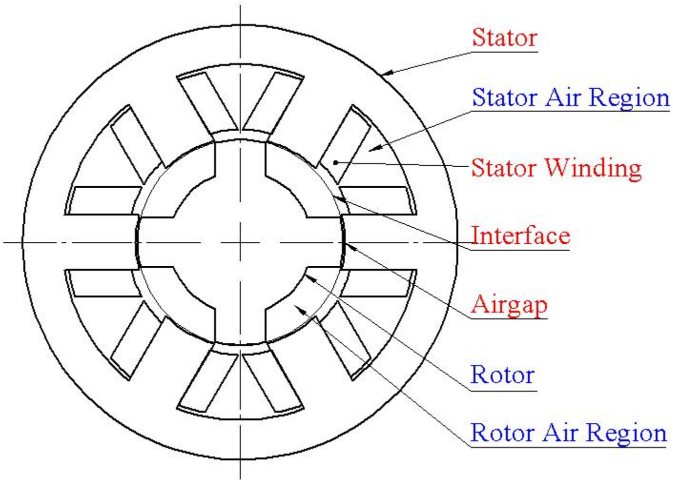

Fig. 2. Front View of SRM

TABLE II. PROPERTIES OF MATERIALS

Material	Thermal conductivity (W/m-K)	Density (kg/m^3)
Air	0.024	1.165
Steel	40	7850
Copper	380	8940

A. *Results of Flow Analysis*

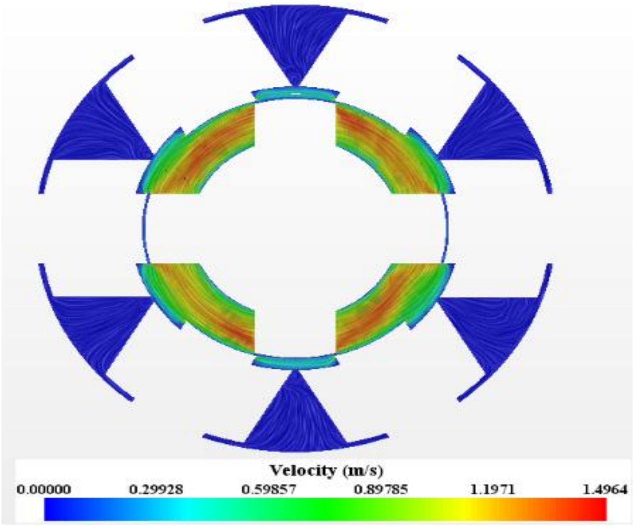

Fig. 3. Velocity distribution in SRM

Figure 3 shows the air velocity distribution inside the SRM for the speed of 1000 rpm. From the simulation results, it is observed that the air velocity at stator and rotor interface is 0.6 m/s. The outcomes of the analysis show higher air speed in the middle of the rotor air region and it is low near to back iron as well as interpolar region. The air flow inside the stator air region is very low due to the flow obstructions by the stator windings. This reduces the convection coefficient on the stator's inner surface area and increases the stator temperature.

IV. HEAT SOURCE

The two primary elements of electromagnetic losses in a motor are copper losses in the windings and core losses in the laminations. These losses are the heat source for the temperature rise. For any motor, the copper loss can be estimated from the formula given in (1). Due to proximity and skin effects, the value of R is greater than the DC resistance. The value of core loss in a separated conductor depends on the proximity of the conductor to the steel core. In addition, the magnetic field created by a single conductor influences other conductors [5]. This is known as proximity effect. Considering the above effects, the expression for the calculation of core losses in the SRM is given as in (2).

$$Core\ loss = I^2 R \tag{1}$$

Where
I = Rms Average Current (Ampere)

R = Effective resistance of one phase winding (Ohm)

$$\begin{aligned} &Total\ \ loss = Copper\,loss + Core\ \ loss \\ &\qquad\qquad Mechanical\,losses\,(watts) \end{aligned} \qquad (2)$$

The specifications of SRM along with core and copper losses are presented in Table III.

TABLE III. SPECIFICATIONS OF 6/4 SRM

Rotational Speed (RPM)	1000
Average Current (Ampere)	6
Copper loss (watts)	57.15
Core loss (Watts)	18.376

V. STEADY STATE THERMAL ANALYSIS

In steady state analysis, conduction heat transfer with different boundary conditions [5] is obtained from the Fourier law as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \theta}\left(k\frac{\partial T}{\partial \theta}\right)+\frac{\partial}{\partial Z}\left(k\frac{\partial T}{\partial Z}\right)+q=0 \qquad (5)$$

TABLE IV. PHYSICAL DIMENSIONS OF SRM

Area of the coil segment (m^2)	27.68 x10^{-06}
Total coil area (m^2)	332.16 x 10^{-06}
Shaft length (m)	0.08522
Volume of the coil (m^3)	2.83066 x 10^{-5}
Area of the stator (m^2)	1176.6 x10^{-06}
Volume of the stator (m^3)	1.0026 x 10^{-04}

Agreeing to the physical dimensions given in Table IV and from the core and copper losses of the motor, a quantity of heat generated, Q is computed for different parts like stator core and coils as shown in Table V. The material properties, such as thermal conductivity, density, specific heat, etc, are specified for each part of the machine. The ambient temperature was set as 303K and a steady state CFD based thermal analysis were carried out for the given value of Q (W/m3).

TABLE V. QUANTITY OF GENERATION

Heat generation in copper(W/m^3)	Heat generation in Core (W/m^3)
2.019 x 10^7	55322.73

A. *Results of Steady State Thermal Analysis*

Figure 4 shows the temperature distribution of SRM in Steady state condition. From the simulations, the maximum temperature generated inside the machine was found to be 325.3 K. The maximum temperature was generated at coils due to higher copper loss. This heat is transferred to the stator poles through conduction. The stator has a larger volume at the back iron to dissipate the heat received by the stator pole from the coils. Hence the temperature is high at stator pole arc and it is low near the back iron of the stator. In steady state, it is clear that the temperature rise due to copper and core losses depends on the current, flux through the coil and the stator respectively.

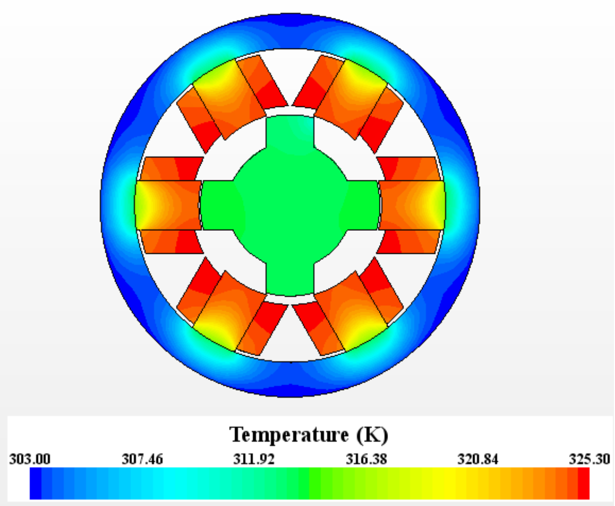

Fig. 4. Steady state temperature distribution.

VI. CONCLUSIONS

The flow distribution and temperature rise in the SRM have been analyzed using 3-D analysis. At 1000 rpm, the velocity at the stator and rotor interface is obtained as 0.6 m/s. The coils are the main source of heat which is present in the stator hence the rise in temperature is maximum in coils and stators. The maximum temperature rise in SRM is 324 K and it is stabilized after 120 s. The result indicates that the flow distribution in stator region is low due to which heat distribution in the stator is high. Whereas, flow of air in rotor region is high thereby heat distribution in this region is very low. Using these results, the weight of materials used and number prototype for testing can be minimized.

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