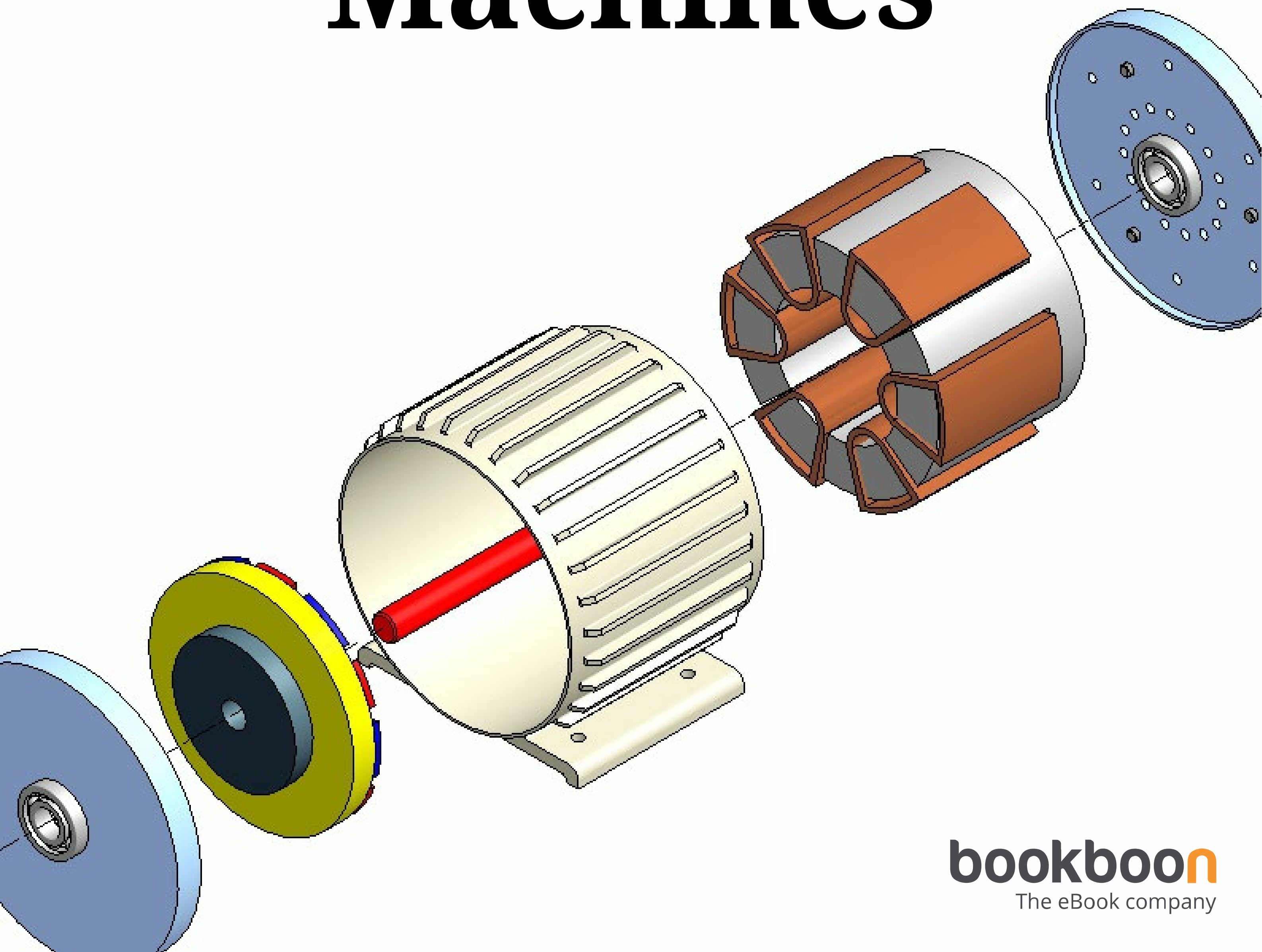
Dr Moez Hadj Kacem; Dr Souhir Tounsi; Pr Rafik Neji

Thermal Modelling of Electric Machines



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THERMAL MODELLING OF ELECTRIC MACHINES

Thermal Modelling of Electric Machines
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CONTENTS

ABSTRACT

This book focuses on the development of a thermal modeling with analytical models for the design of electrical machines. It concerns more particularly machine with permanent magnets. The methods used to determine the critical parameters of thermal modeling are presented first. We then present the complete thermal model that has been developed and confronted with experimental results. This model has very good accuracy and has allowed us to study the effect of different topological variations on the thermal behavior. It was also possible to analyze and compare different cooling strategies. This model can easily be integrated into an optimization process to determine the maximum permissible losses of a given configuration, or to define the cooling method to use. Based on the same principles, we proposed a new model to simulate the thermal exchanges between the conductors in the slots. This model allows us to appreciate the randomness of the arrangement of the conductors in the coil. It can be paired with a more comprehensive model of the machine in order to refine the resolution of the latter and ensure a more accurate analysis of the thermal behavior of the coils.

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GENERAL INTRODUCTION

Permanent magnet synchronous machines (PMSM) gain more and more importance for special drive applications. Up to recent years, PMSM were known for small drives, e.g. for servo applications. In the last years, PMSM are increasingly applied in several areas such as traction, automobiles, etc. Therefore, development of different machine types requires attention to the thermal aspects since, at the end; it is always the thermal constraints that will determine the power rating of the machine. To insure a successful design of the electrical machines, it is necessary to be able to predict an accurate temperature distribution in the most sensitive parts of the machine to prevent the damages that can occur either by breakdown of the stator winding insulation or by the demagnetization of the magnets. Knowledge of thermal behavior in different situations can prevent overheating, but can also improve the utilization of the system at normal operation.

As is known, different calculation methods can be used to analyses the thermal behavior of electrical machines: exact analytical calculation ("distributed loss model"), numerical analysis, and the lumped-parameter or nodal method ("concentrated loss model"). Compared with other methods, the lumped-parameter thermal method is simple and attractive which can give accurate representation of the thermal conditions within the machine. This method has been used for a long time by many authors for calculation of the temperature rises in electric machines, which solves the thermal problems by applying thermal networks in analogy to electrical circuits. Generally, the lumped-parameter thermal model is composed of thermal resistances, thermal capacitances and power losses inside the system. Such a model is based on the hypothesis that the system, under the thermal point of view, can be divided into several parts that are connected to each other by means of thermal resistors and capacitors. In the equivalent thermal network, all the heat generation in the component is concentrated in one point. This point represents the mean temperature of the component. In many literatures [1, 2], during calculation of thermal characteristics using the lumped-parameter method, as heat generators are taken the corresponding power losses in the components. In spite of being popular, generally this method is not applied correctly for elements with distributed heat generation. From the thermal analysis presented in [3,4] it is shown that solving the thermal problems with this method leads to wrong results if the total power losses are taken as heat sources in the thermal network (conventional lumped-parameter method). In the past, this systematic mistake was unknown, but intrinsically eliminated by the fitting procedure. Based on the analysis presented in [1, 2], the required change to the conventional lumped-parameter thermal method to omit this systematic mistake is simple, but decisive:

* Calculating a single lossy element, half of the losses should be applied as heat generator source,
* Calculating a more complex system composed of more than one lossy element, compensating elements have to be introduced into the lumped-parameter thermal network,
* Transient calculations can easily be developed from the described steady state analysis.

1 THERMAL CHARACTERIZATION METHOD OF THE ELECTRIC MOTORS

1.1 INTRODUCTION

The usage of electric drive systems in vehicles has undergone a rapid increase of popularity for some time now and is here to stay. One area where efforts are being directed at technical improvements is the bridge between the electrical and the thermodynamic aspects of electric machines. There are potential benefits to draw from knowing more about the behavior and the effects of the heat that is generated in the machine during operation.

It is of great importance to make sure that its temperature does not reach levels above what is tolerable, especially for sensitive parts such as permanent magnets and winding insulation. For machines used in environments where cooling is an especially challenging task, which is the case for electric vehicles, this understanding is perhaps of even greater importance.

1.2 PROBLEM DESCRIPTION

The thermal limits set the constraints of the machine. Go beyond them and you will decrease the life time of the machine. Do not go near them, and some of the potential of the machine is wasted. If the thermal constraints can be taken into account at an early stage in the optimisation process of the machine design, it is possible to achieve a more homogenous temperature distribution and avoid hot spots in the machine. The information could be useful for improving the overall design in terms of efficiency, torque/power density, overload time capability [5], and requirements on the cooling.

Having a good knowledge of the actual levels means being able to design without having to resort to unnecessary large safety margins, which are usually costly.

A number of existing publications describe different aspects of the thermal modelling of electric motors. On synchronous machines with interior magnets however, it has not been written much. Having a detailed model opens up for a lot of possible questions to be investigated. A closer investigation of the modelling of an IPMSM is of particular interest, as it is the type of electrical motor used in the new Electric Vehicle (EV).

The models should be parametric, and the parameters swept within reason- able intervals based on the uncertainty of and sensitivity to the parameter in question. From this data, the most relevant parameters should be identified, and thus criteria for thermal aspects of designing an electric drive can be formulated.

The model has been based on a PMSM machine situated at Chalmers, upon which thermal measurements will be carried out in the future. Since the model is parameterised, it is general enough to be applicable for investigating changes for a number of different motor designs.

1.3 THERMAL ANALYSIS AND MANAGEMENT OF ELECTRIC MACHINE

In high-performance applications such as hybrid electric vehicles and aerospace, there is a growing need for electric machines with high torque/power densities. A higher power density can be achieved by applying higher current densities to the electric machine windings and/or running the machine at higher speeds. A high current density in the stator winding results in significant copper losses and, in turn, high hot-spot temperatures [1, 2]. Also, high rotor speeds lead to higher current and voltage frequencies that increase the iron losses in the stator and rotor steel laminations and the permanent magnet segments in permanent magnet (PM) machines. The increase in copper and iron losses may, if the resulting heat is not properly dissipated, cause increased temperatures which may be particularly problematic in parts of the machine that are difficult to cool down (e.g. the rotor).

From the beginning of the twentieth century, considerable efforts have been put on dealing with thermal issues of electric machines [3–6]. In this regard, a considerable amount of work has been carried out on the development of complex cooling systems that effectively extract losses from critical parts of the machine [7–9]. Forced air-cooling has been employed to enhance the heat transfer from the housing fins and often from the end winding and rotor surfaces [12, 13]. However, for high current densities, air-cooling may not be sufficient and some form of liquid cooling is required [11]. A housing water jacket enables an effective heat transfer from the active part of the stator winding to the coolant [14, 15].

However, water-cooling does not provide a successful cooling of the end windings which can be particularly problematic for machines with long end windings, e.g. in machines with low pole numbers. Instead of water, oil may also be used as a cooling medium and different oil cooling methods for electric machinery have been proposed [7, 14–15]. In directly-oil-cooled machines, oil is in direct contact with the inner parts of the machine and an effective cooling of both the stator and the end winding body can be realized. A variety of work has been done and published on improvements in the electromagnetic design of different kinds of electric machines to reduce losses, e.g. the iron losses in the stator and rotor laminations, and eddy current losses in the permanent magnets [13–19]. In order to improve the thermal behavior of electric machines, a good knowledge of heat transfer in different parts of the machine is required. Lumped parameter (LP) thermal analysis and numerical methods are the major approaches proposed to model thermal effects in electric machines [12].

1.4 THERMAL EFFECTS OF USING DIFFERENT IMPREGNATION MATERIALS

In this part, thermal effects of different materials used in electric machines are investigated. The materials considered are the impregnation material, filling the stator slots and the end winding bodies, and the steel laminations used to build the stator and rotor parts of the machine.

In addition to thermal conductivity, the thermal impact of different impregnation materials is also dependent on the quality of the impregnation process, the cooling conditions and the loss levels. A winding impregnation process with high quality results in less air pocket in the impregnation body and a higher rate of heat transfer [20]. Moreover, thermal effects of the impregnation material in machines operating under different cooling conditions and levels of loss production are not identical. In this section, first a comparison between the thermal, electrical and mechanical properties of the studied materials is presented and then thermal effects, considering the above mentioned parameters, are studied.

1.4.1 LAWS GOVERNING MODES OF HEAT TRANSFER

Heat, by definition, is the energy in transit due to temperature difference. Whenever exists a temperature difference in a medium or between media, heat flow must. Different types of heat transfer processes are called modes. These modes are shown in Figure I.1. When a temperature gradient exists in a stationary medium, which may be a solid or a fluid, heat flows under the law of conduction heat transfer. On the other hand if the temperature gradient exists between a surface and a moving fluid we use the term Convection [20]. The third mode of heat transfer is termed Radiation and it needs no medium to transfer through since it is driven by electromagnetic waves emitted from all surfaces of finite temperature, so there is a net heat transfer by radiation between two surfaces at different temperatures.

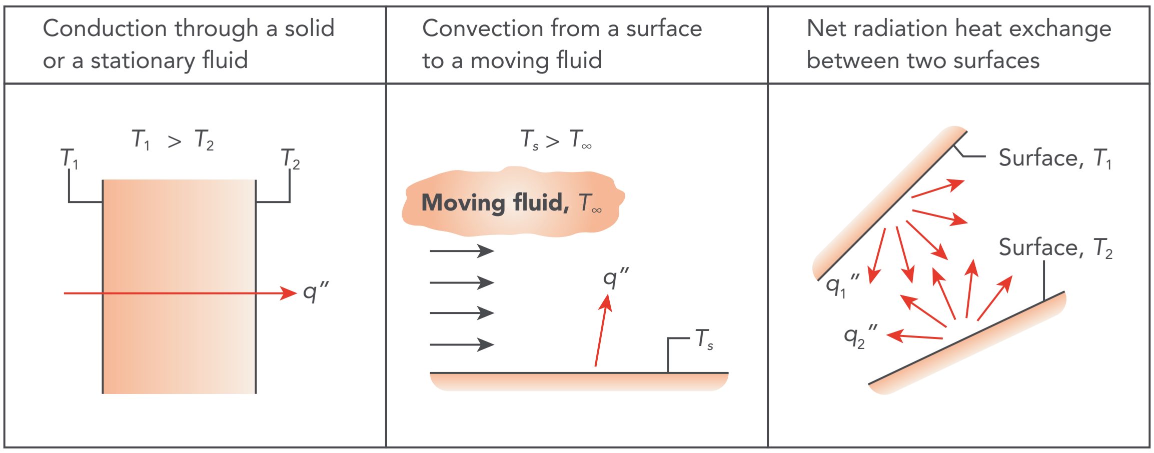


Figure I.1. Conduction convection and radiation modes of heat transfer

1.4.1.1 Thermal conduction

Conduction is the mechanism of heat transfer whereby energy is transported between parts of a continuum by the transfer of kinetic energy between particles or groups of particles at the atomic level [22]. We should conjure up the concept of atomic and molecular activity In gases, conduction is caused by elastic collision of molecules; consider a gas in which there exist a temperature gradient and assume there is no bulk motion. The gas may occupy the space between two surfaces which are maintained at different temperatures as shown in Figure I.2. We associate the temperature at any point with the energy of gas molecules in proximity to the point. This energy is related to the random translational motion as well as to the internal rotational and vibrational motions of the molecules. As shown in Figure I.3. The hypothetical plane at xo is constantly being crossed by molecules from above and below due to their random motion. However, molecules from above are associated with a larger temperature than those from below, causing net transfer of energy in the positive x direction. We may speak of the net transfer of energy by the random molecular motion as a diffusion of energy.

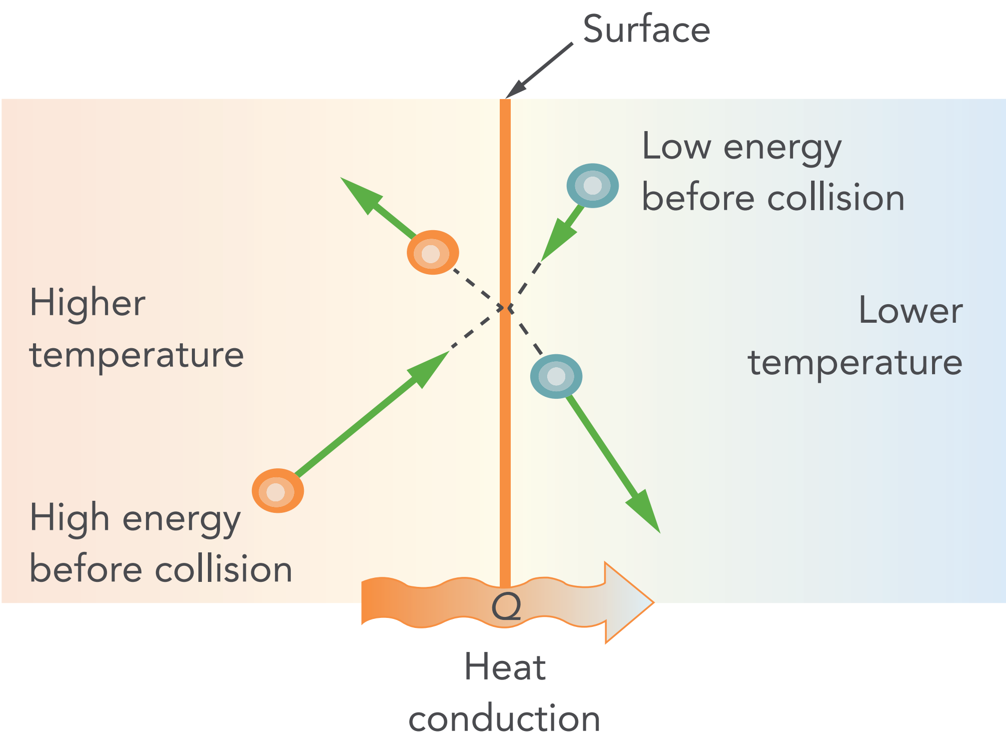


Figure I.2. Conduction heat transfer as diffusion of energy due to molecular activity

In liquids and electrically non conducting solids, it is believed to be caused by longitudinal oscillations of the lattice structure; it is called also lattice waves. Thermal conduction in metals occurs, like electrical conduction, through the motion of free electrons. Thermal energy transfer occurs in the direction of decreasing temperature, a consequence of the second law of thermodynamics. In solid opaque bodies, thermal conduction is the significant heat transfer mechanism because no net material flows in the process [23]. With flowing fluids, thermal conduction dominates in the region very close to a solid boundary, where the flow is laminar and parallel to the surface and where there is no eddy motion. Examples of conduction heat transfer are tremendous. On a summer day there is a significant energy gain from outside air to a room. This gain is principally due to conduction heat transfer through the wall that separates room air from outside air. Also in electronics cooling process conduction is a heat transfer mechanism used in every electronics design. Even if a system is designed for convection cooling of the circuit boards, conduction is still the dominant heat transfer mechanism within the component devices and on the circuit board. This is especially true for power electronics, where concentrations of heat are developed in. components such as power silicon and magnetic. This heat must be transferred via conduction to the component case, the circuit board or a heat sink before it can be handled by the systemlevel cooling mechanism(s). Consequently, all electronics designers must be aware with the techniques of thermal conduction and its analysis.

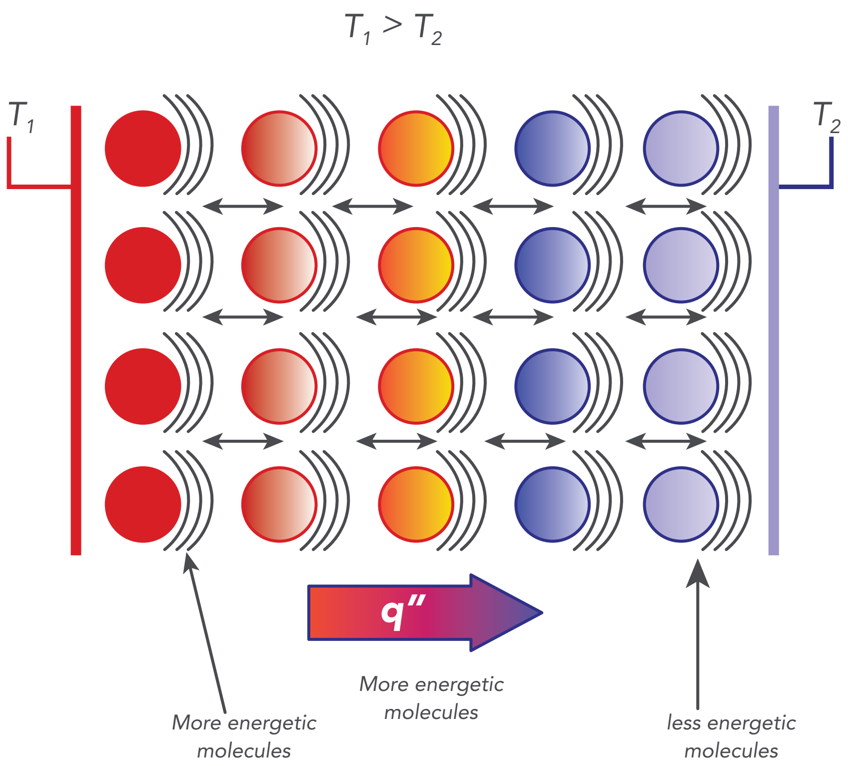


Figure I.3. Conduction in liquids and solids ascribed to molecules vibration (solids), translational and rotational (liquids)

It is possible to quantify heat transfer processes in terms of appropriate rate equations. These equations may be used to compute the amount of energy being transferred per unit time. For heat conduction, the rate equation is known as Fourier's law. Fourier's law is a phenomenological; that is developed from observed phenomena rather than being derived from first principles. The general rate equation is based on much experimental evidence. For the one dimensional plane wall shown in Figure I.4 having a temperature distribution T(x), the rate equation is expressed as The heat flux q" (W/m2) is the heat transfer rate in the x direction per unit area perpendicular to the direction of transfer, and it is proportional to the temperature gradient, dT/dx, in this direction. The proportionality constant k is a transport property known as the thermal conductivity (W/m. K) and is a characteristic of the wall material. The minus sign is a consequence of the fact that heat is transferred in the direction of decreasing temperature.

$$q'' = -k.(dT/dx) \tag{I.1}$$

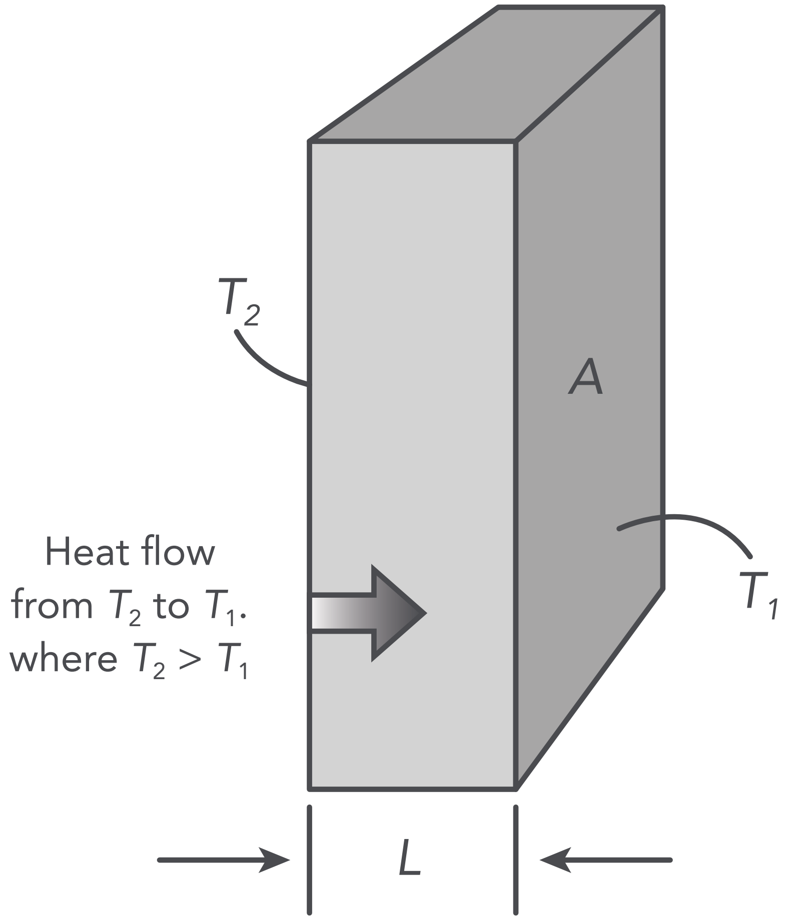


Figure I.4. One- Dimensional heat transfer (diffusion of energy)

Under the steady-state conditions shown in Figure I.4, where the temperature distribution is linear then the temperature gradient may be expressed as

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L} \tag{I.2}$$

And the heat flux is then

$$q''_x = -k\frac{T_2 - T_1}{L} \tag{I.3}$$

Note that this equation provides a heat flux, that is, the rate of heat transfer per unit area. The heat rate by conduction, q_x (W), through a plane wall of area A is then the product of the flux and the area, q_x" = q_x . x A

1.4.1.2 Thermal Convection

This mode of heat transfer involves energy transfer by fluid movement and molecular diffusion. Consider heat transfer to a fluid flowing over flat plate as in Figure I.5.

If the Reynolds number is large enough, three different flow regions exist. Immediately adjacent to the wall is a laminar sublayer where heat transfer occurs by thermal conduction; outside the laminar sublayer is a transition region called the buffer layer, where both eddy mixing and conduction effects are significant; beyond the buffer layer is the turbulent region, where the dominant mechanism of transfer is eddy mixing.

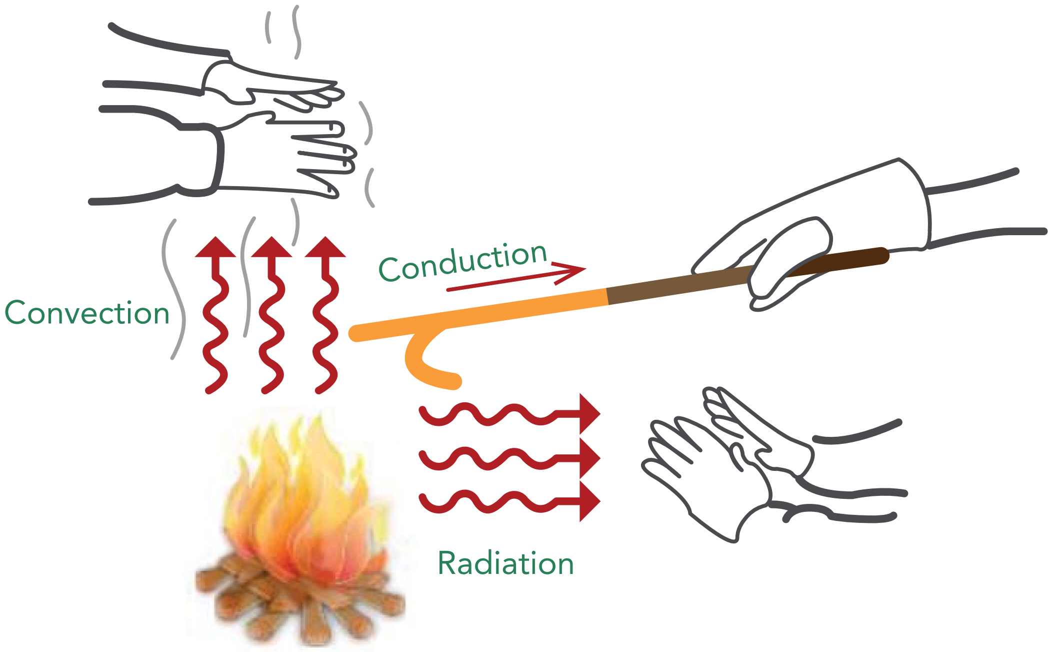
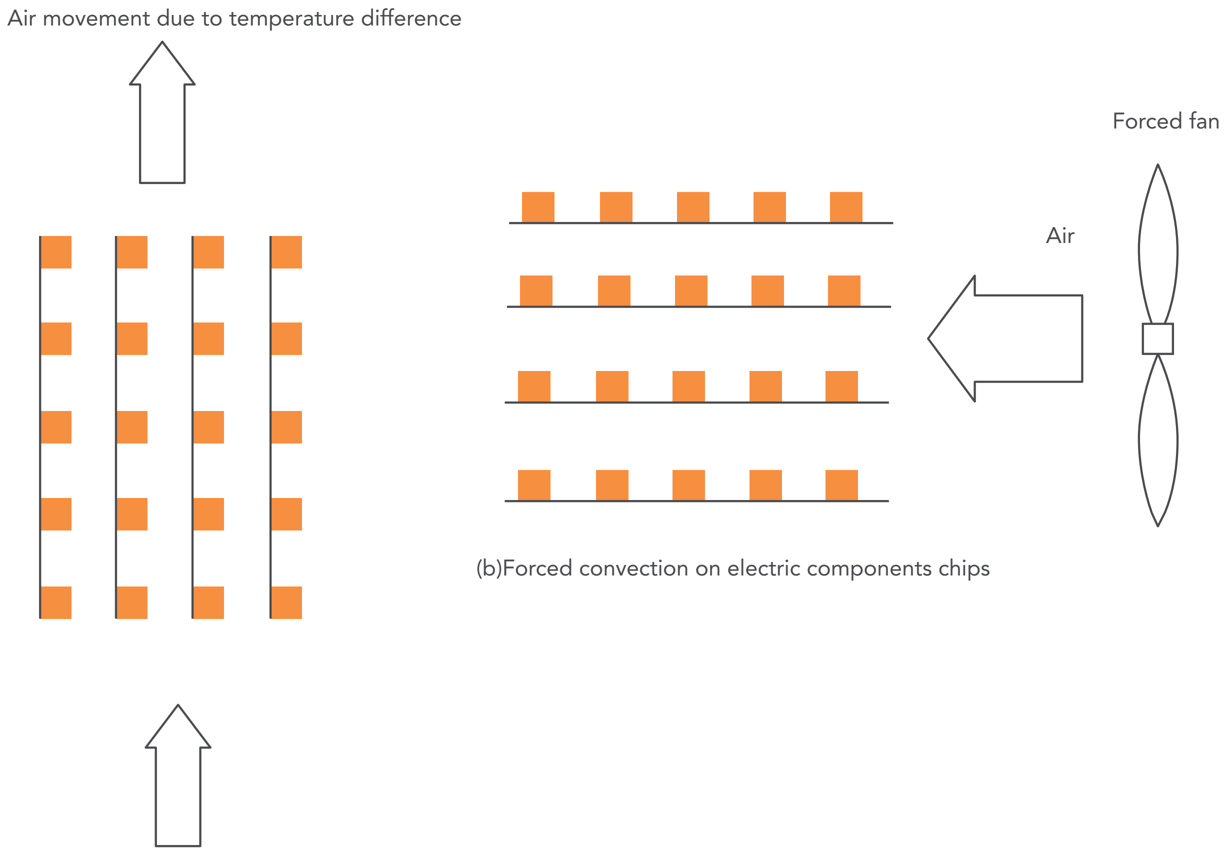


Figure I.5. Thermal Convection

Convection heat transfer may be classified according to the nature of the flow for free or natural convection the flow is induced by buoyancy forces, which arise from density differences caused by temperature variations in the fluid. An example is the free convection heat transfer that occurs from hot components on a vertical array of circuit boards in still air as shown in Figure I.6. Air that makes contact with the components experiences an increase in temperature so that the density is reduced. For a forced convection; the flow is caused by external means, such a fan, a pump, or atmospheric winds. An example of which is the use of a fan to provide forced convection air cooling of hot electrical components on printed circuit boards as shown in Figure I.6.



(a)Free convection on electric components chips

Figure I.6. Free and forced convection

The heat transfer by convection is described by the Newton's law of cooling:

$$q = h.(Ts - Tm) \tag{I.4}$$

Where;
q: Heat transfer rate (W)
h: Heat transfer coefficient ($W/m^2 .K$)
Ts: Wall temperature (K)
Tm: Free stream fluid temperature (K)

The approximate ranges of convection heat transfer coefficients are indicated in Table I.1 for both free and forced convection.

Nature of Flow	Fluid	hc [W/m2 K]
Surfaces in buildings	Air	1 - 5
Surfaces outside buildings	Air	5-150
Across tubes	Gas	10 - 60
	Liquid	60 - 600
In tubes	Gas	60 - 600
	Organic liquid	300 - 3000
	Water	600 - 6000
	Liquid metal	6000 - 30000
Natural convection	Gas	0.6 - 600
	Liquid	60 - 3000
Condensing	Liquid film	1000 - 30000
	Liquid drops	30000 - 300000
Boiling	Liquid/vapour	1000 - 10000

Table I.1: Examples of convection coefficients

1.4.1.3 Thermal Radiation

The mechanism of heat transfer by radiation depends on the transfer of energy between surfaces by electromagnetic waves in wave length interval between 0.1 to 100µm (Figure I.7). Radiation heat transfer can travel in vacuum such as solar energy.

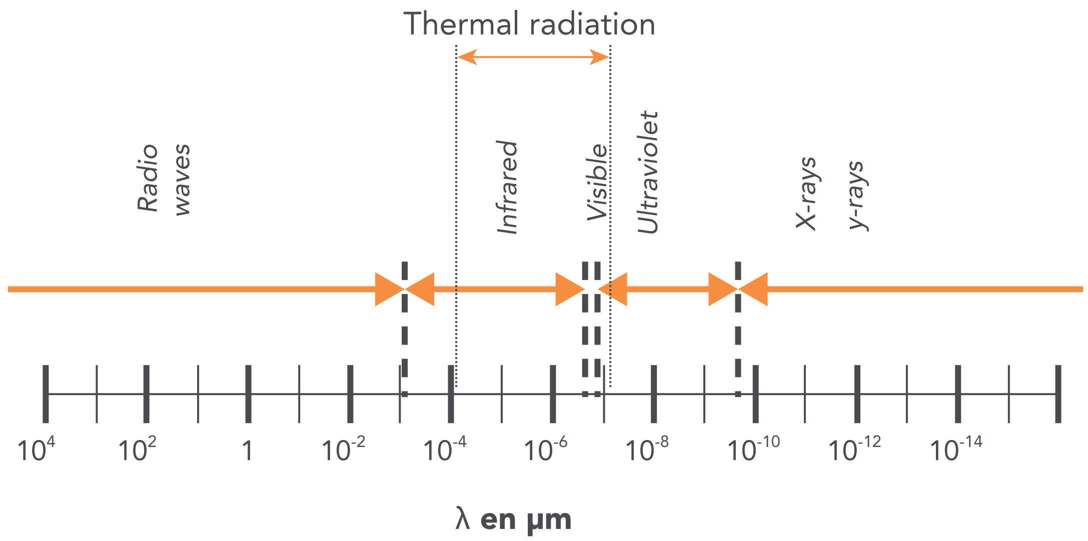


Figure I.7: Subdivisions of the electromagnetic spectrum

Radiation heat transfer depends on the surface properties such as colors, surface orientation and fourth power of the absolute temperature (T^4) of the surface. The basic equation for radiation heat transfer between two gray surfaces is given by:

$$q = \sigma.\varepsilon.f.(T_1^4 - T_2^4)$$

Where: =

- σ: Stefan-Boltzmann constant = 5.67×10-8 $W/m^2.K^4$
- ε: Emissivity of the surface which provide of how efficiently a surface emits energy relative to a black body (no reflection) and it's ranges 0≤ ε ≤1
- *f*: Geometrical factor which depends on the orientation between the surfaces.

1.4.2 THERMAL BEHAVIOR OF MATERIALS

As noted previously, thermal conductivity is a thermodynamic property of a material. From the State Postulate given in thermodynamics, it may be recalled that thermodynamic properties of pure substances are functions of two independent thermodynamic intensive properties, say temperature and pressure. Thermal conductivity of real gases is largely independent of pressure and may be considered a function of temperature alone. For solids and liquids, properties are largely independent of pressure and depend on temperature alone.

Every material used in an envelope assembly has fundamental physical properties that determine their energy performance like conductivity, resistance, and thermal mass. Understanding these intrinsic properties will help you chose the right materials to manage heat flows.

Table I.2 gives the values of thermo physical properties of materials for a variety of materials.

Physical properties	ρ (kg/m^3)	c (J.kg^{-1}.K^{-1})				λ (W.m^{-1}.K^{-1})			
Body	20°C	0°C	20°C	100°C	200°C	0°C	20°C	100°C	200°C
Steel:									
0.5%C……………………………..…	7833	…...	465	…...	…...	55	54	52	48
1.0%C………………………………..	7801	…...	473	…...	…...	43	43	43	42
1.5%C………………………….………	7753	…...	486	…...	…...	36	36	36	36
1.0%Cr……………..………………...	7865	…...	460	…...	…...	62	61	55	52
2.0%Cr………………………………	7865	…...	460	…...	…...	54	52	48	45
0.35%C, 0.75%Mn, 0.35%P, 0.22%Si	……	…...	…...	…...	…...	40	40	38.5	37
Aluminum:									
Pur……………………………………	2707	886	896	936	980	202	204	206	215
3à5%Cu………………………………	2787	…...	883	......	......	159	164	182	194
13%Si…………………………………	2659	…...	871	......	......	163	164	175	185
9%Si, 3%Cu…………………………	2770	…...	960	......	......	......	109	......	......
Copper:									
Pur..	8954	381	383	392	403	386	386	379	374
30%Zn (laiton).....................................	8522	......	125	......	......	......	111	128	144
Iron:									
Pur……………………………………	7897	441	452	489	536	73	73	67	62
0.25%Si………………………………	......	......	......	......	......	......	50		
0.50%Si………………………………	7800	......	......	......	......	......	45		
1.00%Si………………………………	7769	......	460	......	......	......	42		
1.25%Si………………………………	7750	......	460	......	......	......	37		
2.00%Si………………………………	7673	......	460	......	......	......	31		
2.75%Si………………………………	7665	......	460	......	......	......	25		
3.75%Si………………………………	7600	......	......	......	......	......	20		
5.00%Si………………………………	7417	......	480	......	......	......	19		
Melting:									
=4% C ………………………………..	7272	......	420	......	......	......	52		
Insulating:									
winding insulation ………………….....	1200	......	1250	......	......	......	0.15		
Email………………..........................	......	......	......	......	......	......	0.86		
Plastiques……………………………	1100 à 1300	......	1250 à 1700	......	......	......	0.04 à 0.2		
Insulating sheets ………………	......	......	......	......	......	......	0.2		
Cardboard …………………………	1115	......	1760	......	......	......	0.17		
Magnets:									
Nd-Fe-B fritté………………………...	……	…...	……	……	……	…...	6.5		
Ferrites isotropes……………………..	……	…...	……	……	……	…...	5.5		

Table I.2: Thermo physical properties of materials [24]

In rotating machinery, changes in the thermal properties of the materials used are low and very little influence the final result. Here it is assumed that the thermal conductivity, density and heat capacity are constant.[2]

1.4.3 ELECTROMAGNETIC AND THERMAL PHENOMENA

While electromagnetic-thermal interaction plays a crucial role in the operation of electrical machines, it is often avoided to perform such coupled simulation, due to the complex modeling challenges and the computational cost of the problem. In most cases the thermal and electromagnetic domains can be separated in the simulation easily and in a straightforward manner as the electromagnetic phenomena is typically much faster than the thermal. Thermal effects are usually modeled as a "boundary condition" for the electromagnetic domain and temperatures of dependent components (e.g.: those effecting the conductivity) are updated only after modeling several electrical periods, or several seconds of operation, or even several minutes or hours. This approach is a popular and reasonable one for most electrical machine problems also.

There are however a few problem types where the thermal effect could have a more direct and quicker impact on the electro-magnetic behaviour of the system, e.g.: like the case of direct online synchronous machine start up transients. Synchronous motors with starting capabilities often experience large thermal stress in a short period of time – especially in the damper bars – during starting.

In the followings, different approaches for the simulation of synchronous motor start up phenomena with electromagnetic thermal coupling is presented and discussed. Starting from a simple 2D model [1] and finishing with 3D directly coupled electromagnetic thermal model [2], the benefits and difficulties of the approaches are discussed and results are presented.

1.5 THERMAL MODELING OF ELECTRICAL MACHINERY

In high-performance applications such as hybrid electric vehicles and aerospace, there is a growing need for electric machines with high torque/power densities. A higher power density can be achieved by applying higher current densities to the electric machine windings and/or running the machine at higher speeds. A high current density in the stator winding results in significant copper losses and, in turn, high hot-spot temperatures [1, 2]. Also, high rotor speeds lead to higher current and voltage frequencies that increase the iron losses in the stator and rotor steel laminations and the permanent magnet segments in permanent magnet (PM) machines. The increase in copper and iron losses may, if the resulting heat is not properly dissipated, cause increased temperatures which may be particularly problematic in parts of the machine that are difficult to cool down (e.g. the rotor).

From the beginning of the twentieth century, considerable efforts have been put on dealing with thermal issues of electric machines [3–6]. In this regard, a considerable amount of work has been carried out on the development of complex cooling systems that effectively extract losses from critical parts of the machine [7–11]. Forced air cooling has been employed to enhance the heat transfer from the housing fins and often also from the end winding and rotor surfaces [12, 13].

However, for high current densities, air cooling may not be sufficient and some form of liquid cooling is required [11]. A housing water jacket enables an effective heat transfer from the active part of the stator winding to the coolant [14, 15].

However, water cooling does not provide a successful cooling of the end windings which can be particularly problematic for machines with long end windings, e.g. in machines with low pole numbers. Instead of water, oil may also be used as a cooling medium and different oil cooling methods for electric machinery have been proposed [7, 16–18]. In directly-oil-cooled machines, oil is in direct contact with the inner parts of the machine and an effective cooling of both the stator and the end winding body can be realized.

A variety of work has been done and published on improvements in the electromagnetic design of different kinds of electric machines to reduce losses, e.g. the iron losses in the stator and rotor laminations, and eddy current losses in the permanent magnets [19–22].

In order to improve the thermal behavior of electric machines, a good knowledge of heat transfer in different parts of the machine is required. Lumped parameter (LP) thermal analysis and numerical methods are the major approaches proposed to model thermal effects in electric machines [23].

1.5.1 THERMAL MODELING OF ELECTRIC MACHINES: NUMERICAL METHODS

Finite element analysis (FEA) and computational fluid dynamics (CFD) are commonly used numerical methods for thermal analysis of electric machines [23]. In a thermal finite element (FE) model, conduction in solid elements with specified conductivities can be modeled accurately but convection and radiation must be approximated with boundary conditions based on empirical correlations [12, 23]. Therefore, FEA can provide a fairly accurate picture of temperature distribution in complex solid parts of the electric machine, e.g. the winding, provided the boundary conditions are introduced accurately. The thermal FE model of the stationary part of a sample electric machine, implemented using the software JMAG3, is shown in Figure I.7.

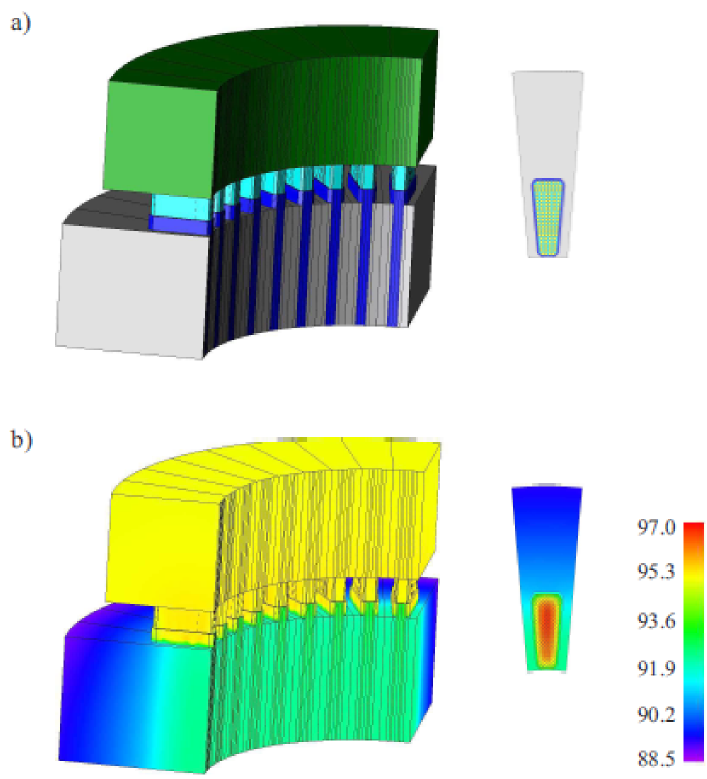


Figure I.7. Thermal FEA of the stationary part of a sample electric machine: a) FE model; b) FEA results.

As can be seen, the solid elements including the stator steel laminations (grey), conductors (yellow), liner (dark blue), impregnation (light blue) and end winding ring (green) are implemented in the FE software and convective heat transfers are modeled using the boundary conditions.

CFD analysis can be used to accurately model convective heat transfer and also fluid flows of the coolant in the electric machines equipped with different kinds of cooling systems [24, 25]. However, implementing and solving CFD and/or thermal FE models of electric machines can be very time-consuming [24, 26]. Therefore, using these numerical methods for example in design optimization procedures, where many design iterations are commonly required, is not recommended.

1.5.2 THERMAL MODELING OF ELECTRIC MACHINES: ANALYTICAL APPROACHES

From the time that thermal issues of electric machines first raised, engineers have tried to develop analytical methods to estimate the temperature distribution in electric machinery [24, 25]. An early attempt made to implement a functioning analytical thermal model to predict the temperatures in different parts of an electric machine is presented in [26, 27] where a simple thermal network is developed for totally enclosed non-ventilated induction motors. Following this work, the thermal model of a totally enclosed fan cooled electric machine was developed and tested by Mellor et al. on a medium (75 kW) and two small size (5.5 kW) induction machines [18].

1.5.2.1 Analogy between Heat Transfer and Electric Circuits

There exists an analogy between the diffusion of heat and electrical charge. Just as an electrical resistance is associated with the conduction of electricity, a thermal resistance may be associated with the conduction of heat. Defining resistance as the ratio of a driving potential to the corresponding transfer rate, it follows from Figure 3.4 that the thermal resistance for conduction is:

$$R_{t,cond} \equiv \frac{T_{s,1} - T_{s,2}}{q_x} = \frac{L}{kA} \tag{I.6}$$

As the electric resistance from Ohm's law

$$R_e = \frac{E_{s,1} - E_{s,2}}{I} = \frac{L}{\sigma A} \tag{I.7}$$

As there is a conduction resistance also there is a convection resistance.

$$q = h\,A\,(T_s - T_\infty) \quad \text{(I.8)}$$

$$R_{t,conv} \equiv \frac{T_s - T_\infty}{q} = \frac{1}{hA} \quad \text{(I.9)}$$

1.5.2.2 Series Circuits

In the series circuits of heat transfer, heat is transferred in a series of stages that aren't necessary of the same heat transfer mode.

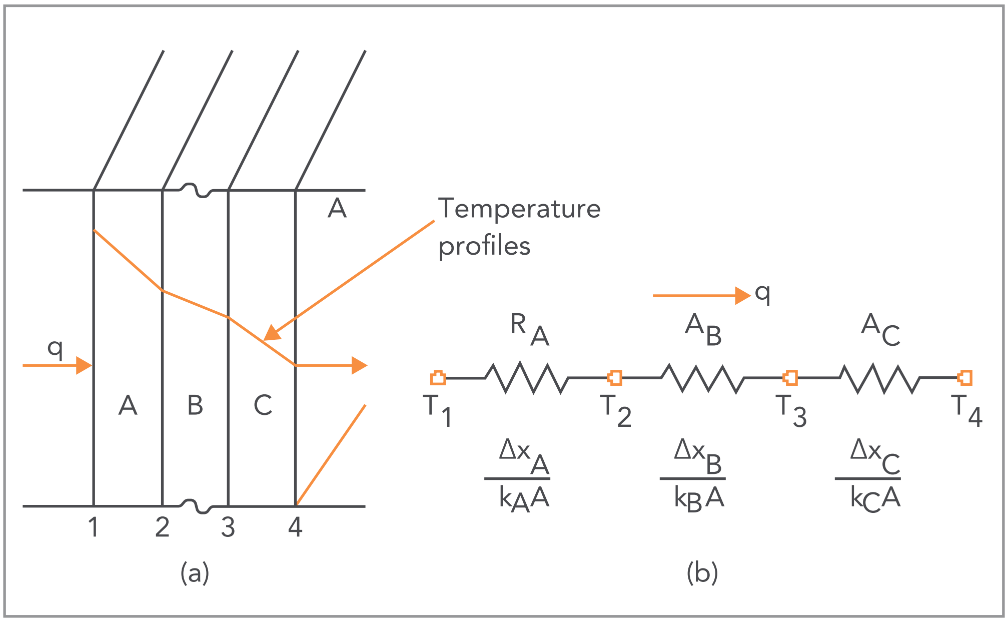


Figure I.8. Series circuits

Figure I.8 shows a plane wall subjected at its end to convective heat transfer. So in this case the heat is first transferred from the hot fluid to the wall surface by convection, then through the wall by conduction, and finally by convection from the second wall surface to the cold fluid. Here the heat quantity in each phase is the same so as current flowing in a series of electric resistances. Then from this analogy we may conclue thar:

$$q = \frac{\Delta T_{overall}}{\Sigma R_t} = \frac{T_{\infty 1} - T_{\infty 2}}{(R_{t,conv}) + (R_{t,cond}) + (R_{t,conv})} = \frac{T_{\infty 1} - T_{\infty 2}}{\left(\frac{1}{h_1 A}\right) + \left(\frac{L}{kA}\right) + \left(\frac{1}{h_2 A}\right)} \quad \text{(I.10)}$$

As

$$i = \frac{\Delta E}{\Sigma R_e} = \frac{E_1 - E_2}{(R_{e,1}) + (R_{e,2}) + (R_{e,3})}$$

Hence, the amount of heat transferred could be expressed as

$$q = \frac{T_{\infty 1} - T_{\infty 2}}{\left(\frac{1}{h_1 A}\right) + \left(\frac{L_A}{k_A A}\right) + \left(\frac{L_B}{k_B A}\right) + \left(\frac{L_C}{k_C A}\right) + \left(\frac{1}{h_2 A}\right)} \tag{I.11}$$

1.5.2.3 Parallel Circuit

In parallel thermal circuits, heat is transferred in parallel through several heat transfer conduits. These conduits may be of various heat transfer mode or from the same mod as is the case shown in Figure I.9.

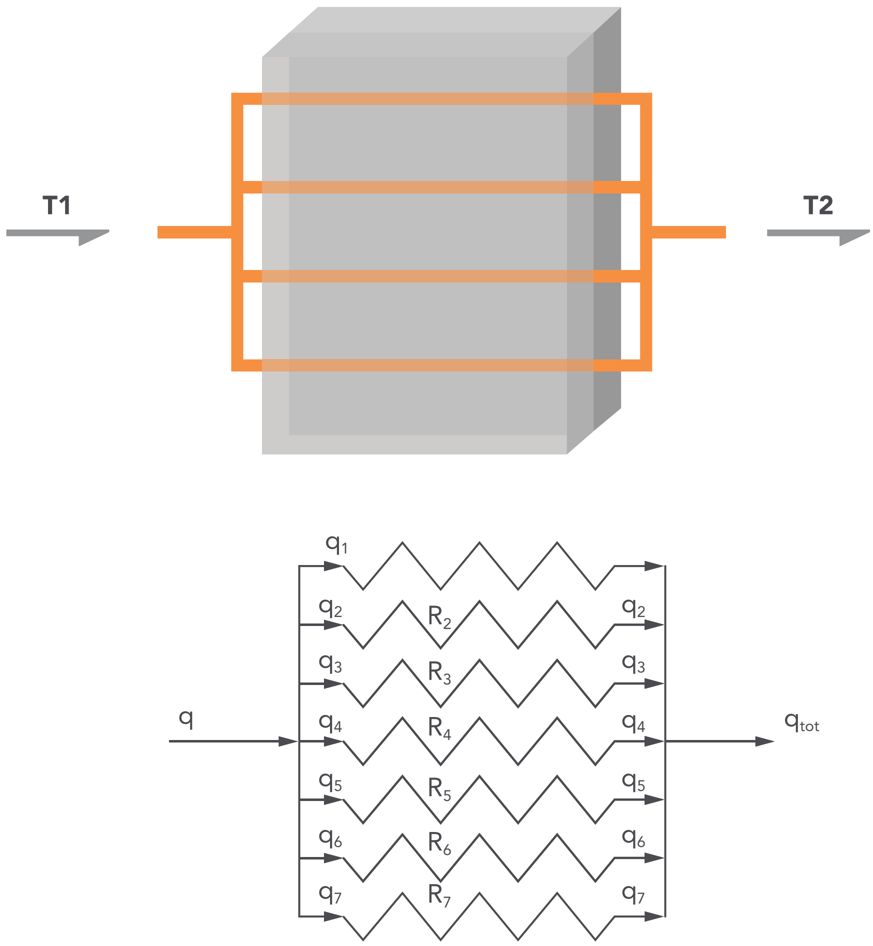


Figure I.9. Parallel Circuit

Now considering the case in Figure I.9.

$$q_i = k_i A_i \frac{\Delta T}{L_i} = \frac{\Delta T}{R_{t,i}} \tag{I.12}$$

And;

$$q_{tot} = \Sigma q_i = \Delta T \left(\frac{1}{R_{t,1}} + \frac{1}{R_{t,2}} + \frac{1}{R_{t,3}} + \frac{1}{R_{t,4}} + \frac{1}{R_{t,5}} + \frac{1}{R_{t,6}} + \frac{1}{R_{t,7}} \right) = \frac{\Delta T}{R_{t,tot}} \tag{I.13}$$

This means that like electric circuits in parallel, the equivalent total thermal resistance would be:

$$\frac{1}{R_{t,tot}} = \sum \frac{1}{R_{t,i}} \tag{I.14}$$

I.5.2.4 Series-Parallel Network Reduction

A thermal network can be extremely complicated so that normal analysis would be exhaustive. In this case, the use of the analogy between thermal and electric network would simplify the analysis. In order to simplify the thermal networks, the series and parallel thermal resistance are combined in order to reach simplified analysis. The following figure shows a circuit with the method of simplification.

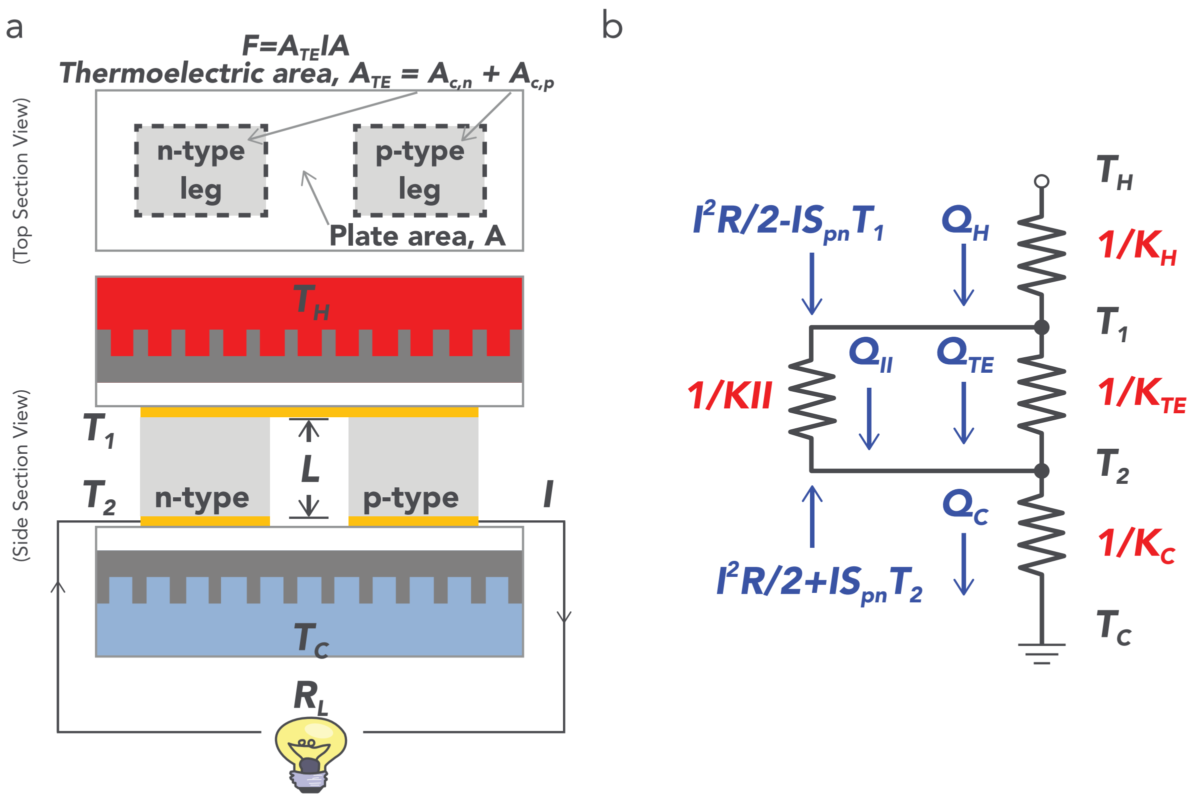


Figure I.10. Mixed Circuit

1.5.3 COMBINED MODES OF HEAT TRANSFER

Most of the practical cases under investigations, heat is transferred by more than one mode; as for examples heat may be transferred by combined convection and radiation, combined convection and conduction, etc.

1.5.3.1 Combined Convection and Radiation

Since these two modes of heat transfer are completely independent, there would be no mutual effect between them. Thus net heat exchange of the surface is the sum of the two:

$$q_{net} = q_{conv} + q_{rad} \tag{I.15}$$

This hypothetical approach seems to be similar to the parallel electrical resistances as shown previously, but the problem here is that no radiation resistance has been defined yet. So let us use a radiant heat transfer in order to express the radiation heat transfer, *q rad*, as a linear function in the temperature difference between the surface temperature and the fluid temperature.

$$q_{rad} = h_r \times A \times (T_s - T_f) \qquad \text{(I.16)}$$

Where;
h_r: radiation heat transfer coefficient, W/m^2.K
A: heat transfer surface area, m2
T_s: surface absolute temperature, K
T_f: enclosure absolute temperature, K
Now it is time to define how the radiation heat transfer coefficient can be obtained

$$h_r = \frac{q_{rad}}{A \times (T_s - T_f)} = \varepsilon \times \sigma \times F_{se} \times \frac{(T_s^4 - T_e^4)}{(T_s - T_f)} \qquad \text{(I.17)}$$

In the above equation, T_e is used to express the enclosure temperature as this is the more general case. But for most of the cases, the fluid adjacent to the surface has the same temperature as that of the enclosure. So for this most likely circumstance the following agree:

$$h_r = \varepsilon \times \sigma \times F_{se} \times \frac{(T_s^4 - T_f^4)}{(T_s - T_f)} = \varepsilon \times \sigma \times F_{se} \times \frac{(T_s^2 + T_f^2) \times (T_s + T_f) \times (T_s - T_f)}{(T_s - T_f)} \tag{I.18}$$

$$h_r = \varepsilon \times \sigma \times F_{se} \times (T_s^2 + T_f^2) \times (T_s + T_f) = \varepsilon \times \sigma \times F_{se} \times ((T_s + T_f)^2 - 2T_sT_f) \times (T_s + T_f)$$

Now if we define the arithmetic means temperature as

$$T_m = \frac{T_s + T_f}{2} \tag{I.19}$$

If further T_s-T_e<<T_s t hen

$$T_m = \sqrt{T_s T_f} \tag{I.20}$$

So we may define the radiation heat transfer coefficient as

$$h_r = 4 \times \varepsilon \times \sigma \times F_{se} \times T_m^3 \tag{I.21}$$

And finally;

$$q_{net} = h_{tot} \times A \times (T_s - T_f) \tag{I.22}$$

Where;

$$h_{tot} = h_{conv} + h_{rad} \quad \text{I.23)}$$

1.6 CONCLUSION

In this chapter, thermal effects of using different winding impregnation materials and steel lamination qualities were evaluated. Two commonly used impregnation materials were first compared with a silicone based thermally conductive impregnation material. Significant reductions in the hot-spot temperature of winding were achieved which is promising for thermal management of electric machines and also the resulting efficiency particularly in high-performance applications.

Electromagnetic – thermal coupling in the simulation of electrical machines is a very important research topic with strong academic and industrial interests. The simulation of the direct online starting of a synchronous machine provides a great basis of comparison for different computation methods. The 2D electromagnetic analysis with averaged thermal model is faster than the 3D Electromagnetic Thermal simulation it cannot provide the detail of possible hot spots.

After analyzing the possible methods, we used the nodal method that fits well with our approach. To validate this approach we propose to establish the equivalent thermal diagram of the actuator. We thus end up in chapter three a pattern consisting of some capacitive and resistive elements can be determined by calculation.

The next chapter is devoted to the implementation of the model and the identification of these parameters and the simulation of the thermal behavior of the actuator.

2 THERMAL MODELING OF A PERMANENT MAGNET SYNCHRONOUS MACHINE FOR ELECTRIC VEHICLE

2.1 INTRODUCTION

Electrical machines are very sensitive to temperature increase of the parts which are especially due to the fragility of their windings [1], [2]. This heating can cause deterioration and the changing characteristics of electrical, magnetic, and mechanical drive system. It is necessary to correctly determine the temperature of the different parts that constitute them. Although all electric machines are the exposed to heat losses [3], those supplied by a static converter deserve special attention. Indeed, recent developments in power electronics and automation as well as the increase in computing power industrial computing systems allow the design of electromechanical actuators which are highly specialized engines strained.

The losses in the machine then increase due to the injection of current harmonics and the temperature rises even more than during normal operation. In this context, a study of the thermal behavior of the motor permanent magnets is useful to fight against the problems already mentioned, and to take into account its influence on the design and control system of traction.

This article tries to solve the issue of development of tools for modeling and simulating the behavior of electro thermal actuator permanent magnet axial flux (PMAF) devoted to electrical attraction.

Our objective requires the development of models for the various components used in the actuator: coil, rotor, stator…etc. The models developed must allow wind to account for the electrical behavior but also the thermal behavior of components.

2.2 OBJECTIVE

The main objective of modeling electro thermal is to respect the thermal constraints related to the functioning of PMSMAF. In fact, the exceeding of the melting temperature of the insulation of the coils is set at 90°C leads to the deterioration of the coils and subsequently to the damage the motor. In addition to that knowledge of the temperatures in different active areas of the engine allows at first to take into account the change of the BH characteristic of the magnets (critical temperature is not to exceed 60°C), and the variation of resistance of MSAPFA phases, strongly influencing the electrical, magnetic and mechanical behavior of the engine. This knowledge of temperatures determines the nature and power of the cooling system to be integrate to PMSMA Fin order to stabilize the operation of the engine in optimum speed.

We set a goal not to exceed the limits of the following temperatures:

- 60°C for the permanent magnets.
- 70°C for the insulation of the coils.

Under these conditions, a model (Figure II.1) will assess from the losses temperature with an accuracy of a few degrees Celsius.

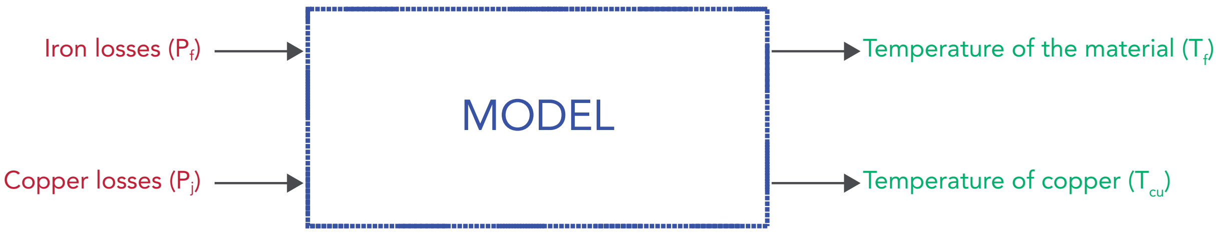


Figure II.1. Presentation of the

2.3 STRUCTURE OF THE MOTOR

The actuator and a synchronous motor with permanent magnets axial flow Figure II.2. Firstly, it is composed of a stator formed by a stack of laminations of ferromagnetic material, and having teeth between which the coils are in brass. And secondly, a rotor made of a ferromagnetic ring mass on which the magnets are fixed.

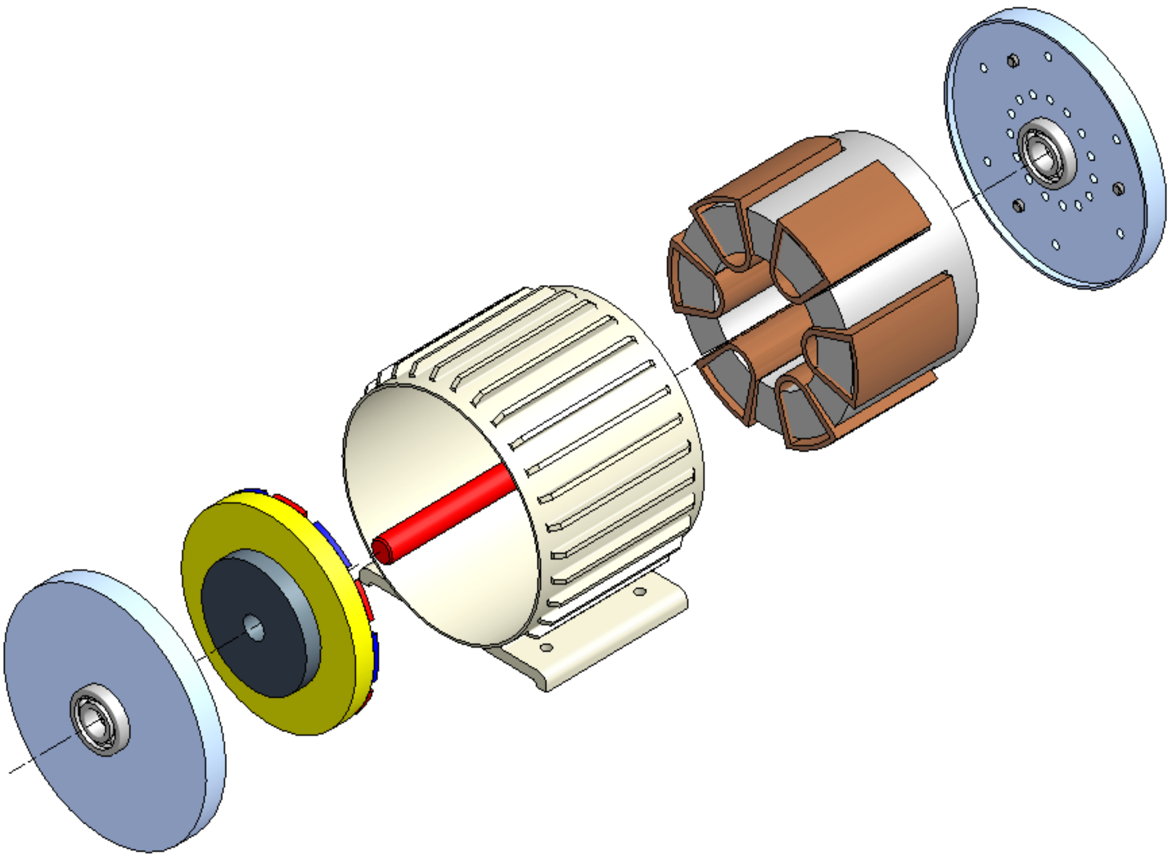


Figure II.2. PMSMAF

Figure II.3 and Table II.1 gives the geometric structure chosen for the characterization PMSMAF.

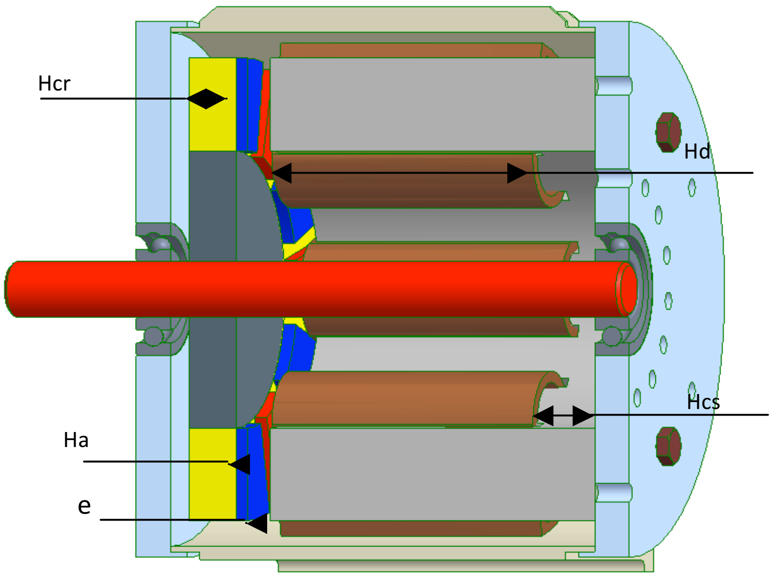


Figure II.2. The geometric parameters of the PMSMA

Number of pole pairs	n	4
Thickness of the gap	e	0.002m
Total number of main teeth	N_{te}	6
Thickness of the stator yoke	H_{cs}	0.035m
Outer diameter of the stator	D_{ext}	0.250m
Inside diameter of the stator	$D_{int.}$	0.150m
Width of a slot	L_{enc}	0.005m
Height of a notch	H_d	0.144m
Thickness of the rotor yoke	H_{cr}	0.026m
Height of a magnet	H_a	0.0067m
Surface of a magnet	S_a	$0.0026m^2$
Thickness of stator perpendicular to plates	E_{cs}	0.050m

Table II.1. The geometric dimensions of the PMSMAF

2.4 CHOICE OF MODELING METHOD

The conventional analytical methods allow the description of heat transfer with acceptable complexity. However these methods require precise knowledge of many coefficients (thermal conductivity, heat transfer coefficient, and emissivity) which is often difficult to obtain.

Methods of finite elements require memory resources and computation time that are not compatible with our approaches which have to allow the modeling of a magnetic component in its environment that is integrated into a power line. Moreover, the models developed should make account of all the phenomena involved in the magnetic component (electrical, magnetic and thermal phenomena).

The nodal method provides the best accuracy of results and simulation time [25–27]. It is therefore compatible with optimization approaches such as performance of electric vehicles. However, it seems best suited to our concerns and to our experimental approach. The component model is divided into zones connected by insulated thermal resistance, the center of an area is called a node. A thermal capacity and a heat source associated with each zone. A system of differential equations is obtained by writing the heat balance at different nodes. A first approximation is to consider the thermal resistances as constants (for better precision thermal resistances can be modeled using analytical relations).

For the components of our synchronous motor, the equivalent circuit can be summed up in a few resistors and capacitors whose values can be obtained by calculation.

2.5 MOTOR THERMAL MODEL

Thermal modeling of electrical machines is a crucial issue, and many studies have been devoted [8]. Several approaches are used to describe the heat transfer and to achieve a satisfactory estimate of operating temperatures. Some approaches lead to a detailed mapping of temperature calculated in all points of the component, others may provide only the calculated temperature at some points of the component.

2.5.1 ASSUMPTIONS USED IN MODELING

We first recall our assumptions about the thermal modeling of magnetic components to justify the principles of adopted measures that lead to the measurement of average temperatures. Temperatures are assumed to be uniform in the material and in the different coils [29].

We consider an ambient temperature of 27°C and we assume a maximum warm-up the allowable to 70°C for the stator winding and insulation. This heating is determined by the temperature resistance of conductors and insulators bottom notches. Similarly, the maximum heating of the magnets (Sm-Co) must be taken into account and we assume a temperature rise of about 60°C.

The heat exchange is assumed to be in the axial direction as the length of the structure in this direction is much lower than that in the radial direction, moreover, the heat exchange sections perpendicular to the axis of the motor, is much greater than those radials [9].

We, also, assume that the heat flux (iron losses) propagates the center of gravity of the head and the stator teeth as for the stator coils (Joule losses) in the axial direction [31].

2.5.2 HEAT TRANSFER IN STRUCTURES PMSMAF

Heat transfer in the PMSMAF is illustrated in Figure II.4 as follows:

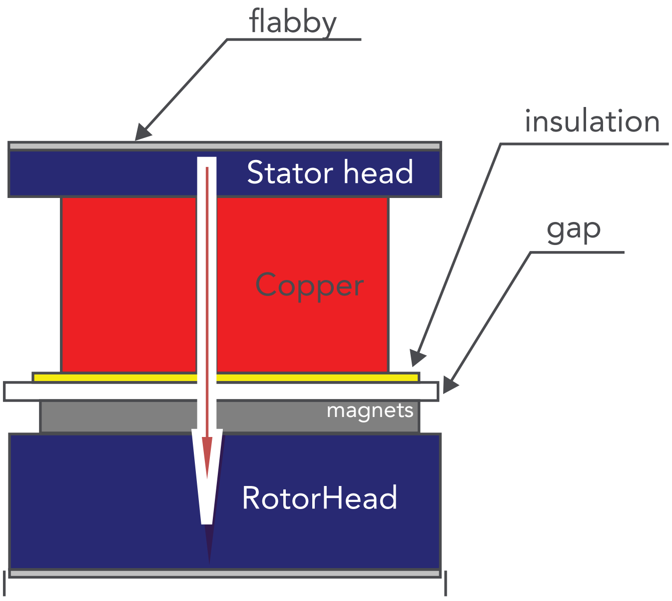


Figure II.4. The heat transfer in the machine

2.5.3 BLOCKS CUTTING MACHINE

For the actuator studied, we selected a cut which comprises eleven blocks based on the map of thermal exchanges in Figure II.5.

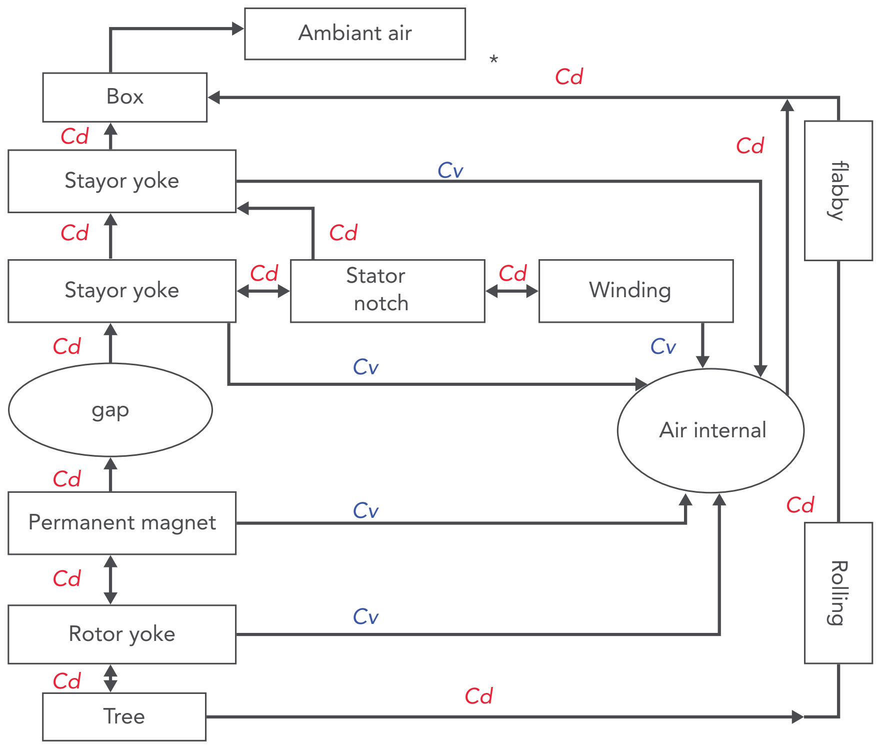


Figure II.5. Cutting the PMSMAF Cd: conduction Cv: Convection

The thermal model will be set up to represent as closely as possible and simply the active parts of the machine (stator windings, stator and rotor magnetic circuits) and the links between them and with the outside. The thin elements such as insulation sheets will be represented by simple thermal resistance.

2.5.4 TRANSIENT THERMAL MODEL

We used a modeling using thermal-electrical analogy. The machine is divided into volume elements exchanging heat between them by conduction or convection. The calculated Joule losses include losses of Joule slots and winding heads. The iron losses are localized at the center of gravity of the head and of the stator teeth.

The thermal model of the PMSMAF transient structure can be represented by a similar electricity network, as described in figure II.6.

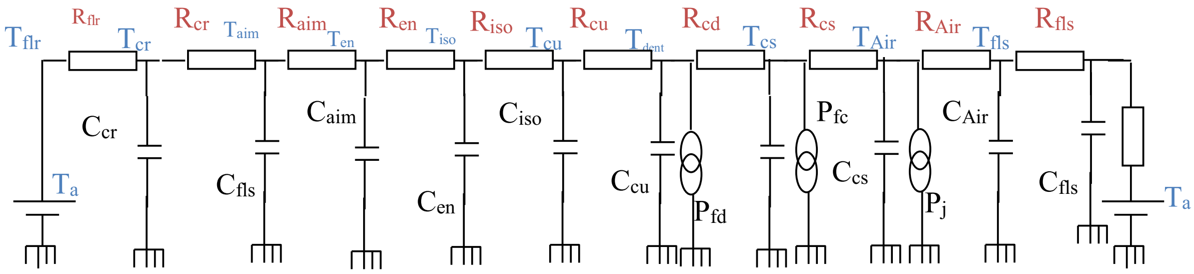


Figure II.6. Model Motor thermal in transient state

We assign the center of gravity of each area as well as a node power sources P_j, P_{fc} and P_{fd} corresponding total Joule losses in the coils and iron losses of the stator yoke and teeth. The variables correspond to the temperatures Ti at the different points of the machine. The expressions of the thermal resistances are deduced from the resolution of the equation of the heat-border areas.

2.5.5 CALCULATING CONDUCTION RESISTANCES

For the sake of simplification, the conduction along the transverse axis of the stator is not taken although it may be crucial in the windings in particular. Heat transfer in a stator element therefore allows one preferred direction, the axial direction.

This is reflected by the following heat equation [30].

$$\frac{\overrightarrow{\Phi_t}}{S_{et}} = -\lambda \times \overrightarrow{grad T} = -\lambda \times \frac{T_1 - T_2}{x_1 - x_2} \vec{x} \quad \text{(II.1)}$$

It follows from (II.1) a general formula of thermal conduction for axial distribution of flow:

$$R = \frac{E}{\lambda \times S_{et}} \quad \text{(II.2)}$$

Where λ is the thermal conductivity, is set the heat exchange section and Φ_t is the total heat flow exchanged and E is the thickness of the heat exchange.

Conduction resistance is derived from the geometric equations of PMAF:

- The conduction resistance of the rotor yoke is expressed by the following relationship [2]:

$$R_{cr} = \frac{H_{cr}}{\lambda_{fer} \times \left(\pi \times \frac{D_e^2 - D_i^2}{4} \right)} \quad \text{(II.3)}$$

Where; λ_{fer} is the thermal conductivity of iron

- The conduction resistance of the magnet is expressed by the following relationship:

$$R_{aim} = \frac{H_a}{\lambda_a \times 2 \times p \times S_a} \tag{II.4}$$

Where; λ_a is the thermal conductivity of the magnets.

- The conduction resistance of the gap is expressed by the following relationship:

$$R_{en} = \frac{e}{\lambda_{air} \times \left(\pi \times \frac{D_e^2 - D_i^2}{4}\right)} \tag{II.5}$$

Where; λ_{air} is the thermal conductivity of air

The conduction resistance of the coils is expressed by the following relationship:

$$R_{cu} = \frac{E_{cu}}{\lambda_{cu}.S_{cu}} \tag{II.6}$$

Where; λ_{cu} is the thermal conductivity of copper is S_{cu} section of the coil and E_{cu} is the thickness of the copper.

- The conduction resistance of the insulation is expressed by the following relationship:

$$R_{iso} = \frac{E_i}{\lambda_i S_i} \tag{II.7}$$

Where λ_i is the thermal conductivity of the insulator, S_i is the cross section of the insulation and E_i is the thickness of the insulation.

- The conduction resistance of insulation is expressed by the following relation:

$$R_{cd} = \frac{H_d}{\lambda_{fer} \times (N_d \times S_d)} \tag{II.8}$$

- The conduction resistance of the stator yoke is expressed by the following relationship:

$$R_{cs} = \frac{H_{cs}}{\lambda_{fer} \times \left(\pi \times \frac{D_e^2 - D_i^2}{4} \right)} \tag{II.9}$$

- The conduction resistance of the air between two modules is expressed as follows:

$$R_{Air} = \frac{E_{air}}{\lambda_{air} \times \frac{\pi \times D_e^2}{4}} \tag{II.10}$$

Where; E_{air} is the thickness of air between two modules.

- The conduction resistance of the plates is expressed as follows:

$$R_{fls} = R_{flr} = \frac{E_{fl}}{\lambda_{fer} \times \frac{\pi \times D_e^2}{4}} \tag{II.11}$$

Where; E_{fl} is the thickness of the flanges.

2.5.6 CALCULATING CONVECTION RESISTANCES

The heat transfer by convection is the preferred mode of transfer within the fluids. Then it is generally much more important than conduction. We must distinguish the natural convection of forced convection [2].

Density differences related to differences in temperature cause movements of the fluid warms on contact with hot bodies and thus carries heat to the cold areas: the natural convection.

The yoke and the outer flanges of the machines, in the absence of the exterior and because fan undergo this transfer mode.

The single network element that refers to a transfer by convection is Rext, which represents the overall thermal resistance between the surface of the casing, the flanges and the ambient air.

$$R_{ex} = \frac{1}{h.S_{ex}} \tag{II.12}$$

Where h is the heat transfer coefficient, we choose h = 30W.K^{-1}.m (natural ventilation) and Sex is the outer surface of the actuator.

2.5.7 CALCULATION OF HEAT CAPACITIES

We will study the thermal phenomena of a transient viewpoint, so it is necessary to involve the heat capacity of the materials making the components of the machine.

Expressions of thermal capacity are calculated from the following relationship between the mass of materials and their massive heat capacity using the following equation [1] and [12]:

$$C = \rho \times V \times c = M \times c \tag{II.13}$$

Where ρ is the density of the material, V is the volume of the material, c is the ca-pacity thermal mass material and M is the mass of the material.

2.5.8 HEAT FLUX

The heat flux Φ_1 corresponds to iron losses in the stator yoke (Pfc). This stream travels from the center of gravity of the stator yoke. It is expressed by the following relationship [10]:

$$\Phi_1 = P_{fc} = q \times f^{1.5} \times M_{cs} \times B_{cs}^2 \tag{II.14}$$

Where q is the quality factor of the sheets, M_{cs} is the mass of the stator yoke and the magnetic induction is B_{cs} in the stator yoke.

The heat flux Φ_2 corresponds to iron losses in the stator yoke (P_{fd}). This stream travels from the center of gravity of the stator teeth. It is expressed by the following equation:

$$\Phi_2 = P_{fd} = q \times f^{1.5} \times M_{ds} \times B_d^2 \qquad (II.15)$$

Where M_{ds} is the mass of the stator teeth and B_d is the magnetic induction in the stator teeth.

The heat flux corresponds to Φ_3 Joule losses in the stator copper (P_j). This flow spreads from the center of gravity of the copper stator. It is expressed by the following relation:

$$\Phi_3 = P_j = \frac{3}{2} \times R \times I^2 \qquad (II.16)$$

Where R is the resistance of the stator winding, it is expressed by the following relationship:

$$R = \frac{r_{cu} \times N_s \times L_{sp}}{\dfrac{C_{dim}}{\sqrt{2} \times \delta \times K_e}} \qquad (II.17)$$

Where; r_{cu} and the resistivity of copper and L_{sp} is the average length of one turn.

2.6 SIMULATIONS RESULTS

2.6.1 MODEL SIMULATION WITHOUT COOLING FINS

The simulation is based on the model established from a preliminary analysis. The analysis and study of the system components, modeling and simulation are the three basic steps of our approach to evaluate the heat transfer in the actuator.

The thermal model developed for the various components of the motor is important implemented MATLAB SIMULINK to estimate the temperatures of the materials.

The simulation of the thermal model of the PMSMAF structure with natural ventilation (convection coefficient equal to 30W.K^{-1}.m) and for operation at steady speed of 80 km/h, shows the evolution of temperatures in the different active parts of the motor (Figure II.7).

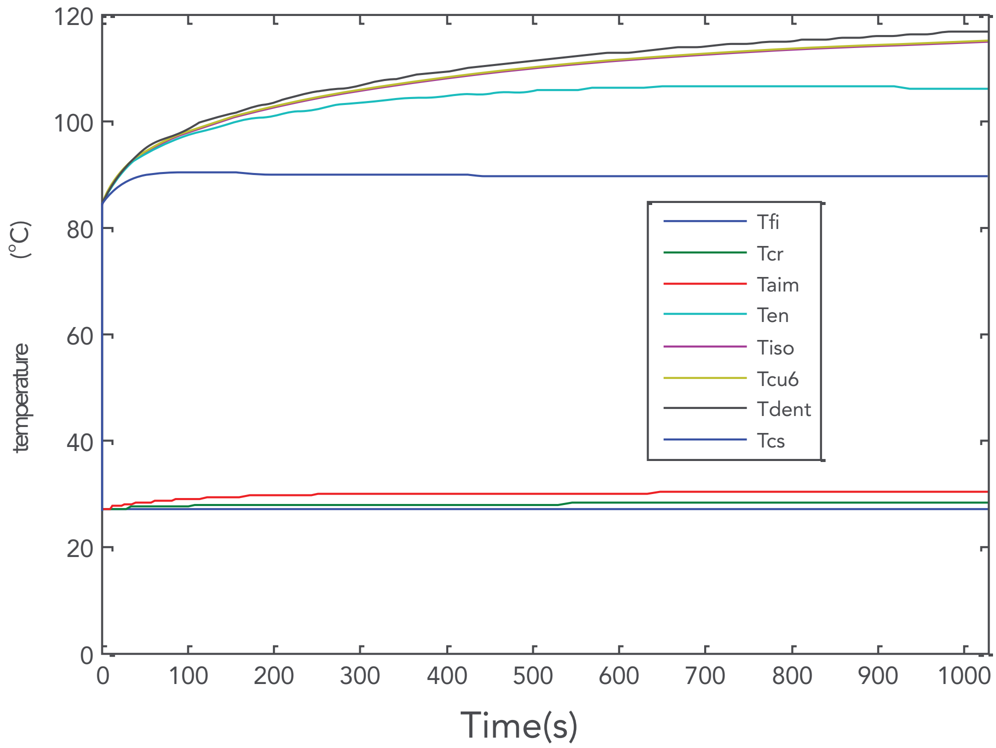


Figure II.7. Evolution of temperatures in different parts active motor for a steady speed of 80 km / h (h = 30)

Where T_{fl} is the average temperature of the plates, T_{cr} is the average temperature of the rotor head, T_{aim} is the average temperature magnets, T_{en} is the average temperature of the air gap, T_{iso} is the average temperature of the insulation, T_{cu} is the average temperature of the copper, the average temperature is T_{dent} teeth stato-cal and T_{cu} is the average temperature of the stator yoke.

This figure shows that there's an overshoot of 47°C for copper and resin, which proves the need for a cooling system. Several simulations are run for several values of convection coefficient for a system of forced ventilation cooling system, led to the establishment of this coefficient at 300 $WK^{-1}.m$.

Changes in temperature in the different active parts of the engine for operation with a cooling system with forced ventilation of the convection coefficient h = 300$WK^{-1}.m$ is illustrated in Figure II.8.

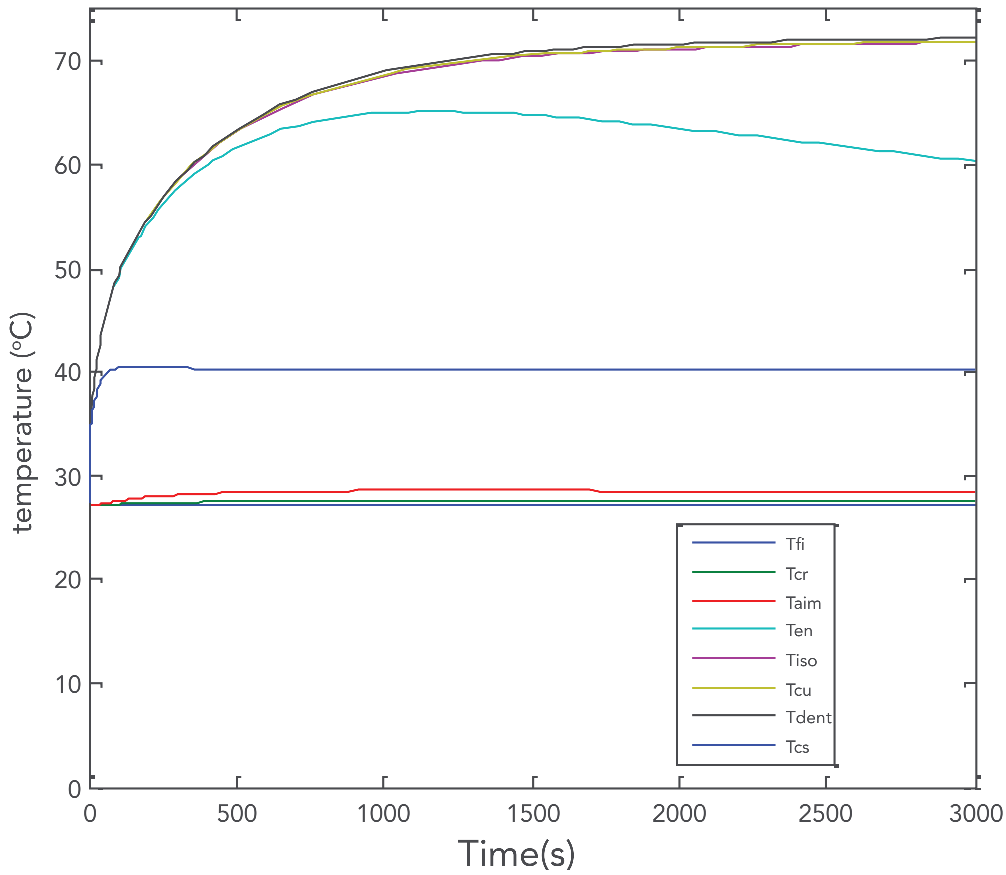


Figure II.8. Evolution of temperatures in different parts active motor for a steady speed of 80 km / h (h = 300)

This figure shows that the temperature of the copper and insulation are reduced to the critical value of 70°C.

2.6.2 SIMULATION MODEL WITH COOLING FINS

The use of the cooling fins to the actuator, for the same size and the same conditions of operations, decreased slightly warming up of engine components (Figure II.9), and this led us to consider setting out another cooling system.

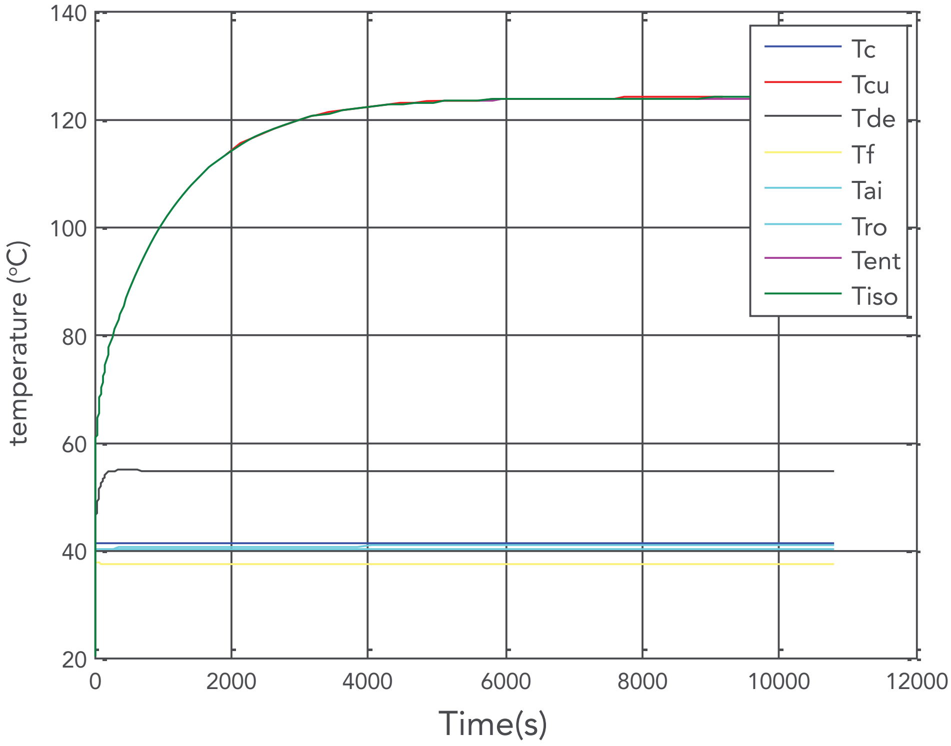


Figure II.9. Evolution of temperatures components MSAPFA with cooling fins obtained by simulation 1D speed = 80km /h

2.7 CONCLUSION

Our objective modeling components PMSMAF require the development of comprehensive models capable of taking into account with the same degree of approximation magnetic, electrical and thermal phenomena. Given these objectives, we have established a set of specifications on the thermal model. This allows to calculate with perecision of few degrees the operating temperature of the component (temperature of the magnetic material and temperature of the windings). The simplicity of therequired pattern is an essential criterion of choice.

And we arrive at a model consisting of some capacitive and resistive elements, the calculation of thermal resistance used to characterize the different heat exchanges within the various components of the thermal model.

Temperature measurements are obtained by simulation in MATLAB. SIMULINK, results have shown the need to consider a system of cooling. The operation of the latter provided protection engine running on missions urban traffic data type.

GENERAL CONCLUSION

Permanent Magnet Motors are popular choices for electric vehicle powertrain applications. The effects of the excessive heat in the magnets can degrade the performance of these machines if not dealt properly. It is therefore critical to develop a complete and representative model of the heat processes in the electric motors. In this book, a simplified analytical model is developed as a thermal circuit with a network of interconnected nodes and thermal resistances representing the heat processes within the PMSM. Both losses induced by sinusoidal and PWM waveform voltage supplies are calculated respectively as heat sources in the thermal circuit. Because temperature-rise inside the magnets caused by eddy current loss can lead to the unpredictable deterioration of the magnets, the circuit takes into consideration the eddy current loss developed in the permanent magnets. The thermal circuit is then solved in MATLAB through a system of linear equations. The results of the analytical model are confirmed through 1-D finite element analysis simulation in software.

The thermal analysis of permanent magnet synchronous motor is presented. The lumped circuit approach is employed in this investigation. The proposed model is compatible with circuit simulators Simulations by MATLAB SIMULINK software performed in order to study the variations of the temperature at any part of the motor, according to the copper losses and the iron losses injected in the motor and the boundary conditions at the cooling systems.

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