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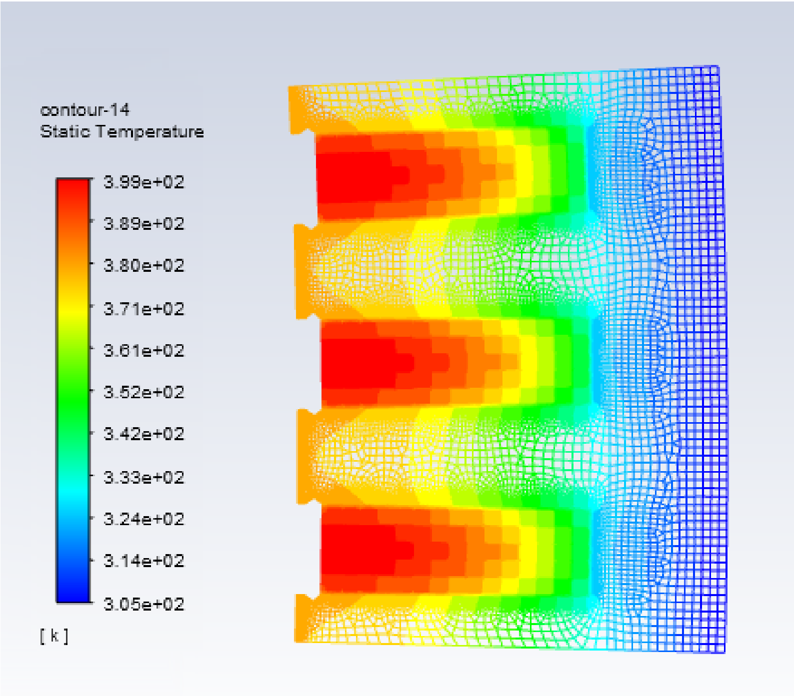
Electrostatical and thermal design of the insulation in a high voltage permanent magnet generator

Mar Segarra Valenzuela



Electrical power department
Chalmers University of Technology
Gothenburg, Sweden 2020

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Abstract

This thesis covers the electrostatical analysis and design of the insulation, performed by means of Matlab and Ansys Maxwell as well as the thermal analysis and design by Ansys Fluent. Both analysis have been done first by calculating analytical approximations and then by simulating the generator under different operating conditions. The approach is quite conservative since the aim of this thesis is to verify that the cool down of an electric machine of this characteristics would be possible. Thermal resistance networks coupled with Ansys Fluent have been used to analyse the heat transfer inside the machine.

Based on the electrostatic analysis, the minimum insulation thickness was designed, a thickness of 1mm in the turn insulation and another milimeter for the groundwall, with this configuration, cooling down the generator with an air cooling system was unfeasible, thus a cooling channel that went through the slots was designed, both the analytical and the numerical analysis verified that the heat was easily evacuated when introducing a water cooling channel inside the slots.

Keywords: High voltage, generator, thermal analysis, electrostatic analysis, numerical simulation, insulation design.

Contents

Chapter 1

Introduction

The environmental problem the world is facing nowadays, force us, to think about ways to increment the percentage of renewable energy we consume, thus to increase the amount of energy we are able to generate.

According to the forecast of the International Energy Agency, the renewable energy share in the power mix should increase from 25 to 66 % by 2040 in order to guarantee universal energy access and combat the climate change and its impacts.

Many hopes are set on offshore wind energy, which is in constant development and currently one of the biggest sources of renewable energy worldwide.

Important obstacles for the exploitation of offshore wind energy are the installation and maintenance costs of the offshore wind turbines. The most powerful wind turbines being used today reach a power of $\approx$ 12MV and have a maximum voltage of a few kV. Therefore, a transformer installed in the nacelle is needed to convert the low voltage of the generator into the high voltage of the distribution networks. A promising scenario can be found in the high power, high voltage, direct-driven, wind power plant, that does not need a 15 ton transformer and thus, reduces significantly both weight and costs of the wind turbine.

1.1 Problem background

One of the most important parts of designing an electrical machine is to design it's insulation and cooling system, since they prevent the engine from suffering a catastrophic failure.

The insulation and refrigeration of high power electrical machines is a science in development, many things are known about heat transfer, an old branch of industrial engineering. However, there are no rules that can be applied to such complex machines as a generator of 20MW of power and 75kV of maximum voltage. The equations that have to be solved inside the machine are complicated differential equations developed in the three coordinates of space. Typically this kind of complex problems, are solved by analytical approximations and simulations of the machine using Finite elements or CFD (computational fluid dynamics).

1.2 Previous work

Many theory has been written about these two topics, heat transfer and electrostatics, as in [3] and [4] respectively. The equations that lead the behaviour at study are completely known.

However, as it was seen before, knowing these equations doesn't solve the complex problems that appear in real engineering designs.

Concerning the insulation design ,many authors have proposed different kinds of machine classification based on cooling systems, like [2] which also propose a simple methods to analytically calculate the electric field in an insulator.

Even though there are many electrostatic analysis of electrical generators there is not a norm that can be used to design the insulation in a generator with this characteristic geometry and voltage.

As for the design of the cooling system of electrical machines, there are many different ways of analysis and programs available to make the process easier. Regarding the analytical resolution of the heat transfer problem, it is possible to find programs like Motor-Cad that constructs complex thermal resistance networks to solve the heat transfer inside the machine, from a series of parameters. There are also many papers and thesis realized by university researchers about the analytical calculation of thermal resistances of each component in the machine, as in [6] or [5]. These studies can be used as an orientation to obtain the thermal resistance in different machines but since the geometries and material properties varies from one machine to another, the final formulas have to be created by each designer.

Finite element and CFD are techniques that have been used by engineers for a long time by now, however, each simulation is different and depends highly on the boundary conditions that the designer sets on the machine at study,

1.3 Purpose

This thesis contributes to the thermal and electrostatic analysis of an off-shore, high voltage, direct driven, wind turbine with a power of 20MW.

The design of such a novel generator involves multiple interacting phenomena, such as electromagnetic, electrostatic, fluid dynamic, and thermal physics, and therefore a multiphysics modelling approach is needed.

My thesis project contributes providing direct feedback for thermal end electrostatic analysis but also a tool for the electrostatic and thermal design that can be used, by the research group, for multiphysical modelling of the generator.

The design of the insulation and cooling systems of electrical machines is a science in development; the electrostatical and the thermal analysis have to be coupled since the insulation is the part of the engine that most influences both of them. From an electrostatical point of view the machine's security coefficient increase at the same rate as the thickness of the insulation. On the contrary, the maximum temperatures reached in the machine decrease as we minimize the amount of insulation material. The most difficult part is to find the equilibrium between electrical safety and controlling the maximum temperature.

Chapter 2

Electrostatic theory

The reason why understanding some concepts of electrostatics, is necessary in the design of generators, is linked to why insulators are used inside the machine.

The windings of the stator are insulated by an insulation system that contains several different components and features, which together ensure that electrical shorts do not occur, that the heat from the conductor I^2R losses are transmitted to a heat sink, and that the conductors do not vibrate in spite of the magnetic forces. Different insulation system components and their specific uses are explain with detail in [2].

Basically the study of electrostatics in generators is necessary because the voltage in the conductors generates an electric field in the insulation, which if high enough, could cause the breakdown of the same, (the current would be able to flow through the insulation), and lead to a ground fault or shorts between the turns. A ground fault happens when the current flow is able to go from the copper conductors to the stator core, possibly causing damage to the stator.

2.1 Electric field

In order to understand the electric field it is necessary to know some crucial concepts. Many information about electrostatic basic concepts can be found in [4]

The most important one is charge, the charge is a property of some fundamental particles (protons and neutrons), it causes the protons to be repelled by other protons and attracted to other electrons and the opposite for electrons.

Two charges q_1 and q_2 at a distance r will either attract or repel each other with a force F given by coulombs'law

$$F = \frac{q_1 q_2}{4pi\varepsilon r^2} \tag{2.1}$$

where ε is the permitivity or dielectric constant of the space= $\varepsilon_r \cdot \varepsilon_0$ (relative permitivity and vacuum permitivity respectively)

An electric field is a region where a charge feels a force. This force is caused by other charges, so a charge or charge distributions creates an electric field in its environment.

The magnitude of the field is characterized by the field strength. The electric field strength is a vector quantity, it has magnitude and direction. To find out the electric field that a charge generates, (this charge is called charge source), we need to use another charge (the test charge), if this test charge experiences a force F, the electric field is given by: $E = F/q$; although in this equation we can see that the magnitude of the test charge, seems to affect the electric field strength magnitude, actually the force, according to Coulomb's law, increases proportionally to the charge. Therefore, in the end the magnitude of the electric field is independent of the test charge.

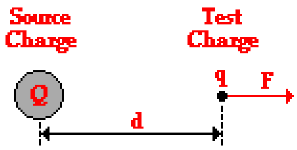

Figure 2.1: Forces between source charge and test charge.

The component of the electric field in a direction is the negative of the rate of change of the potential (potential difference) in that direction. The electric field along the x direction is

$$E_x = -\frac{dV}{dx} \tag{2.2}$$

because of the steady-state requirement that the electric field be normal to the surface of the conductor (and zero inside), regions where the surface has a small radius of curvature (i.e. points and corners) have a high divergence of the field, which from Gauss' Law means a significant local charge density.

2.2 Insulators in electrostatics

The main purpose of the electrostatic analysis in any insulated conductor is to verify that a breakdown in the insulation is prevented.

The insulation materials are dielectrics that resist really well the flow of free electrons. However, they are not able to resist indefinitely amounts of voltage. Every insulator has a limit marked by the property dielectric strength or breakdown voltage, which specifies the maximum voltage per unit length (electric field) that it can stand without suffering a breakdown (current flow inside the insulator).

To sum up, the breakdown strength of the insulator must not be exceeded, i.e. the electric field has to be smaller than the dielectric strength of the insulation material along the complete domain of the problem.

When there is only one insulating material between the charged conductor and the grounded surface, the electric field distribution will be constant in points subject to the same voltage. It can be calculated by

$$E = \frac{V}{d} \qquad (KV/mm) \tag{2.3}$$

where E the electric field and it must be smaller than the breakdown strength of the insulation material.

If instead of one having only one material as insulator, there are two different insulator materials in series the electric field distribution will not be constant anymore.

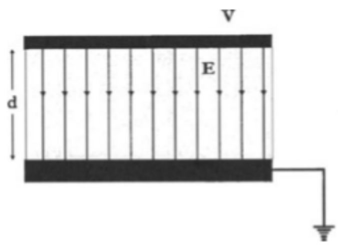

Figure 2.2: Electric field in an insulated conductor.

The relation between the fields in both insulators is given by $\frac{E_1}{E_2} = \frac{\varepsilon_2}{\varepsilon_1}$. This means that the electric field will concentrte more on the insulator with the smaller permittivity. The permittivity indicates how easily a material can become polarized by imposition of an electric field on an insulator.

Using this formula it is possible to derive one to calculate the electric field in each insulator

$$E_1 = \frac{V}{d_1 + d_2 * \frac{\varepsilon_1}{\varepsilon_2}} \qquad (KV/mm) \tag{2.4}$$

The electric field has to be normal to the surface of the conductor, regions with a small radius of curvature, i.e.points and corners, have a high local charge density, i.e. the electric field concentrates in this points, as we will see in the numerical analysis.

Chapter 3

Heat transfer theory

3.1 Basic concepts of heat transfer

Heat transfer is a well known part of industrial engineering and there is many information available concerning this topic [3]. Here I will present the basics of heat transfer and I will explain the correlation between thermal-electrical systems, which I will use to get a simplification of the generator that I am analyzing, to obtain some approximate analytical results.

Heat transfer is thermal energy in transit due to the spatial temperature difference, either in the same medium or between two different mediums.

3.1.1 Modes of heat transfer

There are three different types of heat transfer, these are called modes. When the heat transfer occurs in a stationary medium, solid or fluid, we refer to it as conduction. Convection is used when the heat transfer occurs between a surface an a moving fluid, due to the temperature difference between them. The last mode is thermal radiation, this is the heat transfer, in the form of electromagnetic waves, between two surfaces at different temperatures.

Conduction

It is due to the temperature difference between two regions and it results in a heat flow in the opposite direction of the temperature gradient (from the region with the highest temperature to the region with the lowest temperature)

The flow of heat follows the heat transfer laws and it is possible to calculate once the temperature distribution along the system is known.

The law that governs the relation between the temperature gradient and the heat flow is called the Fourier's law. The general equation for heat conduction in Cartesian coordinates is

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+q_v=\rho c_p\frac{\partial T}{\partial t} \tag{3.1}$$

For an isotropic and homogeneous solid (constant thermal conductivity) it takes the following form

$$q(W/m^2)=-\nabla T(K/m)\cdot k(W/m\cdot K) \tag{3.2}$$

where q is the local heat flux density, and it's relation to the inverse of the gradient is the thermal conductivity k, a property of the material.

For a planar uni dimensional wall, the equation is expressed as

$$q_x = -\frac{dT}{dx} \cdot k \cdot A \tag{3.3}$$

being q_x the heat flux (W) in the x direction and A the cross-sectional area of the wall. For stationary conditions the temperature gradient can be expressed as

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L} \tag{3.4}$$

where T_2 and T_1 are the wall temperatures and $T_2 > T_1$. The uni dimensional heat flux through a wall will be therefore

$$q_x = -\frac{\Delta T}{L} \cdot k_x \cdot A \tag{3.5}$$

with k_x is the thermal conductivity in the x direction, for anisotropic materials.

Convection

The equation that governs this mode is the Newton's law of cooling, and it takes the form

$$q = h \cdot (T_s - T_\infty) \tag{3.6}$$

where q is the convective heat flux (W/m^2), and it is proportional to the temperature difference between the surface of the solid and the fluid. T_s and T_∞ are the temperature of the surface and the temperature of the fluid respectively, and the parameter h ($W/m^2 \cdot K$) is called the convection heat coefficient and it is not a property of the material unlike the conductivity pressent in Fourier's law, it's value depends on the geometry of the surface, the characteristics of the fluid motion and on it's properties: velocity, density, kinematic and dynamic viscosity and specific heat.

The study of the convection heat in a system reduces to study the value of the convection coefficient, and there are many empirical formulas that can be used to approximate it.

Radiation

Any matter at nonzero temperature will emit energy in the form of radiation heat, this energy is transported by electromagnetic waves, as opposed to convection or conduction, this type of heat transfer does not require a medium, it can also occur on vacuum. The equation that rules the radiation heat transfer is

$$q = \epsilon \cdot \sigma \cdot ({T_s}^4 - {T_{sur}}^4)) \tag{3.7}$$

where q is the radiation heat per unit area (W/m^2), ϵ is the materials emissivity, σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \cdot 10^{-8}(W/(m^2 \cdot K^4))$, T_s is the temperature of the surface and T_{sur} is the temperature of the surroundings.

The radiation heat exchange can also be expressed in terms of the radiation heat transfer coefficient h_r

$$h_r = \epsilon \cdot \sigma \cdot (T_s + T_{sur})(T_s{}^2 + T_{sur}{}^2) \tag{3.8}$$

with this approach we can modeled the radiation mode in a manner similar to convection, now the heat is proportional to a temperature difference. However, the radiation heat transfer coefficient depends stongly on temperature, whereas the convection coefficient does not

$$q_{rad} = h_r \cdot A \cdot (T_s - T_{sur}) \tag{3.9}$$

3.2 Thermal-Electrical analogy

3.2.1 Thermal resistances

From (3.5) one can derive a correlation between the heat flux the electric current as well as between the temperature difference and the potential difference. We can asociate a thermal resistance to the heat transfer, with units (K/W), analog to the electric resistance. $A = \frac{V}{R}(\Omega)$.

The thermal resistance to heat conduction on a planar wall can be derive from (3.2)

$$R_{cond} = \frac{\Delta T}{q_x} = \frac{L}{k \cdot A} \tag{3.10}$$

in a cylindrical wall the thermal resistance has the following formula

$$R_{cond} = \frac{ln(\frac{r_{ext}}{r_{int}})}{k \cdot 2 \cdot \pi \cdot L} \tag{3.11}$$

being r_{ext} the external radio, r_{int} the internal radio L the length of the cylinder and k the thermal conductivity of the material in the radial direction.

In the same way it is possible to associate a thermal resistance to convection and radiation, they can be calculated using the following formulas

$$R_{conv} = \frac{1}{h \cdot A} \quad R_{rad} = \frac{1}{h_r \cdot A} \tag{3.12}$$

There is still one last type of thermal resistance and this is the contact resistance between two walls. Normally when it comes to heat transfer analysis the walls are assumed to be in perfect contact, and this resistance is neglected. This rarely happens in reality since for this assumption to be correct it would be required that both surfaces be perfectly smooth. When two real surfaces are pressed together peaks on each surface will contact and form areas of high thermal conductivity while depressions will be occupied by air. As air is a poor thermal conductor this will increase the resistance to heat flow.

$$R_{cont} = \frac{1}{h_c} \tag{3.13}$$

here h_c is the thermal contact conductance and is often determined experimentally. I will not enter, during the analysis part, in the evaluation of the contact resistance.

Empirical methods to calculate the thermal convection resistance

To calculate accurate approximate values of the convection thermal resistance, is determinant to to resolve the the heat transfer problem inside the machine.

The main difficulty in calculating the thermal convection resistance is to calculate the thermal convection coefficient, and tipically this coefficient is calculated using numerical methods like CFD (computational fluid dynamics). The convection coefficient depends on some parameters that relate:

a) The properties of the fluid: viscosity, density and specific heat.

b) The nature of the fluid motion: velocity and whether it is a laminar, turbulent or a transition flow.

c) The surface in contact with the fluid, its form and roughness.

d) The temperature difference between both surfaces.

The most common method to determine this value analytically is by using some dimensionless numbers.

The convection coefficient will be extracted from its relation with the dimensionless Nusselt number (Nu), the ratio of convective to conductive heat transfer at a boundary in a fluid. Convection includes both advection (fluid motion) and diffusion (conduction).

$$h = \frac{Nu \cdot k_{air}}{D} \tag{3.14}$$

where D is a characteristic dimension of the surface (like the diameter in a cylinder) and k_{air} is the thermal conductivity of the fluid at film temperature $T_f = \frac{(T_s - T_\infty)}{2}$, where T_s and T_∞ are the surface temperature and the fluid temperature.

Nusselt number is related with other adimensional numbers:

1) In forced convection, it is related with the Reynolds and the Prandtl numbers.

2)In natural convection, with the Grashof and the Prandtl numbers.

The Reynolds number (Re) is the ratio of inertial forces to viscous forces within a fluid which is subjected to relative internal movement due to different fluid velocities

$$Re = \frac{v_{air} \cdot D}{\nu} \tag{3.15}$$

The Pradndtl number (Pr) relates the viscosity of a fluid with their thermal conductivity, in heat transfer problems it measures the thickness of the boundary layer

$$Pr = \frac{\nu}{\alpha} \tag{3.16}$$

where ν is the kinematic viscosity of the fluid and α is the thermal diffusivity.

The Grashof number (Gr) , is a nondimensional parameter that represents the ratio between the buoyancy force due to spatial variation in fluid density (caused by temperature differences) to the restraining force due to the viscosisty of the fluid

$$Gr = \frac{g \cdot \beta \cdot (T_s - T_\infty) \cdot D^3}{\nu^2} \tag{3.17}$$

where g is the gravity acceleration $g = 9,8m/s^2$, β is 1/T, being T the temperature for which I want the coefficient, ν is the kinematic viscosity of the fluid and D is a characteristic dimension of the surface.

3.2.2 Thermal capacities

The term thermal capacity is included as a tool to analyze transitional heat transference, it represents the capacity of the different parts of the system to store heat by increasing it's temperature. The thermal capacity of a medium $C = \rho \cdot V \cdot c_p$depends on the properties of the material: the density ρ, the specific heat c_p; and on the volume.

3.3 Thermal analysis of electrical machines

There are two main different types of thermal analysis when it comes to electrical machines; analysis by means of algebraic methods and analysis using numerical methods. Both methods can achieve a great precision, and it is normal to use both when designing an electrical machine. Numerical methods usually require more computational resources but less preparation for the set up.

In order for the analytical analysis to be precise, it is required a long preparation time, to create a representation of the machine, that is possible to solve without many computational resources.

The algebraic methods consist on lumped parameter thermal networks, that connect the different parts of the machine. Here, each element of the machine is an independent control volume, normally with a cylindrical form. Through this thermal resistances, one can analyse the thermal interactions between the different elements of the machines.

In a thermal network, it is possible to lump together components that have similar temperatures and to represent each as a single node in the network. These thermal networks are equivalent to the electric networks, as indicated in the section 2.2. The resolution method is using analogies to Ohm's law and other electrical techniques to resolve circuits.

These thermal networks can be either really simple as the one in 3.2 or complicated networks that represent with great accuracy the thermal relation between all the components like in 3.1.

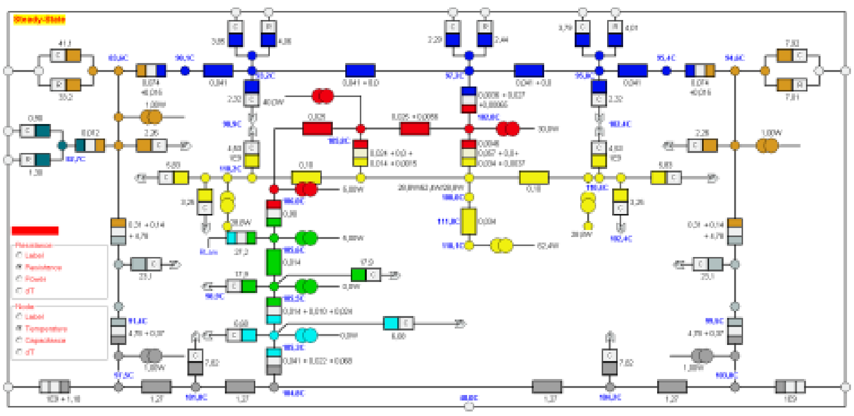

Figure 3.1: Motor-CAD thermal resistance network representation of an electrical machine

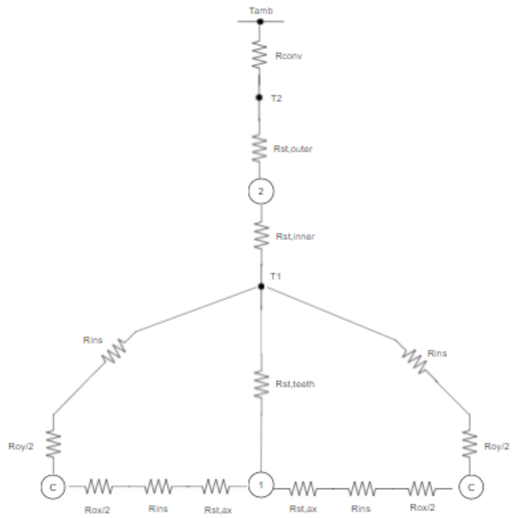

Figure 3.2: Simple thermal circuit for a generator

The numerical methods can be either CFD (computational fluid dynamics) as in figure 3.3 or FE (thermal finite element analysis) as in figure 3.4. They have different purposes but the goal is the same and it is usual to couple both studies.

CFD techniques are used to calculate the parameters related to the fluid motion, such as the heat convection transfer coefficient between the external air and the surface of the generator or the convection coefficient between the water in a cooling channel and the coils. For example, the water flow is defined by the properties of the water, the geometry at study, the velocity of the flow, the temperatures reached in the surface at study and in the fluid.

Once this parameters are calculated (their accuracy is crucial to achieve an accurate solution), they can also be calculated with empirical formulas, the values are used as an input to perform the finite element analysis on the machine to get an accurate representation of the temperature distribution and the heat fluxes.

One example of a programme that perform this kind of numerical analysis is Ansys Fluent, it can perform the CFD analysis in fluid zones and the finite element analysis in the rest of the machine.

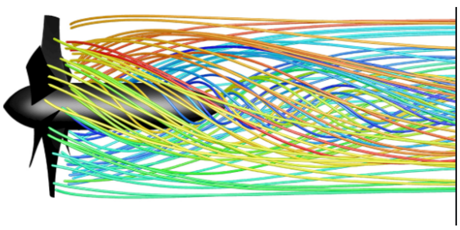

Figure 3.3: Velocity distribution on a turbine (ANSYS)

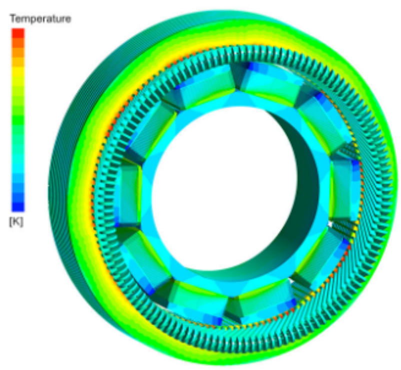

Figure 3.4: Temperature distribution on a generator (ANSYS)

Chapter 4

Classification by cooling system

The electrical machines can be classified by many means, one of them is the type of cooling medium they use. The usual refrigerants are: air, hydrogen and water; however, there are other refrigerant mediums, like synthetic diamond particles or oil. In this thesis I will consider the differentiation between indirect cooling and direct in slot cooling.

In many occasions, especially for large machines with high power capacity, both systems are implemented in different parts of the machine, and together contribute to the well-functioning of the generator.

4.1 Indirect cooling systems

Generators are referred to as being indirectly or conventionally cooled if the windings are cooled by flowing any kind of cooling medium through the air-gap between the stator and the rotor and through the stator surface, this includes cooling jackets that may carry a cooling liquid like water, where the heat created within the conductors must first pass through the insulation and the stator core.

There are two main types:

1) Open ventilated, in an open ventilated cooling system, atmospheric air or another gas like hydrogen is used and the exhaust is released back into the atmosphere. Motors and modern generators rated less than about 100 MVA are almost always cooled by air flowing over the rotor and stator. This is called indirect cooling since the winding conductors are not directly in contact with the cooling air due to the presence of electrical insulation on the windings. The air itself may be continuously drawn in from the environment and then force out of the machine, that is, not recirculated. Forced air cooling uses forced air convection, installing a blower or fan inside of the wind turbine, when the air passes the heat surface at a high speed, it can destroy the boundary layer and reduce the thermal resistance and increase the convective heat transfer coefficient. This cooling system implies that the air has to be filtered to remove humidity.

Almost all large turbogenerators use recirculated hydrogen as the cooling gas. This is because the smaller and lighter hydrogen molecule results in a lower windage loss and better heat transfer than air. It is then cost effective to use hydrogen in spite of the extra expense involved, due to the few percent gain in efficiency.

2) Totally enclosed, some generators don't allow new air to enter inside the engine, instead, they recirculate the same air, which might be internally cooled by

fans and heat exchangers inside the machine. This avoid the contamination of the machine, but increases the volume of the machine and therefore decreases the power density per unit volume.

Air cooling technology is simple, the initial investment and operating costs are low, and easy to maintain and manage . But the cooling effect is influenced by the external environment, with big restriction and small cooling capacity. Open air circulation process may cause corrosion problems in the cabin interior equipment, as the heat evacuation is not uniform, the temperature distribution will also be nonuniform, which can cause material deformation.

4.2 Direct in-slot cooling system

Liquid cooling methods include water or oil going through cooling channels that go directly through each coil of the stator to improve the heat evacuation in the main source of heat. These forced liquid cooling methods indeed improve the heat transfer performance of electric machines comparing to machines with natural convection or forced convection outside the slots.

If the temperature in the generator increases too much, insulation degradation of the coil accelerates, resulting in insulation breakdown, or the cooling water temperature of the stator coil exceeds its boiling temperature resulting in a failure to provide cooling. Therefore the generator is designed so that temperature of each part is suppressed within the limit.

The main purpose of cooling systems design is to decrease the resistance between the cooling medium and the heat source, these steel or copper tubes that contain the cooling, may lead to contact resistance between the cooling channel and the copper turns. In order to decrease this, some machines are directly cooled by cooling liquid passing freely through the conductors and the rest of the machine, this is normally done with oil instead of water to avoid corrosion.

Chapter 5

Electric insulator materials and their properties

There are several properties of insulator materials that is crucial to understand, since a good knowledge of them leads to higher probability of choosing the right material."[8]"

5.1 Electric properties

Insulator materials are substances through which electric current cannot pass easily. Most of their properties are affected in the same way by several operating conditions:

- Temperature, as the temperature increases the resisttivity, dielectric strength decreases.
- Moisture, resisttivity and dielectric strength reduced if the material absorbs moisture.
- Applied Voltage.
- Ageing, as the insulation aged the resistivity and dielectric strength falls.

5.1.1 Resistivity

The resistance offered to the electric flow through the material, in insulators it is around $10^{10-20}\ \Omega \cdot m$.

5.1.2 Dielectric strength

For high voltage engines, this is one of the most important and differentiating properties, the dielectric strength define the thickness of the insulation.

It is the minimum voltage that applied to the insulation will provoke the destruction of it's insulating properties, (the current is able to go through the insulator). It's unit is KV/mm.

5.1.3 Relative permittivity

The dielectric constant or relative permittivity indicates how easily a material can become polarized by imposition of an electric field on an insulator. Relative permittivity is the ratio between the permittivity of the substance and the permittivity of the vacuum.

5.2 Thermal properties

5.2.1 Heat resistance

This is the capacity of an insulating material to withstand temperature variation within desirable limits, without damaging it's other important properties. The insulators can be classified in function of their heat resistance, from lower heat resistance to higher: class Y,A,E,B,F,H,C. For the application under exam, the attention should be laid on materials of class F or higher, which are able to withstand temperatures >150°C.

5.2.2 Thermal conductivity

This characteristic is the one that influences most the thermal design of the high voltage generator. Heat generated due to the I^2 losses in the conductors will be dissipated through the insulator itself, how effectively the heat is removed will depend on the thermal conductivity of the insulator. It is measured in W/mK.

5.2.3 Materials

The three materials that I am going to use to design the insulation of the generator are: PVC, Mica and Mylar.

PVC

PVC is one of the most famous insulator materials worldwide, this is due to its' cheap price and good insulation properties.

Electric properties

The breakdown strength of PVC is ≈ 10-30 KV/mm.

The relative permittivity is 2.7.

Thermal properties

PVC is not a material that stands really high temperatures, it's normal working temperatures are around 60°C and the thermal conductivity is quite low, between 0.14-0.28.

Mica

Mica paper is 100% mica. Mica tape is an inorganic high dielectric tape manufactured with mica paper and laminated to various reinforcing substrates to enable ease of handling. Tapes are available in fully cured, VPI, resin rich (press cure) and B stage.

Electric properties

The electric properties of mica tape or mica based insulator varies a lot between different manufacturers, the general breakdown voltage is really high and can go from 30 KV/mm to 120KV/mm.

Thermal properties

This information comes from a preoduct information sheet of Proffesional plastics [7]

Mica sheets or "stove mica" is used for electrical insulation where high temperatures are encountered. Thermal conductivity is high so mica insulators are useful for heat sinking transistors or other components with electrically conductive cases. The thermal conductivity in mica can be between 0.2 and 0.5 (W/mK), this value is really high for a dielectric material.

It is a class H or C insulator since it's heat resistance can reach the 180°C

Mylar

This information is extracted from DuPont Teijing films. **Electric properties:**

The dielectric strength of Mylar® polyester film is a function of the film thickness. As with most materials, the AC dielectric strength in kV/mm decreases as the film thickness increases. For instance, 6 μm Mylar® film has a dielectric strength of over 600 kV/mm while 350μ m Mylar® has a dielectric strength of about 80 kV/mm at 25°C.

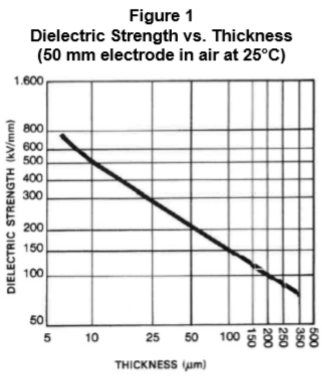

Figure 5.1: Dielectric stength vs thickness

The effect of film temperature on the dielectric strength of Mylar® polyester film is shown in Figure 2; there is a slight decrease in dielectric strength from room temperature up to 150°C.

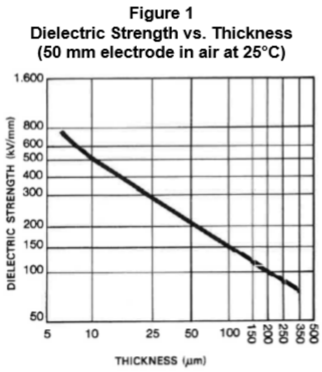

Figure 5.2: Dielectric strength vs thickness

At a constant frequency, the dielectric constant increases as temperature of the film increases above 65 °C.

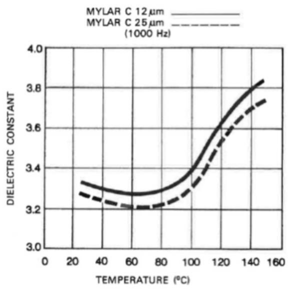

Figure 5.3: Dielectric constant

Thermal properties The maximum service temperature usually recommended for Mylar® polyester film is 150°C . Where extensive exposure, severe environmental conditions, or unusual physical requirements are involved, it may be necessary to reduce service temperatures. However, coatings are available to increase the resistance of Mylar® to the effects of heat aging.

The thermal conductivity is ≈ 0.16 (W/mK)

Material	**Breakdown Strength (KV/mm)**	**Permitivity**
Mica	30-120	5-7
Mylar (polyester film)	30-600	3.2-3.8
PVC	10-30	2.7

Table 5.1: Summary of electric properties insulator materials

Chapter 6

Set up indirect cooling system

The electric generator is a three phase, direct driven, surface mounted permanent magnet machine. The winding arrangement is a concentrated windings characterized by a number of coil per pole per phase equal to 1. The number of slots is equal to 252 and the number of poles is 84.

The FEA for the electrostatic, electromagnetic and thermal analysis are conducted only on a small section enhancing the proprieties of symmetry of the electromagnetic field. The 2D section of the generator object of interest is reported in Fig. 6.1 here it is possible to recognize the stator, the rotor the PM and the coils. In each slot is placed a coil and each coil has 75 turns.

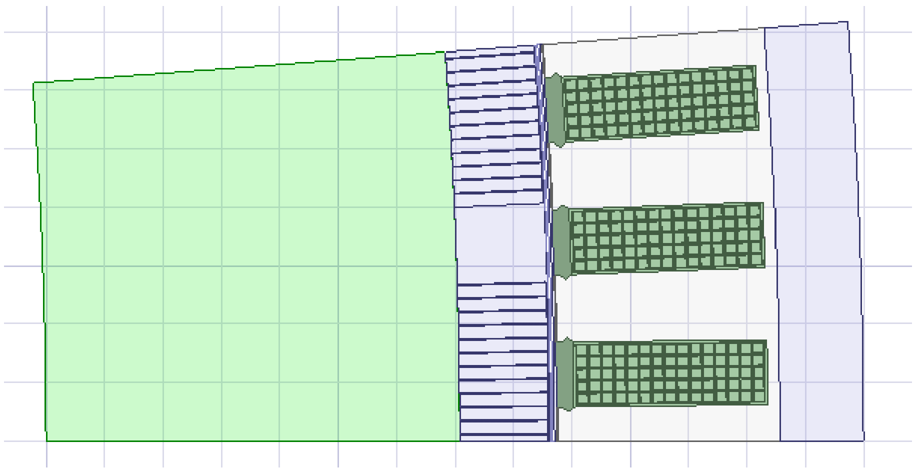

Figure 6.1: One pole of the generator

6.1 Electrostatic analysis with algebraic methods

Each coil is divided in 75 turns. It is possible to define two types of insulation:

1. Groundwall insulation: is the component that separates the copper conductors from the grounded stator core. Thus it is critical to the proper operation of the generator, that it fulfills the thermal, electrical and mechanical requirements

2. Turn insulation: separating adjacent turns in a coil. The purpose of the turn insulation is to prevent shorts between the turns in a coil. The power frequency voltage across adjacent turns in a form-wound multiturn coil is well defined.

Essentially, one can take the number of turns between the phase terminal and the neutral and divide it into the phase–ground voltage to get the voltage across each turn.

There are many insulation materials available nowadays. In this case, and due to the high voltage the coil is subject to, I have decided to start analyzing the coil using Mica, since it is one of the most popular and has great insulation and thermal properties. However the electrostatic simulation will be performed not only using MICA, but also other cheaper materials as PVC, and Mylar polyester film.

The sequence of analysis will be:

1. MICA as groundwall and turn insulation.

2. PVC in both the groundwall and turn insulation.

3. PVC in the groundwall insulation and mica in the turns.

4. Mylar for the groundwall and turn insulation

5. Mylar in the groundwall insulation and MICA in the turns.

The purpose of the electrostatic analysis in any insulated conductor is to verify that the breakdown strength of the insulator is not exceeded, i.e. that the electric field is smaller than the dielectric strength of the insulation material along the complete domain of the problem.

To illustrate this I will use the following formula

$$E = \frac{V}{d} \qquad (KV/mm) \tag{6.1}$$

where E the electric field V is the voltage and d is the thickness of the insulation, and it must be smaller than the breakdown strength of the insulation material.

6.1.1 Analytical results

In order to design the thickness of the insulation and to validate the results obtained from the FEA I have performed an analitical electrostatic modeling.

To model the slot I assume that the slot at both extreme sides is equivalent to a parallel plate capacitor. The insulator is placed in the middle of this two plates (conductors and stator). In this case we have two different layers, the turn insulator and the groundwall insulator.
Fig.6.2 reports a simplified version of the slot in which is possible to identify the dimensions ans the winding distribution. 6.2

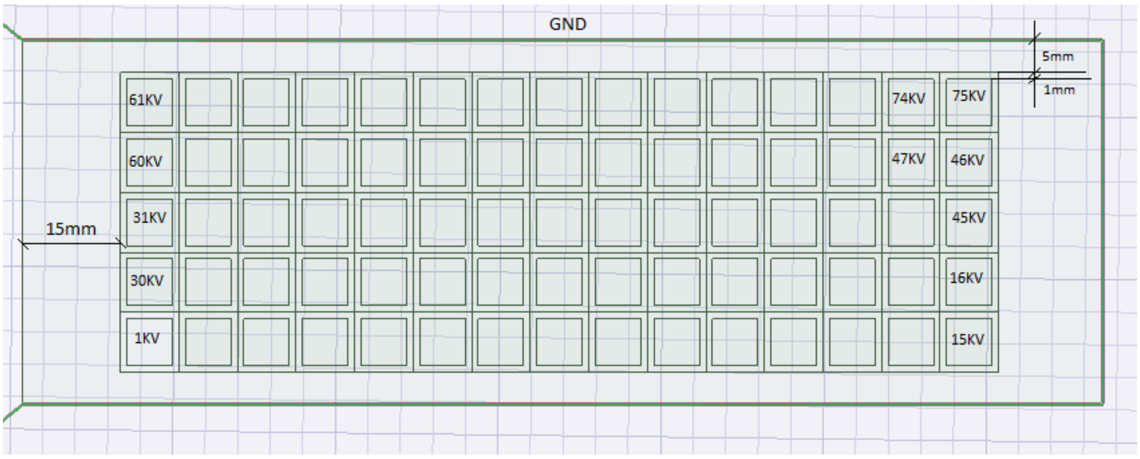

Figure 6.2: Slot

As I am going to analyze the electric field using different materials, the expected electric field distribution and values will also change, depending mostly in whether we use two different materials for the different layers of insulation or the same for both.

To calculate the electric field in the insulation, I assign a voltage to every turn, having in mind that the voltage difference between two adjacent turns is 1 KV and that the maximum voltage in the winding is 75 KV.
In the figure 6.2 the distribution of voltages is schematised, we can see that the highest voltage is reached in the upper right corner and that it decreases 1KV every turn to the left until we reach the left corner, then it continues to decrease 1KV in the turn below and again to the adjacent turns this time to the right. This procedure continues until the end of the coil in the lower left corner.

For this first analysis, the thickness of the turn insulation will be of 1mm, while the groundwall insulation will have a thickness of 15 towards the stator yoke and airgap and of 5 in towards the stator teeth. However this values will change as the analysis move forward to find the optimal values.

When the material for the insulators is the same in both the groundwall and turns the electric field distribution will be constant in points subject to the same voltage. The equation that leads this behaviour is

$$E = \frac{V}{d} \qquad (KV/mm) \tag{6.2}$$

However when we use to different insulator materials in series, such as PVC and mica, with different permittivities, the distribution of the electric field will not be constant anymore.

The relation between the fields in both insulators is given by $\frac{E_{mica}}{E_{PVC}} = \frac{\varepsilon_{rPVC}}{\varepsilon_{rmica}}$

Using this formula it is posible to derive one to calculate the electric field in each insulator

$$E_{mica} = \frac{V}{d_{turn} + d_{groundwall} * \frac{\varepsilon_{rmica}}{\varepsilon_{rPVC}}} \qquad (KV/mm) \tag{6.3}$$

With this in mind I have calculated the expected field using only one material (mica, PVC or MYLAR polyester film). Substituting V=75KV the maximum voltage difference between the coil and the grounded stator, and d=6mm, as the minimum

distance between stator and conductors (the sum of the turn insulator thickness and the groundwall insulator thickness) in 6.2.
Results

$$E = \frac{75000}{0.006} = 12.5 \quad (kV/mm). \tag{6.4}$$

This is the maximum electric field reached in the groundwall insulator under the hypothesis of homogeneous distribution of the electric field.

To calculate the maximum value of the field between turns we use the same approach but this time with V=75-46=29 kV, since it is the maximum voltage difference between turns, with the current winding configuration, and d=2mm.

$$E = \frac{29000}{0.002} = 15 \quad (kV/mm). \tag{6.5}$$

The maximum value of the field expected using PVC in the groundwall insulation and mica in the turns is extracted from 6.3. Where ε_{rmica}=5.7 and ε_{rPVC}=2.7 V=75kV $d_{turn} = 1mm$ and $d_{groundwall} = 5mm$

$$E_{mica} = \frac{75}{1 + 5 * \frac{5.7}{2.7}} = 6.49 \qquad (kV/mm) \tag{6.6}$$

$$E_{PVC} = \frac{75}{5 + 1 * \frac{2.7}{5.7}} = 13.7 \qquad (kV/mm) \tag{6.7}$$

As for mica and MYLAR: ε_{rmica}=5.7 and ε_{rMYLAR}=3.2, V=75kV, $d_{turn} = 1mm$ and $d_{groundwall} = 5mm$

$$E_{mica} = \frac{75}{1 + 5 * \frac{5.7}{3.2}} = 7.57 \qquad (kV/mm) \tag{6.8}$$

$$E_{MYLAR} = \frac{75}{5 + 1 * \frac{3.2}{5.7}} = 13.486 \qquad (kV/mm) \tag{6.9}$$

When we put two different insulator in series the electric field accumulates in those with lower relative permittivity, which is normally the worst insulator. However the electric field in the turns is reduced using this configuration.

Table 6.1: Analytical electric field in the insulation

Component	Thickness x	Thickness y	Max.electric field (kV/mm)
Turn 1 dielectric	1	1	15
Turn (mica and mylar)	1	1	15
Turn (mica and PVC)	1	1	15
Groundwall mica	15	5	12.5
Groundwall PVC	15	5	13.7
Groundwall mylar	15	5	13.5

6.2 Thermal analysis using algebraic methods

Although it is not in the scope of this thesis to perform an exhaustive thermal analysis by means of a highly complicated thermal resistance network, I will perform a simplified analysis to verify the results that I will obtain in the simulation using FE and CFD.

The proposed model is intended to compute the generator over temperature in steady-state condition. For this reason, thermal capacitances have been neglected. The following hypotheses have been assumed.

- The stator and the rotor are thermally independent in this first analysis.
- The temperature distribution inside every element is linear.
- only a $\frac{1}{252}$ of the machine is modeled, the symmetry planes are set on the middle of two adjacent coils.
- The coils are rectangular and there is only heat flux in the x and the y direction.
- The stator teeth are cylindrical but only a portion of the cylinder is evaluated, this portion is related to the relation between the iron volume and the slot volume in the first part of the stator.
- The stator yoke is studied as a cylinder which has only heat flux in the radial direction.
- Each cylinder is thermally symmetrical in the radial direction.
- The heat is evacuated only by convection between the outer stator surface and the air.

The thermal resistance circuit results:

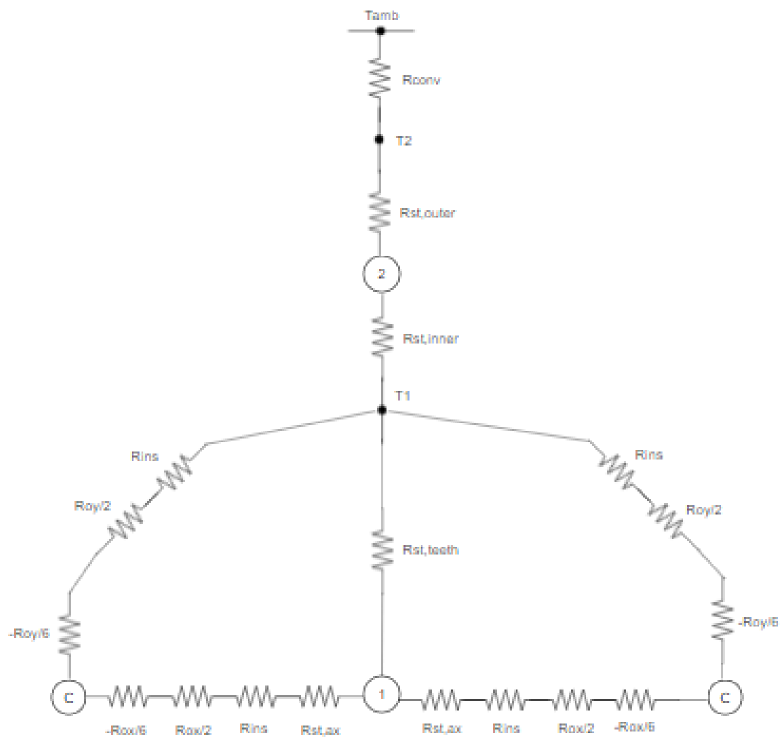

Figure 6.3: Equivalent thermal network for the simplified generator

Here the elements are represented by their averaged temperature, once this is obtain the maximum temperatures can be subtracted from them.

6.2.1 Thermal resistances

The most important step in the elaboration of the thermal circuit is to determine correctly the thermal resistance of each element.

Thermal conductive resistance of the coils

The coils are formed not only by copper but also by the insulating material that separates each turn; therefore, the conductivity can not be assumed to be neither the insulation conductivity nor the copper. To calculate it I have used a expression from [Motor-CAD, 2014], that relates the total thickness of each material in a certain direction and their conductivities with the effective conductivity of the coil in that direction.

$$k_{eff} = \frac{d_{total}}{\frac{d_{mica}}{k_{mica}} + \frac{d_{copper}}{k_{copper}}} \tag{6.10}$$

here d_{total} is the total thickness of both insulation and copper in one direction, d_{mica} is the total thickness of the insulation in one direction, and d_{copper} is the same for copper. The different k represent the conductivities of each material and the effective conductivity of the coil. As I said in the coil we will only have heat flux in the x and y coordinates,

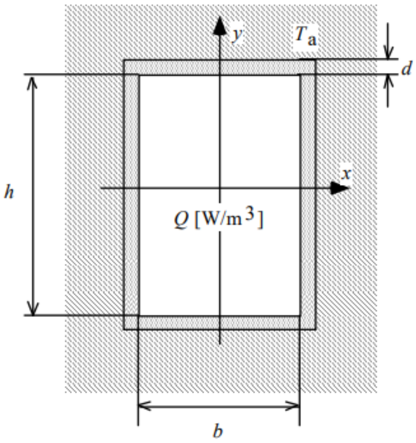

Figure 6.4: Rectangular Slot dimensions

For the slot at analysis h=166mm and b=56mm.

Table 6.2: Thickness and conductivity of mica and copper inside the slot

Component	$d_x(mm)$	$d_y(mm)$	k(W/mK)
Copper	42	132	390
Mica	10	30	0.34

The one dimensional thermal resistances of the slot material are [5]

$$R_x = \frac{b}{h \cdot k_{eff}} \quad R_y = \frac{h}{b \cdot k_{eff}} \tag{6.11}$$

where k_{eff} is the equivalent thermal conductivity of the slot material. The resistance of the grounwall insulation is

$$R_{ins,x} = \frac{d}{h \cdot k_{mica}} \quad R_{ins,y} = \frac{d}{b \cdot k_{mica}} \tag{6.12}$$

Normally the heat flux in the x direction is bigger that the heat flux in the y direction since the resistance is bigger in this one. The general resistance distribution in an element with and without inner source generation are represented in Fig.6.5.

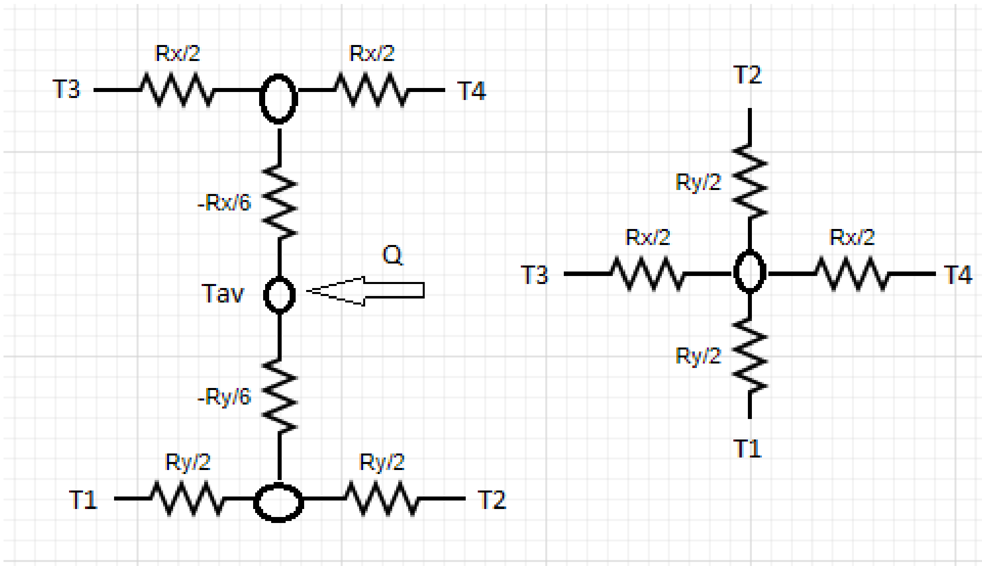

Figure 6.5: Node configuration for two dimensional flow with inner sources and without them

For the coil I have used the configuration with inner sources, and this is why I have a negative resistance in the thermal circuit.

Thermal conductive resistance in the stator teeth

The stator teeth receive the heat flux from the coils, they are simplified to a cylindrical form and the temperature distribution is supposed symmetrical in the radial direction.

$$R_{Steeth} = \frac{ln(\frac{r_{out,slots}}{r_{inner,stator}})}{\frac{2\pi}{n^o slots} \cdot k_{Fe} \cdot L \cdot \rho_{st}} \tag{6.13}$$

where ρ_{st} is the volume iron percentage over the hole volume (stator slots plus stator teeth)

Thermal conductive resistance in the stator yoke

The stator yoke is represented as a cylinder with radial heat flux, it is represented in the circuit by the average temperature of the cylinder in the radial direction. The resistance for the stator yoke upper and lower part is calculated with 3.11

Thermal convection resistance between the stator outer surface and the external air

The equation for the convection thermal resistance is

$$R = \frac{1}{h * A} \tag{6.14}$$

For this first part I will approximate the heat transfer coefficient by an average of the minimum and maximum values for air (10-100). At this point I don't perform a more exhaustive analysis of this parameter because the main goal for now is to obtain the average maximum temperatures that I will have in the machine using only air cooling systems.

Results

The values obtained for the resistance are listed in Table 6.3

Table 6.3: Values of the thermal resistance of several components calculated analytically

Resistance name	Component	Conductivity	Value (K/W)
$Rslot_x$	Coil	k_x=1,897	0,1185
$Rslot_y$	Coil	k_y=1,8741	1,0545
R_{ins}	Groundwall	0,34	0,0236
R_{Steeth}	Stator teeth	16,27	0,1169
R_{conv}	Stator yoke surface	h=50	0,11176
$R_{Fe,ax}$	Stator teeth	16,27	0,00704
R_{Syoke}	Stator yoke	16,27	0,0284

6.2.2 Heat losses

The copper losses are generated by the resistance of the conductors to the current flow. This resistance depends on the resisttivity of the material, which increases with temperature, the increase in resisttivity as a function of the temperature increase is

$$\Delta\rho(T) = \alpha(T - T_o)\rho(T_o) \tag{6.15}$$

where $\Delta\rho(T)$ is the resisttivity increase with respect to the initial temperature (normally 20 °C), $\rho(T_o)$ is the resisttivity at the reference temperature, and α is the temperature resistance coefficient.

Even though in most analysis I will neglect this dependance I will have in mind that the security coefficient has to be higher, when I consider the liability of a cooling system.

The general equation for the Joule heating is

$$Q = I^2 \cdot R \tag{6.16}$$

Where R is calculated by

$$\rho \cdot L/S \quad \Omega \tag{6.17}$$

where L is the length = 1,5m, S is the surface of the conductors and ρ is the electrical resistivity of copper= $1.72 * 10^{-8}$

The peak current that will flow through the conductors will be $I = 400A$, I use this value because it's the highest current that the copper will be subject to in stationary conditions; the current density in each turn is then $I/A = 400/7.39210^{-5} = 5.411(A/mm)$. Which is a value a bit higher above the recommended, normally 5(A/mm) in the copper of the coils for a totally enclosed solution.. The heat generation in the turns for the first analysis with a turn surface of: $7,39210^{-5}\ m^2$ is

$$
\begin{aligned}
&Q(turn) = I^2R = 400^2R = 400^2 \cdot 1.72 \cdot 10^{-8}\frac{1.5}{7,3453 \cdot 10^{-5}} = 55.844 \quad W \\
&V = L \cdot S = 1.5 \cdot 7,392 \cdot 10^{-5} \quad m^3 \\
&q(turn) = 503.64358 \quad kW/m^3
\end{aligned}
\tag{6.18}
$$

this is the heat generated by one turn, in total in the generator each coil has 75 turns and the generator contains 252 slots, therefore the total copper losses add to an amount of around 1MW which is about a 5.28 % of the total power (20MW).

There are other losses in the generator, these are

Magnet losses: 377W (per magnet, each magnet is divided into 23 segments)

$$
q(magnetsegment) = \frac{16.39W}{1.5 \cdot 8,5056e-4} = 12846 \quad W/m^3 \tag{6.19}
$$

Iron loss, is due to the rotation of the core hysteresis effect of eddy current, resulting in hysteresis loss and eddy current loss; Iron losses: 225W, distributed between the stator and the rotor.

Rotor losses

$$
q(rotor) = \frac{112.5W}{1.5 \cdot 0,11325} = 662 \quad W/m^3 \tag{6.20}
$$

Stator losses

$$
q(stator) = \frac{112.5W}{1.5 \cdot 0,061151} = 1230 \quad W/m^3 \tag{6.21}
$$

However, the percentage that this losses represent with respect to the total power is less than 0.16%. It is not the purpose of this thesis to do a precise calculation of the heat transfer inside the machine, accounting to all the losses, but rather, to give an understanding of the feasibility of different cooling systems, this is why, these losses will be neglected in the thermal analysis.

6.2.3 Implementation of the algebraic method

As a first step I will perform the thermal analysis, only on the stator part; which is by far the most delicate part in the heat transfer analysis, considering that the cooling is indirect and the heat generated is evacuated only by:

a) the heat conduction through the different materials

b) the natural convection between the external surface of the stator in contact with air.

In figure 6.6 are represented the simplified heat fluxes inside the machine. The only heat source I will take into account will be the copper heat losses in the coil. And I will introduce them as a inner source in the thermal circuit in 6.4

Solving the thermal circuit, it was possible to obtain the most characteristic temperature of each component , since the main purpose of this analysis is to verify the results that I get using Ansys Fluent, in Table 7.1 the averaged values of the temperatures in relation to the values obtained in the simulation with Ansys, Figure 6.7, can be found.

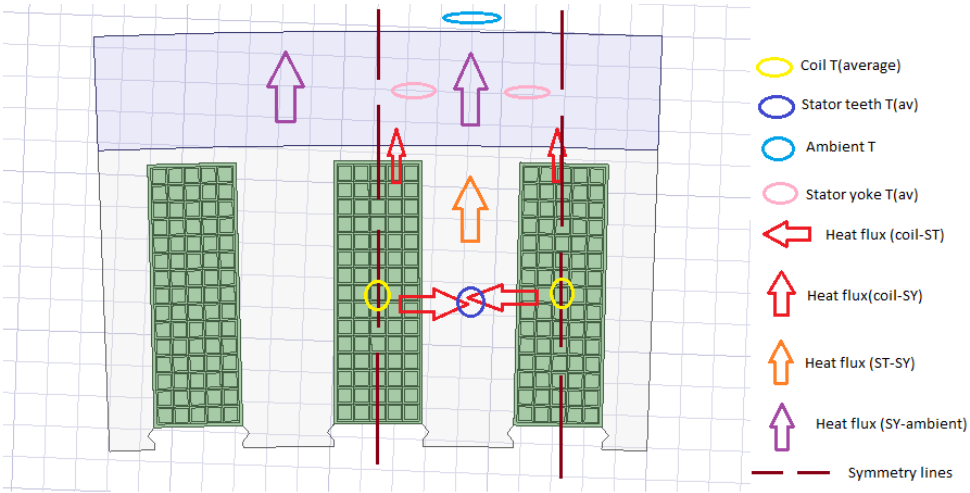

Figure 6.6: Thermal analysis clarification

Table 6.4: Analytical temperatures vs temperatures in the simulation

Component	Model temperature	Min. ANSYS	Max. ANSYS
Coil	1258	941	1245
Groundwall (coil-ST)	1200	910	1200
Stator teeth	1175	910	1127
Stator yoke	838	899	779

Looking at the results it is possible to guess that the approach used to calculate the resistance of the coils results in a bigger resistance than the actual value. However, I will accept this method because it is on the side of security, (higher resistance results in higher temperatures), and because it is not the purpose of this analysis to obtain precise results.

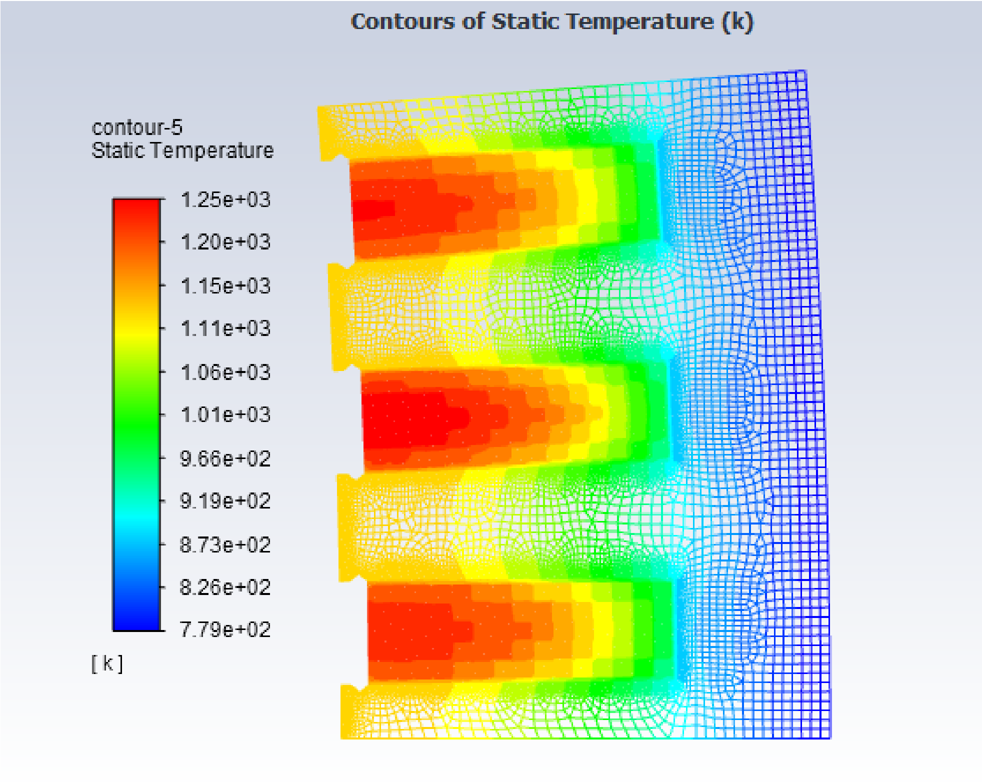

Figure 6.7: Thermal analysis with ansys fluent

Chapter 7

Indirect cooling

In this first part of the analysis I will try to design an air cooled machine that maintains it's temperature levels within an acceptable range; however, as it has been seen in the case set up, only the heat losses in the copper already rise the temperature levels enough to cause the failure of the whole machine.

7.1 Electrostatic analysis

The first step in the design of the insulation of a high voltage generator is to clarify the minimum amount of insulation that prevents electric breakdowns from occurring. I will perform this analysis with the ElectroStatic solver of Ansys. This solver is meant to solve the static electric field without current flowing in conductors (conductors are in electrostatic equilibrium). The conductors are considered perfect such that there is no electric field inside them.

The generator subject of study is a Permanent Magnet Direct Driven generator. It has a form wound stator with multiturn coils, distributed along 252 slots.

I have perform the electrostatic analysis on one slot of the generator, assuming that the symmetry properties allow me to look only at one half of one coil, since every coil occupies two slots.

The analysis sequence is the same as it was in the analytical part.

In this analysis the maximum values of the electric field are found in the corners of the turns with the highest voltage difference with the grounded stator or between the turns, however, this values could be reduced by rounding the corners of the turns by avoiding the concentration effect of the electric field in sharp corners.

7.1.1 Mica as groundwall and turn insulation.

Mica is one of the best insulation materials that have been discovered and are currently at use, not only for its electrical properties but also for the thermal.

Its breakdown strength is around 118 KV/mm, while the maximum electric field to which the insulation is subjected is $\approx$ 22.5 KV/mm in Figure 7.3 it can be seen with detail. Thus, the electrical safety requirements are completely fulfilled with MICA, we can say that the security coefficient using MICA is:

$$X_{MICA} = \frac{118}{22.5} = 5.244 \tag{7.1}$$

This value is quite high and allows us to consider using a cheaper material with worse properties. However, the design of the insulation depends as well on the thermal analysis, and the temperature reached in the generator depends highly on the thermal conductivity of the material. Therefore we have to consider all the options.

The distribution of the electrical field is quite smooth and the numerical results match the expected ones as it can be seen in Figure 7.1 and in Figure 7.2. In the Groundwall insulation the average value for the electric field is 12 KV/mm, which leaves us with a security coefficient of $118/12 = 9.83$ in the Groundwall insulation if the sharp edge in the right corner is overlooked. We can see that the point subject to the biggest electric field is the right upper corner of the coil, firstly because the voltage in that point is 75 KV (the maximum), but also because the electric field is non homogeneous in sharp edges since it tends to concentrate in those points,in this case we reach the value of 22.4 KV/mm .

Between turns the maximum voltage difference is around 24-29KV, and the electric field is $\approx$ 15 KV/mm in this point. The conclusion extracted from this values is that this configuration is using too much mica insulation and that the expense in electric insulation material can be reduced.

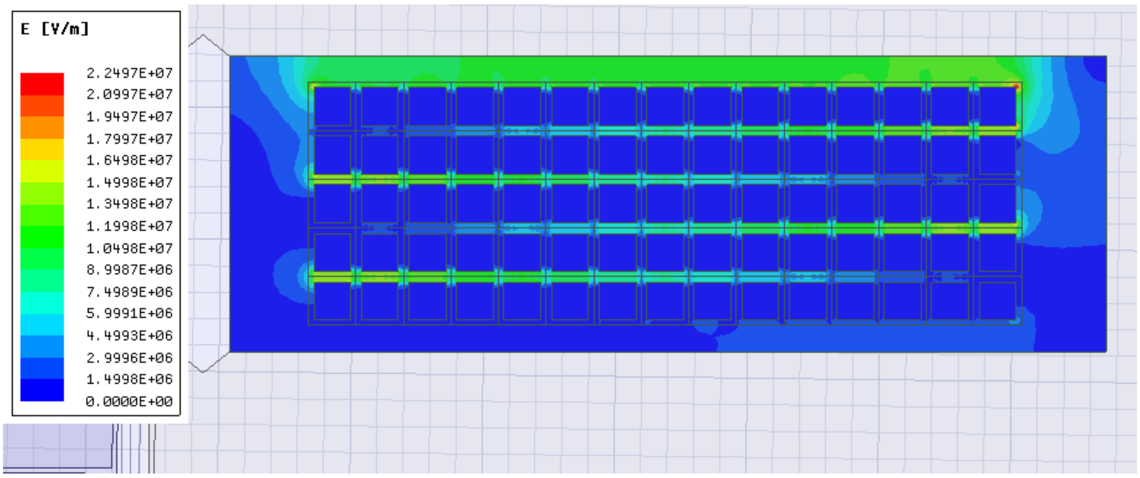

Figure 7.1: The magnitude of the electric field

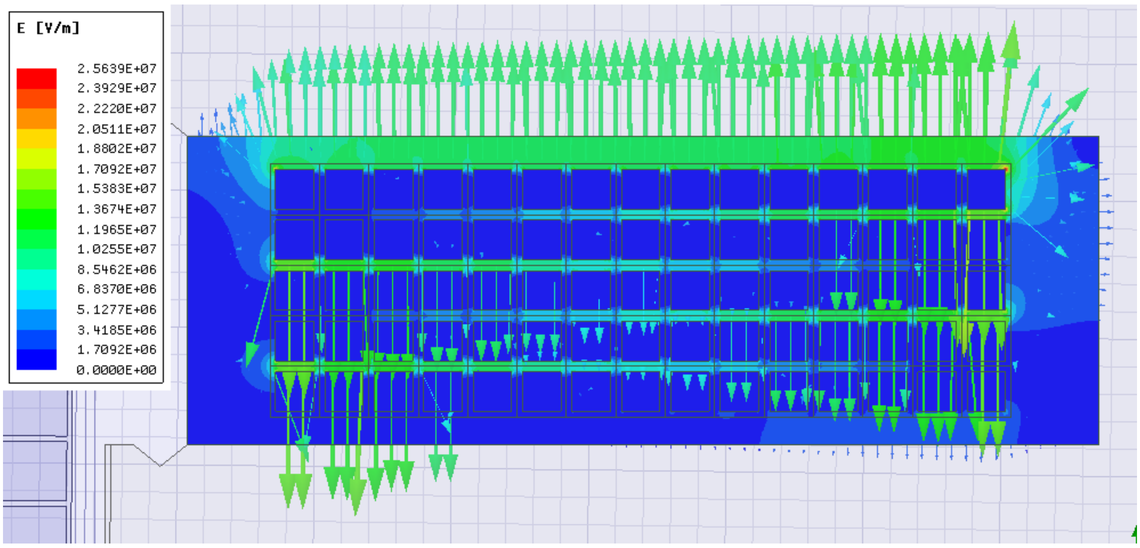

Figure 7.2: The electric field in vectors

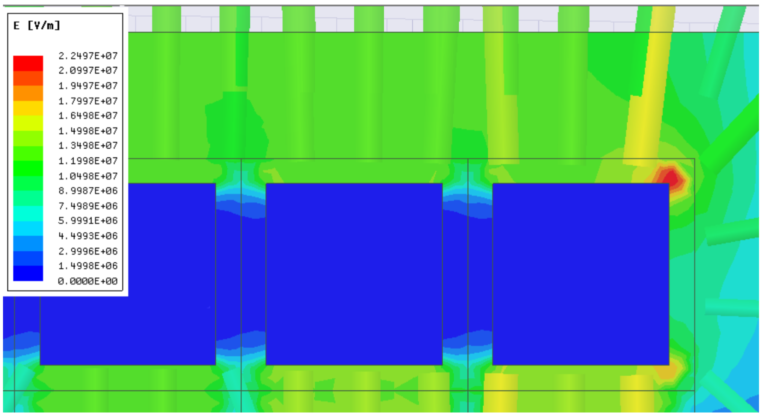

Figure 7.3: Maximum electric field in the turn insulation

7.1.2 PVC in both the groundwall and turn insulation.

In order to consider all the viable options, and having in mind the importance of making the project economically liable, I will perform the analysis using PVC, one of the cheapest insulation material, it does not have the best electrical or thermal properties, but it is widely used for many applications.

In this section I will perform the electrostatic analysis using it as the turn and groundwall insulation. Since we use the same material for both insulators the electric field distribution is not dependant on the material and is the same as in **??**

The average breakdown strength of PVC is ≈ 12-16 KV. The maximum value of the field reached in the insulation is≈ 22.4 KV.

The breakdown strength (12-16 KV) < 22.4 KV. Even if we test the generator with the best PVC insulator, with a breakdown voltage of 30 KV/mm, the security coefficient would be less than 2. Thus, we conclude that using PVC as both the groundwall and turn insulation would not be safe, and would most likely cause a failure in the generator.

7.1.3 PVC in the groundwall insulation and mica in the turns.

It is a common practice to insulate the sator windings using MICA in the turns and a cheaper material for the Groundwall insulation. In this case I will analyse the stator using PVC as the groundwall insulator. However the voltage applied to the windings is very high, and as it has been seen before PVC is not the safest material in this case.

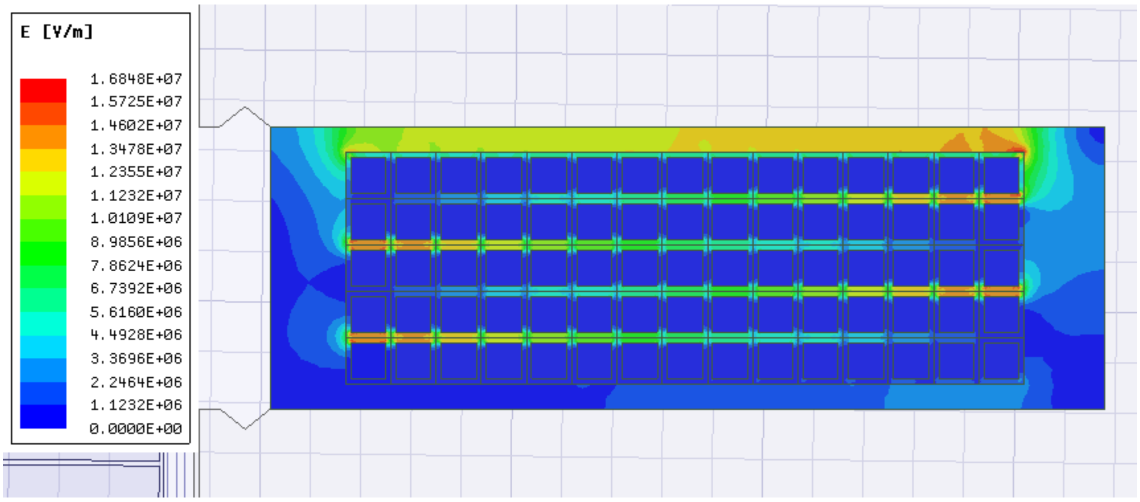

Figure 7.4: magnitude of the electric field

For this analysis we must differentiate between the maximum voltage applied in the groundwall insulation and in the turns insulation.

In this case the results in Figure 7.4 match also the expected ones, we can see that in the turn insulator (mica), the electric field has a smaller value than the one in the groundwall insulator (PVC) and that the relation between both is proportional to the relation between their permittivities.

At the groundwall the electric field reaches a value of $\approx$ 16.8 KV/mm, If we overlook the corner, the maximum value of the electric field in the groundwall is equal to 14KV/mm, even using the best PVC insulator in the market, the security coefficient would hardly reach 2 and the thickness of the groundwall would be too big to allow a good heat transference between the turns and the stator. However, with this configuration we have managed to reduce the general value of the electric field everywhere.

7.1.4 Mylar for the groundwall and turn insulation

This time I am going to use Mylar, a polyester film as groundwall and turn insulation, this material has good electric properties, the breakdown voltage can reach higher values than mica, depending on the thickness of the tape.

However, mylar tape is usually used for really small thickness, and although several layers could be an option, it would not be a smart idea to use it in a groundwall insulation of 15 mm thick.

Numerical results

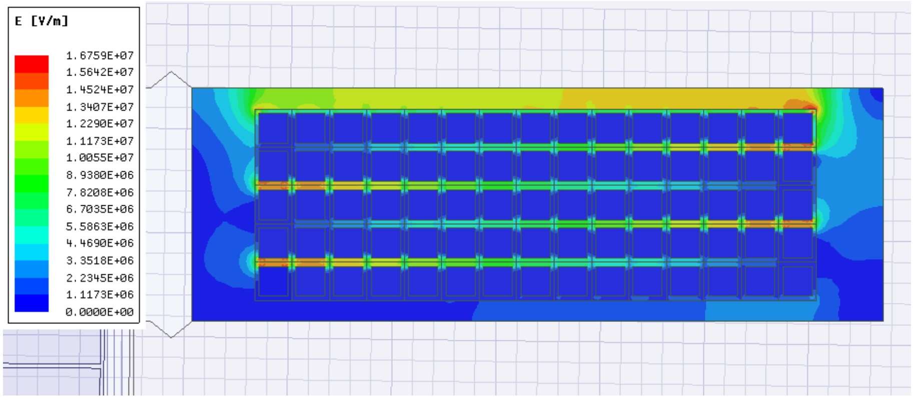

Figure 7.5: The magnitude of the electric field with mylar and mica

Table 7.1: Analytical electric field in the insulation

Component	Analytical results(kV/mm)	Simulation (kV/mm)	security coefficient
Turn mica	15	15	> 5
Turn PVC	15	15	≈ 2
Turn mylar	15	15	> 5
Groundwall mica	12.5	13	> 5
Groundwall PVC	13.7	14	≈ 2

7.1.5 Suitable slot dimensions for different materials

As it was seen mica and mylar are the safest materials, it's security coefficient is really high even when using such a high voltage as 75KV. In order to minimize the cost I will perform the same analysis to find the smallest thickness of the groundwall insulator that allows me to work safely.

Numerical results

From this analysis I have found out that using a insulator material of reasonably high breakdown voltage, we can reach the ideal electrostatic design, 1mm of groundwall insulator at both sides and 1mm of turn insulator thickness.

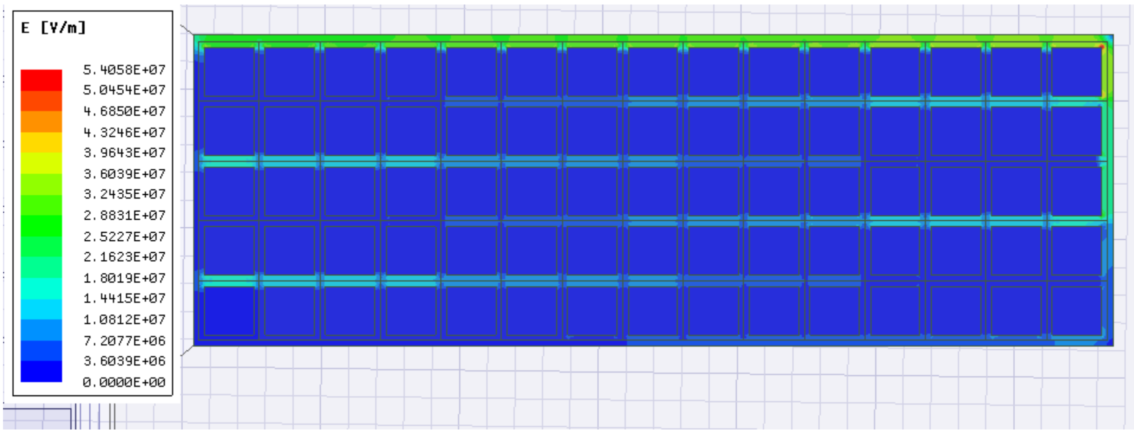

Figure 7.6: Electric field with the smallest insulator

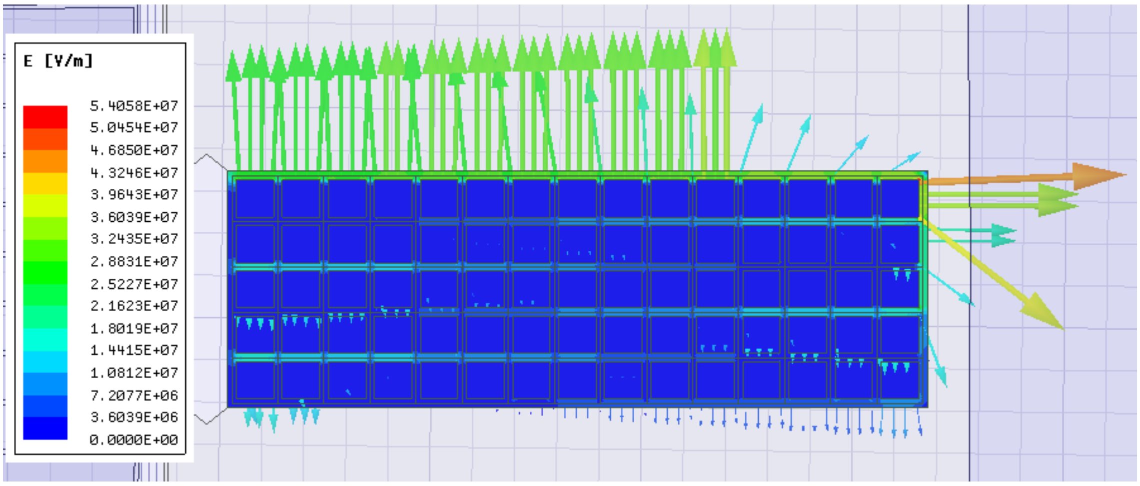

Figure 7.7: Electric field in vectors

The maximum voltage with this configuration is 54 KV in the upper rigth corner, which is as I have said before the hot spot of the insulation system. Therefore we would still have a security coefficient of

$$X_{MICA} = \frac{110}{54} = 2.037 \tag{7.2}$$

For the rest of the machine the security coefficient is $110/36 = 3.05$, safe enough if we consider that the breakdown strength remain constant, although the breakdown strength of mica and mylar can be defined for different temperatures, as the temperature increases the breakdown strength decreases, in order to increase a bit the security coefficient, since it is such a big investment, I have analyzed it for a groundwall of 2mm in each side, the results were:

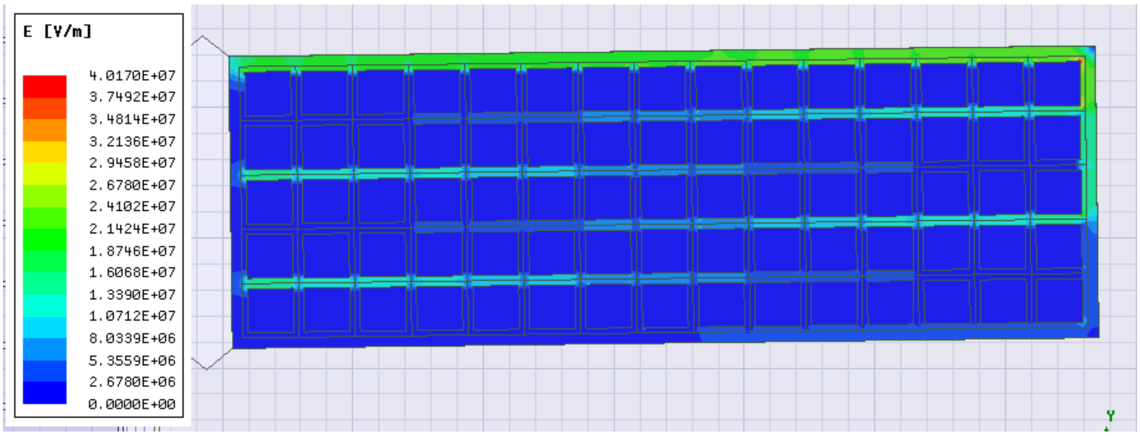

Figure 7.8: Magnitud Electric field

The maximum voltage with this configuration is this time ≈ 40 KV/mm, and the maximum without the corner is ≈ 24KV/mm

$$X_{MICA} = \frac{110}{24} = 4,583 \tag{7.3}$$

Another approach to minimize the cost could be to increase the thickness of the Groundwall insulator to a level such that using PVC becomes a liable option, since it is a really cheap material.

First I analyzed the stator winding using a thickness of the groundwall insulator of 7mm at each side, the results were the following:

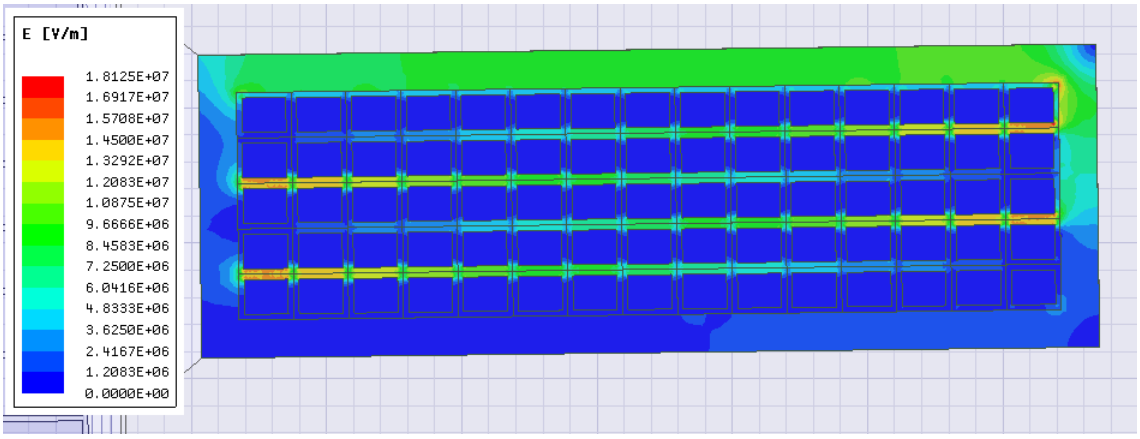

Figure 7.9: Electric field for a PVC groundwall insulation of 7mm

We can see that in most of the insulator the Electric field would be sufficiently low to be considered safe, with a security coefficient of:

$$X_{PVC7} = \frac{15}{7} = 2.1428 \tag{7.4}$$

However in the right upper corner the electric field could be high enough to cause the electric failure of the insulation. Since the security coefficient is ≈ 1.

In this second analysis I use a groundwall insulator of 10 mm thickness the results are better, even though it is still not the safest option.

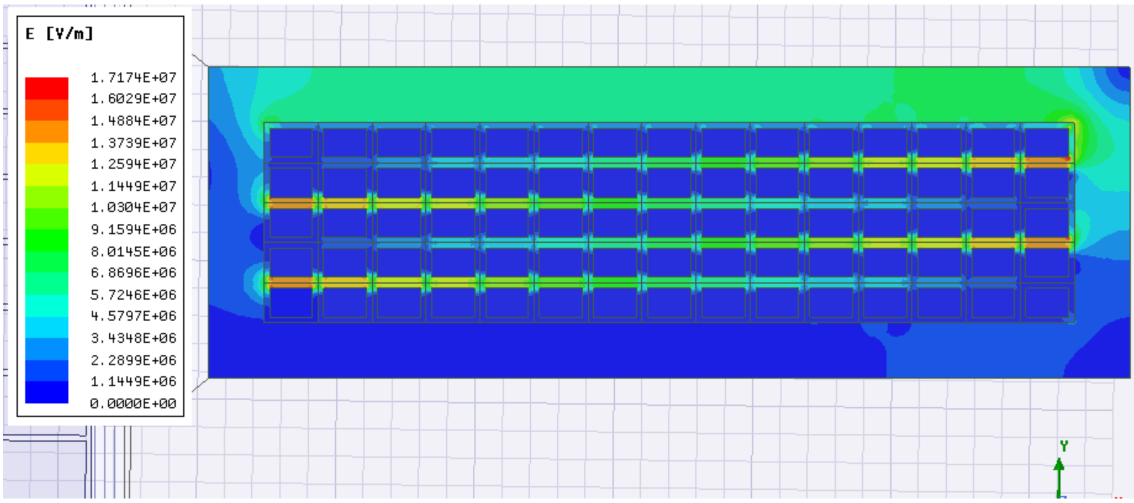

Figure 7.10: Electric field for a PVC groundwall of 10mm

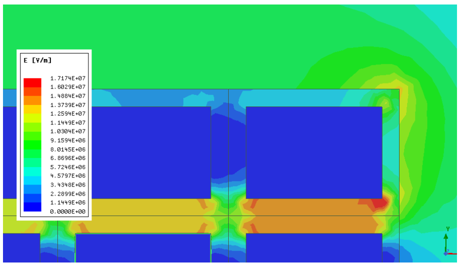

Figure 7.11: Maximum electric field 10 mm

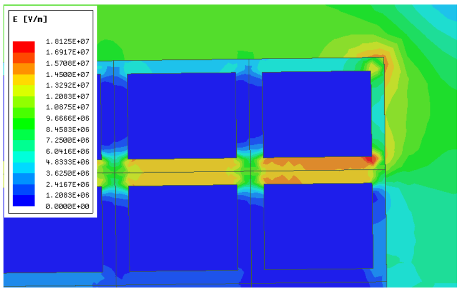

Figure 7.12: Maximum electric field 7mm

The security coefficient of the insulation in the corner is

$$X_{PVC7} = \frac{15}{14} = 1.07 \tag{7.5}$$

not a reliable number, however in the rest of the insulation it can be considered a safe option.

7.1.6 Final outcome

The conclusion I extract from this analysis is that the minimum insulation thickness could be around 1mm for the turns insulation and 1mm for the groundwall, for an insulator material with a dielectric strength >75 KV/mm, which would give us a security coefficient of 2, neglecting the sharp corners, which could be rounded. This material could be either mica or mylar from an electrostatic point of view; further ahead, the thermal properties such as thermal conductivity will become important in the material selection process.

7.2 Thermal analysis

The second part in the process of designing the insulation of a generator is to perform the thermal analysis. This analysis is crucial for the correct performance of the generator, it's as necessary as the electrostatic one, unfortunately to get the best thermal performance the insulation thickness should be as small as possible since insulating materials are no good heat conductors, while the electrostatic analysis demands a certain thickness to avoid electric breakdown.

The main reasons why the thermal analysis in an electrical machine has such a huge importance are:

1) The maximum temperature influences the torque density of the machine, this is the torque (measure of the turning force on an object being rotated) per unit volume. Therefore decreasing it is crucial for achieving the highest efficient possible.

2) The resistance of copper to the flow of current it what causes the main heat losses, and unfortunately it increases with temperature , at 100 degrees celsius, the resistivity of copper is increased by almost 30% compared to room temperature.

3) Some materials such us the permanent magnets present in the generator, (a neodymium–iron–boron (NdFeB) of Hitachi NEOMAX), only withstand continuous maximum temperatures of around 150°C. High temperatures can cause the demagnetization of the magnets. Since the B-H curve depends highly on it.

4) Exposing the machine to temperatures considered too high can cause aging of the material and may cause it to fail eventually, the main cause of failure is the thermal breakdown of the insulation surrounding the cooper windings. Even by using the best electrical insulators, the temperatures in the generator should definitely be kept below 200°C, the main goal is to achieve a maximum temperature of 180°C, less if possible to extend the life of the insulation as much as possible. High temperatures accelerate the aging of the insulation and this decreases the breakdown voltage, this is one of the reasons why the thermal and the electrostatical design must be coupled.

In this first part I will try to implement an air cooling system, but it will probably not be enough to cool down the windings in the coil, due to the high resistance that the electrical insulation presents to the heat transfer inside the coils.

7.3 Worst case scenario

The worst case can be represented by only allowing the heat to go from the coils to the surface of the stator, which is what I have done analytically, and the temperatures, represented in Figure 6.7 reach the 1000 °C. Such high temperatures are due to the low effective conductivity inside the coils and to the fact that the heat can only "escape" the coils through the stator core and in this analysis the surface has a quite low heat convection coefficient.

In reality this temperatures could be even higher because I have neglected the increase in the copper resisttivity with temperature, and this increase is not insignificant.

7.4 Cooled stator surface with a cooling jacket

In the following analysis, the stator, is cooled by a cooling jacket, (water tubes on the surface), this way the heat transfer coefficient between the stator and the exterior increases until maximum values of ≈ 1000 W/mK. This simulation appears in Figure 7.13.The maximum temperature is now 522°C. Still above the acceptable.

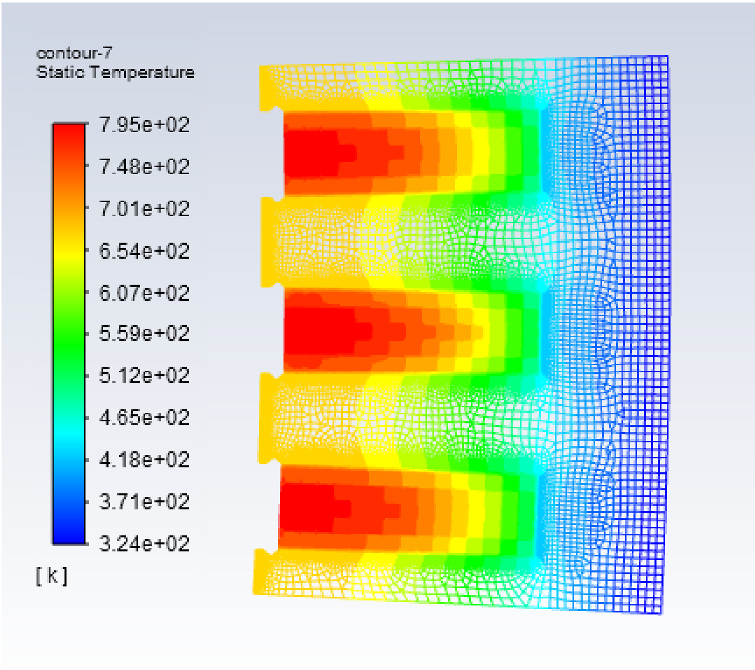

Figure 7.13: Temperature distribution I=400A

I have simulated this situation for different values of current (current density), to see which current density would be small enough to allow the use of air cooling systems, i.e. with which current density, the engine would keep it's maximum temperature below 180°C. The first simulations were performed with a resisttivity of $1.72 \cdot 10^{-8}$, in the second part I use the resisttivity of copper for 150°C equal to $2.53 \cdot 10^{-8}$, to obtain an order of the security coefficient I would need to consider when ignoring the influence of temperature in copper resistance.

Table 7.2: Maximum temperature in the coils vs current density

I (A)	$\rho_I (A/mm^2)$	ρ (W/mK)	Tmax(°C)
400	5.4	$1.72 \cdot 10^{-8}$	522
		$2.53 \cdot 10^{-8}$	727
350	4.73	$1.72 \cdot 10^{-8}$	392
		$2.53 \cdot 10^{-8}$	564
300	4.05	$1.72 \cdot 10^{-8}$	297
		$2.53 \cdot 10^{-8}$	421
250	3.38	$1.72 \cdot 10^{-8}$	200
		$2.53 \cdot 10^{-8}$	301
200	2.7	$1.72 \cdot 10^{-8}$	147
		$2.53 \cdot 10^{-8}$	200
150	2.029	$1.72 \cdot 10^{-8}$	94
		$2.53 \cdot 10^{-8}$	125

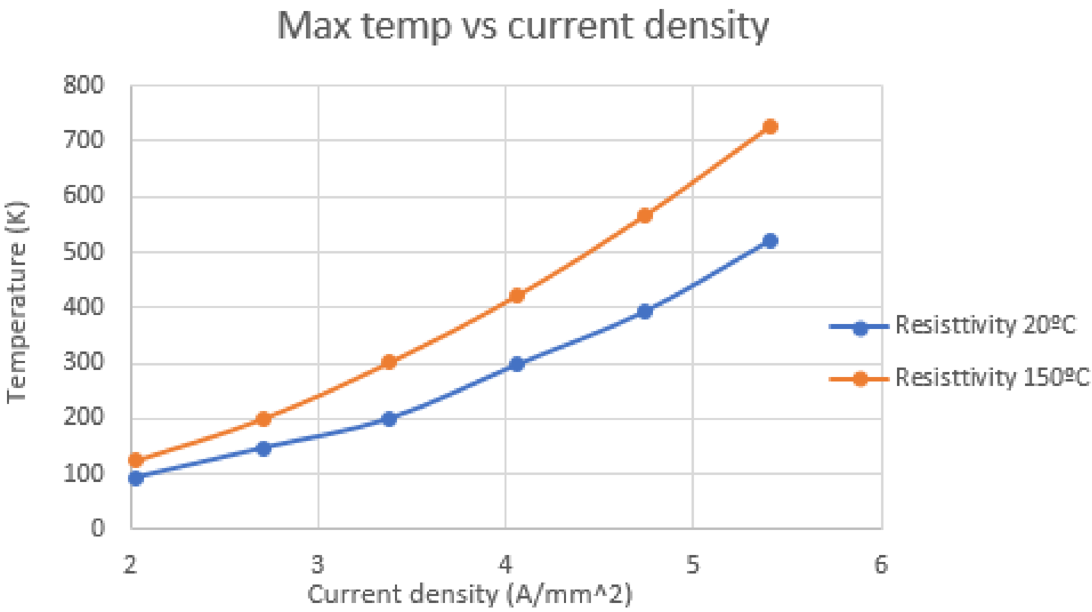

Figure 7.14: Relation between current density and maximum temperature

As we can see in 7.14 the increase of resisttivity in copper due to the temperature really affects the temperature levels, however this calculations were done considering that the resisttivity of copper was, from the beginning of the simulation, equal to the resisttivity when copper is at 150°C. Besides the temperatures reached in the simulation with a current density higher than 3 A/mm^2 are higher than 150 °C, and thus also the resistance of copper.

However 7.14 is useful to get an approximate idea of the liability of air cooling systems in a generator depending on the current density.

As the usual temperature limit inside a generator with good insulator materials is set on 180°C, considering the maximum temperatures reached by the generator, and considering a security coefficient for the increase in resisttivity, I would say that this configuration seems to be safe for current densities < 2.5-2.7 A/mm^2. But not acceptable for the current density that it's supposed to go through the windings in this generator, equal to 5.4 A/mm^2.

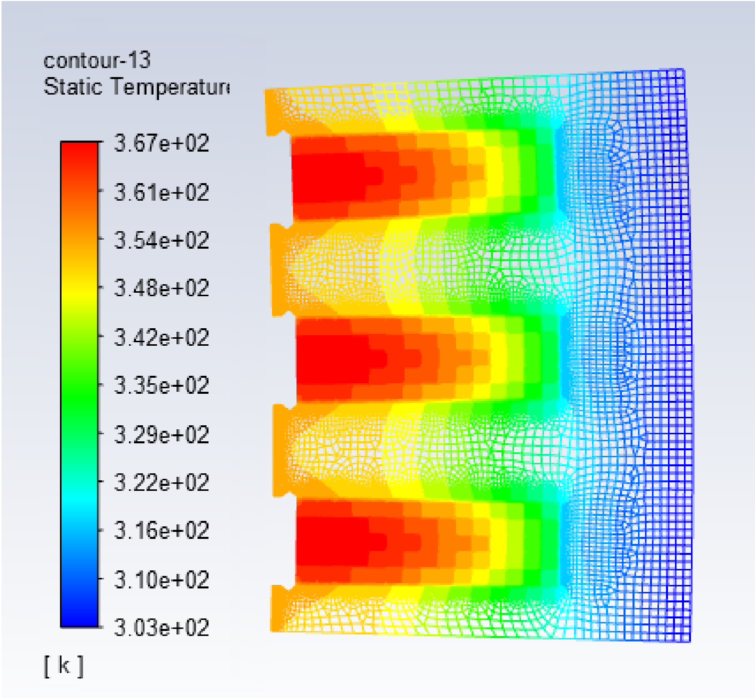

Figure 7.15: Temperature distribution I=150A

7.5 Different winding distribution

As it has been seen, indirect air cooling is not enough to cool down the copper conductors in the coil. In this section a different winding distribution (voltage) in the coils is analysed. In order to find out if reducing the turn insulation thickness, by decreasing to a maximum of 9 kV the voltage between turns, could make the air cooling system feasible.

The new winding configuration can be seen in Figure 7.16

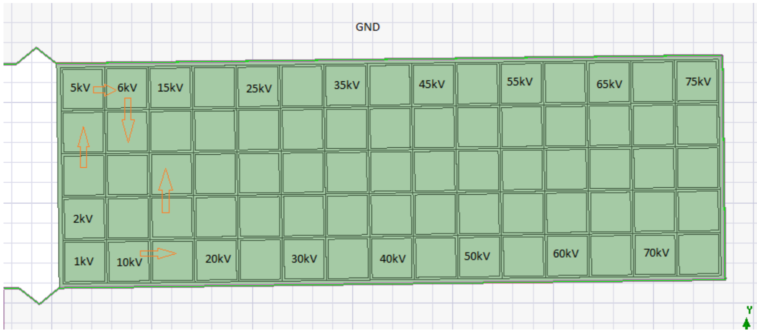

Figure 7.16: Coil geometry

This new voltage configuration has two favorable effects, on one side, the insulation thickness is reduced. Now the turn thickness is 0.5mm while the groundwall thickness remains 1 mm. On the other side, and even more important, the surface of the conductors is increased, thus the resistance that they oppose to the current decrease and the heat generated by the turns as well.

Now the current density is

$$\rho_I = \frac{I}{S} = \frac{400}{97.3} = 4.11 A/mm^2 \tag{7.6}$$

and the heat generated by each turn

$$Q(turn) = 400^2 \cdot R = 400^2 \cdot 1.72 \cdot 10^{-8} \cdot \frac{1.5}{9.73 \cdot 10^{-5}} = 42.4 \quad W \tag{7.7}$$

7.5.1 Electrostatic analysis

The maximum electric field between turns is now 9kV/mm, if a double layer of mylar tape 250 μm is used the breakdown strength of the turn insulation could be higher than 30kV/mm, enoug to prevent the electric breakdown in the turn insulation.

The most dangerous point would be the right side of the coil, where the higher voltages are, since now the distance between the grounded stator core and the coil is only of 1,5 mm. The electric field reaches in this side, nelgecting the corners, a value of $\approx$ 50kV/mm, for this insulation, mica could be used, although the security coefficient would be lower than in the first analysis, it would still be above 2.

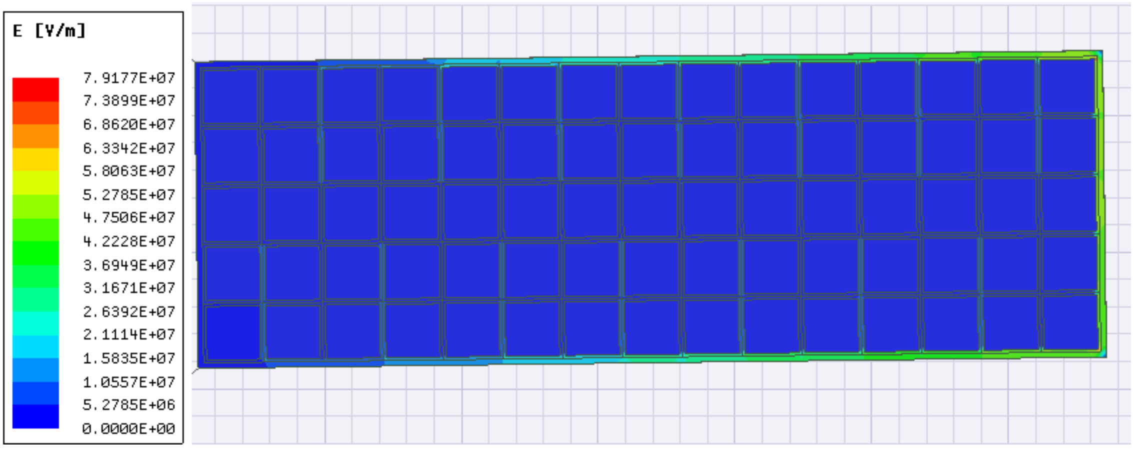

Figure 7.17: Electric field magnitude

7.5.2 Thermal analysis

The main purpose of this analysis is to verify if pushing the insulation thickness to its minimum, it is possible to cool the coils below 180 °C with an indirect cooling system (without cooling channels going directly through the coils).

Stator surface cooled with a cooling jacket

In the first simulation, a cooling jacket in the stator surface is introduced in the simulation by adding a heat transfer convection coefficient of 1000 W/m^2K. The rest of the machine is considered thermally isolated, (all the other walls are adiabatic).

The temperature distribution of Figure 7.18 confirms that removing the heat from the coil conductors is really difficult when all the heat has to be removed first through conduction in the coil and stator core, and then by convection.

The maximum temperatures reach 300°C, the results match the expected maximum temperature for windings subject to a current density of 4.11 with the previous winding configuration, as stated in Figure 7.14. The conclusion extracted from this is that decreasing the resistance of the conductors in this case, has a higher influence in the results than decreasing the insulation thickness.

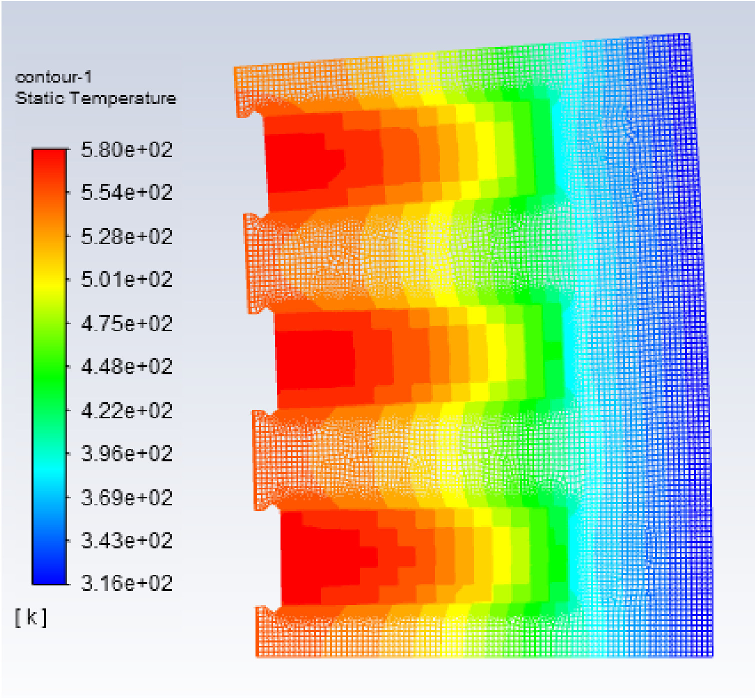

Figure 7.18: Temperature distribution

7.5.3 Heat transfer with the airgap

As a last try to make the indirect cooling work, the heat transfer in the airgap was simulated. The assumptions were the followings:

- The air in the airgap is at 50°C.7
- The heat convection transfer coefficient between the air and the stator surface is around 100 W/m^2K.
- The stator surface has a heat transfer convection coefficient of 1000 W/m^2K.

In this analysis the air in the airgap is supposed to be cooled down and recirculated at a high speed, to achieve the 100 W/m^2K heat transfer coefficient between the stator and coil insulation and the airgap.

The results in Figure 7.19, show that with this configuration it would be possible to cool the coils inside a safe range of temperatures, the maximum temperature is below 180°C. However in this extra analysis the assumptions made about the airgap, are really optimistic, and this would be difficult to achieve in reality.

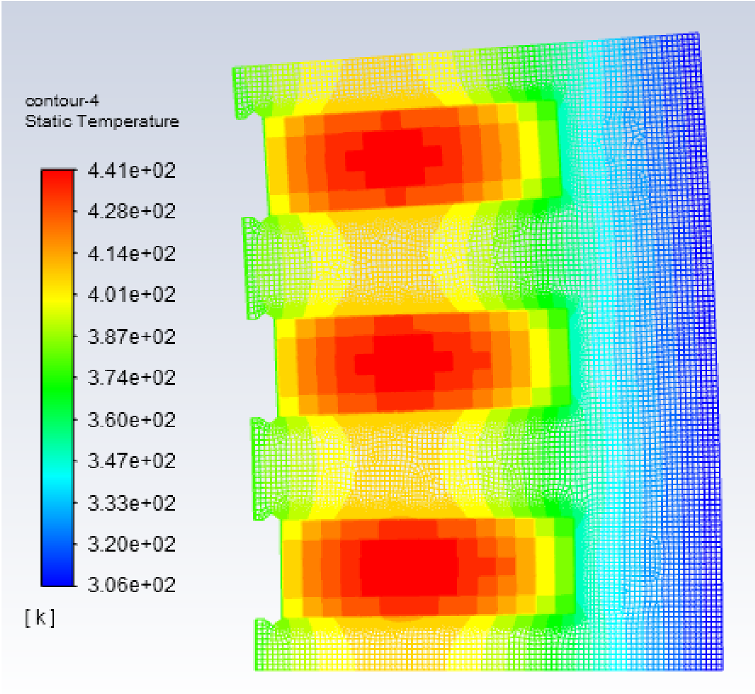

Figure 7.19: Temperature distribution

7.5.4 Conclusions

This last analysis has confirmed that it is really difficult to safely refrigerate the machine, using an indirect cooling system, if not impossible, in the following sections the thesis will focus on analysing a water cooled system, which seems to be the only liable option.

Chapter 8

Water direct in-slot cooled system set up

The second step in the thermal analysis, once the option of using an indirect cooling system to refrigerate the coils has been rejected, is to design an in slot cooling system that consist on cooling channels directly going through the coil windings.

8.1 Thermal set up

Since it is not possible to represent accurately the flow of water in the cooling channel in a 2d planar simulation in ansys, I will first perform an analytical calculation of the heat convection transfer coefficient using the dimendionless numbers stated in 3.2.1.

The cooling channel will have a rectangular form, the first geometry will be a rectangular duct with the dimensions b=23.13mm and a=109.32mm as in Figure 8.1

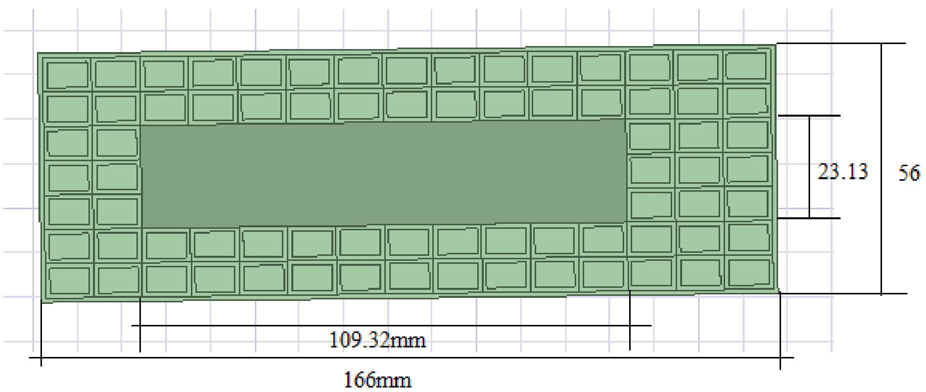

Figure 8.1: Cooling channel geometry

To calculate easily the parameters related with the flow of current in non circular ducts, it is common practice to use the hydraulic diameter

$$D_H = \frac{4A}{P} \tag{8.1}$$

where A is the cross-sectional area of the flow, and P is the wetted perimeter of the cross section. The need for the hydraulic diameter comes from the need to calculate dimensionless quantities such as the Reynolds number.

In the case of a rectangular duct the hydraulic parameter is $D_H = \frac{2ab}{a+b} = 38,19mm$, the volume of the cooling channel is $3.79{\cdot}10^{-3}\ m^3$.

I will make all the calculations as a function of the velocity of the fluid, to see how the convection coefficient varies when increasing the flow of water in the duct.

When calculating these non dimensional numbers for an internal flow, such as the one that we would have in the cooling channels, all the properties have to be evaluated at T_m, which is the mean temperature of the flow. A variation in this temperature can affect severally the results.

The relation between the non dimensional parameters varies mostly depending on whether the flow is laminar or turbulent, but also on if the difference between the temperatures in the surface and in the water is big or not. This methods are extracted from [1].

Laminar flow

For laminar flow ($Re < 2300$), in a channel with fully developed conditions and uniform surface heat flux, the Nusselt coefficient is constant

$$Nu_D = \frac{hD}{K_f} = 4.36 \tag{8.2}$$

therefore the h (convection coefficient) in laminar flows only depends on the conductivity of the fluid and on the hydraulic diameter.

Transitional flow

The transitional flow is that one that is neither laminar nor turbulent, $2300 < Re < 10^5$, to calculate the Nusselt coefficient Gnielinski proposed the following expresion

$$Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \tag{8.3}$$

where from smooth tubes, the friction is given by

$$f = (0.79 ln Re_D - 1.64)^{-2} \tag{8.4}$$

while for rough tubes it can be obtained from the Moody diagram.

This correlation is valid for $0.5 < Pr < 2000$ and $2300 < Re < 5 \cdot 10^6$, with all the properties evaluated at T_m.

Turbulent flow

There are many correlations to calculate the convection coefficient in turbulent flows, I will use two of them, one for small temperature differences between the surface and the fluid, the Colburn equation

$$Nu_D = 0.023 Re^{4/5} Pr^{0.3} \tag{8.5}$$

valid in the range $0.7 \leq Pr \leq 160$, $Re > 10^4$, $L/D > 10$, with all the properties evaluated at the mean temperature of the fluid.

and other for flows with large property variations due to a large temperature difference between the surface and the fluid, the Sieder and Tate equation

$$Nu_D = 0.023 Re^{4/5} Pr^{0.3} \left(\frac{\mu}{\mu_s}\right)^{0.14} \tag{8.6}$$

where μ is the dynamic viscosity of the fluid at Tm and μ_s is the same property but evaluated at the temperature of the surface.

All this correlations are done for fully developped flows, normally, if the tube is sufficiently large, it is reasonable to assume that the average Nusselt number for the entire tube is equal to the value associate with the fully developed region.

I will use the following water properties for different mean temperatures

Table 8.1: Water properties at different temperatures

Tm(°C)	$\rho(Kg/m^3)$	$\mu(Pa \cdot s)$	$Cp(J/Kg \cdot K)$	$k(W/m^2 \cdot K)$	Pradntl
25	997.1	0.0008905	4138	0.5948	6.13
30	995.71	0.000798	4118	0.6145	5.43
40	992.25	0.000653	4074	0.6286	4.5
50	988.02	0.000547	4026	0.6406	3.5
60	983.2	0.000466	4183	0.6770	3

The analytical values of the convection coefficient can be found in Table 8.2.

Table 8.2: Analytical convection coefficient for different fluid velocities

v(m/s)	**Re**	**Nu**	$h(W/mm^2K)$
0.1	4276.2	22.6	353
0.15	6414.2	44.7	696
0.2	8552.3	66.8	1040
0.25	10690	99.6	1550
0.3	12828	113	1750
0.35	14867	125	1950
0.4	17105	138	2150

The evolution of the convection coefficient in relation to the speed in m/s is stated in Figure 8.2

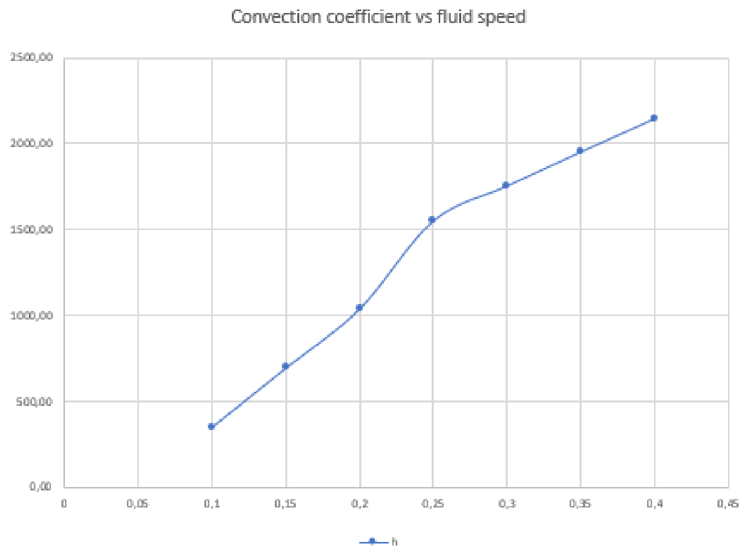

Figure 8.2: Heat convection transfer coefficient vs speed

The next step is to create a simplified thermal network, Figure 8.4, to get an approximate idea of the amount of heat the cooling channels are able to dissipate, i.e. the minimum temperatures that we can reach with this method. This will be done in a similar way as in the analysis for indirect cooling, but this time, the analysis will focus on what is happening inside the coil.

I have made the following simplifications:

1) I analyze one half of a coil, by setting a symmetry axis in the middle of the coil along the y direction.

2)I don't include in this part of the analysis the rest of the generator.

3) The contact resistance between the coils and the cooling channel has been neglected.

3) I have divided the half coil into three different bodies, I will search for the average temperature in each of this parts, this is clarified in Figure 8.3, as opposed to the first analysis in which there was only one averaged temperature for the hole coil. The parts and the assumptions I have made based on the value of the thermal resistances are:

- Part 2 is the upper part of the coil, I have divided it into two parts, I have assumed that the heat generated by the last row of turns (part 2.2) will be mostly transfered to the stator, since the thermal resistance is much smaller than the one in the direction of the cooling channel. The heat generated by them will be deducted from the total heat of part two. On the other side, the heat generated in the turns of part 2 will either go to the Part 1 or to the cooling channel, here I have neglected the heat in the x direction.

- Part 3 is very similar to part 2, with the difference that it has only two rows, therefore one part.

- Part 1 has only on heat flux in the x direction, that is, it only exchanges heat with the cooling channel.

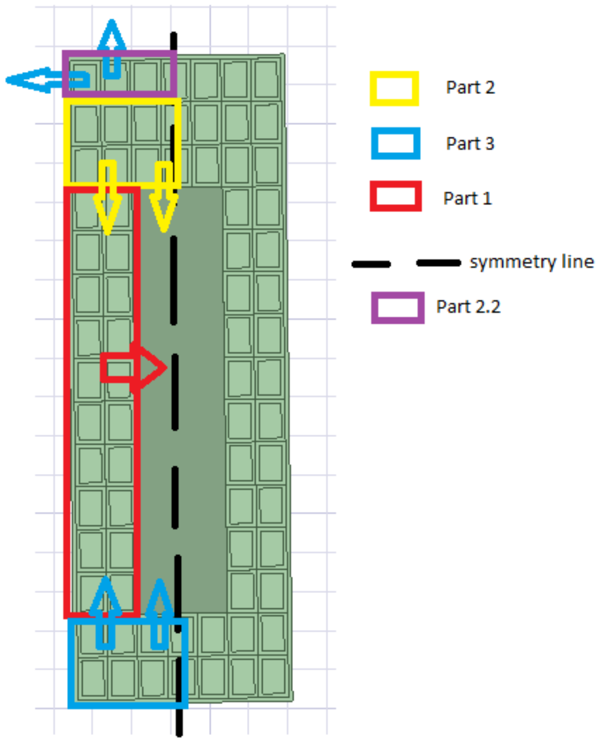

Figure 8.3: Assumptions for the simplified network

The thermal network results in a linear system of equations with 3 unknowns and 3 equations, once the circuit is resolved.

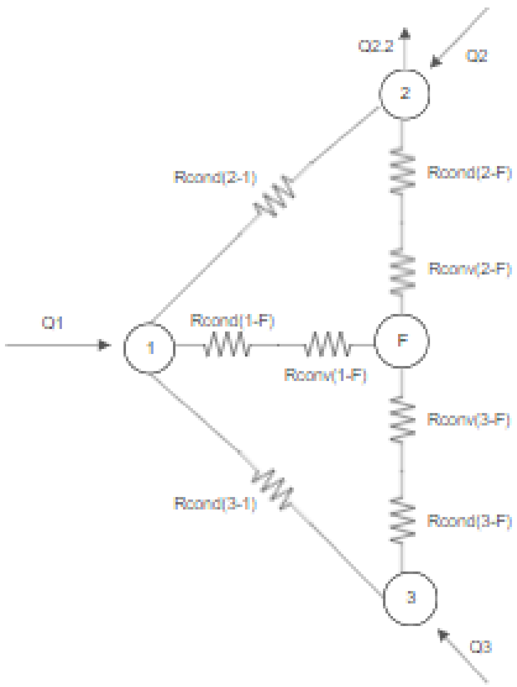

Figure 8.4: Thermal network for the coil with cooling channel

Thermal resistances

The thermal resistances in the coil are calculated in the same way as in the first thermal analysis (5.2.1), having in mind that the coil is a heat source, and therefore a negative resistance has to be included in the total conductive resistance.

Table 8.3: Values of the analytical thermal resistances inside the coil

Resistance name	Part	Conductivity	Value (K/W)
R_{1-F}	1	k_x=1,629	0.08098
$R_{2,3-F}$	2 & 3	k_y=2.152	0.839
$R_{2,3-1}$	2 & 3	k_y=2.152	0.575
$Rconv_{1-F}$	1	h=350	0.01742
$Rconv_{2-F}$	2	h=350	0.1647
$Rconv_{3-F}$	3	h=350	0.1647

$$\begin{aligned}
Rcond_{1-F} &= \frac{R_{1-F}}{2} - \frac{R_{1-F}}{6} \\
Rcond_{2-F} &= \frac{R_{2-F}}{2} - \frac{R_{2-F}}{6} \\
Rcond_{3-F} &= \frac{R_{3-F}}{2} - \frac{R_{3-F}}{6} \\
Rcond_{2-1} &= \frac{R_{2-1}}{2} - \frac{R_{2-1}}{6} \\
Rcond_{3-1} &= \frac{R_{3-1}}{2} - \frac{R_{3-1}}{6}
\end{aligned} \tag{8.7}$$

Heat losses

Adding the cooling channel into the slot means that there is less space for the copper wingdings, i.e. the section for the conductors must be smaller. Since the resistance in the copper is inversely proportional to the area in the conductors, the heat losses in the copper will increase.

I have created the new geometry trying to find a balance between not making the cooling channel too small; so that the temperature of the cooling medium doesn't increase too much during it's way through the coils, and having a conductor surface as big as possible.

The current density is now

$$\rho_I = \frac{I}{A} = \frac{400}{51.0142} = 7.84(A/mm^2) \tag{8.8}$$

The new losses per turn are

$$\begin{aligned}
Q(turn) &= 400^2 \cdot R \approx 80W \\
R &= \frac{1.7210^8 \cdot 1.5}{51.014210^{-6}} = 5.057410^{-4}\Omega
\end{aligned} \tag{8.9}$$

With the heat loss per turn I can calculate the heat generation in each part of the coil $Q1 = 80 \cdot 20 = 1600W$ $Q2, Q1 = \frac{80 \cdot 14}{2} = 560$ I am neglecting the percentage that might go through the groundwall insulation to the stator because the worst situation possible is that all the heat has to be dissipated by the cooling channel.

Analytical results vs Numerical results

I have solved the system of equations for several values of h; to see how increasing the velocity of the cooling medium influences the maximum temperature obtained in the coils, and what is the minimum temperature that I can obtain. At the same time I have done a parallel simulation in Ansys Fluent to verify the results.

Table 8.4: Analytical vs numerical temperatures

h	**Part**	$T_{averaged}$**(K)**	**Min ANSYS**	**Max ANSYS**
350	1	390	360	425
	2	436	395	462
	3	436	395	462
650	1	372	330	405
	2	416	350	444
	3	416	350	444
1000	1	365	320	400
	2	408	360	438
	3	408	360	438
1500	1	361	315	390
	2	403	355	420
	3	403	360	434

The analytical method seems to be accurate enough looking at the relative error in each part, only at the end, when the heat convection transfer coefficient increases, the difference in temperature between part 2 and 1 becomes more noticeable, this is because the heat of the first row of turns in the second part now has a higher resistance in the direction of the stator that in the direction of the cooling channel. However, this difference is not relevant at this point of the study.

It is possible to see that the average temperature is always in the range between the maximum and the minimum obtained but a bit above the average in the simulation.

Table 8.5: Relative error in the analytical calculations

h	Part	Relative error %
350	1	0.6
	2	1.75
	3	1.75
650	1	1.22
	2	4.7
	3	4.7
1000	1	1.4
	2	2.25
	3	2.25
1500	1	2.41
	2	4
	3	1.51

The results of the simulation with a heat transfer coefficient of h=1500 can be seen in 8.5, and the distribution of temperatures of the coil in detail in 8.6

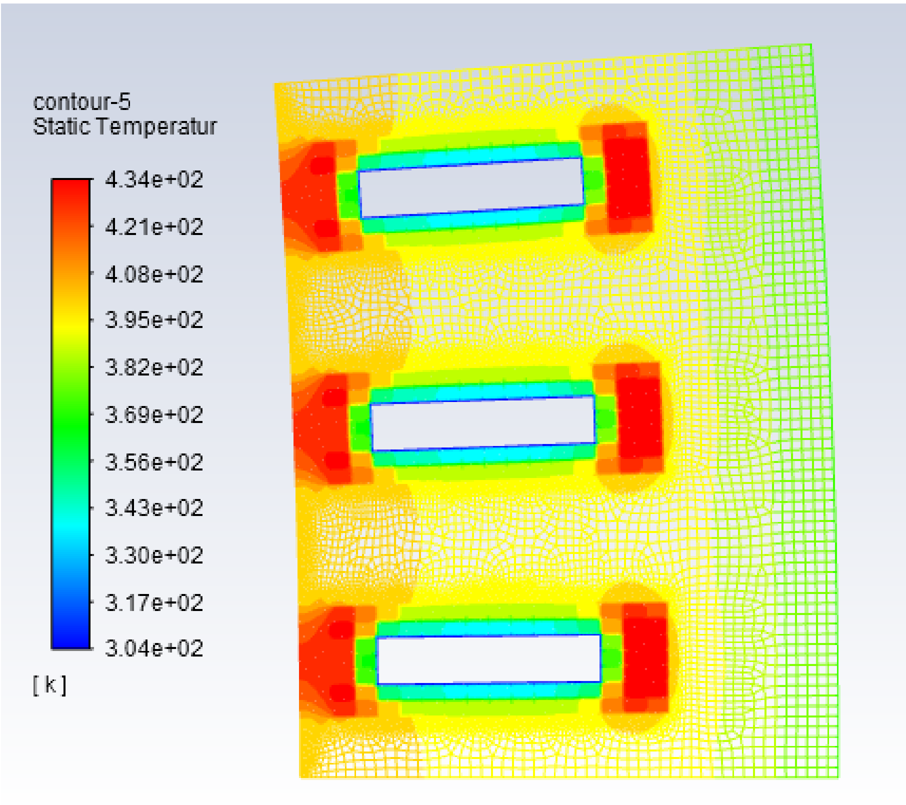

Figure 8.5: Thermal analysis h=1500

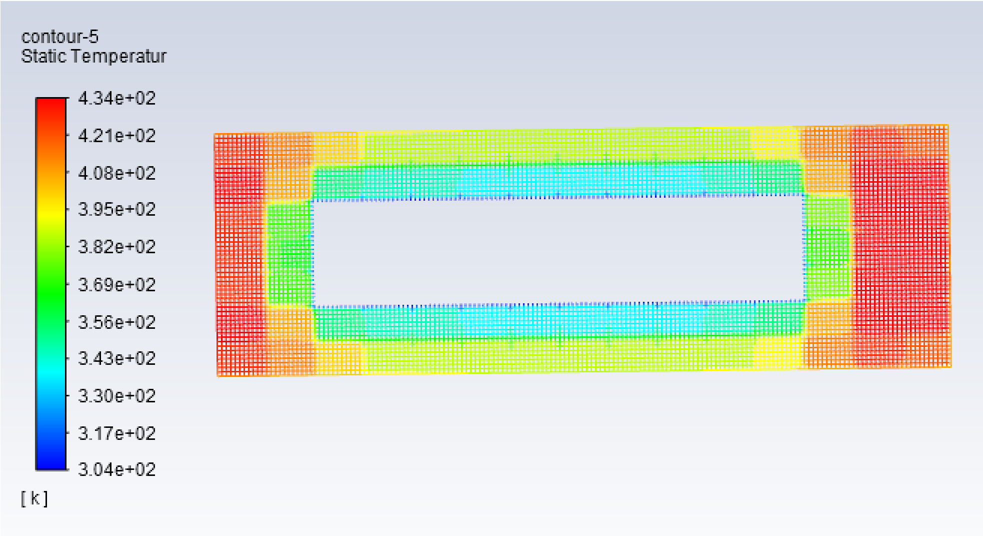

Figure 8.6: Detail of the coil

Chapter 9

In slot cooling

Indirect air cooling was not enough to cool the copper windings in a stator of such voltage and current , as it has been seen the maximum temperatures reached in the slot were of $\approx 1000°C$ in the worst situation, and it could only be reduced to around 500°C, in the bast case scenario. However the temperatures in the stator shouldn't exceed the 190°C; even more, in the normal operating conditions, they should remain under 170°C to ensure that the insulation materials are not damaged by them.

9.1 Electrostatical

As in the other analysis the first step to design the new geometry should be to identify the minimum insulation thickness that prevents electric breakdown. In this part is is really important that the insulation can be as thin as possible since the surface of the conductors will already be reduced by the cooling channel and the smaller this one is the higher the heat losses in the copper.

In a first approach I supposed that the cooling channel, would carry water, this means that the liquid had to be enclosed in a steel or copper duct. It would also be possible to use oil as refrigerant in a similar way as it is done for transformers; in this case the oil could be in direct contact with the turns, with this configuration the contact resistances are eliminated, and the machine is safer from an electrical point of view.

To perform the first estimation I took the quite conservative approach of considering the steel tube grounded (V=0).

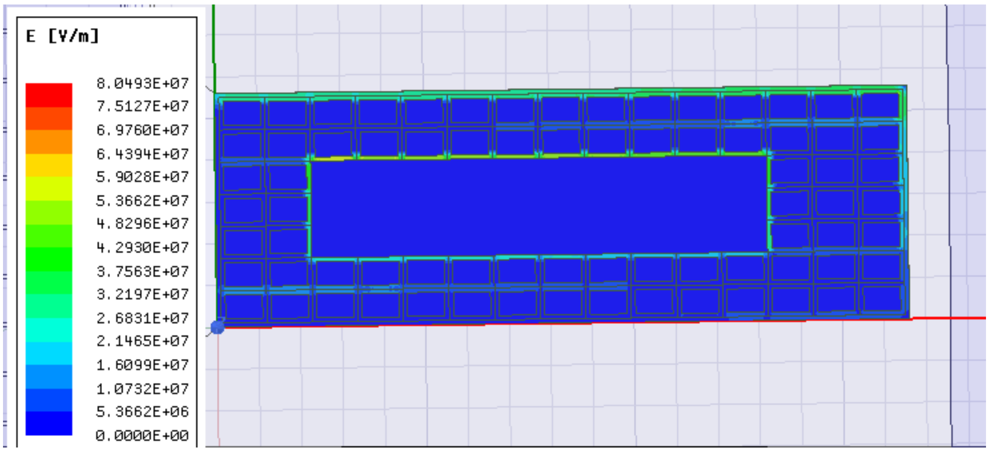

Figure 9.1: Electric field in the slot with cooling channel

Here, due to the sharp corners and the high voltage difference between the grounded duct and some of the turns, the electric field concentrates on the two corners in the upper part in contact with the cooling channel.

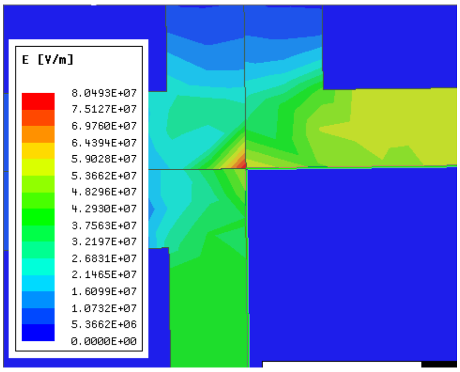

Figure 9.2: Electric field in the left corner

As we can see the maximum electric field for this configuration is 80 KV/mm, considering the dielectric strength of mica equal to 118 KV/mm the security coefficient with this configuration is less than 1.5, not acceptable. However, the approach used in this analysis is too conservative, and by rounding the corners of the turns, or by putting a bit of insulation on the corner the security coefficient is easily increased. To prove this I did and analysis adding an insulation triangle of 0.5mm side in each corner.

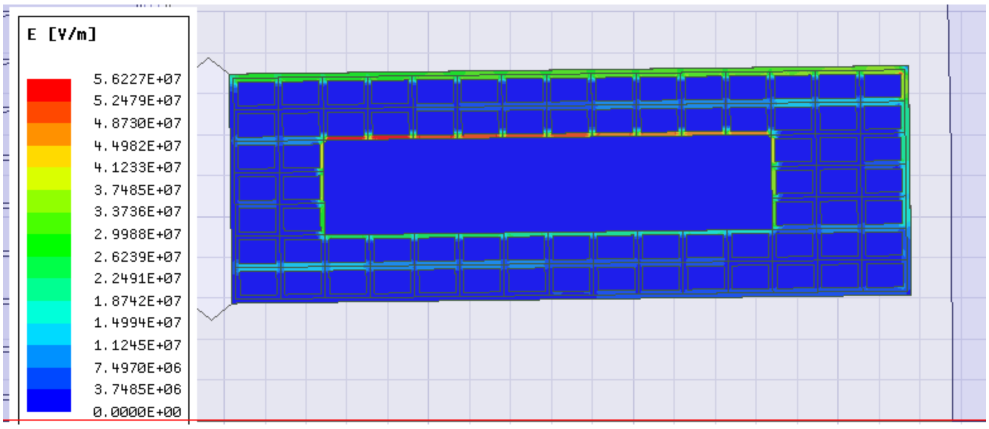

Figure 9.3: Electric field with extra insulation on the corner

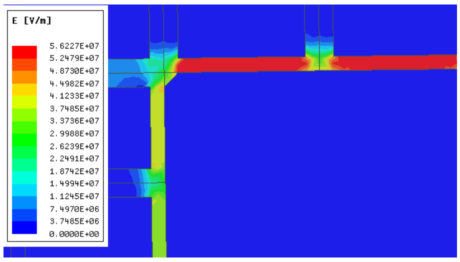

Figure 9.4: Electric field in the left corner with the insulation

This time the maximum voltage is 56 KV/mm, thus the security coefficient would be X_{mica}=2.1, since I consider that the minimum for a security coefficient in this case should be 2, this configuration can be accepted as safe.

Adding some insulation in the corner should have a similar effect as rounding the corner of the turns in those critical points, with the side benefit that there is no extra insulation between the copper and the cooling channel, which would increase the thermal resistance.

Since putting the cooling duct to ground is a quite conservative approach, since the water in the ducts could be ionized water, I have perform the analysis without it being grounded, the results appear in Figure 9.5

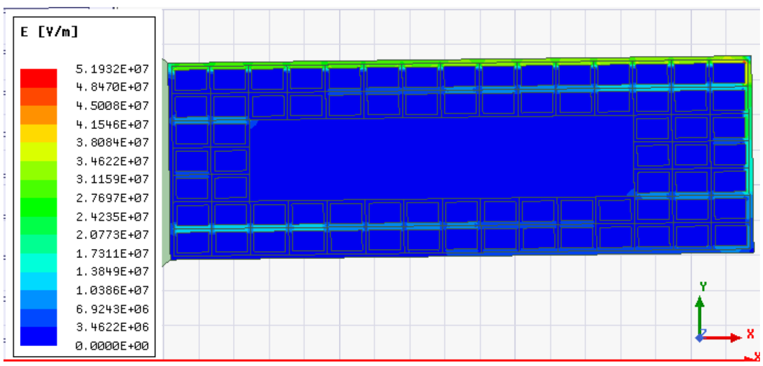

Figure 9.5: Electric field in the coil insulation

I it possible to see that in this case the insulation between the copper and the water channel could be reduced to a really low thickness, besides, between turns the maximum electric field would reach ≈ 15kV/mm, so the turn insulation could be reduced to 0.5mm, and the maximum would be around 30kV/mm, still acceptable, with a good insulator, that has a breakdown voltage > than 80 kV/mm. The groundwall insulation is subject to average voltages of 30kV/mm, if the turn insulation is reduced to 0.5mm, the average electric field in the groundwall in the upper part of the coil would be around 40kV/mm, still safe for mica or mylar.

9.1.1 Conclusions electrostatic analysis

It is possible to maintain the thickness of the insulation calculated in the first analysis for the geometry without the cooling channel, 1 mm thickness for both insulators in both directions. Evenmore, the thickess of the turn insulation could be reduced to 0.5mm considering that the cooling channel in not grounded, this happens for example when we have oil or ionized water as the cooling medium.

9.2 Thermal analysis

In this section, the analysis started with the initial simulation to verify the analytical method, will be done again in the coils of the stator, but this time the goal will be to find the characteristics that would make a cooling channel suitable to cool down this generator.

The cooling channel will go through a certain number of slots before going to the heat exchanger to be cooled down to the initial temperature and repeat the cicle.

The specific heat of water (Cp) is equal to 4138 (J/Kg K) at 25°C, the heat (Q) absorbed by the fluid heats it up in relation to it's specific heat and the flow in the cooling channel, the relation is stated in

$$Q(W) = Cp \cdot F(l/s)\Delta T \tag{9.1}$$

where ΔT is the increase in temperature, therefore, the heat needed to increase the fluid temperature one degree from 25°C with a flow of 1 l/s is $Q = 4138 \cdot 1 = 4138W$. From the simulation performed in the set up, it has been found out that the heat transferred to the water coolant by one coil is around 5100W. This means that in it's way through each coil, the water increases it's temperature around 1.3°C.

The more slots the water can go through before being cooled again the less energy is needed in the cooling process, however, the more water that needs to be pumped, (the bigger the flow) the higher the energy to apply the necessary pressure on the fluid.

In the next pages I will analyse the cooling effectiveness by simulating the heat transfer for different flows and mean temperature of the fluid.

9.2.1 Cooling channel simulation

In order to calculate the convection heat transfer coefficient between the surface of the cooling channel and the water, I have to keep in mind the following parameters:

- Velocity of the fluid
- Mean temperature of the fluid
- Temperature of the surface

The approach to verify the analytical method was very conservative, the velocities of the fluid were really low, but the cooling channel is big enough to carry even 100 l/min of water, from now, I will increase the water flow for a more realistic approach.

As we increase the temperature and velocity of the fluid the convection heat transfer increases.

However, the heat flux is proportional to the temperature difference between the surface and the mean temperature of the fluid, therefore the heat flux decreases as the temperature of the fluid and the temperature of the surface grow closer to each other.

With this in mind, increasing the temperature of the fluid doesn't necessarily have to be bad for the heat transfer, I will have to evaluate different cases to find out which from which values of temperature and water velocity (flow) would it be possible to safely cool down the generator.

The values of the heat transfer coefficient as well as the Reynolds number are stated in 9.1, as it is possible to see, the turbulence of the flow increases with both the speed (or flow = speed·cross-sectional area) and with the temperature.

Table 9.1: Convection coefficient in relation to mean temperature and velocity of the fluid

Fluid flow (l/s)	Temperature (°C)	**Re**	**h**(W/m^2K)
0.75	25	12528	1193
	30	14296	1296
	40	17409	1468
0.875	25	14967	1350
	30	16678	1467
	40	20311	1660
1	25	17105	1502
	30	19061	1632
	40	23212	1847
1.25	25	21381	1796
	30	23826	1951
	40	29015	2209
1.5	25	25657	2078
	30	28591	2258
	40	34818	2556
1.625	25	27795	2215
	30	30974	2407
	40	37720	2725

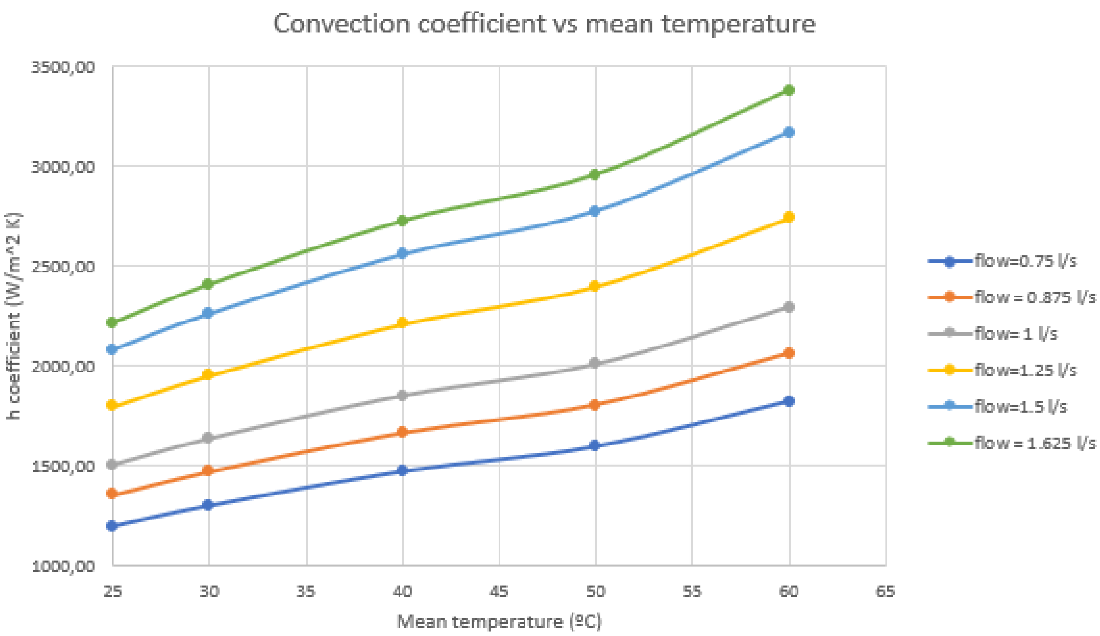

Figure 9.6: Convection coefficient for different flows vs temperature of the fluid.

9.2.2 Analysis for a flow of 1 l/s

1 l/s means 60 l/min, I have performed the simulation assuming a mean temperature of 25 °C in the water to see how large is the amount of heat transferred to the water, and to calculate in a precise way the increase in the water temperature through one slot.

The inputs for the simulation are:

- The heat convection transfer coefficient is 1502 (W/mK)
- The mean temperature of the fluid is 25°C
- The heat convection coefficient between the stator and the surface is 50.

Results

The total heat transferred to one cooling channel is ≈ 5400 W, around a 90% of the total heat produced by the copper losses, therefore the water increases it's temperature in 1.3°C each slot.

The maximum temperature reached in the stator and coils was 435K (162°C). The temperature distribution can be seen in detail in 9.7

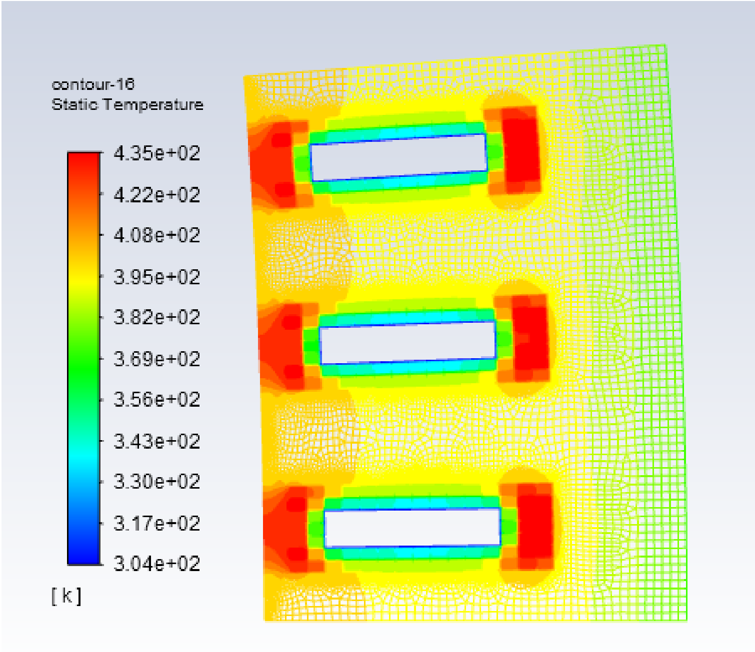

Figure 9.7: Temperature distribution in the stator

If the maximum temperature in the water is set to be 40 °C, the maximum number of slots the water could go through would be 15, after this it should be cooled down and recirculated again.

To see if the water at 40°C would still allow reasonable temperatures I perform the simulations with the following inputs:

- The heat convection transfer coefficient is 1847 (W/mK)
- The mean temperature of the fluid in the last coil is 40°C
- The heat convection coefficient between the stator and the surface is 50.

From the results in 9.8, it is clear that as we increase the temperature of the fluid the heat transfer between the coils and the cooling channel decreases, even though the heat transfer coefficient increases.

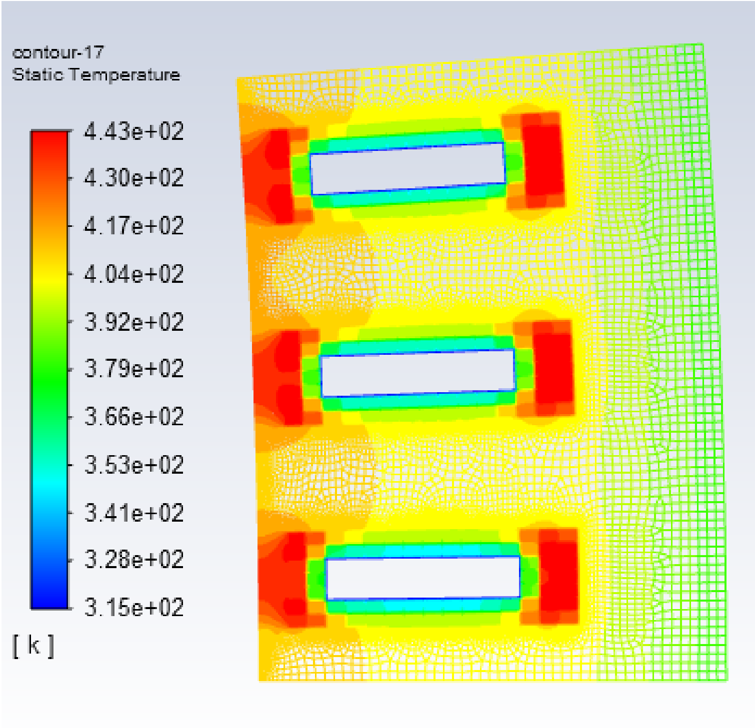

Figure 9.8: Temperature distribution in the stator

The maximum temperatures are around 170°C, since it is below the maximum this configuration could be a good choice, besides, this value could decrease by refrigerating the stator surface with a cooling jacket, this simulation is stated in Figure 9.9. When putting a cooling jacket in the stator surface the temperature decrease until 162°C.

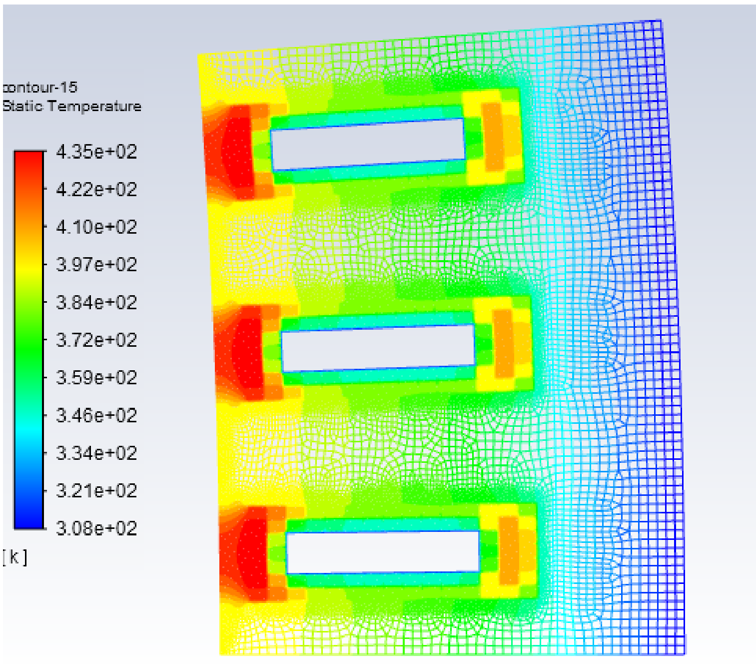

Figure 9.9: Temperature distribution in the stator

9.2.3 Analysis for a flow of 1.625 l/s

The inputs for the simulation are:

- The heat convection transfer coefficient is 2215 (W/mK)
- The mean temperature of the fluid is 25°C
- The heat convection coefficient between the stator and the surface is 50.

Results

The total heat transferred to one cooling channel is ≈ 5400 W, as in the other analysis, but this time the flow is higher and the water increases it's temperature in 0.8°C each slot, the value with respect to the smaller flow decreases, now the water could go through 18 slots before having to be refrigerated.

The maximum temperature reached in the stator and coils was 432K (159°C). The temperature distribution can be seen in detail in 9.10

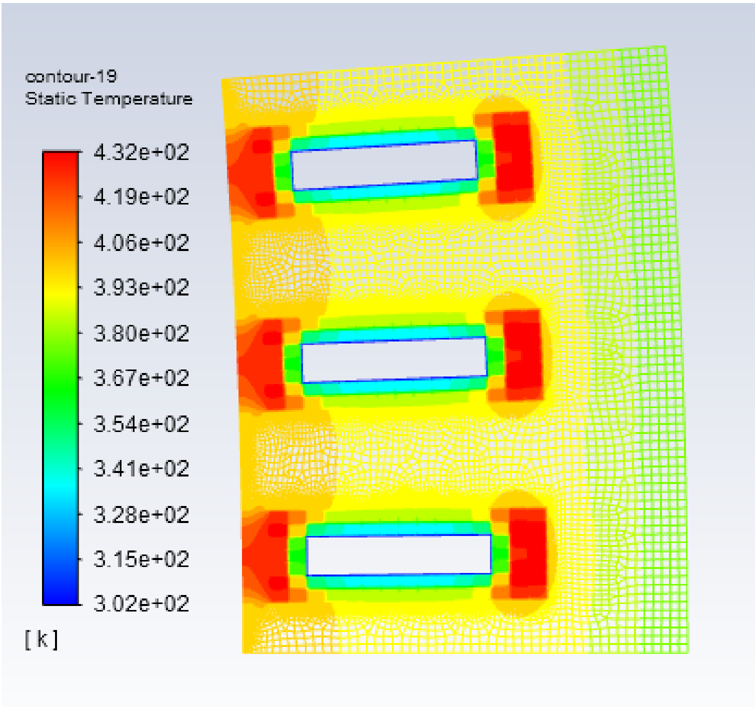

Figure 9.10: Temperature distribution in the stator

The results in the temperature distribution are really similar when introducing a flow of 1.625l/s or another of 1 l/s, the maximum temperatures in both cases are maintained below 170°C. With this configuration, we would have the round number of 14 independent water circuits refrigerating the 252 slots in the generator.

9.2.4 Conclusions

Refrigerating the coils in the generator with cooling channels results really effective, a range of water flows between 1l/s to 1.625l/s can be used and the temperature always remains below the limit operating temperature for the insulation, the final decision about which configuration to use, depends strongly on which one results in a lower power consumption, thus increasing the net power of the machine. But this is not on the scope of this thesis. Besides adding a cooling jacket to the stator can decrease even more the temperatures, leaving the maximum in around 160°C, and thus increasing the live of the components in the machine.

Chapter 10

Conclusion

The main conclusion is that for a 75kV, 20MW generator, and a current density of 7,84 A/mm2 in each conductor, the minimum thickness for the groundwall insulation is 1mm and an in-slot cooling system is needed.

10.1 Indirect cooling system

The main take away from this part is that an indirect cooling system does not cool down the generator effectively below 180°C.

10.1.1 Electrostatic analysis

The minimum insulation depends on the kind of winding configuration, with a voltage difference of 29kV between the turns an insulation thickness of 1mm in the turns and 1mm in the groundwall can be achieved. If this voltage difference is reduced, changing the winding configuration, as we saw to 9kV, it can be even more reduced, to 0.5mm in the turn insulation.

10.1.2 Thermal analysis

After analysing the generator by different means, all the results confirmed that is really difficult, for the heat generated in the turns, to be evacuated properly, when using only an indirect cooling method, even using a cooling jacket in the stator surface.

10.2 Direct in-slot cooling system

Adding a cooling channel in the slots facilitates the evacuation of the heat from the turns, in a way such that it is easy to obtain maximum temperatures below 180°C.

10.2.1 Electrostatic analysis

Adding a cooling channel with pure water or oil as cooling medium can allow for a reduction of the turn insulation thickness between the turns and the cooling channel.

10.2.2 Thermal analysis

Adding a cooling channel in the slots with water as cooling medium, has been proved to be a really good way to remove the heat, a possible cooling channel configuration could be a water flow between 1l/s and 1.625l/s, with 17-14 different water channelings.

References

[1] A.Hormiere. "Determination of the heat transfer coefficient h in a cooling tube." In: (2011).

[2] Stone Boulter Culbert and Dhirani. *Electrical Insulation for Rotating Machines.* Vol. 21. 2004.

[3] Frank P. Incropera and David P. DeWitt. *Fundamentals of heat and mass transfer.* 2011.

[4] Niels Jonassen. *Electrostatics.* Vol. 700. 2002, p. 188. DOI: `\url{https://doi.org/10.1007/978-1-4615-1073-4}`.

[5] Gunnar Kylander. "Thermal modelling of small cage induction motors." PhD thesis.

[6] Jose Angel Malumbres. "Methodology of thermal analysis and design criteria for open-circuit-cooled electrical machines." PhD thesis.

[7] Proffesional plastics. *common insulating materials available from proffesional plastics.* DOI: `https://www.professionalplastics.com/professionalplastics/InsulatingMaterialsList.pdf`.

[8] Barjinder Singh. *Insulating materials.* Tech. rep. Electrical Engg. Goverment Polythecnic college. GTB.GARH DISTT.MOGA.

Chapter 11

Bibliography

(1) Electrical Insulation for Rotating Machines. By Stone, Boulter, Culbert, and Dhirani 1 ISBN 0-471-44506-1 © 2004 Institute of Electrical and Electronics Engineers.

(3)Heat Conduction David W. Hahn and M. Necati Özisik

(4) D. A. Howey, P. R. N. Childs and A. S. Holmes, "Air-Gap Convection in Rotating Electrical Machines," in IEEE Transactions on Industrial Electronics, vol. 59, no. 3, pp. 1367-1375, March 2012, doi: 10.1109/TIE.2010.2100337

(5) https://www.eaton.com/us/en-us/products/motors-generators/high-torque/why-torque-density-is-important-in-machine-design.html

(6) Holman, J. P., Transferencia de calor. Mc Graw-Hill, 1998. [3] Isachenko, V. P., V. A. Osipova y A. S. Sukomel, Heat transfer. Ed. Mir, Moscú, 1977.

(7) Chapman, A. J., Transferencia de calor. Librería Editorial Bellisco, Madrid, 3a edición, 1990.

(8) P. Gnacinski. "Windings Temperature and Loss of Life of an Induction Machine Under Voltage Unbalance Combined With Over-or Undervoltages". IEEE Transactions on Energy Conversion. Vol. 23, Issue 2, pp. 363-371. June, 2008.

(9) A. Boglietti, A. Cavagnino and D. Staton. "Determination of Critical Parameters in Electrical Machine Thermal Models". IEEE Transactions on Industry Applications. Vol. 44, Issue 4, pp. 1150-1159. July/August, 2008.

(10) E.R. Filho and E. Avólio. "Squirrel-Cage Induction Motor Dynamics Simulation Using an Electrical and Thermal Mathematical Model Based on Manufacturer Technical Bulletins Data and on Technical Standard Statements". International Journal of Power and Energy Systems. Vol. 14, Issue 1, pp. 13-16. 1994.

(11) M.J. Durán and J. Fernández. "Lumped-Parameter Thermal Model for Induction Machines". IEEE Transactions on Energy Conversion. Vol. 19, Issue 4, pp. 791-792. December, 2004.

(12) A. Boglietti, A. Cavagnino, M. Lazzari and M. Pastorelli. "A Simplified Thermal Model for Variable-Speed Self-Cooled Industrial Induction Motor". IEEE Transactions on Industry Applications. Vol. 39, Issue 4, pp. 945-952. July/August, 2003.

(13) Qixu Chen, Zhongyue Zou, and Binggang Cao C. H. Lim et al., "2-D lumped-parameter thermal modelling of axial flux permanent magnet generators," 2008 18th International Conference on Electrical Machines, Vilamoura, 2008, pp. 1-6, doi: 10.1109/ICELMACH.2008.4799880.

(14) A. Boglietti, M. Cossale, S. Vaschetto and T. Dutra, "Thermal Conductivity

Evaluation of Fractional-Slot Concentrated-Winding Machines," in IEEE Transactions on Industry Applications, vol. 53, no. 3, pp. 2059-2065, May-June 2017, doi: 10.1109/TIA.2017.2672518.

(15) Gunnar Kylander. Technical Report No. 265.Thermal modelling of small cage induction motors.

(16) Determination of the heat transfer coefficient h in a cooling tube. A.Hormiere. ST-CV, 17/08/2011.