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Thermal Slot Model for Random Wound Electrical Machines Using Statistical Approach

Mathieu Kirouac[1], Maxim Bergeron[2], Jérôme Cros[3], Philippe Viarouge[4]

PG Student, Dept. of Electrical and Computer Engg, Laval University, Québec, Canada[1,2]

Professor, Dept. of Electrical and Computer Engg, Laval University, Québec, Canada[3,4]

ABSTRACT: The heating estimation of random wound coils in electrical machines is a challenge: the number of wires per slot is generally high and the wires are randomly distributed in the slot. This paper presents an original statistical modelling method to evaluate the steady state thermal coil behaviour. This method takes into account the fill factor and can model different wires arrangements using a statistical distribution. The coil section is discretised as a thermal resistances network. Each round wire is associated to a node and linked to others using combined thermal resistances. First, we present the method used to fill the slot with round wires and estimate the gap between them. A mean thermal resistance between two wires is calculated using one-dimensional and bi-dimensional thermal resistances. We also compute extreme values for this resistance. Both values give a baseline to simulate random wires arrangements by using probability density functions. We explain how to take account the boundary conditions and solve the problem. The 2D slot model version is validated by finite elements analysis and experimental comparisons. According to the experimental results, it was possible to identify the best random distribution of thermal resistances which represents the wire arrangement in slot geometry. Finally, we present how to make a 3D model version and we present a case study of a concentrated winding for a permanent magnet machine.

KEYWORDS: Electrical machine, thermal models, mush winding, coil, random wound, stochastic wire distribution, statistical model.

I. INTRODUCTION

Thermal modelling of electrical machines is not a simple task; some critical parameters are difficult to model and play an important role in the global thermal machine behaviour. A hot spot is generally located in the coil and thereby constitutes the main heat stress due to the thermal limitations of wire insulation. There are two types of electrical machine winding; the random wound coils and the form wound coils [1]. Random wound (or mush winding) is difficult to simulate because of the stochastic wire arrangement.For effective motor design and production process, it is essential to be able to properly simulate the thermal behaviour of random windings.

Finite element analysis(FEA) requires large computing time and processing capacities. This numerical method can take account of all wire positions inside a slot to simulate the random wire placement.This approach has been used by several authors to validate thermal models and hot spot estimation methods[2], [3].

The most common thermal modelling method to represent a coil in a slot is to use an equivalent homogeneous thermal conductivity. This thermal conductivity depends mainly on the fill factor and the random placement of the conductors in the slot. This value is generally estimated experimentally[4]–[7]. However, [3] shows that some homogenization analytical formulations for random wire distribution may be adequate. This homogenization approachcan be applied for both numerical methods[8]and analytical lumped circuit. Detecting the hotspot in a coil requires a sufficient discretization and distributed copper losses. To use a single thermal resistancein lumped circuit to determine the hotspot it is necessary to calibrate it to give the sametemperature rise.

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Another analytical approach has been proposed by [5], [7], [9]. It consists of a layered winding model made of a small network of thermal resistances that represents successive slices of copper, insulation and impregnation/air material.

A stochastic method is proposed in this paper to model the random winding using an intuitive and realistic approach. It is based on a probability density functionto simulate random wires arrangement in the slot. It offers a very good accuracy with a negligible memory requirement and time calculation. It can be used to study the random characteristics of a coil, like the wire distribution, the quality of impregnation and the residual air quantity. This 2D slot model can be easily included in a more global thermal model to improve precision on the winding slot thermal distribution. A significant advantage of this model is that it can be directly coupled with an electric circuit to determine the local values of copper losses influenced by the resistivity variation in each strand of wire.A multi-slice model is simple to implement. It canevaluate the 3D heat flux exchanged along the conductors and estimate the temperature distribution in different regions of the coil.

First, we present the method used to discretize the coil section as a 2D thermal resistances network. Each round wire is associated to a node and linked together using combined thermal resistances. This modelling method is based on the following assumptions:

- The thermal conductivity in the conductor is sufficiently high and the conductor size is sufficiently small to assume an uniform temperature distribution in each slice of conductors
- The electrical insulation material is thin enough to assume that the heat flow is transmitted only radially.

These are commonly valid assumptions for wire-wound machines.First, we present the method used to fill the slot with round wires and estimate the gap between them. A mean thermal resistance between two wires is calculated using shape factors. We also compute extreme values of this resistance due to varying distances between two adjacent wires. Both values give a baseline to simulate random wires arrangements by using probability density functions. We explain how to take into account the boundary conditions and solve the 2D problem. Then, the model is validated by experimental comparisons. The results show the critical importance of linking the loss model to the thermal model to get accurate temperature distribution and losses in the coil under study. It is also shown that the probability function used has a significant impact on the temperature distribution. Finally, we presenta 3D coil model based on a multi-slices approach. This allows considering the flux exchanged between the conductors in the third dimension.

II. WIRE SLOT FILLING MODEL

Random wound coils have stochastic wire distribution in each coil section.Consequently, it is impossible to know the real position of each conductor. We use a conventional approach with staggered or by square arrangements to identify the thermal couplings between adjacent conductors. However, these thermal coupling are modelled with variable thermal resistances and probabilistic distributions are used to define each resistance. First, we describe the wire placement method in a slot (or slot filling model). Fig.1 shows two types of cell configuration (staggered and square).

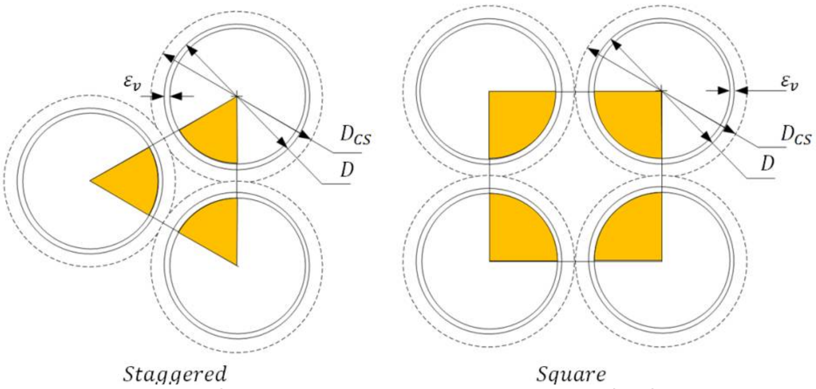

Fig. 1: Uniform wire placement and theoretical fill factor

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The theoretical fill factor Cu_{th}, is the wire cross-sectional ratio between copper area on (copper+ insulation) area, given by the following expression for staggered (1) and square (2) arrangements. D is the wire diameter, ε_v is the thickness of the wire insulation and D_{CS} is the distance between the center of two conductors.

$$Cu_{th} = \frac{\pi(D-2\varepsilon_v)^2}{2\sqrt{3}{D_{CS}}^2} \qquad (1)$$

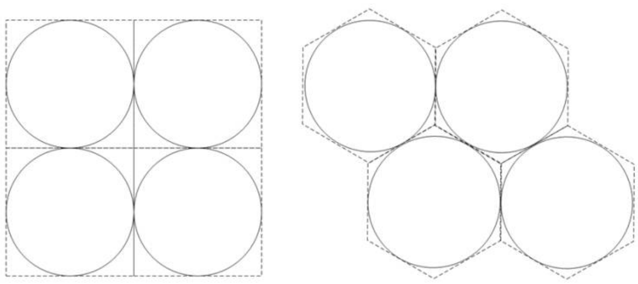
$$Cu_{th} = \frac{\pi(D-2\varepsilon_v)^2}{4{D_{CS}}^2} \qquad (2)$$

In practice, it is impossible to reach the maximum theoretical values of fill factor $(Cu_{th})_{max}$ obtained when $(D_{CS}/D) = 1$. This means that the wires are not all in contact and there is an air gap between them. In addition, another factor that reduces the fill factor is the bad arrangement on the periphery of the slot. Using small conductors allows being closer to the theoretical value. Another way is to press the coils and deform the circular wire shape as proposed by [10]. Doing so, a maximum of 81% is achieved.The wire distribution (staggered or square) has a noticeable influence on the theoretical value of the fill factor. The electrical insulation type (Single or Quadruple build) also has an important effect, particularly for thin conductors. Generally, fill factor values of 0.3 to 0.4 are used in industry applications to simplify winding realizations.

In the model, the staggered and square arrangements are realized with an iterative algorithm. It arranges uniformly a given number of conductors, strand by strand, in the slot section.

III. THERMAL RESISTANCE BETWEEN TWO WIRES FOR UNIFORM WIRE DISTRIBUTION

We must evaluate the thermal resistance between two wires with uniform wire distribution. To do that, we discretize the slot area as several elementary cells of hexagonal or square shape depending on the selected wire distribution (Fig 2).



$N = 4$ $\qquad$ $N = 6$

Fig. 2: Elementary Cells arrangements

Each side of an elementary cell is coupled with the adjacent cell. The thermal resistance which binds two conductors is difficult to estimate. It depends on the electrical insulation material and the gap between the wires.The model uses a combination of one-dimensional resistance for the wire varnish and two-dimensional resistance for the gap between the wires. As stated before, we assume that the heat flow is transmitted only radially inside the wire varnish because the varnish is thin. Consequently, this heat transfer can be modelled using one-dimensional thermal resistance (3). The variable (k_v) is the thermal conductivity of the varnish and (w) is the thickness of the slice studied. The angle θ is given by (4) and depends of the cell shape.

$$R_v = \frac{\mathrm{Log}(D/(D-2\varepsilon_v))}{(\theta_N \cdot w \cdot k_v)} \qquad (3)$$

$$\text{Square shape}: \theta_{N=4} = \pi/2$$
$$\text{Hexagonal shape}: \theta_{N=6} = \pi/3 \qquad (4)$$

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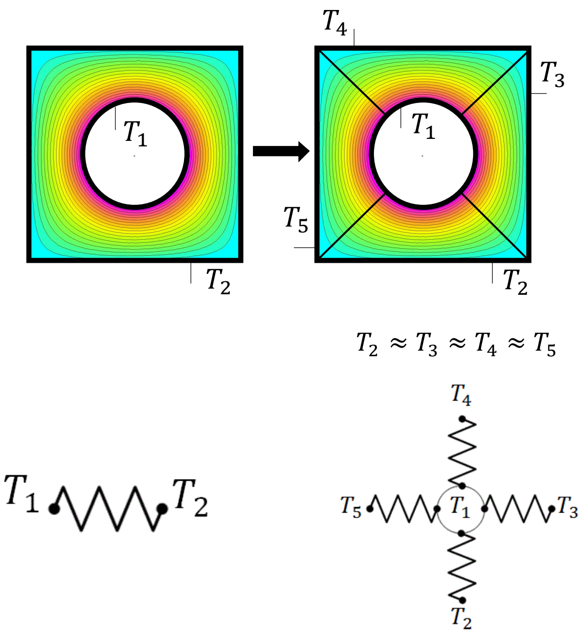

$$R_{S_{f_N}} = \frac{1}{\left(S_{f_N} \cdot w \cdot k_r\right)} \quad (5) \qquad R_N \cong \frac{N}{\left(S_{f_N} \cdot w \cdot k_r\right)} \quad (6)$$

Fig. 3: Shape factor assumption and equivalent thermal resistance diagrams of each cell

Fig. 3 illustrates the calculation of the 2D thermal resistance between two adjacent conductors. This method uses the conduction shape factors expressions,S_f developed by [11] for a cellhaving N sideswitha circle included. It is assumed that the temperature differences betweenT_2, T_3, T_4 and T_5 are small enough that the thermal flow is proportional to the shape factor divided by the number of sides. According to this principle, it is possible to link the wires depending on the type of cell used (Fig 2). Finally, (7) gives the average thermal resistance.(k_r)isthe conductibility of impregnation/air. One can use this average value to model a uniform distribution of conductors having the same thermal resistance between each other (Fig 4).

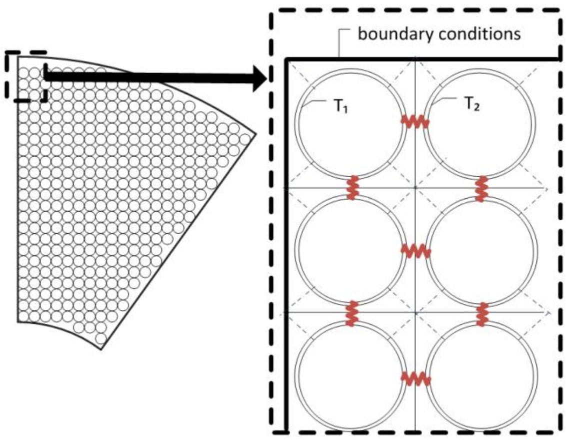

Fig. 4: Thermal network

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$$R_{mean} = 2\left[\frac{N}{\left(S_{f_N} \cdot w \cdot k_r\right)} + R_v\right] \qquad (7)$$

IV. THERMAL RESISTANCE BETWEEN TWO WIRES FOR RANDOM WIRE DISTRIBUTION

The previous modelling does not represent the real situation. In practice, the variation of the gap thickness between two conductors affects the thermal coupling. Furthermore, the residual air quantity after the impregnation process can locally raise also the value of the combined thermal resistance. This is why two expressions are defined to estimate the minimum and maximumtheoretical resistance values for a given slot geometry. It provides a baseline to model the variability of the thermal couplings in the slot area. Indeed, we can generate a vector of random resistances for the slot area by using three different types of random distribution: normal, uniform and Weibull function. Resistance values taken from the random distribution are allocated randomly in the whole slot area. Fig 5, Fig 6 andFig 7 show a few examples of random thermal resistances distribution.The distribution is color coded to give a comprehensive overlook on the value of the wire-to-wire thermal resistance

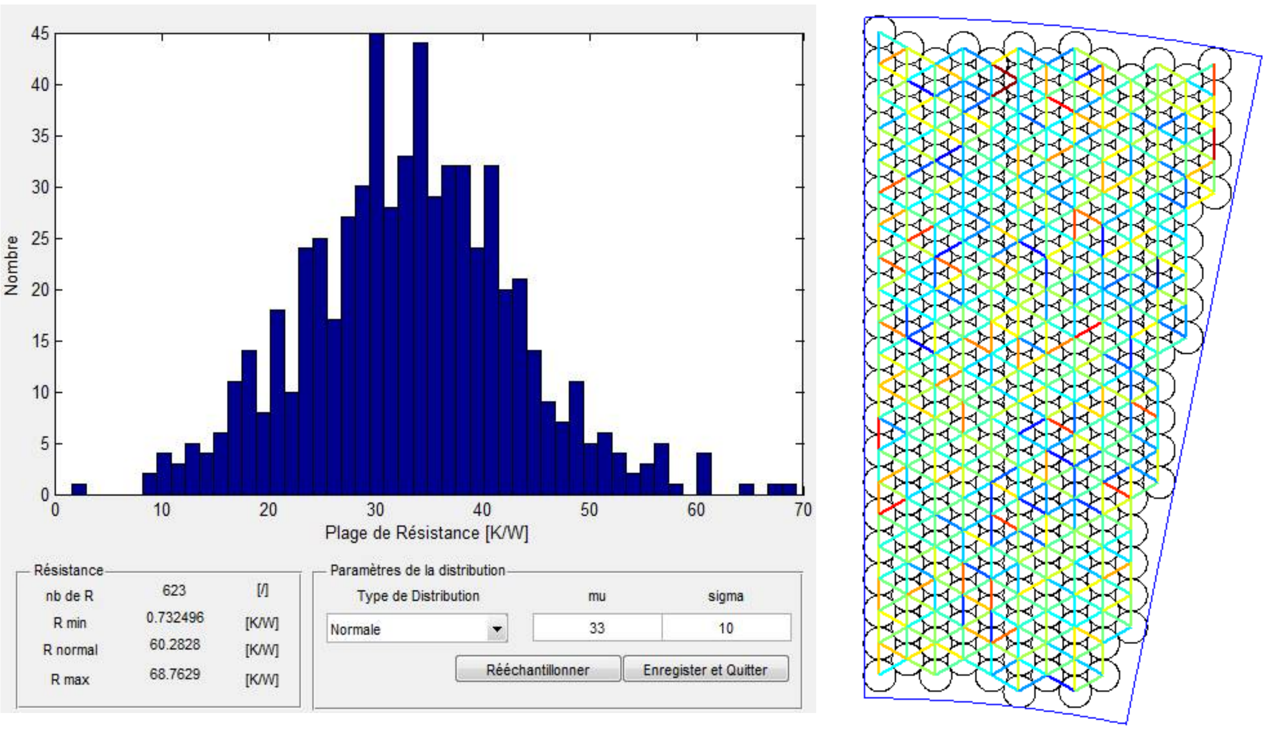

Fig 5: Thermal resistance networks example for wire distributions with normal distribution. (Red-high values, Blue-low values)

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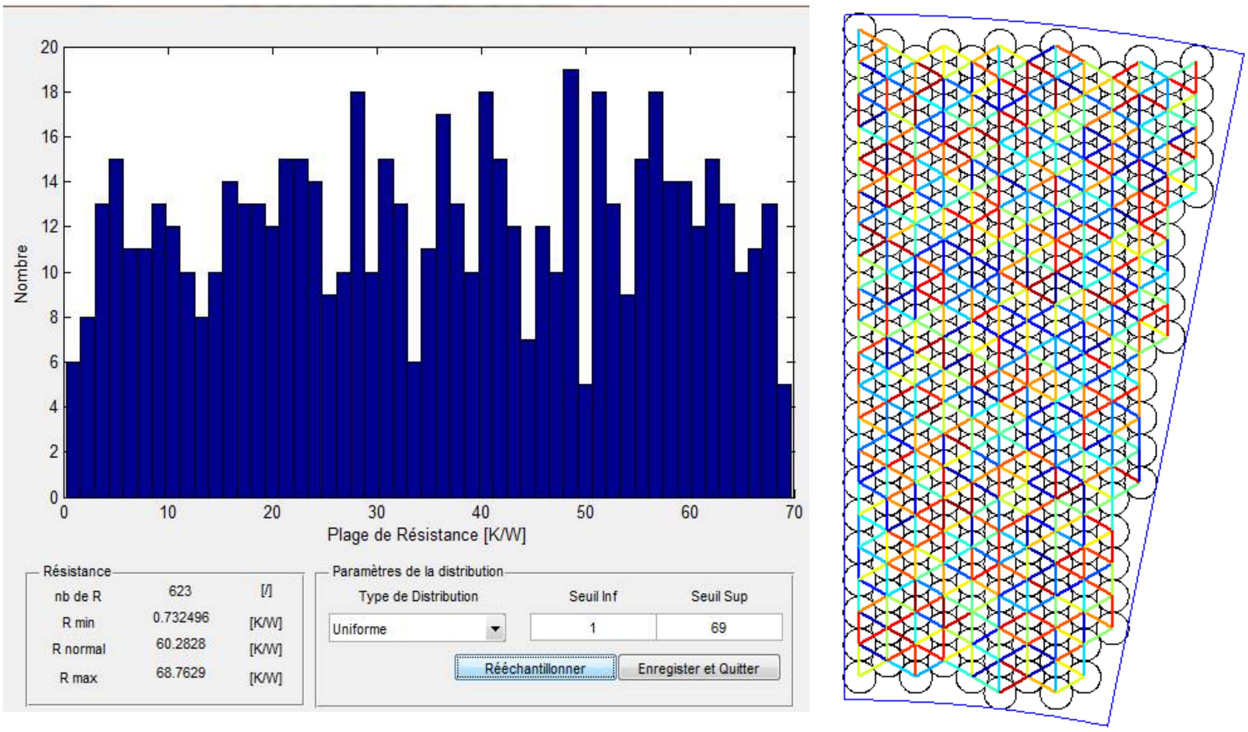

Fig 6: Thermal resistance networks example for wire distributions with random uniform distribution. (Red-high values, Blue-low values)

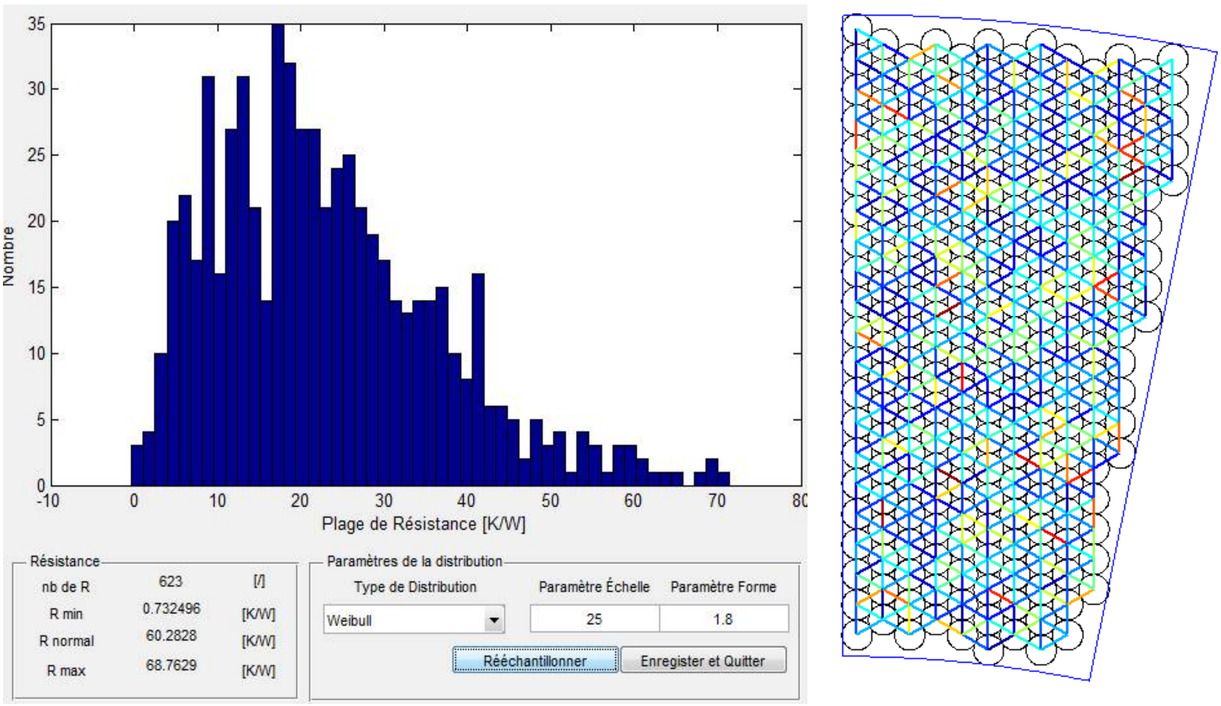

Fig 7: Thermal resistance networks example for wire distributions with Weibull distribution. (Red-high values, Blue-low values)

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Equation (8) gives the maximum wire-to-wire resistance using the thermal conductivity of the air, (k_{air}), for the calculation of the shape factor. This approach simulates an air bubble between two adjacent wires when resin impregnation process is used.Otherwise, it has the same value as the average resistance. To evaluate the minimum resistance (9), we consider the maximal fill factor when the coil was pressed enough to deform the wire geometry in a square or hexagonal shape. This resistance value is dependent on the equivalent length L_N, to one side of a hexagon (10)or square (11) with the same circular wire section.

$$R_{max} = 2\left[\frac{N}{(S_f \cdot w \cdot k_{air})} + R_v\right] \quad (8)$$

$$R_{min} = \frac{2 \cdot \varepsilon_v}{(w \cdot k_v \cdot L_N)} \quad (9)$$

$$L_{(N=6)} = \sqrt{\pi D^2/6\sqrt{3}} \quad (10)$$

$$L_{(N=4)} = \sqrt{\pi D^2/4} \quad (11)$$

V. MATRIX SYSTEM AND BOUNDARY CONDITIONS

Our thermal model is linked to a loss model considering the copper losses for a constant current. To find the steady-state, a balance equation (12) is associated to each node and the whole system can be described by a simple linear matrix problem (13).

$$\sum_{j=0}^{n}\left(\frac{T_i - T_j}{\boldsymbol{R}_{i,j}}\right) = -\dot{q}_\iota \quad (12)$$

$$[\boldsymbol{R}][\boldsymbol{T}] = [\boldsymbol{S}]$$
$$[\boldsymbol{T}] = [\boldsymbol{R}]^{-1}[\boldsymbol{S}] \quad (13)$$

The resistance matrix is built step by step for uniform or random distributions of conductors.To take into account the influence of temperature on the resistivity, the solving method must iterate and compute a new loss vector [S] evaluated with the temperature distribution of the previous iteration. A few iterations are enough to converge to the final steady state temperatures.The application of boundary conditions could easily link the slot model with another more global model. It can also be used independently by adjusting the boundary conditions with the desired studied case. Table I shows different types of boundary conditions with their respective equations. (T_i)is the node temperature for which the condition is applied. As for ($T_{b.c}$), it corresponds to the fixed temperature. ($q_{b.c}$) is associated to heat transfer. (T_0) is the ambient temperature in the case of a convection boundary condition or with thermal resistances. ($h_{b.c}$)is the convection coefficient apply on the surface (A). Column $[\boldsymbol{R}_{i,i}]$ in table I shows the mathematical expression applied on the diagonal element for the associated boundary condition. Following the same principle, the column $[\boldsymbol{S}_i]$in table I indicates the mathematical expressionfor the loss vector. Those boundary conditions allow enough flexibility to simulate different thermal conditions on slot periphery.

I. Boundary conditions parameters

$B.C.$	$Equation$	$[\boldsymbol{R}_{i,i}]$	$[\boldsymbol{S}_i]$
$Temperature$	$(T_i - T_{b.c})/R_{min}$	$1/R_{min}$	$T_{b.c}/R_{min}$
$Imposed\ Flux$	$q_{b.c}$		$-q_{b.c}$
$Convection$	$h_{b.c}A(T_i - T_0)$	$h_{b.c}A$	$h_{b.c}AT_0$
$Resistance$	$(T_i - T_0)/R_{b.c}$	$1/R_{b.c}$	$T_0/R_{b.c}$

For non-uniform boundary conditions, the model uses a third-order polynomialexpression to simulate the possible variation on each border of the slot.

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VI. COMPARISON WITH FINITE ELEMENTS AND ANALYTICAL FORMULATIONS FOR UNIFORM WIRE PLACEMENT

The 2D slot model can be compared to other methods in the case of a uniform wire placement with different fill factors. We carried finite element simulations to study square slot geometries. Ten simulations were performed with 16 to 400 conductors distributed in the slot area. The borders of the slot were imposed with a uniform temperature in order to impose the hot spot in the center of the study domain. This simplifies the comparison with the analytical model. The maximum error value obtained on the hot spot was 0.7%. This demonstrates the accuracy of the model for a negligible computation time compared to the FEM.

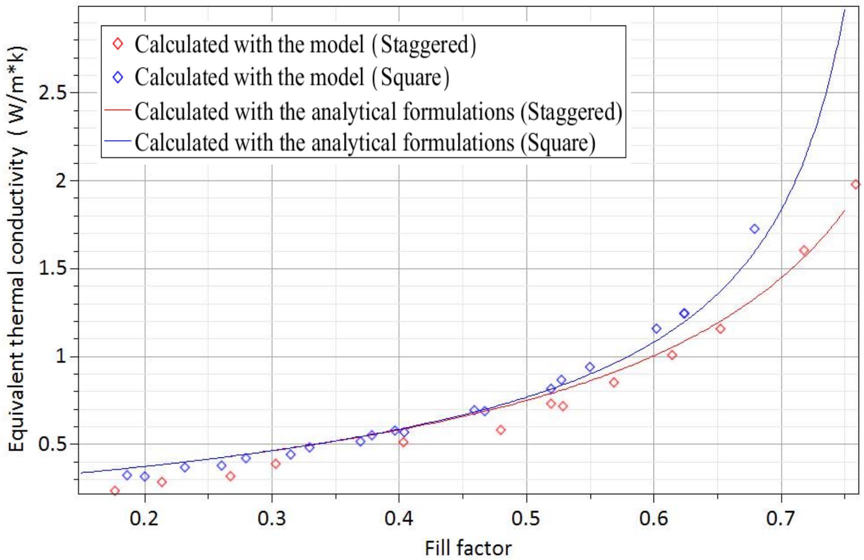

Fig 8:Comparison of equivalent thermal conductivity determined from the model (dot) and analytical formulation defined by [12]. ($\boldsymbol{k_v = 0.25\ W/m}$℃)

Another comparison was done for the equivalent thermal conductivity of a homogeneous material calculated with the model and the analytical formulations proposed by [12]for regular staggered and square arrangement. The results are shown in Figure 8. The model produces an acceptable error on thefilling factor range of 0.3 to 0.6.This comparison shows that the equivalent thermal conductivity obtained experimentally could be used with the model to correlate random distribution.

VII. EXPERIMENTAL VALIDATIONS ON AN UNIMPREGNATED AIR CORE

To validate the 2D thermal coil model,experimental tests were carried on anunimpregnatedcoil. The coil characteristics aregiven in Table II.Ten thermocouples were used: five of them were inside the coil at different heights; the five others were distributed on the outer faces. A dc current was applied until the coil reached a thermal steady state.The test configuration was adapted to a 2D analysis, since the cooling condition was similar over the entire periphery and does not produce significant heat flows into the third dimension. Thermography was used to accurately adjust the boundary conditions of the model with the temperature on each face. Third-order polynomial equation was evaluated to fit the temperature shown in the Fig.9. The experimental results show a temperature difference of about 20 Celsius degrees between the thermocouples inside the coils and those on the outer faces. In this case, the temperature effect on the resistivity has a noticeable impact. Indeed, the model shows that the variation ofresistivityincreasesthe total losses by 14%.Thatshows the importance of taking the local resistivity into account to obtain realistic losses and thermal distribution. Generally, it is crucial for structures having large slot dimensions and large temperature differentials.

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VII. EXPERIMENTAL PARAMETERS

Section	*Wire*	*Coil*	*Steady Result*
39mm X 97mm	AWG 11 D = 2.354mm ε_v = 0.027mm	n = 480 $turns$ l_{mean} = 524 mm CU_{real} = 51% $R_{20°C}$ = 1.05Ω	I_{DC} = 5.133A V_{DC} = 6.158V R_S = 1.20Ω P = 31.6W

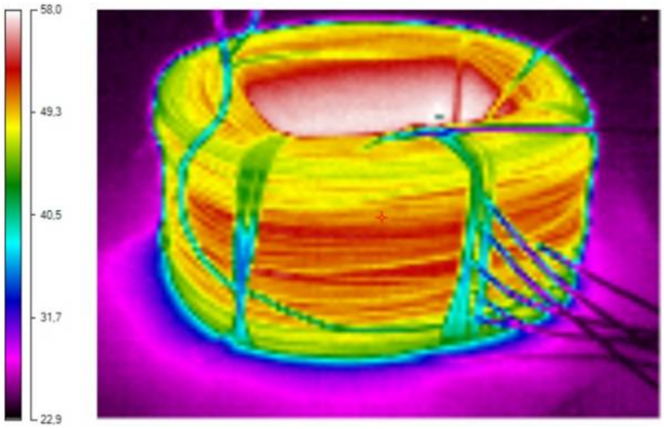

Fig 9: Thermography of experimented coil

1) Simulation with an unique value of thermal resistance

First, we can simulate a coil section as an uniform arrangement of conductors having the same thermal coupling between adjacent conductors. For the resistance matrix, the same value of thermal resistance equal to average value is used but the maximum temperature is overestimated. In the case of the studied coil, the thermal model can be fitted as shown in table III, but we must use a higher thermal conductivity for the air gap between the wires. This conductivity is set to 0.13$(W/m \cdot K)$(near four times the conductivity of air). The fitting was achieved by modifying the parameter with the most influence on the thermal behavior(k_r), to obtain the temperature distribution similar to the experiment. Fig. shows the comparison between both results.

Table III Results for Uniform distribution

Type of distribution	*Wire Gap Conductivity* k_r $[W/m \cdot K]$	T_{max} [°C]	T_{mean} [°C]	P_{tot} $[W]$
Uniform	k_{air} (0.03)	87	70	33.6
	4k_{air} (0.13)	66	59	32.4

These results were expected since a random arrangement of conductors improves the ability of dissipation compared to an uniform arrangement[4]. Thus, to represent correctly the thermal behaviour of the coil using the same thermal resistance value for every conductor, the wire gap conductivity must be artificially increased to take into account the randomness of the wire position.Therefore, this method using a unique resistance value is not suitable because it is difficult to predict at what level it is necessary to increase the conductivity without having experimental results.

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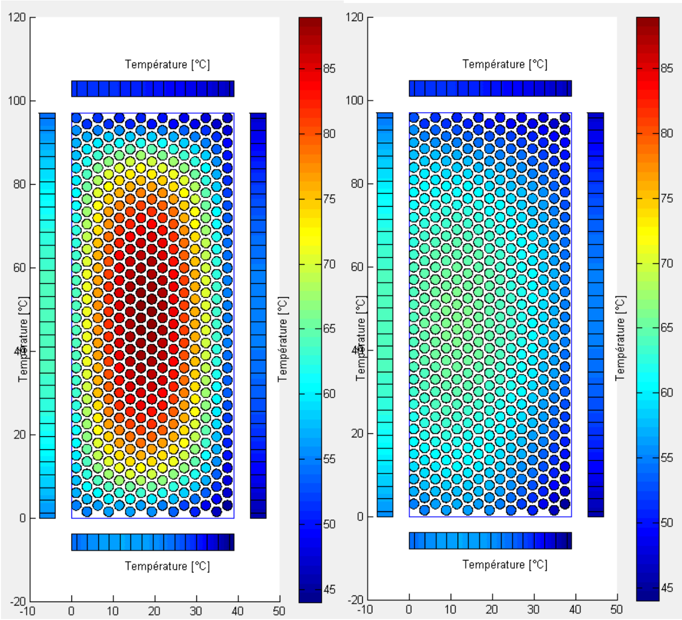

Fig. 10: Comparison between uniform distribution (left- k_r = 0.03 $W/m \cdot K$) and uniform fitted distribution (right - k_r = 0.13 $W/m \cdot K$)

2) Random distribution of several thermal resistances

A random distribution of several thermal resistances values is well suited to simulate the real physical thermal behaviorof a random winding. It creates also preferential dissipation paths between proximate conductors. Table IV summarizes the results for different probabilistic functions of resistance valuesas presented in section IV.The temperature isolines of arandom uniform distributionare irregular contrary of the normal distribution. In both cases, the values are overestimated compared to the experimental values. In the case under study, they showed no interesting results. The Weibull random distribution is the best fit to represent the random arrangement of conductors. Fig 11 compares the temperature distribution of the fitted uniform arrangement presented in the section 7.1 with the Weibull distribution.

IX. RESULTS FOR DIFFERENT THERMAL DISTRIBUTION

$Type\ of\ distribution$	T_{max} [°C]	T_{mean} [°C]	P_{tot} $[W]$
$Normal$	74	63	32.9
$Random\ uniform$	70	61	32.7
$Weibull$ $\lambda = \frac{2}{3}\left(\frac{R_{max} + R_{min}}{2}\right)$ $k = 2$	67	60	32.6

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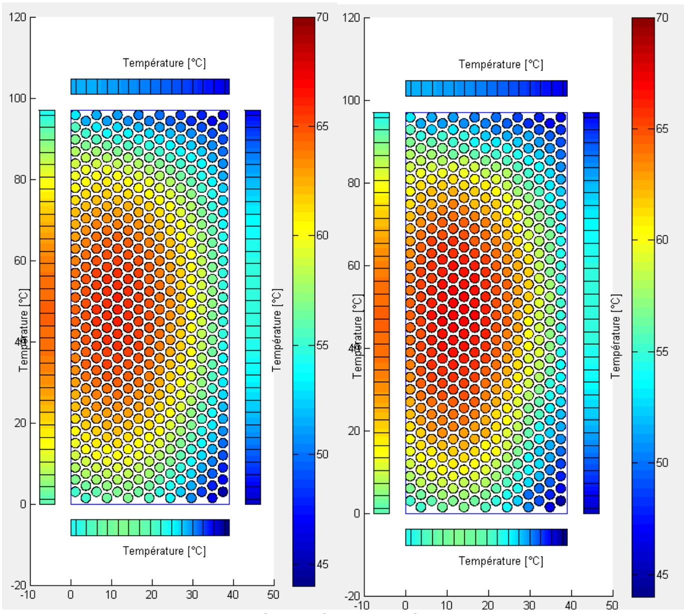

Fig 11: Comparison between uniform fitted (left) and Weibull distribution (right)

X. EXTENSION TO 3D ANALYSIS AND APPLICATION

The 2D coil section model has a limited validity to study a motor winding, because there are temperature differences between a coil section inside the magnetic coreandthe end windings. However, a complete 3D coil model can be made using a multi-slices2D model representation. The coilis divided in several slices. An axial thermal resistance (14) is applied to connect together a same wire strand in the different slices. $(k_{cu})$is the thermal conductivity of the electrical conductor.

$$R_a = \frac{4w}{k_{cu}\pi(D-2\varepsilon_v)^2} \tag{14}$$

The multi-slices approach facilitates mathematical construction of the problem.The overall model produces a sparse matrix (15) and the dimension is defined by the number of conductors multiplied by the number of slices.A coupling matrix $\left[\boldsymbol{R_c}\right]$hasone non-zero elementper row and its location depends on the correspondence of the wire of one layer to the other. This can easily be automatically generated to simulate coils with regular turns or withtwisted and woven conductors.

$$[R] = \begin{bmatrix} [R_1] & [R_{C1}] & [\ ] & [R_n] \\ [R_{C1}] & [R_2] & [R_{C2}] & [\ ] \\ [\ ] & [\ddots] & [\ddots] & [\ddots] \\ [R_n] & [\ ] & [R_{n-1}] & [R_n] \end{bmatrix}, [S] = \begin{bmatrix} [S_1] \\ [S_2] \\ [\vdots] \\ [S_n] \end{bmatrix} \tag{15}$$

To validate the 3D model construction, we applied this method for a concentric coil of a permanent magnet machine having a current density of 1.86 $(\mathrm{A/mm^2})$, with a filling factor of 0.26. The coil is made of 17 turns with 7 wire strands in parallel and twisted together in the end winding. So we assume that the current is equally distributed in all conductors. The 3D model is made up of 10 slices; 6 for the coil in the magnetic core and the others for the coil ends.

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Each layer uses a different random distribution of Weibull as defined in section 6. A global thermal model of the machine was used to define the boundary conditions but this model is not discussed here. For all coil faces in contact withthe magnetic core, we used a resistance boundary condition, like presented in the table I, to simulate the slot liner and contact resistances. For the other faces, we used convection boundary convection.

The 3D simulation (Fig.12-13) shows that the thermal flux exchanged in the third dimension are important. Indeed, it can be seen that the hot zone is not located at the same place in the end-winding of the coils and in the other coil sections. An air gap separates the two coils in the slot. By adjusting the boundary conditions of the model we could study the effect of cooling in this channel. In this simulation the hot spot is in the centre of the coil (slice 3 and 8) because of boundary conditions. Temperatures on slices (1-5 and 6-10) are not the same. Thedifferences are directly linked to the twisting of wires formed between the slice 5-6.The average temperature of each layer is similar (117°C), consequently the losses are evenly distributed in the coil. These results show the good behavior of the model for a mush winding simulation.

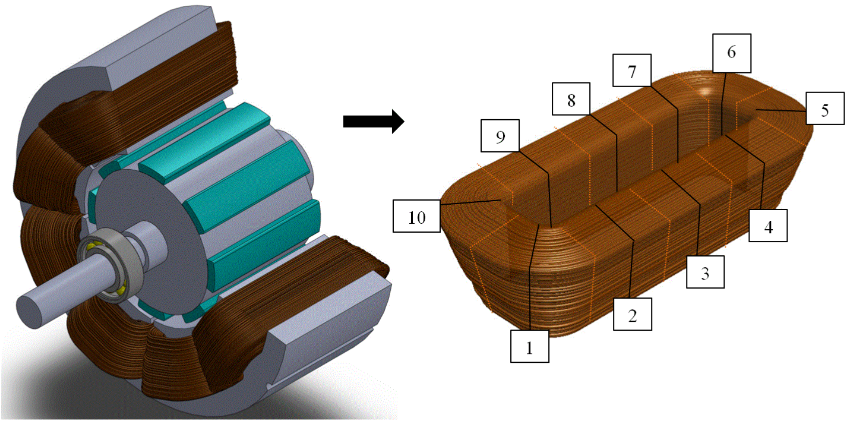

Fig 12: (Left) PM motor, (Right)the multi-slice approach applied to a coil.

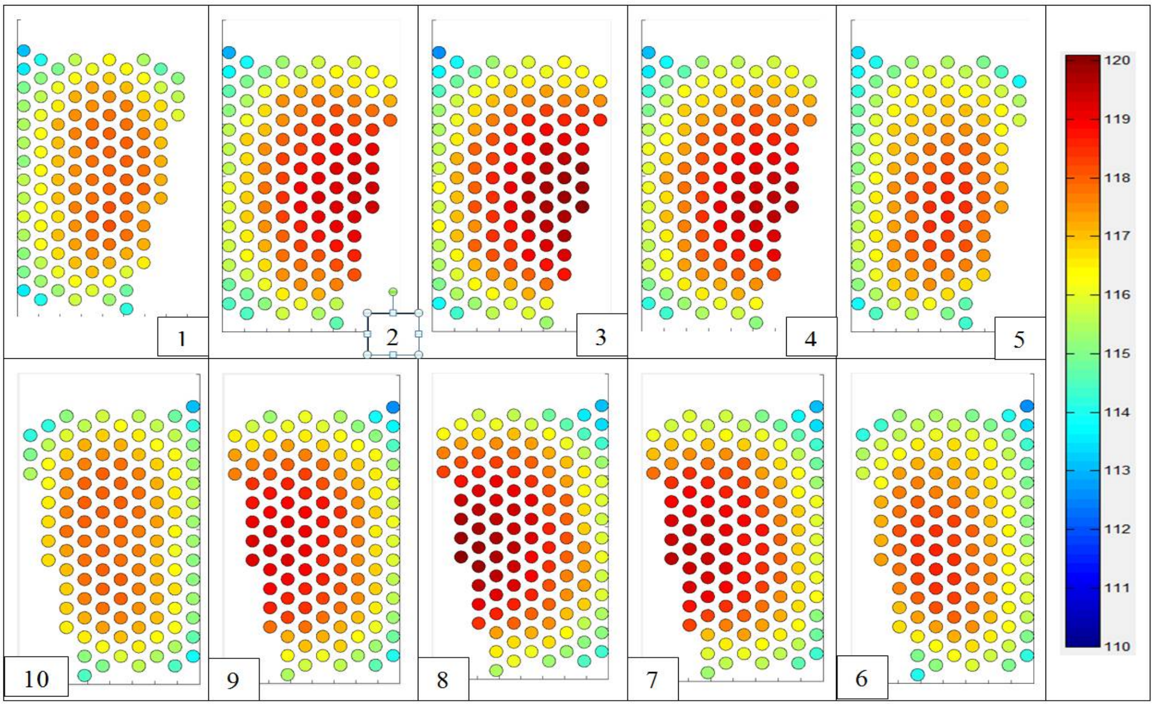

Fig 13: 3D concentrated coil modelling of PM motor according to the number in fig 12, (T in Celsius)

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XI. CONCLUSION

This paper presented a 2D and 3D steady state thermal model for random wound coils. The model takes into account the fill factor and can arrange the wires with different patterns in a given slot. The uneven wire-to-wire thermal resistance is modelled by applying different statistical distributions. According to the experimental results, the best fit was obtained with the Weibull distribution.

The models could easily be improved to achieve transient studies. The representation of all the conductorsin the slot also gives the opportunity to study special coil configurations, for example, when several conductors are connected in parallel. The thermal effectsof unbalanced currents or circulating currents in parallel paths can be easily analysed. The electric coupling could also be improved to take into account the influence of current harmonic of modern inverter and the skin effect. The study in this article showed that the method is not limited to the electrical machine design but can also be a tool for analysis and diagnosis.

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