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Original
Evolution and Modern Approaches for Thermal Analysis of Electrical Machines / Boglietti, Aldo; Cavagnino, Andrea; D., Staton; M., Shanel; M., Mueller; C., Mejuto. - In: IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS. - ISSN 0278-0046. - STAMPA. - 56:3(2009), pp. 871-882. [10.1109/TIE.2008.2011622]

Availability:
This version is available at: 11583/1938008 since:

Publisher:
IEEE

Published
DOI:10.1109/TIE.2008.2011622

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02 September 2025

Evolution and Modern Approaches for Thermal Analysis of Electrical Machines

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***Abstract*—In this paper, the authors present an extended survey on the evolution and the modern approaches in the thermal analysis of electrical machines. The improvements and the new techniques proposed in the last decade are analyzed in depth and compared in order to highlight the qualities and defects of each. In particular, thermal analysis based on lumped-parameter thermal network, finite-element analysis, and computational fluid dynamics are considered in this paper. In addition, an overview of the problems linked to the thermal parameter determination and computation is proposed and discussed. Taking into account the aims of this paper, a detailed list of books and papers is reported in the references to help researchers interested in these topics.**

***Index Terms*—Computed fluid dynamic, electrical machines, finite-element analysis (FEA), lumped-parameter thermal network (LPTN), thermal model, thermal parameter identification.**

I. Introduction

IN THE PAST, the thermal analysis of electric machines has received less attention than electromagnetic analysis. This is clear from the number of technical papers published relating to each of these particular subjects. This inequality is particularly true for small- and medium-sized motors. Traditionally, for such machines, motor designers have only superficially dealt with the thermal design aspects, maybe by specifying a limiting value of current density or some other rudimentary sizing variable. The problem with such sizing methods is that they do not give an indication of how the design may be improved to reduce temperatures.

With the increasing requirements for miniaturization, energy efficiency, and cost reduction, as well as the imperative to fully exploit new topologies and materials, it is now necessary to analyze the thermal circuit to the same extent as the electromagnetic design.

Manuscript received January 28, 2008; revised December 1, 2008. Current version published February 27, 2009.

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Digital Object Identifier 10.1109/TIE.2008.2011622

In fact, there should be a strong interaction between the electromagnetic and thermal designs as it is impossible to accurately analyze one without the other, i.e., the losses are critically dependent upon the temperature and vice versa.

Currently, the interest in thermal analysis involves not only the electrical machine but also the drive and power converter design [1], [2]. A possible reason why thermal analysis has received less attention than electromagnetic analysis is that electric-motor designers usually have an electrical engineering background, while thermal analysis is a mechanical engineering discipline.

Electric-motor thermal analysis can be divided into two basic types: analytical lumped-circuit and numerical methods. The analytical approach has the advantage of being very fast to calculate; however, the developer of the network model must invest effort in defining a circuit that accurately models the main heat-transfer paths [3]–[6].

In its most basic form, the heat-transfer network is analogous to an electrical network, and the analysis consists of the calculation of conduction, convection, and radiation resistances for different parts of the motor construction. The formulations for such resistances are really quite simple. The conduction resistance is equal to the path length divided by the product of the path area and the materials' thermal conductivity. The convection and radiation resistances are equal to one divided by the product of the surface area and the heat-transfer coefficient. The radiation-heat-transfer coefficient is simply a function of the surface properties, i.e., the emissivity and the view factor. The emissivity is known for different types of surface, and the view factor can be calculated based on the geometry. The convection-heat-transfer coefficient is most often based on empirical formulations based on convection correlations which are readily available in the heat-transfer literature. Fortunately, there is a wealth of convection correlations for most of the basic geometric shapes used in electrical machines, both for natural and forced convection cooling (i.e., cylindrical surfaces, flat plates, open- and closed-fin channels, etc.). The most common and useful convection correlations are even available in undergraduate textbooks on heat transfer [7]–[12].

The main strength of numerical analysis is that any device geometry can be modeled. However, it is very demanding in terms of model setup and computational time. There are two types of numerical analysis: finite-element analysis (FEA) and computational fluid dynamics (CFD). CFD has the advantage that it can be used to predict flow in complex regions, such as around the motor end windings [13], [14]. FEA can only be used to model conduction heat transfer in solid components.

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For convection boundaries, the same analytical/empirical algorithms used in the lumped-circuit analysis must be adopted (i.e., convection correlations).

Taking into account the survey approach of this paper, a short historical evolution on electrical-machine thermal analysis is hereafter included.

Before the advent of computers, motor sizing was traditionally made using the so-called D^2L, D^3L, and D^xL sizing equations, where the designer provided limiting values of specific magnetic and electric loadings and/or current density from past experience [15]. This method of sizing does not involve thermal analysis directly, the specific magnetic loading and current density being limited to prevent overheating. At this time, simple thermal-network analysis based on lumped parameters were also used by some designers to perform rudimentary thermal analysis; however, the thermal networks were kept as simple as possible so they could be calculated by hand, e.g., maybe just one thermal resistances to calculate the steady-state temperature rise of the winding. With the introduction of computers to motor design, the complexity of the thermal networks increased. A reference paper highlighting the introduction of more complex thermal networks calculated using computers was published in 1991 by Mellor *et al.* [3]. Thermal-network analysis has become the main tool used by many researchers involved in thermal analysis of electrical machines, both for steady-state and transient analyses [16]. A further factor that has led to increased interest in thermal-network analysis was the introduction of induction motor inverter supplies. Several authors have studied the effect of increased losses, resulting from six-step and pulsewidth-modulation voltages, on motor temperatures [17], [18].

Thermal analysis has always received less attention than electromagnetic design. However, in the new century, the topic had started to receive more importance due to market globalization and the requirement for smaller, cheaper, and more efficient electric motors. In many cases, the software used for the design of electric machines has now adopted improved thermal modeling capabilities and features enabling better integration between the electromagnetic and the thermal designs [19], [20].

Several interesting papers have been published in recent years on thermal analysis of electric machines. References [19] and [20] deal with coupled electromagnetic and thermal analysis with the thermal network solved using network analysis. In [20], the losses are calculated using analytical methods [21], while in [19], electromagnetic FEA is used. In [22], a thermal-network method is proposed to account for combined air flow and heat transfer, i.e., for forced air cooling in stator and rotor core ducts in this case. In [23], a combined network and CFD method is used to model the machine. Network analysis is used to calculate conduction through the electromagnetic structure while CFD is used for convection at the surface. The use of CFD for prediction of convective heat transfer is expanded in Section VI. Calibration with measured data is typically used to calibrate thermal resistances that are influenced by the motor manufacturing process [4], [6], [24]. An example is the thermal interface resistance between stator lamination and housing, which is influenced by the method used to insert the stator in the frame.

II. Thermal Network Based on Lumped Parameters

This section details the main concerns relating to lumped-parameter thermal-network (LPTN) analysis. Analytical thermal-network analysis can be subdivided into two main calculation types: heat-transfer and flow-network analyses. Heat-transfer analysis is the thermal counterpart to electrical-network analysis with the following equivalences: temperature to voltage, power to current, and thermal resistance to electrical resistance. Flow-network analysis is the fluid mechanics counterpart to electrical-network analysis with the following equivalences: pressure to voltage, volume flow rate to current, and flow resistance to electrical resistance. In the heat-transfer network, a thermal resistance circuit describes the main paths for power flow, enabling the temperatures of the main components within the machine to be predicted for a given loss distribution.

As is well known, 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. Nodes are separated by thermal resistances that represent the heat transfer between components. Inside the machine, a set of conduction thermal resistances represents the main heat-transfer paths, such as from the winding copper to the stator tooth and back iron (in this case, the heat transfer is through the winding insulation consisting of a combination of enamel, impregnation, and slot-liner materials), from the tooth and stator back iron nodes to the stator bore and housing interface, etc. In addition, internal convection and radiation resistances are used for heat transfer across the air gap and from the end windings to the endcaps and housing. External convection and radiation resistances are used for heat transfer from the outside of the machine to ambient. In the past, due to limited computational capabilities, simple thermal networks with few thermal resistances, capacitances, and sources were adopted. Nowadays, much more detailed thermal and flow networks can be quickly solved, including a high number of thermal and flow elements. An example of a detailed heat-transfer network is shown in Fig. 1. Detailed information on this thermal network can be found in [35].

Lumped-circuit thermal models have been extensively utilized and validated on numerous machine types and operating points. Such a wide range of studies has increased confidence in such thermal models.

As an example of this approach, the thermal model shown in Fig. 1 has been used to analyze a 22.5-kVA synchronous machine, shown in Fig. 2.

The model calculates both the air flow and heat transfer in the machine. Air flow and temperature rise for all stator and rotor nodes were within 10% of the measured values [25].

Analytical lumped-circuit techniques are also very useful in determining the thermal model's required discretization level. This refers to the number of sections used to model the electrical machine as a whole, or some of the more critical components, both in the axial and radial directions. In [25], studies have been performed to determine the required discretization level for a synchronous generator, with particular attention being given to the winding area. Due to its low thermal

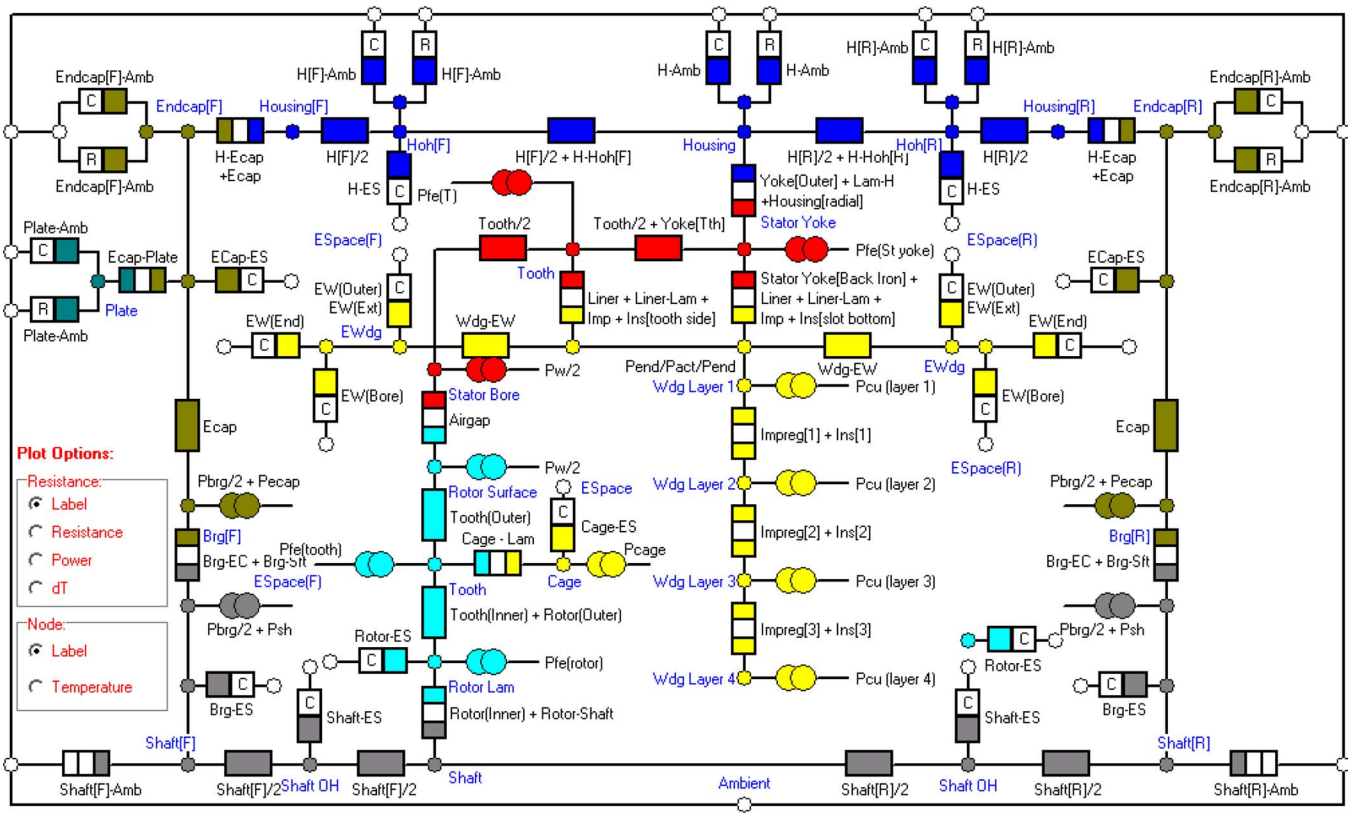

Fig. 1. Example of heat-transfer network for an electric motor.

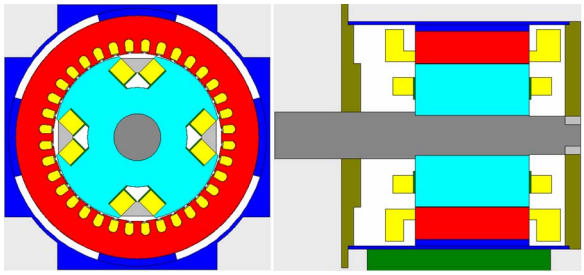

Fig. 2. Radial and axial cross sections of the modeled alternator.

conductivity [2–3 W/(m ·°C)], this area is of great thermal significance and has to be analyzed with care.

In the real winding, the heat generation is distributed over the section, and this paper highlights the impact upon accuracy of specifying such a loss in the discrete nodes. A number of rotor winding models were used, ranging from a "single-block" (1 × 1) representation to a rotor winding represented by 100 smaller sections (10 × 10). These two models are shown in Fig. 3.

In Fig. 4, the trend of the predicted averaged node temperatures as a function of the number of network nodes per section is shown. Concentrating all loss in one node in the 1 × 1 network results in an unrealistic gradient between the wall and the winding center. Thus, a suitable formula must be used to derive the average section temperature (20.2 °C) from a single-node temperature and wall temperatures; otherwise, it could be wrongly interpreted as the whole winding section being at 60.5 °C. The winding discretization level of 10 × 10 yields more accurate predictions (average 17.7 °C, peak 35.8 °C) without the need for the formula when compared

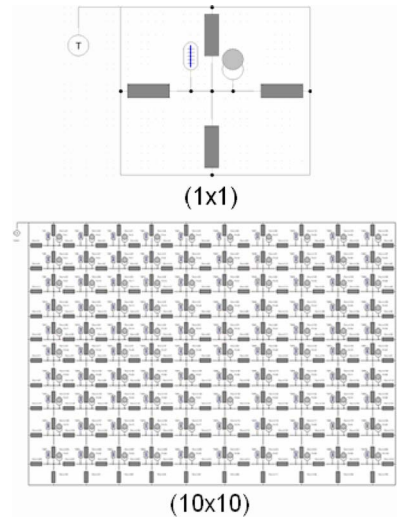

Fig. 3. Rotor winding models of (top) 1 × 1 and (bottom) 10 × 10.

with FEA results (average 17.0 °C, peak 37.2 °C). To sum up, using lower levels of discretization reduces the accuracy of the results, while increasing the node numbers unnecessarily complicates the thermal model.

As previously reported, lumped thermal parameters analysis involves the determination of thermal resistances. The main methods used for the calculation of conduction, radiation, and convection thermal resistances are hereafter summarized.

It is important to remark that these methods for the thermal resistance determination have general validity and they are not linked to the thermal-network complexity.

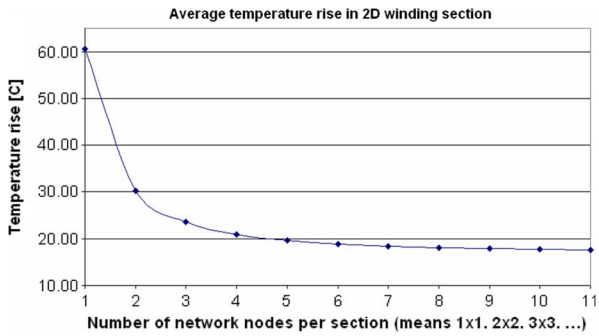

Fig. 4. Rotor winding discretization results up to 11 × 11.

A. Conduction Heat Transfer

Conduction thermal resistances can be simply calculated using the following:

$$R = \frac{L}{kA} \tag{1}$$

where L (in meters) is the path length, A (in square meters) is the path area, and k (in watt per meter degree Celsius) is the thermal conductivity of the material. In most cases, L and A can simply be gained from the components' geometry. The only complication is in assigning a correct value to L for thermal resistances due to the interface gap between components. As discussed in [24] and [26], experience factors are very important for a correct prediction of this thermal resistance. Commercial software packages typically provide details on various types of material with different roughness and manufacturing techniques to aid the user to set such interface gaps. Sensitivity analysis with values between the minimum and maximum expected values is always useful to gain a thorough understanding of the problem.

B. Radiation Heat Transfer

Radiation thermal resistances for a given surface can be simply calculated using

$$R = \frac{1}{h_R A} \tag{2}$$

where A (in square meters) is the surface area and h_R (in watt per square meter degree Celsius) is the heat-transfer coefficient. The surface area is easily calculated from the surface geometry. The radiation-heat-transfer coefficient can be calculated using the following:

$$h_R = \sigma \varepsilon F_{1-2} \frac{\left(T_1^4 - T_2^4\right)}{(T_1 - T_2)} \tag{3}$$

where $\sigma = 5.669 \times 10^{-8}\ \mathrm{W/(m^2 \cdot K^4)}$, ε is the emissivity of the surface, F_{1-2} is the view factor for dissipating surface 1 to the absorbing surface 2 (the ambient temperature for external radiation), and T_1 and T_2 are, respectively, the temperatures of surfaces 1 and 2, in units of kelvin. The emissivity is a function of the surface material and finish, for which data are given in most engineering textbooks [7]–[12]. The view factor can easily be calculated for simple geometric surfaces, such as cylinders and flat plates; however, it is a little more difficult for complex geometries, such as open-fin channels. In these cases, books are available to help with the calculation of the view factor [27], [28].

C. Convection Heat Transfer

Convection is the transfer process due to fluid motion. In natural convection, the fluid motion is due entirely to buoyancy forces arising from density variations in the fluid. In a forced convection system, movement of fluid is by an external force, e.g., fan, blower, or pump. If the fluid velocity is high, then turbulence is induced. In such cases, the mixing of hot and cold air is more efficient, and there is an increase in heat transfer. The turbulent flow will, however, result in a larger pressure drop; as a consequence, with a given fan/pump, the fluid volume flow rate will be reduced. Convection thermal resistances for a given surface can be simply calculated using

$$R = \frac{1}{h_C A}. \tag{4}$$

The previous equation is basically the same equation as for radiation but with the radiation-heat-transfer coefficient replaced by the convection-heat-transfer coefficient h_C (in watt per square meter degree Celsius). Proven empirical heat-transfer correlations based on dimensionless analysis are used to predict h_C for all convection surfaces in the machine [3]–[12], [24], [29].

D. Flow-Network Analysis

Forced convection heat transfer from a given surface is a function of the local flow velocity. In order to predict the local velocity, a flow-network analysis is performed to calculate the fluid flow (air or liquid) through the machine. Empirical dimensionless analysis formulations are used to predict pressure drops for flow restrictions, such as vents, bends, contractions, and expansions [24], [29]–[34]. The governing equation that relates the pressure drop (P, in pascal, equivalent to an electrical voltage) to the volume flow rate (Q, in cubic meters per second, equivalent to electrical current) and fluid-dynamic resistance (R, in kg/m^7) is

$$P = RQ^2. \tag{5}$$

In (5), the formulation is in terms of Q^2 rather than Q due to the turbulent nature of the flow. Two types of flow resistance exist. The first exists where there is a change in the flow condition, such as expansions, contractions and bends. The second is due to fluid friction at the duct wall surface; in electrical machines, this is usually negligible compared with the first resistance type due to the comparatively short flow paths. The flow resistance is calculated for all changes in the flow path using

$$R = \frac{k\rho}{2A^2} \tag{6}$$

where ρ (in kilograms per cubic meter) is the air density (depending on the temperature), A (in square meters) is the flow area, and k is the dimensionless coefficient of local fluid resistance whose value depends upon the local flow condition (obstruction, expansion, contraction, etc).

Many empirical formulations are available in the technical literature to calculate the k factor for all changes in the flow section within the motor. A merit of thermal tool [35] is to automatically select the most appropriate formulation for all the flow paths involved (i.e., a sudden contraction when air enters the stator/rotor ducts, a 90° bend where the air passes around the end winding, etc.).

III. Analytical Thermal-Network Analysis Software

The main characteristics of analytical software packages used in thermal analysis of electrical machines are discussed in this section. Analytical thermal-network analysis software packages can be subdivided into three types, namely, dedicated software for thermal analysis of electric motors, general-purpose network solvers with library components that can be used for thermal analysis, and custom packages written by the electrical-machine designers for a particular machine type. There are very few commercial software packages for electric-motor thermal analysis. One of the most widely used tools is given in [35]. The main advantage of the package is that the user needs only to input details of geometry, winding, and materials used, and the software automatically sets up the thermal network and selects the most appropriate analytical formulations for each of the circuit components. Thus, the user need not be an expert in heat-transfer analysis in order to use the software. The main limitation of such dedicated software is that the geometry is based on a fixed set of topologies (i.e., preparameterized models). If the user's geometry is not similar to any of the built-in topologies, then a model cannot be implemented. Ideally, such packages should have some advanced features such that the user can edit the thermal circuit to model minor modifications to the geometry [35]. It is important to underline that most motor topologies are relatively standard from the thermal point of view.

If a totally new type of structure is being analyzed, then there can be advantages in the user developing a completely new thermal network in a simulation tool. Such packages usually have powerful network editors with drag-and-drop interfaces. An example of this type of package is given in [36]. This tool has features to help the user set up thermal networks in terms of thermal libraries. In particular, powerful "wizard" dialogs are used to select geometry and material data from which the most appropriate analytical mathematical formulations are automatically selected. Thus, the user sets up the thermal circuit from a geometric point of view rather than spending time researching heat-transfer formulations. This is also the typical approach used by a motor designer when developing thermal-analysis software for their own company use. For established machine topologies for which design evolves slowly, impressive user interfaces and topology flexibility can be replaced by available measured results, allowing for the validation and fine tuning of such in-house software. Simultaneous iterative solutions of heat generation; fan and flow circuit parameters; surface heat transfer; and conduction in solid material can be carried out for both steady-state and transient simulations. In addition to geometry and material changes, effects, such as varied load, ambient conditions, filter, or blockage effects, can be studied with the package.

A further advantage of commercial packages used for thermal analysis is that they can be programmed to use sophisticated integration techniques that are tolerant of stiff sets of equations and nonlinearities [38]. Stiffness can be a major problem when calculating the thermal transient response of motors, which are constructed with parts having very different mass values. For example, as the air-gap thermal capacity is much less than that of the winding, the air-gap thermal capacity will influence the integration step length but have little influence on the thermal response of the machine [50]. Moreover, network-based solvers that represent the system in terms of differential algebraic equations rather than ordinary differential equations have advantages in terms of stability for very nonlinear systems [36].

It is important to highlight that, in order to obtain an accurate thermal model for an electrical machine, both analytical formulation and numerical method benefit from the previous experience of the designer. As discussed in Section VI, this is due to some thermal phenomena being dependent upon the component manufacturing process.

IV. Thermal Analysis Using FEM

FEA is now a standard tool for electromagnetic analysis. Both 2- and 3-D models are used (see Section VII). Often, software packages for electromagnetic analysis also include a module for thermal analysis [39]. At first glance, FEA seems more accurate than thermal-network analysis. However, FEA suffers from the same problems previously described, with uncertainty in the computation of thermal resistances due to interfaces and convection.

In fact, an accurate FEA solution requires the knowledge of the same thermal parameters discussed in Section II. A superficial knowledge of the geometrical and material properties used in a machine construction is often not sufficient to give an accurate prediction of the thermal performances.

The main role of FEA is in the accurate calculation of conduction heat transfer in complex geometric shapes, such as heat transfer through strands of copper in a slot. For this problem, FEA analysis can be used to calculate the equivalent thermal conductivity that can then be used in the network analysis [40].

One problem with this calculation is that some assumptions must be made regarding the randomness of the conductor placement, the impregnation goodness, and any gaps between the slot liner and the stator lamination. This approach is much easier for winding types that have a known conductor placement, i.e., for wound or precision windings.

In Fig. 5 a steady-state thermal 2-D FEA solution of a set of rectangular-shaped copper conductors in a slot is shown [26]. A fixed temperature boundary condition is applied to the outer

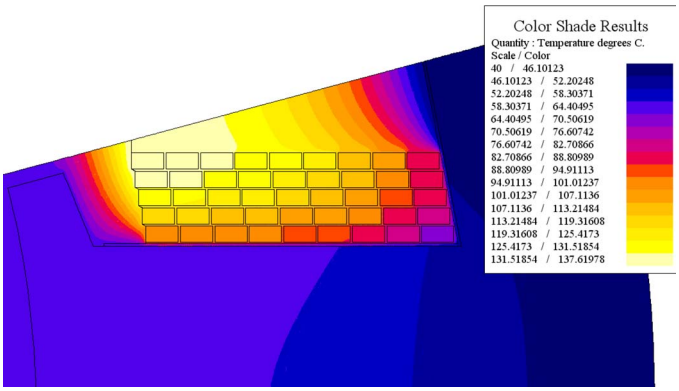

Fig. 5. Steady-state 2-D FEA of the temperature rise in a slot with rectangular copper conductors.

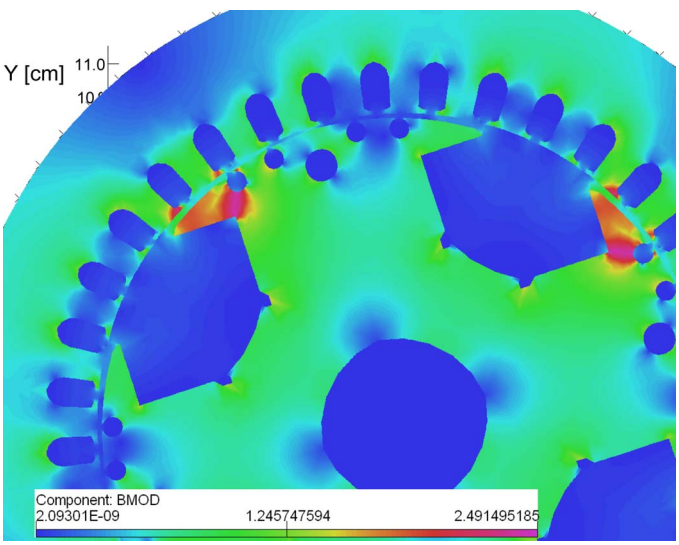

Fig. 6. Magnetic flux distribution across machine radial cross-section.

surface of the stator lamination, and a fixed amount of copper loss is applied to the problem. This simple boundary condition is possible, as the designer is only interested in calculating the temperature difference between the winding hotspot and tooth/stator back iron.

It is important to underline that simple thermal resistances in the lumped circuit can then be calibrated and used to give the same temperature rise, avoiding time-consuming tasks, such as mesh definition and heat-field computations [24].

FEA can be used to modify thermal networks to take into account a specific loss distribution. In many LPTNs, it is assumed that the loss distribution across the electrical machine is uniform; however, FEA results clearly illustrate the nonsymmetrical nature of the operational flux density and related power loss distribution inside the machine, as shown in Fig. 6 for a salient pole synchronous machine [25].

As a consequence, FEA results can be used to define the thermal-network discretization level and a more realistic injection of the losses in the network nodes. It is important to underline that FEA applications are very time consuming for the actual geometry discretization and modification, even if a parametric approach for the geometry definition is used. As a consequence, considering that the majority of FEA electromagnetic packages include finite-element thermal-analysis facilities, FEA can be considered a convenient solution in a very complex geometry not approachable with lumped parameters.

V. Thermal Analysis Using CFD

CFD applied to the design of an electrical machine primarily aims to determine coolant flow rate, velocity, and pressure distribution in the cooling passages or around the machine, as well as the levels of surface heat transfer for subsequent analysis of temperature in the active material and remaining solid structures. This method can replace the combination of traditional 1-D ventilation resistance networks, based on correlations for pressure drops across local and friction resistances, and correlations for surface-heat-transfer coefficients. The history of CFD use for studying aspects of electrical machines spans more than two decades, back to the days of simple purpose written CFD codes and early days of commercial codes. The limitations of the software and hardware of this age meant steep calculation costs and only a little practical benefit for the industry. The industry benefited more by engaging in university research projects that evaluated the capability of CFD as physical models for phenomena such as turbulence or rotation effects, which could lead to a variation in results [41]. Numerous papers were published, which dealt with the comparison of predicted surface-heat-transfer coefficients with those measured experimentally or determined by established correlations [42]. In the 1990s, the confidence in CFD and the evidence of its practical use in the design of machines started to emerge. Coolant flow optimization studies and isolated fan design were the most common examples. Computer hardware limitations still meant heavy use of periodic assumptions and coarse computational meshes, unless parallel computing was available.

With the recent arrival of affordable 64-b computing power, the investment in CFD capability guarantees a good return even with a single license on a dedicated workstation.

Without proper understanding of fluid flow in or around the machines, continuation in the trend of increasing the power density will not be possible. Modern CFD codes are mostly based on the finite-volume technique solving Navier–Stokes equations complimented by a selection of validated and proven physical models to solve 3-D laminar or turbulent flow and heat transfer to a high degree of accuracy. Major challenges for CFD vendors now lie in bringing the codes to a wider engineering community [43]. Experts on CFD are not as much segregated from other engineers due to the in-depth knowledge of the underlying fundamental physics but due to the skills it takes to convert geometry into a discretized mesh (or grid). The complexity of the meshing process lies in reducing the amount of detail in the machine without impacting on the accuracy of the solution. In most cases today, CFD analysis would start with some form of 3-D native model produced in a CAD package. The deciding factor for choosing a CFD package is how tolerant it is to deficiencies in the particular geometry meshing software. Many CFD users, including those working with the leading commercial codes, have experienced periods of frustration when dealing with real geometry. When meshing

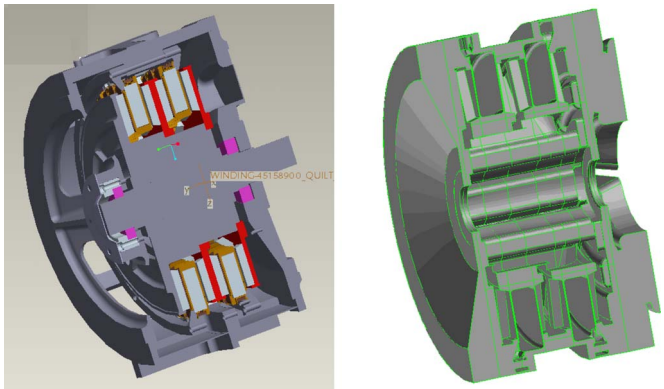

Fig. 7. CAD model in preparation for analysis of ventilation in a 60-kW axial flux generator. Picture on the right shows the fluid region (inverted volume).

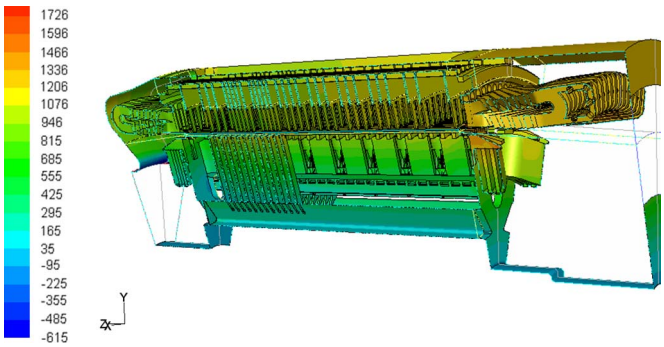

Fig. 8. Static pressure (in pascal) distribution in a generator ventilation circuit. Increased complexity of model leads to only one-pole periodicity modeling.

internal volumes of electrical machines, one has to observe certain rules to avoid excessive numbers of cells in the mesh. Very narrow gaps between rotor and stator or in radial channels require high aspect ratio hexahedral elements, which usually rule out automated meshing techniques. A very good practice, often unavoidable, is subdividing the whole domain to volumes that are easier to mesh (Fig. 7). The splitting is required by some CFD codes also to separate domains with rotation associated with rotating and stationary parts.

To provide a rough guide on the size of models and required computer power, a 64-b workstation with 8 GB of RAM is a recommended minimum industry standard, typically needed to perform an analysis of air flow and convective heat transfer for a 180° periodic or full model, depending on the level of details, for internal flow. This corresponds to the discretization of the fluid region to approximately eight million cells.

In case of machines with many internal cooling ducts, one-pole periodicity may result in consuming the same resource.

The types of CFD analysis for an electrical machine can be divided into the following.

1) Internal flow—either in a through-ventilated machine, where ventilation is driven by a fan (Fig. 8) or self-pumping effect of rotor, or in a totally enclosed fan-cooled (TEFC) motor/generator to assess the air movements that exchange heat from winding overhangs to frame.
2) External flow—flow around the enclosure of a TEFC motor/generator (Fig. 9).

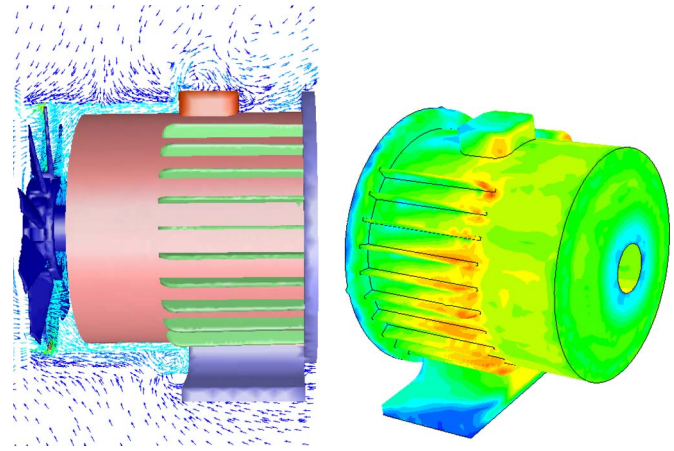

Fig. 9. Velocity vectors around TEFC generator (cowling not depicted) and resulting contours of frame surface-heat-transfer coefficients.

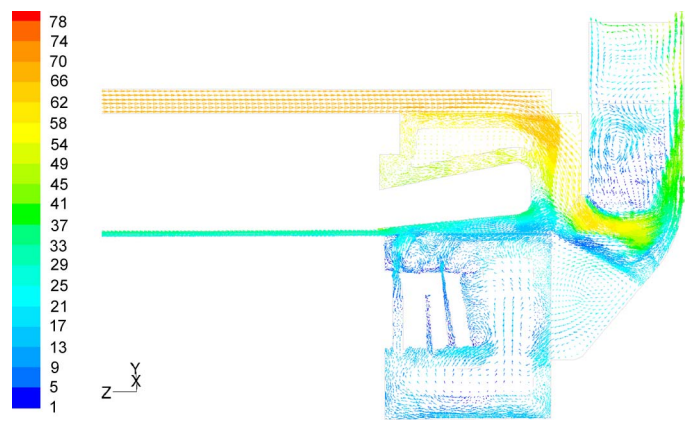

Fig. 10. Velocity vectors (relative to rotor) through fan, showing how the position of the fan results in only 20% of fan passage having radial flow out, with the rest filled with recirculation.

3) Fan design and performance studies—due to cost of material, manufacturing processes, space, or access constraints, fans employed in electrical machines often have a very poor aerodynamic efficiency (Fig. 10). In the case of radial fans, there are rarely any means of pressure recovery at exit. CFD offers a great deal of help in improving fan design and its interaction with the cooling circuit.
4) Supporting analysis—water flow in cooling jackets and cooling of associated power electronics (Fig. 11).

Using an example of rotating machine analysis, CFD takes inputs in the form of realistic geometry and boundary conditions. The geometry defines lengths and cross-sectional areas for passages of flow, which are the most decisive for pressure drops in the system. As boundary conditions, coolant mass flow rate or total pressure at inlet, static pressure at outlet, and rotating speed are used. For the energy equation, the surface heat flux or presumed temperatures of surfaces must be given. For the latter, predicted surface-heat-transfer coefficients are not a function of temperature itself if the flow is turbulent, as it is in the majority of cases. Analysis results are verified easiest for the flow rate where measurements are frequently carried on prototype machines by traversing with a velocity probe in a duct

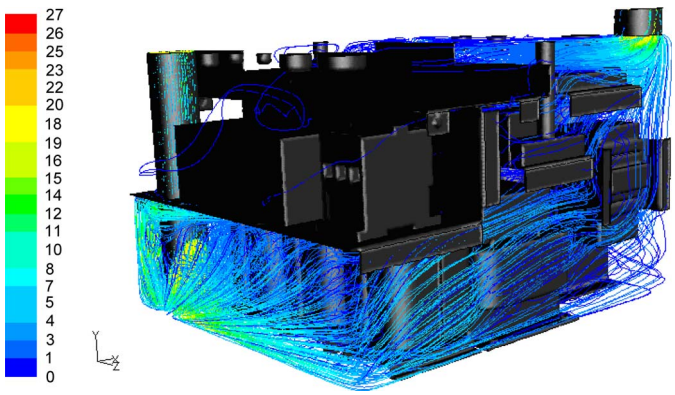

Fig. 11. Air flow path lines inside a power electronics enclosure, colored by velocity magnitude (in meters per second).

with a known cross-sectional area mounted to a machine inlet. Surface-heat-transfer predictions are often not verified directly but the agreement of subsequent thermal-network modeling is compared with heat runs on machines instrumented with resistance temperature detectors or thermocouples.

The secondary function of CFD can be to solve heat flow paths all the way into the regions of their origin by means of conduction. This is essentially extending the CFD capability by FEA thermal solution, often referred to as conjugate heat-transfer modeling [44]. In an R&D environment, it may be useful in prototype design work for validating lumped-parameter thermal models; otherwise, in most cases, it devalues the primary objective of CFD by introducing additional assumptions related to manufacturing processes and material properties. A link between CFD and a lumped thermal parameter circuit is much more meaningful for a design engineer wishing to perform analysis of a number of design iterations and settings. It has been proven in the design office environment that including solid regions in a CFD analysis prolonged preparation by increasing the complexity of setup, with little appreciable benefit. On the other hand, the conduction modeling capability of CFD can be used separately by disabling flow equations (leaving just one equation for energy) to undertake studies, such as detailed temperature distribution in stator slots (Fig. 12).

While attempting the CFD analysis for an electrical machine, the most common assumptions or simplifications are as follows.

1) Periodicity: Depending on the position of inlets and outlets, terminal connections, etc., in the case of internal flow or orientation in the environment for external flow, this may impact upon the accuracy of results and requires good judgment on the part of the analyst.
2) Steadiness of flow and heat transfer with rotation: Transient flow solutions are, in most cases, unnecessary, as time-averaging models give close results at a fraction of time. Some heat-transfer augmentation due to pressure waves from rotor onto stator and back in salient pole machines was reported in [38]; however, such differences are small and local.
3) Surface roughness: Data for surface roughness are very difficult to obtain and particularly difficult to input, as many surfaces have a specific type of roughness, such as one-directional roughness (back of laminated core), or some surfaces are more uneven, in flatness, rather than rough.
4) Geometry of complex structures can be simplified, e.g., porosity model can be applied to simplify the geometry of bar-wound overhangs.

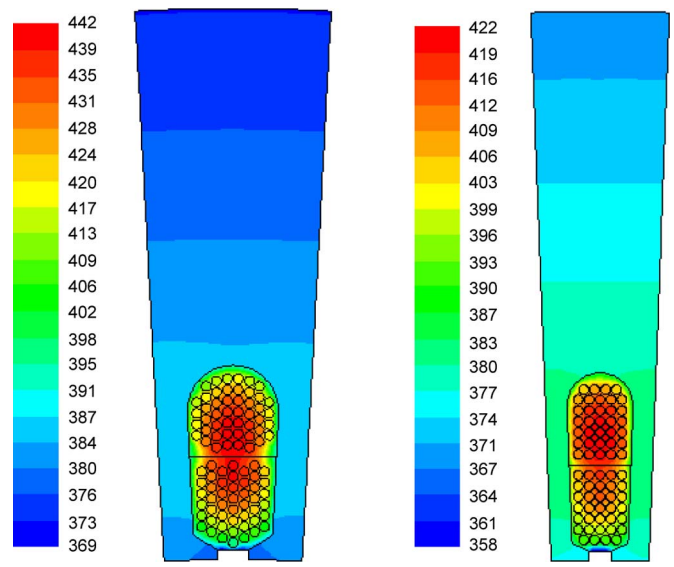

Fig. 12. Temperature (in kelvin) prediction on two lamination designs with windings at the same current density.

The following most common mistakes are made when attempting a CFD analysis.

1) Not allocating sufficient computer resource, resulting in too coarse a computational mesh.
2) Deficiencies in computational mesh (highly skewed cells) can vary, in effect, from the inability to obtain a solution to large local errors in the flow field and heat transfer.
3) Unsuitable type of cells resulting in excessive mesh size, often due to automated meshing, e.g., using tetrahedral cells in rotor–stator air gap instead of high aspect ratio hexahedral cells.
4) Poor definition of boundary conditions, where results of any analysis can be only as good as the input data.

There are multiple ways of looking at the role of CFD in the future. There is no doubt that CFD, as a discipline, will become more popular and widespread — a cost-effective tool for innovation. The vendors and academic circles will continue to enhance the capability of commercial codes for more complex physics phenomena; this is, however, unlikely to influence accuracy of solutions for electrical machines as achieved today. From the industrial viewpoint, CFD can be used to identify possibilities for segmentation of product ranges, e.g., for high-efficiency continuous operation or low-cost standby units. It is within the scope of CFD to evaluate efficiency improvements in electric machines, which can be translated to cost savings during operation.

VI. Thermal Parameter Determination

As discussed in the previous sections, the accuracy of both sophisticated and simple thermal networks is dependent upon

several parameters for which reliable data may be difficult to find. In fact, many of the complex thermal phenomena inside electric machines cannot be solved by pure mathematical approaches using a closed relationship. Designers with extensive working experience on similar designs using comparable manufacturing processes can make a correct choice of such parameter values. For designers approaching their first thermal analysis, these choices are more difficult. It is particularly important for the user to have available reasonable starting values for the less well known and defined parameters. The authors have researched reliable relationships to be used in the determination of the more complex thermal parameters [4], [24], [26], [45]–[47]. From the sensitivity point of view, the weight of these parameters on the thermal-analysis results has been investigated in [47]. Such information can be used successfully to set default parameters in thermal-analysis software to give reasonably accurate predictions at the start of the design process before manufacturing methods and tolerances have been fully thought out [24], [35]. Expected upper and low limits of such parameters, based on experience, can be built into automated sensitivity analysis so that the designer can quickly access the main constraints to cooling and quantify the effects of manufacturing options and tolerances. In the following, a summary of the obtained results is reported.

A. Equivalent Thermal Resistance Between External Frame and Ambient Due to Natural Convection

In totally enclosed machines with no fan or with a shaft-mounted fan operating at slow speed, the thermal resistance R_0 (in degree Celsius per watt) between the housing and ambient is often the largest single resistance between winding and ambient. When the total area A of the external frame is known, (7) can be initially used, taking into account both convection and radiation heat transfers

$$R_0 = 0.167A^{1.039}. \tag{7}$$

An alternative is to make a first estimate of the convection and radiation-heat-transfer coefficients and then calculate R_0 using (2) and (4). Typically, the combined natural convection and radiation-heat-transfer coefficient lies in the range 12–14 $\mathrm{W}/(\mathrm{m}^2 \cdot {}^\circ\mathrm{C})$ for simple geometric shapes [49].

An interesting experimental method can be found in [48].

B. Equivalent Thermal Conductivity Between Winding and Lamination

It is widely recognized that the thermal behavior of the wires inside the slot is very complex. The thermal resistance can be computed using (1); however, the value of the thermal conductivity k is not easily defined. A possible approach to simplify the thermal resistance computation is to use an equivalent thermal conductivity of the system winding impregnation and insulation $(k_{\mathrm{cu,ir}})$. This equivalent thermal conductivity depends on several factors, such as material and quality of the impregnation, residual air quantity after the impregnation process, and so on. If the equivalent thermal conductivity $k_{\mathrm{cu,ir}}$ is known, the thermal resistance between the winding and the stator lamination can be easily computed. When the slot fill factor K_f, the slot area A_{slot}, and the axial core length L_{core} are known, (8) can be used as a rough guide

$$k_{\mathrm{cu,ir}} = 0.2749\left[(1-k_f)A_{\mathrm{slot}}L_{\mathrm{core}}\right]^{-0.4471}. \tag{8}$$

The quantity inside the square bracket represents the available net volume for the wire/slot insulation and the impregnation inside the slot.

An alternative approach is to subdivide the winding in the slot into a number of thermal resistances from the slot center to the slot wall. The resistance values can be calculated from the knowledge of the slot shape, slot fill, and impregnation goodness. Full details of the resulting model are given in [49].

C. Forced Convection-Heat-Transfer Coefficient Between End Winding and Endcaps

The thermal resistance between winding and endcaps due to force convection can be evaluated by (4). Again, the value of h_C is not simple to define. For totally enclosed machines, the value of h_C can be evaluated by (9) as a function of the air speed inside the motor endcaps

$$h_C = 6.22v \tag{9}$$

or by (10) to account for combined natural and forced convection

$$h = 41.4 + 6.22v. \tag{10}$$

Other alternative relationships are also available [24], [29], [45], [49] and give similar results.

D. Radiation-Heat-Transfer Coefficients

The thermal resistance for radiation can be evaluated using (2) when h_R is available. Inside and outside the motor, several parts exchange heat by radiation. In some cases, such as aerospace applications, all the heat transfer is due to radiation. The following values of the radiation-heat-transfer coefficients can be initially used [46]:

8.5 $\mathrm{W}/(\mathrm{m}^2 \cdot {}^\circ\mathrm{C})$ between copper–iron lamination;
6.9 $\mathrm{W}/(\mathrm{m}^2 \cdot {}^\circ\mathrm{C})$ between end winding–external cage;
5.7 $\mathrm{W}/(\mathrm{m}^2 \cdot {}^\circ\mathrm{C})$ between external cage–ambient.

E. Interface Gap Between Lamination and External Frame

The interface gap between the lamination and the external frame is due to imperfections in the touching surfaces, and it is a complex function of material hardness, interface pressure, smoothness of the surfaces, and air pressure. The interface gap between stator lamination and external frame is very important because most of the motor losses cross this surface. For industrial induction motors, interface gap values between 0.01 and 0.08 mm have been found. As the interface gap between the lamination and the external frame is not only dependent on the frame material but is also strongly influenced by the stator core

assembly and by the core–external frame inserting process, it is not possible to compute its value. A value of 0.03 mm can be considered a reasonable value to be used as a default at the start of the design process. Sensitivity analysis, with the interface gap varied between 0.01 and 0.08 mm, gives a quick evaluation of its importance on the design under consideration. In many cases, it is not that important. However, in highly rated machines, such as those with housing water jackets, it can be significant.

VII. Final Remarks

In the previous sections, an overview of the most used techniques for the electrical-machine thermal analysis has been reported. Hereafter, a critical discussion on these approaches is included.

The LPTN is the most used and friendly solution for a fast- and low-computation time-consuming thermal analysis. The accuracy of this method is strongly dependent on the thermal parameters, particularly the heat-transfer coefficients.

It is important to underline that an accurate prediction of the electric machine thermal performances is not a simple task, even if the machine geometry and the properties of the used materials are well known. This is because many of the complex thermal phenomena that occur in electric machines cannot be solved by pure mathematical approaches. In most cases, empirical data must be used to calibrate analytical models in order to get acceptable results from the accuracy point of view. The high calculation speed is one of the major advantages of the thermal-network analysis, particularly when a large number of calculations are required, for example, when a parameter sensitivity analysis of the thermal network has to be performed [47]. In addition, the LPTN is surely the approach that allows for the development of self-made thermal-analysis tools.

The finite-element method (FEM) thermal analysis is often used because this tool is available together with the electromagnetic one; in fact, the most important software tools for FEM electromagnetic studies have embedded the FEM thermal analysis. The FEM approach requires a quite long "preprocessing" time to input the machine geometry under study, and the computation time is longer with respect to the thermal network. In fact, FEM suffers from long model setup and computation times. From this point of view, the FEM approach is quite interesting when a "parametric model" facility is available. In this case, the software changes, in an automatic way, the model dimensions and/or the material property in defined ranges, allowing one to analyze the influence of these variations on the overall thermal performance.

In addition, the most important limitation of the FEM solution is that the software uses analytical/empirical-based algorithms for convection boundaries, exactly as in the lumped-circuit analysis. As a consequence, the result accuracy is dependent on the same factors previously described for the thermal network. For these reasons, the only advantage of the FEM method is that it can model solid component conduction more accurately than the thermal network. The 3-D FEM thermal analysis presents the same advantage and disadvantage for the 2-D approach, with very high long model setup and computation times. Obviously, the 3-D approach is required when the problem cannot be reduced in an equivalent 2-D problem (i.e., to study both the radial and axial heat fluxes).

The main strength of the numerical CFD approach is that is can be used to predict the flow in complex regions, such as around the end windings. Both 2- and 3-D models can be used depending on the geometry under analysis. The 3-D model suffers from very long model setup and computation times. Hence, its use is devoted and recommended when sophisticated simulations are imposed by the high costs of the prototypes; the typical cases are big motors or generators. It is important to underline that the data obtained using CFD are useful for improving the analytical algorithms used in the FEM model or in the thermal networks.

In conclusion, several approaches are available to develop a thermal analysis of electrical machines. All these approaches have both advantages and disadvantages, as largely discussed in this paper. As a consequence, the methodology selection is in the hands of the designers, which have to take into account the project development costs (i.e., time, result accuracy, and available resources) and the product marked value.

About the future expectations on the use of the thermal network, FEM, and CFD approaches, it is the authors' opinion that the CFD methods will be more and more attractive due to the increase of the PC computational speed and the availability of more friendly pre- and postprocessing software. In addition, a cost reduction of the CFD software can be expected, together with the availability of specific tools and libraries devoted to electrical machines.

As a final comment, the authors want to underline that this paper has to be considered as a survey work concerning the most used approaches for the electrical-machine thermal analysis. Examples of the described techniques for specific applications can be found in the papers [51]–[64] recently published in the Special Section "Thermal Issues in Electrical Machines and Drives" by the IEEE Transaction on Industrial Electronics, vol. 55, no. 10, October 2008.

VIII. Conclusion

In this paper, a summary of the evolution of thermal analysis of electrical machines was given. The most common methods used for thermal analysis were compared, and their strengths and weaknesses are discussed. This paper has given constructive suggestions for researchers involved in thermal analysis of power electronics and power converters, as well as electrical machines. A useful list of books and papers was given for designers wishing to carry out further electric-motor thermal-analysis research.

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