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Multiphysic Design and Modeling of Rotating Electrical Machines

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***Abstract*— This paper presents a general overview on design process of electrical machines considering a multiphysic point of view, and a road map for a comprehensive design approach is drawn. The objective multi-physical criterion including electromagnetism and mechanics physics, thermodynamics, fluid dynamics, structural dynamics, noise and vibration are discussed. Also, various modelling methodologies are presented and compared in terms of computational-time resources and accuracy. Current state of art in this approach will be presented highlighting the advantages and disadvantages of such methodologies.**

Keywords—Electrical machines, multiphysic design and modelling, electromagnetics design, thermal modelling, acoustic noise, rotordynamics, materials characteristics, heat distribution, computational fluid dynamic, finite element method.

I. INTRODUCTION

Electrical machines have been extensively used as a fundamental component in a wide range of applications that require high power / torque at high efficiency and small size, such as power generation, automotive, propulsion in aerospace and defence industries [1].

Concerning the rapid progress of electrification in the automotive industry, a large number of research projects that are currently carrying out on the electrification of airplanes, replacing jet engines with electrical machines, to have more or fully electric aircraft [2].

Different machine topologies have been introduced and investigated considering the mentioned application. For example, various structures of synchronous machines including cylindrical rotor, salient-pole, homopolar, permanent magnet (PM), and induction machines are widely used for power generation applications [3]. Although different types of PM machines are well-accepted in propulsion and traction application because of their high efficiency [4], PM-assisted synchronous reluctance motors are also attracting a lot of attention because of their good performance and reasonable cost. Also, the application of superconducting materials recently has been drawn attention in electrical machines which allows building high-power machines at very high efficiency with small size, specifically for airplane propulsion systems [5], [6].

With respect to the pointed-out applications, it is not an exaggeration if said electrical machines are the principal component in modern technologies. All the mentioned final applications require a compact, high performance, high operation reliability, low emission, and cost-effectiveness products. Considering all these aspects, the design of electrical machines is a challenging task for an electrical engineer. Apart from that, since electrical machines are electromechanical energy converters, their design, and modelling, either rotating or linear, are an inherent multiphysic problem that makes the design of electric machines very challenging.

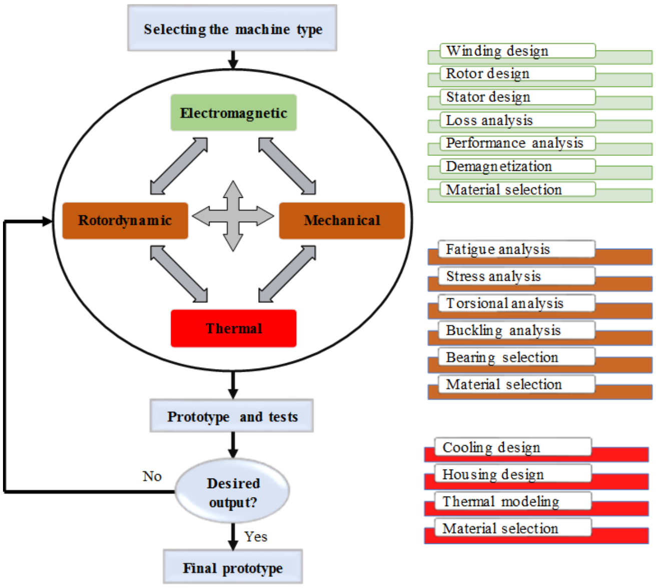


Fig. 1: Practical multiphysic design procedure of electrical machines.

Design of electrical machine is a multidiscipline engineering problem that consists of many different subproblems directly connected such as electromagnetics, mechanics, thermodynamic, fluid dynamics and material science, vibrations, stress, acoustics noise, rotordynamics, fatigue, power electronics, tribology, control theory, and mathematics. Thus, as represented in Fig. 1, a realistic multiphysic design procedure of electrical machines entails uninterrupted iterations between electromagnetic, thermal, structural, rotordynamics, and systematic designs based on different theoretical analyses, numerical simulations, and experimental tests [7]–[11].

Traditionally, the design of electrical machines is considered mainly as an electromagnetic problem, and later the thermal and structural analyses are separately carried out for design evaluation. To prevent any failure, especially in high power / torque density or high-speed applications, some constraints are taken into account during the electromagnetic design based on experience as well as physical concepts. For example, sometimes the machine designers empirically approach the thermal design aspects by imposing limits on current density in coils or of the magnetic flux density in the magnetic cores, or limits of some sizing variables. However, they may not provide enough accuracy and do not guarantee a comprehensive design machine.

Numerous methodologies have been developed and presented in order to precisely predict the design performance of electrical machines and avoid the time and expenses of prototyping. In general, these computation methods can be divided into three approaches:

1) Classical analytical analysis
2) Numerical techniques
3) Lumped parameters models

The analytical analysis is based on fundamental physics theory such as Maxwell and heat transfer equations. Usually, implementing them for complex geometries is quite challenging. Numerical methods can be divided into integral equations solved by boundary element method, and differential equations solved using finite difference and finite element methods (FEM). Among the mentioned numerical techniques, FEM has been well adopted more than others for solving complicated engineering problems. However, its computation time is relatively high. Lumped parameters model is a simple solution that models the machine with an electrical circuit having several linear and nonlinear elements and computes the potential of the nodes and flowing currents in the branches. A large number of elements leads to obtain more accuracy but on the other hand, solving the nonlinear circuit increases the computation time. The major differences among these methods are diverse mathematical formulations as well as their solving procedures. Therefore, a trade-off between accuracy, complexity and the required computational time is mandatory.

The thermal and mechanical design are as important as the electromagnetic part. In addition, the material properties used in electrical machines play a crucial role in the design process, even if it could be said that material characteristics are the main reason for a multiphysic design.

II. CHALLENGES AND OPPORTUNITIES IN MULTIPHYSICS DESIGN AND MODELING

An electrical machine is a complex electromechanical device which consists of different parts including the electromagnetic parts (rotor, stator and excitations), coolant, housing, and mechanical components such as shaft and bearing. This set of parts can be considered as a system. Basically, two design approaches can be followed for design of electrical machines: i) component design and ii) system design. In the first approach, all the parts can be designed and optimized separately while in the second approach the design and optimization of the machine are carried out based on iterative procedure among all components.

Although the first methodology is quite easy and straightforward, the resultant system may not be the optimal solution. In other words, the optimal design of each component cannot guarantee that the whole system is the best solution. On the other hand, the coupled design of the system components approach seems quite complicated and may be time-consuming, but the output design is the best solution. It should be highlighted that the computation time is highly dependent on the methodology applied for design and modelling of each component.

A. Electromagnetic Design

The working principle of electrical machines is established on the electromagnetic theory. The electromagnetic design of electrical machines is the core of multiphysic design, and it is derived from magnetic field calculation which allows computing the machine parameters.

1) Electromagnetic sizing

The initial step in the design of electrical machines can start by defining certain basic characteristics including machine type (asynchronous, synchronous, reluctance machines, etc), the structure of the machine (axial or radial flux, internal or external rotor, single or multistage machines, round or salient poles), rated torque / power, rated speed, the number of poles, and rated voltage. Moreover, electrical loading, the current density in the slots, and flux density in the airgap are some of the required values for an electromagnetic design that are chosen based on the machine structure and cooling system of the machines. Having known these input design parameters, the rotor and stator geometries can be obtained based on Essen's rules [7]–[10].

2) Magnetic material

Selection of hard and soft magnetic, conductive and insulation materials have a great impact on electromagnetic design. Soft magnetic materials can be divided into non-grain-oriented and grain-oriented magnetic materials. Non-grain-oriented electrical steels have uniform magnetic properties in all directions but limited saturation flux density and magnetic permeability. These materials are the most well-accepted soft materials used for rotating electrical machine designs. Silicon-iron, amorphous, nickel-iron, and cobalt–iron are the well-known alloys in this group of materials. Although the saturation level of silicon-steel is lower in comparison with the other types, it is by far the most used soft magnetic materials, around 80 % of the market, because of their cost compared to the other ones. Grain-oriented steels have optimal properties in the rolling direction that are usually used in transformer applications [12], [13].

Soft magnetic composite (SMC) materials are pure iron powder particles electrically coated with insulating films which lead to high electrical resistivity. So, SMCs feature low eddy current losses in electromagnetic applications. The powder form of this metallurgical material allows building complex shape electrical machines like axial-flux, transverse-flux, and claw-pole machines. Also, new magnetic materials and structures have been introduced, like dual-phase [14] and multilayer magnetic materials [15], [16], even if more investigations for their usage are required.

Hard magnetic materials, referred also as permanent magnets, are advantageous for their capability to produce a magnetic field without continuous expenditure of energy. They can retain their magnetization against external fields and their own demagnetizing field, a feature exploited in a great number of applications [13]. Alnico, hard ferrites, Samarium–cobalt (SmCo), neodymium iron boron (NdFeB), and bonded magnets are the widespread alternatives. NdFeB features the highest remanence flux and coercive field, and together with the SmCo are the most expensive ones.

Conducting materials are prominent in electrical machines used in winding and bars in the stator and rotor structures. Copper and aluminium are the most famous conducting materials. Superconducting tapes feature almost zero resistivity at very low temperature (e.g. at −196°C for liquid nitrogen coolant).

Insulation materials are mainly used to protect the conducting part from the lamination part, preventing short-circuit and fixing the winding. Polyamide-imide, polyester, glass–mica tape, mica paper, and epoxy glass are common in electrical machine applications [17], [18]. Also, they should have a good thermal conductivity for the cooling purpose.

3) Winding design

Windings in electrical machines can be classified as armature windings, rotating-field winding, field or magnetizing winding, damper winding, commutating winding, and compensating winding [7]–[9]. Also, the armature windings can be seen in concentrated, distributed, and ring or core-wound forms. Although distributed winding has the longest end-winding as well as higher volume of copper, it is the main winding type because of its superior performance in terms of harmonic contents of generated air gap magnetomotive force waveform. Ring winding is not common due to the building complexity.

The winding fill factor is one important point in winding and stator design. In the conventional machine, the winding fill factor is very low due to the round shape of the wire, around 0.25-0.5 depending on the winding type and machine size. Recently, rectangular conductors have gained attentions to improve the winding fill factor such as foil winding and hairpin windings [19], [20].

B. Thermal design

The main aim of thermal design is to evaluate the heat distribution in the electric machine structure. The heat is generated by power losses, and it has a great impact on the machine performance since the insulation materials degraded by increasing the temperature. Furthermore, the magnetic and mechanical properties of materials are temperature dependent. Usually, the cooling system type is chosen at the beginning of the design procedure on the basis of the selected application.

1) Working temperature of electrical machine

The insulation materials used in electrical machines are highly temperature dependent. On the basis of IEEE Std. 117, the insulation class for electrical equipment can be classified into class A (105°C), B (130°C), F (155°C), H (180°C), N (200°C), and S (220°C) [21]. Normally, electric machines should operate at a lower allowed temperature. The insulation is directly associated with the lifetime of the machine.

The impact of excessive temperature on the electrical machine is quite destructive, and it leads to reduce the lifetime of the machine. A fairly accurate approximation of the Arrhenius equation, for each 10°C of temperature rise reduces the lifetime by half.

2) Thermal properties of magnetic materials

The working temperature of the machine influences the properties of magnetic materials, in detail the saturation point, hysteresis, and eddy current losses. In low-carbon steels and low-silicon laminations, the saturation knee decreases around 10 % by increasing the temperature, which leads to decrease the anisotropy energy, depending on the materials [13]. The total core losses decrease due to the additional effect of the increasing electrical resistivity. This reduction is approximately linear for the temperature between 20°C and 200°C [22]. Also, it has been reported that the iron losses of non-oriented silicon steel are more influenced by temperature than grain-oriented ones [13]. In cryogenic temperature, the knee point of BH as well as the permeability of the lamination material increase. Also, as reported if the temperature decreases after a specific value, the permeability decreases even less than room temperature [13], [22], [23].

The hard magnetic materials are highly temperature-dependent. In general, increasing the temperature leads to decrease the residual flux density of the magnet. On the other side, in the cryogenic condition the remanent flux density of the PM increases, around 20 % [24]. It is worth to mention that cryogenic temperatures heavily affect the conducting and insulation material properties.

Not only are the magnetic properties of the materials affected by the working temperature, but also the mechanical properties of the materials such as stiffness and young module impacted by changing the temperature [25].

3) Power loss

There are different power losses in electrical machines. These losses are the main source of generated heat in the machine structure. In general, the loss components can be divided into electromagnetic loss and mechanical loss. The electromagnetic losses are mainly generated in the active part of the machine including rotor, stator, and excitations [26]. Some of these loss components are production technologies dependent, such as the loss increases due to the welding or punching of the laminations [27]. In order to take into consideration these losses, some correction factors, that are obtained based on the experimental tests, are usually applied during the loss calculation. Moreover, the machines are fed by power electronic converters that impose not sinusoidal voltage waveforms causing some extra losses too. In addition, windage and bearing losses should be taken into consideration from the mechanical part.

4) Cooling techniques

The cooling systems of electrical machines can be categorized into passive cooling and active / forced cooling depending on the heat transfer mode or generated cooling flows. Passive cooling techniques denote systems without a fan or pump and feature lower power loss.

Passive cooling methods work based on natural convection and radiation to dissipate the generated heat from the machine to the environment. The cost of passive cooling and its noise emission are typically very low. However, this technique is usually adopted for small size machines. Considering fin or heatsink on the outer part of stator or machine frame is one of the most common solution to enhance convection heat exchange.

Forced cooling techniques feature an active mechanism for circulating the fluid, either gas or liquid, in different parts of the machine structure. This technique is well-known and widely used in a large number of applications like automotive industry. Force cooling can be as simple as using a fan enclosed in the machine structure or it can be much more complicated system for liquid channels. For example, a liquid cooling system can be distributed through the channels in different regions of the machine such stator and rotor yoke, stator slots, and shaft [28]. These channels can be axial or spiral. Fig. 2 represents an interior PM V-shaped machine equipped with finned frame and channels liquid cooling system using water channels on the stator surface. Also, there are some applications that submerge the whole machine in a fluid such as cryogenic liquefied gas application [29]. Fig. 3 summarizes various cooling methods in electrical machine application. Recently, some new cooling techniques have been presented that mainly focus on using materials, like metal foam for the machine housing, nanofluids or ionic coolant systems [30].

5) Frame design

The housings of the machine are designed to protect the stator and machine component from foreign objects such as water, dust, sand, and moisture. The frame can have different shapes depending on the available volume on the final application as well as cooling system requirements. For example, it can be round, polygonal or finned.

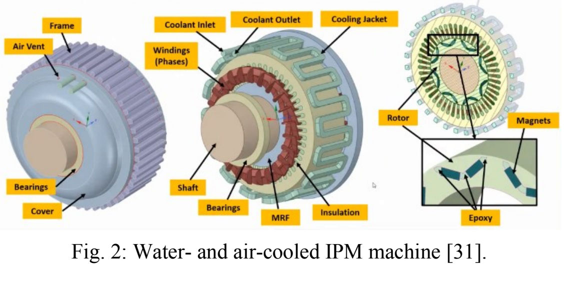


Fig. 2: Water- and air-cooled IPM machine [31].

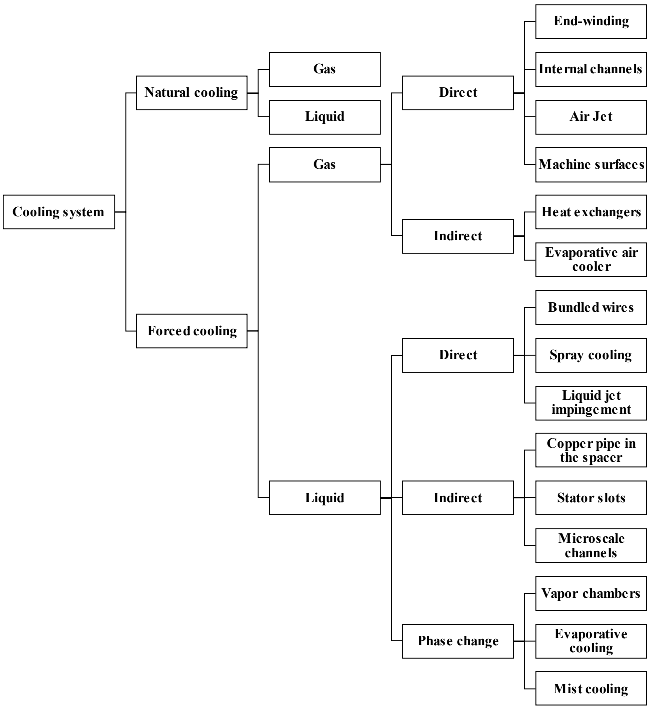


Fig. 3: Different cooling systems used in electrical machines.

However, in some specific applications, such as airplanes and satellites frameless machines are preferred to reduce the volumes and weight. It should be highlighted that the frame considered for industrial machines is selected based on the IEC 60072-2, but for specific applications. Generally, it can be designed based on the machine size and characteristics.

6) *Thermal modeling*

There are several methods for the thermal analysis of electrical machines including lumped parameter thermal networks, computational fluid dynamics (CFD), and hybrid methods. Lumped parameter thermal networks can estimate the temperature in different parts of the machine. However, it often requires dedicated experimental-based calibrations to enhance the accuracy.

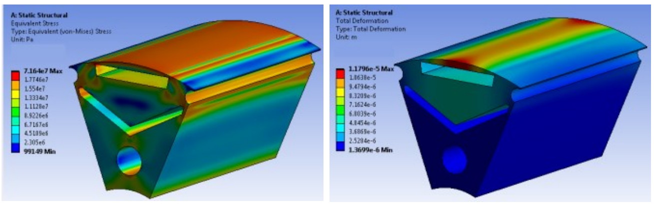
CFD is based on Navier-Stokes equation solved using numerical approaches. It is a well-recognized tool for the analysis of fluid flow and heat transfer, 3D turbulent flows with temperature-dependent properties, multiphase flows, and compressible flows. For example, CFD can be used to study the dynamics of liquid sprays on the end-windings [32].

C. *Mechanical design*

Mechanical design aims to evaluate the structural stability of the geometry obtained by the electromagnetic design. This results in a '*fully-optimized*' design, enhancing the machine efficiency and operation reliability (e.g. taking into account the losses of mechanical nature, such as friction and vibrations). Mechanical design can be divided into several studies including stress and strain analysis, fatigue analysis, modal and vibration analysis, buckling, bearing analysis, and rotordynamics.

1) *Fatigue analysis*

Due to typical cyclic loading in electrical machines, a progressive and localized structural damage may be initiated on small microscopically scale, and rapidly grow to significant macroscopically scale cracks. Eventually, this issue causes material failure at a stress level smaller than the material yield tensile strength or even ultimate tensile strength.



(a) (b)

Fig. 4: Examples of stress (a) and deformation (b) for an IPM motor.

2) *Stress analysis of rotor / stator*

Stress analysis reveals the ability of the machine structure or component to tolerate various loads without failure. This analysis paves the way to accomplish the best performance of electric machines.

Electrical machines are exposed to several types of disturbances and stress that are due to the external or internal conditions. For instance, mechanical / electric unbalanced system, harmonics, voltage / current/ frequency variations, supply interruptions, unstable cooling system, large variations in ambient temperature and humidity. These conditions deteriorate the winding insulation mechanically and may lead to an insulation failure.

The ration of length to diameter of the machine ($\lambda = L/D$) is one important design parameter that has a great influence on the mechanical behaviour of the rotor. Small value of λ leads to high centrifugal forces at the rotor surface as well as high tangential speed. This centrifugal force causes stresses in the circumferential and radial directions. These force components should be carefully investigated specially on the small ribs of IPM machines. It should be highlighted that stress affects the magnetic properties of materials and causes an increment of hysteresis loss due to the increase of coercivity under the stress [33]. Fig. 4 shows an example of stress and deformation analyses due to the centrifugal force on a delta shape IPM machine using a commercial software. This type of analysis is today commonly available, and it can also be performed on the basis of analytical procedure [33].

3) *Torsional analysis*

Torsional analysis estimates the twisting interaction between the rotor and the coupling load. Torsional resonance is the major reasons of vibration or noise in electrical machines at certain speeds. This issue can lead to fatigue damage too. In order to calculate the torsional resonance frequencies of the machine, it is required to obtain rotor inertias and shaft stiffness. It should be noted that shaft stiffness depends on the material properties, the size, and the length of the shaft [34], [35].

4) *Buckling analysis*

Buckling refers to the sudden deformation of a structural component under load due to the loss of stability of the machine component, and it is usually independent of material strength. This loss of stability usually occurs within the elastic range of the material. It should be highlighted that the load at which buckling happens is dependent on the stiffness of the machine, not upon the material strength. Euler's critical load and Johnson's parabolic formula are used to determine the buckling stress in slender columns.

The Buckling analysis in the electrical machine application can be performed to assess the stability of different components of the machine. For example, some ducts are considered in the structure of the rotor / stator by I-beams or Π-beams that function like spacers for the ventilation purpose.

5) *Shaft design*

In electrical machines, shaft is the main component to transmit torque / power to the external load. Shaft is exposed to different combined impact of tension, compression, bending, and torsion while the machine is rotating. Thus, it should be designed maximum stiffness and rigidity and minimum deflection [36].

6) *Vibration and acoustic noise*

Acoustic noise due to the electric machines may consist of different components including mechanical noise, electromagnetic noise, and aerodynamic noise.

Mechanical noise is related to relevant motion between the machine components, such as bearings and their defects, sliding contacts, bent shaft, rotor unbalance, and shaft misalignment. Electromagnetic noise is because of rapid variation in the electric and magnetic field in the machine, and it is related to parasitic effects due to higher space and time harmonics, eccentricity, phase unbalance, slot openings, and magnetic saturation. Aerodynamic noise is generated by the flowing of fluids inside the machine.

Reducing the acoustic noise is a target to design a high-performance machine. There are several suggested approaches to reduce the noise, such as optimization of slot opening, skewing, increasing the air gap length, harmonic current injection, etc [37].

7) *Rotordynamics*

Rotordynamics is concerned to analyse the behaviour and stability of rotating machinery. At basic level, rotordynamics is about the mechanical structures supported by bearings and affected by internal phenomena that rotate around a single axis. As the speed of rotation increases the vibration amplitude may pass through one or more critical speeds. This amplitude is commonly excited by unbalance of the rotor. If the vibration amplitude at these critical speeds is excessive, a failure occurs. So, it can be said that rotordynamics plays a key role in improving the safety as well as the reliability of electric machines [35].

III. EXAMPLES OF MULTIPHYSICS DESIGN AND MODELING APPROACHES OF ELECTRICAL MACHINES

The majority of the performed studies have focused on electromagnetic design and modelling of electrical machines, while less attention has been paid on thermal and mechanical design. There are limited studies considered multiphysic approach for design and modelling of the machine. In the following, a brief short literature review on multiphysic design and modelling of electrical machines is presented.

In [38], a high-speed PM machine has been designed considering multiphysic constraints to prevent mechanical failure. In detail, the mechanical strength, rotordynamics, mechanical losses, and the thermal field have been set as the design constraints of the design process. The machine has been designed based on analytical methodology. However, optimization and some of the mechanical parameters as well as thermal analysis have been carried out using FEM simulations.

In [39], a 2D-FEM electromagnetic model coupled with a detailed thermal equivalent circuit model has been considered for designing of a linear PM machine. The geometric parameters have been implemented in FEMM software and particle swarm optimization algorithm used for the design optimization. Also, a mesh-based thermal equivalent circuit has been employed to estimate the thermal parameters. Thanks to the high number of nodes considered for the thermal model, he obtained results were comparable with the experimental tests.

In [40], multidisciplinary design optimization of PM synchronous generators for wind energy conversion application has been proposed. Many detailed design parameters including geometrical, economical, magnetic, electrical, and thermal constraints have been taken into consideration. The proposed model consists of several analytic and semi-analytic sub-models. It included six sub-models that describe the geometric, thermal, electromagnetic, and economic aspects of the PM synchronous generator. In addition, the statistics of the wind speed that governs the wind turbine behaviour. Although the presented model satisfied many details, the structural model of the PM generator has not been considered.

In [41], an IPM machine for compressor application has been modelled based on a multiphysic analytical procedure. All the physics of the machine have been modelled. An equivalent *dq* model based on the determination of flux density waveforms in the different axes of the *dq* reference frame has been considered for the electromagnetic part. Also, a steady-state thermal model compounded of thermal resistance and heat sources have been used. It should be highlighted that the loss components of the machine have been considered in detail, and their thermal effects have been applied to the materials. Besides, the centrifugal force, mechanical stresses, static and dynamic deformations have been computed in the mechanical model. The models have been coupled for design optimization and pareto front of efficiency and weight of the machine is obtained.

In [42], a multi-objective and multiphysic design of a double V-shaped IPM machine has been proposed using analytical design for electromagnetic, thermal, and structural parts. The obtained electromagnetic design was based on the nonlinear analytical model, Ampere's theorem and the flux conservation law [43]. The local saturation near the iron bridge, slot leakage flux as well as winding leakage flux have been taken into consideration. It should be highlighted that the accuracy of this approach is in very good agreement with results obtained from FEM simulations.

A comprehensive multiphysic analytical based model of spoke-type PM machine has been presented in [44]. Reluctance network model (mesh-MEC) together with lumped parameters thermal network and lumped parameters mechanical model have been employed for electromagnetic, thermal, and mechanical models, respectively. It should be highlighted that the mechanical model is more advanced in comparison to the other studies, and it is based on a four-node 2D isoparimetric quadrilateral element having 2 degrees of freedom in X and Y direction for each node. Also, it makes possible to generate the elements that are non-rectangular having curve sides which are suitable for cylindrical structures. In addition, the modal analysis, structural harmonic analysis, and also acoustic analysis can be performed by the proposed model. Also in this case the comparison between the analytical model and FEM simulations are in very good agreement considering the limited time and computational resources required for the approach. So, it can be applied for predesign and modelling of electrical machines.

A similar approach for the design of a V-shape IPM machine has been also proposed in [45]. A simple hybrid MEC model has been employed for the electromagnetic design which makes the computation very fast. Since the thin rotor bridges may lead to mechanical problems, maximum shear stress in the inner and outer bridges is evaluated during the proposed design procedure. Moreover, a thermal equivalent circuit has been developed to estimate the temperature in different parts of the machine. The presented methodology has been validated by FEM. The saturation on the rotor pole was neglected in this study.

IV. CONCLUSION

This paper presents the concept of multiphysic design of rotating electrical machines. The important design aspects in electromagnetics, mechanics, and thermodynamics have been outlined, including valuable examples reported in literature. The roles of materials at the design stage has been also summarized. Although coupling several physics seems complicated, it can make faster and cheaper the overall design process, reducing the prototyping needs to get successful products. Finally, the proposed survey reveals that the development of highly integrated multiphysic design approaches is still an open and original research field. The proposed survey can be useful both to experienced readers and students that approach these challenging topics, summarizing in an effective way the latest journal paper.

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