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Review Article

Finite Element Analysis of Electrical Machines: Recent Trends and Developments

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Abstract

Finite element (FE) method, is the most popular numerical approach to low-frequency electromagnetic modeling, especially in the field of electrical machines. Although FE method is nowadays widely used by experts, still it can find widespread efforts toward additional developments that make it more applicable to various problems. This paper takes a look at the state of the arts in the electromagnetic modeling of electrical machines via FE analysis. The addressed subjects cover new techniques for loss calculation in electrical machines, the state of art toward more efficient computation, which is a serious challenge for numerical methods, and modeling efforts for the hysteresis phenomenon. The paper tries to address a portion of the recent hot topics of FE analysis of electrical machines. The authors believe that the paper will give a brief but useful insight into the challenges and developments of FE applications in electrical machine analysis, as the most practical numerical tool in this area.

Keywords: Finite element analysis; electrical machines; loss calculation; efficient computation; hysteresis modeling.

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1. INTRODUCTION

Finite element (FE) method was firstly introduced at the beginning of the 1940s, through the studies in aerospace and structural engineering and the name “finite element” was used firstly by a civil engineer Prof. “Clough” [1]. The method was applied to electrical engineering in 1965 [2], but the particular application in electrical machines was reported by “Silvester” and “Chari” [3]. Also, [4-12] can be mentioned as the first publications about FE analysis of electrical machines. After several decades, FE method could be found as a well-known numerical modeling method in different areas of science and engineering. Consequently, several textbooks have been published related to fundamentals and implementation of electromagnetic modeling, using FE [13-19]. Modeling of electrical machines is of particular importance in various problems such as design, optimization, control, fault diagnosis, etc. Although using the analytical methods is cost-effective, they are restricted by accessibility and also undesirable initial assumptions which affect their accuracy [20-22]. However, the numerical methods (especially the FE method) may be achieved usually by arbitrary precision considering nonlinearity and anisotropy. The main challenge of these methods is the high cost of calculations that may make them sometimes hard or inapplicable to be used. Therefore, one can see recently additional efforts to overcome the remained issues associated with them. In this regard, we focus on recent modifications of the FE method in the modeling of electrical machines. Regarding that the electrical machines are in fact multi-physics devices, it should be noted that only the electromagnetic modeling aspect - as the most common aspect - is the subject of the study in this paper. The reviewed topics are categorized into three parts: loss calculation, efficient and fast calculation and hysteresis phenomenon. It should be mentioned that it doesn’t cover all of the performed researches, but some most considerable of them.

2. LOSS CALCULATION

One of the most common objectives of electrical machines modeling is to predict their losses. This has gained more attention due to the importance of efficiency modification over recent years. Moreover, precision loss calculation may be important for thermal design aspects. Although, it can find various empirical and analytical formulas for different loss components, most accurate results have been found through massive numerical models. In this regard, the attempts are directed toward more accurate calculation with fewer costs. In the following, the performed researches are presented for three groups

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of loss components, i.e. Joule loss, iron loss, and stray load loss.

2.1. Joule loss

Joule losses occur in current carrying conductors, due to their non-zero resistance and create a significant portion of the total losses in electrical machines. In lots of the FE studies, the resistance of the conductors assumed to be constant, exclusive of the electromagnetic effects. However, this assumption may lead to a significant error, especially in the case of existing high-frequency currents. Indeed, the induction effect of time-varying current in an individual conductor and the mutual induction with nearby conductors in a multi-turn slot winding, which are known respectively as skin and proximity effects, cause uneven distribution of current in the conductors' cross section area (CSA). Fig. 1 shows the proximity phenomenon for two typical adjacent conductors. To consider the mentioned effects, the ordinary solution is to define a detailed geometry of the coils in the slots, to mesh them and to solve the diffusion equation in the slot area. This procedure that is also mentioned as the "*brute force method*", makes the computation extremely time-consuming, since the CSA of a single conductor is very small compared to the rest of the machine geometry and the size of elements in each CSA must be smaller than to achieve correct results. Therefore, such an approach is usually utilized in studies, for verifying their alternative solutions [23, 24].

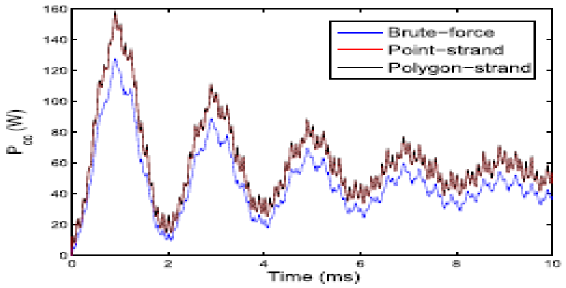

Fig. 1. CIRCULATING CURRENT LOSSES CALCULATED BY BRUTE FORCE, POINT STRAND AND POLYGON STRAND METHODS [34]

There is an alternative method for such problems, called "winding homogenization". In this method, the area corresponded to the winding assumed to be homogenous with uniform coarse meshes. Then, the skin and proximity effects can be calculated, considering complex coefficient for the reluctivity of the winding area, and adding a complex coefficient to the corresponding impedance in the coupled circuit [25]. The required parameters of these coefficients are frequency-dependent and can be determined with a separated simple FE model or even analytically [26]. Determined parameters must be calculated for particular CSA geometry and winding arrangements. The computed meshes in a typical winding are compared in Fig. 2 for brute force and winding homogenization methods. The novel method has been developed for different problems, including frequency domain [27], time domain [28], 3-D problem [26] and a high power induction motor [29].

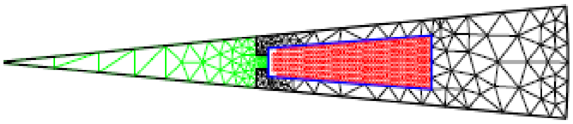

Fig. 2. SLOT DOMAIN (RED AREA) IS REDUCED FROM THE WHOLE MODEL [35]

Low power electrical machines are usually constructed with random wound windings. Also, in these cases, it is a common technique to use parallel strands to decrease the skin effect loss. This will be subjected to circulating currents between parallel strands which may increase the Joule loss, significantly, and also produce torque ripple [30]. In fact, circulating currents mean the uneven currents in the parallel strands. In the studies based on the homogenization technique, parallel strands are always ignored. Moreover, in this method, the conductors arrangement in a slot must be quite regular, which is not always the case in most of the stranded windings. Therefore, it can find other researches to compute the circulating currents losses. However, most of these methods are either verified by the brute force method [31, 32] or disregard the proximity effect [33, 34].

In a particular method assuming thin strands compared to the depth of penetration, two methods are proposed to obtain the circulating currents loss [34]. The first one assumes constant vector potential in each strand CSA and the second one is based on an approximation of the strands with a polygon. Both methods lead to a coarser mesh compared to the brute force method, while the results are reasonably accurate as can see in Fig. 3.

The mentioned methods are restricted for merely proximity loss or circulating current loss. Fortunately, the innovations haven't stopped and the latest methods have offered new solutions. In newly reported studies, novel methods have been introduced based on a pre-computation approach, where the slot areas are analyzed before the main FE solving. The slot area may be assessed by an impulse response function [35] or pre-calculated shape functions as the reduced bases technique [36].

In the first case, the studied domain is decomposed into two parts including slot domain and rest of the study domain (Fig. 4), then the slot domain is modeled with a pre-calculated impulse response functions and couples to the other domain by enforcing the continuity of the magnetic vector potential on the boundary. The winding arrangement and configuration can be arbitrary and all the skin, proximity and circulating current losses are considered.

In the other similar method, the diffusion problem coupled with the external circuit should be solved in a slot and the solution is considered as the shape function corresponding to all slots. The slots are coupled with the remaining model on the boundary of the slot.

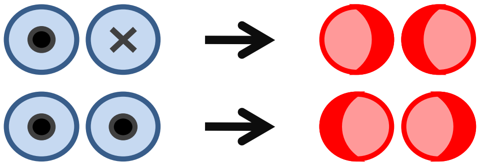

Fig. 3. PROXIMITY EFFECT FOR SAME AND OPPOSITE DIRECTION OF CURRENT

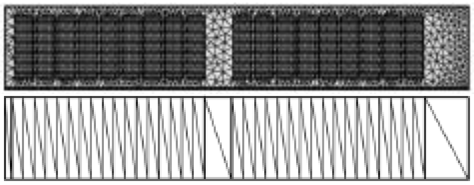

Fig. 4. MESH COMPARISON IN BRUTE FORCE METHOD AND HOMOGENIZED MODEL [29]

2.2. Iron loss

The iron losses can be decomposed into three parts: eddy current loss, hysteresis loss, and excess loss, classical formulas of which are presented in [37]. Frequently, iron loss in a FE program is calculated through a post-processing procedure. Total iron losses are approximated by Fourier decomposition of the calculated flux density and using a lookup table that includes the iron losses density for various frequencies provided empirically. In the following, a review will be presented on newer approaches for the iron loss calculation.

1) Eddy current losses: In the modern approaches, the eddy current loss is computed by direct calculation of the diffusion equation in laminated cores, in order to obtain more precise results. For this task, the easiest way is to consider zero or low values for the conductivity perpendicular to the laminations [38]. But a more precise method is to solve the equation in each lamination, separately that needs a quasi brute force meshing [39], which is obviously a huge task.

Innovative techniques have been proposed to avoid the extra calculation cost of the brute force method, using 3D FEM [40, 41], 2D FEM [42] and combined 2D and 1D FEM [43]. Additional calculation reduction has been validated via a small signal FE analysis with inclusion the eddy current of the laminated core for 2D and 3D models [44].

Similar to the previous part, the homogenization technique can be also utilized in the laminated core, for eddy current calculation. The required parameters could be calculated by analytical solving of Maxwell equations and an easier meshing of the studied area will be possible, without the need for considering the individual iron sheets [45, 46]. Although the circulating currents between laminations are ignored in all of these methods, they are considered in a recent study, where a 2D modeling is addressed [47].

Recently, the application of the permanent magnet (PM) machines is growing, quickly. These machines are mostly supplied by power electronic devices that contain the modulation frequency component in their voltage, which can induce considerable eddy currents in the conductive rare earth PMs. Hence, analyzing the eddy currents in PMs are of great importance. The challenge is that the accurate prediction of such loss needs to a 3D FE model to be developed [48] that is time consuming. Therefore, the efforts are mostly toward replacing the 2D models with acceptable results. The 2D model of the entire machine coupled with a 3D model of only PMs [49], the combined two radial and axial 2D models [50] and the 2D model combined with analytical calculations [51] can be mentioned in this regard.

2) Hysteresis loss: Hysteresis loss analysis is a more complicated task, especially in the case of non-sinusoidal excitations, which widely exist in switching drive suppliers [52]. The most significant results of such excitations are minor hysteresis loops and dc-biased induction that make the modeling procedure to be complex. These effects are taken into account in the proposed models in [53] and [54] respectively.

More accurate calculation of hysteresis loss needs to a proper definition of the hysteresis behavior of the ferromagnetic material, coupled with the FE model. To this end, different approaches have been studied and among them, Preisach model and Jiles-Atherton model are used rather than the others. The first one can accurately describe the hysteresis loops considering the magnetic history and minor loops, while the second one offers a good approximation of major and minor loops by a more simple approach [55]. The modeling of the hysteresis phenomenon will be discussed more in the next part of this paper and here, we will focus on loss calculation methods. The Preisach model coupled with the FE analysis of synchronous reluctance motor and synchronous generator is developed in [56] and [57], respectively.

Generally, the accuracy of iron losses calculation depends strongly on the precise definition of flux density distribution in the iron parts, which is influenced by the eddy currents distribution that results in a flux density skin effect [58]. Furthermore, exact modeling of the hysteresis property of ferromagnetic cores helps to take its multi-valued magnetic characteristic into account and precise obtaining of the flux density for particular magnetic field intensity will be possible. Therefore, in the latest researches, one can see considerable trends in analyzing both hysteresis property and eddy currents, simultaneously. This is due to the existing interaction effect between the eddy current and hysteresis losses that could be significant [59]. For this purpose, a hysteresis model should be coupled to a magneto-dynamic (eddy current) FE model, since the static hysteresis models (e.g. Jiles-Atherton) don't consider the eddy currents, inherently [60]. As an example, a modified Jiles-Atherton model is used in [61] to evaluate the a high-frequency permanent magnet machine losses. However, implementation of such a program across the laminated cores of electrical machines is expensive. Therefore, it can see lately some efforts to reduce the FE calculations by using a homogenization technique, named "*heterogeneous multi-scale method*" (HMM), which is developed for magneto dynamic modeling of laminations taking hysteresis loss as well as eddy currents into account [62-64].

The principle of multi-scale methods is to couple a micro-scale problem with a macro-scale one, which can be used in numerical calculations such as FE to reduce the computations. The micro-scale problems are defined on small parts of the entire domain during a step called "down-scaling" with fine meshes. The macro-scale problem that covers the whole domain is defined on a coarse mesh, use the micro-scale solutions via another step called "up-scaling". Fig 5 shows these two steps. The HMM has been extended also to deal with soft magnetic composite material loss analysis [65].

2.3. Stray load loss

Stray load losses refer to the losses which alters with load changes, and is not measurable accurately, the value of which is almost near 15% of total losses [66]. These losses arise from different sources and most of the research's concern with a special source, where the aim is to observe their changes with the machine loading. For instance, slot harmonics are of common sources of these losses. A 3D model including both time domain and frequency domain studies is used to predict stray load losses in an induction motor [67]. It can be important to take the end leakages of the machine into account, but it needs essentially to provide a 3D model [66, 68].

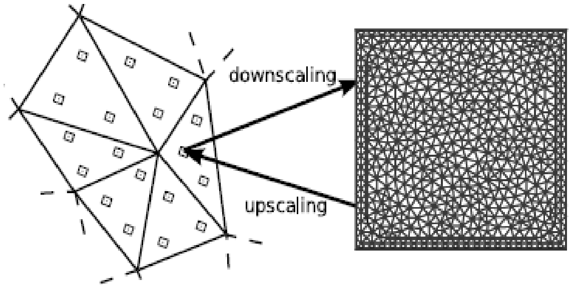

Fig. 5. DOWNSCALING AND UPSCALING WITHIN THE MULTISCALE MODEL [65]

3. EFFICIENT AND FAST CALCULATION

All numerical modeling methods are subjected to a high value of computation cost. Thus, it will restrict their application, especially when several models have to be analyzed in a procedure, such as a search-based optimization or an automatic control problem. Therefore, any solution deals with a more efficient and faster calculation will be desirable. Accordingly, several investigations have been carried out with this aim since the first decades of the FE appearance. For example, due to the special geometry of electrical machines, size reduction, using the symmetry or periodicity of the model, is a common technique for engineers, while proper boundary conditions must be provided [19]. Nowadays, such studies cover a considerable number of recent researches. Here, we will introduce some notable subjects in four categories.

3.1. Element size definition

A usual challenge in a FE study is to define the size of the elements. This is an important step of the modeling, which should be performed, carefully. One of the merits of the FE method is its flexibility to have different size of elements with different orders in the same model that results in an easier approximation of the studied region and more accurate results. Usually, it is not common to use high order elements, but the acceptable precision is achieved by selecting enough small element sizes, especially wherever the field changes, intensively. However, the smaller the elements are, the more calculation cost will be needed. To deal with this issue, the proposed solution is to use an "adaptive mesh" algorithm. The algorithm consists of two steps: 1) error approximation, 2) automatic mesh refinement. After an initial mesh, the aforementioned procedure is executed, iteratively, for each time step. References [69, 70] proposed error approximation criteria, while mesh modifications can be done using the algorithms presented in [71-73].

3.2. Quick access steady state response

In a large number of studies, the aim is to obtain the steady state response, while it will be achieved after a considerable computation time, corresponding to the transient part. Accordingly, there are techniques associated with fast steady state accessibility. Using "time-harmonic" solver is a common method which can take the motion into account [74, 75]. "Harmonic balance" is another technique that is based on the decomposition of the inputs into sinusoidal components and calculating each steady state response considering the nonlinearity, although with some limitations [76]. Furthermore, the so-called "*proper generalized decomposition*" approach uses temporal Eigenmodes instead of a-priori defined Fourier basis to reduce the size of the harmonic-balance problem [77]. Also, there are techniques that use correctness factors to pass the transient regime more quickly, e.g. "*shooting Newton*" and "*error correction*" methods. "*Rung Kutta*" method can also be mentioned in this category, which has the advantage of more accuracy for the same time step [78]. More useful descriptions of these methods can be found in [79].

3.3. Parallel computation

Since the development of numerical methods in different applications is highly dependent on the growth of microprocessors technology, the advent of multi-core processors has been of considerable attention [80]. However, recently these developments are observed in implementing parallel computations rather than increasing the processor frequency. Parallel computation techniques can be performed primarily, by parallel solving the algebraic systems [81, 82]. Another technique to perform the parallel computation is known as "*domain decomposition method*". In this technique, the whole studied domain could be divided into several sub-regions; the calculations of each one are carried out via a separated processor and the relation between the processors is determined by a certain algorithm. Fig. 6 shows a typical domain decomposition during the modeling of a permanent magnet motor. The method is extended for 3D problems based on the edge elements so that it can consider the motion in the simulation [83]. In the problems containing rotor movement, the domain decomposition should be done at the beginning of each step, which results in an additional task, compared to non-parallel processing. To overcome this drawback, the initial decomposition should be defined properly, so that it remains unchanged till the end of the simulation [84].

3.4. Model order reduction

The so-called model order reduction (MOR) methods adopt a slightly different approach. Instead of optimizing the model size a priori (i.e. by using optimal element sizes) or improving hardware utilization via parallel processing, they aim to reduce the complexity of an existing model. Typically, Eigen-like decompositions are applied for this purpose. As the approaches typically require an intensive pre-computation step, they can be best suited for applications where repeated simulations of the same system are required, such as efficiency map calculation or embedded control.

Perhaps the most popular family of approaches is based on the Proper Orthogonal Decomposition (POD) [85, 86]. First, the FE problem is solved in several different combinations of e.g. d- and q-axis currents, rotor angle, eccentricity, and so on. The solutions are then collected in a snapshot matrix, which is then singular-value decomposed. A low-rank approximation of the original problem is then assembled from the largest singular values and the corresponding (left or right) singular vectors. The basic POD approach suffers from the nonlinearity of the problem, requiring regular updates to the low-rank system. At least two methods have been proposed to overcome this problem. The orthogonal interpolation method (OIM) updates the right singular vectors by means of polynomial or Fourier interpolation, while retaining the same singular values and left singular vectors [87]. Another approach uses the dynamic mode decomposition (DMD), modeling the system as a sum of exponentially decaying modes [88].

3.5. Skewing approximation

Commonly, the slots of the rotor or the stator of low and medium power electrical machines are skewed to overcome the slot effects, such as torque harmonics and vibrations. It could also be applied to permanent magnets to obtain the same results. In order to take the skewing into account, it will be necessary to utilize a 3D model that makes it possible to consider the axial dimension changes, too, but at the considerable cost of model size increment. The "*Multi-slice approximation*" is an applicable alternative that is used widely in recent years so that 3D modeling can be avoided [89-91].

A certain number of slices must be selected at the first step, and then they will cut off the machine tangent to the 2D plane by particular spaces (Fig. 7). Often the slices distribution (spacing) is uniform, while one may use a Gaussian distribution to obtain a better approximation [92]. Each slice represents a 2D model of the machine at its intersection; therefore, the more the slice numbers, the better the approximation, and the larger computation costs. The 2D problems associated with each slice must be solved in coupled, which make it possible to take electrical current connections between slices into account. The method has been extended to consider more 3D effects, such as interbar currents [93], which are increased in skewed rotors of induction motors. Also, multi-slice problems are greatly proper to be solved through a parallel computation that leads to the faster solution [94].

4. HYSTERESIS PHENOMENON AND FE

Hysteresis property is a feature that can be seen in various physical devices. Mathematical modeling of this phenomenon is a difficult task, because of its complex dynamic behavior. On the other hand, a correct representation of the magnetization characteristic of magnetic materials is necessary to have accurate modeling results. The most common targets of modeling the hysteresis in a FE study are hysteresis loss and hysteresis torque evaluations. In section II, some researches associated with the calculation of the hysteresis loss was introduced. While in this section we will address the hysteresis modeling techniques that are used in FE analysis of electrical machines and their challenges. Using phenomenological models of hysteresis are more affordable compared to micro-magnetic models. Preisach model is a purely mathematical model that is used widely for hysteric magnetic studies, while, differential equation based models are also popular for the same task. Hodgdon model and Jiles-Atherton model are well-known examples of this type of methods, which are physics-based models. All these models can be utilized in a static or dynamic and scalar or vector formulation, depending on the situations of the problem. It can find brief and useful knowledge of these concepts in [95] and more detailed contents can be found in [15]. Combining hysteresis models with the FE solving of Maxwell equations leads to accurately define the flux density distributions, thus the hysteresis torque can be computed. Accordingly, one can find some successful efforts recently to coupling the mentioned hysteresis models with the FE analysis of electrical machines, in order to calculate the hysteresis torque. In this regard, one can mention Preisach [96-100], Jiles-Atherton [101-103] and Hodgdon models [104, 105]. Although, approximated models, such as elliptical hysteresis descriptions can be used instead, with some acceptable results [106]. Besides of the hysteresis motors, accurate modeling of hysteresis will be important in the cases where it can affect the system performance, significantly, such as inrush current study of the transformers [107] and self-excited induction generators [108].

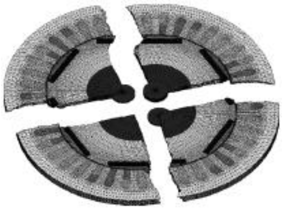

Fig. 6. DIVIDING the model into 4 submodels [83]

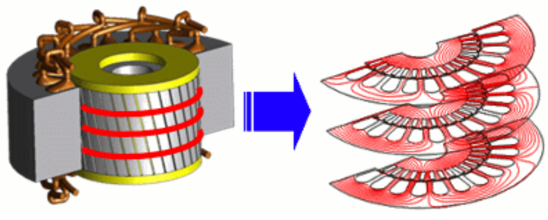

Fig. 7. APPROXIMATING the skewed slots by considering 3 slices of the machine

There are various kinds of hysteresis models except for the mentioned ones; each one has its own advantages and drawbacks. For instance, Hysteron model [109, 110], play model [111, 112], etc, all have been used in coupling with the FE model. A comparison for some of the phenomenological and physical-based models is presented in [60] in terms of their performance and capabilities. Among all, the Jiles-Atherton model has advantages in relatively simple implementation and acceptable accuracy, and so is of great interest in recent years [108, 113, 114]. Also, since the Preisach model is, probably, the most accurate hysteresis model, it has been used widely, too [58, 115-118]. Based on a comparison of the performance of these two models presented in [119] the accuracy of Jiles-Atherton model can be almost same as the Preisach's, with 2.8-3.9 times less time consumption, whereas, Preisach model can represent wider classes of materials [120]. However, the sustainable numerical implementation [121-123] and model parameters identification [60, 124, 125] are other challenges that should also be considered.

5. CONCLUSION

In this study, recent topics about the FE analysis of electrical machines were addressed, briefly. Since the use of FE models for analyzing the electrical machines is much practical, there are lots of issues related to its developments and only some of the most important subjects were highlighted in this paper.

In the Joule loss studies, novel methods to analyze the frequency dependent losses, i.e. skin and proximity effects losses, and circulating currents between random wound strands were mentioned. New approaches for eddy current loss calculation in laminated iron and also in permanent magnets were introduced. Besides, different methods to predict the hysteresis loss of ferromagnetic materials solely and considering eddy currents were pointed, too. Computation reduction of FE analysis is of great interests. Some of the most significant efforts for this purpose were presented in five groups, including efficient mesh sizing, quick steady state accessibility, parallel computing, model order reduction, and skewing approximations. The last part dealt with techniques and challenges of modeling the hysteresis phenomenon of ferromagnetic materials in a FE study. This paper shows some of the recent trends in the development of the FE modeling of electrical machines and emphasizes that there remain lots of issues associated to this field, although the FE is the most common numerical model for electrical machines.

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