Topology Optimization for Enhancing Electric Machine Performance: A Review

Mohamed Reda Mahmoud[1,2,3*]
Mohamed.Reda@UGent.be
mohamed.hassan@mu.edu.eg

Mohamed N. Ibrahim[1,2,4]
Mohamed.Ibrahim@UGent.be

Peter Sergeant[1,2]
Peter.Sergeant@UGent.be

[1]*Department of Electromechanical, Systems, and Metal Engineering,Ghent University, 9000 Ghent, Belgium*
[2]*FlandersMake@UGent, Core Lab MIRO, 3001 Leuven, Belgium*
[3]*Electrical Engineering Department, Faculty of Engineering, Minia University, Minia 61111, Egypt*
[4]*Department of Electrical Engineering, Kafrelshiekh University, Kafrelshiekh 33511, Egypt*

***Abstract*—Exploring the design space is essential in the pursuit of developing high-performance and power-dense electric machines. This article explores the transformative potential of topology optimization (TO) in enhancing the performance of electric machines. Conventional techniques for optimizing the design of electric machines use optimization algorithms to determine geometric variables within a predefined range. However, these methods are limited by manufacturing constraints and the designer's expertise in parameterization. On the other hand, topology optimization aims to enhance the performance of electric machines by manipulating the distribution of materials as a design factor. The enhancement is facilitated by additive manufacturing (AM), particularly via the manufacturing of intricate metal parts. In this paper, the main concepts of topology optimization in electric machines are reviewed. Firstly, the requirement for topology optimization is illustrated, and both the achievements and challenges of this technique over the traditional parametric optimization are described. Then, a description is given of different topology optimization methods that were reported in the literature. Finally, the development opportunities of this technology are shown in the electric machine design field.**

***Index Terms*—Topology Optimization, Electric Machines, Additive Manufacturing, SRM, SynRM, and PM Machines.**

I. INTRODUCTION

Nowadays, electric machines play a critical role in different industries, including transportation, renewable energy, and industrial automation. As the demand for a new generation of high-performance and power-dense electric machines necessitates an investigation of the design space in order to pick out promising designs [1]. Topology optimization has emerged as a powerful tool in the field of electric machine design, offering unprecedented opportunities for enhancing their efficiency, power density, and overall performance [2].

Optimization in electrical machine design refers to the process of enhancing an electrical machine design to maximize its performance and/or cost-effectiveness. The objective is to attain the optimal equilibrium between design goals and limitations, encompassing power density, torque density, efficiency, dimensions, weight, cost, and materials [3]. Conventionally, maximizing the performance of electric machines is achieved through parametric optimization [4]. Conventional optimization strategies for the design of electric machines aim to identify the optimum values of parameterized geometric variables by varying them within a predetermined range. Parametric optimization only optimizes shapes within established boundaries and cannot change the design topology [5]. In contrast, topology optimization overcomes these restrictions by enabling modifications to the structure design throughout the optimization process, leading to the discovery of highly optimized solutions [6].

The primary difference between parametric and topology optimization methodologies is the obligation to predefined all possible geometries. In contrast to parametric optimization, TO approaches do not require the initial description of all geometric possibilities. This freedom in designing the final shape allows topology-optimized machines to perform better [7].

Topology optimization in the field of electric machines is more recent than for structural applications. The use of TO approaches, specifically for electric machine design, gained attention in the last two decades. Since then, researchers studies have been conducted to study various TO methods and algorithms that have been built for electric machines, including permanent magnet machines, switching reluctance machines, and synchronous reluctance machines. The area is evolving as researchers work to address problems like computer complexity, modeling accuracy, and manufacturing restrictions. The historic evolution of TO in electric machine design has offered new opportunities for improving machines performance [8]–[11].

The main contribution of this paper is to present a review of the concepts of TO and the benefits of implementing it in the field of electric machine design. This review article provides a thorough overview of the present advances in topology optimization for electric machines. The paper explores the various aspects of the TO field in electric machine design, including methodologies, applications, challenges, and future directions.

This article is organized into six sections. The TO definition and concepts are described in section II, followed by explanations of different TO methods for electric machines in section III. Section IV reviews the improvement of electric machine design obtained based on TO. Section V presents the challenges and development Opportunities, followed by the conclusion drawn in Section VI.

II. CONCEPTS OF TOPOLOGY OPTIMIZATION

In this subsection, the state-of-art of Topology optimization (TO) is presented. TO focuses on optimizing the layout and distribution of material inside a given design area to accomplish desired performance objectives. A TO problem consists of four essential elements: design space, objective function, design variables, and constraints. The design space defines the region in which the optimization process occurs. It denotes the volume or area in which the material distribution and structural layout can be changed. The design variables are characteristics that determine how materials are distributed or shaped inside the design space. These variables may include material densities, nodal displacements, or geometric characteristics that affect the structure topology. The objective function measures the performance goals that will be accomplished by TO. The constraints are requirements that must be met during the optimization process. These restrictions may include stress limits, displacement constraints, manufacturing constraints, or geometric constraints.

Discreteizing the design domain is the initial step towards solving the topology optimization problem.Then, the magnetic problem is analyzed numerically using techniques such as the Finite Element Method (FEM). To ensure convergence, the objective function is assessed. Re-analysis may be necessary if sensitivity analysis and an optimization technique update the design variables and it has not converged [12]. This procedure is continued until convergence is attained. For a clearer understanding, Fig. 1 illustrates the flowchart of the TO approach.

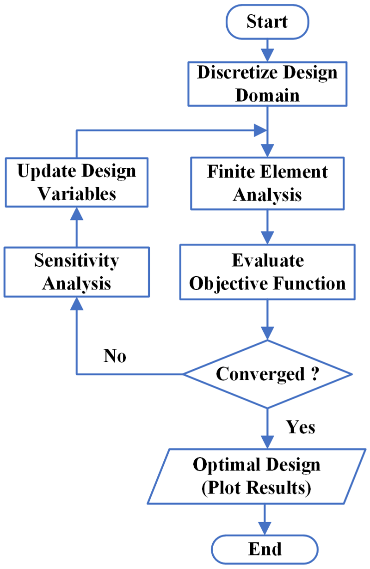


Fig. 1. Flowchart of the topology optimization process.

III. TOPOLOGY OPTIMIZATION METHODS

Topology optimization methods for electric machines involve mathematical algorithms and techniques to optimize the material distribution within the design space of the machine. These methods aim to find the optimal layout of the machine that maximizes its performance while satisfying various constraints. The commonly used TO methods for both electromagnetic devices and electric machines include the homogenization-based method, Density-Based method, Level Set method, Bi-directional Evolutionary Structural Optimization (BESO), and the ON-OFF method. Each of those techniques are illustrated in this section.

A. Homogenization-Based Method

In 1988, Bendsøe and Kikuchi introduced the homogenization method, which was applied to structural applications [13], [14]. In the homogenization method, the discrete design space is composed of finite elements. Each element consists of numerous micro structures, typically rectangular cells with rectangular holes. The dimensions (x_e,y_e) and angle of rotation of each hole serve as the design variables for optimization as shown in Fig. 2. In the homogenization approach, a cell is considered "solid" when the hole disappears, while it is classified as "void" if the hole has the same dimensions as the cell. Consequently, only the material within the micro scale cell is altered, rather than the entire mesh element. During the optimization process, the material is transferred between different regions of the design domain, resulting in the attainment of the optimal material distribution.

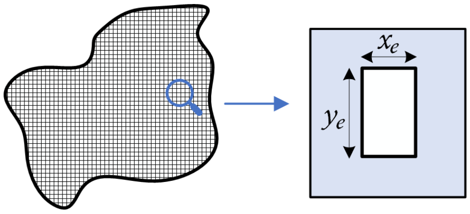


Fig. 2. The homogenization method microstructure

In 2000, Yoo and Kikuchi applied the homogenization method for the optimization of an electromagnetic device for the first time without mentioning the strengths and weaknesses of the obtained design [15], [16]. This strategy appears to be dropped in favor of the other methods discussed below.

B. Density-Based Method

The density-based TO method was first developed for the solid mechanics [14]. It is a simple technique that has gained popularity for electric machine TO, even for multi-material TO problems. This technique represents the material material property (e.g. permeability) as a continuous function. The optimization approach uses a gradient-based optimizer, which is dependent on the sensitivity of both the objective and constraint functions to material property within each element [17]. Using the density method, the design variables are made continuous varying between 0 and 1 as shown in Fig. 3.

The objective of the density method is to maximize/minimize the objective function by identifying the material type to be assigned to each element. It depends on interpolation, filtering, and projection techniques, and the material penalization function was initially a simple power-law. This leads to the SIMP (Solid Isotropic Material with Penalization) approach [5].

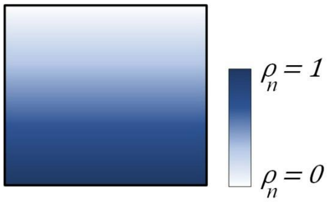


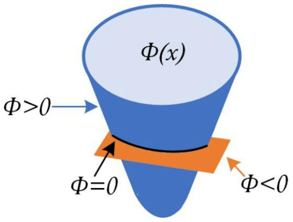
Fig. 3. The density-based TO.

C. Level Set Method

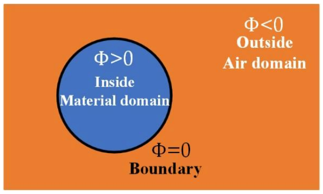
The level set method is the topology optimization technique that is used to represent the material boundaries. It is a mathematical method that was developed by Osher and Sethian [18]. The level set function is used to identify the material boundaries between the ferromagnetic material domain and another domain filled with air, as illustrated in Fig. 4. The level set function $\phi(\mathrm{x})$ represents the computational design domain and is defined as:

$$\phi(\mathrm{x}) = \begin{cases} \phi(\mathrm{x}) < 0 & air \\ \phi(\mathrm{x}) = 0 & boundary\ \ edge \\ \phi(\mathrm{x}) > 0 & ferromagnetic\ \ material \end{cases}$$

where x is an arbitrary position in the design domain. The purpose of level set topology optimization is to identify the best distribution of material in a design space to achieve certain design objectives by calculating the value of $\phi(\mathrm{x})$ at each point (x).



(a) Intersection of a plane and a surface



(b) Top View

Fig. 4. Material boundary representation using the level set method.

D. ON-OFF Method

The ON-OFF approach is the most basic topology optimization technique. This technique entails subdividing the geometry into several elements (cells), usually finite-element analysis (FEA) mesh elements for electric machines, and altering the material given to each element [6], [19]. For two materials, each element is represented by a variable normalized density ρ_n which can be classified as either air ($\rho_n = 0$) or iron ($\rho_n = 1$) as shown in Fig. 5. This technique is reasonably simple to implement using an evolutionary algorithm. This technique can be used with different numerical optimization methods, including evolutionary and gradient-based algorithms, to achieve optimal designs [5]. The main demerit of using the ON-OFF optimizing technique is the disjointed designs which are difficult to manufacture. Filters, such as the Gabor filter, should be used to overcome this drawback.

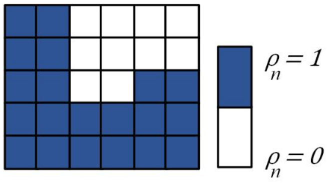


Fig. 5. The ON-OFF method.

E. BESO Method

In 1998, Querin et al. [20] introduced the bi-directional evolutionary structural topology optimization (BESO) technique, which employs binary design variables. While Classical Evolutionary Structural Optimization (ESO) is limited to removing material from a structure, and Additive Evolutionary Structural Optimization (AESO) algorithms can only add material, BESO stands out by enabling the bidirectional addition or removal of material [21].BESO is considered an enhanced ON-OFF method. BESO uses the sensitivity of the optimization objectives to identify elements in the design space that need material upgrades, such as switching from iron to air. The sensitivity of each element is measured using the BESO sensitivity number. The BESO sensitivity number accelerates the optimization process as compared to the basic ON-OFF technique, which does not take topological sensitivity into account and relies only on heuristic algorithms.

IV. ELECTRIC MACHINES IMPROVEMENT USING TOPOLOGY OPTIMIZATION

The majority of topology optimization studies on electric machines have so far concentrated on either maximizing the machine torque density or shaping the torque profile by modifying the material distribution in the rotor. Furthermore, minimizing the losses, and improving the temperature distribution are important objectives in machine design. In this section, the improvement archived using TO for different electric machines is introduced.

A. Switched Reluctance Machine (SRM)

The switched reluctance machine (SRM), the synchronous reluctance machine (SynRM), and the permanent magnet PM machines have been extensively studied machines in TO-based designs. SRM performance is improved using TO. Torque ripple is one of the main problems for SRM which makes the motor operate acoustic noise and suffer from high vibration, especially at low speeds. Applying TO using the level set method effectively reduces the torque ripple as expressed in [22]. Fig. 6 presents the initial and optimized design of the 8/6 SRM. The torque ripple is reduced based on the level set optimization as shown in Fig. 7.

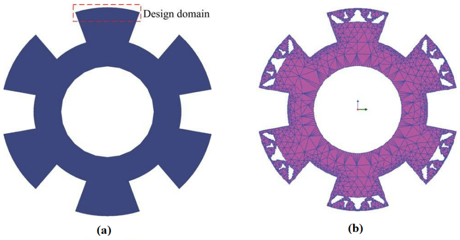


Fig. 6. The 8/6 SRM designs: (a)The initial (b) optimized design [22].

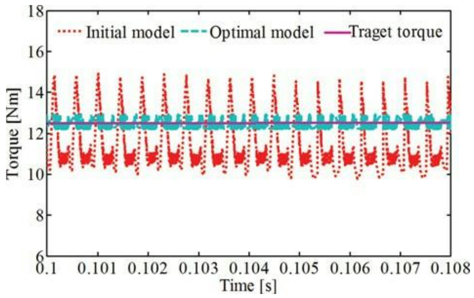


Fig. 7. The 8/6 SRM torque waveform [22].

In 2019, the SRM was optimized in terms of both the torque and the mass by applying additive manufacturing together with TO. The obtained results provided significant improvement for the torque. However, the designed geometry, as shown in Fig. 8, was sensitive to both the mesh density and the material identification. Furthermore, the rotor mass was not decreased significantly [23]. A three steps SRM design optimization was introduced in [24]. The design process consists of shape optimization, sensitivity analysis, and TO. This design improves both the SRM performance, in terms of minimizing the torque ripples, and the optimization process by decreasing the computational burden. Ref. [25] presented a gradient-based TO algorithm that was formulated to minimize the torque ripple. However, the designed SRM was asymmetry which may cause mechanical unbalance. Table I summarizes the improvement of SRM using TO.

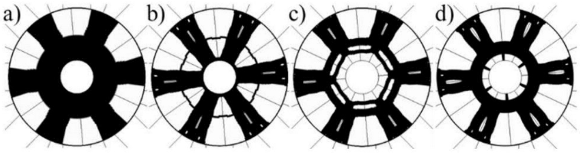


Fig. 8. TO results for different elements: a) 21295 elements b) 51786 elements c) 102144 elements d) 171388 elements [23].

TABLE I
SUMMARY OF TOPOLOGY OPTIMIZATION METHODS APPLIED TO SWITCHED RELUCTANCE MACHINE

Ref.	Optimization Method	Objective Function
[22]	Level Set Method	Minimize torque ripple
[23]	SIMP Method	Maximize torque Minimize rotor mass
[25]	Density-based Method	Minimize the first torque harmonic Minimize torque ripple
[24]	ON/OFF method	Minimize torque ripple
[26]	Density-based Method	Maximize average torque Minimize torque ripple

B. Synchronous Reluctance Machine (SynRM)

Synchronous reluctance machines (SynRMs) offer cost-effective solutions for many industrial and transportation applications. Therefore, it is important to achieve an optimal design with high performance. Topology optimization plays an important role in enhancing the SynRM design. In [27], the factors that clarify the reasons for torque ripples and the methods of reduction by examining the influence with rotor shape were analyzed using the TO technique. The designed flux barrier rotor structure promises a torque ripple reduction. Yoshitsugu and Hajime proposed a TO approach using the Gabor filter [28]. The applied TO was the normalized Gaussian network (NGnet) based on the ON-OFF technique. The designed SynRM, shown in Fig. 9, has a maximum average torque, and simultaneously a minimum torque ripple. However, both [27], [28] proposed a torque ripple reduction without studying the mechanical strength of the designed rotor and mentioned the computation time of the optimization process. To overcome the computation time problems associated with TO in previous studies, a density-based TO was applied to a SynRM rotor to optimize the design with better optimization process performance [29]. Furthermore, computationally efficient TO was proposed based on SIMP to maximize the machine torque. This study used torque curve interpolation to calculate the optimal current phase angle in terms of the designed variable [30].

Using level set topology optimization, a new design is proposed to resolve the shape optimization of the SynRM. The objective of the design was to maximize torque by designing the rotor form by dispersing ferromagnetic material across its design domain [31]. Moreover, a method of moving asymptotes (MMA) based TO was proposed to improve the torque characteristics and to provide robustness with respect to the mechanical structure of the rotor [32]. In addition to the previous improvements, a new study aimed to reduce iron losses and enhance the torque characteristics using the level set method-based TO was introduced in [33]. A deep geometry optimization was performed with the objective of modifying the rotor shape to create a better trade-off between rotor durability and motor performance. To accomplish this, a topology optimization was utilized to establish the guideline for the ideal positioning and thickness of the ribs, illustrating the impact on performance [34]. The optimized rotor of the SynRM is shown in Fig. 10. A summary of the TO methods applied to SynRM is illustrated in Table II.

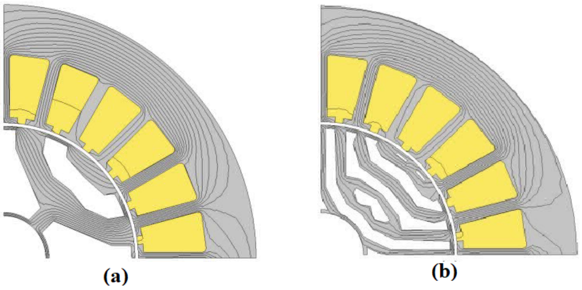


Fig. 9. The obtained smoothed rotor shapes. (a) NGnet (b) Gabor filter [28]

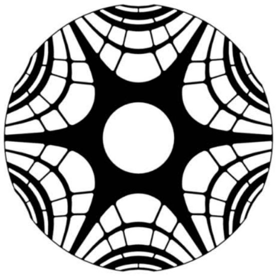


Fig. 10. The TO designed SynRM rotor [34]

TABLE II
A SUMMARY OF TOPOLOGY OPTIMIZATION METHODS APPLIED TO SYNCHRONOUS RELUCTANCE MACHINE

Ref.	Optimization Method	Objective Function
[31]	Level Set Method	Maximize the average torque
[35]	ON/OFF Method	Maximize the dynamic torque
[27]	ON/OFF method	Minimize the torque ripple
[28]	NGnet based on ON-OFF	Maximizing average torque Minimize the torque ripple
[29]	Density-based Method	Maximizing average torque
[30]	SIMP Method	Maximize the machine torque
[34]	SIMP Method	Maximize the machine torque
[33]	Level set method	Minimize the iron losses

C. Permanent Magnet Machine

Permanent magnet machines are frequently regarded as a superior alternative for a wide range of industrial and transportation applications due to their impressive performance, high power density, and efficiency. Reducing cogging torque and magnetic energy variation were the objectives of TO that applied to the design process of the interior permanent magnet (IPM) motor stator [36]. The TO density-based method used a reaction-diffusion (R-D) equation to reduce the cogging torque. The study [37] proposed a TO based on the binary evolutionary algorithm to minimize the weight, torque ripple, and cogging torque of the permanent magnet synchronous motor (PMSM). TO concerns also with the winding design of the machine. A level-set TO strategy was applied to optimize the winding design of the PM motor to maximize the motor torque [38]. A sensitivity-based ON-OFF topology optimization is applied to optimize the design of the IPM motor to improve the motor performance. This method can be enhanced by using mathematical concepts of the topological derivatives (TDs) [9]. Table III presents the performance improvement of the PM machines using different TO techniques.

TABLE III
A SUMMARY OF TOPOLOGY OPTIMIZATION METHODS APPLIED TO PERMANENT MAGNET MACHINES

Ref.	**Optimization Method**	**Objective Function**
[36]	Density-based Method	Minimize cogging torque
[38]	Level set method	Maximize the torque
[7]	ON-OFF based NGnet	Maximize the average torque
[37]	Binary Evolutionary Algorithm	Minimize the weight and torque ripples
[9]	Gradient-based ON/OFF method	Maximize average torque
[39]	Level set method	Maximizing average torque Minimize torque ripples
[40]	ON/OFF method	Minimize torque ripples
[41]	NGnet method	Maximizing average torque Minimize torque ripples
[42]	MMA method	Maximize average torque
[43]	NGnet Method	Minimize iron losses

D. Comparison Between Topology Optimization Techniques

In this section, a comparison between different TO methods applied in electric machine design is illustrated. This comparison reveals distinct advantages and trade-offs inherent to each method. Level set methods stand out for their ability to generate high-quality designs with clear, smooth boundaries, making them ideal for applications requiring precise material definition, albeit at the cost of high computational demands and implementation complexity [31]. In contrast, density-based methods (e.g. SIMP) are renowned for their efficiency and versatility, adept at handling a broad range of design problems. However, they may produce intermediate densities requiring further processing and are sensitive to penalization parameters [2]. BESO offers a balanced approach, delivering robust, clear designs through gradual material evolution, with moderate computational requirements and implementation ease, yet necessitating careful parameter tuning [44]. On-Off Methods yield discrete, easily manufacturable solutions with high precision but are limited by their computational intensity and formulation complexity, thus best suited for smaller-scale applications [45]. These methods collectively illustrate the balance between computational efficiency, design quality, and application suitability in optimizing electric machine designs as illustrated in table IV.

V. CHALLENGES AND DEVELOPMENT OPPORTUNITIES

Although topology optimization has been extensively studied in the field of structural mechanics, its application to the identification of optimal electric machine designs is still a new and growing area of research. TO of electric machines presents several challenges that need to be addressed for successful implementation. These challenges include:

A. Computational Complexity

Topology optimization entails solving sophisticated mathematical models and running iterative simulations to find the best material distribution within the design space. Electric machines frequently have complex geometries and incorporate multi-physics phenomena, which can dramatically increase computational cost and time. Efficient algorithms and computational strategies, such as parallel computing and surrogate modeling, are required to handle this difficulty and reduce computational load.

B. Manufacturability

The manufacturability of the optimized design is considered one of the main challenges that face the TO of electric machines. The designs optimized by TO always have jagged surfaces, uneven material distribution, and irregular features which made the manufacturing process with traditional techniques unrealistic. AM presents a solution for the fabrication process of optimized designs. However, the present state of AM technology poses difficulties in attaining the desired performance, particularly concerning magnetic materials that exhibit limited magnetic properties.

C. Structural Integrity (Mechanical Concerns)

Enhancing the electromagnetic performance in the design with volume reduction constrain is the essential objective of TO, but it has a significant drawback. TO focus on improving electromagnetic characteristics, often leading to designs that have weak mechanical strength. This issue is particularly evident in synchronous reluctance machines (SynRM), where the optimal design may feature excessively thin ribs that are impractical from a structural integrity standpoint. In order to overcome this limitation, it is necessary to integrate TO with structural analysis, considering the mechanical constraints of the machine.

D. Multi-Materials

Electric machines consist of different materials, e.g.: iron, copper, and permanent magnets (PMs). While applying TO for single-material electric machine parts is relatively simple, as in the case of SynRM which has a homogenous material, optimizing parts with several materials can be complex. It is still in the early stages of development to optimize multi-materials machines, such as PM machines which are necessary to optimize various materials. Moreover, when handling PMs, further constraints related to the magnetization vector must be considered. However, references [17], [45]–[47] studied the multi-material TO, it is not easy to implement.

E. Multi-Objective Optimization

Electric machines frequently have many different objectives, such as increasing power density, reducing losses, and ensuring structural integrity. Topology optimization must manage these competing aims at the same time. Determining the trade-offs between various objectives and finding the best compromise solution is a difficult challenge. This difficulty is frequently addressed using advanced multi-objective optimization approaches such as evolutionary algorithms and Pareto optimization.

Topology optimization, as applied to electric machine design, is an emerging optimization technique. While topology optimization allows for greater design flexibility, there are still limitations. Some of these limitations include the following. The resulting microscopic features may be difficult to manufacture, however spatial filtering can help to alleviate this. To tackle these challenges, ongoing research, and development in TO for electric machines are required. This could include developing new manufacturing procedures to produce optimal designs, experimentation with new materials and designs to attain the needed attributes, as well as developing new optimization algorithms to minimize simulation time and complexity. By solving these challenges, not only increases the efficiency and performance of electric machines but also accelerates progress in industries that rely on electric machine technology.

TABLE IV

Comparison between topology optimization methods in the electric machines

Metric	Level Set Method	Density-Based method	ON-OFF Method	BESO Method
Optimizer Type	Flexible	Gradient based	Evolutionary	Gradient assisted
Computation time	Optimizer dependent	Fast	Extremely slow	Fast
Material Boundaries	Clear and smooth	Intermediate densities possible	Discrete solutions	Clear and interpretable
Solution Quality	High	Good	High	High
Efficiency	Moderate	High	Low	Moderate
Popularity	High	Very high	Medium	Low

VI. CONCLUSION

This paper highlights the significance of topology optimization (TO) in improving the performance of electric machines. Various TO methods, including homogenization method, density-based method, ON-OFF optimization algorithms, Bi-directional Evolutionary Structural Optimization (BESO), and level set method, have been reported. TO has shown promising results in enhancing electric machine performance by optimizing structural layout and material distribution. The application of TO has led to improvements in efficiency, torque density, weight reduction, and minimizing losses in different types of machines, such as SRMs, SynRMs, and PM machines. However, challenges exist, including manufacturability, mechanical strength of the designed motor, multi-material designs, computational complexity, and multi-objective optimization. Despite these challenges, TO remains a valuable tool for enhancing electric machine performance. Future research should focus on addressing the challenges. Overcoming these challenges will enable the widespread application of TO in electric machine design and optimization.

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BIOGRAPHIES

Mohamed Reda Mahmoud was born in Minia, Egypt, in 1995. He received the B.Sc. and M.Sc. degrees in electrical and electronic engineering from Minia University, Egypt, in July 2018 and January 2023, respectively. He is currently Ph.D. researcher with the Department of Electromechanical,Systems and Metal Engineering, Ghent University, Gent, Belgium. He has been an assistant lecturer (on leave) in Electrical and Electronic Engineering Department, Mini University, Egypt since February 2023. His research interests include the field of power electronics, motor drives, electric vehicles, topology optimization, analytical modeling of electrical machines and additive manufacturing of electromagnetic components for magnetic actuators and electric machines.

Mohamed N. Ibrahim (Senior Member, IEEE) received the M.Sc. degree in electrical power and machines engineering from Tanta University, Egypt, in November 2012, and the Ph.D. degree in electromechanical engineering from Ghent University, Belgium, in December 2017. He became a Teaching Assistant and an Assistant Professor (on leave) with the Electrical Engineering Department, Kafrelsheikh University, Egypt, in November 2008 and April 2018, respectively. Since December 2017, he has been a Postdoctoral Researcher with the Department of Electromechanical, Systems and Metal Engineering, Ghent University. Since August 2023, he has been an Associate Professor (on leave) with the Electrical Engineering Department, Kafrelsheikh University. He is currently an Affiliate Member of Flanders Make, the strategic research center for the manufacturing industry in Flanders, Belgium. He has over 100 publications and one patent in this research field. His research interests include electrical machines and drives for sustainability. He serves as an Associate Editor for IEEE TRANSACTIONS ON MAGNETICS and as the Guest Editor for Energies, Mathematics, and Electronics.

Peter Sergeant (Senior Member, IEEE) received the M.Sc. degree in electromechanical engineering and the Ph.D. degree in engineering sciences from Ghent University, Ghent, Belgium, in 2001 and 2006, respectively. He became a Post-Doctoral Researcher at Ghent University in 2006 (Post-Doctoral Fellow of the Research Foundation-Flanders). Since 2012, he has been an Associate Professor at Ghent University. He is currently a Professor of electrical drives at Ghent University and a Core Lab Manager in the cluster motion products of Flanders Make. His research interests include electrical machines and drives for industrial, automotive, and sustainable energy applications, with a focus on accurate modeling, prototyping and testing of machines and drives, for improving reliability, energy efficiency, and power density.