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ORIGINAL ARTICLE

Design Optimization Methods for Electrical Machines: A Review

Mohd. Fairoz Bin Omar[1] · **Erwan Bin Sulaiman**[1] · **Irfan Ali Soomro**[1,2] · **Md. Zarafi Bin Ahmad**[1] · **Roziah Aziz**[1]

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Abstract
Most of the appliances in industrial equipment and systems uses electric machines. They fill the various requirements for global sustainability not only physically or technologically but also environmentally. Therefore, progressively complex engineering domains and constraints are involved in the design optimization process such as electromagnetics, structural mechanics, and heat transfer. This paper aims to present a review of the design optimization methods for electrical machines, including design analysis methods and models, optimization models and algorithms. Several efficiency optimization methods are highlighted such as Gradient Based Algorithm, Tabu Search, Genetic Algorithm, Differential Evolution, Particle Swarm Optimization, Multi-objective Algorithm and Deterministic Optimization Method. Meanwhile, Deterministic Optimization Method has been presented on Field excitation, Permanent magnet and Hybrid excitation flux switching machines for the optimization. From the literature reviews, it is observed that DOM algorithms gained the best design technique for electric machines to produce optimal performances.

Keywords Deterministic optimization method · Genetic algorithm · Multi-objective algorithm · Particle swarm optimization · Tabu search

1 Introduction

Optimization is a very popular term in modern design of electrical machines and devices in general. By reason of the everlasting competition in the world markets, increased cost of electrical energy and pressures for its conservation, design optimization of electrical machines has become more and more interesting and important. The objective of the optimization process is usually to minimize either the initial cost of the machine or its lifetime cost including the cost of lost energy. Other objectives such as mass minimization or efficiency maximization may also be appropriate in some situations [1]. In much more competitive markets and challenging application areas, it is of primary importance to reduce the design and manufacturing process of new products as much as possible.

As an electric machine is the back-bone of many electric drives, maximizing their performance takes top priority. Advances and trends in mathematical modelling and computer simulation, together with the availability of sophisticated optimization techniques, have opened the way to a new approach for electrical machine design. The already proven reliability of today's optimization strategies allows speed up of the final product definition, reduces the prototyping needs for project validations, and minimizes development and manufacturing cost. The potentialities offered by modern optimization techniques are grown of interest for industry year after year, giving the reason for their massive penetration into the design chain [2].

Figure 1 shows optimization algorithms for the design optimization of electrical machines as well as other electromagnetic devices [3]. From the figure, there are two main types, gradient based algorithms (GBAs) and intelligent optimization algorithms (IOAs). From the figure, there are eighteen types of optimization algorithms that have been used in electric machine designs, such as conjugate gradient algorithm (CGA), sequential quadratic programming (SQP) algorithm, estimation of distribution algorithm (EDA),

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✉ Irfan Ali Soomro
eng.irfansoomro@gmail.com

[1] Research Center for Applied Electromagnetics (EMCenter), Institute of Integrated Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia

[2] Electrical Engineering Department, Quaid-E-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan

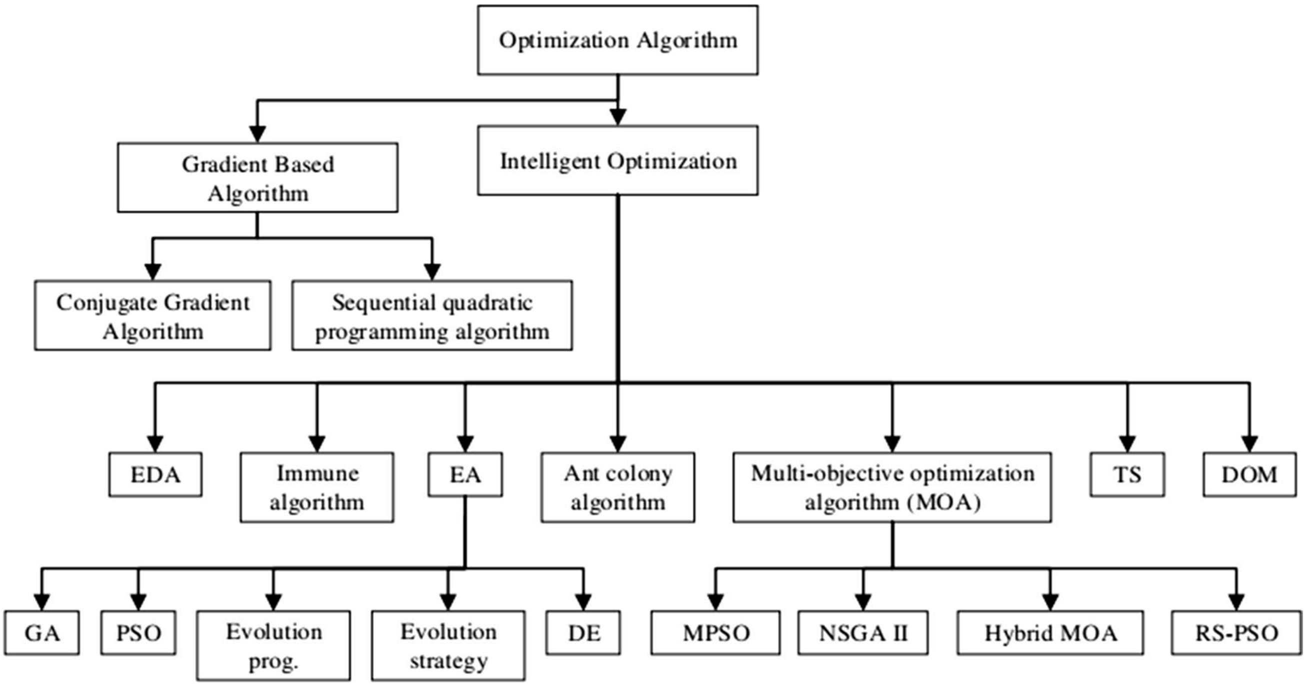


Fig. 1 Optimization algorithm for electric machine designs [3]

immune algorithm, evolutionary algorithm (EA), evolution programming, evolution strategy, and ant colony algorithm. However, based on preliminary studies on academic and industry fields, most of them prefer to use the following optimization algorithms; conjugate gradient algorithm (CGA), sequential quadratic programming (SQP) algorithm, tabu search (TS), and deterministic optimization method (DOM), while genetic algorithm(GA), differential evolution (DE) algorithm, and particle swarm optimization (PSO) are three of five major subclasses of EA. For the widely used modified PSO (MPSO), nondominated sorting genetic algorithm (NSGA II), hybrid multi-objective algorithm (hybrid MOA), and response surface-PSO (RS-PSO), are the four optimizations under multi-objective algorithm (MOA) [2–4].

1.1 Gradient Based Algorithm (GBA)

Conjugate based algorithms (GBAs), such as CGA and their non-linear versions are simple in implementation [5]. The non-linear CGA is an optimization method that uses the gradient to discover the minimum of a non-linear function and has less memory requirements [6]. It has been successfully functional for the optimization of fuel consumption in industry appliances [7]. The conjugate gradient algorithm can also be employed to optimize motor performances, as estimated based on magnetic circuit model [8, 9].

Another type of GBA is sequential quadratic programming (SQP) algorithm. SQP algorithm is one of the most successful methods for the numerical solution of constrained nonlinear optimization problems. The SQP algorithm relies on a profound theoretical foundation and provides powerful algorithmic tools for the solution of large scale technologically relevant problems. For example, Bazzo et al. [10] used the SQP algorithm in optimization of PMSG design due to its ability to deal with large constraints number and requires only some iterative processes. In 2018, double-stator permanent magnet doubly salient (DS-PMDS) machine has been proposed. The main objective of this study is to design and optimize the DS-PMDS by using parametric sensitivity analysis (PSA) combined with the SQP algorithm. Table 1 shows the performances of the initial and the optimized DS-PMDSs. After optimization and adjustment, the average output torque increased by 15%, while torque ripple reduced by 42%. In addition, the average of core loss at 750 rpm has been reduced from 59.9 to 34.4 W [11].

However, the SQP is one of the more classical optimization algorithms that is generally not successful in solving such complex engineering optimization problem, and

Table 1 Performance of the initial and the optimized DS-PMDSs

Parameter	Unit	Initial design	Optimized design	Changed (%)
Torque ripple	%	58.6	33.5	Reduced—42.8
Torque	Nm	28.7	33.6	Increased—17.1
Efficiency	%	93.3	95.2	Increased—2.04

thus, global optimum solution is hard to be obtained [12]. Therefore, intelligent optimization algorithms, taking the concept of "population" and "evolution", proposed TS, GA, DE, PSO, MPSO, NSGA II, hybrid MOA, RS-PSO, and DOM for the optimization of electrical machines in the past several decades [13, 14].

1.2 Tabu Search (TS)

Tabu Search (TS) is a metaheuristic method designed for finding approximate solution for hard combinatorial optimization problems in designing an electric machine. The main advantage of this algorithm is that a solution can be obtained quickly compared to other techniques like simulated annealing (SA) and hybrid algorithm [15]. Ho et al. [13] proposed an improved TS (ITS) algorithm for the global optimizations of electromagnetic devices by improving previous TS algorithm. The ITS with an aspiration factor is based on the success of methods such as the systematic diversification, the memorization of previously visited subspaces, as well as the intensification process for neighborhood creations. As a result, the iteration number that has been taken for ITS is 1842, approximately 5 times lower than SA.

In addition, Yang et al. [16] has presented design optimizations of electromagnetic devices using sensitivity analysis and TS algorithm. The main objective of the research was to propose a new approach for design optimization of electromagnetic devices using TS algorithm coupled with sensitivity analysis. To validate the proposed method, comparison of the normalized fitness functions between TS without sensitivity factor and TS with sensitivity factor has been made as illustrated in Fig. 2 [16]. The accurate solution for the TS with sensitivity factor has been achieved when iteration number reached 30, while for TS without sensitivity, the solution has been achieved when iteration number reached 180.

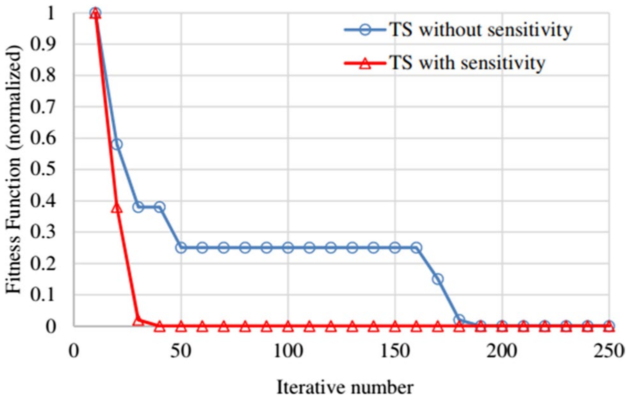


Fig. 2 Convergence condition and the normalized fitness function over 250 iterative times [106]

Moreover, a concept of general flux switching electric machines based on a unified theory and its application to develop a novel doubly fed dual stator motor (DFDSM) for electric vehicles (EVs) has been proposed in a previous research [17]. The design method using numerical finite element method (FEM) and improved TS algorithm have been used to find the optimal values of the geometry parameters of the proposed DFDSM, in which optimal torque performance and optimal power efficiency value can be obtained. In order to achieve optimal performances, all parameters of the motor are optimally designed, such as the diameters of outer and internal stator, size of slot and the dimension of permanent magnet, while the outer diameter and stack length of the motor are fixed by space available in EV. The performances of the initial and the optimized design are demonstrated in Table 2. From the results, the torque of 113 Nm has been obtained from the optimized design, increased by 9.71% from the initial design. Torque density has increased by 9.73% from 8.53 to 9.36 Nm/cm^3. Meanwhile, the efficiency achieved at 92.4% marked an increment by 0.98% from 91.5% due to the decrease of loss from 748 to 664 W.

1.3 Genetic Algorithm (GA)

Genetic algorithm (GA) uses objective functions that need to be initially defined to obtain the optimum performance of each electric machine design. The objective function covers all geometric dimensions of the machine and large subset of the constraints need to be determined to ensure the feasibility of the machine. One of the main advantages of GA is that the solution is global minimum and it does not require the use of derivative functions that is difficult to obtain or may not exist [18, 19]. Additionally, GA that is combined with coarse mesh finite element method (FEM) can reduce the design time of electrical machines to achieve certain specifications. For example, automatic design of IPMSM with adoption of a coarse mesh of the FEM geometrical models have been proposed in previous studies [20, 21]. Since the target is the design of motors with large high-efficiency operation areas, the proposed combination of GA and coarse meshes has been proven to be a valuable technique to speed up optimization process by reducing the number of FEM

Table 2 Performances comparison of the initial and the optimized DFDSMs

Parameter	Unit	Initial design	Optimized design	Changed (%)
Torque density	Nm/cm^3	8.53	9.36	Reduced—9.73
Torque	Nm	103	113	Increased—9.71
Total loss	W	748	664	Reduced—11.30
Efficiency	%	91.5	92.4	Increased—0.98

meshes. Figure 3 shows the general block diagram of GA in design optimization of three-phase IM, and explanation of implementation can be found in a previous research [22].

Recently, GA has been applied in design optimization of a three-phase IM with external rotor [23]. The main objective of this research is to produce a three-phase IM with external rotor in compliances with the IE3 category of the IEC 60034-30 standard for industrial fans. The optimization process has been conducted using a population-based search algorithm characterized as theoretically simple, easy to implement and computationally efficient. In order to achieve the optimal performances, two different objective functions were determined, based on efficiency and power factor. Besides, there are five constraints that have been set, namely breakdown torque, lock rotor torque, rotor torque, filling factor and slip. The numerical analysis of the initial and optimized designs of the IM were implemented through JMAG Designer 13.1. Performance comparison between the initial and the optimized designs is illustrated in Table 3. The torque of 2.11 Nm is obtained from the optimized design, 26.2% lower than the initial design. However, the efficiency of the optimized design has increased by 13.5% from 72.87 to 82.73%, while power factor of 86.38 achieved from the optimized design has increased by 38.5%.

Table 3 Performance of the initial and the optimized IMs with external rotor

Parameter	Unit	Initial design	Optimized design	Changed (%)
Torque	Nm	2.86	2.11	Decreased—26.2
Efficiency	%	72.87	82.73	Increased—13.5
Power factor	–	62.31	86.38	Increased—38.5

Besides, in view of renewable energy and environmental protection for long-term continuous operation and high-load rate motors, developing the electric motor becomes an important way to control the pollutants emission, which has been adopted by various countries [24]. Li et al. [25] proposed a multi-physical field collaborative optimization method of the premium IM based on the GA to reduce the cost by improving the utilization of the materials. Initially, the cost and efficiency are taken as bi-objective; the magnetic circuit optimization based on GA is established to get the initial electromagnetic scheme. At this point, the parameters of the premium IM are automatically transferred to a 2D transient electromagnetic field calculation model in order to determine the performances of the premium motor. The optimization method is composed of four parts; first is to determine the stator and rotor topologies of the premium, second is to optimize the initial electromagnetic scheme by the magnetic circuit method based on GA. The third one is to determine the electromagnetic performances of the PIM by considering the nonlinear saturation of the magnetic core and the skin effect of the rotor bars, and the last part is to get the thermal distribution. Performance comparison between the initial and the optimized designs is illustrated in Table 4. From the optimization of 50 HP PIM, the copper weight has been reduced by 13.3% from 25.33 to 21.97 kg, while iron weight of the optimized premium IM is reduced by 0.66%, from 203.3 to 201.9 kg. Meanwhile, the efficiency of 94.72% obtained from the optimized PIM had a 0.2% increase from the initial PIM.

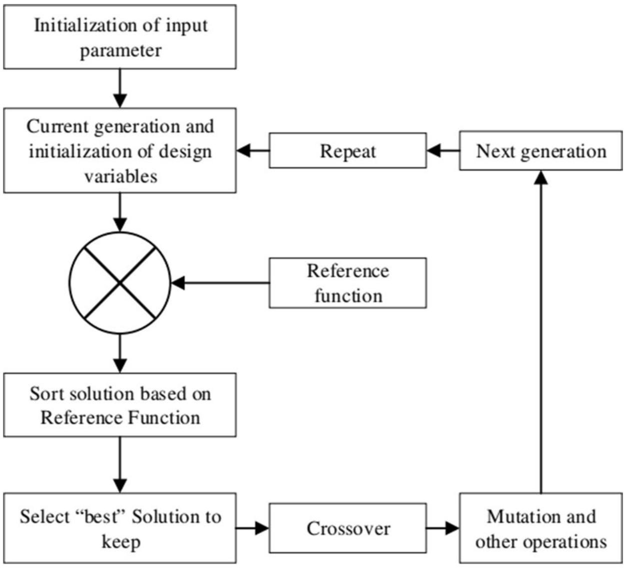


Fig. 3 The main steps in genetic algorithm [22]

Although GA has advantage of global minimum solution [18], the performances of GA is sensitive to the running coefficients, and makes computational efficiency of GA becomes less and not robust compared to other intelligent algorithms such as differential evolution (DE) and particle swarm evolution (PSO) [26]

1.4 Differential Evolution (DE)

Differential Evolution (DE) proposed by Storn and Price in [27] is a global optimization algorithm, related to evolutionary algorithm (EA). The DE algorithm involves maintaining

Table 4 Performance of the initial and the optimized PIMs

Parameter	Unit	Initial design	Optimized design	Changed (%)
Copper weight	kg	25.33	21.97	Decreased—13.3
Iron weight	kg	203.3	201.9	Decreased—0.66
Efficiency	%	94.53	94.72	Increased—0.20

a population of candidate solutions subjected to iterations of recombination, evaluation, and selection. The recombination approach involves the creation of new candidate solution components based on the weighted difference between two randomly selected population members added to a third population member. This perturbs population members that are relative to the spread of the broader population. In conjunction with the selection, the perturbation effect selforganises the sampling of the problem space, bounding it to known areas of interest [28, 29].

Chen et al. [30] have proposed an efficient electromagnetic structure optimization algorithm which combines DE algorithm and machine learning technologies called hybrid DE algorithm. The proposed algorithm is applied to optimize the resonant frequencies of an antenna with six variables. In order to verify the performances, the proposed algorithm is compared with GA optimization. As a result, to achieve lower resonances of − 26 dB and − 31 dB, the simulation numbers of 347 and 442, respectively have been obtained from the proposed algorithm, 82.3% and 77.99% lower than GA optimization.

Recently, various studies have been conducted to produce high-speed electric machines with high efficiency for electric vehicles (EVs) [31, 32]. Therefore, aspects such as temperature, and the loss of iron and copper at high speeds should be taken into account [33, 34]. In 2017, Fodorean et al. proposed a new design of high-speed permanent magnet synchronous machine (HS-PMSM) using hybrid DE algorithm for EV propulsion [35]. The main purpose of this study is to produce high-speed and high-power density of HS-PMSM by combining two objective functions. Then, the optimal solution is obtained thru a composite single-objective function. The first objective was to minimize the active part weight such as copper, iron, and magnetic weight, and the second objective was to maximize output power. Performance comparison between the initial and the optimized designs is illustrated in Table 5.

By employing the proposed hybrid DE algorithm, iron loss has been reduced by 29.6%, and copper loss has been increased by 26.8%. Besides, power density has increased by 40.1% from 2.42 to 3.39 kW/kg, while the efficiency of 96.07% from the optimized HS-PMSM is after an increment by 1.01%

1.5 Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is an optimization technique which provides an evolutionary based search. This algorithm is introduced by Dr. Russ Eberhart and Dr. James Kennedy [36]. PSO algorithm is useful for parameter optimization in continuous, multi-dimensional search spaces. Similar with GA, PSO takes the concept of "population" and "evolution" [37, 38]. This technique can optimize multiparameter, constraints, non-linear objective functions, and is superior in solving complex combinatorial optimization problems efficiently and effectively. It can generate high-quality solutions with minimum computation time and stable convergence characteristic compared to other evolutionary algorithms such as evolution strategy and evolution programming [39]. It has been successfully applied for real-world problems, particularly in electromagnetics and electric machine designs [40, 41].

Lee et al. [42] has introduced a new PSO algorithm with intelligent particle number control for optimal design of IPMSM. The main objective of this research is to propose an improved PSO algorithm to reduce the number of function calls by using the exploration and exploitation. Then, the proposed improved PSO is applied to minimize the total harmonic distortion (THD) of back-emf in IPMSM. The initial and optimized topologies of the IPMSM are illustrated in Fig. 4. By using the improved PSO, average function calls from ten simulations have been reduced by 26.7% from 2775 to 2038. The back-emf THD of the

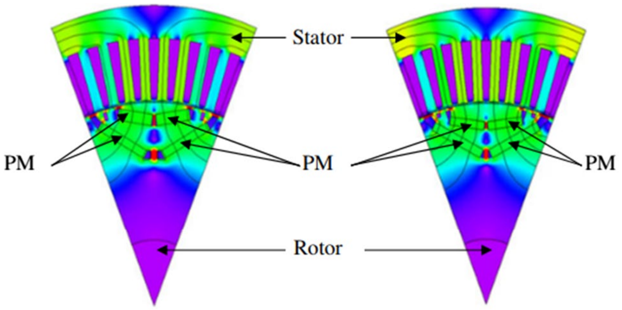


Fig. 4 Magnetic flux density of IPMSM, **a** initial design, and **b** optimized design [107]

Table 5 Performance of the initial and the optimized HS-PMSMs

Parameter	Unit	Initial design	Optimized design	Changed (%)
Iron loss	W	225.73	158.9	Reduced—29.6
Copper loss	W	273.98	374.04	Increased—26.8
Power	kW	20.00	20.005	Increased—0.025
Power density	kW/kg	2.42	3.39	Increased—40.1
Efficiency	%	95.96	96.07	Increased—1.01

optimized design is reduced from approximately 8.5–2.0%, with a back-emf amplitude of 31.9 Vrms.

Moreover, cogging torque is one of the critical aspect concerns when designing high performance PMSMs, since it results in torque ripples leading to increased mechanical vibration and noise, which are unwanted in high-accuracy electric machines. Examples of analytical approaches for calculation of air-gap fields and cogging torque have been proposed in [43–46].

Besides, many practical methods to reduce the cogging torque have been developed, such as adjusting parameters of rotor and stator [47–49] and slot-pole numbers combination as well as auxiliary teeth and slots [50, 51]. Xue et al. [52] proposed an analytical prediction and optimization of cogging torque for 24-slot/4-pole (24S-4P) and 12-slot/8-pole (12S-8P) surface-mounted PMSMs (SM-PMSMs) using PSO algorithm. The PSO algorithm adaptively updates the velocities and members' positions of the swarm, and was combined with T-1 PSO [53] and T-II PSO [54] algorithms. Performance comparison between the initial and the optimized designs are listed in Table 6. For the 24S-4P SM-PMSM design, the optimized design under radial magnetization has produced cogging torque of 0.08 Nm, 86.7% lower than the initial design, while for the 12S-8P SM-PMSM design, the cogging torque has reduced by 60.0% from 1.75 to 0.7 Nm. Besides, the THD for the optimized design of 24S-4P SM-PMSM is reduced by 27.4%, and for the optimized design of 12S-8P SM-PMSM, the THD is reduced by 35.7%. However, flux density of the 24S-4P SM-PMSM optimized design has reduced by 4.76% from 1.05 to 1.0 T, while for the 12S-8P SM-PMSM design, the cogging torque has reduced by 3.06% from 0.98 to 0.95 T.

Qu et al. [55] have proposed an optimal design of axial flux permanent magnet machine (AFPMSM) using analytical approach and PSO for industrial applications. The objective of the research is to maximize torque and to minimize the weight of the AFPMSM. Table 7 shows the results of the initial and the optimized designs. From the table, torque of the optimized design has increased by 11.7% from 2.22 to 2.48 Nm, while the weight of 25.8 kg of the optimized design, is after a decrease by 3.01%. Efficiency of 92.3% achieved from the optimized design, marked a slight decrease by 0.12% from the initial design. Besides, the peak cogging torque has reduced by 28.6% from 1.4 to 1.0 Nm.

Table 7 Performance of the initial and the optimized AFPMSMs

Parameter	Unit	Initial design	Optimized design	Changed (%)
Efficiency	%	92.4	92.3	Decreased—0.12
Torque	Nm	2.22	2.48	Increased—11.7
Total weight	kg	26.6	25.8	Decreased—3.01
Cogging torque	Nm	1.40	1.00	Decreased—28.6

Although the PSO has advantage in searching global optimum and is composed of simple equation, when particles approach global optimum, numerous particles do not converge at global optimum and continues to move around through the search plane, which results in unnecessary function calls. This behavior is revealed due to the location and velocity vectors of faraway particles which are considered when vectors of the whole particles are updated. To solve the issue, new location and velocity vectors need to be assigned for faraway particles [56].

1.6 Multi-Objective Algorithm (MOA)

Multi-objective optimization algorithm (MOA) has become popular in this field nowadays, as design optimization of electrical machines is multi-objective in nature, such as maximizing the torque and minimizing the torque ripple, and maximizing the power density and minimizing active material cost. To solve this kind of optimization problem, MOAs are required. They can provide a Pareto solution set with a single run. This solution set consists of many non-dominated optimal design solutions for the designer to select based on a specific application [57]. Some popular multi-objective optimization algorithms are response surface PSO (RS-PSO), response surface sequential non-linear programming (RS-SNP), Taguchi method (TM), hybrid multiobjective (HMO) algorithm, and non-dominated sorting GA II (NSGA II).

Response surface (RS) method is a statistical tool to build an empirical model of a response with respect to some input variables. In the interior PM (IPM) machine design, RS optimization example is described in [58]. Ma et al. [59] proposed a response surface PSO algorithm (RS-PSO) for

Table 6 Performance of the initial and the optimized SM-PMSMs

Parameter	24S-4P		Changed (%)	12S-8P		Changed (%)
	Initial	Optimized		Initial	Optimized	
Cogging torque (Nm)	0.60	0.08	86.7	1.75	0.70	60.0
THD (%)	39.8	28.9	27.4	36.1	23.2	35.7
Flux density (T)	1.05	1.00	4.76	0.98	0.95	3.06

Table 8 Performance comparison obtained from the RS-PSO algorithm

Parameter	Unit	Initial design	Optimized design	Changed (%)
Torque ripple	%	25.12	18.30	Decreased—27.1
Torque per weight	Nm/kg	1.251	1.370	Increased—9.51
Efficiency	%	89.50	88.70	Decreased—0.89

Table 9 Comparison of electromagnetic performances

Parameter	Unit	Initial design	Optimized design	Improvement (%)
Cogging torque	Nm	2.96	1.730	41.6
Torque	Nm	23.19	25.49	9.91
Torque ripple	%	28.04	27.09	3.39
Back-emf	V	142.3	155.8	9.49
THD	%	11.35	1.340	88.2

Table 10 Comparison of performance

Parameter	Unit	Initial design	Optimized design	Improvement (%)
Torque ripple	%	17.1	8.68	49.2
Torque density	Nm/mm^3	963.4	1075.38	11.6
Efficiency	%	92.84	93.31	0.5

design optimization of switched reluctance motors (SRMs) based on the combination of PSO approach and constructed response surface (RS) models. Objective functions of the purposed RSPSO is to maximize the torque per weight and efficiency, while minimizing torque ripples. The RS-PSO algorithm framework begins with the optimization model, design space reduction through sensitivity analyses, construction of the optimal third-order RS models, and PSO-based multi-objective optimization coupled with the constructed RS models to generate the Pareto optimal solution. Pareto optimal solutions are defined as a set of feasible solutions that cannot be improved without deteriorating other objectives [60]. Performances obtained from RS-PSO algorithm based on FEA is listed in Table 8. From the table, torque ripple is improved by 27.1% from 25.12 to 18.31%. Torque per weight of 1.37 Nm/kg from the optimized design has increased by 9.51%, while efficiency of 88.7% had a decrease by 0.89% from the initial design.

Zhu et al. [61] proposed MOA of an outer-rotor v-shaped permanent magnet flux switching motor (PMFSM) based on multi-level design method. A multi-level method refers to two different levels of optimization, in which a multi-objective method through RS and sequential non-linear programming (RS-SNP) algorithms is applied for optimization in level 1, while a single-objective method is used for optimization in level 2. The corresponding comparison results of the initial and optimized design are listed in Table 9. From the table, torque ripple is improved by 3.39% from 28.04 to 27.09%. Cogging torque of 1.73 Nm from the optimized design had a decrease by 1.6%, while average torque of 25.49 Nm has increased by 9.91% from the initial design. Besides, the amplitude of the back-emf is increased from 142.3 to 155.8 V, indicating an enhancement of 9.49%. Meanwhile, the THD of back emf is decreased by 88.2% from 11.35 to 1.34%.

Another MOA in design optimization of electric machines is performed using FEA coupled with the Taguchi method (TM). The TM was developed based on the concept of orthogonal array, which is proven to be effective in reducing the number of experiments in optimization process to find a better combination of the parameter values [62]. Hwang et al. [63] has presented an integrated approach using the TM and fuzzy logics for solving multi-objective optimization problems for permanent magnet synchronous motor (PMSM). There are three objective functions, namely the minimization of torque ripple, and the maximization of torque density and efficiency. In order to verify the robustness of the design, the signal-to-noise (S/N) ratio that determines the deviation between the desired and the experimental is used to transform the performance characteristics in the optimization process. Table 10 shows the comparison between the initial and the optimized designs. From the table, combination of the fuzzy-based Taguchi method has produced torque density of 1078.38 Nm/mm^3, 11.6% higher than the initial design. The efficiency is increased by 0.5% from 92.84 to 93.31%, while torque ripple of 8.68% shows reduction by 49.2%.

Additional example of design optimization by FEA combined with the TM has been proposed by Lin et al. [64]. The study proposed MOA optimization in the design of six-phase copper rotor IM mounted with a scroll compressor. The objectives of this study were to increase efficiency, power factor and output torque, and to minimize manufacturing cost. The proposed algorithm had combined the modified PSO [65] and the TM [66] with numerical design compatibility of IM based on FEA [67, 68]. As a result, the iron and winding weight values were reduced to 8.21 and 3.56 kg. The manufacturing cost and starting current had reduced to $243.16 and 18.72 A, respectively. Meanwhile, power factor, efficiency, and output torque

Table 11 Performances of the initial and the optimized PMSGs

Parameter	Unit	Initial design	Optimized design	Changed (%)
Cost	$	140,000	135,000	Decreased—3.57
Efficiency	%	90	96	Increased—6.70
Power	MW	3.66	3.13	Decreased—14.5
Torque per weight	Nm/kg	15.6	13.6	Decreased—12.8

Table 12 Performances of the initial and the optimized designs of HPIM

Parameter	Unit	Initial design	Optimized design	Changed (%)
Copper volume	cm^3	389.43	290.81	Increased 25.3
Aluminum volume	cm^3	369.23	251.32	Increased 31.93
Efficiency	%	89.21	89.5	Increased 0.33
Power	W	156.82	149.59	Decreased 4.61
Torque	Nm	29.94	30.01	Increased 0.23

increased to 0.95, 90.8%, and 11.6 Nm, respectively. In addition, input power had reduced to 2.35 kW.

The non-dominated sorting genetic algorithm (NSGA) is a multiple objective optimization algorithm and the NSGA II is developed from NSGA [69]. The objective of the NSGA II algorithm is to improve the adaptive fit of a population of candidate solutions to a Pareto front constrained by a set of objective functions [70]. The NSGA II has been applied in an analytical model of optimal PM synchronous generator (PMSG) designs in [71]. The PMSG is designed using an analytical model, and a mixed-integer constrained with multi-objective optimization problem has been solved by applying synchronous NIMBUS method [72], through IND-NIMBUS software. This method is also useful for designing and teaching purposes of electrical machines. The objective function of this study is maximizing efficiency, and minimizing losses and costs. Table 11 shows the comparison between the initial and the optimized designs. As a result, efficiency of the optimized PMSG increased by 6.7% from 90 to 96%, and the cost decreased from 1,700,000 € to 1,300,000 €. However, output power decreased by 14.5% from 3.13 to 3.66 MW. Torque per weight of 13.6 Nm/kg achieved from the optimized design, had a decrease of 12.8% from the initial design.

In 2017, multi-objective optimization of high-phase induction machines (HPIMs) using NSGA-II is proposed in [73]. There are two objective functions, namely efficiency, and volume of conductor material. The first objective is to maximize efficiency, while the second is to minimize volume of copper and aluminum used in the stator and rotor, respectively. Table 12 shows the result of a comparison between the initial and optimized of HPIM. Copper volume of 290.81 cm^3 is obtained from the optimized design, 25.3% lower than the initial design, while the volume of aluminum is reduced by 31.93% from 369.23 to 251.32 cm^3. Meanwhile, the efficiency and torque of 89.5% and 30.01 Nm, respectively have been obtained from the optimized design, increased by 0.33% and 0.23%, respectively from the initial design. However, the power produced from the optimized design has decreased by 4.61% from 156.82 to 149.59 W. Nevertheless, the NSGA II is one of the most widely used algorithms for solving multi-objective problems due to the advantage of multiple objective functions capability in a single optimization processes. However, the disadvantages, such as slow operational speed due to their long computing time and too many setting parameters need to be overcome.

Table 13 Characteristics of the initial and the optimized PMSMs

Parameter	Unit	Initial design	Optimized design	Improvement (%)
Torque	Nm	7.43	7.43	Unchanged
Efficiency	%	83.6	86.7	3.70
THD	%	5.40	4.70	12.9
Torque ripple	%	1.70	1.20	29.4
Total weight	kg	2.82	2.81	0.35

To overcome the drawback of NGSA II, the hybrid multi-objective (HMO) algorithm has been introduced in [74] for optimal design of PMSM. The HMO is a combination of artificial bee colony-strength pareto and evolutionary algorithm (ASMA), the Artificial Bee Colony (ABC) algorithm [75] and strength pareto evolutionary algorithm (SPEA) [76], along with modified differential evolution (DE) algorithm [77]. Table 13 shows the performances of the initial and the optimized design of PMSM. The back-emf THD, torque ripple, and weight of the optimized design are reduced by 12.9%, 29.4% and 0.35%, respectively. The efficiency of the optimized design is increased by 3.7% from 83.6 to 86.7%, while torque of 7.43 Nm remains unchanged. In addition, the authors claimed that ASMA is 60% faster than the NSGA II and SPEA methods in the process of optimization. However, due to a lot of optimization algorithms combination, ASMA has an issue regarding the time consuming in its computation part. Hence, this makes the ASMA a complex algorithms and are not practical in the design of complex electric machine structure.

1.7 Deterministic Optimization Method (DOM)

Nowadays, various studies on the electrical machines designed for various applications such as electric vehicles, downhole machines, and electric scooters have been done utilizing the deterministic optimization method (DOM) algorithms [78–81]. The DOM algorithm is performed by changing the design sensitivity parameters in one sequence directly, part by part, and repeated until the design achieves the highest performance of torque, power, and efficiency. Figure 5 illustrates the flow of DOM [82, 83].

Ahmad et al. proposed three-phase outer rotor hybrid excitation flux switching machine (OR-HEFSM) for electric vehicles (EVs) by using DOM in [84, 85]. The main objective of this research is to overcome the drawbacks of the initial design [86] that prevent the machine from achieving maximum performances. Initially, the proposed OR-HEFSM is designed using the commercial FEA package via JMAG Designer software, while DOM is used to obtain the optimal performances. Table 14 and Fig. 6 show the performance and structure, respectively of the initial and the optimized designs. From the table, the power is increased by 75.4% from 83.03 to 145.6 kW. The distance between FEC and armature coil slots allowed the magnetic flux to flow smoothly as indicated by dotted circle in Fig. 6, hence increasing torque production. The optimized design has produced torque of 335.1 Nm, 37.6% higher than the initial design.

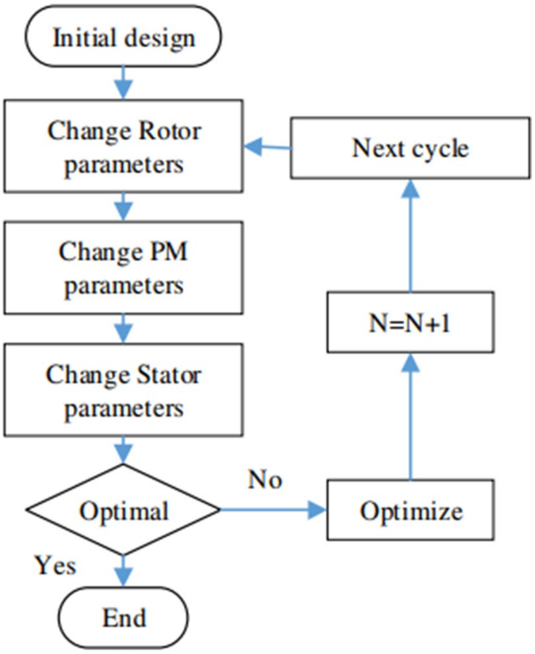


Fig. 5 General flow of deterministic optimization method [61]

Table 14 Performances of the initial and the optimized OR-HEFSM designs

Parameter	Unit	Initial design	Optimized design	Improvement (%)
Torque	Nm	243.5	335.1	37.6
Power	kW	83.03	145.6	75.4
Efficiency	%	Undisclosed	87.96	N/A

Mazlan et al. [87] proposed design optimization of single-phase OR-HEFSM for EVs utilizing DOM algorithm involving nine parameters. These nine parameters cover all parts of the motor design, three of which from the rotor, two from PM, and four from stator, while the air-gap between stator and rotor is kept constant. Performances of the initial and the optimized designs are listed in Table 15. From the table, cogging torque and weight of 0.44 Nm and 28.41 kg respectively, obtained from the optimized design, showed an increase of 51.7% and 18.8%. Besides, torque, power, and back-emf have improved by 19.7%, 1.94%, and 16.9%, respectively.

Sulaiman et al. [88] presented optimal design of single-phase 4 Slot-10Pole E-core HEFSM using parameter sensitivity. DOM algorithm is utilized on the initial design in an effort to enhance the performances of torque and power. The nine parameters sensitivity is illustrated in Fig. 7. The optimal performances of torque and power are achieved through 3 cycles of optimization and the results are illustrated in Table 16. From the table, the back-emf and cogging torque have reduced by 12.2% and 57.7%, respectively. Besides, torque and power of the optimized design have increased 14.8% and 66.8%, respectively, while efficiency of 86.4% is 26.1% higher than the initial design.

Furthermore, Khan in [89], has enhanced the performances of the initial threephase field excitation flux switching machine (FEFSM) design using deterministic optimization of nine parameters defined in rotor, field excitation coil (FEC) slot and armature slot areas. After design optimization, FEFSM has achieved the maximum torque of 25.9 Nm and optimum power of 4.97 kW which are approximately 2 times higher than the torque and power of the initial design. The average efficiency of the optimized design was 66 0.57% which is far better than the initial design.

The DOM algorithm was also used in the design optimization of three-phase 12Slot-8Pole (12S-8P) FEFSM with salient rotor for EVs [90]. The design and performances of the initial FEFSM has been conducted using FEA numerical

Fig. 6 Comparison of initial design and the optimized design [84]

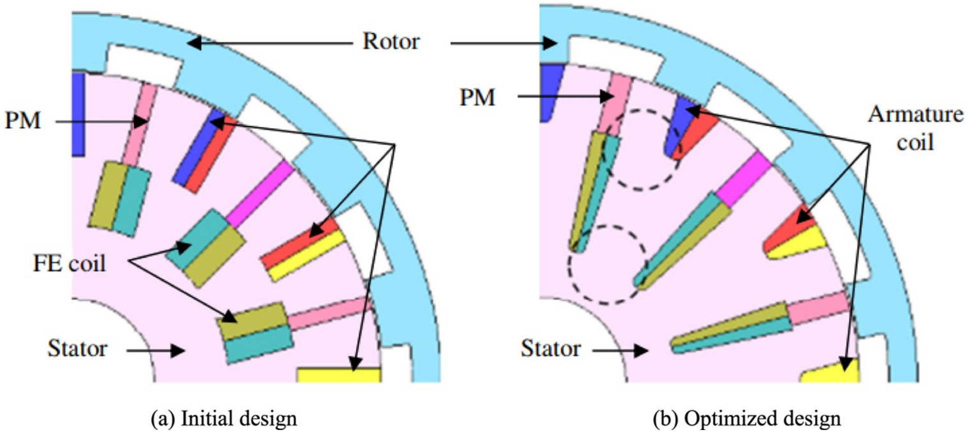


Table 15 Performances of the initial and the optimized single-phase ORHEFSM

Parameter	Unit	Initial design	Optimized design	Changed (%)
Back-emf	V	43.74	36.36	16.9
Cogging torque	Nm	0.290	0.440	51.7
Torque	Nm	107.5	138.2	19.7
Power	kW	17.02	41.18	1.94
Total weight	kg	27.87	28.41	18.8
Efficiency	%	Undisclosed	91.99	N/A

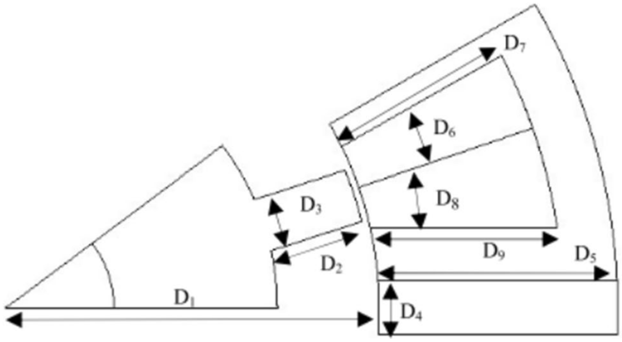


Fig. 7 Parameter sensitivity of single-phase E-core HEFSM [88]

Table 16 Performances of the initial and the optimized single-phase HEFSM

Parameter	Unit	Initial design	Optimized design	Changed (%)
Back-emf	V	49.0	43.0	12.2
Cogging torque	Nm	52.0	22.0	57.7
Torque	Nm	182.0	208.9	14.8
Power	kW	29.5	49.2	66.8
Efficiency	%	68.5	86.4	26.1

approach through JMAG designer. To achieve the target requirements, the authors have applied DOM by adjusting seven design parameters of the initial design while keeping the air gap constant. Table 17 shows the performances of the initial and optimized FEFSM designs. From the table, torque of 23.34 Nm is obtained from the optimized design, 206.7% higher than the initial design, while the motor power has increased by 111.6% from 2.49 to 5.27 kW. The back-emf produced from the optimized design is 5.8 times higher than the initial design, while cogging torque has reduced by 28.6% from 7 to 5 Nm.

DOM algorithms have also been combined with other methods to further improve motor performance. In 2016, the optimal design of 12 slots-14 poles FEFSMs for electric boat by using DOM and GA is presented in [91]. The optimization process is divided into two levels, with DOM algorithm in the first level, and GA in the second level. At the first level, seven parameters of the initial design have been optimized via DOM, while in the second level, single-objective optimization is conducted using GA. Performances of the initial and the optimized design are illustrated in Table 18. After two levels of optimizations, the torque has increased 5.7 times from 4.1 to 23.52 Nm, while the motor power of 8.57 kW had an increase by 71.4%. In addition, the optimized design recorded a reduction of cogging torque by 32.1% from 8.25 to 5.6 Nm.

Based on previous studies, many researchers have adopted DOM into design optimization of permanent magnet flux switching machine (PMFSM) [92–94]. Recently, Kumar et al. [95] have proposed three-phase outer rotor PMFSM (OR-PMFSM) for downhole applications. The objectives of this study are to maximize torque and power, and to minimize the weight of PM. Initial design is conducted using analytical sizing equations and simulated using FEA solver, while the design optimization of seven design free parameters is updated through DOM algorithm. The optimal performances of OR-PMFSM is obtained at the fifth cycle of optimization. The summarized performances of the initial

Table 17 Performances of the initial and the optimized 12S-8P FEFSM designs

Parameter	Unit	Initial design	Optimized design	Changed
Back-emf	V	4.95	28.5	5.8 times higher
Cogging torque	Nm	7.00	5.00	Reduce of 28.6%
Torque	Nm	7.61	23.34	Increase of 206.7%
Power	kW	2.49	5.27	Increase of 111.6%

Table 18 Comparison of the initial and the optimized 12S-14P FEFSM designs

Parameter	Unit	Initial design	Optimized design	Changed (%)
Cogging torque	Nm	8.250	5.600	32.12
Torque	Nm	4.100	23.52	473.7
Power	kW	5.000	8.570	71.40

Table 19 Performances of the initial and the optimized OR-PMFSM designs

Parameter	Unit	Initial design	Optimized design	Changed (%)
PM weight	kg	1.26	0.79	37.3
Cogging torque	Nm	3.30	1.80	45.5
Back-emf	V	875	375	57.1
Torque	Nm	16.4	33.6	104.9
Power	kW	4.10	4.50	9.76
Efficiency	%	92.1	94.7	2.80

and the optimized designs are outlined in Table 19. After the optimization, PM weight of 0.79 kg is obtained from the optimized design, with approximately 37.3% reduction from the initial design. Torque and power of 33.6 Nm and 4.5 kW respectively, obtained from the optimized design, had an increase by 104.9%, and 9.76%. In addition, cogging torque and back-emf of the optimized design have been reduced by 45.5% and 57.1%, respectively, while efficiency of 94.7% marked an increase by 2.8%.

Laili et al. [96] proposed single-phase 4Slot-8Pole PMFSM with salient rotor for electric bicycle applications. The objectives of this study are to increase torque of previous single-phase PMFSM [80] by using DOM algorithm. After optimization, torque has increased by 44.1% from 3.4 to 4.9 Nm, while the power and efficiency obtained from the optimized design are 195 W and 89.8%, respectively.

In this sub-topic, the previous optimization algorithms have been reviewed, each algorithm has their own advantages and disadvantages. Summary of achievements based on various optimization algorithms is listed in Table 20. From the table, GBA is the classic optimization algorithms that are generally successful in solving simple engineering optimization problems. It has produced high percentage in reduced ripple torque. However, GBA using the SQP method shows that it is difficult to achieve global optimum when optimization is performed on a complex design [12].

In addition, GA and DE show the highest percentage increase of power factor and torque density, while PSO records the highest percentage decrease of torque ripple compared to other algorithms. However, optimality of the solutions generated for single-objective optimization solved via EAs such as GA, PSO and DE is not guaranteed due to the definition of Pareto optimality, where the classification is achievable only if some of the objectives are to be improved and other objectives are permitted to impair [71, 97, 98]. TS is a stochastic method popularly used in electromagnetics and the main advantage of this algorithm is solution can be obtained quickly compared to simulated annealing algorithm. Nevertheless, the major drawback accompanying this kind of method is the slow convergence speed or excessive computational burden, and this has led to its lack of robustness [99].

Moreover, in the MOAs such as RS-PSO and NSGA II, they are found to have a high percentage increase for torque per weight and efficiency. Besides, the highest reduction percentage of THD has been generated from the RS-SNP algorithm, while for torque ripple, the highest percentage has been obtained from the TM algorithm. However, the efficiency produced by RS-PSO algorithm is decreased, and a lower percentage of efficiency is noted from TM and HMO algorithms, causing these three algorithms not to be preferred when optimization is performed on the initial designs that have low efficiency.

Furthermore, in terms of back-emf, cogging torque, torque, power, total weight and efficiency, of which many researchers have made as key elements to consider when designing an electric machine [100–105], the DOM algorithm has taken the highest yield in achieving the highest percentage of increment compared to the other algorithms. From the table, by utilizing DOM algorithm, performances of back-emf, cogging torque, and total weight torque can be decreased by 57.1%, 57.7%, and 18.8%, respectively, while torque, power, and efficiency can be increased by 104.9%, 75.4%, and 26.1%, respectively.

Table 20 Achievement obtained based on various optimization algorithms

Algorithm/parameter	Change (%)										
	GBA	TS	GA	DE	PSO	DOM	MOA				
							RS-PSO	RS-SNP	TM	NSGA II	HMO
Back-emf	–	–	–	–	–	57.1 (decr.)	–	9.49 (decr.)	–	–	–
Torque ripple	42.8 (decr.)	–	–	–	–	–	27.1 (decr.)	3.39 (decr.)	49.2 (decr.)	–	29.4 (decr.)
Cogging torque	–	–	–	–	86.7 (decr.)	57.7 (decr.)	–	41.6 (decr.)	–	–	–
Torque	17.1 (incr.)	9.71 (incr.)	26.2 (decr.)	–	11.7 (incr.)	104.9 (incr.)	–	9.91 (incr.)	–	0.23 (incr.)	–
Torque density	–	9.73 (decr.)	–	–	–	–	–	–	11.6 (incr.)	–	–
Torque per weight	–	–	–	–	–	–	9.51 (incr.)	–	–	12.8 (decr.)	–
Power	–	–	–	0.025 (incr.)	–	75.4 (incr.)	–	–	–	4.61 (decr.)	–
Power density	–	–	–	40.1 (incr.)	–	–	–	–	–	–	–
THD	–	–	–	–	27.4 (decr.)	–	–	88.2 (decr.)	–	–	12.9 (decr.)
Total weight	–	–	–	–	3.01 (decr.)	18.8 (decr.)	–	–	–	-	0.35 (decr.)
Efficiency	2.04 (incr.)	0.98 (incr.)	13.5 (incr.)	1.01 (incr.)	0.12 (decr.)	26.1 (incr.)	0.89 (decr.)	–	0.5 (incr.)	6.7 (incr.)	3.7 (incr.)
Total loss	–	11.3 (decr.)	–	–	–	–	–	–	–	–	–
Power factor	–	–	38.5 (incr.)	–	–	–	–	–	–	–	–
Copper weight	–	–	13.3 (decr.)	–	–	–	–	–	–	–	–
Iron weight	—	–	0.66 (decr.)	–	–	–	–	–	–	–	–
Iron loss	–	–	–	29.6 (decr.)	–	–	–	–	-	–	–
Copper loss	–	–	–	26.8 (incr.)	–	–	–	–	–	–	–
Flux density	–	–	–	–	4.76 (incr.)	–	–	–	–	–	–
Cost	–	–	–	–	–	–	–	–	–	3.57 (decr.)	–
Copper volume	–	–	–	–	–	–	–	–	–	25.3 (incr.)	–
Aluminum volume	–	–	–	–	–	–	–	–	–	31.93 (incr.)	–

In conclusion, not even one of the above aforementioned algorithms is capable to optimize all parameters when designing an electric machine. However, observations on literature reviews have shown that the DOM algorithm is the best in design optimization of electric machines to produce optimal performances.

2 Analysis of FEFSM, PMFSM and HEFSM Using DOM Technique

In this section, various designs comprised of field excitation (FE) PMFSM and HEFSM are optimized using DOM as shown in Figs. 8, 9 and 10. Figure 11 shows the plot

Fig. 8 Field Excitation FEFSM **a** initial and **b** optimized design

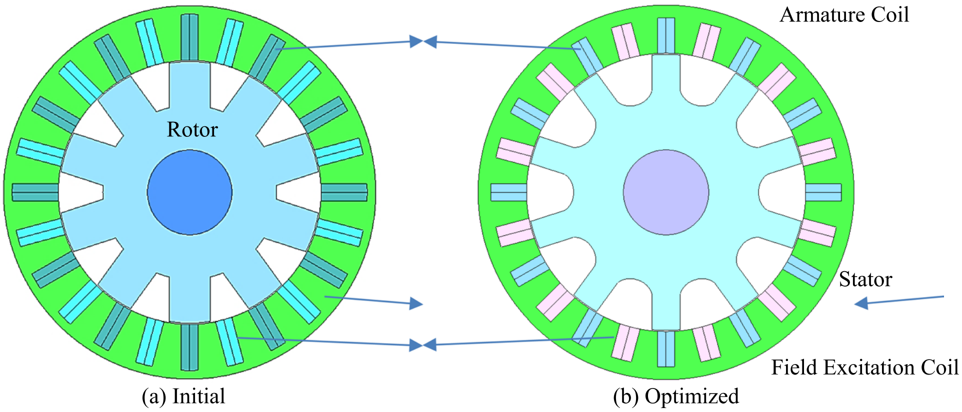


Fig. 9 Hybrid Field Excitation HEFSM **a** initial and **b** optimized design

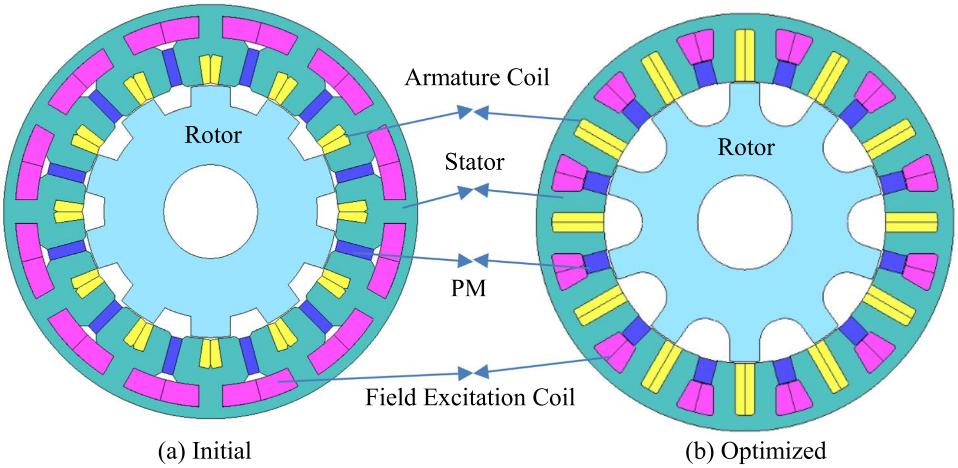
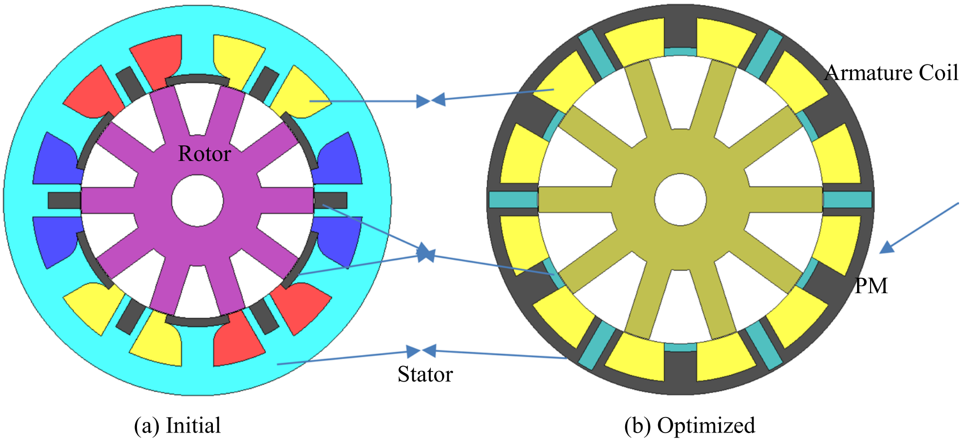


Fig. 10 Permanent Magent PMFSM **a** initial and b optimized design



of average torque values of the designs. From the plot, all the designs show a significant change in the torque from initial to optimized, in which initial torque values of FEFSM, PMFSM and HEFSM at 23.97 Nm, 26.34 Nm and 20.52 Nm, respectively, increased to 41.95 Nm, 47.43 Nm and 51.28 Nm, respectively, after implementing DOM.

3 Conclusion

This paper describes various optimization methods for electrical machines named, Gradient Based Algorithm (GBA), Tabu Search (TS), Genetic Algorithm (GA), Differential Evolution (DE), Particle Swarm Optimization (PSO) and Multi-objective Algorithm (MOA) methods

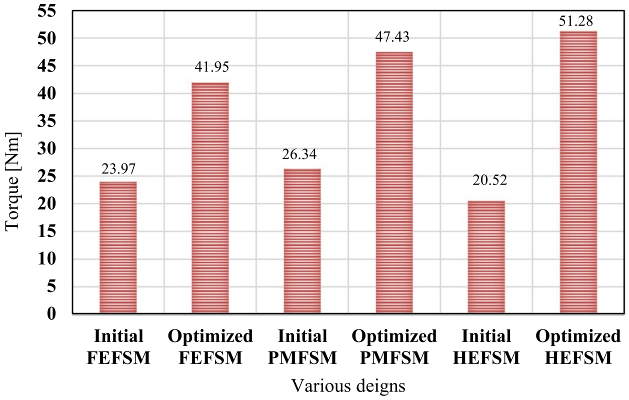


Fig. 11 Torque values of various designs

were discussed. From the review it is found that different optimization methods are suitable for different parameters. For example, torque ripple decreases in GBA by 42.8%, cogging torque reduction in PSO by 86.7%, increment of average torque in DOM by 104.9%, increase in power and efficiency by 75.4% and 26.1%, respectively in DOM compared to other optimization methods. As DOM had much impact on the comparison of the performance than others. Thus, it can be concluded that DOM can be considered an appropriate optimization method for the optimal performance of machines. It has also been verified using the DOM method from the analysis of FEFSM, HEFSM and AlCiRaF PMFSM. The result obtained after optimization of selected motors found that 60% torque increase in optimized HEFSM, the optimized design of FEFSMs has a torque increment of 42.86% and optimized AlCiRaF PMFSM torque increment is 44.46%.

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Mohd. Fairoz Bin Omar was born in Johor, Malaysia, on May 12, 1986. He received Diploma in Electric and Electronic Engineering from Politeknik Ibrahim Sultan in 2008. Since October 2008, he has been working under Asian Geos (M) Sdn. Bhd as Technician. He received his B.E Degree in Electronic Engineering and M.E Degree in Electrical Engineering from University Tun Hussein Onn Malaysia, in 2014 and 2016, respectively. Currently, he got his Ph.D. Degree at Department of Electrical Power Engineering, University Tun Hussein Onn Malaysia. His research interests include single-phase field excitation flux switching machines (FEFSMs) for lightweight applications.

Erwan Bin Sulaiman was born in Johor, Malaysia, on August 31, 1978. He received his B.E and M.E degrees in Electrical Engineering from University of Malaya in 2001 and University Tun Hussein Onn Malaysia (UTHM) in 2004. He got Doctor Degree in Electrical Engineeringfrom Nagoya Institute of Technology (NIT), Japan in 2012. Currently, he is serving as an associatate professor at Department of Electrical Power Engineering, University Tun Hussein Onn Malaysia. His research interests incorporate design optimizations of HEFSM, WFFSM, in particular, for HEV drive applications.

Irfan Ali Soomro is a researcher. He received bachelor's degree in Electrical Engineeing from Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh, Pakistan. Currently he is a full-time researcher at Universiti Tun Hussein Onn Malaysia (UTHM). Currently, he is pursuing his research in electrical power engineering at the same university consecutively. His research interest includes design of flux switching motor.

Md. Zarafi Bin Ahmad was born in Johor, Malaysia, on 11 July 1979. He received his BE degree in electrical engineering from University Technology Mara in 2003 and ME degree in electrical engineering from University Technology Malaysia in 2006. He has been a lecturer at University Tun Hussein Onn Malaysia since 2006. He got PhD student from University Tun Hussein Onn Malaysia. His research interests include electric machine design and drive control.

Roziah Aziz was born in Johor, Malaysia on May 26, 1982. She received her B.E and M.E Degrees in Electrical Engineering from Universiti Teknologi Malaysia in 2005 and UTHM in 2008. She received Doctor Degree in Electrical Engineering from Newcastle University, UK in 2020. Her research interests include design optimizations and temperature modelling of permanent magnet synchronous motor (PMSM) for EVs.