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A Review of Electrical Machine Optimization Methods with Emphasis on Computational Time

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## **Abstract:**

Electrical machine optimization process becomes increasingly demanding with higher-performance requirements for the electrical machine and its drive/control. This can significantly increase the computational requirement of the optimization process. This paper presents a review of the state-of-the-art in term of optimization of electrical machines. The review will cover modeling, analysis and optimization algorithms with emphasis on the computational efficiency. The paper will also focus on optimizing electrical machines for a wide constant power speed range which requires including multiple operating points (in some cases representative of a drive cycle)in the optimization process. Systematic approaches that focus on the reduction of computational time are discussed and compared. Future directions and potential research areas are also discussed.

# SECTION I. Introduction

An advanced and high-performance electrical machine design requires a well-suited optimization method with computational efficiency especially when a higher-accuracy FE-based solver is used. For several applications including traction and industrial applications, electrical machine design optimization process and analysis become increasingly demanding due to high performance requirements for example high speed, high torque/power density, high efficiency, and lower manufacturing cost. Also, in many cases, system-level optimization is required taking into consideration the power converter and its control. Taking the US Department of Energy (DPE)Freedom CAR DOE 2020 specifications as an example, the specifications require 14 000 rpm maximum speed, 30 kW continuous power, peak specific power density of at least 1.6 kW/kg, as well as maximum efficiency of 95%. Many researches have attempted to meet these specifications by developing high-performance motors using new materials and novel motor topologies [1], [2]. However, such demanding specifications make the electrical machine design optimization more complicated. Effectively, such optimization requires methods that can have multiple objectives, computationally-efficient, take saturation effects into consideration, and have the ability to evaluate multiple operating points to account for the wide constant power speed range (CPSR), as well as a system-level optimization.

This paper aims to present a comprehensive review of electrical machine design optimization methods with special focus on computational time, speed range, driving cycle, as well as search algorithms. Several optimization methods are covered and compared.

# SECTION II. Review of Computationally Efficient Optimization Design Methods

This section investigates electrical machine optimization approaches to reduce computational time.

## A. Modeling Techniques-Response Surface Method (RSM)

There are several modeling techniques that can significantly reduce computational time for electrical machines. These include analytical models [3]–[4][5], magnetic equivalent circuit models, intelligent models and response surface models. The response surface model (RSM)is one of the most popular methods that is applied to electrical machine design optimization. It has relatively high accuracy and is not as time-consuming as FE analysis (FEA).

A response surface method was proposed in [6] to optimize an electromagnetic device without using 2D and 3D FEA. In the RSM, an empirical model, which involves the relationship between responses and input variables, has to be created to replace FEA. The authors in [6] use a C-core actuator as a case study to use RSM to minimize the size of the actuator based on an established C-core model. The method was extended to an IPM machine in [7]–[8][9][10][11]. In [7], a second-order response surface model was used to develop an approximate model of PM flux linkage, d-axis inductance and q-axis inductance based on three input design variables. Using the empirical model developed, a wide CPSR is obtained by optimizing the three input variables. In [8] the RSM is used to optimize the shape and location of permanent magnets in an IPM machine in order to reduce vibration and torque ripple. In order to alleviate the problem caused by very time-intensive FE computation, authors in [9] developed a non-linear surrogate model using multi-layer perceptron (MLP)neural networks to act as a direct mapping between the design and the target parameters. The averaged simulation results indicate that the non-linear surrogate models can lead to a reduction of the total run-time of the optimization process by 46-72%.

Even though RSM is a computationally efficient approach, a nonlinear model has to be developed based on performance data collected and nonlinear algorithms. The optimization accuracy highly depends on the accuracy of the approximate models. Other authors in [10]–[11][12][13] also developed the relationship between input variables and response by means of the Kriging model and radial basis function (RBF).

## B. Magnetostatic Fe-Based Methods

Finite element analysis is the most powerful tool for linear and nonlinear analysis of electrical machines. However, the adoption of FEA in the multi-objective and large-scale design variables optimization process with the wide speed range of operation has generally been very challenging since FEA of a large number of designs can significantly increase computational time and require significant computational resources while running the optimization. In order to overcome this drawback, magnetostatic FE-based methods instead of time-stepping FEA have been widely used.

Field Reconstruction (FR)is one of these methods and has been used to optimize the stator current waveform to minimize torque ripple and radial force with a constraint of torque density [14].

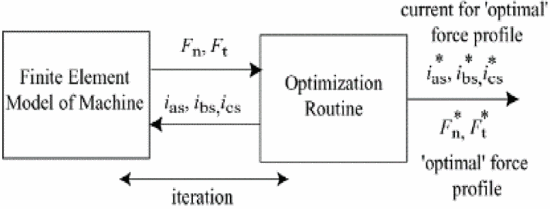
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Fig. 1 Optimization routine in which FEA is used for determining optimized stator excitation [14]

The entire force and torque profile at arbitrary rotor positions can be reconstructed using magnetic fields over a single stator tooth pitch using equation [(1)](https://ieeexplore.ieee.org/document/#deqn1). The excitation current that is obtained in the optimization routine as shown in Fig. 1 is obtained based on the cost function of minimum force ripple. Effectively, the flux density is the only value that needs to be evaluated using an FEA model.

(1)

where  is the slot pitch.  and  are the normal and tangential flux density components at  **slot**.  and  represent the flux density components generated by a current of  injected in the  slot at position .

However, the FR technique assumed that iron operates in a linear magnetic region and saturation effects were ignored. In addition, only torque performance has been investigated.

Computationally-efficient FEA (CE-FEA)was presented in [15]–[16][17], [21]–[22][23][24][25][26][27][28][29]. In the CE-FEA, both magnetic and electric circuit symmetries of the PM machine was exploited to reduce the number of magnetostatic FE solutions. The authors in [15] and [16] used only one magnetostatic FE solution for fundamental flux linkage and average torque computation. Three magnetostastic FE solutions are used for torque ripple, back emf and terminal voltage. With the CE-FEA method, a reduction of one to two orders of magnitude of computational time compared to time-stepping FEA was achieved. In [17], three design variables are used to optimize three performance parameters, namely, average torque, efficiency, and torque ripple. In the optimization process, the flux linkages and back emf in phase “A” have been constructed based on a limited number of magnetostastic FE solutions. They are calculated using the following equations:

(2)(3)

where  is the space angle in electrical measure;  is the rotor speed in electrical measure. Same quantities for phases  and  can be obtained using similar equations.

Stator core losses have been included in the CE-FEA method in [21] according to the following equations:

(4)(5)

where and  are hysteresis losses and eddy current losses, respectively; n is the harmonic order;  is the amplitude of the flux density for the  harmonic;  is the fundamental frequency.  and  is hysteresis losses coefficient and eddy current losses coefficient respectively, which can be expressed using a third-order polynomials, as validated in [18]–[19][20].

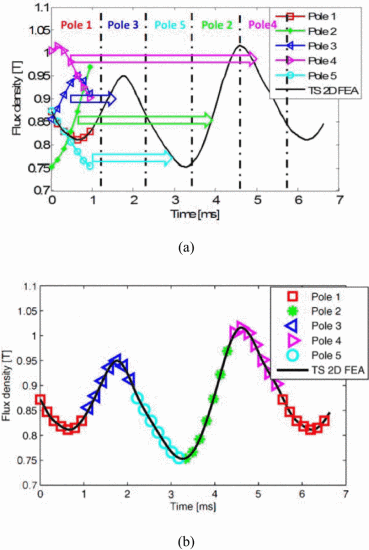
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Fig. 2 PM flux density waveform construction using CE-FEA [21]

The calculation of magnet losses is also included in the optimization process using the CE-FEA method in [18]. Authors used 7 magnetostatic solutions to produce the discrete points in each pole.

The PM flux density waveform corresponding to an entire cycle can be constructed based on each individual pole (1/6 cycle)using CE-FEA techniques, as illustrated in Fig. 2(a). Fig. 2(b) presents the comparison of calculated PM flux density using CE-CEFA vs. conventional time-stepping FEA. PM eddy-current losses can be calculated based on the simulated results.

A multi-objective design optimization using combined Design of Experiments (DOE)and Differential Evolution (DE)was presented in [22]. In this paper, CE-FEA method was used to evaluate the performance, namely torque ripple, material cost, and losses. The combined DOE and DE method using CE-FEA method were further improved and verified in [23]. The output torque was also constructed using a similar equation [(2)](https://ieeexplore.ieee.org/document/#deqn2-3) based on the magnetostastic FE method so that torque ripple can be investigated. A multi-objective design optimization method taking into account calculation of current angle corresponding to the maximum torque per ampere (MTPA)was presented in [15] using CE-FEA method. The optimal current angle γ*MTPAwas* calculated as follows:

(6)

A new optimization algorithm, Combined Multi-Objective optimization with Differential Evolution (CMODE)was developed in [25] to further reduce the computational time based on the CE-FEA method. The authors in [26] extended the method to include multiple operating points and used three different current densities to approximately account for naturally cooled, fan-cooled and liquid-cooled machines. The sensitivity analysis of these three classes was also investigated and it was concluded that the correlation between design variables and performance metrics can be significantly affected by the machine's electric loading. The method was further extended for optimization of IPM machines for efficient operation over an extended speed range [27].

## C. Parallel Processing Method

For FE-based simulation method, a computer cluster and software can be used in parallel to speed up the optimization process. In this case, the optimization process has to be designed to be compatible with parallel processing. In [30], a high-throughput computing (HTC)environment combined with the DE algorithm was used to evaluate designs by means of parallel processing capabilities of a large number of computers. An FEA also was used to maximize the electromagnetic performance at rated operating conditions: speed is 2800 rpm; output power is 30 kW; torque is 102.3 Nm. The total of 50 generations including 4250 designs are evaluated. Comparison of computational time concludes that the total time required for the optimization to converge in the HEC environment is 1.04 days, while the total time is 29.93 days in a single computer environment. Although the computational time has been significantly reduced, creating the HTC environment requires 10,000 cores computing systems, as well as a large number of FEA software licenses which might not be available in most cases. In [31] computers cluster and parallel computing method for reducing computational time were also discussed.

## D. Optimal Search Algorithms

Nowadays, with the increasing complexity of electric machine design, investigating all possible design combinations is challenging and might not be necessary. Therefore, the adoption of efficient search algorithms continues to gain attention by many researches. A novel method for handling the constraint inequality functions instead of the common method of Lampinen's approach has been presented in [32] in order to reduce the overall computational time. In [33], some simplified models that are used to create an approximate relationship between input design variables and output performance metrics (including objective functions and constraints)have been reviewed. A SPM motor was used to compare the response surface and differential evolution algorithms in term of computational effort. The results show that DE has advantages over RS when more designs variables are considered. In [34], a case study was presented to verify that a surrogate model combined with asynchronous and synchronous optimization algorithms are able to improve the search behavior of optimization procedure.

## E. Subspace Method

For optimization methods based on approximate models, modeling sampling resolution has high impact on computational time. In order to obtain an approximate model, some points have to be sampled by a sampling method. Effectively, the sampling method has to take into account the character of each model to ensure satisfactory modeling accuracy. Evaluation of some objective functions and constraints might need less sampling resolutions while for others might need more sampling to ensure accuracy. Based on this logic, a multi-objective sequential optimization method (SOM)has been presented in [35]. The Kriging modeling method (which is an approximate model to formulate the complex objective functions and constraints to reduce computational time. It is similar to the response surface model (RSM). The details of the model can be found in [11])was used to evaluate the objective functions using a couple of different subspace sets to reduce computational time. In [36], the method was upgraded to an improved SOM with orthogonal experimental design technique by which the sampling efficiency can be improved significantly (the number of sampling points can be significantly reduced)and therefore lead to reduce the computational cost of FEA

The same idea can be applied to FE-based optimization methods to reduce computational time [37]. For the FE-based method, the resolution of the FE model can significantly impact the computational efficiency and optimizational accuracy. Some electrical machines' characteristics which include high-frequency oscillation require high FE resolution while others might not. Therefore, a separate set divided by the frequency of waveform should be defined to evaluate the electric machine's performance in order to reduce computational time.

## F. Other Methods

In addition, the mesh resolution and geometric symmetry also can be exploited in the FE model to reduce the computational time without negatively impacting the optimization accuracy [21]. The tradeoff between accuracy and computational time should be also considered. For example, machine designers might reduce the number of magnetostastic FE solutions in order to save time if the frequency of the torque waveform is low or the torque ripple is relatively small.

## G. Comparison between Different Optimization Methods

Comparison of the aforementioned optimization methods is summarized in terms of computing system cost, time consumption and complexity in Table I. Even though the parallel processing method has advantages in the computational time and accuracy, which effectively depends on the computational capability of the computer system, the cost is the highest due to using an expensive powerful computer system and a large number of FEA software license. Inversely, a magnetostatic FE-based method can have high accuracy and low computing cost, as well as satisfactory computational time if the optimal algorithms and subspace methods are applied to the optimization procedure.

**Table I.**Comparison of different optimization methods

|  |  |  |  |
| --- | --- | --- | --- |
| Optimization Methods | Computing Cost | Computational time | Complexity |
| Modeling techniques response surface method | Low | Fast | High |
| Magnetostatic FE-based methods[15]-[17] | Low | Fast | High |
| Parallel processing methods [30][32] | High | Fast | Moderate |
| Optimal search algorithms[32][33] | Low | Speed up optimization procedure | Moderate |
| Subspace method[35] | Low | Speed up optimization procedure | Low |
| Other methods (Mesh resolution and geometric symmetry) | Low | Speed up optimization procedure | Low |

# SECTION III. Optimization of Electrical Machines to Achieve a Wide Speed Range

The IPM machine is well-suited for high-performance variable speed drives and extended CPSR which is required in traction application. Therefore, there is increasing interest in optimizing electrical machines that can achieve a wide CPSR. However, this requires more computational time since multiple operation points have to been considered. Therefore, some computationally-efficient optimization methods taking a wide speed range into account are discussed in this section.

In [38], optimization of the PM volume in an IPM machine was investigated for a wide speed range with fixed stator geometry. An FEA model was used to predict the torque-speed curve. Furthermore, the paper mainly focused on the effect of the variation of the PM remnant flux density on the efficiency at two fixed operating points. The same method based on an FEA model was also used for maximizing torque at the base speed and maximum speed to achieve a wide flux-weakening region [39]. A time-stepping adaptive FEA combining a Rosenbrock search algorithm was used in [40] to develop an optimization process that considers mechanical stress concentration in the rotor to maximize the torque and minimize core losses. Effectively, these papers only investigated the effect of variation of PM on the flux weakening capability, which provides a method for selecting an optimal PM topology and location (The stator geometry was fixed. The focus has been on optimizing PM location and volume to maximize torque). The run-time in these methods is fairly fast because only PM location and topology has been investigated. In addition, the phase voltage constraint was considered in [38] and [39] when torque versus speed characteristic was predicted. In [40], in order to simplify the analysis, the current angle is fixed to be 80 deg under flux-weakening operating condition even though the voltage constraint was considered. But performance evaluation in these papers does not include efficiency prediction.

In [41], an approximate Kriging modeling combined with a genetic algorithms (GA)was used to achieve the optimal design of a concentrated flux interior permanent magnet (CFIPM)motor (which is essentially a variant of IPM). Optimization objectives included maximizing the efficiency and torque at two fixed operating points, which are base speed and maximum speed. As shown in Fig. 3, only 5 variables related to PM geometry and location are optimized to target maximum efficiency and torque. In addition, efficiency, and d-q axis inductances were calculated using time-stepping FEA, which will inevitably increase computational time. In [41], an optimization process of synchronous reluctance (SyR)and IPM motors to achieve a wide CPSR (with minimum torque ripple objective)was investigated by means of FE-based multiobjective genetic algorithm (MOGA). The proposed design procedure was divided into three consecutive steps: global search MOGA (GS-MOGA)of a SyR machine, local search MOGA refinement (LS-MOGA)and off-line definition of the PM remanence Br. As shown in Fig. 4, local variables related to PM geometry and location are optimized.

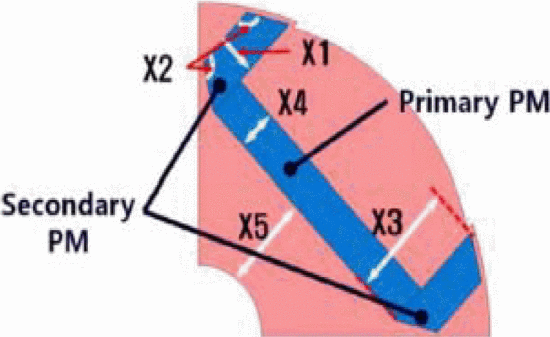
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Fig. 3 Selected optimization design variables [41]

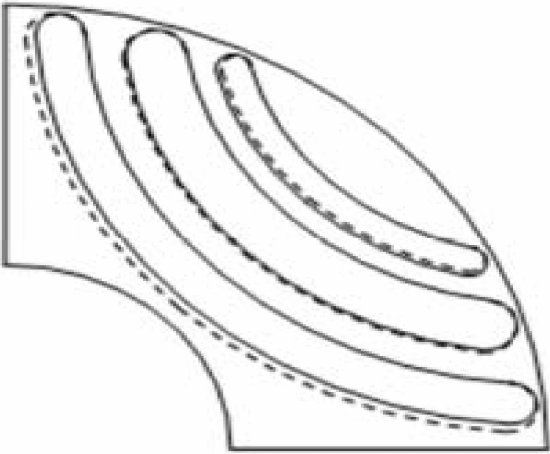
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Fig. 4 Optimal rotor geometry [42]

The total computational time for finding a good approximation of the optimal solution is around 10 hours for a three-layer SyR machine. However, only torque was evaluated in the three-step optimization procedure based on MOGA. The method was also extended for considering rotor losses for a wide CPSR [43]. Three optimization objective functions: average torque, torque ripple, and CPSR were targeted using computationally-efficient FE static solutions. The three-objective optimization procedure takes around 130 hours on a standard laptop computer. However, a simplified motor model without taking saturation effects into consideration was used in the evaluation of the three objective functions. In addition, voltage constraint has not been discussed.

Another method was presented in [44] for investigating the optimization of a saturated IPM synchronous motor for a wide CPSR. The method takes into account the saturation effect by means of nonlinear motor modeling and maximum voltage limit at the flux-weakening region. As illustrated in Fig. 5, only three design variables that highly influence the flux profiles are selected as input variables. Response-surface method combined with a genetic algorithm (GA)was used to optimize the CPSR of the motor while delivering peak-torque as a constraint.

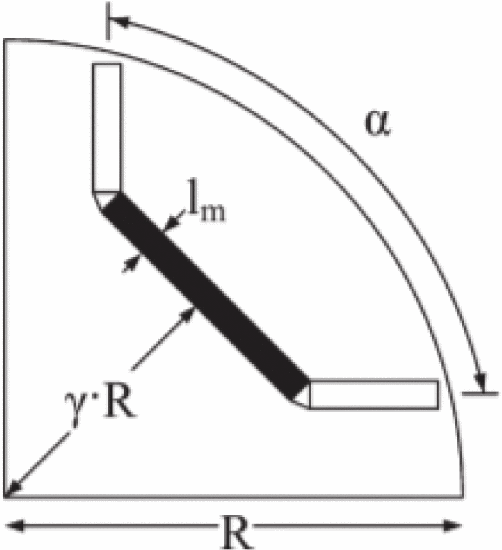
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Fig. 5 Optimal rotor geometry [44]

All of the above methods only investigated PM geometry and location to maximize torque at fixed operating point. Although these methods can save computational time by different modeling methods and small-scale optimization variables these optimization methods cannot ensure other critical performance metrics such as efficiency and cost

A multi-objective optimization procedure to maximize the output power in the flux weakening region based on large-scale variables (including both stator and rotor variables)was presented in [45]. In order to maximize the output power, the authors achieved the best possible match between the machine characteristic and the machine rated current. The maximum back emf at the top speed has not been allowed to exceed the rated terminal voltage. Another design optimization procedure considering large-scale variables was presented in [46]. Authors proposed an FE-based optimization procedure for a wide CPSR operation with the aim of maximizing the output power by maximizing the torque at the base and maximum speed. The maximum torque per ampere trajectory with voltage constraint has been included in the optimization procedure. Both optimization methods did not address the cost of computational power needed. In addition, efficiency has not been investigated in these optimization procedures.

In order to achieve wide CPSR, authors in [47] proposed a CE-FEA method to minimize the absolute difference between the machine rated current and characteristic current. In order to investigate efficiency in the optimization procedure, stator core losses and copper losses have been included. The optimization procedure was extended for maximizing efficiency over the entire operating range by a new design optimization algorithm [27]. The proposed CE-FEA method in these two papers includes efficiency calculation and aims to maximize the efficiency and minimize the cost of PMs. In addition, a large-scale design variables including stator and rotor have been considered in the CE-FEA method.

**Table II**Summary of design optimization for wide cpsr

|  |  |
| --- | --- |
| Category | Features |
| Local variables optimization [38]-[44] | • Significant reduction in computational time (only 10 hours for a three layers SyR machine) [42]  • Less complexity [44]  • Does not include machine cost and efficiency |
| A large-scale variables optimization [45]-[47] | Investigate the effect of different variables on motor performance in a comprehensive way  • Include efficiency calculation [27],[47]  • Save computational time if using magnetostatic FE-based method [47] |

Table II illustrates the summary of recent computationally-efficient design optimization methods that cover/target wide CPSR. They are divided into two categories: local variables optimization and large-scale variables optimization.

# SECTION IV. Driving Cycle and System Level Optimization

Up to date, design optimization of electric machines is often performed at one operating point, usually the rated operating point. However, the actual motor operation depends on the driving cycle of the operation, especially in traction applications. A driving cycle is a series of operating points representing the speed/torque of a vehicle versus time, accounting for several vehicle modes of operation, e.g., idling, acceleration, cruising, as well as deceleration. Typical driving cycles are usually described by hundreds of operating points, for example, the Urban Dynamometer Driving Schedule (UDDS), US06 Supplemental Federal Test Procedure (US06/SFTP), the New European Drive Cycle (NEDC). For each of the operating point in a specific driving cycle, the performance of the candidate design should be analyzed. Hence, a significant amount of computational time is required.

In order to reduce the computational time for a wide CPSR and driving cycle, the method of “energy center of gravity” has been proposed in [48] by selecting a limited number of representative operating points at which the energy is concentrated (the machine spends a significant amount of time at these operating points). In this method, the motor speed range was conveniently superimposed on a grid of uniformly rectangular areas. For each of these rectangular areas, a representative operating point (speed, torque)was evaluated in terms of the geometrical center of gravity. Each representative speed-torque operating point is related to a weighted coefficient. The areas with a higher weighted coefficient correspond to the operating regions with higher clustering of working points. Furthermore, the driving cycle optimization procedure was extended in [49] and applied to ferrite PM-assisted synchronous reluctance (PMASR)motor for traction application. Although the driving cycle optimization has been performed considering the MTPA and the maximum torque per volt (MTPV)trajectories in some papers, the current angle was fixed and calculated based on the initial geometry. Effectively, the current angle has to vary based on the different operating points and the region of operation. Additionally, torque ripple has not been investigated.

On the other hand, electric machines and their corresponding drives are the two key components for any device which needs an electrical drive system. In previous work, only the performance of the electrical machine was taken into consideration in the optimization process. However, it is much more important to achieve the optimal performance for the entire system rather than only the optimal performance of any of the components (motor or drive). Moreover, the optimal performance of the whole system cannot be ensured by assembling the individually optimized machine and optimized drive. Hence, system-level optimization should be considered.

In [50], the electrical machine, as well as its corresponding control system, were investigated and optimized simultaneously. The motor-drive system includes a PM transverse flux machine and a field-oriented control (FOC)scheme. In addition to four parameters of the machine (number of turns, the axial width of PM, etc.), two parameters of the drive including proportional and integral factors in FOC are set as variables in the optimization process. In [41], a multilevel design optimization method is proposed for a motor-drive system including a flux-switching PM machine and a field-oriented control system, based on a sequential subspace optimization method. In this work, cogging torque, torque ripple, and average torque are set as three objectives. In [52], a deterministic approach for system-level design optimization methods for electrical drive systems was proposed. The deductive system-level design and optimization framework for drive systems is shown in Fig. 6. By contrast, a robust approach for system-level design optimization of the electrical drive system was presented in [53]. In this work, the unavoidable uncertainties in the manufacturing processes were taken into account in the optimization to improve the product's reliability and quality in mass production.

The system-level design optimization methods are relatively straightforward to implement. However, the computational cost is usually very high since the optimization problems of the motor-drive systems are generally nonlinear and multidimensional. Therefore, more efforts are still needed to reduce the computational time/cost to be suitable for system-level optimization.

# SECTION V. Potential Future Research and Conclusion

This paper provide an overview of optimization methods that can be used for designing electrical machines/drives with a special focus on computational time/efficiency. Given the multiple objectives and multiple constraints typically required in the optimization process of electrical machines/drives, a CE-FEA method can be a promising option when combined with suitable search algorithms and subspace methods. FEA-based methods can provide a systematical and accurate analysis for the multiple optimization objectives and constraints, as well as taking saturation effects into account. **It** is noteworthy that the trade-off between accuracy and computational has to be carefully considered based on the different optimization objectives and constraints. Future research areas can include optimizing electrical machines that include various advanced materials as well as more advanced system level optimization.

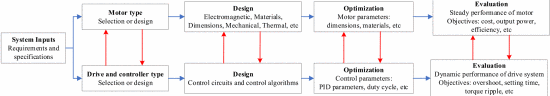
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Fig. 6. System-level design optimization framework for drive systems.

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