Optimization of Electromechanical Energy Converters with a Solid Rotor Output Parameters in ANSYS RMxprt

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Abstract
The paper is devoted to finding the set value of the torque of an electromechanical energy converter with a solid rotor by solving an optimization problem in the Optimetrics module of the ANSYS Maxwell software. A feature of the material described in the paper is the simultaneous optimization solution using the Sequential Nonlinear Programming (Gradient) algorithm and the solution of the field problem using the finite element method to determine the torque at each step of the iteration. The paper describes in detail the setting of the research tasks, the basic model of the electromechanical energy converter with a solid rotor in ANSYS Maxwell 2D, the settings of the Optimetrics module, the task of the objective function and varied parameters, the convergence task with respect to the magnitude of the rotation torque, and the derivation and analysis of the results obtained during the optimization. The techniques described in this paper can be applied to any other type of electric machines.

INTRODUCTION

The main problem in the design of electromechanical energy converters is to create such conditions that electric machines are sufficiently productive and reliable in operation, consume a small amount of energy, perform specified operations with given accuracy and high efficiency [1, 2]. All the listed properties of machines can be achieved only by choosing their rational and optimal design parameters.

Numerical methods based on the finite element method allow obtaining the most detailed and accurate picture. These methods make it possible to perform calculations of a steady-state or transient process in a three-dimensional problem statement and to determine parameters in any part of the motor [3–7].

In general, most optimization methods are programmable on modern electrical machine calculation software packages such as COMSOL Multiphysics, JMAG-Designer, and ANSYS Maxwell. COMSOL Multiphysics is quite a powerful tool that can be used to analyze both separate and interconnected physical processes [8]. The development environment allows to go through all stages from the construction of a geometric model, the assignment of material properties and the description of the physics of the task to the solution and visualization of modeling results.

It is also worth highlighting the program for modeling, development and design of electrical devices JMAG Designer [9]. JMAG was originally released as a design support tool for devices such as motors, drives, circuit components, and antennas. The software package uses simulation technology to accurately analyze a wide range of physical phenomena, including complex geometry, various material properties, heat and structure at the center of electromagnetic fields. Another advantage of JMAG Designer is that it can be used to investigate not only problems related to electromagnetic compatibility, but also vibrational phenomena related to magnetostriction.

COMSOL Multiphysics and JMAG Designer have parametric and nested optimization but require a different approach to modeling.

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Among the existing optimization programs, the most convenient and easiest to use for the calculation and optimization of electromechanical energy converters is the ANSYS Maxwell program [10–14]. The program offers four modules and six optimization algorithms. Among them, such modules as Parametric (parameterization) and Optimization (optimization) are most often used in engineering practice. In the use of optimization algorithms, special advantages cannot be singled out, because each algorithm is determined by its own advantages and disadvantages, while there are no radical differences between them [15–22].

The paper shows the capabilities of the ANSYS Maxwell software in the field of optimization of electromechanical energy converters, which are based on finite element methods that allow calculations with high accuracy. All this makes it possible to optimally use the time of engineering work, and an engineer equipped with modern design and optimization technologies has the opportunity to spend more time not on calculations, but on the search for creative and innovative ideas for further improvement of the design of electromechanical energy converters.

IMITATION MODEL

The task of optimizing the parameters of electromechanical energy converters is one of the main stages of calculation before starting the manufacture of experimental samples [23–29]. ANSYS Maxwell has a specialized Optimetrics module that allows to perform optimization calculations based on one or more optimality criteria using a number of algorithms, including genetic ones. The advantage of using ANSYS Maxwell is that the optimization is not performed using mathematical models with concentrated parameters, but directly on the basis of field calculations using the finite element method, which significantly brings the result closer to real prototypes.

This paper provides detailed step-by-step instructions for setting up the Optimetrics module to obtain the given torque value of a multifunctional electromagnetic energy converter (EMC) [30]. According to the principle of its operation, the MFEC is an induction machine with a solid rotor, and its structural features are an internal stator and an external hollow solid rotor [31].

The MFEC model with mesh plot in Maxwell 2D is shown in Fig. 1. In the MFEC model on Fig. 1 additional geometry is created in the form of concentric arcs, making it possible to construct distribution graphs of electromagnetic quantities along them.

Before starting the optimization, it is necessary to set several parameters in the form of variables, to use them later in the Optimetrics module. Local variables of the project are listed in Table 1. But this is not enough to perform optimization - the created local variables must be marked as available for the Optimetrics module.

**Table 1. Project local variables**

<table>
<thead>
<tr>
<th>Name</th>
<th>Variable</th>
<th>Value</th>
<th>Unit</th>
<th>Evaluated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil total excitation current</td>
<td>Im</td>
<td>4616</td>
<td>A</td>
<td>4616</td>
</tr>
<tr>
<td>Stator air gap diameter</td>
<td>Dstat</td>
<td>370</td>
<td>mm</td>
<td>370</td>
</tr>
<tr>
<td>Air gap</td>
<td>air_gap</td>
<td>2</td>
<td>mm</td>
<td>2</td>
</tr>
<tr>
<td>Rotor height (wall thickness)</td>
<td>rot_height</td>
<td>10</td>
<td>mm</td>
<td>10</td>
</tr>
<tr>
<td>Rotor inner radius</td>
<td>Rrot_in</td>
<td>0.5 * Dstat + air_gap</td>
<td>mm</td>
<td>187</td>
</tr>
<tr>
<td>Rotor outer radius</td>
<td>Rrot_out</td>
<td>Rrot_in + rot_height</td>
<td>mm</td>
<td>197</td>
</tr>
</tbody>
</table>

**Figure 1.** MFEC model in ANSYS Maxwell 2D
In the project properties, on the "Optimization/Design of Experiments" tab, it is need to select the checkbox near the name of the required variables and, if necessary, set their minimum and maximum values (Fig. 2). In this project, the full current Im, rotor thickness rot_height and air gap height air_gap are selected as optimization parameters.

The next step is to select the target parameters to be optimized. In this project, this is the rotor moving torque value.

After the task in the project tree in the Torque "Parameters" category (Fig. 3) was formed, it must be entered separately in the cache of the solver settings (Fig. 4). To gain access to the Torque variable in the Optimetrics module, it is needed to additionally select "Use this expression for convergence" in the Convergence column of the Expression Cache tab and, if necessary, apply the deviation percentage (Fig. 5). Next, it is needed to analyze the project so that the Torque variable from Expression Force is added to the optimization settings.

With the current initial parameter data (Table 1), the obtained torque value in performed analysis is 2212.6 Nm (Fig. 6). Optimization is designed to select such parameters, that will allow obtaining a torque value of 2300 Nm.
Figure 4. Analysis setup modification in Expression Cache tab

Figure 5. Adding Torque variable to Expression Cache
In the settings of the Optimetrics module, it is needed to select the variables that will be used in the optimization calculations (Fig. 7).

On the Goals tab, among several algorithms (Fig. 8), Sequential Nonlinear Programming (Gradient) will be used in this work.

After selecting the optimization algorithm, in its settings, by clicking the "Output variables" button, the following auxiliary variables are created:

- **target**: 2300 (Fig. 9) – parameters will be selected for this torque value in Nm;
- **cost1**: \((\text{target} - \text{ExprCache(Torque)})^2\) (Fig. 10) – square error of torque value deviation.

Now it is time to add the newly created parameter cost1 for optimization (Fig. 11).

Finally, 100 iterations of the optimization algorithm and the minimum in the selection condition were selected for the parameter of the target function cost1 (Fig. 12). Minimizing the cost parameter will lead to finding the values of the variables at which the torque becomes as close as possible to the given value.
Figure 9. Creating target variable (torque value)

Figure 10. Creating cost variable

Figure 11. Adding cost variable to optimization list
The results of the performed optimization are shown in Fig. 13, 14. On Fig. 13 optimization results are sorted by increasing cost value. On Fig. 14 plot is showing dependence of cost value from the evaluation (iteration number). As can be seen from the optimization results (Fig. 13, 14), the specified torque value of 2300 Nm is obtained with the following parameters (evaluation No. 15):

- full current 5091.6 A;
- rotor thickness 20 mm;
- height of the air gap 3 mm.

The obtained optimal parameters were applied to the MFEC project in Maxwel 2D and a field calculation was carried out using the finite element method. In Fig. 15 shown a window of torque calculation results with the parameters found during the optimization. As can be seen from the obtained results, the target torque value 2300 Nm was achieved.

In Fig. 16 shown a picture of magnetic flux density distribution, Fig. 17 - distribution of the vector magnetic potential. In Fig. 18, 19 shown the distribution of magnetic flux density along the arcs of the auxiliary geometry.
Figure 14. Optimization results in a graph view

Figure 15. Obtained torque value after optimization

Figure 16. Magnetic flux density at optimized parameters
Figure 17. Vector magnetic potential distribution

Figure 18. Magnetic flux density distribution: arc in the air gap (red) and arc at the rotor middle line (blue)

Figure 19. Magnetic flux density distribution on arcs above rotor: “Arc Level 1” is close to rotor and “Arc Level 4” is at the furthest distance from the rotor.
CONCLUSIONS

This paper shows the practical use of the Optimetrics module in ANSYS Maxwell, in which the objective function was minimized depending on three variable parameters. According to the optimization results, the full current of the stator winding, the height of the air gap, and the thickness of the rotor, at which the torque acquires the specified value of 2300 Nm with a minimum deviation, were determined.

The approach described in the paper can be applied to traditional electric machines, and its feature, in comparison with mathematical optimization algorithms, is the finding of parameters compatible with the simultaneous determination of magnetic field components through field calculations using the finite element method.

Further research will be related to solving the inverse problem – determining the main geometry sizes and winding data of the MFEC according to the optimal values obtained during the optimization.

DISCLOSURE STATEMENT

No potential conflict of interests was reported by the author(s).

REFERENCES


Оптимізація вихідних параметрів електромеханічних перетворювачів енергії з масивним ротором в Ansys RMxprt

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Анотація. Стаття присвячена знаходженню заданого значення обертового моменту електромеханічного перетворювача енергії з масивним ротором шляхом вирішення оптимізаційної задачі в модулі Optimetrics програми ANSYS Maxwell. Особливістю матеріалу, описаного в статті, є сумісне вирішення оптимізації з використанням алгоритму Sequential Nonlinear Programming (Gradient) та одночасним вирішенням польової задачі методом Maxwell 2D, налаштування модулю Optimetrics, завдання цільової функції та варіювання параметрів, завдання конвергенції щодо величини моменту обертання та виведення і аналіз отриманих в ході оптимізації результатів. Прийоми, які описані у цій статті, можуть бути застосовани до будь-яких інших типів електричних машин.

Ключові слова: електромеханічний перетворювач енергії, твердий ротор, Ansys, Maxwell, Optimetrics, оптимізація, функція витрат.
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