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This study presents a stepwise optimal design strategy (SODS) which effectively utilizes the magnetic equivalent circuit (MEC), the finite element method (FEM), and an optimization algorithm for the design of an interior permanent magnet synchronous motor for fuel cell electric vehicles (FCEV). The proposed strategy respectively uses the MEC, the FEM, and the optimization algorithm by dividing the entire design into the initial, detailed, and the optimal design stage. The proposed design strategy can be widely used as a design technique of electric machines since it can not only reduce computational cost but also accurately consider the diverse design cases.

Index Terms— Fuel cell electric vehicle, interior permanent magnet synchronous motor, magnetic equivalent circuit, optimal design

I. INTRODUCTION

As an important part of the movement to the eco-friendly automobile in the industry, fuel cell electric vehicles (FCEV) powered by hydrogen are emerging as the next generation of automobiles in the near future [1]. The traction motor of the FCEV requires not only the wide operating range and but also compactness due to the limited mounting space, so that the high efficiency and high-torque-density characteristics are essential. Interior permanent magnet synchronous motor (IPMSM) is the most suitable type for FCEV traction application in those respects since they have excellent field weakening characteristic and can utilize reluctance torque as well as the magnet torque [2].

In the design of IPMSM, a finite element method (FEM), which can analyze complex structures and nonlinear characteristics, is commonly used because the quite accurate electromagnetic field analysis which is the basis for accurate estimation of motor performances is guaranteed. However, since the design of the IPMSM requires a considerable amount of analysis, it is time-consuming for the designer to utilize the FEM in the whole design procedure, which takes several minutes to tens of minutes for an analysis [3].

Meanwhile, a magnetic equivalent circuit (MEC) is an analytical method that can rapidly analyze the electrical machines. Although the MEC has the advantage on the short computation time, it also has difficulty to utilize the whole design procedure due to the somehow lower accuracy compared to the FEM [4].

To address this problem, this study presents a stepwise optimal design strategy (SODS) which performs the design process step by step. At first, in the initial design stage, the MEC is used to quickly derive the average torque, the back-electromotive force (back-EMF), and the total harmonic distortion (THD) according to the design variables of the motor. In second, the difficult characteristics to calculate by the MEC such as cogging torque, torque ripple, demagnetization, and stress derived using FEM at the detailed design stage. Finally, optimization algorithm is used to derive optimal design with design variables and objective performances. The proposed

II. PROPOSED STEPWISE OPTIMAL DESIGN STRATEGY

This study proposes the SODS which can conduct a motor design more efficiently by sequentially utilizing the MEC, the FEM, and an optimization algorithm. Fig. 1 shows the procedure of the proposed SODS which consists of initial design stage using the MEC, detailed design stage using FEM, and the optimal design stage using an optimization algorithm.

The proposed design strategy was applied to the design of an IPMSM for FCEV. As shown in Fig. 2, the target IPMSM has multi-segmented and multi-layered (MSML) type rotor with 8 poles and 36 slots and the dimensions of the stator outer and the axial length are 240 mm and 230 mm, respectively. The rated torque of the motor is 300 Nm at 3600 r/min, and the rated current is 360 A_rms. The details of each design stage are as follows.

A. Initial design using the MEC

In the initial stage of the motor design, it is very important to examine the effects of various design variables various viewpoints. Therefore, it is very effective to utilize the MEC

Fig. 1. Process composition of the proposed stepwise optimal design.
which can rapidly grasp the motor performances even though the accuracy of the results is somewhat lower.

For example, the analysis time taken to extract the average torque per each current phase angle of an analysis model can be significantly reduced from a few hours to a few seconds. We utilized the MEC which consists of the no-load analysis, the q-axis analysis, and the d-axis analysis stages and can consider the saturation effect by an iterative calculation routine with actual material B-H data. The illustration in Fig. 3 shows the q-axis analysis model of the IPMSM which includes the magnetomotive force (MMF), several airgap reluctances, and the iron core reluctances. More details of the MEC which we utilized will be included in the full paper.

B. Detailed design using the FEM

In the detailed design stage, highly accurate design using the FEM is conducted. The FEM is very useful and popular for the analysis of IPMSM since it can accurately analyze the complex structures with the nonlinear characteristics considering the magnetic saturation in the iron core. Hence, the accurate analysis result can be derived based on the initial design derived by the MEC. Furthermore, it is possible to derive the results such as the cogging torque, the torque ripple, the iron loss, the demagnetization, and the stress characteristics which are difficult to be considered by the MEC in the initial design.

III. DESIGN RESULTS

Table I shows the design results of the IPMSM for FCEV designed by applying the SODS described above. Through the initial design using the MEC, the design with high back-EMF, high torque, and low THD characteristics was derived. In the detailed design stage, more detailed designs and various motor performances were derived through FEM analyses. Finally, in the optimal design stage, the minimization of the torque ripple by optimization of the shape parameters was performed while satisfying the requirements.

C. Optimal design using the immune algorithm

Finally, we perform an optimal design which satisfies various requirements in the optimal design stage. In the design of the electric machine, optimization algorithms are widely used to find the optimal design solution. In this study, optimal design is performed using an immune algorithm (IA) which is one of the nondeterministic optimization algorithms with fast convergence and high diversity.

The IA is used to optimize the problem based on the concepts of the affinity and the expectation, which are motivated from an immune system of human body to produce an antibody against an antigen. In this study, an optimal design for minimizing the torque ripple of the base IPMSM model obtained from the previous detailed design stage. The detailed optimization parameters and descriptions of design variables will be described in the full paper.

IV. CONCLUSION

This paper contributes to the SODS with efficient optimal design process of the MSML type IPMSM. In particular, not only rapid design but also accurate design results based on the MEC, the FEM and the optimization can be derived. Hence, the proposed SODS can be widely used for the various IPMSM design with various design parameters and cases.

REFERENCES


