

Efficient Analysis of Efficiency Map for Externally Excited Synchronous Motors Using Equivalent Magnetic Circuit-Based Deep Transfer Learning

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Externally excited synchronous motors (EESMs) have high degree-of-freedom in controlling the current vector for armature winding, field current, and rotational speed, so that EESMs can be operated in wide torque and speed range. In general, 2-D finite element analysis (FEA) is used for analysis of efficiency map for EESMs because of its high accuracy. Therefore, a lot of 2-D FEA should be performed repeatedly according to the current vector, field current, and rotational speed to calculate the flux linkage and iron loss of the EESMs. This leads to increased costs in designing high-efficiency EESMs, so the development of an analysis technique for efficient efficiency map is necessary. This paper proposes an equivalent magnetic circuit (EMC) based deep transfer learning for efficient analysis of efficiency map for EESMs. EMC allows us to calculate flux-linkage and iron loss of EESMs rapidly, but correction method should be accompanied because of its relatively low accuracy compared to 2-D FEA. The proposed method incorporates a large amount of EMC-based flux-linkage and iron loss, and a small amount of 2-D FEA-based flux-linkage and iron loss so that the efficiency map for EESM can be predicted accurately with reduced computation cost. The proposed method is applied to analysis of the efficiency map, and its validity is verified through simulation and experimental results.

Index Terms—current vector control, deep transfer learning, efficiency map, equivalent magnetic circuit, externally excited synchronous motors.

I. INTRODUCTION

EXTERNALLY EXCITED SYNCHRONOUS MOTORS (EESMs) are generally used for traction motor in electric vehicles (EVs) because EESMs can be widely operated in high and low speed regions [1]. Unlike permanent magnet machines, EESMs have additional degree-of-freedom in controlling the field current for achieving wide operating range with high torque density. This is also advantageous in that it can rule out failure due to demagnetization of permanent magnets during operation of EESMs.

As the field winding of EESMs is excited using brush and slip ring, field-weakening control can be directly performed using field current controller. Thus, EESMs have four degree-of-freedom in control which are the current vector of armature winding, field current, and rotational speed [2]. Therefore, analysis of efficiency map for EESMs requires high computation cost because the optimal combination of current vector and field current is different for each torque and rotational speed.

The efficiency of EESM is determined by how the current vector is controlled, so that it is important to use propose current vector control strategies for high efficiency drive of EESMs. The most permanent magnet machines use maximum torque per ampere (MTPA) for managing the temperature of armature winding, but this strategy increases the field current to reduce the armature current in EESMs. Then, it raises concerns about temperature rise in the field winding due to the heat dissipation structure of the field winding. Therefore, maximum efficiency control is widely used in EESMs for high efficiency drive [3].

In designing a traction motor, it is essential to satisfy the peak

torque and maximum output power, and it is also very important to maximize the efficiency of the main operating points. Therefore, the analysis of efficiency map for EESMs is important in machine design. The efficiency of EESMs is affected by the copper loss and iron loss, so that 2-D finite element analysis (FEA) is generally used for accurate calculation of iron loss. However, efficiency mapping for EESMs using 2-D FEA requires high computation cost, thus it is not efficient for the design of EESMs.

In this paper, a deep transfer learning (DTL) method based on an equivalent magnetic circuit (EMC) is proposed for the efficient analysis of efficiency maps in EESMs. The proposed method utilizes a large amount of low-fidelity performance of EESM calculated using EMC and a small amount of high-fidelity performance of EESM calculated using 2-D FEA [4]. Although the results of EMC are inaccurate compared to the 2-D FEA, these results are suitable for modeling trends similar to those calculated with 2-D FEA. Then, the gap between the EMC and 2-D FEA is corrected by using the high-fidelity dataset. Finally, the accurate efficiency map of EESM can be derived using the proposed method with low computation cost.

II. ANALYSIS OF EFFICIENCY MAP FOR EESMS

Since the specifications of EESM are aimed for EV traction, field-weakening control is necessary for high-speed operation. Fig. 1 shows the flowchart of conventional efficiency mapping process for EESM. The d , q -axis flux-linkage map according to current vector and field current are required for calculating electromagnetic torque and d , q -axis voltage, then the optimal current vector can be achieved using these characteristics. Iron loss map according to rotational speed as well as current vector and field current is also necessary to calculate efficiency for

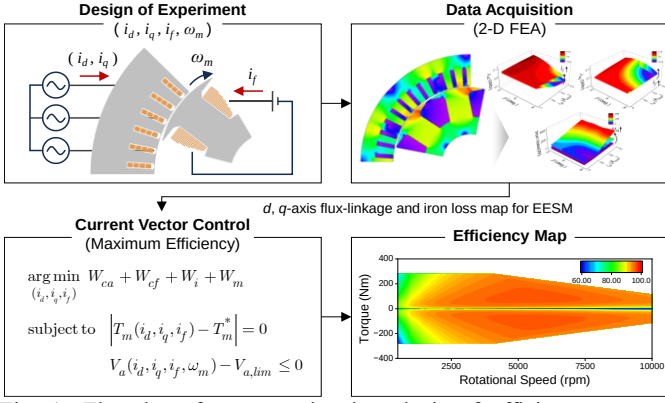


Fig. 1. Flowchart for conventional analysis of efficiency map of EESMs.

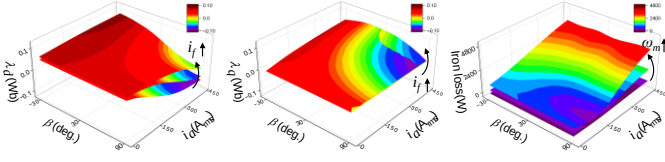


Fig. 2. Electromagnetic characteristics map for EESM: (a) d -axis flux-linkage, (b) q -axis flux-linkage, and (c) iron loss.

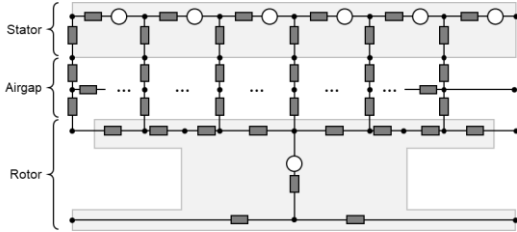


Fig. 3. Equivalent magnetic circuit for rapidly analysis of characteristics for EESM.

each torque and rotational speed. These maps can be obtained accurately using 2-D FEA, and the resolutions for those maps should be set high to avoid errors during the interpolation process as listed in Table II. Then, the characteristics for EESM are shown in Fig. 2(a)-(c). It can be seen that 10,000 2-D FEA are required to map the characteristics of the EESM because it has four control degrees-of-freedom.

III. EFFICIENT ANALYSIS OF EFFICIENCY MAP FOR EESMS USING EMC-BASED DTL

A. Equivalent Magnetic Circuit

EMC is an effective analytical method that can rapidly calculate the magnetic flux density of airgap, stator and rotor core by assuming the flux path of the EESM as shown in Fig. 3. EMC approximates the results of 2-D FEA because it can take into account the magnetic saturation but has lower accuracy in high-load regions compared to 2-D FEA because it does not consider every magnetic flux path in EESM. However, it has an advantage in computation cost compared to 2-D FEA because EMC considers only limited magnetic reluctances in airgap, stator and rotor core. Therefore, EMC is suitable for constructing a large amount of dataset with low-fidelity and low computation cost. On the other hand, 2-D FEA is suitable for building a small amount of dataset with high-fidelity and high computation cost.

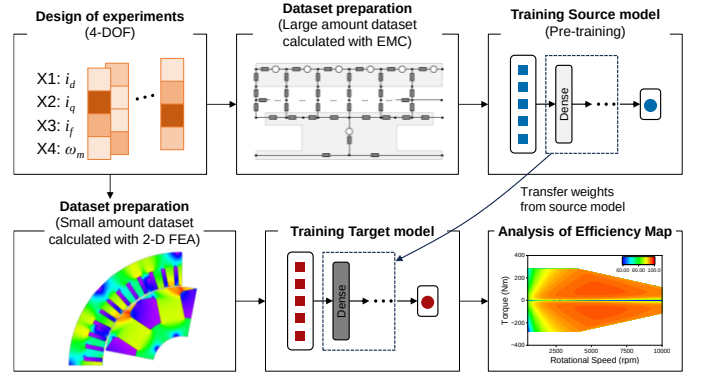


Fig. 4. Process of EMC-based DTL for efficient analysis of efficiency map for EESM.

B. EMC-Based Deep Transfer Learning

Since DTL is constructed using a large amount of low-fidelity dataset and a small amount of high-fidelity dataset, it is suitable for calculating the efficiency map of EESM using dataset constructed with EMC and 2-D FEA. Fig. 4 shows the flowchart of EMC-based DTL for efficient analysis of efficiency map for EESM. After constructing the low-fidelity and high-fidelity dataset using EMC and 2-D FEA, source deep neural networks (DNNs) for predicting d , q -axis flux-linkage and iron loss are trained with EMC-based low-fidelity dataset. Then, weights and bias for target DNNs are set using the trained weight and bias of source DNNs, and additionally trained using 2-D FEA-based high-fidelity dataset. Finally, maximum efficiency control is conducted for calculating the efficiency of EESM according to torque and rotational speed.

IV. CONCLUSION

This paper proposes an equivalent magnetic circuit-based deep transfer learning for efficient analysis of efficiency map for EESM. Since the EESMs have four degrees-of-freedom in control which are current vector, field current, and rotational speed, high computation cost is required for analysis of efficiency map. Therefore, low-fidelity with low computation cost dataset for predicting d , q -axis flux-linkage and iron loss is calculated with EMC, and high-fidelity with high computation cost small amount of dataset is constructed using 2-D FEA. Then, the efficiency map for EESM can be calculated with high accuracy using only a very small amount of 2-D FEA data. In the full paper, the validation for the proposed method will be verified through simulations and experiments.

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