

Improved Frozen Permeability Method Considering Load Condition Flux Path for Dual Stator Permanent Magnet Synchronous Motor

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The dual stator permanent magnet synchronous motor is suitable for air mobility applications, where safety must be ensured, due to its structural and electrical advantages in facilitating redundancy. To achieve such safety, accurate motor performance prediction is essential, which requires precise mathematical modeling and accurate parameter estimation. Although finite element analysis (FEA) is highly accurate, it involves high computational cost. Instead, frozen permeability method has been widely used. However, conventional frozen permeability method for dual stator modeling is somewhat inaccurate. The primary issue arises from treating permanent magnets as air for phase flux linkage calculation, failing to replicate the mid-section of the flux path in dual stator permanent magnet synchronous motor, which leads to errors in calculating the phase flux linkage. In this paper, an improved frozen permeability method is proposed to more accurately describe the flux path under load conditions. The proposed method retains the permanent magnets during phase flux linkage calculation. Additionally, it includes an extra calculation process to separate the field flux linkage, enabling a more accurate parameter estimation compared to conventional methods. Finally, to validate the proposed method, the torque estimated using both the conventional and proposed methods is compared against the torque obtained from the FEA.

Index Terms—Dual stator, frozen permeability method, magnetic flux path, parameter estimation.

I. INTRODUCTION

DUAL stator permanent magnet synchronous motor (PMSM) is suitable for air mobility applications where safety must be ensured, as its two separated stators and the independent drive of two inverters provide structural and electrical redundancy [1]. Compared to other mobility applications, air mobility requires a high level of safety, which makes accurate performance prediction essential.

Finite element analysis (FEA) is primarily used for accurate motor performance predictions; however, it involves heavy computational cost in terms of both time and resources. Parameter-based models, utilizing lookup tables created through pre-simulated FEA, can reduce this computational cost by lowering data volume [2]. The parameters that constitute the lookup table are inductance and flux linkage, and the frozen permeability method (FPM) is primarily used for their accurate estimation. The conventional FPM treats the permanent magnet (PM) as air to calculate the phase flux linkage; however, this approach is inaccurate as it fails to properly represent the flux path under load conditions in a dual stator PMSM, leading to inaccurate parameter estimation that causes errors in torque prediction, control performance.

In this paper, an improved frozen permeability method (FPM) is proposed to address the limitations of the conventional approach by more accurately representing the flux path under load conditions in a dual stator PMSM. In the proposed method, the PM is retained as a magnetic source in the phase flux linkage calculation, and the flux linkage caused by the PM is separated from the total flux linkage. This enables more accurate parameter estimation compared to the conventional method, which is validated through a comparison between the torque calculated using the derived parameters and the FEA torque.

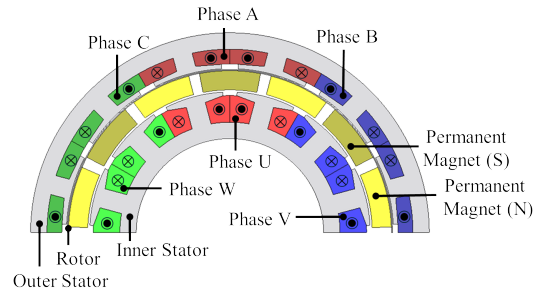


Fig. 1. Structure of dual stator PMSM.

II. DUAL STATOR PMSM

Fig. 1 shows the structure of a dual stator PMSM. It consists of two stators, inner and outer, separated by a rotor rotating between them. The inner and outer stators each generate independent three-phase rotating magnetic fields through separately controlled inverters. This configuration includes two air gaps, with the PM positioned between them. The PM is centrally located along the flux path of the motor, which crosses the two stators. Consequently, if the flux path under load conditions in the PM and air gaps are not properly replicated during parameter estimation, it affects the prediction of the flux linkage. This is particularly critical for the mutual flux between the armature sets that crosses the air gap.

III. FROZEN PERMEABILITY METHOD

A. Conventional Method

The conventional method reflects saturation under load conditions by fixing the permeability of each element at the operating point through load analysis. Subsequently, magnetic sources, including the armature winding and the permanent magnet, are individually applied, and the phase flux linkage is calculated to estimate the inductance [3]. However, when applied to a dual stator PMSM, the conventional method has

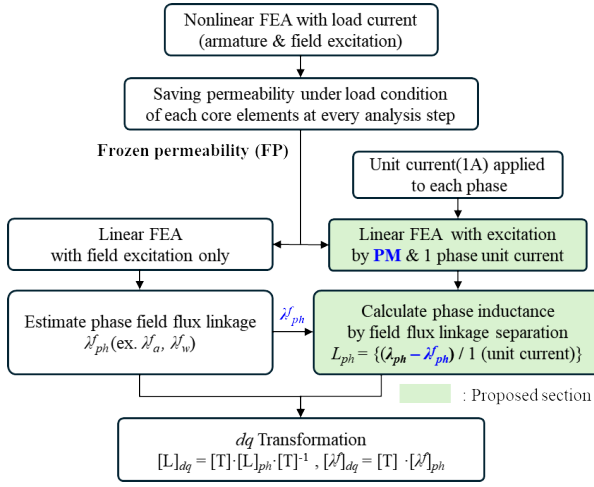


Fig. 2. Flow diagram of proposed FPM.

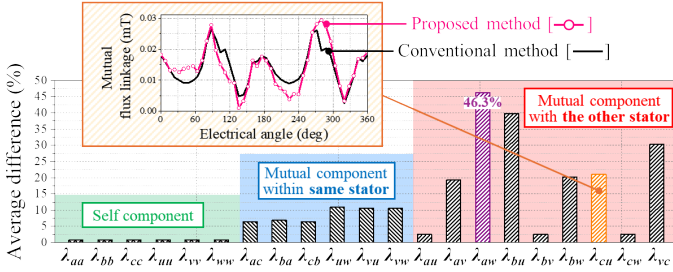


Fig. 3. Phase flux linkage difference between the conventional method and proposed method.

errors reaching several percent. These errors are mainly caused by treating the PM, located in the middle of the dual stator structure, as air when deriving the phase flux linkage. This results in the flux path being distorted due to the non-static permeability at the mid-section of the flux path.

B. Proposed Method

The process of the proposed method is shown in Fig. 2. The main difference from the conventional method is that the PM is retained as a magnetic source when calculating the phase flux linkage, preserving the flux path between the air gaps under load conditions. Additionally, an extra step is introduced to separate the field flux linkage from the calculated phase flux linkage because the PM is included, and this is shown below

$$\lambda_{ph} = \lambda_{\alpha\beta} - \lambda_{\beta}^f, \quad \alpha, \beta \in \{a, b, c, u, v, w\}. \quad (1)$$

Where λ_{ph} represents the phase flux linkage, $\alpha\beta$ indicates that the flux generated by phase β is linked to phase α , and λ_{β}^f represents the field flux linkage linked to phase β . The terms inside the braces denote the three phases of each armature set.

Fig. 3 illustrates the difference in phase inductance between the conventional method and the proposed method. The average difference in mutual components between the sets located on opposite sides of the air gap reaches up to 46.3% due to the difference in the representation of the flux paths. Fig. 4 compares the errors between the torques calculated using the conventional and proposed methods with the FEA torque. The proposed method has a lower error compared to the conventional method, regardless of the magnitude and phase

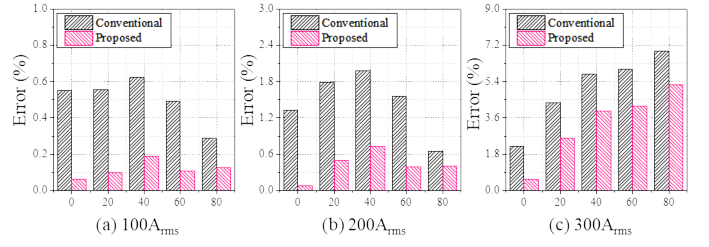


Fig. 4. Torque error comparison according to each FPM.

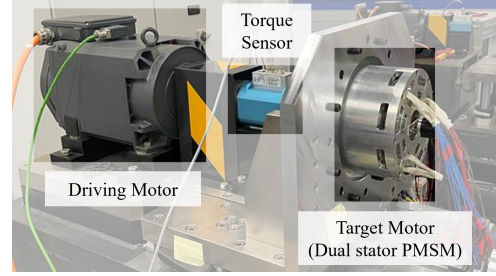


Fig. 5. Experimental setup.

TABLE I
TORQUE COMPARISON ACCORDING TO EACH FPM

Load current [A _{rms}]	Conventional [Nm]	Proposed [Nm]	FEA [Nm]
50	218.2	217.9	217.9
100	396.2	394.3	394.0
150	513.0	508.3	507.8
200	601.2	593.7	593.3
250	678.3	668.5	667.6
300	751.0	739.2	734.9

of the load current, as confirmed through this comparison. Table 1 presents the torque estimated through each FPM and the FEA torque under different load conditions. To produce the maximum torque, current was applied only in the q-axis. Through the proposed method, the difference is reduced from over 16 Nm to less than 5 Nm. This comparison demonstrates that the proposed method provides a more accurate parameter estimation compared to the conventional method.

IV. FUTURE WORKS

Fig. 5 shows the experimental setup, consisting of a scaled-down motor suitable for experimental testing. Using this setup, further validation will be performed through experiments in the full paper. Additionally, a verification on the reduction in errors, with the proposed method, will be conducted when the mutual inductance is increased due to the independently controlled inner and outer armature currents.

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