Study on Lumped Magnetic Circuit in Interior PM Machines for Aircraft Electric Green Taxiing Systems

Pengfei Zhang* and Yaohua Hu

Aviation Key Laboratory of Science and Technology on Aero Electromechanical System Integration, Nanjing Engineering Institute of Aircraft Systems, Nanjing 211106, China

*Email: zhangpf@neias.cn

Abstract. This paper considers the possibility of adopting a V-shaped interior permanent magnet (IPM) machine for Electric Green Taxiing (EGT) application. This rotor topology of the IPM machine has been optimized to reduce the torque ripple and iron loss. An analytical lumped magnetic circuit model was adopted to minimize the total harmonic distortion (THD) of air-gap flux density for the V-shaped IPM machine. The results of analytical lumped magnetic circuit model were compared with finite-element analysis (FEA). With the optimized rotor structure parameters, the torque ripple at the maximum torque per ampere and iron loss at the flux-weakening control were investigated.

1. Introduction

The concept of using electric machines for the aircraft traction during taxi phase is a current technology challenge driven by the global effort for environmentally responsible air transportation [1-3]. There are several types of electric machines that could be used for electric taxi applications. Interior permanent magnet (IPM) machines have many merits compare with surface-mounted permanent magnet machines, such as wide constant-power speed range, low EMF and flux-weakening ability, so it has more popular for the aircraft electric green taxiing systems [4].

In order to calculate the harmonics in the air-gap flux density distribution for the IPM machines, a lumped magnetic circuit model usually is a good compromise between simplicity and accuracy [5]. A parametric design for rotor geometry was applied to find the best shape for the rotor spatial MMF distribution that can minimize the harmonic distortion or torque ripple [6].

This paper presents a lumped magnetic circuit model to compute the flux density distribution in the air gap, minimize THD of the air-gap flux density for the V-shaped IPM machines. The results of analytical lumped magnetic circuit model were compared with FEA, it proves to be useful to confirm the rotor geometry. Using the optimized rotor structure parameters, iron losses under the flux-weakening control were investigated.

2. Machine Specification

The V-shaped IPM machine and gears are installed on main land wheel. The structural diagram of the V-shaped IPM machine is shown in Figure 1. The stator has the iron core and three phase windings, and the rotor has the magnets, ribs, bridges, barriers, and the shaft. The power rating is 30 kW continuous, the rated torque is 100 Nm, the over load torque is 200 Nm, the rated speed is 3000 r/min, the maximum speed is 9000 r/min, the reduction ratio of the gears is 36.
3. Study on Lumped Magnetic Circuit

3.1. Flux line distribution of the V-shaped IPM machines

In order to highlight the influence of rotor design parameters and provide a simple and useful means at early design stage, analytical models will be developed for the V-shaped IPM machine in this section, with the open-circuit and assuming a smooth stator, i.e., neglecting the slotting effect. Figure 2 shows the Flux line distribution of the V-shaped IPM machines. The flux line 1 represents the leakage flux through the bridge1, flux line 2 represents the leakage flux through the barrier1, flux line 3 represents the leakage flux through two bridges, flux line 4 represents the leakage flux through the barrier2, and flux line 5 represents the leakage flux through the rib1.

Figure 1. Proposed IPM machine for electric green taxiing systems.

Figure 2. Flux line distribution of the V-shaped IPM machines.
FEA predicted no-load flux lines of the V-shaped IPM machine are shown in Figure 3. The no-load air-gap flux density distribution is curve 1, which can be simplified to curve 2, where the \( N_p \) is the number of magnet poles, and the \( a_p \) is the pole-arc to pole-pitch ratio.

![Figure 3](image)

**Figure 3.** Equivalent no-load air-gap flux density distribution of the V-shaped IPM machine.

### 3.2. Analysis of lumped magnetic circuit

Figure 4(a) shows the lumped magnetic circuit associated with the fluxes excited by magnets. \( \phi_{g1} \) is the air-gap fluxes excited by PM over one magnet pole, while the corresponding reluctances is \( R_{g1} \). \( \phi_{r1} \) and \( \phi_{mo} \) are the flux sources and the leakage fluxes of PM over one magnet pole, the corresponding leakage flux reluctances is \( R_{mo} \). \( \phi_{ml2} \) and \( \phi_{ml4} \) are the leakage fluxes of PM over barrier 1 and barrier 2, the corresponding leakage flux reluctances is \( R_{ml2} \) and \( R_{ml4} \). \( \phi_{ml1} \), \( \phi_{ml3} \) and \( \phi_{ml5} \) are the leakage fluxes of PM over bridge 1, two bridges and rib 1, the corresponding leakage flux reluctances is \( R_{ml1} \), \( R_{ml3} \) and \( R_{ml5} \). \( R_1 \) and \( R_2 \) are the reluctances of the rotor yoke and the stator yoke. In general, there is no significant magnetic saturation in the yokes. Therefore, and may be neglected in comparison with \( R_{g1} \). \( \phi_{ml1} \) and \( \phi_{ml3} \) can be simplify \( \phi_{ml13} \), the corresponding leakage flux reluctances is \( R_{ml13} \), so Figure 4(a) can be simplified of Figure 4(b). Figure 4(b) also can be simplified circuit of Figure 3(c) due to symmetry.

![Figure 4](image)

**Figure 4.** Lumped magnetic circuit of the V-shaped IPM machine. (a) Lumped magnetic circuit. (b) Simplified circuit of Figure 4(a). (c) Simplified circuit of Figure 4(b).
With reference to Figure 2, the following expressions can be obtained:

\[ \phi_{i1} = B_i A_{m1} = 2B_i w_{ml} l_d \quad (1) \]

\[ R_{g1} = \frac{g}{\mu_i A_{g1}} \quad (2) \]

\[ A_{s1} = \frac{2\pi\alpha_p (l_{sto} - g / 2) l_d}{N_p} \quad (3) \]

\[ R_{m1} = \frac{l_{M1}}{\mu_0 A_{m1}} = \frac{l_{M1}}{2\mu_0 A_{m1} l_d} \quad (4) \]

\[ R_{ml2} = \frac{l_{M1} - h_4}{\mu_0 A_{ml2}} = \frac{4(l_{M1} - h_4)}{\mu_0 (2h_2 \sin(\alpha_1 - 90\degree) + 3h_3 + h_4) l_d} \quad (5) \]

\[ R_{ml4} = \frac{l_{M1} - h_4}{\mu_0 A_{ml4}} = \frac{2(l_{M1} - h_4)}{\mu_0 (h_2 + h_6) l_d} \quad (6) \]

Where \( \mu_0 \) is the permeability of air, \( \mu_r \) is the magnet relative recoil permeability, \( B_r \) is the magnet remanence, \( l_d \) is the lamination stack length, \( g \) is the air-gap length, \( l_{sto} \) and is the stator bore radius. \( l_{M1} \) is magnet length, while \( w_{ml} \) is magnet width, \( h_1 \)–\( h_6 \) are barrier width, \( \alpha_1 \) is the angle of \( h_2 \) and \( h_3 \).

Because of the saturation in the bridge, \( R_{ml13} \) and \( R_{ml5} \) are nonlinear. But the leakage flux through the bridge can be approximated as:

\[ \phi_{ml13} \approx B_s A_{ml13} = B_s l_d (b_1 + b_2) / 2 \quad (7) \]

\[ \phi_{ml5} \approx B_s A_{ml5} = B_s l_d b_4 / 2 \quad (8) \]

where \( A_{ml13} \) and \( A_{ml5} \) denotes the cross-sectional area of the bridge and rib, \( b_1 \) and \( b_2 \) are the bridge width, \( b_3 \) are the rib width. \( B_s \) is the saturation level on the B-H curve of the lamination, which is 2 T. This simplification may cause some errors because of the variation in magnetic saturation level in the bridges and ribs under different loading conditions. However, since the bridges and ribs are usually designed to be highly saturated even at open-circuit, the accuracy of lumped magnetic circuit models will still be acceptable, as will be illustrated later.

From Figure. 4(c), the Kirchhoff’s law is applied to node ①, and loop 1-3:

\[ \begin{cases} \phi_{i1} = & \phi_{m1} + \phi_{ml2} + \phi_{ml4} + \phi_{ml13} + \phi_{ml5} \\ 4R_{m1} \phi_{m1} = & 2R_{ml2} \phi_{ml2} = 2R_{ml4} \phi_{ml4} = 4R_{g1} \phi_{i1} \end{cases} \quad (9) \]

\[ \begin{pmatrix} 1 & 2 & 2 & 1 \\ 0 & -R_{ml2} & 0 & 0 \\ -R_{ml4} & 0 & 0 & -R_{g1} \\ 0 & 0 & -R_{ml4} & R_{g1} \end{pmatrix} \begin{pmatrix} \phi_{m1} \\ \phi_{ml2} \\ \phi_{ml4} \\ \phi_{i1} \end{pmatrix} = \begin{pmatrix} \phi_{i1} - 2\phi_{ml13} - 2\phi_{ml5} \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (10) \]

Therefore, the average air-gap flux density excited by PM1 is

\[ B_{g1} = \frac{\phi_{i1}}{A_{g1}} \quad (11) \]

Table 1 lists the design parameters of the V-shaped IPM machine.
Table 1. Design parameters of the V-shaped IPM machine.

| Design Parameters | Value | Design Parameters | Value | Design Parameters | Value |
|-------------------|-------|-------------------|-------|-------------------|-------|
| \( N_p \)         | 8     | \( h_1 \) (mm)    | 3.39  | \( l_{SID} \) (mm)| 80.95 |
| \( a_p \)         | 0.75  | \( h_2 \) (mm)    | 5.0   | \( l_a \) (mm)     | 45    |
| \( b_1 \) (mm)    | 1.6   | \( h_3 \) (mm)    | 1.0   | \( B_r \) (T)      | 1.22  |
| \( b_2 \) (mm)    | 2.0   | \( h_4 \) (mm)    | 2.2   | \( B_{sat} \) (T)  | 2.0   |
| \( b_3 \) (mm)    | 1.2   | \( h_5 \) (mm)    | 0.5   | \( \mu_0 \)        | \( 4\pi \times 10^{-7} \) |
| \( l_{M1} \) (mm) | 7.6   | \( h_6 \) (mm)    | 3.0   | \( \mu_r \)        | 1.08  |
| \( w_{M1} \) (mm) | 20.5  | \( a_1 \) (deg)   | 155   | \( H_c \) (A/m)    | -89900 |
| \( g \) (mm)      | 0.73  |                   |       |                   |       |

Figure 5 shows the air-gap flux density distribution of the V-shaped IPM machine. Figure 5(a) compares the analytical lumped magnetic circuit results and the finite-element analysis (FEA) results when the \( a_p \) is 0.75. The airgap flux density result of the analytical method is 0.762 T, the FEA result is 0.742 T, they have very good agreement. Figure 5(b) shows the analytical lumped magnetic circuit results when \( a_p \) from 0.75 to 0.9. Figure 5(c) shows the amplitude of the fundamental airgap flux density and THD with different \( a_p \). The lowest THD of the \( a_p \) is located at the 0.75, therefore, the optimized rotor structure parameters \( a_p = 0.75 \) is selected.

Figure 5. Air-gap flux density distribution of the V-shaped IPM machine. (a) \( a_p = 0.75 \). (b) \( a_p \) from 0.75 to 0.9. (c) Amplitude of the fundamental airgap flux density and THD with different \( a_p \).

3.3. The average torque, torque ripple, and iron loss

Figure 6(a). shows the torque waveforms of the optimized rotor at the maximum torque per ampere (MTPA) control. The average torque of the model II is 106.59 Nm. The torque ripple of the model I is 10.49%. Figure 6(b). shows the iron loss under flux-weakening control (FWC) at 9000 r/min, the
amplitude of phase voltage is 150 V, the amplitude of phase current is 200 A, and the current angle is 80 deg. Iron losses consist of core loss and magnet eddy current loss. It is observed that the eddy current loss of stator and rotor is higher than hysteresis loss, the iron loss of the machine is 1239.61 W.

![Figure 6](image-url)

**Figure 6.** The torque ripples and core loss density of the V-shaped IPM machines when the \(a_p\) is 0.75. (a) Torque waveform. (b) Iron loss at 9000 r/min.

### 4. Conclusion

This paper considers the possibility of adopting a V-shaped IPM machine for EGT systems. An analytical lumped magnetic circuit model was adopted to minimize the total harmonic distortion (THD) of air-gap flux density for the V-shaped IPM machines. The results of analytical lumped magnetic circuit model were compared with finite-element analysis (FEA), they have very good agreement. Using the optimized rotor structure parameters, the average torque of the machine is 106.59 Nm, the torque ripple of the machine is 10.49%, and the iron loss of the machine is 1239.61 W at 9000 r/min.

### Acknowledgments

This work was supported by the Aeronautical Science Foundation of China under Project 2018ZC09002.

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