AXIAL-FLUX PERMANENT-MAGNET MOTOR DESIGN FOR ELECTRIC VEHICLE DIRECT DRIVE USING SIZING EQUATION AND FINITE ELEMENT ANALYSIS

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Abstract—The design process of a double-sided slotted TORUS axial-flux permanent-magnet (AFPM) motor suitable for direct drive of electric vehicle (EV) is presented. It used sizing equation and Finite Element Analysis (FEA). AFPM motor is a high-torque-density motor easily mounted compactly onto a vehicle wheel, fitting the wheel rim perfectly. A preliminary design is a double-sided slotted AFPM motor with 6 rotor poles for high torque-density and stable rotation. In determining the design requirements, a simple vehicle-dynamics model that evaluates vehicle performance through the typical cruising trip of an automobile was considered. To obtain, with the highest possible torque, the initial design parameters of the motor, AFPM’s fundamental theory and sizing equation were applied. Vector Field Opera-3D 14.0 commercial software ran the FEA of the motor design, evaluating and enhancing accuracy of the design parameters. Results of the FEA simulation were compared with those obtained from the sizing equation; at no-load condition, the flux density at every part of the motor agreed. The motor’s design meets all the requirements and limits of EV, and fits the shape and size of a classical-vehicle wheel rim. The design process is comprehensive and can be used for an arbitrary EV with an arbitrary cruising scenario.

1. INTRODUCTION

Protection of natural environments sparked interest in electric vehicle (EV), a non-polluting personal transport. EV first appeared in 1870 but was for many years not further developed. The past 10 years, however, have seen developmental progress of EV [1]. Battery, electric

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motor, motor drive circuit, and transmission gears make up EV’s power system. Researchers and designers look into increasing the efficiency and reliability of EV power systems. Improvement of each subsystem increases the overall efficiency, and consequently, the driving range. One reason for EV’s little commercial success over the past century is that its efficiency had yet to reach the public’s expectations for it [2]. Low price and simple but strong physical structure are the reasons for induction motor’s wide application in EV [3]. Also, it can withstand high overloading and have low torque ripple. Its disadvantages, however, are low power-density, huge size and average efficiency. Permanent-magnet motor competing with induction motor in EV application has recently been developed; it fulfills the required high efficiency, small size, and high power density [4–7]. A motor designed for EV can be classified as direct drive or indirect drive [8,9]. Direct drive excludes transmission gears and mechanical differential including the associated energy losses. The motor is mounted inside vehicle wheel rim and turns the wheel directly, so it must be compact and have high torque [10].

Permanent-magnet machines generally can be axial-flux or radial-flux [11]. Advantages of axial-flux permanent-magnet (AFPM) motors over conventional radial-flux permanent-magnet (RFPM) motors include high torque-to-weight ratio, good efficiency, adjustable air-gap, balanced rotor-stator attractive forces, and better heat-removal [12–14]. They can be easily and compactly mounted onto vehicle wheel, fitting the wheel rim perfectly, suitable for direct drive applications. AFPM machines can be single-sided or double-sided, with or without armature slots, with or without armature core, with internal or external permanent-magnet rotors, with surface-mounted or interior permanent-magnet, and single-stage or multistage machines [15]. Double-sided configurations have either external stator or external rotor. An external stator means fewer permanent magnets but poor use of winding, whereas an external rotor is considered particularly advantageous to machine topology. Topologies for double-sided AFPM machines are one-stator-two-rotor (TORUS) and two-stator-one-rotor (AFIR) [16]. Among various configurations, slotted TORUS AFPM is the most applicable [17]; double-sided slotted TORUS AFPM configuration thus is the subject of this paper, as is its design for EV application.

Huang et al. derived the general-sizing and power-density equations for RFPM machines, also a systematic method for comparing the capabilities of machines of various topologies [18]. In 1999, they developed the sizing equation for AFPM machines [19]. Aydin et al. presented optimum-sized AFPM machines for TORUS and
AFIR topologies [20, 21]. Since then, there have been only a few papers reporting application of sizing equation to AFPM machine design, no doubt because of its limits (e.g., magnet skewing and winding configurations cannot be considered) [22]. Unlike traditional RFPM machines, AFPM machines have a unique construction, including a complex magnetic circuit that usually needs 3D Finite Element Analysis (FEA) for design of the machines. FEA, though accurate, has a long computation time that still can increase with the remodeling (including re-meshing) required when machine geometry changes. A solution to this problem is the application of 3D FEA complementarily to sizing equation. The electromagnetic torque against diameter ratio is extracted from AFPM machine’s fundamental equation, to obtain maximum torque. A sizing equation capable of calculating, with acceptable accuracy and speed, flux distribution and torque characteristics, is then applied to obtain the initial AFPM motor dimensions, before FEA is applied, for permanent-magnet skewing, accuracy enhancing, and the desired electric motor parameters.

This research aims for an electric motor that is suitable for electric vehicle application. The limits of the sizing equation used in the design was overcome by FEA, which increased accuracy, so the resulting motor has high power density, a most-sinusoidal back-EMF waveform, and reduced torque.

The paper is organized as follows: Section 2 presents the basic equations for vehicle dynamics; Section 3 extracts the sizing equations that give the TORUS AFPM machine its power-producing potential; Section 4 presents the electromagnetic field analysis via FEA on the proposed motor topology, from the sizing equation, for the desired parameters, results of the FEA simulation results and of the sizing equation compared; Section 5 concludes with discussing the results.

2. VEHICLE DYNAMIC, DESIGN RESTRICTIONS AND REQUIREMENTS

A simple model of vehicle dynamics that evaluates vehicle performance is herewith presented. A simplified vehicle driving resistance force or road load ($F_{rm}$) consists of rolling resistance force ($f_{ro}$), climbing resistance force ($f_{st}$), and aerodynamic drag force ($f_l$):

$$F_{rm} = f_{ro} + f_{st} + f_l \quad (1)$$

Rolling resistance force ($f_{ro}$) is caused by on-road tire deformation:

$$f_{ro} = f_r \cdot M \cdot a_g \quad (2)$$
where $f_r$, $M$, and $a_g$ are rolling resistance coefficient, vehicle mass, and gravity acceleration, respectively. Climbing resistance ($f_{st}$ with positive operational sign) and downward force ($f_{st}$ with negative operational sign) are given by:

$$f_{st} = M \cdot a_g \cdot \sin \alpha$$

(3)

where $\alpha$ is angle of vehicle movement relative to horizon. Aerodynamic drag force ($f_t$) is air viscous resistance on vehicle:

$$f_t = \frac{1}{2} \rho_a \cdot C_d \cdot S \cdot (v + v_0)^2$$

(4)

where $\rho_a$ is air density, $C_d$ is air-resistance coefficient, $S$ is frontal projected area, $v$ is vehicle speed, and $v_0$ is headwind speed. Acting as propulsion, driving force is applied to wheels to overcome driving resistance. Driving force lower than driving resistance does not make vehicle roll. In angular movement, minimum required torque for vehicle propulsion is:

$$\tau_{min} = r \times F_{rm}$$

(5)

where $r$ is position vector. Minimum power required is thus:

$$P_{min} = \tau_{min} \cdot \omega_m$$

(6)

where $\omega_m$ is angular speed. The energy required for acceleration ($a$), too, must factor in calculations of the vehicle movement. The power required to accelerate the EV is:

$$P_{accel} = M \cdot v \cdot a$$

(7)

The power required in total is:

$$P_{out} = P_{accel} + P_{min}$$

(8)

In designing the motor propulsion, the vehicle dynamics should first be determined. Fig. 1 is an EV cruising scenario that includes the EV’s typical-trip elements such as increased speed, constant speed, and braking action. Power needed by the vehicle is calculated from the proposed driving cycle in Fig. 1, together with Equations (1) to (8). Note that in this study, 4 motors were needed, mounted onto the vehicle wheels to provide the required power. Table 1 lists the parameters of the study.

The design of an AFPM motor appropriate for an electric vehicle should consider both requirements and limits. Some of the motor’s parameters and characteristics cannot vary much, the inability either inherent or owing to material and/or application limits. Table 2 lists the limits of the design procedure.
3. THE AXIAL-FLUX PERMANENT-MAGNET MOTOR DESIGN PARAMETERS

3.1. The Fundamental Design Equations

The air-gap flux density ($B_g$) is calculated by using remanence flux density ($B_r$) and the relative permeability ($\mu_{ra}$) of the permanent magnet, also the geometrical dimensions of the air-gap, and the permanent magnet geometry as in [15]:

$$B_g = k_{\sigma pm} \frac{B_r}{1 + \mu_{ra} k_{CG} \frac{S_{pm}}{S_g}}$$

(9)

where, $g$ and $L_{pm}$ are respectively the air-gap thickness and permanent magnet thickness; $S_g$ and $S_{pm}$ are respectively the air-gap area and

![Figure 1. Proposed driving cycles for electric-vehicle design.](image)

**Table 1.** Parameters used in this study.

| **Vehicle Specification**          |       |
|-----------------------------------|-------|
| Weight of Vehicle                 | 80kg  |
| Weight of Passengers              | $4 \times 70$ kg |
| Wheel Diameter                    | 0.35 m |
| Tire Set                          | 4 units |
| Rim Diameter                      | 14 inch |
| Drive System                      | direct-drive |
| Frontal Area ($S$)                | 2.5 $m^2$ |
| Air Resistance Coefficient ($C_d$)| 0.35  |
| Tire Resistance Coefficient ($f_r$)| $2.5 \times 10^{-3}$ |
| Air Density ($\rho_a$)            | 1.22 kg/m$^3$ |
| Maximum Speed ($v_{max}$)         | 120 km/h |
Table 2. Design restrictions and requirements.

| Dimensional Constrains       |       |
|-----------------------------|-------|
| Stator Outer Diameter       | ≤ 350 mm |
| Total Axial-Length          | ≤ 100 mm |

| Material Limitations         |       |
|-----------------------------|-------|
| Permanent Remanence         | 1.3 T |
| Stator and Rotor Core Flux Density | \( B_{cs}, B_{cr} \leq B_{\text{max}} = 1.5 \, \text{T} \) |

| Limitations on Power System |       |
|-----------------------------|-------|
| Rated line-to-line Voltage  | ≤ 150 V |

| Requirements                |       |
|-----------------------------|-------|
| Minimum Torque              | 33 Nm |
| Output Power                | 10 kW |
| Motor Efficiency            | ≥ 90% |

permanent magnet area. \( k_{PM} \) is a factor that takes into account the leakage flux and \( k_C > 1 \) is the Carter coefficient. The air-gap magnetic flux density in fact reduces under each slot opening, owing to decreased magnetic permeance. The Carter coefficient considers this change in magnetic flux density (caused by slot opening) by defining a fictitious air-gap greater than the physical one, and is computed from [15]:

\[
k_C = \frac{t}{t - \gamma g}
\]

where \( t \) is the average slot pitch, and the fictitious air-gap coefficient \( \gamma \) is defined by:

\[
\gamma = \frac{4}{\pi} \left[ \frac{W_s}{2g} \tan^{-1} \left( \frac{W_s}{2g} \right) - \ln \sqrt{1 + \left( \frac{W_s}{2g} \right)^2} \right]
\]

where \( W_s \) is the width of the slot opening. Fig. 2 is construction of the double-sided slotted AFPM machine including its configurations for rotor, stator, and slot. Assuming a sinusoidal waveform for the air-gap flux density, the average electromagnetic torque \( \tau \) of a double-sided AFPM motor is calculated from:

\[
\tau = \frac{\pi}{4} B_g A_{lin} D_o^3 \lambda (1 - \lambda^2)
\]

where \( A_{lin} \) is the linear current density of the machine’s inner radius and \( \lambda \) is AFPM diameter ratio \( D_i/D_o \); \( D_o \) is diameter of the machine’s outer surface; \( D_i \) is diameter of the machine’s inner surface. For a given outer diameter and magnetic and electrical loading, AFPM
Figure 2. Double-sided axial-flux permanent-magnet construction. (a) Stator and rotor of the AFPM machine configuration. (b) Internal stator slot configuration.

Figure 3. Per-unit electromagnetic torque $\tau_{pu}$ against diameter ratio $\lambda$.

machine’s diameter ratio $\lambda$ is very important as it determines the motor’s maximum torque. Fig. 3 shows the per-unit electromagnetic torque against the diameter ratio. The maximum torque is achievable when $\lambda \approx 0.58$.

3.2. The Sizing Equation

The main dimensions of each electrical machine are determined via electrical-machine-output power equation. Assuming negligible leakage inductance and resistance, the rated power is expressed as [19]:

$$P_{out} = \eta \frac{m}{T} \int_0^T e(t) \cdot i(t) \, dt = m k_p \eta E_{pk} I_{pk}$$

(13)
$e(t)$ is phase air-gap EMF, $i(t)$ is phase current, $\eta$ is machine efficiency, $m$ is the number of machine phases, and $T$ is the period of one EMF cycle; $E_{pk}$ and $I_{pk}$ respectively are peaks of phase air-gap EMF and of current; $k_p$ is electrical power waveform factor, defined as:

$$K_p = \frac{1}{T} \int_0^T \frac{e(t) \cdot i(t)}{E_{pk} \cdot I_{pk}} dt = \frac{1}{T} \int_0^T f_e(t) \cdot f_i(t) dt$$

where $f_e(t) = e(t)/E_{pk}$ and $f_i(t) = i(t)/I_{pk}$ are expressions for normalized EMF and current waveforms. For effect of current, the current waveform factor ($k_i$) is defined as:

$$k_i = \frac{I_{pk}}{I_{rms}} = \frac{1}{\sqrt{\frac{1}{T} \int_0^T \left( \frac{i(t)}{I_{pk}} \right)^2 dt}}$$

where $I_{rms}$ is phase-current rms value. Table 3 lists typical waveforms and their corresponding power-waveform factor ($k_p$) and current-waveform factor ($k_i$) [18]. The peak value of phase-air-gap EMF for AFPM motor in Equation (13) is:

$$E_{pk} = K_e N_{ph} B_g f_e \left( 1 - \lambda^2 \right) D_o^2$$

$K_e$ is EMF factor, incorporating winding distribution factor ($k_w$) and per-unit portion of air-gap area (total) spanned by machine’s salient poles (if any); $N_{ph}$ is the number of winding turns per phase; $B_g$ is the air-gap flux density; $f_e$ is the converter frequency; $P$ is the machine pole pairs. Equation (13)’s peak phase current is:

$$I_{pk} = A \pi k_i \frac{1 + \lambda}{2 m_1 N_{ph}} \frac{D_o}{\pi}$$

where $m_1$ is the number of phases of each stator, and $A$ is electrical loading. A general-purpose sizing equation for AFPM machines takes the following form:

$$P_{out} = \frac{1}{1 + k_w} \frac{m}{m_1} \frac{\pi}{2} k_i k_p k_L \eta B_g A \frac{f_e}{D} \left( 1 - \lambda^2 \right) \frac{1 + \lambda}{2} D_o^2 L_e$$

$L_e$ is the motor’s effective axial length; $k_w$ is the electrical loading ratio of the rotor and the stator; $k_L$ is the aspect ratio coefficient pertinent to a specific machine structure, with considerations for the effects of losses, temperature rise, and the design’s efficiency requirements. Machine torque density for the total volume is defined as:

$$\tau_{den} = \frac{P_{out}}{\omega m \frac{\pi}{4} D_{tot}^2 L_{tot}}$$
Table 3. Typical prototype waveforms.

| Model       | $e(t)$ | $i(t)$  | $k_i$ | $k_p$ |
|-------------|--------|---------|-------|-------|
| Sinusoidal  | ![Waveform](waveform1.png) | ![Waveform](waveform2.png) | $\sqrt{2}$ | $0.5\cos\phi$ |
| Sinusoidal  | ![Waveform](waveform3.png) | ![Waveform](waveform4.png) | $\sqrt{2}$ | 0.5    |
| Rectangular | ![Waveform](waveform5.png) | ![Waveform](waveform6.png) | 1       | 1      |
| Trapezoidal | ![Waveform](waveform7.png) | ![Waveform](waveform8.png) | 1.134   | 0.777  |
| Triangular  | ![Waveform](waveform9.png) | ![Waveform](waveform10.png) | $\sqrt{3}$ | 0.333  |

$\omega_m$ is rotor angular speed, $D_{\text{tot}}$ and $L_{\text{tot}}$, respectively, are the total of the machine’s outer diameter and total of the machine’s length including stack outer diameter and end-winding protrusion from radial and axial iron stacks.

The generalized sizing equation approach can easily be applied to double-sided AFPM TORUS-type motor. The outer surface diameter ($D_o$) can be written as:

$$D_o = \sqrt[3]{\frac{P_{\text{out}}}{2\pi m_1 k_e k_p k_i A B g \eta f_e P_c (1 - \lambda^2)}} \frac{1 + \lambda}{2}$$  \hspace{1cm} (20)

The machine outer diameter total $D_{\text{tot}}$ for the TORUS motor is given by:

$$D_{\text{tot}} = D_o + 2W_{\text{cu}}$$  \hspace{1cm} (21)

where $W_{\text{cu}}$ is protrusion of the end winding from the iron stack, in radial direction. For back-to-back wrapped winding, protrusions exist towards the machine axis as well as towards the outsides, and can be calculated as:

$$W_{\text{cu}} = \frac{D_i - \sqrt{D_i^2 - \frac{2AD_{\text{ave}}}{k_{\text{cu}} j_s}}}{2}$$  \hspace{1cm} (22)
where $D_{ave}$ is the average diameter of the machine, $J_s$ is the slot current density, and $k_{cu}$ is the copper fill factor. Axial length $L_e$ of the machine is given by:

$$L_e = L_s + 2L_r + 2g$$  \hspace{1cm} (23)

$L_r$ is the rotor’s axial length, and $g$ is the air-gap length. Axial length of the stator $L_s$ can be written as:

$$L_s = L_{cs} + 2L_{ss}$$  \hspace{1cm} (24)

Note that for slotted machines, depth of the stator slot is $L_{ss} = W_{cu}$. Axial length of stator core $L_{cs}$ can be written as:

$$L_{cs} = \frac{B_g \pi \alpha_p D_o (1 + \lambda)}{4pB_{cs}}$$  \hspace{1cm} (25)

where $B_{cs}$ is the flux density in the stator core, and $\alpha_p$ is the ratio of the average air-gap flux density to the peak air-gap flux density. Axial length of the rotor, $L_r$, becomes:

$$L_r = L_{cr} + L_{pm}$$  \hspace{1cm} (26)

$L_{pm}$ is the permanent-magnet length; axial length of the rotor core, $L_{cr}$, is:

$$L_{cr} = \frac{B_u \pi D_o (1 + \lambda)}{8pB_{cr}}$$  \hspace{1cm} (27)

where $B_{cr}$ is flux density in the rotor disc core, and $B_u$ is the flux density attainable on the permanent-magnet surface. Permanent-magnet length $L_{pm}$ can be calculated as:

$$L_{pm} = \frac{\mu_r B_g}{B_r - (k_d B_g/k_p)} k_C g$$  \hspace{1cm} (28)

where $\mu_r$ is the magnet’s recoil relative permeability, $B_r$ is the permanent-magnetmaterial-residual-flux density, $k_d$ is the leakage flux factor, $k_C$ is Carter factor, $k_f = B_{gpk}/B_g$ is the peak value corrected factor of the air-gap flux density in radial direction of the AFPM motor. These factors can be obtained from FEM analysis [20].

4. SIMULATION RESULTS AND DISCUSSION

3D-FEA analyzed the magnetic circuit and power density of the double-sided slotted TORUS AFPM motor, for an overall picture of the saturation levels in various parts of the motor, and to extract the motor’s characteristics. An advantage of 3D-FEA is that various components of flux density can be calculated highly accurately [23, 24]. Note that FEM (Finite Element Method) facilitates field analysis of
electromagnetic problems with complex geometries [25–28]. The design was simulated on commercial Vector Field Opera 14.0 3D software [29]. Corresponding materials and circuit currents were assigned to each block of the model. The simulation model reached the output (10 kW) targeted for EV. The motor’s 3D model is symmetric, so 6 magnetic poles were sliced to reduce simulation/calculation time, and the model became one magnetic pole piece. For simulation, input parameters to be considered were permanent-magnet thickness, air-gap width, and magnetic properties of all the active materials. Table 4 lists the motor’s design dimensions and specifications.

Table 4. The motor’s final design dimensions and specifications.

| Parameter                                              | Value   |
|--------------------------------------------------------|---------|
| Rated Voltage (Line-Line RMS)                         | 130 V   |
| Rated Power                                            | 10 kW   |
| Number of pole pairs                                   | 3       |
| Number of phases                                       | 3       |
| Drive Frequency                                        | 50      |
| Efficiency                                             | 91.5%   |
| Outer Diameter                                         | 240 mm  |
| Inner Diameter                                         | 139 mm  |
| Inner to Outer Diameter’s Ratio                        | 0.58    |
| Magnet’s axial length                                  | 12 mm   |
| Pole Pitch                                             | 117°    |
| Permanent magnet Skew                                  | 7°      |
| Stator-yoke thickness                                  | 41 mm   |
| Rotor-yoke thickness                                   | 9 mm    |
| Slot Bottom Width                                      | 6       |
| Slot Top Width                                         | 3       |
| Slot Depth                                             | 11 mm   |
| Slot Top Depth 1                                       | 3       |
| Slot Top Depth 2                                       | 3       |
| Number of slots                                        | 18      |
| Number of winding turns per phase                      | (18 × 10)/3 |
| Air-Gap Flux Density                                   | 0.71 T  |
| Air-gap length                                         | 2 mm    |
Figure 4. Field analysis of an AFPM machine, in vector field opera 14.0 software. (a) 3D auto-mesh generation. (b) Flux-density plot.

Figure 4 shows only one twelfth of the motor modeling the structure of the FEA-designed AFPM: 60 degrees of the entire motor structure and 1 pole, fulfilling symmetry conditions. The whole machine comprises 18 slots and 3 pole-pairs. Fig. 4(a) (generated on Vector Field Opera 14.0 software) is a 3D auto-mesh: tetrahedral elements with 6 nodes fitting circular shape of the layers starting from inner to outer diameter of the AFPM machine [29]. Fig. 4(b) is the distribution of the magnetic flux density in various sectors of the AFPM machine. Appendix A presents the optimized winding configuration for various numbers of slots of the brushless DC AFPM motor. The best winding configuration (for 18 slots) was used here, giving as sinusoidal waveform as possible (see Fig. A1(d)). Magnetic flux density evaluation in the various sectors of an AFPM machine is important because if the flux density of the core or the teeth goes to saturation, machine efficiency reduces, affecting operation. Fig. 5 is the air-gap flux density distribution, in average radius. The maximum flux density is obviously 0.95 Tesla, averaging 0.71 Tesla.

Figure 6 shows the magnetic flux density in stator yoke and teeth at average radius. The maximum magnetic flux was 0.95 Tesla, averaging 0.67 Tesla. The flux density in the stator teeth reaches 1.5 Tesla, which, based on material limits, is the maximum allowable value. Fig. 7 is the magnetic flux density distribution in average radius for rotor yoke and magnet surface. Figs. 5, 6, and 7 give the flux density distribution, all in average radius, in Tesla. The presentation enables comparison of the simulation results from FEA with those obtained from the sizing equation. Table 5 lists the average magnetic flux density compared between FEA simulation results and sizing equation analysis.
Figure 5. Magnetic flux density distribution of air-gap, for average radius.

Table 5. Magnetic flux density compared among various parts of the motor, at no-load condition.

|                | Air-gap | Stator yoke | Rotor yoke | Magnet surface |
|----------------|---------|-------------|------------|----------------|
|                | $B_g$   | $B_{cs}$    | $B_{cr}$   | $B_m$          |
|                | Ave.    | Max.        | Ave.       | Max.           | Ave.           | Max.           |
| FEA            | 0.71    | 0.95        | 0.67       | 0.95           | 0.82           | 1.15           | 0.97           | 1.10           |
| Sizing Eq.     | 0.70    | 0.95        | 0.64       | 0.95           | 0.80           | 1.10           | 0.96           | 1.10           |

at no-load condition, for various parts of the motor design. The flux density obtained from FEA was a little less than that calculated theoretically via the sizing equation, owing to core magnetic reluctance having been neglected. In real conditions, however, flux density of the different core parts decreases via MMF drop.

The slotted-TORUS configuration used in this paper is north-north magnet arrangement. The phase winding is wound around the stator core, giving a short end-winding. It reduces copper losses, but the main flux has to flow circumferentially along the stator core. Figs. 8 and 9 respectively show the magnetic flux path in the stator teeth and the magnetic potential vectors for the rotor magnets, modeled in Vector Field Opera-3D 14.
4.1. Back-EMF Waveform

One well-known approach to minimizing cogging torque is magnet skewing. It also reduces back-EMF total harmonic distortion (THD) and eliminates some of the undesired harmonic components. The
maximum magnet skewing angle relative to the stator teeth should be equal to the slot pitch, not exceed it. Fig. 10(a) shows magnet’s geometric skewing relative to stator teeth. Fig. 10(b) shows the back-EMF THD variation versus magnet skewing angle $\theta_i$. The aim is to design an AFPM machine that has a sinusoidal waveform (the back

Figure 7. Magnetic flux density distribution for average radius, on (a) rotor yoke; (b) magnet surface.
EMF should be as sinusoidal as possible). The minimum THD occurs when the magnet skewing angle is 7 degrees. Fig. 11 shows the back EMF at 1000rpm rated speed, also the FEA-calculated THD and back-EMF RMS. The Fourier transform of the back-EMF waveform is obtained as indicated in Fig. 12. THD significantly decreased from 26.7% to 3.1% after a 7-degree optimized magnet-skewing.

4.2. Torque

In torque performance assessment, both torque density and torque ripple must be considered. As do RFPM machines, AFPM machines,
too, produce undesirable performance-affecting torque ripples. Main sources of torque ripple are: cogging torque, non-ideal back EMF waveforms, and saturation of machine’s magnetic circuit. In designing a motor, undesired harmonics that make back EMF non-ideal are reduced by creating a back-EMF waveform that is as sinusoidal as possible. Saturation of the proposed machine’s magnetic circuit in various motor parts was controlled by FEA simulation of its electromagnetic field. Cogging torque is also an issue in machine design. It results from permanent magnet’s tendency to align itself at the position of minimum magnetic reluctance path between rotor and stator. Permeance variation in the slot opening leading tangential forces in the rotor, owing to flux entering the teeth, creates an

Figure 10. Permanent magnet skewing. (a) A diagram of magnet’s geometric skewing relative to stator teeth. (b) THD variation versus permanent magnet skewing angle $\theta_i$. 

![Diagram of magnet's geometric skewing relative to stator teeth and THD variation versus permanent magnet skewing angle $\theta_i$.](image-url)
oscillatory output called cogging torque, which introduces noise and vibration, both of which degrade the response of high-performance motion control particularly at low speed and light loads.

An effective, most simple and common technique to reduce cogging torque is skewing. It is done by either stator slots or rotor permanent magnet skewing. Since stator slot skewing is relatively difficult to
Figure 13. Cogging torque versus mechanical angle.

achieve in AFPM machines, the magnets instead are skewed. Fig. 13 shows the cogging torque of the AFPM machine, with, and without, permanent magnet skewing. Pre-skewing peak cogging torque was 3.3 Nm. Skewed magnets reduce cogging torque; at 7-degree skewing, peak cogging torque reduced to 2.1 Nm (a 36% reduction).

4.3. Efficiency

For accurate assessment of machine efficiency and thermal behavior, calculation of the losses is crucial. Machine efficiency is:

$$\eta = \frac{P_{out}}{P_{out} + P_{cu} + P_{cor} + P_{rot}}$$

where $P_{cu}$, $P_{cor}$, $P_{rot}$ are respectively copper losses, core losses, and rotational losses. Copper loss ($R_s \times I^2$) makes up most of the loss total. Stator resistance ($R_s$) depends on load and on winding temperature [30].

$$R_s = \frac{2 N_{ph-s} (l + l_e)}{\sigma_T N_{ph-p} s_{cu}}$$

$N_{ph-s}$ is the number of winding turns in series per phase, $N_{ph-p}$ is the number of winding turns in parallel per phase, $\sigma_T$ is electric conductivity of wire at temperature $T$, and $s_{cu}$ is cross-sectional area of wire. Thin parallel wires minimized skin effect, eliminating its consideration in Equation (30). $l$ and $l_e$ respectively are coil length and end-winding length.
Hysteresis loss \( P_h \) and eddy current loss \( P_e \) make up the motor core loss and can be calculated from:

\[
P_h = \frac{k_h \cdot B_{m}^{n} \cdot f^2}{\rho} \tag{31}
\]

\[
P_e = \frac{k_e \cdot B_{m}^{2} \cdot f^2}{\rho} \tag{32}
\]

\( k_h, k_e, B_{\text{max}}, \) and \( \rho \) respectively are hysteresis constant, eddy current constant, maximum flux density, and core material density. FE-AC analysis was repeated for every space harmonic component (up to the 49th order) and for every current waveform’s simulated time harmonic component, to get the eddy current losses in the stator steel. The stator of an axial-flux motor is laminated either spirally or axially (see Fig. 14 for their configurations). Each made from silicon steel, the thickness of the laminating silicon steel paper is 0.1 mm. In this work, spiral lamination was used in the simulations. The core loss for the stator laminated 0.1 mm thick, calculated via FE-AC analysis, was 63 W.

Figure 15 shows the motor’s efficiency in various speeds. Rotational loss (which includes windage and friction losses) was estimated from the following Equation [31]:

\[
P_{\text{rot}} = \frac{1}{2} c_f \rho_r \left( \pi n^3 \right) \left( D_o^5 - D_i^5 \right) \tag{33}
\]

where \( c_f \) is friction coefficient, \( \rho_r \) is density of the rotating part, and \( n \) is rotation speed (in ‘rotation per second’). Efficiency of the laminated-stator motor, obtained with full loading at full load, was 91.5 %. 

Figure 14. Spiral and axial lamination of an axial-flux motor’s stator. (a) Spiral lamination. (b) Axial lamination.
5. CONCLUSION

The design and simulation of a slotted TORUS AFPM motor for EV application has been presented. The motor produced 10 kW power and the maximum amplitude of the sinusoidal back EMF was 105 V at 1000 rpm rated speed. Its design met specifications and requirements of EV direct drive. The requirements had been determined through a simple model of vehicle dynamics that considered a cruising scenario. Limits to material and application were considered as well. The motor’s performance was increased by optimizing the design parameters (air-gap length, permanent-magnet size and material, magnet orientation, and winding configuration) via sizing equation and Finite Element Analysis. The simulated and desired values agreed. Comparison of FEA and sizing equation shows the design’s flux density at no-load condition and in various parts of the motor agreeing. The design process is comprehensive and can be used for an arbitrary EV considering an arbitrary cruising scenario.

APPENDIX A. WINDING CONFIGURATIONS

A method described in [32] was used to place the coils. There are infinite possibilities for pole and slot-count combinations as there are for winding layouts; assumptions are necessary, either for focus or for scope limitation, so desirable windings can be found. The assumptions were:

a) Three-phase motor.

Figure 15. Efficiency versus speed.
b) All slots filled; the number of slots is thus a multiple of the number of phases (i.e., $N_s = k \times N_{ph}$); for three-phase motors, the number of slots is thus always a multiple of three.

c) Two coil-sides in each slot, the winding can be classified as double-layer winding.

d) Balanced-windings only, i.e., only pole and slot-count combinations that result in back EMF of phases B and C being $120^\circ_E$ offset from back EMF of phase A.

e) Coils have equal number of turns, all spanning equal number of slots, implying same-sized coils and therefore same resistance and same inductance.

The assumptions routinely lead to motors capable of high performance, and to motors that are readily wound. Motors can be wound violating one or more of the assumptions, but they may be more difficult to wind; such winding could also lower performance. Fig. A1 shows the coil arrangements (9, 12, 15, 18, 21, and 24 slots) that gave the best sinusoidal waveforms. A, B, and C represent the phases, and + and − represent direction of the windings.

The number of winding configuration options can also be increased by short-pitching the fractional-slot structures. The 15-slot stator was

| Configuration Number | Number of Slots | Coil Pitch/Pole Pitch | Number of slots in each pole per phase ($N_{spp}$) |
|----------------------|-----------------|-----------------------|-----------------------------------------------|
| 1                    | 9               | 2/2.25                | 0.75                                          |
| 2                    | 12              | 2/3                   | 1                                             |
| 3                    | 12              | full-pitch            | 1                                             |
| 4                    | 15              | 2/3.75                | 1.25                                          |
| 5                    | 15              | 3/3.75                | 1.25                                          |
| 6                    | 18              | 3/4.5                 | 1.5                                           |
| 7                    | 18              | 4/4.5                 | 1.5                                           |
| 8                    | 21              | 3/5.25                | 1.75                                          |
| 9                    | 21              | 4/5.25                | 1.75                                          |
| 10                   | 21              | 5/5.25                | 1.75                                          |
| 11                   | 24              | 4/6                   | 2                                             |
| 12                   | 24              | 5/6                   | 2                                             |
| 13                   | 24              | full-pitch            | 2                                             |
Figure A1. Stator winding constructions for 9, 12, 15, 18, 21, and 24 slots. (a) 9-slot double-layer stator winding (coil span = 2). (b) 12-slot double-layer stator winding (full-pitch). (c) 15-slot double-layer stator winding (coil span = 2). (d) 18-slot double-layer stator winding (coil span = 4). (e) 21-slot double-layer stator winding (coil span = 5). (f) 24-slot double-layer stator winding (full-pitch).

designed with a 3-slot coil span, but a 2-slot coil span is possible, reconfiguration for it easy. For an 18-slot structure, 3-slot coil span, and for 21-slot structure, both 3-slot and 4-slot coil spans can be considered. For the 13 stator configurations in Table A1 and their possible magnet spans, their losses, back-EMF harmonic content, and pulsating torque components were investigated. Efficiencies were found to not differ much except at lower speeds, where the differences were more pronounced (owing to copper losses). The worst structure in terms of copper losses was found to be 24-slot, full-pitched.
APPENDIX B. NOMENCLATURE

A electrical loading total [A]

\( A_{lin} \) linear current density of the machine’s inner radius [A/m]

\( B \) magnetic flux density [T]

\( B_{cr} \) rotor-disc flux density [T]

\( B_{cs} \) stator-core flux density [T]

\( B_g \) air-gap flux density [Wb/m²]

\( B_{gpk} \) peak value of air-gap flux density [Wb/m²]

\( B_m \) permanent magnet flux density [T]

\( B_{max} \) maximum flux density [T]

\( B_r \) permanent-magnet residual-flux density [T]

\( B_a \) flux density on permanent-magnet surface [T]

\( C_d \) air-resistance coefficient

\( D_{ave} \) machine stator average diameter [m]

\( D_i \) machine stator inner diameter [m]

\( D_o \) machine stator outer diameter [m]

\( D_s \) slot depth [m]

\( D_{tot} \) machine outer diameter total [m]

\( E_{pk} \) peak value of phase-air-gap EMF [V]

\( F_{rm} \) vehicle driving resistance force[N]

\( I_{rms} \) phase current rms value [A]

\( I_{pk} \) phase current peak value [A]

\( J \) external current density [A/m²]

\( J_s \) slot current density [A/m²]

\( H \) magnetic field intensity [A/m]

\( K_e \) EMF factor

\( K_{n \times n} \) stiffness matrix

\( L_{cr} \) rotor-core axial length [m]

\( L_{cs} \) stator-core axial length [m]

\( L_e \) effective axial length of motor [m]

\( L_{pm} \) permanent-magnet length [m]

\( L_r \) rotor axial length [m]
\begin{itemize}
  \item $L_s$ stator axial length [m]
  \item $L_{ss}$ stator slot depth [m]
  \item $L_{tot}$ machine axial length total [m]
  \item $M$ vehicle mass [kg]
  \item $N_{ph}$ number of winding turns per phase
  \item $N_{ph-s}$ number of winding turns in series per phase
  \item $N_{ph-p}$ number of winding turns in parallel per phase
  \item $N_s$ number of slots [m]
  \item $P$ number of motor pole pairs
  \item $P_{accel}$ power required to accelerate [W]
  \item $P_{cor}$ core losses [W]
  \item $P_{cu}$ Copper losses [W]
  \item $P_{rot}$ rotational losses [W]
  \item $P_{nom}$ nominal power [kW]
  \item $P_{min}$ minimum required power [W]
  \item $P_{out}$ rated power [W]
  \item $R_s$ stator resistance [Ω]
  \item $S$ frontal projected area [m²]
  \item $S_g$ air-gap area [m²]
  \item $S_{pm}$ permanent magnet area [m²]
  \item $T$ period of one EMF cycle [Sec]
  \item $V_{nom}$ nominal voltage (line to line RMS) [V]
  \item $W_{cu}$ end-winding protrusion from iron stack [m]
  \item $W_s$ Slot opening width
  \item $W_{sb}$ Slot bottom width [m]
  \item $a$ vehicle acceleration [m/s²]
  \item $a_g$ gravity acceleration [m/s²]
  \item $c_f$ friction coefficient
  \item $d_1$ slot top depth 1 [m]
  \item $d_2$ slot top depth 2 [m]
  \item $e(t)$ phase-air-gap EMF [V]
  \item $i(t)$ phase current [A]
\end{itemize}
\( f_e \) electrical frequency [Hz]
\( f_e(t) \) normalized EMF waveforms
\( f_i(t) \) normalized current waveforms
\( f_l \) aerodynamic-resistance force [N]
\( f_r \) rolling-resistance coefficient
\( f_{ro} \) rolling-resistance force [N]
\( f_{st} \) climbing-resistance force [N]
\( g \) air-gap length [m]
\( g_{n \times 1} \) excitation vector
\( k_C \) Carter coefficient
\( k_L \) aspect ratio coefficient
\( k_{cu} \) copper fill factor
\( k_d \) leakage-flux factor
\( k_e \) eddy current constant
\( k_h \) hysteresis constant
\( k_i \) current waveform factor
\( k_p \) electrical power waveform factor
\( k_f \) peak value corrected factor of air-gap flux density
\( k_w \) winding distribution factor
\( k_{\sigma PM} \) a factor that takes into account the leakage flux
\( k_\varphi \) electrical loading ratio
\( l \) coil length [m]
\( l_e \) end winding length [m]
\( m \) number of phases
\( m_1 \) number of phases of each stator
\( n \) rotation speed [rs\(^{-1}\)]
\( r \) position vector [m]
\( s_{cu} \) cross-section area of wire
\( t \) average slot pitch [m]
\( v \) vehicle speed [m/s]
\( v_0 \) headwind speed [m/s]
\( \Phi \) winding flux linkage [Wb]
\( \Psi \) magnetic vector potential [V \cdot s \cdot m\(^{-1}\)]
\( \alpha \) vehicle movement angle [Rad]
\[ \alpha_p \] average air-gap flux density to its peak value ratio  
\[ \gamma \] air-gap fictions coefficient  
\[ \gamma_p \] pole pitch [in degrees]  
\[ \eta \] motor efficiency  
\[ \theta_i \] Permanent magnet skew [in degrees]  
\[ \lambda \] diameter ratio  
\[ \mu \] permeability [A · m\(^2\)]  
\[ \mu_0 \] Permeability of free space [A · m\(^2\)]  
\[ \mu_r \] Relative permeability  
\[ \mu_{ra} \] relative permeability of the permanent magnet  
\[ \rho \] core material density [kg/m\(^3\)]  
\[ \rho_a \] air density [kg/m\(^3\)]  
\[ \rho_r \] density of the rotating part of the motor [kg/m\(^3\)]  
\[ \sigma \] electrical conductivity [Ω · m]  
\[ \sigma_T \] electric conductivity of wire [Sm\(^{-1}\)]  
\[ \tau_{den} \] torque density [N · m/cm\(^3\)]  
\[ \tau_{min} \] minimum required torque [N · m]  
\[ \omega_m \] angular speed [Rad/s]  

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