Preliminary Electromagnetic Sizing of Axial-Flux Induction Machines

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Abstract—This paper presents a preliminary electromagnetic sizing algorithm for double-rotor axial-flux induction machines (DR-AFIMs). The proposed algorithm is based on a geometrical approach and limits the use of empirical factors and past experience. The sizing equations for all the main geometrical and operational machine parameters are derived and a concise outline of the electromagnetic sizing algorithm is provided. The efficacy of the implemented algorithm is validated using finite-element DR-AFIM models. The achievement of the targeted specifications in the preliminary DR-AFIM designs is proven and demonstrated.

Index Terms—Axial-flux induction machine, double-rotor, finite-element method, preliminary electromagnetic design, sizing equations.

I. INTRODUCTION

Axial-flux machines are well-studied topologies known to offer high power and torque densities. Their ability to exhibit higher active-material utilization, better overall cooling effectiveness and lower moment of inertia can render them competitive against their radial-flux counterparts [1]–[3]. Their compact design and favorable diameter-to-length ratio makes them a perfect fit for several applications, especially when the short axial length of the machine is critical [4].

Axial-flux induction machines (AFIMs) can demonstrate considerable benefits such as construction simplicity, mechanical robustness and reduced cost compared to axial-flux permanent-magnet structures [5], [6]. The high reliability and the non-dependence on rare-earth materials of AFIMs have lead many researchers to study thoroughly their structure and analyze their performance [7]–[10]. In order to balance the high arising axial forces between the stator and the rotor, it is preferable to opt for double-sided AFIM configurations [7], [11].

The electromagnetic design and analysis of AFIMs is commonly performed by employing numerical approaches based on the finite element method (FEM) [7], [12], [13]. The first step in the AFIM design process is the critical selection

of appropriate values for the geometrical and operational design parameters. With the aim to fulfill the required specifications, the main design parameters are usually determined using general sizing equations [14], [15]. However, it is common practice that the proposed sizing equations rely to a great degree on empirical factors and past experience and, thus, may lead to significant discrepancies between the analytical estimation and the numerical result [5], [16].

In [17], a preliminary electromagnetic sizing procedure for radial induction machines is introduced. The advantage of this procedure is that it adopts a geometrical approach to the design problem, while minimizing the use of empirical factors. Hence, the proposed sizing method results in reliable preliminary solutions that meet the required specifications.

Following the principles described in [17], a preliminary electromagnetic sizing algorithm for double-rotor AFIMs (DR-AFIMs) is introduced in this paper. The proposed algorithm can be easily adapted to accommodate for single-rotor AFIM designs. The paper can be outlined as follows: in Section II, the sizing equations for the main design parameters of the DR-AFIM topology are derived. Section III presents the outline of the preliminary DR-AFIM electromagnetic sizing algorithm while Section IV focuses on the numerical validation of the proposed algorithm by performing FEM simulations. Conclusions are drawn in the last section of the paper.

II. DESIGN PARAMETERS

A. Magnetic flux per pole

Assuming that the air-gap flux density B_δ is purely sinusoidal, it can be expressed as

$$B_\delta = \hat{B}_\delta \sin\left(\frac{p}{2}\theta - \omega_s t\right) \quad (1)$$

where $\hat{B}_\delta$ is the amplitude, p the number of poles, θ a mechanical angle spanning along the air-gap circumference and ω_s the angular electrical frequency.

Integrating (1) over the area of one pole, the fundamental air-gap magnetic flux per pole ϕ_p can be found for each air-gap as

$$\phi_p = \frac{(D_o^2 - D_i^2) \hat{B}_\delta}{2p} \quad (2)$$

where D_o is the outer diameter of the machine and D_i the inner diameter.

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The direction of the magnetic path of ϕ_p through the stator yoke to the two rotors is illustrated in Fig. 1, together with the main geometrical sizing parameters that will be introduced in the following subsections.

Fig. 1. The main magnetic flux paths and the design parameters in a DR-AFIM.

B. Rotor parameters

The maximum magnetic flux in the rotor yoke $\phi_{r,y}$ and the rotor tooth $\phi_{r,t}$ can be expressed as

$$\phi_{r,y} = \frac{\phi_p}{2} \quad (3)$$

$$\phi_{r,t} = \frac{\pi (D_o^2 - D_i^2) \hat{B}_\delta}{4Q_r} \quad (4)$$

where Q_r is the number of rotor slots.

Therefore, the axial length of the rotor yoke $l_{r,y}$ can be found as

$$l_{r,y} = \frac{2\phi_{r,y}}{(D_o - D_i) \hat{B}_{r,y} C_{r,lam}} = \frac{\hat{B}_\delta (D_o + D_i)}{2p \hat{B}_{r,y} C_{r,lam}} \quad (5)$$

where $\hat{B}_{r,y}$ is the maximum flux density in the rotor yoke and $C_{r,lam}$ the rotor-lamination stacking factor.

In this analysis, the width of the rotor slot is selected to be constant for different machine radii. With this approach, the moment arm is equal to the average of the inner and outer radii of the machine torus. Thus, the width of a rotor tooth varies with the machine radius. Considering that the maximum air-gap flux density is the same regardless of the radial position, and the ratio of rotor-tooth width to rotor-tooth pitch is smallest at the inner machine diameter D_i , the highest rotor-tooth flux density is found here. The width of the inner-diameter rotor tooth $w_{r,t,inner}$ is thus obtained

$$w_{r,t,inner} = \frac{\pi \hat{B}_\delta D_i}{Q_r \hat{B}_{r,t} C_{r,lam}} \quad (6)$$

where $\hat{B}_{r,t}$ is the maximum flux density in the rotor tooth.

Based on the above analysis, the rotor-slot width $w_{r,sl}$ can be determined using the expression

$$w_{r,sl} = \tau_{r,inner} - w_{r,t,inner} \quad (7)$$

where $\tau_{r,inner}$ is the rotor-slot pitch at the inner machine diameter D_i .

In addition, the rotor-slot height $h_{r,sl}$ is equal to

$$h_{r,sl} = \frac{A_{r,sl}}{w_{r,sl}} = \frac{\hat{i}_r}{\hat{J}_r C_{r,fill} w_{r,sl}} \quad (8)$$

where $A_{r,sl}$ is the area of the rotor slot, $\hat{i}_r$ the fundamental rotor-bar current amplitude, $\hat{J}_r$ the peak fundamental current density in the rotor bars and $C_{r,fill}$ the rotor-slot fill factor.

C. Stator parameters

On the stator side, the maximum magnetic flux in the yoke $\phi_{s,y}$ and the tooth $\phi_{s,t}$ can be expressed as

$$\phi_{s,y} = \phi_p \quad (9)$$

$$\phi_{s,t} = \frac{\pi (D_o^2 - D_i^2) \hat{B}_\delta}{4Q_s} \quad (10)$$

where Q_s is the number of stator slots.

Consequently, the axial length of the stator yoke $l_{s,y}$ can be obtained from the following equation

$$l_{s,y} = \frac{2\phi_{s,y}}{(D_o - D_i) \hat{B}_{s,y} C_{s,lam}} = \frac{\hat{B}_\delta (D_o + D_i)}{p \hat{B}_{s,y} C_{s,lam}} \quad (11)$$

where $\hat{B}_{s,y}$ is the maximum flux density in the stator yoke and $C_{s,lam}$ the stator-lamination stacking factor.

Considering a stator slot with constant width and similar assumptions as in the rotor case, the width of the stator-inner tooth $w_{s,t,inner}$ and the stator-slot width $w_{s,sl}$ are found as

$$w_{s,t,inner} = \frac{\pi \hat{B}_\delta D_i}{Q_s \hat{B}_{s,t} C_{s,lam}} \quad (12)$$

$$w_{s,sl} = \tau_{s,inner} - w_{s,t,inner} \quad (13)$$

where $\hat{B}_{s,t}$ is the maximum flux density in the stator tooth and $\tau_{s,inner}$ is the stator-slot pitch at the inner machine diameter D_i .

Assuming series-connected stator-windings, the required number of turns per stator slot n_s can be determined as

$$n_s = \frac{2\hat{E}_s}{\pi \hat{B}_\delta (D_o^2 - D_i^2) q_s f_s k_1} \quad (14)$$

where $\hat{E}_s$ is the amplitude of the fundamental induced stator-phase voltage, q_s the number of stator slots per pole per phase, f_s the synchronous frequency and k_1 the fundamental winding factor. In reality, an approximated integer value of n_s should be selected.

In (14), $\hat{E}_s$ can be substituted with

$$\hat{E}_s \approx \hat{V}_s - \Delta \hat{V}_s \quad (15)$$

where $\hat{V}_s$ is the fundamental stator-phase voltage amplitude and $\Delta \hat{V}_s$ the fundamental stator-phase voltage-drop amplitude [17].

From the above, the stator-slot height $h_{s,sl}$ can be estimated as

$$h_{s,sl} = \frac{A_{s,sl}}{w_{s,sl}} = \frac{n_s \hat{i}_s}{\hat{J}_s C_{s,\text{fill}} w_{s,sl}} \quad (16)$$

where $A_{s,sl}$ is the stator-slot area, $\hat{i}_s$ the amplitude of the fundamental stator phase current, $\hat{J}_s$ the peak fundamental stator current density (in the conductors) and $C_{s,\text{fill}}$ the stator-slot fill factor.

D. Electromagnetic torque and current requirements

The fundamental air-gap flux density $B_{rb,\nu}$ corresponding to the rotor bar in slot ν can be expressed as

$$B_{rb,\nu} = \hat{B}_\delta \sin\left(\frac{\pi p(\nu-1)}{Q_r}\right), \quad \nu = 1, 2, \dots, Q_r \quad (17)$$

Furthermore, the rotor-bar current $i_{rb,\nu}$ in the slot ν can be defined as

$$i_{rb,\nu} = \hat{i}_r \sin\left(\frac{\pi p(\nu-1)}{Q_r} - \theta_0\right), \quad \nu = 1, 2, \dots, Q_r \quad (18)$$

where θ_0 is the angular shift between the rotor-bar current and the induced rotor-bar voltage. Assuming that θ_0 is approximately zero at rated condition, the total induced electromagnetic torque T_e in the DR-AFIM can be found as

$$\begin{aligned} T_e &= 2C_{T_e} \sum_{\nu=1}^{Q_r} B_{rb,\nu} i_{rb,\nu} \frac{(D_o^2 - D_i^2)}{8} \\ &= \frac{C_{T_e} \hat{B}_\delta \hat{i}_r Q_r (D_o^2 - D_i^2)}{8} \end{aligned} \quad (19)$$

where C_{T_e} is a factor (typically in the range of 0.9 – 0.95 for radial-flux machines) introduced in [17] to account for the phase delay θ_0 , the machine friction losses and the impact of higher spatial harmonics.

If $\hat{i}_r$ is referred to the stator side, $\hat{i}_r'$ is obtained as

$$\hat{i}_r' = \frac{Q_r}{n_s Q_s k_1} \hat{i}_r. \quad (20)$$

Therefore, the required $\hat{i}_s$ can be estimated as

$$\hat{i}_s = \frac{\hat{i}_r'}{\cos \phi} \quad (21)$$

where $\cos \phi$ is the power factor.

E. Air-gap length

Using Ampère's law at no load condition, the effective air-gap length δ' can be obtained

$$\delta' = \frac{\mu_0 Q_s k_1 n_s \hat{i}_s \sin \phi}{\pi p \hat{B}_\delta}. \quad (22)$$

Hence, the air-gap length, δ can be determined as

$$\delta = \frac{\delta'}{C_{s,c} C_{r,c}} \quad (23)$$

where $C_{s,c}$ and $C_{r,c}$ are the Carter factors of the stator and the rotor, respectively [18].

F. Operating slip

The fundamental magnetomotive force (MMF) $F_{w,k}$ in the air-gap due to the stator current in phase k can be expressed as

$$F_{w,k} = \frac{2Q_s k_1 n_s i_{s,k}}{\pi p m} \sin\left(\frac{p}{2} \left(\theta - (k-1) \frac{4\pi}{mp}\right)\right) \quad (24)$$

where m is the number of phases in the stator winding. Thus, the total fundamental air-gap MMF due to the m -phase stator current excitation can be found

$$F_s = \frac{Q_s k_1 n_s i_s}{\pi p} \sin\left(\frac{p\theta}{2}\right) \quad (25)$$

as well as the total fundamental air-gap flux density B_s

$$B_s = \frac{\mu_0 F_s}{\delta'} = \frac{\mu_0 Q_s k_1 n_s i_s}{\pi p \delta'} \sin\left(\frac{p\theta}{2}\right) \quad (26)$$

Therefore, the magnetizing inductance L_m can be determined

$$\begin{aligned} L_m &= \frac{D_o^2 - D_i^2}{8i_{s,1}^2} \int_0^{2\pi} B_s F_{w,1} d\theta \\ &= \frac{(D_o^2 - D_i^2) \mu_0 Q_s^2 k_1^2 n_s^2}{4\pi \delta' m p^2}. \end{aligned} \quad (27)$$

The equivalent rotor-bar resistance R_r can be expressed as

$$R_r = R_b + (R_{\text{scr},i} + R_{\text{scr},o}) \left(\frac{Q_r}{\pi p}\right)^2 \quad (28)$$

where R_b is the rotor-bar resistance and $R_{\text{scr},i}$ and $R_{\text{scr},o}$ the resistances in the inner and outer short-circuit ring respectively [19].

Thus, the slip s at a selected operating point can be estimated using the electromagnetic torque expression in one of the two equivalent circuits of the DR-AFIM

$$\frac{T_e}{2} = \frac{mp}{4} L_m \hat{i}_s^2 \frac{\frac{L_m s \omega_s}{R_r'}}{1 + \left(\frac{L_m s \omega_s}{R_r'}\right)^2} \quad (29)$$

where R_r' is the rotor resistance referred to the stator side and is defined as follows

$$R_r' = \frac{n_s^2 Q_s^2 k_1^2}{Q_r m} R_r. \quad (30)$$

III. PRELIMINARY ELECTROMAGNETIC SIZING ALGORITHM

A. Design considerations

Based on the analytical derivations in Section II, DR-AFIM geometries that successfully meet the specified torque-capability requirements can be generated. It should be noted that the sizing equations can be easily adapted

to accommodate single-rotor AFIM designs. In this design process, certain aspects need to be further considered:

- The parameters D_i and D_o are determining factors during the design process of an axial-flux machine. The optimal value of the split ratio, $\lambda = D_i/D_o$, varies depending on the application [11], [14], [20]. Commonly-used values for AFIMs are in the range of: $0.5 \leq \lambda \leq 0.7$ [5], [9], [21].
- The electrical loading should be selected wisely, bound by thermal limitations arising from the winding insulation and the cooling of the machine [22]. As a measure of electrical loading, the peak fundamental linear current density $\hat{A}_s = \hat{J}_s/\tau_{s,inner}$ is used.
- The parameters $h_{s,sl}$ and $h_{r,sl}$ should be reasonably limited in order to avoid geometries with increased stator-slot and rotor-bar leakage flux.
- The cross-sectional area of the squirrel-cage short-circuit ring A_{scr} should be evaluated especially in the innermost diameter of the AFIM, in order to verify that there is enough available space between the rotor core and the shaft. If the current density in the short-circuit ring is assumed equal to the current density in the rotor bars, A_{scr} can be approximated as:

$$A_{scr} = \frac{Q_r A_{r,sl}}{\pi p}. \quad (31)$$

- In this analysis, non-skewed rotor bars are considered. In order to incorporate the skewing effect, an equivalent rotor-bar area should be approximated depending on the skew angle that is selected [3].

B. Design algorithm outline

Taking into account the design considerations outlined in Section III-A, a preliminary sizing algorithm of DR-AFIM geometries can be developed. This algorithm should reiterate in order to examine all possible candidate geometries within the specified boundaries of D_i and D_o . In each iteration, the design algorithm consists of the following steps:

- **Step 1:** Selection of incrementally larger D_i within its specified limits.
- **Step 2:** Selection of incrementally larger D_o that respects the predefined limits of λ , $[\lambda_{min} \lambda_{max}]$. If λ exceeds these limits, the algorithm should restart at step 1.
- **Step 3:** Calculation of $l_{r,y}$, $w_{r,t,inner}$ and $w_{r,sl}$ according to (5)-(7). If $w_{r,sl} < 0$, the algorithm should return to step 2 and proceed to the next iteration.
- **Step 4:** Derivation of $\hat{i}_r$ based on the specified torque requirement from (19).
- **Step 5:** Computation of $A_{r,sl}$ and $h_{r,sl}$ according to (8).
- **Step 6:** Estimation of n_s from (14) and approximation to the closest integer number.
- **Step 7:** Derivation of $\hat{i}_r'$ and $\hat{i}_s$ according to (20) and (21) respectively.

Fig. 2. Outline of the proposed preliminary electromagnetic sizing algorithm for DR-AFIM geometries.

- **Step 8:** Calculation of $l_{s,y}$, $w_{s,t,inner}$ and $w_{s,sl}$ according to (11)-(13). If $w_{s,sl} < 0$, the algorithm should return to step 2 and proceed to the next iteration.
- **Step 8:** Computation of $A_{s,sl}$ and $h_{s,sl}$ according to (8).
- **Step 9:** Calculation of $\hat{A}_s$. If $\hat{A}_s$ exceeds its selected limits, the algorithm should restart at step 2.
- **Step 10:** Selection of δ based on (23).
- **Step 11:** Estimation of s at the selected operating point based on (29).

The outline of the design algorithm is illustrated in the flowchart of Fig. 2. In this flowchart, indices i and j are the iteration counters of the examined D_i and λ respectively.

IV. ANALYTICAL RESULTS

TABLE I
SET 1 DR-AFIM SPECIFICATIONS

Mechanical power, P_m (kW)	20
Torque, T_e (Nm)	140
Number of poles, p (-)	4
Number of phases, m (-)	3
Number of stator slots, Q_s (-)	36
Number of rotor bars, Q_r (-)	30
Electrical frequency, f_s (Hz)	50
Peak stator current density, $\hat{J}_s$ (A/mm ²)	5
Peak rotor-bar current density, $\hat{J}_r$ (A/mm ²)	4
RMS phase voltage, V (V)	400

A set of design specifications for a DR-AFIM are tabulated in Table I. In order to generate suitable geometries for these specifications, the preliminary sizing algorithm outlined in the previous section is used. In this study, the parameters λ and $\hat{A}_s$ are set within the range of: $0.5 \leq \lambda \leq 0.7$ and $24 \text{ kA/m} \leq \hat{A}_s \leq 40 \text{ kA/m}$, in accordance to relevant literature. Maps of the main design parameters (axial length L_a , outer torus diameter D_o , rotor current $\hat{i}_r$, air-gap length δ as well as area of the torus, $\hat{A}_{\text{torus}} = \pi(D_o^2 - D_i^2)/4$) are illustrated in Figs. 3 – 6. These maps can serve as a useful tool to determine fundamental geometrical quantities for desired intersection points on the provided variation grids of λ , $\hat{A}_s$ or $\hat{i}_r$.

Fig. 3. Diameter ratio λ and linear current density $\hat{A}_s$ variation grid with respect to axial length L_a and torus area $\hat{A}_{\text{torus}}$ in the DR-AFIM designs.

V. NUMERICAL VALIDATION

The designs obtained from the sizing algorithm are validated in terms of torque capability via 2D FEM analysis. For

Fig. 4. Diameter ratio λ and linear current density $\hat{A}_s$ variation grid with respect to outer diameter D_o and rotor current $\hat{i}_r$ in the DR-AFIM designs.

Fig. 5. Rotor current $\hat{i}_r$ and linear current density $\hat{A}_s$ variation grid with respect to axial length L_a and diameter ratio λ in the DR-AFIM designs.

Fig. 6. Diameter ratio λ and linear current density $\hat{A}_s$ variation grid with respect to air-gap length δ and axial length L_a in the DR-AFIM designs.

the comparison, the DR-AFIM designs satisfying the specification set 1, as tabulated in Table I, are utilized. In total, approximately 2000 designs are simulated and compared. The respective distribution of the torque error, ϵ_{T_e} , is depicted in Fig. 7. Positive error quantities indicate torque values higher than the reference and vice versa. The absolute error values are below 5% for all simulated sets of variables.

In addition, the comparison between the magnetic flux density values specified in the preliminary sizing algorithm and the respective values estimated by FEM is performed. The sampling points are shown in Fig. 8 for two different combinations of machine configurations and specification sets, listed in Table I and Table II. The calculated error values, as tabulated in Table III, follow the same trends for the different specification sets and lie within reasonable ranges. Aligning with the torque-error definition, the same convention applies here.

TABLE II
SET 2 DR-AFIM SPECIFICATIONS

Mechanical power, P_m (kW)	30
Torque, T_e (Nm)	300
Number of poles, p (-)	6
Number of phases, m (-)	3
Number of stator slots, Q_s (-)	36
Number of rotor bars, Q_r (-)	30
Electrical frequency, f_s (Hz)	50
Peak stator current density, $\hat{J}_s$ (A/mm ²)	5
Peak rotor-bar current density, $\hat{J}_r$ (A/mm ²)	4
RMS phase voltage, V (V)	400

The results show a good agreement between the analytical and the numerical method, both in terms of torque capability and magnetic loading of the machines. Therefore, the accuracy and performance prediction capability of the implemented algorithm are validated.

VI. CONCLUSION

In this paper, a preliminary electromagnetic sizing algorithm for double-rotor axial-flux induction machines is presented. This algorithm is based on a geometrical approach, avoiding to a great extend the use of empirical factors and

Fig. 7. Comparison between the specified T_e and the numerically computed $T_{e,FEM}$ for DR-AFIM geometries with different diameter ratio λ and linear current density $\hat{A}_s$.

TABLE III
COMPARISON BETWEEN THE MAGNETIC FLUX DENSITY VALUES SPECIFIED IN THE PRELIMINARY SIZING ALGORITHM AND THE RESPECTIVE FEM VALUES AT THE INNER TORUS DIAMETER

Parameter	Specified	Set 1 specs	Set 2 specs	FEM point
$\hat{B}_\delta$	0.7 T	0.76 T (+8.6%)	0.73 T (+4.3%)	a
$B_{s,t}$	1.6 T	1.59 T (-0.6%)	1.57 T (-1.9%)	b
$B_{s,y}$	1.4 T	1.43 T (+2.1%)	1.48 T (+5.7%)	c
$B_{r,y}$	1.4 T	1.36 T (-2.9%)	1.31 T (-6.4%)	d
$B_{r,t}$	1.4 T	1.38 T (-1.4%)	1.34 T (-4.3%)	e

past experience. A detailed derivation of the sizing equations for all the main geometrical and operational machine parameters as well as a concise outline of the electromagnetic sizing algorithm is presented. An extensive comparison between the analytically estimated and the numerically computed performance of DR-AFIM designs is performed. The achievement of the targeted torque and magnetic field values in the resulting designs renders the proposed sizing algorithm an accurate tool in the initial design process of DR-AFIMs.

Fig. 8. Magnetic vector potential isovalue lines and magnetic flux density colour map for 2 DR-AFIM designs that meet the set 1 and set 2 specs.

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VII. BIOGRAPHIES

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