Conference Paper

The application of slotless skewed windings to a rim driven fan for aircraft electrical propulsion (AEP)

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The Application of Slotless Skewed Windings to a Rim Driven Fan for Aircraft Electrical Propulsion (AEP)

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***Abstract*—This paper investigates the slotless winding characteristics of motors intended for aircraft electrical propulsion (AEP), together with a preliminary design study of a winding model derived from a Faulhaber configuration. Geometrical relationships and magnetic requirements driving the design, such as the width of each phase coil side, the skew angle, and the winding arrangement, are analysed. Finally, electromagnetic (EM) simulations were conducted to study the electromagnetic performance of the Faulhaber model and the influence of the stator conductor skewness. Upon analysis of the results, it is found that the skew angle should remain low to assure efficiency, while it should also be great enough to satisfy the geometric and magnetic requirements. In conclusion, the paper proposes a hybrid slotless winding configuration based on the Faulhaber structure, which is a trade-off between efficiency and end-winding length for a motor powering a rim driven fan.**

***Keywords*—electrical propulsion, high-speed electric motor, EM simulation, slotless windings, rim driven fan**

I. Introduction

The rising awareness about climate change is leading human activities to engage in a transition toward more environmentally friendly processes. While this change is taking place in many sectors, the aviation industry is tending to evolve through the development of new technologies that could make electric or hybrid flight viable [1]-[3]. In fact, the entire power chain from energy storage and inverters to electromechanical actuators is required to be safe, efficient, and lightweight. Several architectures of electrically powered aircraft propulsion systems have already been devised with hybrid and full electric architectures [4],[5]. Subsequently, the studies of components and devices belonging to the propulsion system of hybrid and full electric aircraft are increasingly worthy of consideration since their use can be extended to the next generation of electric aircraft. Therefore, electric motor topologies specifically designed for aircraft propulsion need to be re-evaluated to reach the next steps of electric flight.

Conventional slotted motors are widely used for a large variety of industrial, domestic, and transportation applications; prototypes of electric aircraft and drones also mainly use this motor topology [4],[6]. Slotless motors have rarely been considered for aircraft electrical propulsion (AEP) despite their possible benefits in terms of weight, harmonic reduction, vibration reduction and operational performance [4],[7]-[9]. To date, slotless windings have been mainly used with small high-speed motors. This type of winding can be integrated into reluctance, induction, and synchronous ac motor architectures.

However, aerospace propulsion applications require large motors with high power density and efficiency. As a promising solution, thin and large motors for new multistage contra-rotating rim driven fan (RDF) configurations are considered in [4],[10].

This paper aims to evaluate a skewed slotless winding configuration applicable to the requirements for aerospace propulsion applications using a high-speed rim driven fan proposed in [11],[12]. The study focuses on the electromagnetic (EM) behaviour of the winding and its geometric parameters. The EM simulations are performed with ANSYS MotorCAD.

II. Slotless Winding Model

A. Choice of Winding Structure

This section describes the selection of an appropriate winding structure for aerospace propulsion applications. The main purpose of the stator winding is to generate a rotating magnetic field. Therefore, the winding geometry directly influences the characteristics of the rotating field [13]. In the case of a slotless design, the magnetic field produced by the windings is more uniform than in a slotted winding motor [14]. The coils of the slotless winding are arranged more evenly and continuously around the stator perimeter, providing an improved distribution of the quasi-sinusoidal magnetic field since the iron teeth are excluded from the motor design.

Additionally, slotless windings can be installed in the motor airgap area and the conductors can be skewed to exclude the end windings, which are part of the winding that does not create useful torque [8],[9].

The benefits related to the uniform characteristics of the magnetic field and the possible reduction of end-windings are smooth operating behaviour and improvement of performance and reliability.

The smooth operating behaviour discussed in [6],[7],[15],[16] includes the following advantages:

- Reduced noise, vibration, and harshness.
- Reduced torque ripple and no reluctance cogging torque.

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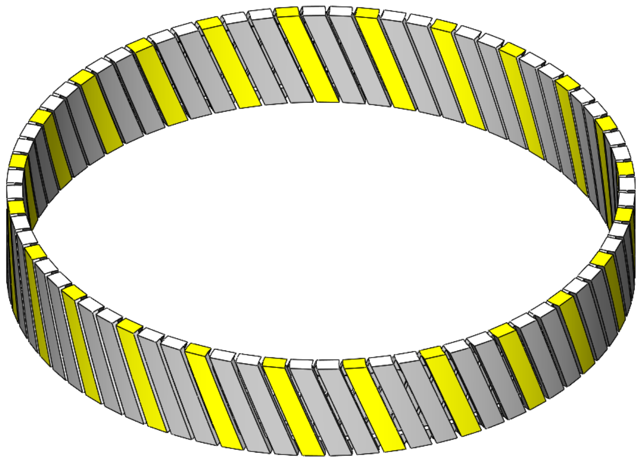
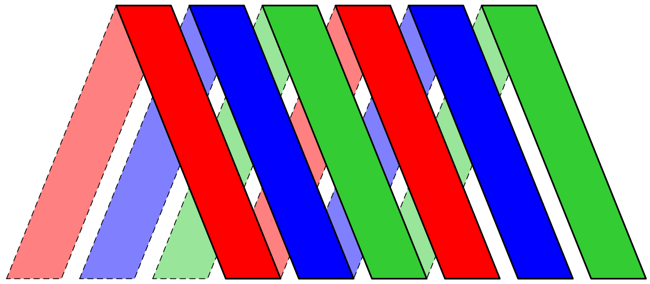


(a)



(b)

Fig. 1. Skewed slotless structure model for AEP rim driven fan: (a) 3D representation; (b) planar representation.

- No vibration of the windings inside the slots.
- Balanced magnetic pull which is especially desirable at high-speed operation to eliminate the rotor and stator resonance issues.

As discussed in [7]-[9], motor performance and reliability are improved due to the slotless winding arrangement. The improvements are formulated as follows:

- The local variations of reluctance in the azimuthal direction are neglected due to the teeth and slots absent, which suppresses the induced asynchronous harmonics, reduces the eddy current losses and rotor heating, and hence extends the magnetic limit.
- PM slotless configurations are less sensitive to rotor demagnetisation due to the reduction of rotor heating; hence, the power is only limited by the thermal limit and the cooling capabilities.
- The magnetic circuit of the slotless motor operates at a reduced saturation ensuring a proportional relation between the motor current and the shaft torque. In slotted motors, the teeth are saturated at the current close to the rated value; therefore, applying an overcurrent has a minimal impact on the increase in torque output, but results in the temperature increasing. Hence, the slotless winding arrangement provides a better peak loading behaviour.
- At high-speed operation, the magnetic loss is dominant over conductor loss; skewed slotless windings are more efficient since there are no end connections, whereas at low speed the slotless straight windings are preferable.
- The skewed windings having no end-windings ensure reduced coil resistance and armature power loss.
- Weight reduction as there is no need for extra iron for teeth .

B. Model Topology

Among the numerous topologies of slotless winding structures (skewed, rhombic, and diamond), this study is focused on the skewed slotless structure (Fig. 1). Different sources refer to this structure as skewed or zigzag [17]; however, in this paper, the authors refer mainly to it as Faulhaber [18].

The windings aim is to be incorporated into a motor powering a rim driven fan, therefore the winding sizing is very different from the research done in this field. The sizing requirement is driven by the need for multiple-stage contrarotating fans to maximise the thrust produced [1],[10]. The axial length of the winding should be short and the diameter should be large to accommodate the fan.

The case of interest is a surface mounted Halbach array of permanent magnet ac synchronous motor (SMPM) as shown in Fig. 2. Several studies [2],[6],[19]-[21] determined the suitability of this configuration for AEP due to its high-power density and efficiency. In this study, a three-phase

TABLE I. MOTOR SIZING

Rim radius	R_{rim}	100 mm
Shaft exterior radius	R_{shaft}	107 mm
PM exterior radius	R_M	110mm
Sleeve exterior radius	R_{sleeve}	111 mm
Airgap length	t_{air}	1.5 mm
Winding exterior radius	R_w	118.5 mm
Winding thickness	t_w	6 mm
Stator Iron exterior radius	R_{iron}	245 mm
Winding axial length	h	50 mm

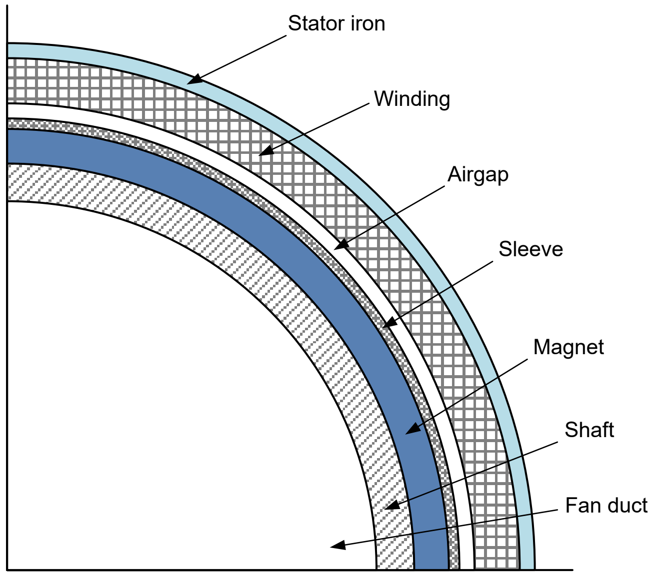
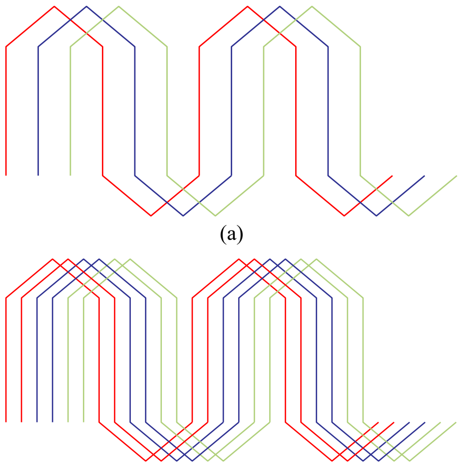


Fig. 2. SMPM motor structure axial view for RDF.



(a)

(b)

Fig. 3. Wave winding pattern 4 poles 3 phases:
(a) 1 slot per pole per phase, (b) 2 slots per pole per phase.

skewed slotless winding is considered. Motor sizing is given in Table I and is based on data from [10] for a dual-stage rim driven fan for AEP.

C. Simplifying Assumptions

The modelling has been conducted under the following simplifying assumptions:

- The skew angle is defined as the angle between a conductor and the line traced at a given azimuthal location. The absolute value of the skew angle is the same for all phases.
- To establish the geometrical requirements and due to the large diameter of the winding compared to its axial length, the cylindrical shape is transformed into a planar model where the curvature is ignored.
- For 3D electromagnetic simulations, the magnetic interactions between the layers are neglected, and it is assumed that a conductor skew angle direction does not influence the equivalent magnetic field produced in the radial direction. The modelling of complex 3D skewed structures is not supported on Ansys MotorCAD. Subsequently, although a model with slotless skewed conductors is used, the conductors are parallel with the same skew angle.
- For 3D electromagnetic simulations, each skewed coil side is located at its mean azimuthal location, therefore the use of a single layer winding is possible since all coil sides are located at a different azimuthal location around the stator. The fill factor for each phase coil side is conserved.

III. Methodology

A. Winding Layout Arrangement

In general, the conductor arrangement of skewed windings is similar to the slotted wave winding design (Fig. 3). Contrary to other types of winding arrangement, such as lap and concentric windings, this arrangement does not involve loops, where the end-windings are located only on one side of the windings, between each coil side of each phase. Therefore, the end windings can be eliminated or greatly reduced by skewing the conductors.

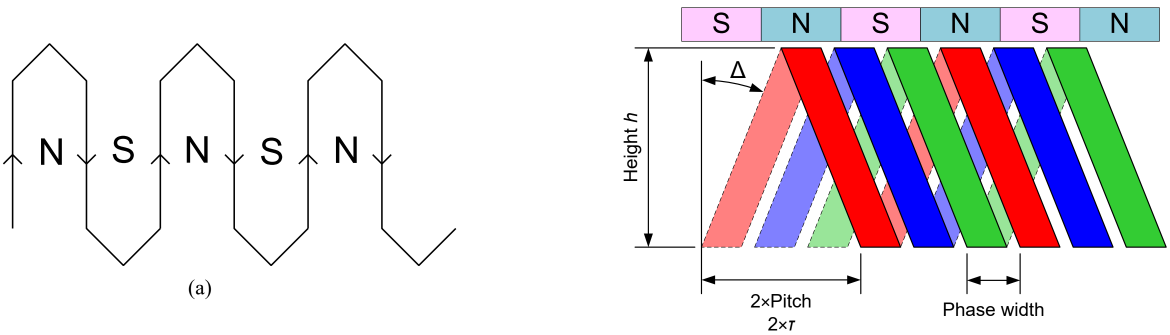
Various winding design methods have been developed and have been the subject of extensive research for many years. The procedure developed in [22] allows for determining a Winding Distribution Table (WDT) which can be used to define the winding layout arrangement for symmetrical windings regardless of the end-winding locations. This procedure is used to establish the winding arrangements for various combinations of poles and slots.

Fig. 3 shows that the factor that modifies the arrangement for wave winding is the number of slots per pole per phase (Q). It can be seen that Q drives the number of consecutive similar phase wave patterns in adjacent slots. However, due to the slotless nature of the windings, the term "slot" refers to a division of the stator perimeter. Consequently, for the same configuration, a higher value of Q expresses a higher value of the slot number having a smaller size of each slot. As there is no physical barrier between "slots", the adjacent similar phase wave patterns can be merged, and the model can be described as wave windings with $Q = 1$ since Q adjacent slot widths are equal to the width of one slot if $Q = 1$.

Therefore, it can be assumed that the skewed slotless winding arrangement is only affected by the number of poles and phases. The former requires adding or removing wave patterns, the latter influences the number of coil sides between each similar phase coil side.

B. Faulhaber Structure Geometric Requirements

The winding is composed of two layers. One layer is made of positively skewed conductors, while the conductors of another layer are negatively skewed. The connection between each coil side is made on the top and bottom faces of the windings (Fig. 4b). There are trigonometric relationships between the axial length, length, skew angle, and phase width of the windings of each phase. For wave windings, each pattern generates a pair of poles (Fig. 4a), therefore a high number of poles implies more "waves", therefore, a narrower skew angle and thinner phase width. Similarly, a short winding perimeter and a long winding axial length require a low skew angle.



(a)

(b)

Fig. 4. (a) single phase wave winding and corresponding magnetic poles; (b) three-phase slotless skewed windings.

These relationships are described as:

$$\tau = \frac{L}{p} \quad (1)$$

$$w = \frac{2 \times L}{m \times p} = \frac{2\tau}{m} \quad (2)$$

$$\Delta = \tan^{-1}\left(\frac{\tau}{h}\right) \quad (3)$$

where τ is the pitch length, L is the length of the windings, p is the number of poles, w is the phase width, m is the number of phases, Δ is the skew angle, h is the windings axial length.

In slotless windings derived from the Faulhaber model having a fixed skew angle, the end-winding length could be greater than zero. Thus, (3) becomes:

$$\frac{l_{EndWing}}{2} + h \times \tan\Delta = \tau \quad (4)$$

where $l_{EndWing}$ is the end-winding length for one wave pattern.

IV. Results and Discussion

A. *Skew Angle Influence on Motor Performances*

The skew angle is a fundamental parameter in regard to the radial magnetic field generated by each conductor. The torque produced depends on the radial magnetic field strength; therefore, by skewing the winding, the magnetic flux is weakened. This phenomenon is the result of magnetic field division into several components, namely, the radial field and unwanted transverse fields [23].

The MotorCAD EM simulation results shown in Fig. 5a and Fig. 5b highlight that the reduction of the radial flux implies a reduction of the output power and, therefore, a reduction of efficiency and shaft torque. However, the relationship between the torque, the efficiency, and the skew angle are not proportional. Although the electromagnetic power decreases with the increase of skew angle, for low skew angles, the electromagnetic properties such as torque and efficiency are less affected. This behaviour, explained as the total loss value, is also not proportional to the skew angle (Fig. 5d), whilst the Joules effect loss is increased while the skew angle, the armature ac loss, and the stator iron loss are decreased. It can be assumed that the Joule effect loss increases with the length of the windings. Consequently, the skew angle is not responsible for the increase in Joule losses. Therefore, a winding structure that suppresses or reduces the end-windings such as the Faulhaber configuration will reduce the total losses with the increase of skew angle. As a result, for low angles, loss reduction benefits offset the weakened flux due to the conductor skewness, whereas at high angles, the flux weakening is dominant.

AEP applications require high efficiency above 90%, therefore, skewed winding designs are required to have a low skew angle.

Skewing the conductors also lowers the back EMF and the torque ripple experienced. However, Fig 5c shows that the percentage of torque ripple compared to the torque

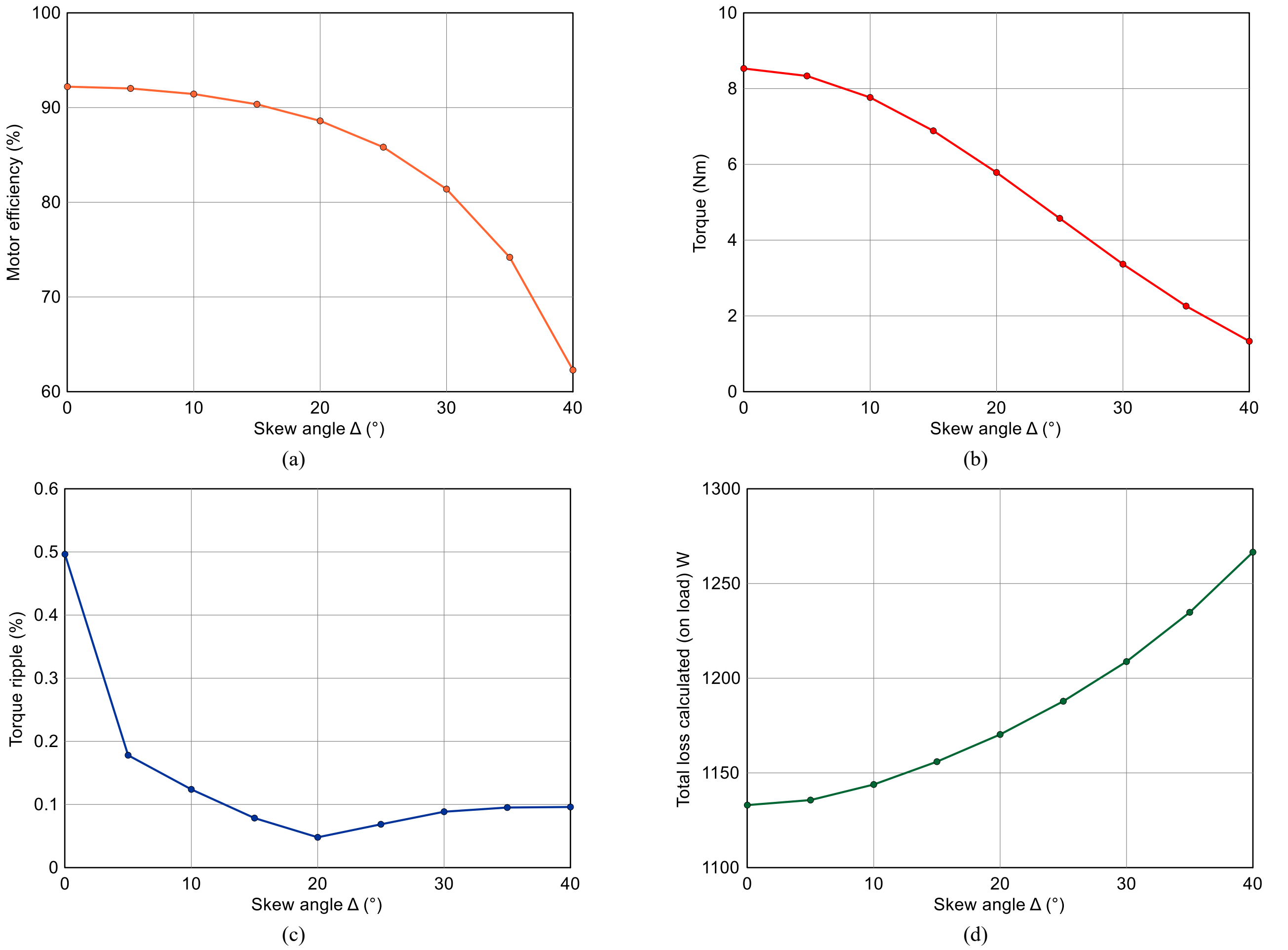


Fig. 5. 3-phase, 12 poles wave winding motor characteristics vs skew angle: (a) efficiency; (b) torque; (c) torque ripple; (d) total loss calculated (on load).

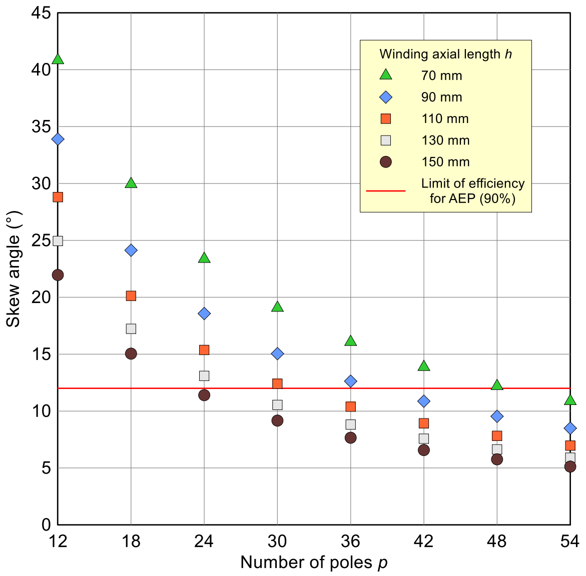


Fig. 6. Skew angle versus numbers of poles for various Faulhaber winding axial lengths and a fixed winding mean diameter of 231mm.

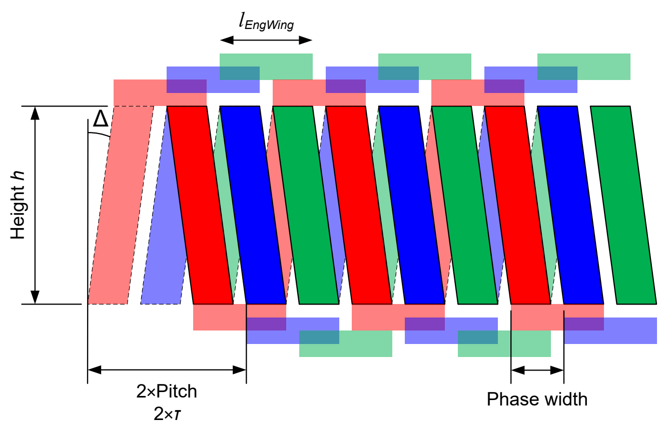


Fig. 7. Optimised slotless hybrid 3-phase windings planar model.

generated is drastically lowered by the skew of the stator conductors until stabilisation around 20° of skewness.

It was considered that further investigations and more precise simulations are required to establish the loss of efficiency related to the skew angle and the better trade-off between efficiency and skew angle.

B. Faulhaber Model for Rim Driven Fan

The Faulhaber winding model could theoretically be a promising candidate for AEP. Indeed, the suppression of end-windings increases the efficiency and provides an armature weight reduction, while stator skew allows for

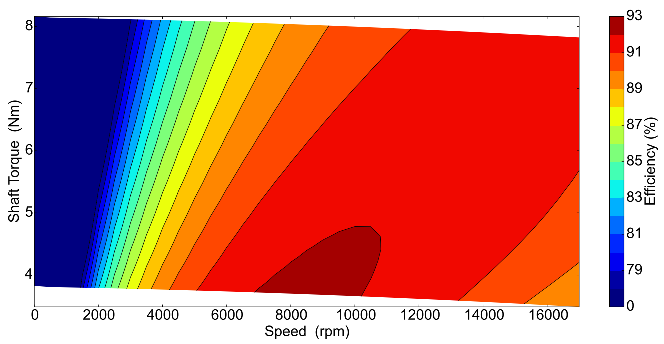


Fig. 8. Torque vs speed efficiency map for the optimized slotless design.

TABLE II. FAULHABER WINDING CONFIGURATION

Number of poles	p	48
Windings axial length	h	80 mm
Number of phases	m	3
Skew angle	Δ	10.7°

TABLE III. HYBRID OPTIMIZED WINDING MOTOR CHARACTERISTICS AND PERFORMANCES COMPARED TO SLOTTED LAP WINDING MOTOR

Motor Characteristics	Slotted 72 slots lap windings	**Optimized hybrid slotless windings**
Specific Power (kW/kg)	4.063 kW/kg	**4.686 kW/kg**
Efficiency (%)	91.257%	**91.187%**
RPM	15,000 rpm	**15,000 rpm**
DC Bus Voltage	440V	**600V**
Max Current (Peak)	40A	**32A**
Shaft Torque (Nm)	7.0898 Nm	**7.4437 Nm**
Number of poles	12	**12**
Number of phases	3	**3**
Skew angle (°)	0°	**12°**
Windings axial length (mm)	40 mm	**40 mm**
Armature mass reduction compared to straight conductors (%)	/	**7.57%**
End-windings length reduction compared to straight conductors	/	**14.06%**
Torque ripple (%)	33.082%	**0.0482%**

smoother operation. However, to meet the AEP requirements regarding efficiency, the skew angle should be less than 12°.

According to (1)-(3), the skew angle can be reduced by 3 factors:

- Increasing the number of poles.
- Diminishing the circumferential length of the windings (i.e., the motor diameter).
- Augmenting the axial length (h) of the motor windings.

However, if the physical dimensions of the windings are fixed, the number of poles should be adjusted to obtain a skew angle in the 0° to 12° envelope (Fig. 6).

For example, a configuration based on RDF sizing is shown in Table II. This configuration provides an armature weight reduction of 14.41% compared to an unskewed model with end-windings.

However, no satisfactory results of the EM simulation provided the required performance for the AEP in terms of efficiency and torque with a large number of poles.

C. Optimised Hybrid Windings for RDF

To overcome the issue related to the efficiency skew angle relationship, a slotless configuration based on the Faulhaber model is tested (Fig. 7). The model topology is similar to the design described in Section III(B). However, the skew angle is fixed; therefore, the length of the end-windings is greater than 0 as established in (4).

Consequently, this model is less restrictive than the traditional skewed model and it provides the best compromise between the characteristics of Faulhaber windings and unskewed slotless windings.

A model based on the hybrid configuration and the sizing of Table I offers satisfying results regarding AEP RDF requirements, as shown in Table III and Fig. 8.

V. Conclusion

With the benefits of the review of the slotless winding structure for AEP, this study has developed a method to design a Faulhaber slotless winding structure based on the magnetic and geometric characteristics of an electric motor. The application of this method shows the limits of the use of skewed slotless configurations without end-windings for motors powering multistage rim-driven fan applications. In fact, a large and thin motor sizing requires a large number of poles to maintain a narrow skew angle to provide high efficiency. However, the EM simulation assessment of a 48-pole Faulhaber winding for AEP RDF applications demonstrated poor results at the speed considered (15,000 RPM). Consequently, a hybrid configuration was proposed based on the Faulhaber model. This slotless geometric layout is driven by the skew angle; hence the efficiency can be met without drastically increasing the number of poles. Although this optimised shape includes end-windings, they are reduced by the selected skew angle. The EM simulation assessment has shown promising results; however, more precise and complete simulations are required to confirm its viability for AEP RDF applications.

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