Flat winding made of aluminum or copper sheet for axial flux machines

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Abstract
A novel flat winding topology has been proposed as an alternative to conventional windings with stranded round wires and other bar wound windings. The proposed winding is manufactured from thin conductor sheets by industrial tools such as stamping press, laser cutter, or water jet. As these tools are widely used in the production of electric machines, the flat winding topology can provide ease of manufacturing without significant modification to the production line. Besides, superior current ratings, shortened end windings, and high fill factors are other advantages of flat winding. Its performance is measured by comparison study between flat wired prototype machine and the stranded wired machines with similar ratings presented in the literature. The proposed winding is implemented on an axial flux permanent magnet machine. Analytical modeling is presented, including field modeling, voltage, torque derivations, and loss modeling. Then, experimental verification of a 1.4-kW and 26-Nm prototype with copper and aluminum flat windings is presented, and the performances of two are compared.

1 | INTRODUCTION

It is well-known that the winding of an electric machine significantly affects the performance of the machine by determining critical parameters such as current density, fill factor, or winding losses. Therefore, researchers have paid significant attention to the novel winding topologies with the increasing demand for high-performance and cost-effective electric machines. With that motivation, a novel winding topology, called flat winding, is presented as an alternative to the conventional windings with stranded round wires. The proposed winding is made of a thin conductor sheet (such as copper) with a thickness of 1-2 mm.

Compared with conventional windings with stranded round wires, the flat winding topology proposes the following advantages:

- Flat winding provides ease of manufacturing because it can be manufactured using widely used industrial tools such as stamping press, laser cutter, or water jet. These tools are commonly used in the manufacturing of electric machines, therefore the flat winding can be manufactured easily without significant modification on the production line.
- Flat winding is made of many flat wires with a large cross-sectional area compared with stranded round wires, enabling to achieve superior current ratings, without any need for parallel connections, which eliminates the circulating current risk.
- Due to its rectangular shape, and large cross-sectional area, flat winding significantly improves the fill factor and torque density.
- The end winding length is reduced with this topology. Therefore, end winding losses are reduced, increasing efficiency.

The presented flat winding is a candidate to be used in many electric machine topologies. It is implemented on an axial flux permanent magnet (PM) air-cored machine. The authors of this paper have presented a PM linear machine with the proposed winding in [1]. The electric machine designed with flat winding can be used in applications requiring high current ratings, such as traction or renewable energy applications.

Nowadays, hairpin, or sometimes called bar-wound or flat winding, is widely studied [2–4]. In fact, this type of winding is commercialized in traction applications, such as in Toyota Prius [5] and Chevrolet Volt [6]. The superiorities and the main benefits are:

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differences of the proposed flat winding over hairpin winding are as follows:

- While hairpin winding is manufactured from readily available and enameled bar-wound conductors, the flat winding is manufactured from thin conductor sheets by cutting and bending operations.
- Since the flat winding is made of a thin conductor sheet, it has a smaller thickness to width ratio than hairpin winding. To illustrate, the hairpin winding used in 2017 Prius motor has dimensions of $2.24 \times 3.81$ mm [7]; however, the prototype in this study has dimensions of $1 \times 5$ mm.
- Related to the point above, hairpin winding suffers from elevated AC losses on windings due to its large cross-sectional area and requires improved cooling. However, since flat wire in this study is made of thin conductor sheet and stacked through thickness in the circumferential direction, AC losses are significantly reduced, as shown experimentally in Section 4.
- The winding material can affect the efficiency, cost, and mass of an electric machine as will be evaluated in Section 5. The conductor sheets with different materials, such as aluminum, are widely available. This provides the flexibility in material selection of the proposed flat winding, which is made of a thin conductor sheet. However, the aluminum hairpin winding is not preferred due to mechanical problems and currently not available in the market.

As an alternative to the mentioned winding topologies, there are also other uncommon winding topologies studied in the literature. For example, in [8,9], casting production of electric machine windings is proposed; however, similar to hairpin windings, they also suffer from elevated AC losses. Lomheim in [10] presents a winding design, which is manufactured from 4-mm-thick copper using water jet. Different from the proposed winding, in [10], the entire winding of a phase is manufactured as one piece, and overlapping regions are milled using computer numerical control (CNC) machine, which leads to the non-uniform cross-sectional area through the coil. The design in [10] suffers from AC losses with a measured efficiency of 25%. Lastly, there are examples, in which the windings are printed on a printed circuit board (PCB) [11,12]. Compared with flat winding, PCB winding is not suitable for kW-range power applications due to the limited number of copper layers, and copper thickness on PCB. Also, it is not cost-effective compared to the flat winding topology.

This study is organized as follows. In the following section, the topology employing flat winding stator is introduced. In Section 3, analytical modeling of the presented machine is delivered. In this section, field modeling, voltage, torque derivations, and analytical loss modeling are presented. In Section 4, experimental verification of the model is followed with 1.4-kW prototype. Lastly, copper and aluminum are evaluated as flat winding material in terms of losses and efficiency, both analytically and experimentally.

2 | THE PROPOSED DESIGN

Flat winding topology is implemented on the axial flux PM machine in this study. It has a double-sided rotor with surface mounted NdFeB magnets, and one air-cored stator, as shown in Figure 1. Also, mechanical assembly with other machine parts is depicted in Figure 2. The stator is made of novel flat wire topology and coated with epoxy for mechanical integrity. Unlike the conventional axial flux machines that use sector-shaped magnets, the magnets are placed on rotor discs in diagonal structure, as shown in Figure 3. This structure enables the use of flat windings and reduces the end winding length. In the figure, it can be seen that the end windings are shorter compared with the conventional stranded-wired stators.

At this point, the selection of the PM or pole shape needs further investigation. The conventional sector-shaped PMs are not suitable for the flat winding topology, which is shown in Figure 4. Note that the usage of the conventional sector-shaped PMs results in the cancellation of the torque produced on the flat wire conductors numbered 1 and 2 because they are under the effect of the same pole although they carry current at different directions. To prevent the torque cancellation on conductors 1 and 2, the pole area should be within the first region shown in Figure 4. Similarly, to prevent the torque cancellation on conductors 2 and 3, the pole area should be within the second region. Therefore, the actual pole area should be within the third region, which is the intersection of the first and second regions. The maximum torque and flux linkage are obtained by full utilization of the allowed pole area. Thus, in the proposed design, diagonally placed PMs are used on the rotor side.

The manufacturing steps of flat wire are shown in Figure 5. It is made of a 1-mm thick conductor sheet. The conductor sheet should be thin as eddy current losses or AC losses increase with the thickness of the conductor. The piece shown in Figure 5b is cut from the conductor sheet in Figure 5a using planar cutting tools such as stamping press, laser, or water-jet.

![Figure 1](image-url) Axial flux PM machine with flat winding stator
In Figure 6, a photo is shown, which is taken during the manufacturing of flat wire using a laser cutter. The cut piece is then bent to give the form in Figure 5c,d. This piece is named the flat wire, and several flat wires compose the flat winding. The single loop of flat winding comprises four flat wires, as shown in Figure 3. They are welded to each other at the end windings for electrical connection. The desired number of flat wires can be connected in series according to voltage and current specifications. The three-phase stator made of flat wires is shown in Figure 7. To have mechanical rigidity, the windings are mold inside the epoxy. Isolation papers are placed between two adjacent conductors for electrical isolation.

To increase the winding factor of the three-phase stator, instead of three-phase configuration with a phase difference of 120°, six-phase configuration with a phase difference of 60° is preferred. Then, the phases with 180° phase difference are connected in reverse polarity in series, and three-phase stator configuration with a phase difference of 120° is achieved. This adjustment provided 3.5% increase in the winding factor and thus rated voltage for the manufactured prototype.

There are two main challenges for the proposed design. The number of loops made of flat wires is limited due to space limitations in the circumferential direction, which reduces the induced voltage magnitude. In order to overcome this problem, all of the loops in a phase are connected in series. Another challenge for the proposed design is the eddy current losses. It is known that eddy current losses on windings due to external PM field, whose analytical derivation will be given in the following section, are proportional to the cross-sectional area of the conductors perpendicular to flux passing direction. To limit these losses, flat wires are stacked through thickness in the circumferential direction, and a thin conductor sheet is used, resulting in a reduction of eddy current losses on windings due to external PM field.
alternatives. This example shows the advantage of flat winding in terms of losses and efficiency in addition to other advantages such as ease of manufacturing. Thus, one can conclude that the proposed flat winding is a promising alternative to conventional stranded wires.

3 | ANALYTICAL MODELING

It is known that finite element analysis (FEA) is time-consuming, and the analytical model of the design is required for quick analysis at the initial design stage. In order to achieve this, firstly, analytical modeling of the no-load magnetic field is presented using magnetic scalar potential. Then, the rated phase voltage and torque of the proposed machine are derived. Lastly, analytical modeling of the conduction and eddy current losses are presented.

The magnetic field in the air gap is created by PMs on the rotor. This field can be distorted by the magnetic field created by current-carrying armature coils on the stator, called armature reaction. However, the proposed topology is air-cored and has a large magnetic air gap compared with iron-cored machines. Therefore, armature reaction is low and negligible [15–17]. Accordingly, only no-load magnetic field by PMs is considered in the study.

Several methods are presented in the literature to derive the no-load magnetic field model of a PM electric machine. In [18–20], authors used magnetic scalar potential for field analysis. A quasi 3D computational method using vector potential is developed in [21,22]. Magnetic scalar potential is used with Fourier analysis and Laplace equations for the field analysis of the axial flux machine.

The details of the magnetic field derivation are presented in another publication of the authors [1]. In the study, a linear motor variant of the proposed axial flux PM topology is presented, where there are two stationary magnet rails and one mover composed of flat windings. For the field derivation using magnetic scalar potential, first, the magnetization of the PMs is represented using the Fourier series. Then, using magnetic scalar potential and constitutive relations, magnetic flux density and field intensity in the air gap with some unknown coefficients are derived. To obtain the field solution, boundary conditions are also considered. In the end, a fully analytical representation of the magnetic field is obtained. For further details and derivation steps, one can refer to [1].

The analysis concludes that the axial component of the magnetic field at the air gap of the machine, \( B_{ax} \), can be written as [1,18–20]:

\[
B_{ax} = -\frac{\mu_0 I_n}{\tau_p} \sum_{n=1,2,3...}^{\infty} \left( C_1 e^{\pi n \gamma / \tau_p} - C_2 e^{-\pi n \gamma / \tau_p} \right) \cos\left( \frac{\pi n \tau_H}{\tau_p} x \right)
\]

(1)

where \( n, \mu_0, \) and \( \tau_p \) represent \( n \)th order space harmonic, permeability of free space, and pole pitch, respectively. Also,


TABLE 1 Performance evaluation of the proposed topology employing flat winding stator and permanent magnet machines with conventional stranded wire

| Topology            | This paper | WEG motor [13] | Marcic et al. [14] |
|---------------------|------------|---------------|-------------------|
| Winding type        | Axial flux PM | Radial flux PM | Radial flux PM    |
| Power               | 1.4 kW     | 1.5 kW        | 1.5 kW            |
| Frequency           | 35 Hz, 50 Hz | 50 Hz         | 50 Hz             |
| Rotational speed    | 525 rpm, 750 rpm | 1500 rpm     | 1500 rpm          |
| Conduction loss     | 110 W, 54 W | -             | 211 W             |
| Eddy current loss on the windings | 53 W, 108 W | -             | -                 |
| Efficiency          | 89%        | 88%           | 85%               |

Figure 8 No-load air gap flux density. (a) Comparison of analytical and FEA results at mean radius (b) Spacial distribution

(a)

![Analytical calculation and FEA results](image)

(b)

![Spacial distribution](image)

Figure 9 A section of the machine

C1 and C2 represent unknown coefficients to be determined by the boundary conditions, and x and y represent circumferential and axial positions, respectively.

In order to measure the accuracy of the analysis, the magnetic flux density distribution of the prototype machine that will be presented in the next section is obtained both analytically with the presented method, and using FEA. ANSYS Maxwell 3D solver is used for this purpose. In Figure 8a, analytical and FEA results are presented, which is obtained at mean radius under no-load condition. Also, spacial distribution of the flux density by FEA is given in Figure 8b. Focusing on the comparison of two results, there is a small dissimilarity between two results at zero crossing regions, resulting from differences between third harmonics. This dissimilarity is mainly caused by the assumption that diagonally placed magnets are approximated as sector-shaped magnets as in [1]. Overall, less than 2% error is observed, and the analytically obtained results are in good agreement with the FEM results.

Rated phase voltage and torque equations for the proposed machine can be derived using the presented magnetic field model. For reference to these calculations, in Figure 9, a section of the rotating magnets and a single loop of the flat winding are shown. Using this representation, open circuit RMS phase voltage of the machine, \( V_{ph} \), is obtained as:

\[
V_{ph} = B_{f,ax} \omega r_{mean} \frac{l}{\sqrt{2}} 2m k_w
\]

where \( B_{f,ax} \) is RMS of flux density in the axial direction, \( \omega \) is the rotational speed, \( r_{mean} \) is the mean radius shown in Figure 9, \( l \) is the conductor length in a flat wire shown in Figure 9, \( m \) is the total number of flat wires per phase, and \( k_w \) is the winding factor of the stator. Note that voltage is induced in the part of the flat wire that is perpendicular to both velocity and flux density vectors. Since the velocity vector is in the circumferential direction, and flux density vector is in the axial direction, only the flat wire's radial projection induces a voltage, as shown in Figure 9. Also, note that there are four conductors with length \( l \) per flat wire, but two of them actively induce voltage at any time instant.

Phase current is determined according to the wire cross-sectional area, \( A_{ws} \), and RMS current density, \( J \). Combined with voltage equation in (2), the output torque of the proposed machine can be expressed as:
Lastly, conduction losses and eddy current losses on flat windings are modeled analytically for the proposed machine. Conduction losses on flat windings, \( P_c \), can be derived as:

\[
P_c = 3 I_{ph}^2 R_{ph}
\]

where \( I_{ph} \) and \( R_{ph} \) are the phase current and resistance of the flat windings, respectively. Phase resistance can be calculated using flat wire geometry and dimensions.

Attention should be paid for the analytical modeling of eddy current losses on flat wires. Eddy current losses in flat windings are considered for the proposed topology. The analytical model proposed in [23] is used for eddy current loss modeling on flat windings. This study proposes that the volumetric specific eddy current loss on flat wires, \( P_{sp} \), in W/m³ is calculated as [23]:

\[
P_{sp} = \frac{t^2 (2\pi f_c)^2 B_1^2}{24 \rho} k_1
\]

where \( t \) is the flat wire thickness, \( f_c \) is the electrical frequency, \( B_1 \) is the peak flux density of the fundamental component, \( \rho \) is the resistivity of the flat wire material and \( k_1 \) is the factor that includes the effect of harmonics. It is also calculated as:

\[
k_1 = \frac{B_1^2 + 3^2 B_3^2 + 5^2 B_5^2 + \cdots}{B_1^2}
\]

where \( B_n \) is the peak flux density of the \( n \)th harmonic component, and \( B \) is the peak flux density including all harmonics. Then, eddy current losses on flat windings can be calculated by multiplying the total volume of flat wires and specific loss, calculated in Equation (5). Other losses of the machine, such as eddy current losses on magnets and rotor cores, and friction losses are negligible compared to presented losses; therefore, they are not modeled in the study.

4 | EXPERIMENTAL VERIFICATION

Experimental verification is needed to verify the accuracy of the proposed analytical models and present the advantages of the flat winding. For this purpose, a prototype is designed using analytical models and optimized by genetic algorithm. The single objective optimization aims to minimize the active mass of the machine. Optimization parameters are determined as outer diameter and magnetic loading of the machine, and optimization problem is solved with efficiency and frequency constraints. At the end of the optimization process, 1.4 kW, 26 Nm, and 48 V axial flux machine employing proposed novel flat winding with copper material is obtained, and the overall parameters are presented in Table 2. In the prototype, N42M grade NdFeB magnets, which have remanence flux density around 1.39 T, are used due to their high performance. Also, the back-emf frequency of the machine is 35 Hz, and the machine can be driven in the motoring mode with a variable frequency motor drive at various rotational speeds.

To limit eddy current losses on windings due to external PM field and the large cross-sectional area, the thickness of the flat wire is selected as 1 mm. Copper flat wire material is used for the prototype at this stage, and experimental and analytical comparative study with aluminum counterpart is given in the following section. With copper flat winding, 110 W of conduction losses, and 53 W of eddy current losses are observed. This shows the critical advantage of the proposed flat winding over other bar wound or hairpin winding topologies: Using

| Parameter                  | Value   |
|----------------------------|---------|
| Line voltage               | 48 V    |
| Line current               | 20 A    |
| Rated power                | 1.4 kW  |
| Rated torque               | 26 Nm   |
| Rotational speed           | 525 rpm |
| Pole number                | 8       |
| Frequency                  | 35 Hz   |
| Efficiency                 | 89%     |
| Axial length               | 77 mm   |
| Outer diameter             | 300 mm  |
| Current density            | 4 A/mm² |
| Active mass                | 29 kg   |
| Air gap flux density       | 0.6 T   |
| Conduction losses          | 110 W   |
| Eddy current losses        | 53 W    |
| Phase resistance           | 93 mΩ   |
| Phase inductance           | 90 μH   |
| Number of loops per phase  | 20      |
| Air gap clearance          | 2.3 mm  |
| Flat wire dimensions       | 1 × 5 mm³ |
| PM dimensions              | 60 × 60 × 12 mm³ |
| Remanence flux density     | 1.39 T  |
thin flat wires and stacking them through thickness in the circumferential direction, the eddy current losses can be suppressed significantly, even less than the conduction losses.

The torque density of the proposed design is 0.90 Nm/kg. This value is slightly lower than other studies in the literature, such as 4 kW axial flux machine with torque density of 1.67 Nm/kg in [24], or 2.1 kW axial flux machine with torque density of 1.87 Nm/kg in [25]. The reason for this is that in this study, the aim is to emphasize the advantages of flat winding structure and verify the proposed analytical model. In that context, manufacturing tolerances are kept high to make manufacturing easier. For example, the air gap clearance is 2.3 mm in the prototype, which is quite large for this diameter and power ratings, resulting in low torque density. Additionally, the prototype machine is naturally cooled. With forced cooling, torque density of the machine can be increased.

As the first step of manufacturing, flat wires are manufactured from 1-mm thick copper sheet using a laser cutter, as shown in Figure 6. They are bent to give a V-shaped form. Then, a three-phase flat winding stator is assembled by combining 240 flat wires. Isolation papers are placed between flat wires for electric isolation. The tips of flat wires are connected with connectors, and they are soldered. For that purpose, 240 solderings are done for the prototype machine. One manufacturing difficulty of the proposed flat winding is soldering of the end winding. There have to be as many soldering points as the number of flat wires used in the stator. However, this difficulty can be overcome with automated soldering techniques. Lastly, the stator is coated with epoxy for mechanical rigidity, as shown in Figure 7. The selection of the epoxy material should be carefully made. The selected epoxy should have high thermal conductivity so that the heat on the wires can be evacuated easily. It is also important that the chosen epoxy material withstand the mechanical forces over the range of operating temperature [24].

Then, two rotor sets with 8 poles are manufactured. As core material, S355 magnetic steel, which has a saturation flux density of 1.9 T, is selected [26]. The diagonal placement of the PMs should be accurately made. For this purpose, during prototyping, the magnets' positions are outlined on the rotor core using CNC, and the magnets are glued to their positions. Then, the stator is placed between two rotor sets connected with the shaft. With the assembly of other machine parts, the prototype machine in Figure 10 is obtained.

Experiments are conducted with the setup shown in Figure 11. During the tests, the manufactured machine is run as a generator, and its shaft is coupled mechanically to a DC machine working as the prime mover. The temperature of the stator windings is measured by PT 100 sensors placed inside the epoxy.

The machine under test is rotated at rated speed of 525 rpm with DC motor to obtain open circuit characteristics at no-load. The induced voltage in terminals of the machine is saved, and the results are compared with analytical and 3D FEM results in Figure 12. Less than 2% difference is observed between analytical, experimental, and 3D FEM results. These results validate the proposed analytical model and material properties.

At rated speed operation, voltage, and current measurements of the prototype machine under full-load and half-load conditions are given in Figure 13. At full-load operation, the phase voltage is decreased by 4.6% compared with the half-load condition due to voltage drop on the armature resistance. Also, there are harmonics in the current waveform, thought to be caused by the unbalance at the load. In the same figure, expected full-load current waveform also given, which is obtained by analytical solution. The harmonics difference between analytical and experimental full load current explains this unbalanced load. As a next step, at rated speed, the thermal characteristic of the prototype is obtained experimentally for full-load and half-load operations. The results in Figure 14 show that the maximum temperature rise of the windings under natural cooling is 32°C under the full load operation of 20 A and 1.4 kW, and 17°C under the half load operation. These results are also verified with steady-state FEA by SolidWorks simulation tool with less than 1.5°C accuracy. At rated operation, the current density is 4 A/mm². According to experimental findings, if the temperature rise is allowed to be 75°C, the current density on flat wires can be increased up to 7 A/mm². It should be noted that these results are obtained under natural cooling, and machine is capable of operating at higher current densities if forced cooling is used.

To verify analytical loss modeling, various measurements are taken from the manufactured prototype. First, eddy current losses on the flat windings due to external PM field will be verified. To achieve this, the manufactured machine is rotated at rated speed under no-load condition (i.e. open circuit) such that conduction losses are eliminated. In that case, there is no output power, and input power is consumed only as eddy losses.
current loss, friction, and windage losses. At this operation condition, no-load losses are measured as 63 W. Additionally, friction and windage losses are measured as 8 W at rated speed, when the stator is removed from the assembly, and the machine is rotated with the prime mover. Thus, it is concluded that the eddy current losses of the copper flat winding stator due to external PM field at rated speed is 55 W. This value is close to the 53 W of loss obtained from analytical eddy current loss calculation in Equation (5) with less than 4% difference. This small difference is mainly caused by less than 2% difference in analytical field modeling and manufacturing tolerances.

Secondly, conduction losses due to phase currents are obtained experimentally using the total loss measurement at the rated operation of 1.4 kW at steady-state temperature. Total loss is measured as 180 W, which includes both conduction losses and no-load losses. Thus, it is concluded that conduction losses are 117 W, which is in close agreement with the analytical conduction loss calculation of 110 W. The small difference is mainly caused by the cable resistance of the measurement devices in the experiment setup. As the current rating of the machine is high (20 A), the losses on the cables of the measurement devices start to make a difference. Using these loss measurements, the efficiency of the prototype machine is calculated as 88%, which is very close to the 89% efficiency calculation obtained by the analytical model. The loss and efficiency comparison results are tabulated in Table 3. Overall, obtained results are in close agreement with analytical calculations, and the proposed analytical models are verified with experimental data.

In Figure 15, loss density distribution on the windings is plotted under rated operation, which is obtained using ANSYS Maxwell 3D solver. The losses include both conduction losses and eddy current losses on windings resulted from the external magnetic field. This loss distribution depends on the time and position of the rotor due to changing phase currents, and the distinction of the phases is clear due to conduction losses in the figure.

5 | COPPER VS. ALUMINUM FLAT WINDING

It is uncommon for conventional stranded-wired electric machines to see aluminum windings due to higher electrical resistivity compared to copper ones. Due to the small cross-sectional area of the wire, conduction losses dominate the eddy current losses on the windings for these stranded-wired machines. Therefore, the usage of aluminum stranded wire is not preferred as it increases the machine’s losses due to increased DC resistance.

However, for the wires with large cross-sectional area, the AC losses start to take place. As analytically modeled in Equation (5), it is seen that eddy current losses decrease when the resistivity of the material increases due to the increased skin depth of the material. Therefore, due to its higher resistivity,
TABLE 3 Loss and efficiency comparison of the prototype with copper stator

|                     | Analytical model | Experimental |
|---------------------|------------------|--------------|
| Eddy current loss   | 53 W             | 55 W         |
| Conduction loss     | 110 W            | 117 W        |
| Phase resistance    | 93 mΩ            | 100 mΩ       |
| Efficiency (rated operation) | 89%          | 88%         |

FIGURE 15 Total loss density distribution on the windings, including both conduction and eddy current losses due to external PM field

aluminum results in lower AC losses than copper, and it may be favorable in terms of total losses and efficiency for some applications. With that motivation, the feasibility of copper and aluminum will be evaluated.

Aluminum and copper has the following significant differences:

- Electrically, copper is 63% more conductive than aluminum [27].
- For the same volume, aluminum is 70% lighter compared to copper, which makes aluminum favorable in terms of weight [28].
- From the cost perspective, aluminum is 70% cheaper per mass compared to copper, providing cost-effective solutions [29].

The feasibility of two alternatives is evaluated both analytically and experimentally. For that purpose, an aluminum flat winding stator for the prototype machine is manufactured, as shown in Figure 16. The aluminum stator has the same dimensions as the copper counterpart.

The first difference between the two alternatives appears in manufacturing. For end winding connections of copper flat winding, soldering is enough to connect two flat wires electrically. However, for the aluminum flat winding, more advanced welding solutions such as tungsten inert gas, ultrasonic or laser welding need to be employed. From this perspective, the manufacturing cost of the aluminum stator may be higher depending on the solution applied, even if the material cost is less.

The eddy current losses of two stators due to external PM field at various rotational speeds are obtained analytically and experimentally, and the results are presented in Figure 17. For the analytical modeling, the method presented in Equation (5) is used. The good agreement between analytical and experimental results are observed for both copper and aluminum stators. As analytically modeled in Equation (5), it is seen that the eddy current losses are proportional to the square of the electrical frequency or speed. Also, it is observed that copper has higher eddy current losses compared to aluminum at any speed due to its lower resistivity and smaller skin depth. Additionally, note that at the rated speed, eddy current losses of the copper stator is 60% more than that of aluminum.

To evaluate the performance of both designs deeper, total losses of each design, including both conduction and eddy current losses, at each operating point on the torque-speed plane are plotted in Figure 18, for copper and aluminum stators. For the copper stator, high losses are observed at high-speed regions, resulting from high eddy current losses. For the aluminum stator, high losses are observed equally at both high speed and high torque regions. Derived from these findings, the efficiency maps of two machines with different stator winding materials are given in Figure 19. From the efficiency maps, it is seen that the most efficient operating points of copper design are in high torque regions, whereas for aluminum design, the most efficient operating points are in the high speed region.

Lastly, derived from these results, the favorable material in terms of losses and efficiency are shown on torque-speed plane in Figure 20. This analytical finding is also experimentally verified at the crossed operating points by loss comparison of two designs. One can conclude from these results that at high speed region, eddy current losses dominate, and aluminum is more favorable due to its high resistivity. However, at high torque or high current region, copper material is more advantageous due to its high conductivity. These results show that the material selection significantly affects the losses and efficiency of the machine.

As a case study, two designs employing copper and aluminum flat winding stators are compared at two operating points in Table 4. For the first operating point, the rated
operation of 26 Nm and 525 rpm is selected. At the second operating point, the machine delivers rated power at a higher speed of 1000 rpm. The designs are compared in terms of losses, efficiency, flat winding weight, and cost at these two operating conditions. For the total loss and efficiency calculations, conduction losses, eddy current losses on windings due to external PM field, friction and windage losses are considered.

At 525 rpm, the aluminum design has 70% more losses than the copper design, mainly due to elevated conduction losses at high torque. From the weight and cost perspective, the aluminum winding has 30% weight, and 9% cost of the copper winding, which could be the reason for the preference for some applications. At 1000 rpm, the aluminum design has 23% less total losses, as well as weight and cost advantages stated above. Thus, aluminum design is favorable at this operating point in terms of all parameters evaluated.

6 | CONCLUSION

The following conclusions are drawn through the research conducted in this study:

- **FIGURE 17** Eddy current losses on copper and aluminum stator windings due to external PM field obtained analytically and verified experimentally

- **FIGURE 18** Total losses of the machines with different flat winding materials plotted on torque-speed plane. (a) Copper (b) Aluminum

- **FIGURE 19** Efficiency map of the machines with different stator materials. (a) Copper (b) Aluminum

- **FIGURE 20** Favorable material in terms of losses and efficiency on torque-speed plane
The flat winding topology is a promising alternative to the conventional windings with stranded round wires due to its ease of manufacturing advantage. They can be manufactured with widely-used electric machine manufacturing tools such as stamping press, laser, or water jet. No significant modification on the production line is needed.

Superior current ratings and high fill factors are achievable with flat winding topology. Additionally, reduced end windings increase the efficiency of the machine.

AC losses on windings can be significantly reduced by using thin conductor sheet during manufacturing and stacking flat wires through thickness in the circumferential direction, which is a significant problem with similar topologies, such as hairpin winding.

By comparing the flat wired prototype machine and the stranded wired machines in the literature, it is shown that even if flat winding introduces some AC losses due to large cross-sectional area, the conduction losses are reduced, and higher efficiency is observed. This comparison shows the advantage of flat winding over stranded round wires.

The good agreement between analytical, experimental, and FEA results proves the accuracy of the analytical models of the proposed topology.

With natural cooling, the current density of 7 A/mm² is seemed to be thermally safe according to the experimental results. However, the electrical loading can be further increased with forced air cooling.

Depending on the operating point, copper or aluminum may result in superior performance in terms of efficiency and losses. While aluminum is favorable at high speed region due to suppressed eddy current losses, copper is favorable at high torque/current region due to suppressed conduction losses.

Due to its cost and weight advantage, it is possible that aluminum can find application areas with the proposed topology.

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