DEVELOPMENT OF A TRACTION ASSISTANT PROTOTYPE BASED ON A SPHERICAL INDUCTION MOTOR

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January 2018

Abstract

The aim of this work was to develop a prototype based on an improved version of windings for a spherical induction motor, along with developing its thermal and mechanical project. The improved version of a planar winding configuration was adapted to a spherical configuration to fit into a wooden prototype that was created to test the electromagnetic system and determine its equivalent circuit components. The prototype was successfully built and the new windings shown to generate 133% more torque than the previous version. A CAD model was designed and computational simulations were performed to simulate its mechanical and thermal behavior under nominal conditions. The mechanical simulations shown that the model was sturdy enough to sustain a 1400 N compression load at ease, resulting in a maximum strain of 88 MPa, which is far below the yield strength of the 2014-T6 Aluminum alloy that has been chosen for the project material. The thermal simulations predict a 50 ºC reduction of the maximum temperature reached by the motor at the same nominal conditions that were considered for all tests performed with the wooden prototype.

Key-words: Induction machine; spherical rotor; fins; convection; equivalent circuit.

NOMENCLATURE

- $B_r$ Radial magnetic flux density [T]
- $B_l$ Biot number
- $\varepsilon$ Efficiency
- $F_T$ Total force [N]
- $F_{T\text{double}}$ Total force for the double-layer [N]
- $f$ Grid frequency [Hz]
- $h$ Heat transfer coefficient [W/m²·k]
- $I_m$ Magnetization current [A]
- $I_r$ Rotor current [A]
- $I_s$ Stator current [A]
- $J_i$ Current density [A/m³]
- $k$ Conductivity coefficient [W/m·k]
- $L_c$ Characteristic length
- $\Omega$ Rotor speed [rpm]
- $P$ Active power [W]
- $P_{mec}$ Mechanical power [W]
- $Q$ Reactive power [var]
- $R_r$ Rotor resistance [$\Omega$]
- $R_s$ Stator resistance [$\Omega$]
- $R_T$ Transverse resistance [$\Omega$]
- $S$ Apparent power [VA]
- $s$ Slip
- $T_\theta$ Electromagnetic torque [Nm]
- $U_s$ Stator voltage [V]
- $X_m$ Magnetization reluctance [$\Omega$]
- $X_T$ Transverse reluctance [$\Omega$]
- $Z_l$ Longitudinal impedance
- $Z_T$ Transverse impedance

1. INTRODUCTION

The study of spherical electrical drives has been taking place for the past couple of years with great expectations and fascination. However, its introduction into the industry and society has been consistently postponed due to some obstacles that are inherently linked to its practical application, along with the fact that cylindrical engines had reached its plateau of efficiency.

The study of spherical rotor drives has been taking place recently while there has been allocated efforts on finding solutions that provide a wider scope to solve some current problems existing with biomedical engineering [1]-[2], robotics [3] and industry [4]-[10]. Due to the advances on new materials development and computational methods, it has been possible to conceive experimental models that promise significant improvements in terms of agility, precision and cost-quality relation.
comparing to conventional electromechanical systems that allow several degrees of freedom [11].

The types of spherical drives more common nowadays are: permanent magnets [10]-[13]; variable reluctance [14]; and induction motors [15]-[16]. The developed drive fits in the latter. Spherical drives do present some considerable obstacles and handicaps, namely: lack of viable options for the bearings; if direct transmission is used then the tire would have to be extremely complex, expensive, difficult to replace and inevitably hard to find an optional solution between efficiency and comfort; and difficulty to cool the rotor and stator windings due to the encapsulated form of the spherical configuration.

2. Project of the several containing elements of the spherical induction drive

2.1. Planar configuration of improved windings

A new winding configuration has been developed to provide an increase in the total torque produced along with a reduction of the copper needed. This development has been achieved by [18] and here adapted to a spherical arrangement. Table 1 shows the most relevant results of the numerical simulations performed comparing the new single layer windings with the previous double-layer windings in a planar arrangement. The double-layer winding configuration is displayed at figure 1 while the improved single-layer winding configuration is shown at figure 1, both in a planar arrangement.

Table 1 – Results from numerical simulations comparing both winding configurations in planar arrangement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single-layer</th>
<th>Double-layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av. Current density, $J_i$</td>
<td>$1.23 \times 10^6$</td>
<td>$2.53 \times 10^6$</td>
</tr>
<tr>
<td>Total force, $F_T$ [N]</td>
<td>0.192</td>
<td>0.260</td>
</tr>
<tr>
<td>$\frac{F_T - F_{T\text{double}}}{F_{T\text{double}}} \times 100%$</td>
<td>-</td>
<td>35.4%</td>
</tr>
</tbody>
</table>

2.2. Winding conversion from planar into spherical arrangement

Before proceeding to the construction of the prototype with the new winding configuration, a set of numerical simulations were performed to compare both configurations now in a spherical arrangement. The results of these numerical simulations are shown in table 2, showing once again the supremacy of the single-layer.

Table 2 – FEA results for the double and single-layer configurations of the spherical drive

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single-layer</th>
<th>Double-layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av. Current density, $J_i$</td>
<td>$1.82 \times 10^6$</td>
<td>$3.63 \times 10^6$</td>
</tr>
<tr>
<td>Radial magnetic flux density, $B_r$ [mT]</td>
<td>33.5</td>
<td>67.1</td>
</tr>
<tr>
<td>Electromagnetic Torque, $T_e$ [Nm]</td>
<td>0.0334</td>
<td>0.0667</td>
</tr>
<tr>
<td>Torque increase</td>
<td>-</td>
<td>+99.7%</td>
</tr>
</tbody>
</table>
To convert the planar arrangement into a spherical one, the windings were winded in a planar die that had in consideration the final spherical dimensions, and were then bent by hand to fit into the spherical casing of the wooden prototype.

Figure 3 shows the bottom layer of the double-layer arrangement already fit into the stator casing and ready to receive the top layer orthogonally laid on top of this one.

By observation of figures 3 and 4 it can be easily concluded that it is not possible to fit a set of magnetic slots that would be firmly fixed to the stator frame due to the orthogonality of the winding direction between both layers. This is a significant handicap of this configuration which results in a too large air gap between stator and rotor iron.

Figure 5 shows a first view of the wooden prototype created to test the single-layer winding configuration. On this picture it can be seen that only two out of four quadrants were considered for this prototype since the main purpose was to validate the functioning of this set of windings, and for such a purpose, a single direction of rotation is enough to prove it works. If four quadrants of windings were used, how to fit the four spherical bearings into such a compact arrangement of windings and magnetic slots could have been an issue. This way, these bearings were rather comfortably placed on the two idle wooden blocks as could be carefully seen on Figure 5.

Figure 4 shows the assembly of both layers of windings for the double-layer configuration. A simple graphical legend was added to be easier to recognize both layers and windings of each phase.

Figure 5 shows a detailed view of the prototype showing its single-layer winding configuration.

2.3. CAD model

In order to simulate this motors behavior in several working conditions, two CAD models were built: one created at SolidWorks to simulate the mechanical performance of the created structure; and one created at COMSOL to perform electrical, magnetic and thermal simulations. The results of these simulations will be presented further on.

An extruded view of the electromagnetic system of the COMSOL model is shown at figure 6 for better understanding of its arrangement. The copper windings are supposed to represent a biphasic system with 2 pole pairs each.

At figure 7 it is shown a cut view explaining the main components of the electromagnetic system and its main dimensions. The small gap there is between each quadrant is reserved for the windings' intersections which has to take place. The windings connections cannot be understood from this figure, but they will be explained ahead.
The iron cores of both rotor and stator are meant to be made out of Somaloy®, even though at the construction of the prototype the stator ended up being built out of an assembly of several pieces of electrical steel stacked on top of each other summing up to 4 mm total thickness.

2.4. Mechanical project
The mechanical structure was conceived in order to encompass the electromagnetic system that has just been presented, and to sustain the external load that may be applied to the application on which this drive may be suited.

This spherical drive is a scale model of a larger one that was conceived to be adapted to a wheelchair that was meant to have a maximum load of 140 kg, which would result in a 1400 N force. Even though this smaller version of the wheelchair drive would not be subject to a 1400 N load, nevertheless this was the value considered for the project for safety reasons.

Figure 8 illustrates the force flux between the drive top and the ground, passing through the aluminum structure, the bearings and the rotor in between. It can be seen that the force flux does not pass through the finned walls, but rather through the base of the block that underlies right below the bearings and is sturdily attached to the wheelchair structure, here represented by an ordinary black slab.

Figure 9 shows a trimetric view of the conceived structure, without the electromagnetic circuit and without its lid. It can be seen that the casing walls are composed of several fins intended to dissipate the heat generated by the stator windings. This motivation will be further explained in detail.

On figure 10 it is shown a side view of the casing with its lid on top. Here it can be seen the profile of the fins and the groove reserved for the winding turns. The purpose of the lid is to not let the rotor fall off its placement since the drive will be place upside down, like could be understood on figure 8. The lid will also provide some extra strength to the casing walls.
in case some random external force is applied to them.

Figure 9 – Trimetric view of the proposed design for the spherical drive casing

Figure 10 – Side view of the structural casing with its lid put on

The material for this structure should be one with good thermal conductivity, should be lightweight and should have enough strength to support any mechanical load at ease. Considering this, there was no option but to choose an aluminium alloy, in this case the 2014-T6 which is also appropriate for foundry applications and is not too expensive. The properties of this alloy are shown on table 2.

Figure 11 shows dimetric projection of a cut plane showing the existing holes. The ones on the base are meant for anchoring the structure to the application, the small ones inside the walls are meant for the bearings, and the ones on the top fin are used to bolt the lid to the stator casing.

A simple mesh was created on SolidWorks just for the stator casing in order to perform some mechanical simulations. This mesh ended up having 19651 elements and 36206 nodes, which proved to be enough for the intended simulations.

2.5. Thermal project

Most of the thermal motivations that lie beneath the design that has just been presented have already been revealed and could be easily predicted by looking at the geometry itself.

The fins are all parallel to each other and to the horizontal plane in order to provide maximum aeration when the vehicle is moving, since the moving direction is also horizontal. Maximum aeration of the entire surface means maximum heat removal through forced convection.

All fins have the same external radius for practical purposes (e.g. to fit inside a given casing with constant width), but all internal radius are different due to the spherical configuration of the internal casing, which results in different fin lengths. This different fin length results in different heat dissipation capacity, which goes in line with the changing combination of heat generation and surface exposure along the vertical axis. The bottom windings are more internal which means they have less aeration and are prone to reach a higher temperature, thus they would benefit from having an increased fin area. Besides this, the lower windings may also dissipate some heat through the base of the structure, which would then transfer the heat to the bolts and the anchored vehicle.

The fin width to air gap ratio is very identical, which is common on applications that are meant to be exposed to forced convection. In
In this case, the fins were designed to be 3 mm thick and the air gap between fins to be 4 mm. Another relevant fin characteristic that was considered during this work is the fin’s aspect ratio, i.e. the proportion between its width and its length. The aspect ratio is said to be good whenever the Biot number of a given surface is kept way below the unity value. The Biot number is given by equation 1, on which $L_c$ represents the characteristic length, $h$ the heat transfer coefficient (in this case, merely the convection coefficient due to low heat transfer through radiation), and $k$ the thermal conductivity of the body material.

$$Bi = \frac{L_c h}{k} \quad (1)$$

By assuring a low Biot number, it means that the heat transfer through conduction within the surface material is greater than the heat removal through convection. Considering the heat convection coefficient is determined by the air flow speed, and this one is a fixed value, the goal would be to deliver as much heat to the fin tip as possible. The heat transfer coefficient is also dependent on the temperature difference between the surface and the environment, which brings even greater resolution to what has just been said. The wooden prototype, the aluminium structure and the electromagnetic circuit were all three designed on COMSOL for further numerical simulation. A different mesh was created for each combination.

The mesh for the electromagnetic system, only containing the elements shown on figure 6, ended up having 242571 elements. This is the foundation of the electrical drive, therefore will be present whatever the stator casing will be. The mesh for the electromagnetic system and the wooden block contains 267637 elements. The wooden block was designed as being cylindrical, closed 360° and having the same height as the real wooden prototype. This mesh is shown at figure 12.

The model encompassing the electromagnetic circuit and the aluminium casing ended up having 172699 elements, and its final look may be seen at figure 13.

3. **Methodology for Computing the Equivalent Circuit**

On this third chapter it will be presented the several methods and equations used to characterize the prototype by its equivalent electrical circuit and also how to determine the efficiency of the fins and the overall amount of heat transferred through them. Electrical engineers are well versed at understanding the behavior of a given electrical motor by means of its equivalent circuit. Figure 14 shows the equivalent circuit of a typical single-phase induction machine, which will be used to characterize the spherical induction machine prototype.
Figure 14 – Equivalent circuit of the single-phase induction machine

A set of experimental tests were done in order to determine the lumped parameters of the equivalent circuit, namely the open-circuit test, the blocked-rotor test and the load test. With the open-circuit test, one may be able to compute the magnetic reluctance by using equation 2. The values of the apparent, the active and the reactive powers are given by equations 3, 4 and 5, respectively.

\[
X_m = \frac{Q}{I_s^2} \tag{2}
\]

\[
S = U_s \cdot I_s \tag{3}
\]

\[
P = U_s \cdot I_s \cdot \cos \phi \tag{4}
\]

\[
Q = U_s \cdot I_s \cdot \sin \phi \tag{5}
\]

With the blocked-rotor test, it is now possible to compute the transverse resistance, the rotor resistance and the transverse reactance, by using equations 6, 7 and 8, respectively.

\[
R_T = \frac{P}{I_{ef}^2} \tag{6}
\]

\[
R_r = R_T - R_s \tag{7}
\]

\[
X_T = \frac{Q}{I_{ef}^2} \tag{8}
\]

The rotor current and the magnetization current are the most important currents which summed would result in the stator current. These two are given by equations 9 and 10.

\[
I_r = \frac{U_s}{Z_t} \tag{9}
\]

\[
I_m = \frac{U_s}{X_m} \tag{10}
\]

Where \(Z_t\) is the longitudinal impedance and is thus given by equation 11.

\[
Z_t = R_t + j \cdot X_t + R_r \frac{1 - s}{s} \tag{11}
\]

Finally, the electromagnetic torque, the mechanical power and the motor efficiency can now be computed referring to equations 12, 13 and 14, respectively.

\[
T = \frac{2 \cdot R_r (1 - s) I_r^2}{s \cdot \Omega (2f/60)} \tag{12}
\]

\[
P_{mec} = 2 \cdot R_r \cdot I_r^2 \frac{1 - s}{s} \tag{13}
\]

\[
\varepsilon = \frac{P_{mec}}{P} \tag{14}
\]

4. Prototyping and Experimental Results

The current chapter present the most interesting notes about the construction of the prototype, and also the results of the tests performed with it right after.

4.1. Creation of the single-layer prototype

As mentioned before, the prototype structure was built out of wood, which is a cheap and handy material to work around, and is also relatively safe to use due to its poor thermal and electrical conductivity. Figure 17 shows a top view of the final prototype, without the rotor put in place, while figure 18 shows the prototype with the rotor on place to better understand how close the top magnetic slots are to the rotor.

Figure 15 – Top view of the prototype, showing the windings of the two active quadrants

Figure 16 – Top view of the prototype with the rotor on place
Figure 19 shows the final winding connections considered for the prototype in order to maximize the magnetic field induced. The desired winding direction order can be succinctly summarized by the following order: +A1 +B1 -A1 -B1 +A2 +B2 -A2 -B2.

Figure 17 – Windings connection between the two quadrants

4.2. Experimental results

The first tests to be done were to evaluate the magnetic field induced by the new set of windings compared to the double-layer arrangement. Figure 20 shows the results of the double-layer, while figure 21 shows for the single-layer, both at the same nominal conditions. It could be readily seen that the single-layer prototype produces a greater maximum and average magnetic field throughout the polar coordinate. With the open-circuit tests, the four main parameters were able to be obtained, namely the transverse and rotor resistances, and the transverse and magnetization reluctances.

\[
\begin{align*}
R_T &= 2,54 \, \Omega \\
R_r &= 0,29 \, \Omega \\
X_T &= 1,37 \, \Omega \\
X_m &= 8,43 \, \Omega
\end{align*}
\]

Since the prototype doesn’t have enough torque to perform normal load tests, an external drive was needed to be mechanically assembled in parallel to the prototype. Figure 22 shows how this final assembly looked like.

A large set of load tests were performed in order to characterize the behavior of the machine at several speeds. At the end, lumped parameters model was obtained and its prediction of the real behavior was considerably accurate. Figure 23 shows a comparison between the results of the single-layer model vs. the experimental ones done back then on the double-layer prototype. A 133% increase in the maximum torque was obtained, along with a more natural torque vs. speed curve.

Figure 20 – Mechanical assembly of the auxiliary drive to the single-layer prototype

Figure 21 – Torque comparison between double and single-layer winding configurations

Figure 24 shows the mechanical power behavior of the 2 winding configurations. Once
again, the single-layer fashion showed its supremacy, even though not with such a large discrepancy. The single-layer curve shows a typical behavior of an induction machine. 

![Figure 22](image22.png)

**Figure 22** – Mechanical power comparison between double and single-layer winding configurations

Figure 25 shows the evolution of the efficiency vs. slip for both winding configurations as well, showing radical differences between both. 

![Figure 23](image23.png)

**Figure 23** – Efficiency comparison between double and single-layer winding configurations

Some few thermal tests were also performed in order to determine the temperatures reached by the wooden prototype windings. Figure 26 shows the evolution of one of these tests, showing the temperature is within a safe range for most of the conductor insulators. Each sensor was placed inside and at the center of each winding.

![Figure 24](image24.png)

**Figure 24** – Temperature evolution of single-layer prototype windings at near nominal conditions

5. NUMERICAL SIMULATION RESULTS

The current chapter shows some results from a set of mechanical and thermal simulations.

5.1. Mechanical simulations

Mechanical simulations were performed for the aluminium casing itself. A 1400 N load was evenly distributed between the 4 bearing holes, and the base was anchored. On figure 27 it can be seen the purple arrows being applied to the holes. Since the force flows from the bearing holes to the base of the structure, the walls will remain untouched by this compression force. Figure 28 shows precisely that: the entire casing is at rest, except for the holes where there is some light strain. Even the maximum strain, 88.1 MPa, is around 20% of the material’s yield strength.

![Figure 25](image25.png)

**Figure 25** – Vertical forces applied to the bearing holes

![Figure 26](image26.png)

**Figure 26** – Results of the mechanical simulations

5.2. Thermal simulations

The thermal simulations were performed on COMSOL, under steady state conditions. In this case, the electromagnetic circuit had to be included with the aluminium casing since it is where the heat comes from, and it encloses the internal walls of the casing, leaving no room for aeration.

Table 3 shows the main properties considered for the all materials present in the thermal simulations.
All simulations were done considering only 2 quadrants were actually generating heat, to be consistent with the experimental tests.

<table>
<thead>
<tr>
<th>Property</th>
<th>Al</th>
<th>Cu</th>
<th>Cu</th>
<th>Wood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity, $k$ [W/m·K]</td>
<td>155</td>
<td>400</td>
<td>26.0</td>
<td>0.20</td>
</tr>
<tr>
<td>Specific heat, $c_p$ [J/kg·K]</td>
<td>880</td>
<td>385</td>
<td>440</td>
<td>2500</td>
</tr>
<tr>
<td>Density [kg/m$^3$]</td>
<td>2800</td>
<td>8960</td>
<td>7400</td>
<td>700</td>
</tr>
</tbody>
</table>

Figure 29 shows the results of the simulation done for the wooden model. By looking at the maximum temperature achieved on the simulation, and comparing to the ones obtained on the experimental tests (figure 26) it can be concluded that the results were considerably accurate. The rest of the temperature distribution cannot be confirmed since it would require a thermal camera for it.

![Figure 27 – Temperature distribution for the wooden block model at nominal conditions](image)

![Figure 28 – Temperature distribution for the aluminium casing at nominal conditions](image)

Figure 30 shows the simulation of the aluminium casing at the same nominal conditions as all other tests. A great temperature drop had happened, and an almost homogenous temperature distribution takes place within the aluminium. This is an indicator that in fact the Biot number might be small enough to safely consider it below the unitary value. These results are quite promising and give motivation for further developments of this motor.

6. CONCLUSIONS

The single-layer prototype proved to be superior in all aspects to the previous one, with a double-layer configuration. At the same nominal conditions, a higher magnetic field was produced throughout the polar angle range. This consequently resulted in a greater torque and mechanical power produced by the drive.

The lumped parameters of the equivalent circuit obtained from the experimental tests shown to provide a good prediction of the real behavior of the drive at a few set of conditions near the nominal values.

A computational model of the stator casing was created to perform some numerical simulations of its mechanical and thermal behavior. Simulation results shown that the model is sturdy enough and that would be able to drop the maximum temperature of the machine by 50 ºC at the same near-nominal conditions.

REFERENCES


