Considerations on the Preliminary Sizing of Electrical Machines with Hairpin Windings

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Abstract—Although the standard preliminary sizing of electrical machines equipping random windings is well consolidated and is worldwide acknowledged to be a good starting point for the design, there is no proof of accuracy and confidence when it comes to hairpin windings. This winding technology is gaining extensive attention due to its inherently high slot fill factor, good heat dissipation, strong rigidity, and short end-windings. These features make hairpin windings a potential candidate for some traction application to enhance power and/or torque densities. In this paper, a comparative design is done using the classical sizing tools available in the literature between two surface-mounted permanent magnet synchronous machines, one featuring a random winding and one with a hairpin layout. The study aims at highlighting the hairpin winding challenges at high frequency operations and at showing limits of applicability of these standard approaches when applied to this technology. For verification purposes, finite element evaluations are also performed.

Keywords—Hairpin windings, hairpin design, machine design, sizing

I. INTRODUCTION

Widespread research in the area of electric machines for traction applications is pushing the boundaries for high speed and power density with innovations in cores, magnets and winding designs [1]. These innovations also seek higher efficiency and lower costs. However, while higher speeds mean higher power for a given torque [2], they also result in additional losses in cores and windings thus lowering the overall efficiency, and in structural challenges relative to the rotating components. Hence, the design of an electric machine compliant with all the objectives mentioned above is a very complex task.

Permanent magnet (PM) motors are the most popular candidates for electric machines in traction applications [3]. Among these, interior PM (IPM) machines provide high power density, high efficiency and wide speed range, that are all required for traction applications. The stator winding of PM traction machines can be wound randomly, using stranded wires, or with form-wound windings made of flat bar conductors with a rectangular cross-section [4]. Form-wound windings are gaining popularity in traction applications. The most evident benefit of bar-wound windings over random-wound ones is the increased slot fill factor, i.e. the ratio between conductive and insulation materials inside the slot. In fact, random windings are made of wires with a circular cross-section, which will never match the slot shape, whatever it is. Contrarily, the flat rectangular wires can perfectly fit the shape of the slot when this is also rectangular, i.e. the slot features parallel sides along the radial machine direction. To strengthen this concept, in Figure 1a) and b), the “layered” round wire winding methods are illustrated, whereas Figure 1c) shows a rectangular wire winding layout [5].

Of all the bar-wound windings, the hairpin type is rather widespread. Here, a flat rectangular copper wire is preformed into a “hairpin” shape and inserted into the slot, and then the open sides are suitably twisted and welded to form a coil. In comparison with round windings, the end-winding length is thus shortened and, consequently, the DC copper loss is reduced [6]. Besides this end winding feature, the flat and “massive” shape of each hairpin leg reduces the DC copper loss produced by the active parts compared to their round-wound counterpart. Besides, in a series-production context, the hairpin windings manufacturing can be advantageous in terms of costs and cycle times in comparison with the traditional, often manual, random winding method [7]. For all these reasons, in traction applications, hairpin technologies are gaining more and more attention due to their potential in achieving higher power and torque densities [8-11]. However, this technology presents some drawbacks too. One of the major open points is the power loss at high frequency operations, which poses a limit on the applicability of machines with hairpin windings for high-speed applications. Many methods have already been proposed to overcome such problems.

Figure 1 Qualitative view of a slot cross section for (a) regular round winding, (b) modified round winding, (c) rectangular winding
major challenge, [2], [12-15] and this is where the on-going research is focusing.

On the other hand, only a few works deal with a comparison in terms of design procedure between random and hairpin windings [16-17]. Therefore, in this paper, the aim is to use the classical sizing equations typically used for random-wound electric machines also for the preliminary design of machines equipping hairpin windings. As a case study, a surface mounted PM motor intended for a traction application is considered and a comprehensive comparison between random and hairpin winding designs is provided. Finite element (FE) evaluations are also performed for validation purposes, finally highlighting the limits of applicability of the classical sizing equations to the design of electrical machines with hairpin windings.

II. PRELIMINARY DESIGN PROCESS

A. Starting requirements and assumptions

The design process is initialized by defining some basic machine performance requirements, such as output power, speed, voltage and desired efficiency. The values of such input parameters are listed in Table I.

The second step is that of making some assumptions on the materials and the cooling system. M330-50A and NdFeB are used for cores and PMs respectively, whereas natural convection is hypothesized as a heat extraction method. This permits defining magnetic and electric loadings and the maximum flux density values allowed in the various parts of the motor. Some additional choices on the outer rotor diameter to axial length ratio, airgap thickness, PMs’ span, number of slots-per-pole-per-phase and number of poles are initially made. The choice of the expected speed and the pole number is based upon the desired operating frequency chosen for the design exercise, i.e., 200 Hz. For a fully fair comparison between round and hairpin windings, the same number of slots-per-pole-per-phase, i.e. q = 3, is assumed and the stator structure is based on a distributed full-pitch, single-layer winding. Given the low degrees of freedom allowed by hairpin windings, the number of conductors per slot, which is usually derived from the rated voltage was related to the decision of fixing the number of conductors per slot, which is usually derived from the rated voltage instead. However, the major difference in the calculations is dictated by the choice of the fill factor. While for round windings \( k_f \) is relatively low and, thus, this is taken equal to 0.5, in hairpin windings the fill factor is higher and it is then assumed equal to 0.8 in this design exercise. These choices make the hairpin design inherently more compact than the round design, i.e. the outer stator diameter is smaller. Another important point of difference to mention is the slot shape. As recalled in Section I, a trapezoidal slot shape is envisioned for the machine with random windings, whereas a rectangular shape is considered for the machine with hairpin windings.

It must be mentioned that some of the design parameters which were considered here as input design choices could be envisioned as output variables to be refined according to design requirements and constraints. However, for the sake of this paper, the described design process is reasonable.

B. Sizing calculations

Having preliminarily selected the D/L ratio, the starting point for the motor sizing, either with random or hairpin windings, is the torque expression given in (2). In (2) \( B \) is the RMS value of the fundamental airgap flux density \( B_{max} \) obtained from (3) using the Fourier series decomposition of a square wave waveform. Equation (2) permits finding the values of \( D \) and \( L \). Then, hypothesizing in the PMs the same

\[
B_{max} = \frac{\Phi_{PM}}{\pi} \sin \left( \frac{\Phi_{PM} L}{180} \right) \quad (3)
\]

\[
l_m = \frac{\mu r I_g}{\Phi_{ag} n} - 1 \quad (4)
\]

\[
A = \frac{1}{nD} \quad (5)
\]
\[
W_y = \frac{\phi_p}{2B_k L} \tag{6}
\]
\[
W_t = \frac{\rho_{avg}^2}{B_r} \tag{7}
\]

C. Power losses

However, besides these design aspects, the most important factor to consider when designing an electrical machine with hairpin windings is the AC Joule losses. In random windings with stranded conductors, the AC losses can be neglected. Contrarily, in hairpin windings, AC losses need to be carefully considered and determined.

1) Copper loss: the DC resistance \( R_{DC} \) of a machine phase depends on the total length of one coil \( L_c \), the number of turns in series \( N \) and parallel paths \( a \) per phase, the cross-sectional area of the conductor \( S \), and the conductivity of the conductor material \( \sigma_c \) [6]. Considering a uniform current distribution at any frequency in stranded conductors, the losses associated with the DC resistance is the only contribution in the random winding design. In hairpin conductors, the skin and proximity effects and the ensuing flux density in the \( n \)-th section (see Table II).

\[
\Delta R_k = \Delta (\xi) + \Delta (\eta - 1) \Delta (\xi) \tag{8}
\]
\[
\Delta (\xi) = \frac{\sin \frac{\pi}{2} \sin \frac{\pi}{2} \cosh \frac{\pi}{2} \cos \frac{\pi}{2}}{ \sinh \frac{\pi}{2} \cosh \frac{\pi}{2}} \tag{9}
\]
\[
\psi(\xi) = 2\xi \frac{\sinh \xi - \sin \xi}{\cosh \xi + \cos \xi} \tag{10}
\]
\[
\xi = h_c \omega_0 \frac{1}{\sqrt{2} \mu_0 \sigma_c \frac{P_c}{b}} \tag{11}
\]

2) Iron loss: the laminations’ manufacturers usually give the loss density in \( W/kg_c \) at a specific frequency and flux density values. This includes both eddy current and hysteresis losses. Analytically, iron losses can be found by dividing the magnetic circuit of the machine into \( n \) sections, in which the flux density is approximately constant. Once the masses \( m_{Fe,n} \) of the different \( n \) sections are calculated from the volumes and mass densities, the losses \( P_{Fe,n} \) in these parts can be approximated as in (12). Here, \( k_{Fe,n} \) are “loss” coefficients that, for a synchronous machine, can be imposed equal to 2 in teeth and to 1.6 in the yoke; \( P_{Fe,0} \) is the loss density at 1 \( T \) and at the designed frequency of 200 Hz; \( B_{Fe} \) is the maximum flux density in the \( n \)-th section (see Table II).

\[
P_{Fe} = \sum_n k_{Fe,n} P_{10} \left( \frac{B_{Fe}}{17} \right)^2 m_{Fe,n} \tag{12}
\]

3) Mechanical and additional losses: a preliminary approximation of the mechanical losses can be also obtained using (13), where \( P_B \) and \( P_w \) are the friction and windage losses, respectively; \( k_m \) is an empirical coefficient from achieved by Reynolds constant for an Aluminium coolant

\[
P_{mech} = P_B + P_w = k_m m_{Fe,r} n_m 10^{-6} + 2D^3 n_m^3 L_0 10^{-14} \tag{13}
\]

D. Design at increased frequency operation

To emphasize the high-frequency challenges of hairpin windings, the same design exercise described above is performed by selecting an operating frequency of 1000 Hz. To do so, a rated speed of 15000 rpm is initially assumed and the rated voltage value is increased up to 630V. Other quantities like flux densities, current density, expected output power and efficiency, materials, etc. are the same as the design carried out at 200 Hz. This design should result in a smaller motor with higher AC losses in the hairpin winding, thus eventually lowering the efficiency. It is expected that the constant factor of the reduced conductor height parameter (\( \xi \)) would be increased significantly in higher frequency for hairpin winding than the round one. Referring to (12), a higher value of \( P_{Fe,0} \) is selected to take into account the frequency dependence of iron losses.

E. Summary of results

The geometries resulting from the preliminary analytical design process introduced above are illustrated in Figure 2, where random and hairpin winding machine designs at 200 Hz and 1000 Hz can be observed. A summary of the results obtained through the formulas introduced above is provided in Table IV for all the considered case studies. In general, smaller machine designs are achieved by increasing the operating frequency, for both random and hairpin windings. Consequently, volumes and masses are reduced at 1 kHz. Also, for a given frequency, the core size decreases from round to hairpin. This causes a reduction of iron losses by 24.6% at 200 Hz and by 24.2% at 1000 Hz. Unlike the volume,
it is irrefutable that with the choice of using a higher slot fill factor in the hairpin winding designs the mass density in round winding becomes higher than the hairpin one. The mass density in the round winding is more than hairpin one with 8.4% in 200 Hz and 28.8% in 1000 Hz. The higher fill factor used also results in higher DC copper loss in the hairpin winding. On the other hand, according to the hypotheses done above, the AC copper losses are considered only for hairpin windings. This permits considering the mass of the stator yoke and teeth, stator yoke and airgap of all the considered machines. Also, when evaluating different frequency operations, the frequency of the machines equipped with hairpins are analyzed. Also, when taking skin and proximity effects into account, these are much higher at high frequency. The next section aims to validate the analytical results through purposely built FE models of the machines and, most importantly, to provide a critical analysis on the limits of applicability of the analytical sizing tool for hairpin windings.

III. FE ANALYSIS – VALIDATION AND DISCUSSION

The geometries resulting from the preliminary sizing tool shown in Figure 2 are imported in the FE-based MagNet software for validation purposes and for carrying out in-depth critical analyses. A major difference in terms of modelling consists of using “stranded” and “solid” conductors for random and hairpin windings, respectively. This permits taking skin and proximity effects into accounts when the machines equipped with hairpins are analyzed. Also, when evaluating different frequency operations, the frequency of the current sources used to feed the three machine phases, as well as the speed imposed on the rotating components, are opportune set. A suitable transposition in the hairpin winding models is used to avoid the presence of circulating currents among conductors [1].

A. Validation of analytical results

Before discussing the comparison between analytical and FE results in terms of global output quantities, such as those reported in Table III, the conditions in Table II for flux densities should be fulfilled. In Figure 3-6, the flux densities hypothesized for the analytical sizing (see Table II) are plotted as constant quantities in red, whereas the FE results are shown in blue as a function of the angular coordinate on a stator reference frame at a fixed rotor position. The three subplots of these figures report the flux density absolute values in the teeth, stator yoke and airgap of all the considered machines. In particular, the results for the motor with round windings at 200 Hz and 1000 Hz are shown in Figures 3 and 5 respectively, while those for the motor with hairpin windings at 200 Hz and 1000 Hz are shown in Figure 4 and 6. The match in any part of the studied machines is acceptable when the analytical findings are compared to the maximum flux density values obtained via FE analyses.

Regarding the output torque, Figure 7 plots the relevant trends for random and hairpin designs at 200 Hz obtained via the FE model, whereas Fig. 8 shows the same quantities but at 1000 Hz. These FE torque evaluations are relatively close to

| Table III: Summary of the Analytical Designs for Both Random and Hairpin Windings |
|-----------------|-----------------|-----------------|-----------------|
| Main parameter  | Round winding   | Hairpin winding | Round winding   | Hairpin winding |
|                 | Analytical      | FEM             | Analytical      | FEM             |
| L₀ (PM thickness) | 3.36            | 3.36            | 3.36            | 3.36            |
| D (outer rotor diameter) | 144.6          | 144.6           | 84.6            | 84.6            |
| L (stack length)    | 159.1           | 159.1           | 93              | 93              |
| wₜ (tooth width)    | 2.3             | 2.3             | 1.4             | 1.4             |
| wₛ (stator yoke thickness) | 12             | 12              | 7               | 7               |
| Dₛ (outer stator diameter) | 222.6          | 204.3           | 148.1           | 132             |
| Stator core mass    | 15.36           | 12.47           | 3.96            | 3.12            |
| Rotor core mass     | 20              | 20              | 4               | 4               |
| Copper mass         | 17.72           | 25.3            | 6.96            | 16.16           |
| PM mass             | 1.316           | 1.316           | 0.45            | 0.45            |
| Pₜ,DC (DC copper losses) | W              | 141             | 194             | 53              | 83.68           |
| Pₜ,AC (AC copper losses) | W              | 138             | 307             | 53              | 322.5           |
| Pₚ (iron losses)    | W               | 471.4           | 355.47          | 1809            | 1350            |
| PM losses           | W               | 19.3            | 13.92           | 15.6            | 12.88           |
| Pₘₐₓₜ (mechanical losses) | W              | 194             | 194             | 361.4           | 361.4           |
| Pₚₐₜ (additional losses) | W              | 47              | 47              | 47              | 47              |

| Table IV: Comparison Between Analytical and FE Results |
|-----------------|-----------------|-----------------|-----------------|
| Main parameter  | Round winding   | Hairpin winding | Round winding   | Hairpin winding |
|                 | Analytical      | FEM             | Analytical      | FEM             |
| Pₚₓₜ,(power losses of stator) | W              | 471.4           | 414             | 141             | 170.9           |
| Pₚₓₜ,(DC copper loss) | W              | 141             | 194             | 194             | 194             |
| kₑₑₜₜ(Rₑₑₜₜ/Rₑₑₜₜ) | -               | 1               | 1               | 1.6             | 4               |
| Pₜ,AC           | W               | 138             | 170.9           | 307             | 763             |
| Torque Mean value | N.m            | 120.85          | 117.5           | 122.7           | 113.5           |
| Volume power density | MW/m³        | 6.25            | 5.69            | 7.4             | 6.88            |
| Mass power density | W/kg          | 728.35          | 708.16          | 666.95          | 616.95          |
| Volume torque density | KN.m/m³    | 19.88           | 19.33           | 23.55           | 21.79           |
| Mass torque density | N.m/kg        | 2.32            | 2.21            | 2.12            | 1.96            |
| Efficiency      | (%)             | 95.67%          | 93.02%          | 97.14%          | 89.85%          |
| Output power    | KW              | 37.97           | 36.91           | 38.55           | 35.66           |

A. Validation of analytical results

Before discussing the comparison between analytical and FE results in terms of global output quantities, such as those reported in Table III, the conditions in Table II for flux densities should be fulfilled. In Figure 3-6, the flux densities hypothesized for the analytical sizing (see Table II) are plotted as constant quantities in red, whereas the FE results are shown in blue as a function of the angular coordinate on a stator reference frame at a fixed rotor position. The three subplots of these figures report the flux density absolute values in the teeth, stator yoke and airgap of all the considered machines. In particular, the results for the motor with round windings at 200 Hz and 1000 Hz are shown in Figures 3 and 5 respectively, while those for the motor with hairpin windings at 200 Hz and 1000 Hz are shown in Figure 4 and 6. The match in any part of the studied machines is acceptable when the analytical findings are compared to the maximum flux density values obtained via FE analyses.

Regarding the output torque, Figure 7 plots the relevant trends for random and hairpin designs at 200 Hz obtained via the FE model, whereas Fig. 8 shows the same quantities at 1000 Hz. These FE torque evaluations are relatively close to
the values assumed in the analytical calculations, with errors ranging from 2.3% to 7.22%. The exact average values are reported in Table IV, where also a comprehensive summary between the two methods for both random and hairpin designs is provided, at both 200 Hz and 1000 Hz. Most of the analytical values differ by 10% compared to FE results. However, the AC losses present the highest inaccuracy when comparing the two methods. For the hairpin design, the error

for $k_w$ is ≈60% at 200 Hz and ≈63.6% at 1000 Hz. Consequently, the comparison in terms of overall copper losses and efficiency is not accurate for hairpin windings, whereas for random windings is reasonable. In Table IV, power and torque densities for all the motors have been also compared for the sake of completeness.
B. Further considerations and discussion

Always for the sake of clarity and completeness, comparing the overall performance of random and hairpin winding designs, it can be concluded that at low frequency (200 Hz), the round winding design presents higher efficiency, mass torque and power density than the hairpin winding. This is due to the lower amount of copper used for the design of the latter. On the other hand, the hairpin winding designs have higher volume torque and power densities than the random winding ones at both the investigated frequencies.

Recalling that this work aims to prove the applicability of the classical preliminary sizing equations also for machines equipping hairpin technologies, it can be concluded that for an accurate estimation of AC copper losses and efficiency the analytical sizing tool cannot be used, regardless the frequency at which the machine is designed. On the other hand, this classical sizing approach can be used for accurately estimating quantities, such as the output torque and power, as it shows an acceptable accuracy (or at least similar to that achieved when the sizing equations are applied to the design of machines with random windings).

IV. CONCLUSION

In this paper, a comparative analysis was carried out between two surface-mounted permanent magnet synchronous machines for traction applications, one featuring a random-wound winding with round conductors and the other one equipping a hairpin winding. These two machine preliminary designs were performed at two different frequencies, i.e. 200 Hz and 1 kHz, to highlight the high-frequency challenges associated with hairpin conductors.

After the preliminary design process, carried out leveraging on the classical sizing equations for electrical machines, finite element models were built for validation purposes. The comparative analysis showed acceptable accuracy for most of the electromagnetic quantities of interest. However, when it came to AC losses and efficiency, the validity of the preliminary sizing tool highlighted significant limitations, although an AC losses prediction model was implemented for hairpin windings. Therefore, while for random-wound windings the classical sizing equations could be used with a certain level of “safety”, hairpin windings require more accurate and in-depth analyses and the relative sizing tools need to be improved.

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