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AC losses reduction in Hairpin Windings produced via Additive Manufacturing

R. Notari, M. Pastura, S. Nuzzo, D. Barater, G. Franceschini, C. Gerada

Abstract – **One of the key challenges of hairpin windings is the reduction of their high losses at high-frequency operations. Hairpin layouts comprising conductors with variable cross sections have proven good loss performance in previous studies. However, they come at the cost of significant manufacturing complications.**

The aim of this work is to design hairpin layouts featuring reduced losses compared to classical configurations, exploiting the flexibility enabled by additive manufacturing. In this context, the choice of a proper material with relatively high conductivity and low ecological impact plays an important role. Hence, this article first presents an overview of materials that can be used for the winding additive manufacturing, aiming to select the most suitable one for the application at hand. Then, the loss performance is evaluated and compared against classical copper hairpins. The results demonstrate that opportunely selected alloys featuring asymmetric configurations can compete against classical hairpin windings.

Index Terms— **Aluminium Hairpins, Hairpin, AC losses, Additive Manufacturing, Asymmetric windings**

I. INTRODUCTION

In the last decade, the research interest for hybrid and pure electric vehicles has significantly grown due to restrictions in greenhouse gas emissions. In this context, hybrid and pure electric powertrains capable to meet the modern markets' standards are being developed and implemented [1].

The need for high power density and efficiency has become a central concern in the transportation sector and, in order to reach these requirements, the trend is to increase the fundamental operating frequencies of electrical machines and to reduce the switching times. However, higher excitation frequencies increase Ohmic and iron losses, as well as faster commutation devices are known to trigger the degradation of winding insulations of electrical machines [2].

Currently windings represent one of the main bottlenecks, so unconventional solutions are required to improve the performance of electrical machines. Of these, hairpin windings are becoming more and more popular, and many manufacturers are investing on this technology, especially in the automotive field [3]. The main reasons of their success relate to the higher fill factor, greater thermal conductivity, and higher automation of the manufacturing process compared to conventional random windings [4], [5]. On the other hand, hairpin windings present several challenges. In automotive applications, where the operating frequency can reach values above 1 kHz, high AC losses occur within the conductors. AC losses in hairpin conductors are mostly due to skin and proximity effects [6], which make the current flow through a reduced portion of the conductor cross section, with the worst scenarios occurring on the closest conductors to the air gap. As a result, at high frequency operations, the overall efficiency tends to decrease. Some practical solutions have been proposed to reduce AC losses [7]. These include decreasing the total amount of copper in the slot and pushing the conductors towards the slot bottom; increasing the number of conductors, whose effectiveness depends on the frequency range; adopting new winding concepts, such as segmented or asymmetric bar layouts [3].

Asymmetric hairpins, which feature a variable cross section along the stator slot as reported in Fig. *1*, have shown promising results in terms of loss reduction [8]. However, these would have a significant impact on the manufacturing process, since the asymmetric layout implies the need of hairpins with legs featuring different cross sections to guarantee the change of layer. Alternatively, single leg conductors could be used (I-pins), but this would double the number of welding points [3]. However, these complications relate to conventional hairpin winding manufacturing lines, where copper wires are used to create the hairpin conductors.

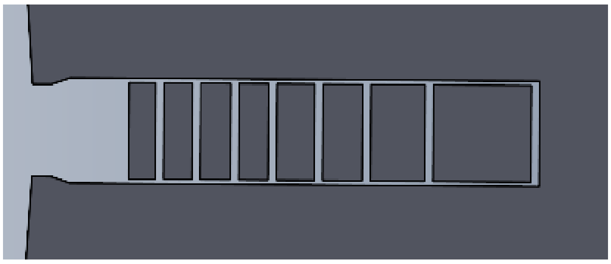

Fig. 1- Example of 8 asymmetric hairpins within a slot

An interesting possibility which would overcome the above challenges associated to asymmetric hairpin layouts is additive manufacturing (AM). Concerning the use of material, AM is economical for its capability of optimizing the topology of components and their internal structure [9],[10]. The fabrication freedom, free of moulds, dies or stamps, also suggest streamlined prototyping, production, and logistics of new "4.0 factories", allowing mass customisation of goods. Additional key benefits of AM include [11] - [13]:

• Increased power density of components, resulting in a reduction in size and mass.

• Part count reduction, leading to simplified assembly and supply chains.

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• Increased manufacturing efficiency and reduced lead times.

• Lower running costs.
• Material waste reduction.
• Reduced assembly and inspection costs.

However, AM presents also some critical aspects, the most relevant of which is the materials' availability [14].

Considering the above, this paper aims to propose and design asymmetric winding layouts featuring reduced losses than classical hairpin configurations. Another objective of this work is to investigate technological effort and sustainability aspects of winding process, thanks to the use of Aluminium alloys for AM, which have lower Environmental Load Unit (ELU) compared to copper [15],[16].

II. MATERIAL AND PROCESS SELECTION

As highlighted in the previous section, the material availability is one of the main challenge of AM [14]. Therefore, a detailed review and research on AM-feasible materials is performed, taking into account aspects like the technological process and the production sustainability. In particular, the objectives which have been adopted for the selection of the materials are the maximization of the performance and the reduction of the ecological costs, focusing also on the minimization of the net cost. In addition, considering the application at hand, the material selection needs to focus on high-conductivity materials. Hence, aluminium and copper alloys' families are analysed via Grant Selector CES Edupack, a comprehensive database of information on materials and processes [17].

A. Process selection

The selection of a material for a specific application also depends on the technological process being adopted. Therefore, the impact of the production process and the near net shape cost need to be considered. The National Institute of Standards and Technology (NIST), i.e. a government institution of technology in USA, developed a research [11] achieving a comparison between subtractive manufacturing and AM. Table I shows the results of the analysis of Hopkinson and Dickens [11], comparing different production rates for Injection Moulding (IM) and AM, which are suitable candidates for windings.

It can be noticed in Table I that the subtractive process is cheaper in the large scale production with the same productive hours, while, considering time to market, it becomes disadvantageous for its longer time to assembly the production chain. It is important also to mention the cross over point for the two different process in which an annual machine cost per part is estimated, where the machine completely depreciates after eight years; that is, it is the sum of depreciation cost per year (calculated as machine and ancillary equipment divided by eight) and machine maintenance cost per year divided by production volume. The result is a machine cost per part, as seen in Fig. *2*.

TABLE I
COST COMPARISON OF INJECTION MOULDING AND ADDITIVE MANUFACTURING FOR A SELECTED PRODUCT BUT DIFFERENT PRODUCTION SIZE [11]

	IM 5000	IM 20 000	IM 100 000	IM 500 000	AM P730	AM P390
Machine operator cost per part	0,018	0,009	0,004	0,001	0,054	0,117
Material cost per part	0,011	0,011	0,011	0,011	0,382	0,36
Machine cost per part	0,083	0,042	0,024	0,014	0,867	0,694
Assembly cost per part	0,035	0,035	0,035	0,035	0,012	0,012
Mould cost per part	6,24	2,9	1,075	0,335	0	0

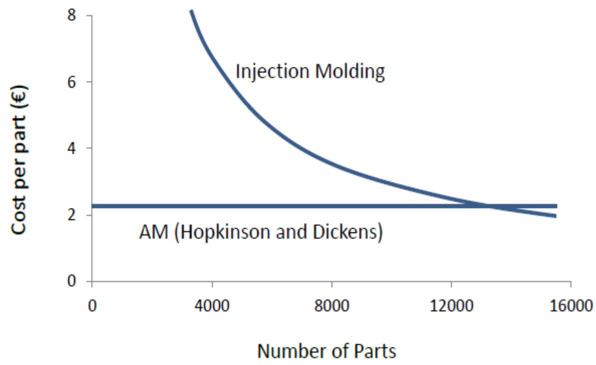


Fig. 2 -Hopkinson and Dickens cost model compared to injection moulding [11]

Due to the huge production rate and the low cost for production, the IM is advantageous for a large scale production but, when a short time production or a limited scale production is needed, AM is convenient. This is the case of this research, where the final aim is to build a small sample proving the feasibility of the asymmetric hairpin layout. Another relevant aspect is the elimination from the manufacturing process of the bending and welding phases, normally used for the conventional hairpin production [5].

B. *Material selection*

Due to the recent climate agreements, the ecological impact has become tremendously important. A recent analysis attested that the aluminium alloys are hundreds less impacting compared to a copper based one [16], as shown in Table II. It seems evident how searching an aluminium alloy, capable of matching the electrical proprieties of copper and its alloys, reduces the ecological impact without compromising the efficiency. With this in mind, starting on CES software from the definition of an x-y plane having the electrical conductivity in %IACS on the x-axis and the percentage of aluminium on the y-axis, the investigation was focused on bulk materials of species featuring a conductivity higher than 55%IACS and an Aluminium percentage higher than 80%.

TABLE II
ESTIMATION OF PRODUCTION AND ENVIRONMENTAL IMPACT OF ALUMINIUM AND COPPER ALLOYS IN ENVIRONMENTAL LOAD UNITS OVER WEIGHT OF MATERIAL [16]

Material	ELU/kg of material
Al	0.159
Cu	131.0

Table III reports the first selection results showing the species of interest, among which the alloy *Aluminium 383.0 (A03830)* stands out for its conductivity. Another prominent species is *Aluminium 6016* (*ENAW60616)*, which has a slightly lower conductivity than pure aluminium (*Aluminium*) and could be a viable alternative due to its high conductivity.

TABLE III
ELECTRICAL CONDUCTIVITY (>55%IACS) OF THE SELECTED BULK MATERIALS

Material	Aluminium	ENAW6016	A03830	C18100
Electrical conductivity [%IACS]	65.51	61.6	78.4	75
Electrical conductivity [MS/m]	38	34.54	44.485	43.4

The properties of the species identified in Table III in relation to pure (*C10100*) and AM selective laser melting (SLM) [18] copper (*C18100*) are shown in Fig. *3*.

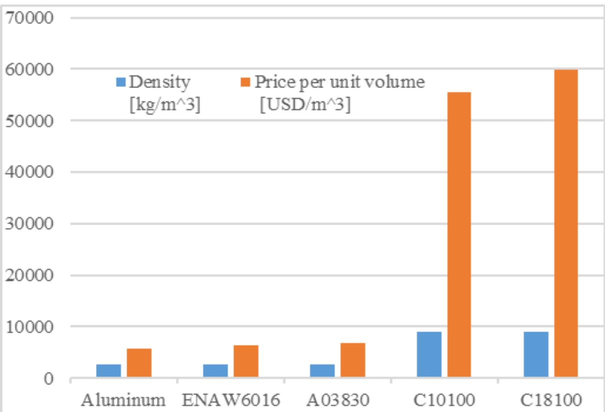


Fig. 3 - Proprieties of selected bulk materials under analysis

Changing the alloy ensures low ecological impact, as well as a reduction in the overall cost of the product and a decrease in the weight of the finished product, which are important aspects for the automotive and aerospace industries [1].

III. METHOD OF INVESTIGATION

A. Preliminary analyses

In order to more accurately evaluate the most suitable material for the application at hand, a finite-element model (FEM) is built to calculate the Ohmic losses in all materials under analysis. For these preliminary FEM evaluations, an electrical machine, with series connected conductors of the same dimensions (classical configuration), designed for automotive applications is taken as benchmark. The most relevant stator features are reported in Table IV [8], including the dimensions of the hairpin conductors.

TABLE IV
CHARACTERISTICS OF THE STATOR EMPLOYED FOR THE RESEARCH

Number of slots	24	Teeth length [mm]	20
Stator core	M270-35A	Teeth width [mm]	4.32
Stator outer radius [mm]	110	Number of conductors per slot	8
Stator inner radius [mm]	70	Conductor height [mm]	1.85
Machine length [mm]	92	Conductor width [mm]	3.90

The machine has been analysed by means of 2D time harmonic simulations with sinusoidal current source, using a FEM-based software package, i.e. MagNet. The mesh used is the result of a trade-off between accuracy and computational effort, with a high refinement in the conductors to accurately take into account skin and proximity effects. In addition, for the same reasons, each hairpin is modelled as a solid conductor. A 2D representation of the built FEM model is shown in Fig. *4*, where only a portion of the stator is modelled and only one phase is considered.

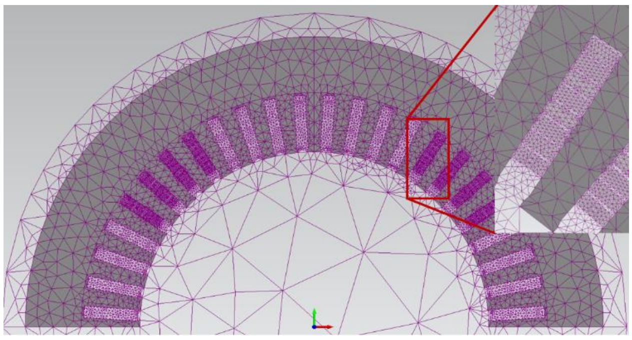


Fig. 4- 2D FEM view of the case study highlighting the mesh used.

The results of the FEM simulations are shown for the different materials under analysis in Fig. *5*, where the copper losses are plotted against the source frequency ranging from 0Hz (DC current) to 1.2kHz.

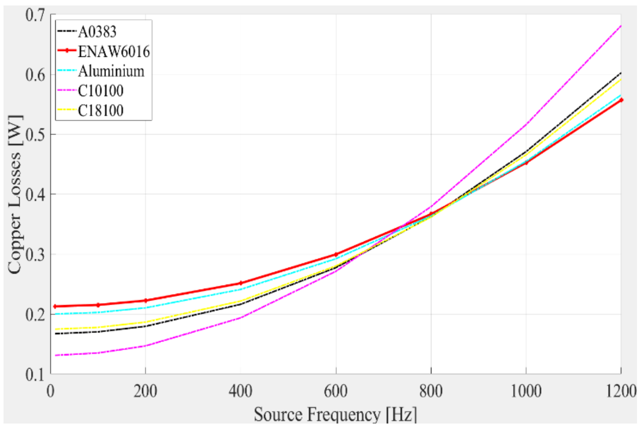


Fig. 5- AC losses in classical hairpin configurations for different materials as a function of frequency

It seems clear that the species of greatest interest, both technologically and electrically, are the *ENAW6016* and the *A03830*. A summary of the reasons is given below:

- the cost is 9.33 times lower than *C18100* which is the copper normally adopted in AM;
- the conductivity of *ENAW6016* is only 10% lower than the widely adopted AM copper alloy, while the conductivity of *A03830* is 4% higher;
- in the *700-1000 Hz* range, AC losses in Aluminium alloys are rather lower than pure copper, highlighting the potential of these materials in transport applications.

At this point, the feasibility for AM needs to be investigated and the sole possible solution, at the moment, that could be produced with Wire Arc AM is the *ENAW6016* [15]. Other solutions, either aimed at the adoption of Selective laser melting (SLM) or Selective laser sintering (SLS) or at using other species, are in the pipeline and will be published in future research publications.

B. FEM investigations on the selected material

After the identification of the most suitable material, the work proceeds as follows:

1) Adopt an analytical model and find an optimum winding size and layout to reduce losses leveraging on the asymmetric hairpin concept;
2) Run FEM simulations aimed to verify the losses.

Regarding 1), to analyse asymmetric configurations, the classical analytical model [19] needs to be slightly modified. More in detail, the conductor height should not be considered as a constant value. This means that the updated analytical model is based on the same foundation as the classical one, but the boundary conditions should vary for each conductor. The analytical model described in [20] is implemented in Matlab environment to predict the current density distribution within each conductor. Then, a genetic algorithm is used to find an optimal solution consisting of a hairpin layout with conductors featuring variable cross sections inside the stator slot. The algorithm includes the possibility of decreasing the total amount of copper in the slot as well as pushing the conductors towards the slot bottom in order to minimize the AC/DC losses ratio. In addition, it can modify the number of conductors, whose effectiveness depends on the frequency range and adopting new winding concepts, such as segmented or asymmetric bar layouts.

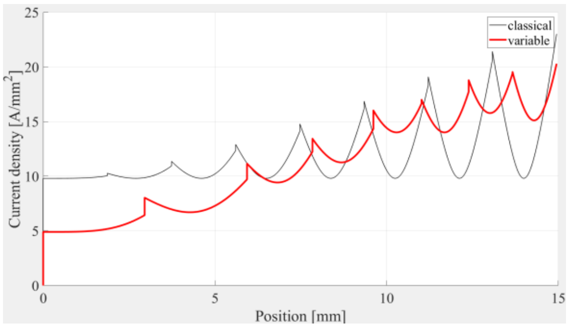
This optimisation algorithm is launched to obtain the configuration that minimises the losses through the cross-section variation of each conductor. The optimal solution features conductors with decreased cross-section from the slot bottom to the air gap.

The reference geometry remains the 24 slot layout previously analysed with eight conductors. The frequencies considered, both in the Magnet and Matlab models, are the same as the initial model so that the results can be fairly compared. Although the analysis should consider a number of operating points, only the results at the frequency of *650Hz* are shown for the sake of simplification. This operating condition is within a typical automotive frequency range. In Table V, the heights of the different conductors resulting from the optimization algorithm are reported.

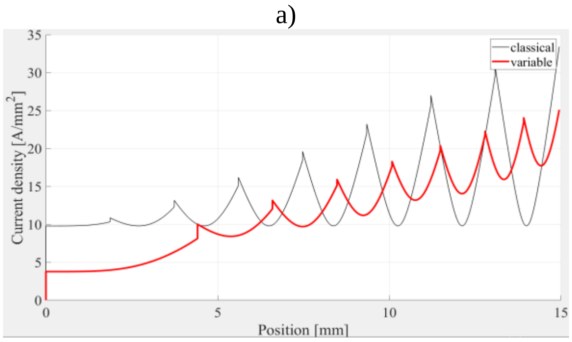
TABLE V
CONDUCTORS DIMENSION

Layer	Dimensions [mm]	Layer	Dimensions [mm]
1	4.19	5	1.31
2	2.32	6	1.26
3	1.71	7	1.22
4	1.63	8	1.14

The different current distributions in the classical and optimal (variable) configurations under analysis are shown below in Fig. *6*, where the effectiveness of the method can be observed.



a)



b)

Fig.6 - Current density distribution for classical and optimal (variable) ENAW60616 conductors at 650Hz a) and b) 1000Hz.

At this point, once the decrease in current density has been verified through the analytical formulas, the FEM model previously described is updated in order to verify the losses in the same winding configuration provided by the optimization algorithm. In addition, for the purposes of this paper, a comparison is made among the different materials previously analysed, considering both the optimized layout and the classical one. The relevant results are plotted in Fig. *7* and Fig. *8*, where copper losses vs. frequency are shown. In particular, Fig. *7* compares the optimal (dimensioned) layout using AM ENAW6016 and the standard layout using pure copper C10100. Fig. *8* compares the optimal (dimensioned) layout using AM ENAW6016 and the standard layout using AM copper C18100.

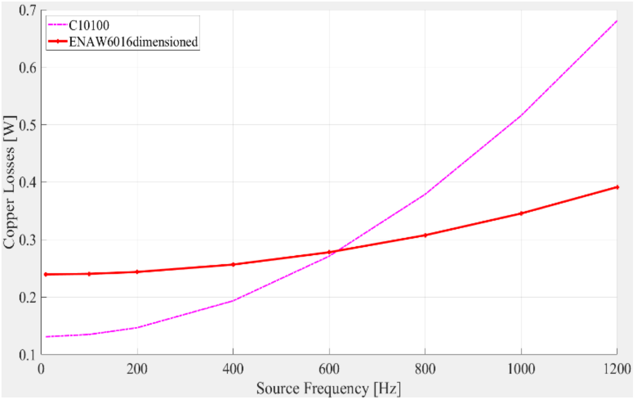


Fig. 7 - Copper losses comparison: dimensioned ENAW6016 vs. classical pure copper

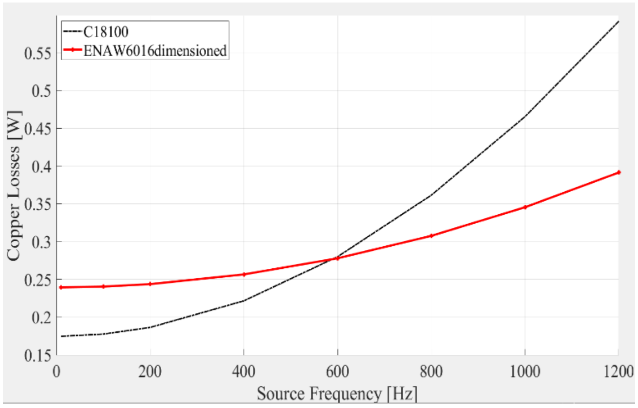


Fig. 8- Copper losses comparison: dimensioned ENAW6016 and classical AM copper

Looking at the results, some observations can be carried out:

- from ≈*600Hz* onward, the optimal ENAW6016 has better performance compared to the classical configurations;
- at *1200 Hz* ENAW6016 features approximately halved AC losses compared to pure and AM copper;
- in the frequency range below *600 Hz*, the differences in losses are not significant, so the selection is justified also for the behaviour at low frequency operations.

Considering the above, it can be concluded that the proposed alloy provides good performance (comparable or superior in certain ranges compared to copper alloys). This demonstrates the potential applicability of AM for windings of electrical machines. In addition, there is also a total reduction in the cost of raw materials for conductors and a simplified production process, which is important for possible future expansion of this technology.

IV. Conclusion

Previous studies showed that moving from a classical to an asymmetric hairpin winding can allow to reduce losses at high frequency operation. However, this comes at the cost of manufacturing complications that can be reduced or eliminated by the flexibility of AM. In fact, this technology can enable additional geometrical degrees of freedom, thus potentially matching the mass production requirements demanded nowadays by the automotive and aerospace sectors.

In this work, aluminium alloys are selected as suitable candidates for proving the asymmetric hairpin winding concept. Adopting aluminium alloys would determine a reduction in the overall cost of the product, as well as a decrease in the weight of the finished product, which can be another important aspect for the automotive industry. In addition, aluminium alloys are highly recyclable and the ecological impact can be reduced both in production and in disposal.

The selected aluminium alloy, i.e. ENAW6016, performed very well in terms of loss reduction after an optimal choice of the cross sections of the various conductors inside the slot. In particular, while copper seems still superior at low-frequency operations, at high frequencies (higher than 600Hz) the AM aluminium alloy achieved significantly lower losses. A prototype implementing the proposed concepts will be built in future for validation purposes.

V. Acknowledgement

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VII. BIOGRAPHIES

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