

Hairpin Windings: an opportunity for Next Generation E-Motors in Transportation

Abstract

The advancements in electrical machines and power electronics technologies seem permitting to achieve the power density and efficiency levels required nowadays by the transportation sector. However, the reliability of components and of their production process is currently a challenge. This is especially true for electrical machines, whose winding processes are still far from obtaining the high levels of automation, programmability and repeatability required by the transportation market. This article looks into hairpin windings and outlines a number of future actions aiming to address these challenges, thus eventually enabling the complete penetration of hairpin windings in transportation.

I. INTRODUCTION

IN the upcoming years, mobility will rely ever more upon electrification [1]. The vehicles' performance is very sensitive to the components' mass. Hence, nowadays, maximizing power and/or torque densities represent a key objective when designing electric drives for transport applications. In this context, both electric motors (EMs) and power electronics (PE) technologies play a key role.

On one hand, at PE-level, wide bandgap (WBG) devices have paved the way for lighter and more efficient power converters [2]. On the other hand, at EM-level, increased power densities are enabled by innovative cooling systems [3], new materials [4] and form-wound technologies, such as hairpin windings [5]. Nevertheless, such new solutions often reflect on increased losses in cores and windings, with limited flexibility to suit the transportation production requirements. Hence, new winding concepts, and flexible and automatized manufacturing processes are required to mitigate these challenges, as EMs intended for transport applications require compact windings with high slot fill factor, low losses, high reliability, etc.

This article further elaborates on the topics discussed in [5], first reviewing hairpin technologies with focus on the fill factor as a key enabler for power density, and then discussing their impact on AC losses,

voltage distribution, thermal management and manufacturing process. Compared to [5], this work provides the authors' vision beyond the state-of-the-art, eventually providing solutions, considering power density, reliability and automation requirements in a comprehensive manner.

II. BACKGROUND: SLOT FILL FACTOR

The choice of an appropriate winding layout represents a key design phase of electrical machines. In general, there does not exist a single, optimal winding structure, rather this depends on the application [6].

The most common winding type is the random-wound one, consisting of insulated round conductors which are wound inside stator or rotor slots to form a coil. The active sides of any coil turn are placed "randomly" against each other [7]. One of the main advantages of such winding is the flexibility. In fact, random-wound windings range from single-layer to multiple-layer structures, from integer to fractional slot windings, from full- to short-pitched layouts, from distributed to concentrated configurations [8]–[10]. However, random-wound windings generally feature a low slot fill factor.

The latter is an indicator of the amount of conductive material located in a slot. Therefore, for a given slot area, maximising it would permit increasing the number of conductors-per-slot for a given wire cross-section, or increasing the wire cross-section (thus the electric loading) for a given number of conductors-per-slot. Hence, it is straightforward envisioning such parameter as a key enabler to increase the power density in EMs.

A number of techniques have been proposed to increase the fill factor [11]–[13]. However, these are often limited to concentrated windings only, the process repeatability is compromised, the risk of damaging the insulation is high and the production cost is usually elevated [14].

Form-wound windings, such as hairpins, feature higher fill factors than round-wound ones [5]. This winding type is constructed starting from pre-formed elements made of enamelled, flat wires. Their rectangular shape inherently fits that of a stator slot with parallel sides and reduces the gaps between conductors. Figure 1 provides an illustrative review of the fill factor enhancement methods, highlighting how hairpin windings are the way forward.

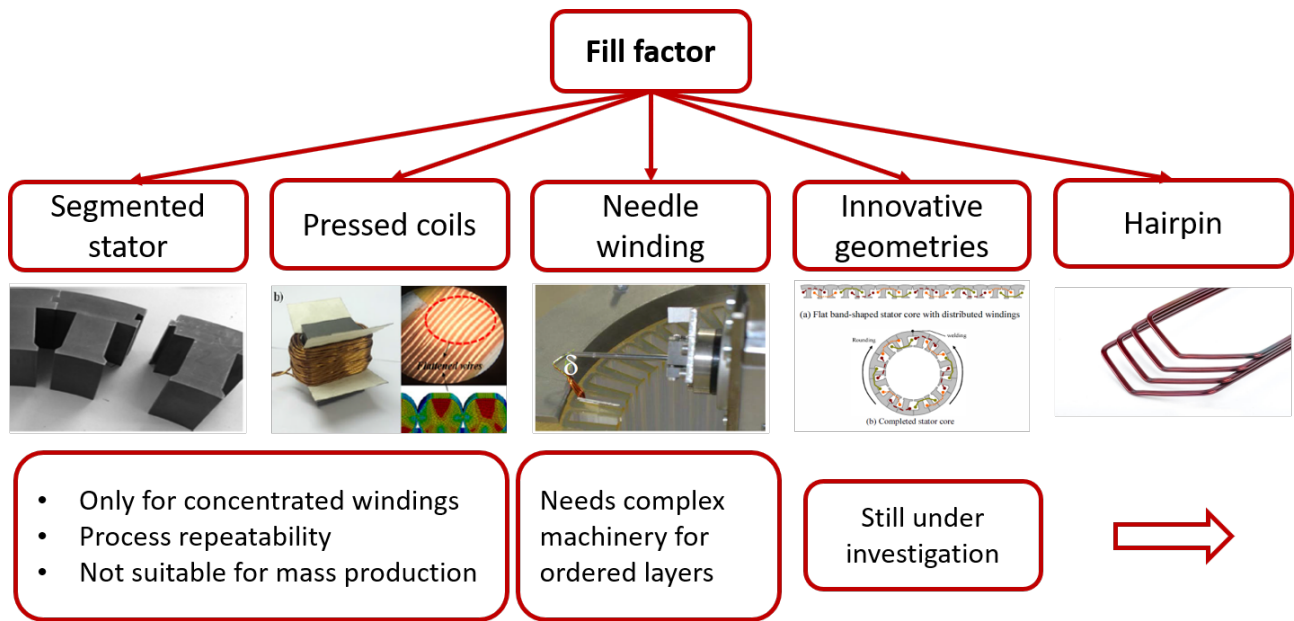


Fig. 1. Review of fill factor enhancement methods

III. HAIRPIN MANUFACTURING: STATE-OF-THE-ART

Also from the manufacturing point of view hairpin windings seem to be the way forward as they enable automatic production in a large scale, which is needed to sustain the green transportation revolution. Preliminary investigations have shown that, considering a production of 1 million units per year, hairpin windings' production costs can be reduced up to 27% compared to random windings [15].

The production of stators equipped with hairpin windings is divided into a number of steps as illustrated in Fig. 2. The four major steps are:

1) *Shaping*: after having stripped and cut a straight conductor of a suitable length, this is bent to achieve a “hairpin” shape. The specific shape has to fit the winding diagram requirements and the overall dimensions of the stator at hand. There are basically two consequent major bends, aimed at obtaining an u-shape first and, then, at shifting one of the two hairpin legs according to the coil pitch and the position in the slot. This process has to be performed accurately and with low tolerances to facilitate the insertion process and avoid stresses on the conductor and its insulation.

2) *Arranging*: after having built all the necessary elementary hairpins, these are inserted in the stator slots. This is usually done manually and the ease of insertion is an indicator of the goodness of the shaping phase.

3) *Twisting*: a gear element twists the free ends of all the hairpins according to the coil pitch and places them in the most suitable position for the contacting step. Twisting is as sensitive as shaping in

terms of conductor and insulation stress.

4) *Contacting*: depending on the number of stator slots and layers, a number of contacting spots significantly higher than in a conventional random-wound winding is necessary. Hence, reliable contacting technologies with short cycle times are required. To establish an electrical connection, the stripping operation (see Fig. 2) is performed first, consisting in removing the insulating material from the conductors. A fatigue endurable mechanical connection and low contact resistances have to be ensured [16]. Laser welding seems the most promising solution for the contacting operation [17], as the materials involved during welding experience low damage during the process. Additionally, from a mass production perspective, laser welding ensures a low cycle time and the process is easily automatable.

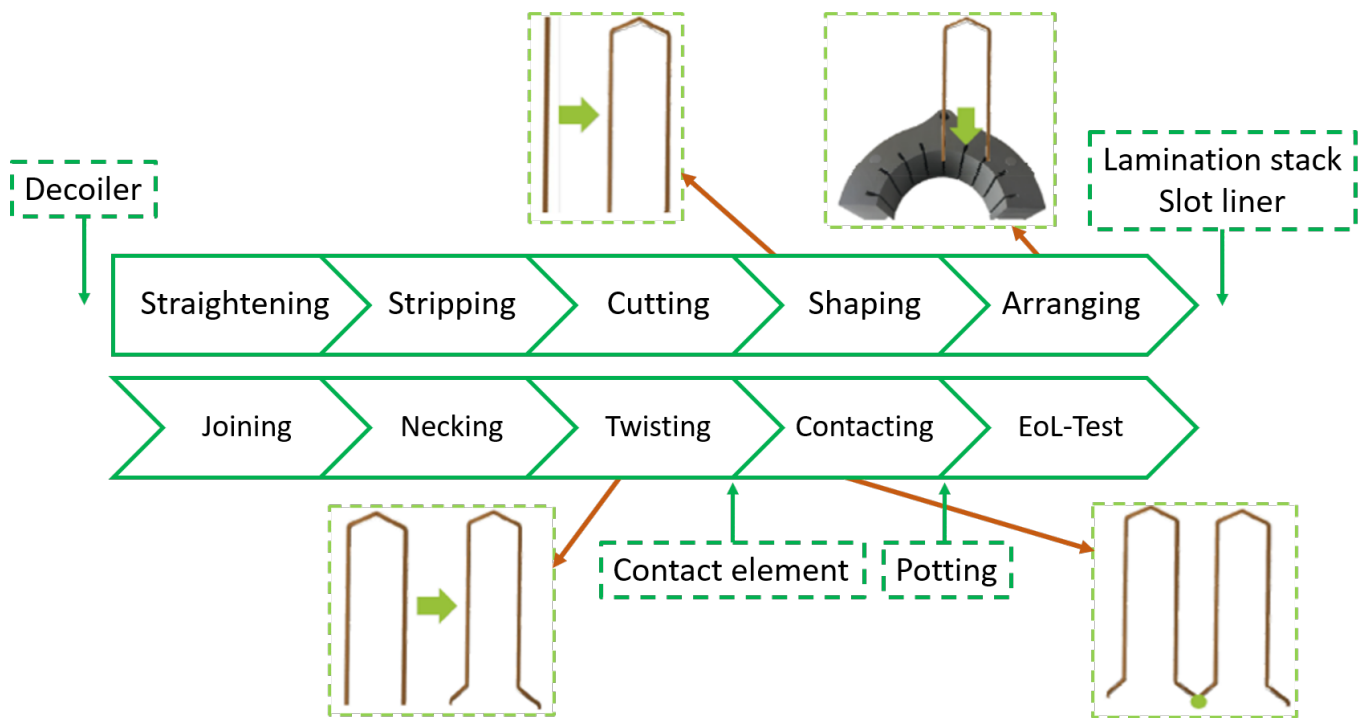


Fig. 2. The whole manufacturing chain of a hairpin winding stator

IV. ELECTROMAGNETIC CHALLENGES OF HAIRPIN WINDINGS: STATE-OF-THE-ART

A. AC losses

Currently, the application of hairpin windings in EMs for transportation is mainly limited by their inherent challenges at high-frequency operations, where skin and proximity effects take place. These phenomena make the total current distribution inside the conductors uneven and, consequently, the effective cross-section through which the current flows is a fraction of the conductor's whole cross-section.

In round conductors, the solutions to mitigate these effects include the use of stranded conductors [6], litz wires [18] and/or twisting/transposition methods [19]. The disadvantage of stranded and twisted conductors lies in the high connecting efforts of the parallel strands and the reduction of allowed conductor stress during the winding process [20]. The fill factor is also compromised.

In hairpins, the stranded conductor concept cannot be applied as flexibly as in round conductors, due to the manufacturing limitations inherent to such technology. To reduce losses in hairpin windings, methods such as removing the closest conductor to the slot opening or reducing the conductors' height while increasing the number of conductors have been described. However, the first solution reduces the fill factor since part of the slot is left empty [21], whereas the second option increases the manufacturing complexity, as a higher number of conductors need to be bent and welded [22].

B. Thermal considerations

As reported above, the losses produced in hairpin windings at high frequency operations can be significant and limit the application of such technology within a certain frequency range, i.e. typically below 1 kHz . On the other hand, the cooling of the conductor can be optimized when hairpins are used. In fact, the area of the conductor directly in contact with the lamination is much higher than that of round wires (i.e. theoretically a single spot), thus increasing the heat exchange between winding and lamination significantly. Additionally, the thermal conductivity augments within the slot since the amount of insulating materials is reduced compared to random-wound windings [23]–[25]. In [23], this concept was experimentally proven by comparing the thermal performance of a hairpin winding machine against a random winding one, both designed for the Chevrolet Voltec electric propulsion system. In [24], it was shown that the hairpin motor designed for the Chevrolet Bolt battery electric vehicle achieves a peak efficiency of 97 %, whereas in [25] a 96.5 % peak efficiency was obtained even though the studied hairpin machine has a wound-field rotor, which typically results in lower efficiency. A review of various solutions based on actual vehicles is presented in [26], where torque and efficiency performance are investigated when moving from random to hairpin designs. Here, the main conclusion is that, if the the same slot area (and not the copper area) is maintained, then the reduction of DC copper losses can overcome the increase in AC losses, resulting in improved performance.

C. Voltage distribution within windings

WBG-based converters are enabling higher operating frequencies for machines. However, their inherently faster commutations and voltage gradients (dv/dt) may trigger voltage overshoots, uneven voltage distributions, partial discharges (PDs) and faster degradation of insulations [27], [28]. With a pure sinusoidal supply voltage, the voltage distribution is even, i.e. the potential difference between two consecutive turns in a coil is the applied voltage divided by the number of turns. Using inverters, the turn-to-turn voltage can be as large as 90% of the applied voltage considering rise times of 50 ns [29].

In this context, random-wound and form-wound windings may experience different levels of stress. In a random-wound stator, the turns near the motor terminals could be positioned against turns near to the winding neutral point. This in turn means that the insulation system should be sized to withstand the maximum supply voltage of the motor. On the contrary, in form-wound windings the insertion process is carefully carried out ensuring that two adjacent turns are located against each other in the slots, thus resulting in the smallest possible voltage difference.

The impact of higher dv/dt on the reliability of EMs is twofold, depending whether the turn-to-turn or turn-to-ground voltages incept PDs within the insulation system [30] or not. In the former case, breakdown can occur in a few hours. Below PD inception, large slew rates speed up intrinsic aging [31].

V. PROGRESS BEYOND THE STATE-OF-THE-ART

As described in the previous sections, several challenges need to be overcome to allow for the complete widespread of hairpin windings in transportation. To address them, the scientific community is pushing towards innovative winding geometries, updated tools of analysis, new cooling concepts, accurate lifetime models and novel manufacturing lines permitting reliable, flexible and fully programmable coil forming setups. In the next subsections, the authors' vision relative to these new developments is reported.

A. Programmable, flexible and reliable coil forming and joining setup

The authors of this article, within the Clean Sky 2 project "Automated Manufacturing of wound components for next generation Electrical machines (AUTO-MEA)" [32], see a number of technological improvements in the next generation manufacturing lines for hairpin stators. These include three main areas/stations:

1) *Forming and shaping*: the three main units of this station need to be updated to achieve flexibility and reliability of the process. These are:

- stripping unit, with laser stripping being the most suitable solution to ensure automated, reliable and accurate removal of the enamel;
- coining and cutting unit, where the conductors, once stripped, are segmented and cut. To facilitate insertion and welding processes, the conductors ends will be first coined into chamfers, then cut by plastic deformation and separated by a clamp. This will reduce the probability of insulation damaging enhancing the reliability of the entire process;
- bending unit, where the conductors are hosted to obtain the desired 3D shape. A current drawback of this process is the lack of flexibility, i.e. several tools needs to be reconfigured when manufacturing different stator designs. Two different degrees of flexibility will be then considered in the near future: hardware and software. The bending device will be equipped with interchangeable accessories and tools (hardware flexibility) to accommodate conductors of different geometries and sizes. Additionally, updated control algorithms will permit realizing a certain number of different geometries per tool (software flexibility).

2) *Insertion and twisting*: Future researches will focus on providing tools for accurate and automatic insertion and twisting of the windings. In particular, within AUTO-MEA, a semi-automatic 3-axes twisting machine will be developed. The adoption of specific tools will reduce the possibility of insulation damaging during this phase.

3) *Welding*: as already described, laser technologies seem the best candidates for welding. However, contacting processes can be improved by further investigating on aspects such as resilience of the melting pot, physical dimension increase of the wire cross-section and repeatability of the joining procedure.

For the sake of completeness, the graphical concepts of the bending unit, the coil insertion station and the welding station are presented in Fig. 3

B. *New winding concepts*

Alternative winding concepts will be envisioned in the upcoming years to reduce AC losses and thus to increase the speed/frequency current limits of hairpin windings. Some examples have been already reported in [5]. These include:

1) *Hairpins with variable cross-section*: the basic idea consists of placing conductors with increasing cross-section along the slot radial direction, as reported in Fig. 4a) for a four layers layout. This solution

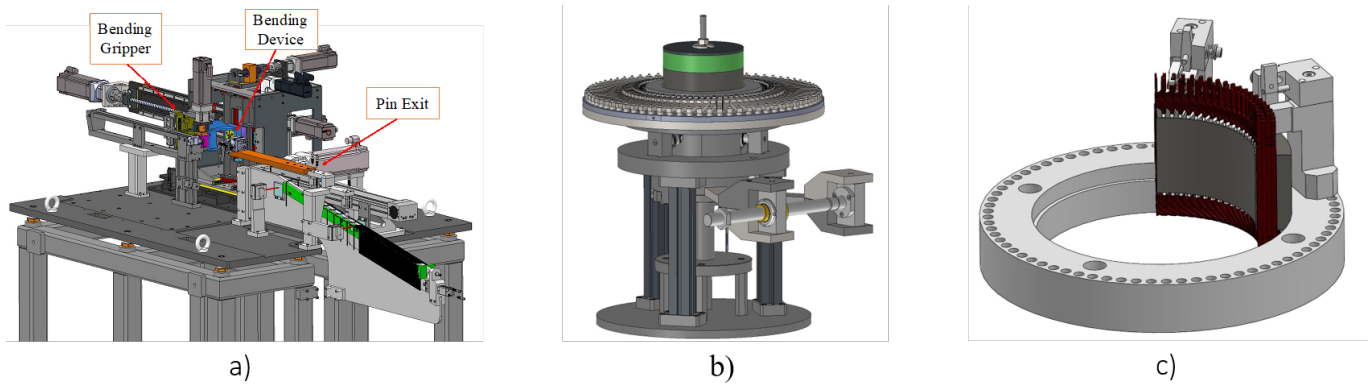


Fig. 3. Details of the manufacturing line: a) bending unit; b) coil insertion station; c) welding station

is already under study [33] and the relevant results in terms of loss reduction are promising. However, the proposed variable cross-section concept must be applied to half of the hairpins located in a slot to minimize the number of elementary hairpins needed. The flexible forming and joining setup proposed above matches this concept perfectly, allowing the automatic tooling reconfiguration.

2) *Hairpins with segmented cross-section*: this method consists of "segmenting" the hairpins near the slot opening in sub-conductors, as done for the last 2 conductors in the example of Fig. 4b). Losses drop significantly with such technique [33]. However, a suitable transposition is required. Also, particular attention should be given to ensure a reliable bending, twisting and welding processes. The relevant complexities will depend on the number of segmented conductors, which will be therefore somewhat limited. Therefore, ways to mitigate this challenge should be investigated in future.

As a preliminary validation for the segmented hairpins, some motorettes emulating stator portions of a realistic traction application [34] have been built. These motorettes are shown in Fig. 5a), where 4 configurations can be observed, with q being the number of slots per pole per phase and k the number of layers per slot. One of these 4 motorettes implements the segmented concept of Fig. 4b). In Fig. 5b), 2 motorettes equipping a random winding are shown, whose full details can be found in [34]. The experimental comparison between hairpin and random windings in terms of DC-to-AC resistance ratio K_{AC} vs. frequency is plotted in Fig. 5c). For the random winding, the minimum and maximum K_{AC} values are found considering the 66 % probability of having a value inside a certain range between a mean value and a standard deviation. Most importantly, Fig. Fig. 5c) highlights that the conventional 8-layer (Q4 8layer) and the segmented (Q4 4layerSEG) hairpin layouts achieve lower losses than the 66% of the possible solutions that can occur in random windings up to 900/1000 Hz. These results, besides proving that some hairpin layouts (including the segmented) can present lower losses than random windings even

at high frequency operations, also demonstrate that the segmented layout can compete against the 8-layer hairpin configuration.

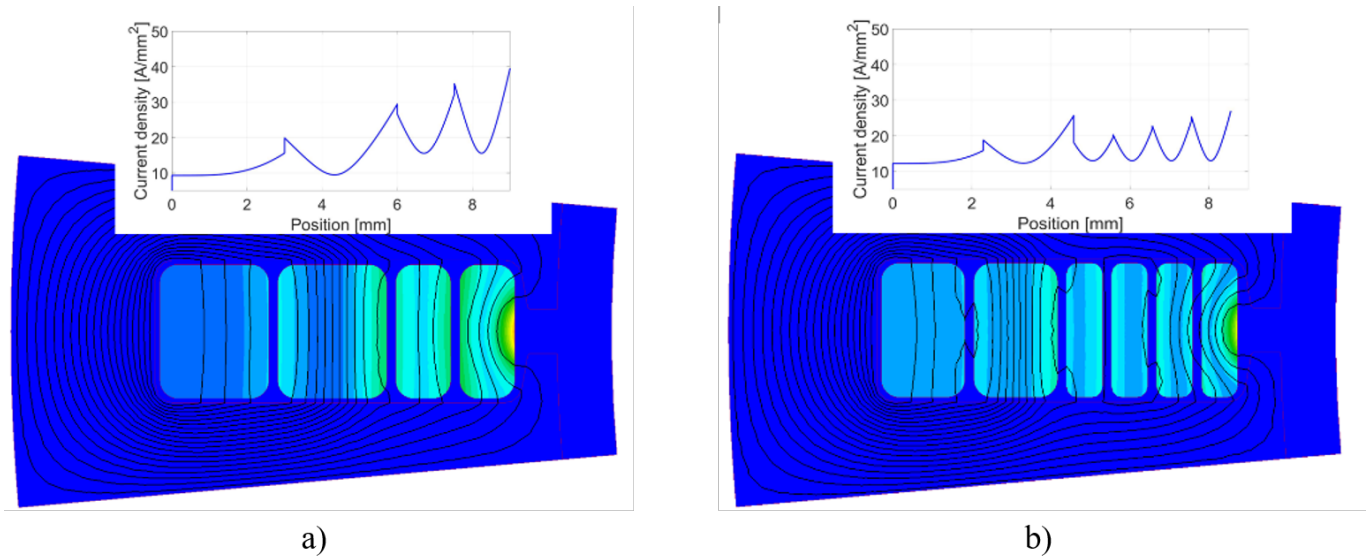


Fig. 4. New hairpin winding concepts: a) variable cross sections and b) segmented cross sections

3) *Hairpins with reinforced insulation layer*: compared to random-wound windings, hairpin windings are less sensitive to the elevated dv/dt generated by the WBG converters feeding them and to the ensuing uneven voltage distribution. However, the very first turn can be somewhat impacted by such phenomena, thus this could be equipped with a reinforced insulation layer to make the voltage distribution even more uniform. This will not have a significant impact on the manufacturing.

4) *Continuous hairpins*: continuous hairpin windings consist pre-formed elements comprising more than one coil. This leads to reduce the number of welding points. The cycle time is also reduced and the winding process is easier compared to conventional hairpins. However, open slot structures or novel stator layouts are necessary to allow their continuous insertion inside the slots. Such new concepts come at the cost of introducing new electromagnetic and manufacturing challenges.

A comparative summary highlighting benefits and drawbacks of classical (i.e. random windings and standard hairpins) and new winding concepts for next generation EMs is provided in Table I, considering an equal equivalent copper area for all the listed winding and conductor types.

C. Thermal management

As reported above, an improved thermal management is achieved when using hairpins. In [35], hollow conductors are proposed to mitigate copper losses, as these allow for axial coolants to flow through the

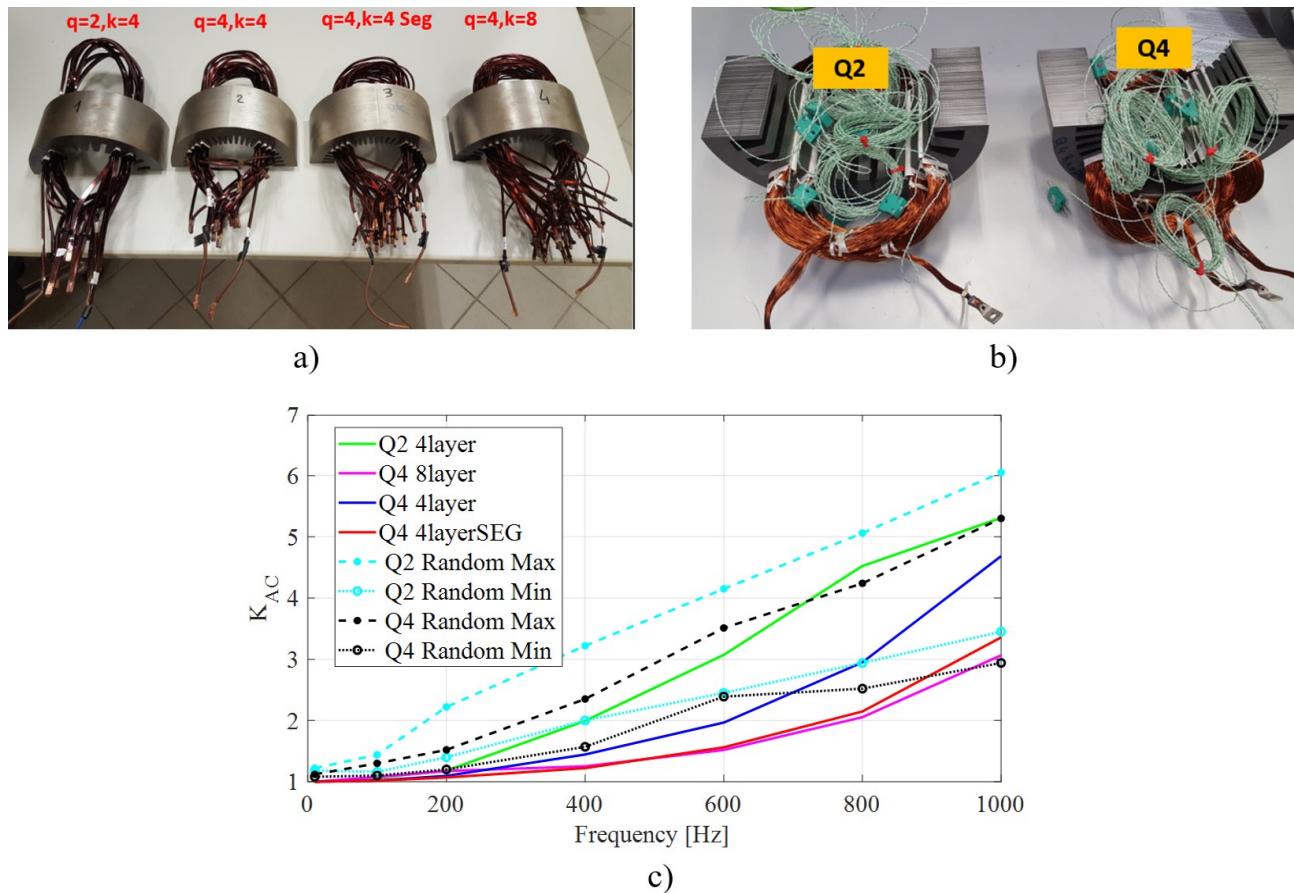


Fig. 5. Comparison between hairpin and random windings: a) hairpin winding motorettes, b) random winding motorettes, and c) resistance factor vs. frequency

TABLE I
COMPARISON AMONG THE PROPOSED NEW WINDING CONCEPTS

Winding type Conductor type	Random		Hairpin				
	Solid	Stranded	Standard	Variable	Segmented	Reinforced	Continuous
Fill factor	- -	-	+ +	+	0	+ +	
AC Copper losses	+ +	- -	+ +	0	0	+ +	+ +
Cooling capability	- -	-	+ +	+ +	+	+	+ +
Preforming effort	- -	-	0	+	+	+	+ +
Assembling effort	- -	- -	0	+	+ +	0	+ +
Connecting effort	- -	0	+	+	+ +	+	-
Voltage distribution	+	+ +	0	0	0	-	0

conductor itself, but the fill factor is compromised. Nevertheless, thanks to a better cooling, a higher current density is achieved but with lower efficiency levels. Further researches are then expected in this direction, aiming to find the best trade-off design which maximizes both torque capability and efficiency. Another interesting research path relates to the machine topology to combine with hairpin technologies, since it seems to play a role as demonstrated in [26]. Additionally, future studies will need to focus on the

cooling of the end windings. In light of this, suitable end winding shapes will be designed in such a way to host dedicated liquid-carrying pipes for a direct cooling. This is a more cost-effective methodology compared to spray cooling and flooded stator technologies typically adopted today and do not suffer reliability and robustness issues.

D. Updated analysis and modelling methodologies

1) *AC losses prediction*: to analyze the new winding concepts introduced above, the classical analytical model used for the AC losses evaluation [6] can no longer be used. In [33], ways of how to update the classical model have been already proposed. Future studies will provide an experimental validation of these concepts.

2) *Stress-strain evaluations*: one of the technological limits of pre-formed elements is due to the stress that insulating and conductive materials experience during bending and twisting. This results in pre-defined width-to-height ratios [36] of hairpins which currently represent a bottle-neck. To enable more flexible designs, detailed analyses through advanced numerical structural tools are suggested to evaluate the maximum deformations. Besides reducing the stress on insulating and conductive materials, these studies will potentially permit reducing the number of bends and/or reduce the end winding lengths and/or creating innovative winding shapes for better thermal management.

3) *Lifetime estimation*: a significant progress beyond the state-of-the-art will be that of prioritizing the reliability as a design objective for EMs equipping hairpin windings. This approach has been already proposed in [37] for low-voltage, random-wound machines. Basing on [27], a comprehensive model able to predict the voltage distribution within hairpin windings will be developed, where converter, cable and motor will be all taken into account. The model will target electrical stress within the winding and it will be tailored for the new winding structures envisioned above. Figure 6 reports a block scheme of the model, where the system geometrical and physical characteristics, along with all the electrical parameters, represent inputs of a computational algorithm that will define the estimated lifetime of the windings against electrical stress and loss distribution. The model, working in conjunction with the flexible coil forming and joining setup, will provide a powerful tool to assess the behaviour and identify the weak points of windings adopted in transport applications. These studies will enhance the reliability of electric drives and will short the design procedures of new products, since the weaknesses of the systems will be identified even at early stage of the design.

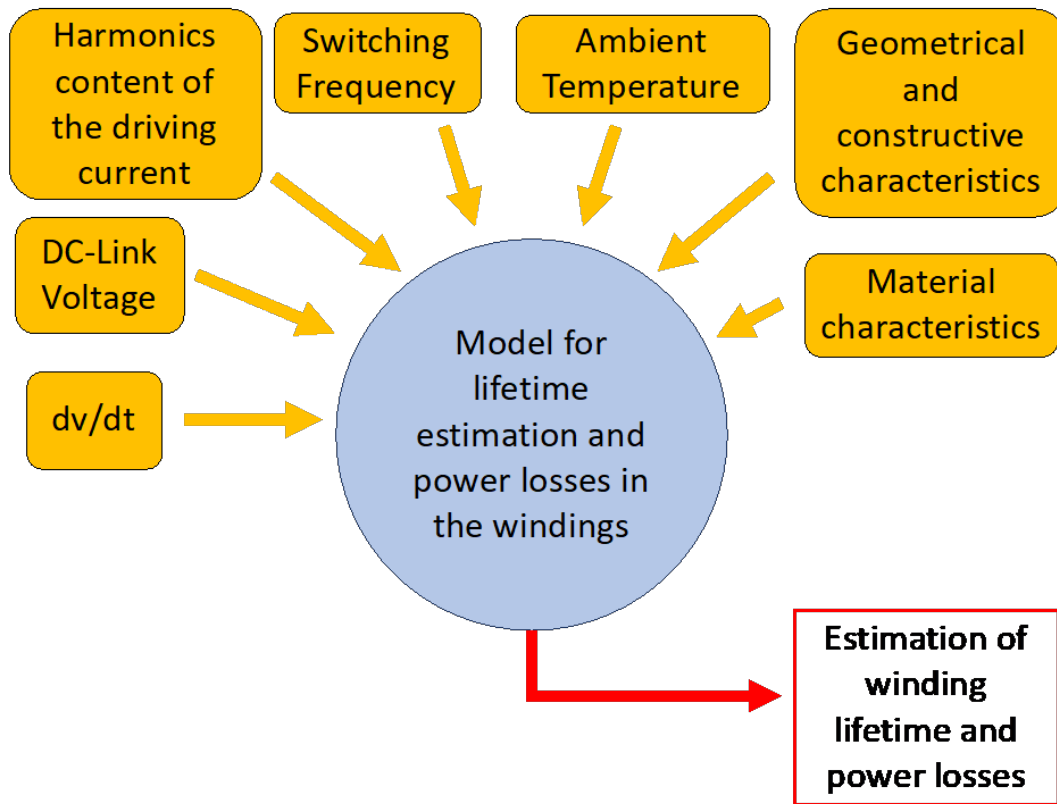


Fig. 6. High-level block scheme of the lifetime prediction model

VI. CONCLUSION

Besides aiming at maximizing efficiency and power density, next generation EMs intended for transport applications should be oriented towards an easier, faster and more reliable manufacturing than today. In fact, while sophisticated thermal management techniques, innovative cooling systems and new materials are enabling increased efficiency and power density levels, EMs' manufacturing represents a major bottleneck and a paradigm shift should soon occur to cope with the high levels of automation, capacity and repeatability required by the transportation sector. In this context, hairpin windings seem a promising technology although they currently present several challenges. To address them, the authors propose a number of actions, mainly consisting of developing a fully programmable, flexible and reliable forming and joining machinery; envisioning innovative winding and core layouts; implementing new electromagnetic, thermal and structural modelling methodologies, as well as reliability and lifetime models.

VII. ACKNOWLEDGMENT

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