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Electric Motors

Process for Manufacturing Stator Wave Windings

Process for Manufacturing Stator Wave Windings for Electric Traction Motors

In compact electric traction machines, the technology used for the stator winding is key to meeting high performance and efficiency requirements at a reasonable cost. Thus, Vitesco Technologies has developed a specific process to manufacture stator wave windings. The endless winding concept offers advantages when applied to designs with a high number of winding layers.

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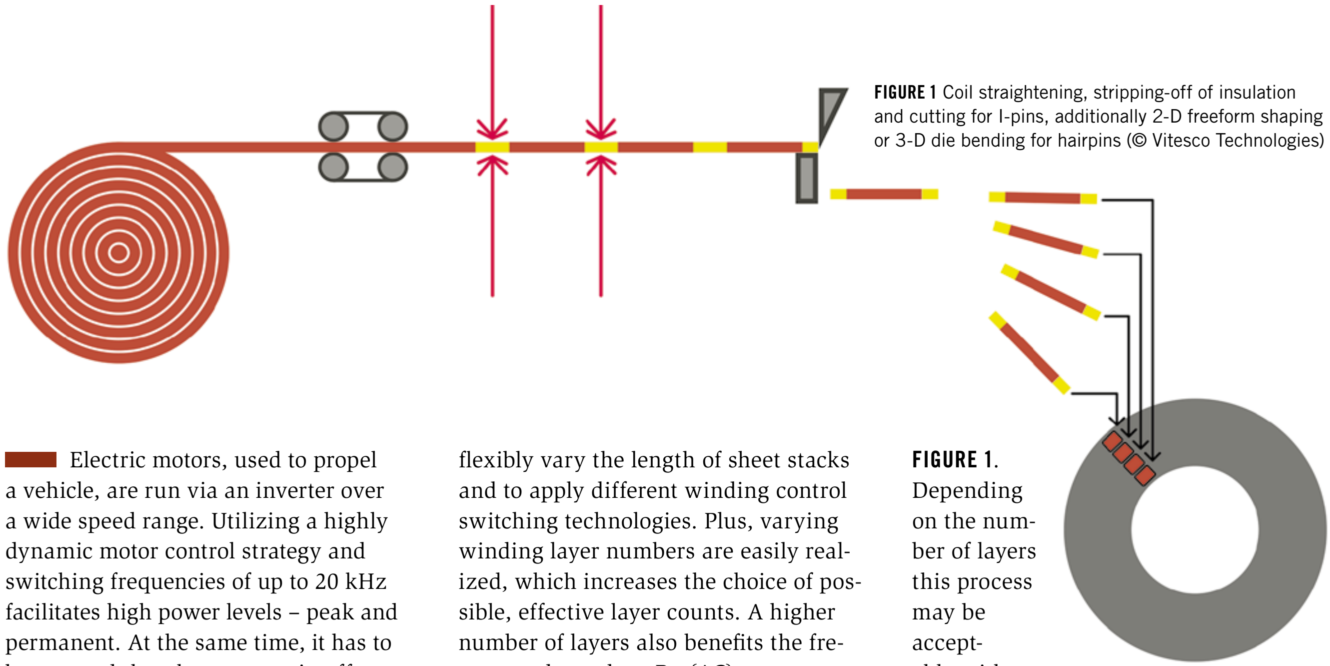

FIGURE 1 Coil straightening, stripping-off of insulation and cutting for I-pins, additionally 2-D freeform shaping or 3-D die bending for hairpins (© Vitesco Technologies)

Electric motors, used to propel a vehicle, are run via an inverter over a wide speed range. Utilizing a highly dynamic motor control strategy and switching frequencies of up to 20 kHz facilitates high power levels – peak and permanent. At the same time, it has to be ensured that the powertrain offers dynamic driving characteristics and that it uses optimal operating points to reach a high level of system efficiency. Also, parasitic effects need to be minimized and a safe system behavior has to be ensured should an error occur on the vehicle level. High-speed axle drives, which are typically implemented as Permanently excited Synchronous Machines (PSMs), require further design decisions to achieve an improved continuous performance and high energy efficiency standards during pre-defined driving cycles.

For electric traction motors, it has proven beneficial to apply stator wave winding concepts with a high copper slot fill factor of between 60 and 70 % and short winding heads to ensure the targeted compact design. A perfect fit between copper conductor and stator slot ensures an optimal heat dissipation, which in turn facilitates very high and permanently usable stator current densities. The target is to bring down the frequency-dependent stator current heat losses ($P_{cu,s}$(AC)) and the additional rotor losses, while optimizing the noise level and potentially also the EMC behavior of the powertrain. Stator wave windings offer specific advantages for that purpose because they make it feasible to flexibly vary the length of sheet stacks and to apply different winding control switching technologies. Plus, varying winding layer numbers are easily realized, which increases the choice of possible, effective layer counts. A higher number of layers also benefits the frequency-dependent $P_{cu,s}$(AC).

WINDING TECHNOLOGIES CURRENTLY IN USE

Currently, plug-in coils have become a popular choice for compact and efficient PSM. Such coils consist of massive copper pins or flat wire profiles (hairpin or I-pin) which are shaped in an automated process, subsequently fitted into the stator slots and bent into their final geometry before they are welded – contacted on one or both sides. Owed to the massive flat copper profiles, both winding technologies deliver higher slot fill factors, shorter winding heads and therefore a higher share of active material in an electric motor. This compact design is used, for example, in highly integrated and highly efficient axle drives.

However, with both winding procedures the efficiency comes at a price. The manufacturing process consists of many steps during which an endless material is first cut down to single pieces; the pieces are then machined to be re-contacted after that in situ. In the case of the I-pin winding technology, the pins are inserted into the slots with the isolation paper already inserted into the slots of the stator core, before the pins get welded from both sides, **FIGURE 1**. Depending on the number of layers this process may be acceptable with two to four layers and large wire cross-sections. With more than four layers, however, the process necessitates a high financial invest and causes uncertainties during manufacturing because the wire cross-sections get smaller which makes welding the pin ends quite a challenge.

INITIAL APPROACH: ENDLESS WINDING FROM THE INSIDE

Two aspects have been pursued for quite a while now to further improve stator wave windings: One goal was to reduce the winding head length by another 15 to 20 mm without impacting the performance. The second and overriding goal was to massively reduce the number of manufacturing steps. To do that, the initial wire cutting process was eliminated. Instead, a pre-formed copper mat is used for the endless winding. To form the mat, the copper wire is fed forward and wrapped around a rotating sword, **FIGURE 2**. The intended number of layers in the stator slots is easily controlled via the length of the mat during pre-forming. Scaling the stator height is done through adjusting the sword height.

The initial approach included a winding process from the inside. The mat is

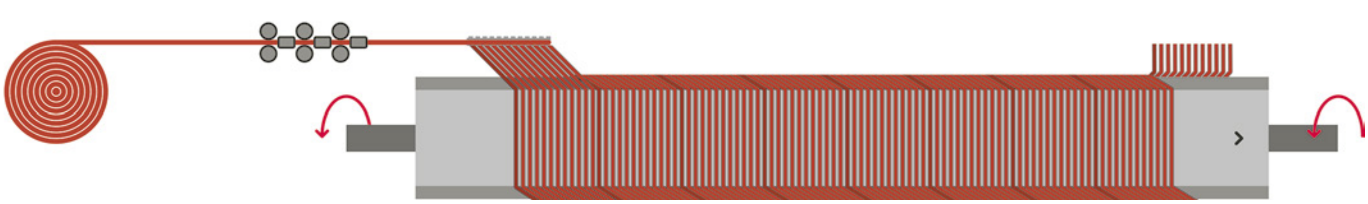

FIGURE 2 Pre-forming the mat by unwinding the coil, straightening it, axial offset and simultaneous sword rotation (© Vitesco Technologies)

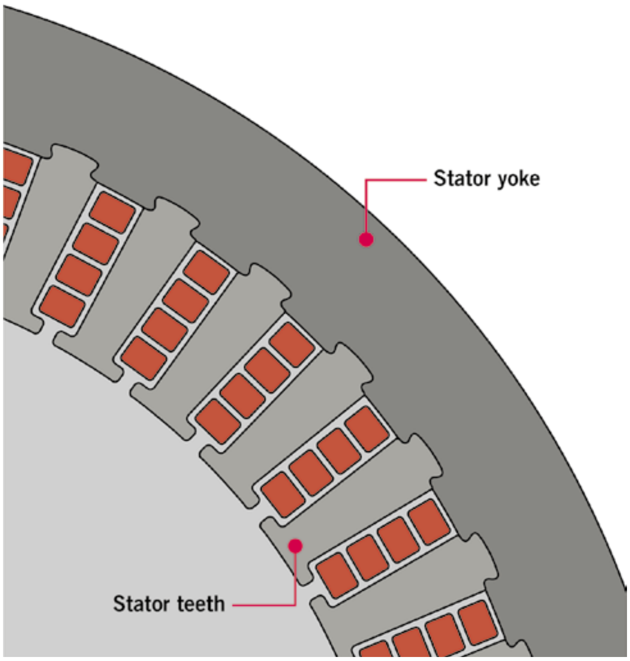

FIGURE 3 Principle of the assembled stator consisting of the yoke and teeth with the pre-formed mat wrapped on from the outside (© Vitesco Technologies)

first wrapped onto a carrier tool. Then it gets compacted to the rotor outer diameter and is fitted into the open slots of the laminated stack via sliders. The slots either remain open or they get covered with deck sliders. This, however, means that a certain minimal inner diameter must not be undercut because there is a limit to the level of possible compacting during wrapping onto the carrier tool and the subsequent expansion into the open lamination slots without damaging the mat. This winding process from the inside requires complex and inevitably sophisticated tools. Still, the idea to use a mat for a stator wave brings many advantages to manufacturing when compared to hairpin or I-pin winding concepts. The major shortcoming of endless winding from the inside as opposed to hairpin winding was the fitting process of the pre-formed mat because it necessitated open stator slots. This slot geometry is reflected in a reduced power and efficiency of the motor because the losses in the stator copper conductors and in the rotor increase. Added to that is a greater risk of noise generation and a slightly lower torque density. Therefore, it appeared that the concept had hit a dead end despite its promising potential.

ENDLESS WINDING FROM THE OUTSIDE WITH AN ASSEMBLED STATOR

This is where the development work started at Vitesco Technologies. While keeping the mat, other characteristic features of the initial concept were modified. The winding technology that is the result of this development process uses an assembled stator consisting of stator teeth and the stator yoke, plus the mat which gets wrapped onto the stator teeth from the outside, **FIGURE 3**.

By splitting up the laminated stator core into stator teeth and stator yoke, the tooth profile with the best stator performance features can be retained. In addition, the split opens up the opportunity to improve the magnetic properties by manufacturing the stator teeth from a high-performance sheet, for instance, by using a so-called grain-oriented sheet. Mounting the teeth in the stator yoke is done via an extremely robust dovetail connection with the shoulder of the dovetail positively fitting into the yoke profile, **FIGURE 3**. Later on in the process, the stator teeth are inserted into the yoke with a slight fit interference via a press fit process. This results in a very stable assembly which has been successfully confirmed on the test bed under extreme conditions. The design has also been confirmed through several boundary part inspections.

The mat is formed by wrapping the copper wires, which are fed from the side and are given a linear offset, around a rotating sword. After that the mat is compressed and the wire ends get stripped on-the-fly while the mat is transported for coiling-up. Parallel to forming the mat, the individual yoke teeth – or a tooth ring – are transported on a separate line to be inserted in a clamping tool, **FIGURE 4**. Within the same manufacturing step, the groove insulation paper is fed, shifted by one tooth. The compressed mat with its stripped wire ends is now wrapped from the outside onto the teeth in the clamping tool. The number of

FIGURE 4 Punch-packed single tooth (left), an optional tooth ring assembly (middle) and a yoke (right) (© Vitesco Technologies)

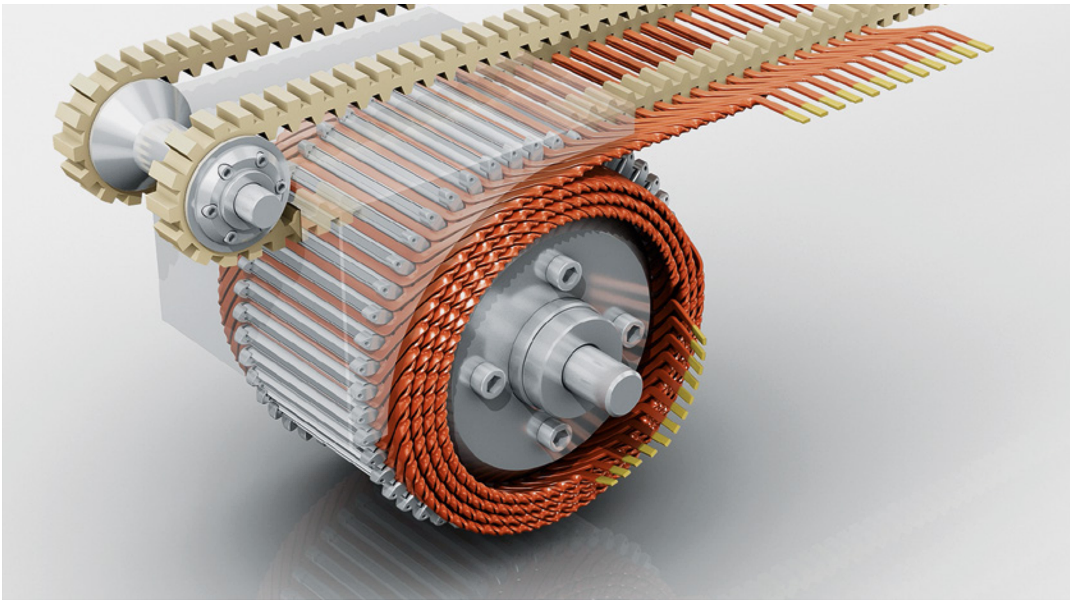

FIGURE 5 Stator wave winding from the outside: The compressed copper mat is wrapped onto the clamping tool carrying the inserted teeth (© Vitesco Technologies)

layers is easily scaled via the length of the mat and the number or revolutions during wrapping, **FIGURE 5**. Subsequently, the assembled laminated stator core in the clamping tool is placed in a press and the stator yoke is forced on. During this step the dovetail joint profile of the teeth is mechanically joined with the yoke. After that the winding head is widened on one side and the clamping tool is removed. The remaining steps until the joining of stator and housing correspond with the common-method stator manufacturing process.

POTENTIALS OF THE WINDING CONCEPT

Endless winding of an assembled stator is especially beneficial for stator wave windings with a high number of winding layers. All the performance features principally listed at the beginning apply. In addition, endless winding delivers yet another step forward in reducing the winding head length when compared to I-pin winding or hairpin winding.

The new technology for winding an assembled stator from the outside delivers – under otherwise identical conditions – practically the same efficiency and performance as a hairpin stator. While it is true that the dovetail joints slightly impact the remagnetizing losses, a high number of layers – which is exactly the core application for the new winding process – reduces the skin and proximity effects through smaller wire cross sections. This offers particular benefits at higher speeds.

Compared to the hairpin winding process, the new winding process drastically reduces the number of production steps which is especially advantageous for designs with six layers or more. In addition, it can be ramped up with an increasing automation level to reach high six-digit annual production unit numbers without any disruptions by adding more production lines that follow the same procedure.

Initial motor samples have confirmed the abovementioned performance features in the real world. Two things are particularly noteworthy in this context. Firstly, the high number of layers shows a positive influence on the frequency-dependent current heat losses. Secondly, the mechanic fatigue strength of the dovetail joints has been proven by endurance testing with over 2500 h runtime.

SUMMARY AND OUTLOOK

The innovative endless winding concept with assembled stator was developed to better meet customer requirements for electric vehicle range, performance and driving fun, while at the same time simplifying manufacturing and increasing process robustness. The new process is especially suited for high automation levels and offers a combination of high robustness and a much lower number of manufacturing steps. The concept is scalable and modular, and it requires a lower investment in comparison to existing concepts such as hairpin and I-pin winding. This makes it the technology of choice for rapidly growing electric vehicle production numbers and the increasing cost pressure that come with them. The process described facilitates the production of very compact, powerful and efficient traction motors with a high copper slot fill factor and a winding head even smaller than that of a hairpin winding.

THANKS

The authors wish to express their gratitude to Aumann AG for the outstanding cooperation on this highly challenging project.

IMPRINT:
Special Edition 2022 in cooperation with Vitesco Technologies GmbH, Postfach 200230, 93061 Regensburg;
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Amtsgericht Wiesbaden, HRB 9754, USt-IdNr. DE81148419

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