Maximising E-Machine Efficiency with Hairpin Windings

White Paper | 2021

Introduction

Requirements for electrical machines in traction applications keep increasing in terms of power density and efficiency. The use of hairpin windings is a relatively new development and sees increasing attention due to its beneficial electromagnetic and thermal performance. Hairpin windings are solid conductors as opposed to stranded wire used traditionally and hence can achieve a high fill factor and good thermal performance. This makes the use of hairpin windings attractive in designs where high power density and efficiency are required.

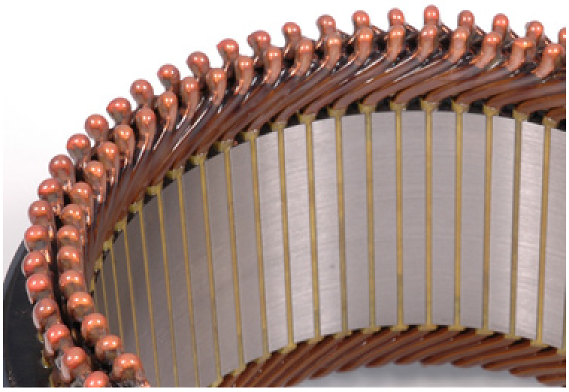

Fig. 1 - Example of a hairpin winding (Source Remy)

Hairpin winding overview

The advantages and disadvantages of hairpin windings can be listed as below:

Table. 1 - Advantages and disadvantages of hairpin windings [1]

Advantages
Fill factor can be up to ~0.75, compared with 0.4-0.6 for conventional round wires
Better thermal performance
Enable a highly automated manufacturing process
Disadvantages
Less flexibility for winding configurations
AC losses
Higher cost

Hairpin windings have the benefit that they enable a highly automated manufacturing process using advanced hairpin winding machinery. There are different manufacturing processes which can be distinguished into axially inserted and radially inserted hairpin windings, the latter also referred to as a continuous hairpin winding. A basic sketch of the production process for axial-insert hairpin windings is shown in Fig. 2. The conductor is bent to form a U-shape and subsequently these preformed conductors are inserted into the stator slots. The end of the conductor is twisted and joined together by a welding process. The assembled hairpin winding is shown in Fig. 3.

The production process for radial-insert hairpin windings is shown in Fig. 4. The conductor is bent to pre-shape the entire winding and subsequently the pre-shaped conductors are inserted into the stator slots. The advantage of this technique is that no welding is needed to contact the adjacent hairpins. The reliability of the winding can be improved, and the production process of the winding can be simplified. However, the pre-shaped winding can be only inserted into the slot radially. Furthermore, open slot is needed for the stator. The assembled hairpin winding is shown in Fig. 4b.

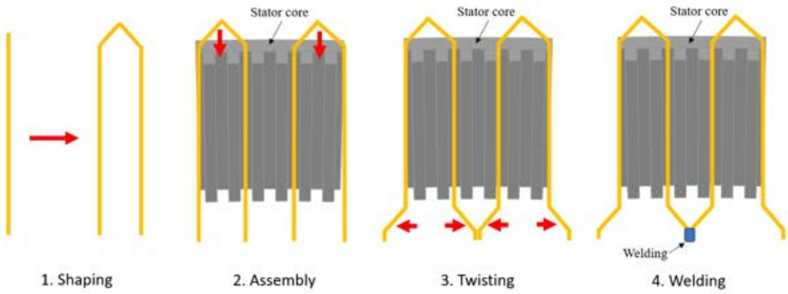

Fig. 2 - The production process of the winding with axial-insert hairpin conductors.

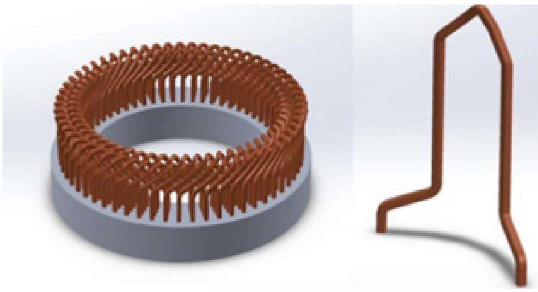

Fig. 3 - Assembled axial-insert hairpin winding in an electrical machine.

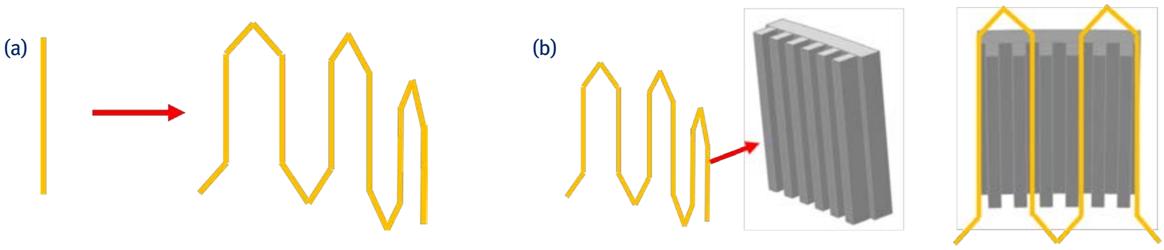

Fig. 4 (a-b) - The production process of the winding with radial-insert hairpin conductors. (a) Shaping of the wire. (b) Assembling the pre-formed winding to the motor.

Hairpin winding modelling in Motor-CAD

Hairpin winding design rules

There is less flexibility in the feasible winding configurations for hairpin windings, hence design rules need to be introduced to check the winding feasibility. These design rules determine whether the positioning of the series conductors (of each phase) in the stator slots is feasible for a certain pole/slot combination and how many parallel paths are possible [2].

The feasibility of different slot/pole combinations is determined based on the Electro Motive Force (EMF). The EMF induced in the conductors of each adjacent slot for a single phase is different. Therefore, to balance EMF, conductors belonging to the same winding path need to be present in each slot/pole/phase, irrespective of the layer.

If multiple parallel paths are required, the impedance for each parallel path must be the same to avoid current unbalance and additional copper losses. This means the hairpin winding should be transposed, i.e. each winding path needs to be located in every layer of the slot. This is due to the fact of the impedance of the conductors in various layers is different. Fig. 5 shows two different feasible configurations for a 36-slot/6-pole machine with 8 winding layers. Fig. 5(a) shows the winding configuration for 1 parallel path, whereas Fig. 5(b) shows the configuration for 2 parallel paths, represented by the red and the green lines, respectively. To balance EMF and avoid current unbalance, each parallel path covers all the layers of the slot and all the slots per pole of that phase.

The design rules of the hairpin winding can be summarised as below:

a. Number of winding layers is even
b. The wires that belong to the same parallel path must cover all the layers of the slot (Ensure same inductance for each parallel paths)
c. The wires that belong to the same parallel path must cover all the slots per pole of that phase (Ensure same Back EMF for each parallel paths)

In Motor-CAD, when the hairpin winding is selected, the hairpin winding feasibility will be checked according to the design rules above. If the hairpin winding is not feasible for the design, a warning will notify the user as shown in Fig. 6, where the number of slots is 36, the number of poles is 6, the winding layer is 2, and the parallel paths is 5. In this case, the Conductor per Parallel Path/(Slots per Pole per Phase) is not an integer, which means that the wires that belong to the same parallel path cannot cover all the slots per pole of that phase.

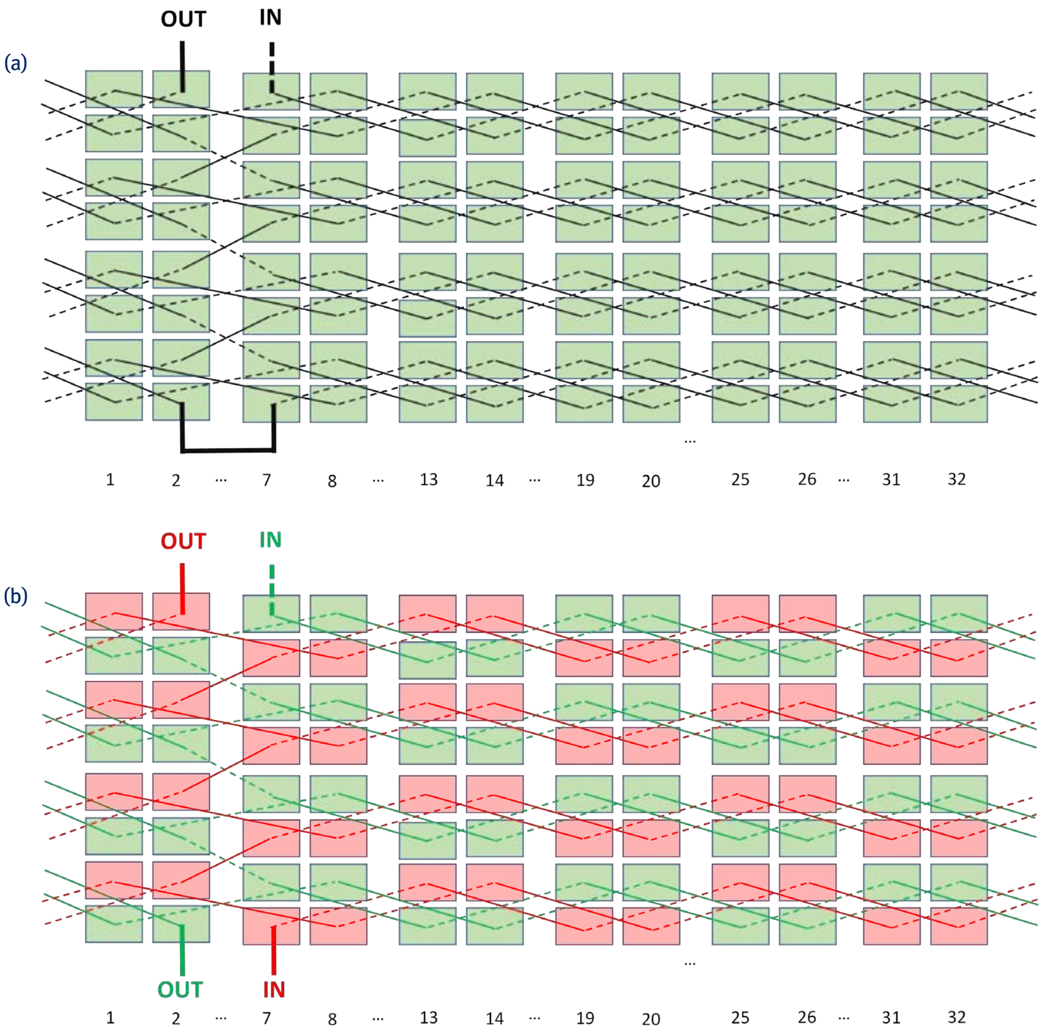

Fig. 5 - Hairpin winding configurations with different number of parallel paths. (a) 1 parallel path. (b) 2 parallel paths.

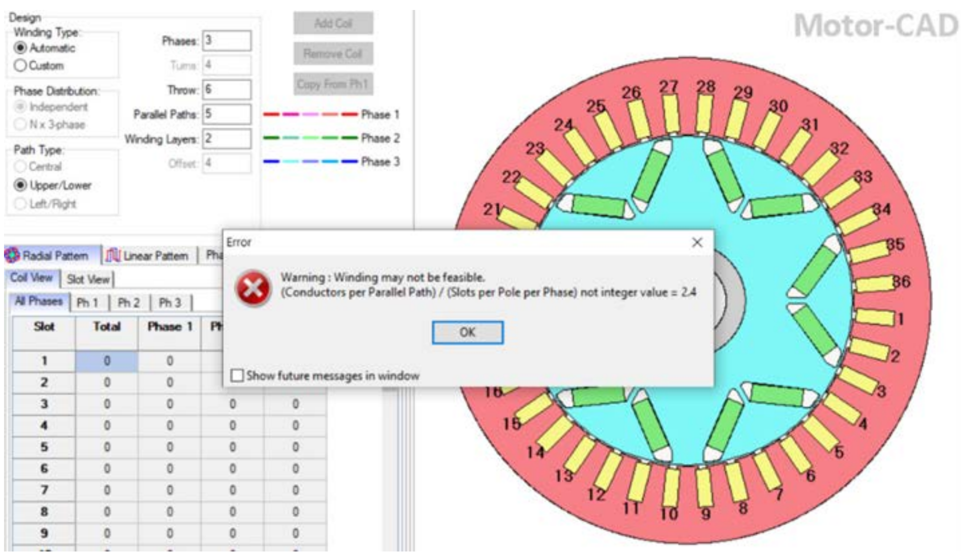

Fig. 6 - Hairpin design check in Motor-CAD showing warning message as design is not feasible.

Modelling hairpin windings with Motor-CAD Software

The modelling of hairpin windings in Motor-CAD is demonstrated on a representative traction motor for automotive EV application is shown in Fig. 7. This is a 36-slot/6-pole machine topology with interior permanent magnets (IPM) in a single layer V-shape arrangement. Fig. 8 shows the torque vs. speed curve and the peak power vs. speed curve of the machine. The efficiency map of the machine is shown in Fig. 9.

The configuration of the hairpin winding is shown in Fig. 5(a). The selected hairpin winding has 1 parallel path and 8 winding layers. Fig. 10(a) shows how the coil configuration of the hairpin winding is defined in Motor-CAD. To implement the coil for the hairpin winding in Motor-CAD, the custom winding design should be selected. In the Winding-Pattern tab, select “Custom” for the winding type. The coil positions can then be defined manually by editing the coil positions. Fig. 10(b) shows the coil locations of phase 1 in the radial view. The linear view of the hairpin winding is shown in Fig. 11.

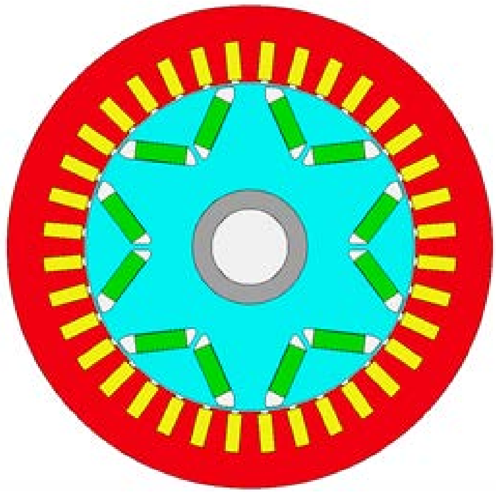

Fig. 7 - The Motor-CAD model of the 36-slot/6-pole machine.

(a)

(b)

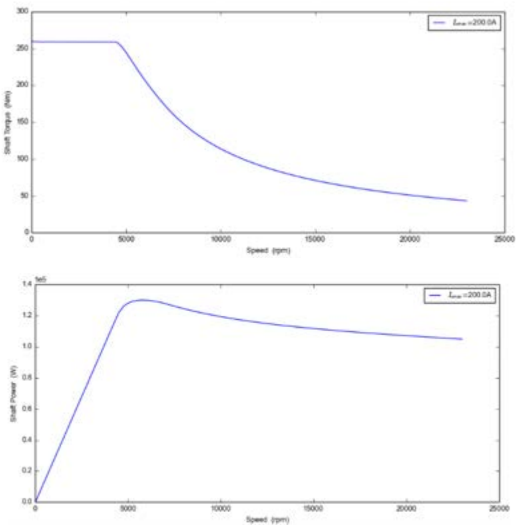

Fig. 8 - Motor performance curves. (a) Peak torque vs. speed. (b) Peak power vs. speed.

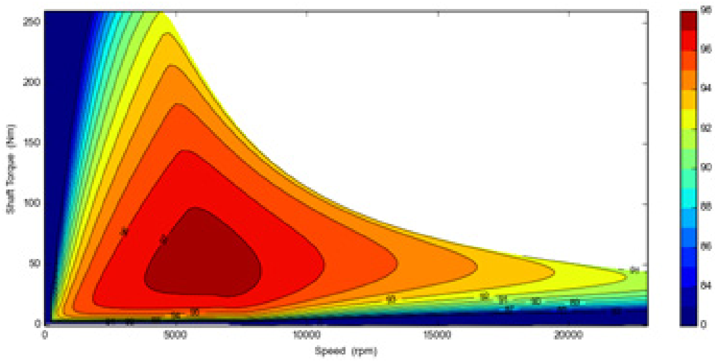

Fig. 9 - Efficiency map.

(a)

(b)

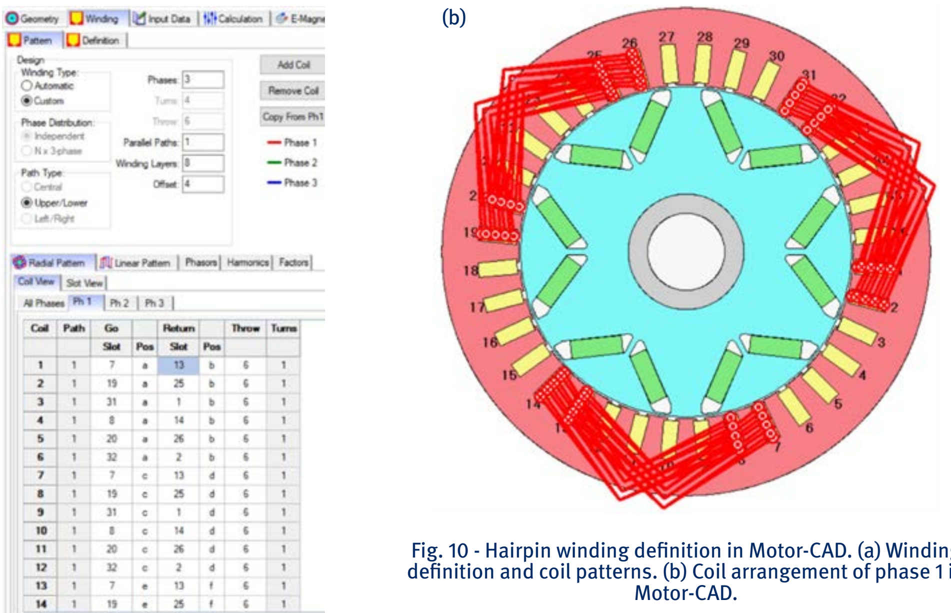

Fig. 10 - Hairpin winding definition in Motor-CAD. (a) Winding definition and coil patterns. (b) Coil arrangement of phase 1 in Motor-CAD.

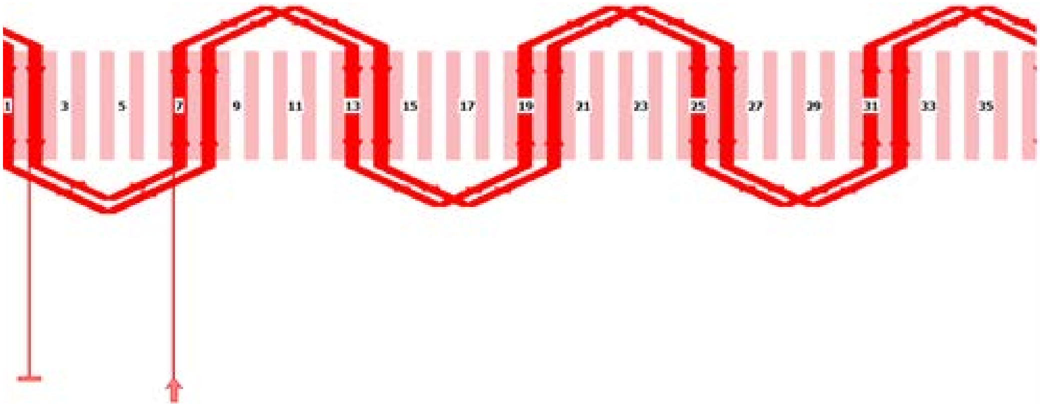

Fig. 11 - Linear view of the winding of phase 1 in Motor-CAD.

Influence of winding layers on the losses

AC copper loss can be introduced in the conductors when the current is alternating, due to skin and proximity effects. Compared with a random wound winding, a hairpin winding has less number of conductors per slot and the conductors are solid, hence skin and proximity effects in hairpin windings can be much more significant. These effects are especially pronounced at high operating speeds, when the AC copper loss can become considerably higher than the DC copper loss. The higher AC losses compared to wound windings can be a possible drawback of the use of hairpin windings in machines for electric vehicles [3] [4]. Therefore, AC loss analysis and reduction for hairpin windings is a key consideration when designing these electric traction motors.

In this section, the AC and DC losses are analysed in Motor-CAD for increasing number of winding layers. Fig. 7 shows the radial view of the machine being studied, it is a 36-slot/6-pole IPM for electric vehicle applications.

In general the AC copper loss can be reduced by increasing the number of winding layers in a hairpin winding [2]. However, this usually also leads to an increase in DC copper loss due to the reduction of the fill factor caused by additional insulation layers between winding layers. Hence, a trade-off between AC and DC copper losses exists when designing the hairpin winding.

In this section, the AC and DC losses are analysed for the machines with different winding layers (2, 4, 6, 8) and different number of parallel paths (1, 2, 3, 4) in Motor-CAD. Fig. 12 shows the stator slot with different winding layers. Fig. 13 shows the fill factor variation with the number of winding layers. The fill factor reaches >0.75 when there are only two winding layers. It decreases with the increase of the winding layers, dropping to around 0.65 for 8 layers.

The winding losses are analysed with sinusoidal current excitation. Fig. 14 shows the resulting AC and DC copper loss variations for increasing number of layers, at 2 different operating speeds, i.e. high speed (12,000rpm) in Fig. 14a and low speed (1,000rpm) in Fig. 14b.

It can be seen that at 12,000 rpm, AC copper loss is the dominant loss component in the winding copper loss. The AC copper loss decreases significantly with increasing winding layers, whereas the DC copper loss increases slightly due to the increase in winding resistance. When considering the total loss it can be seen that increasing the number of layers sees an overall decrease of total loss at the high speed condition.

On the other hand, at 1,000 rpm, the DC copper loss component is dominant in the winding, increasing further with more winding layers due to the lower fill factor. The AC copper loss component is only small, hence the total copper loss tends to increase with higher winding layers.

As AC and DC copper losses vary significantly at different operating points, it is necessary to assess the impact of different layers over the full drive cycle to identify the optimal number of winding layers for the machine. The drive cycle analysis can be done in Motor-CAD in the Lab module under Duty Cycle-Calculation tab as shown in Fig. 15.

The drive cycle analysis results are shown in Fig. 16(a). Under both the NEDC and WLTP drive cycles, the copper loss of the electrical machine reduces significantly when the number of winding layers increases from 2 to 6, whereas the total copper loss of the electrical machine can be seen to increase slightly when the number of winding layers changes from 6 to 8. Therefore, the optimal number of winding layers is identified as 6 to maximize drive cycle efficiency as shown in Fig. 16.

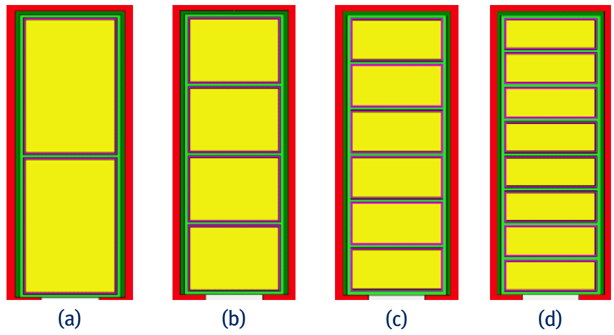

Fig. 12 - Slot view of machines with different winding layers.
(a) 2 layers. (b) 4 layers. (c) 6 layers. (d) 8 layers.

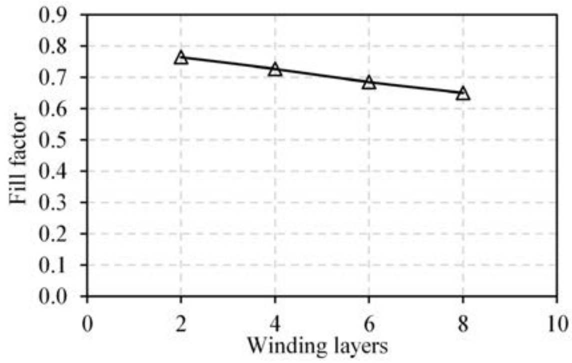

Fig. 13 - Slot fill factors with machines with different winding layers.

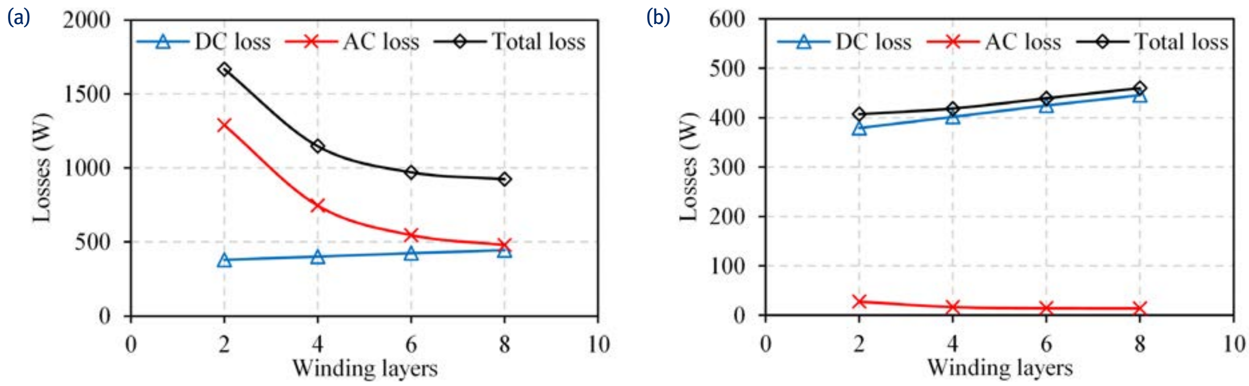

Fig. 14 - Winding losses of the machines with different winding layers. (a) At 12,000rpm, 200A. (b) At 1,000rpm, 200A.

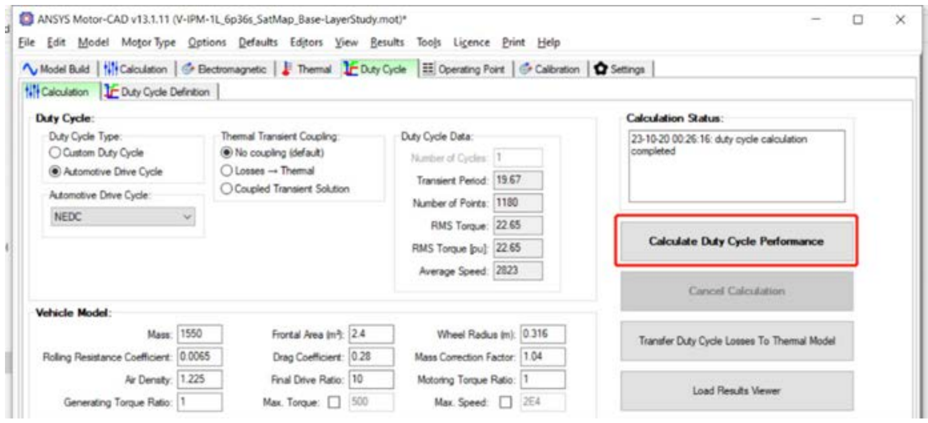

Fig. 15 - Drive cycle analysis in Motor-CAD.

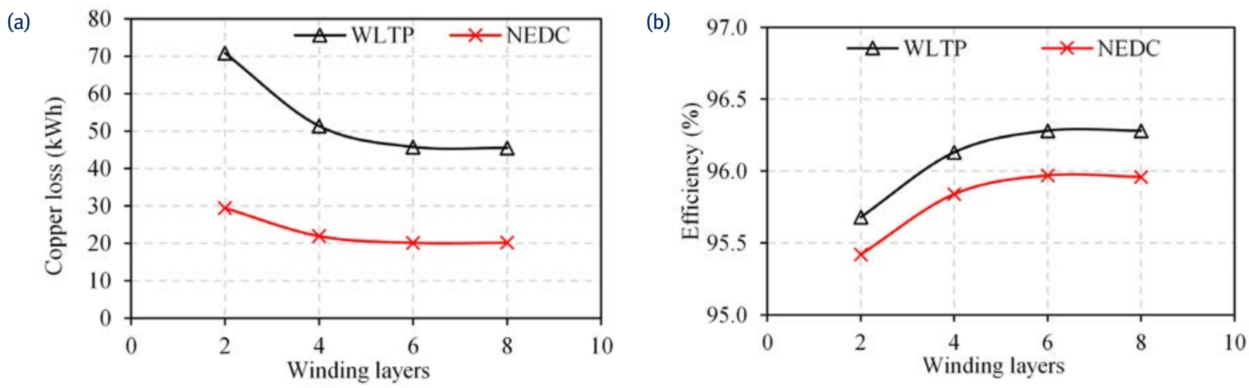

Fig. 16 - Copper loss and efficiency for different drive cycles.
(a) Copper loss. (b) Efficiency.

Conclusions

This paper has demonstrated the bespoke modelling capabilities in Motor-CAD for the analysis and design of hairpin windings. The modelling method of the hairpin winding using Motor-CAD is shown as well as the introduction of design rules and checks in the software. Based on a representative traction motor example, the influence of introducing more winding layers on the copper losses has been analysed, with the following conclusions:

a. Using a higher number of winding layers does not always result in lower copper loss.

b. The trade-off between DC and AC losses under different operating points should be considered when designing for the optimal number of winding layers.

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References

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[2] N. Bianchi and G. Berardi, "Analytical approach to design hairpin windings in high performance electric vehicle motors", 2018 ECCE.

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