Modelling of Hairpin Winding in Motor-CAD

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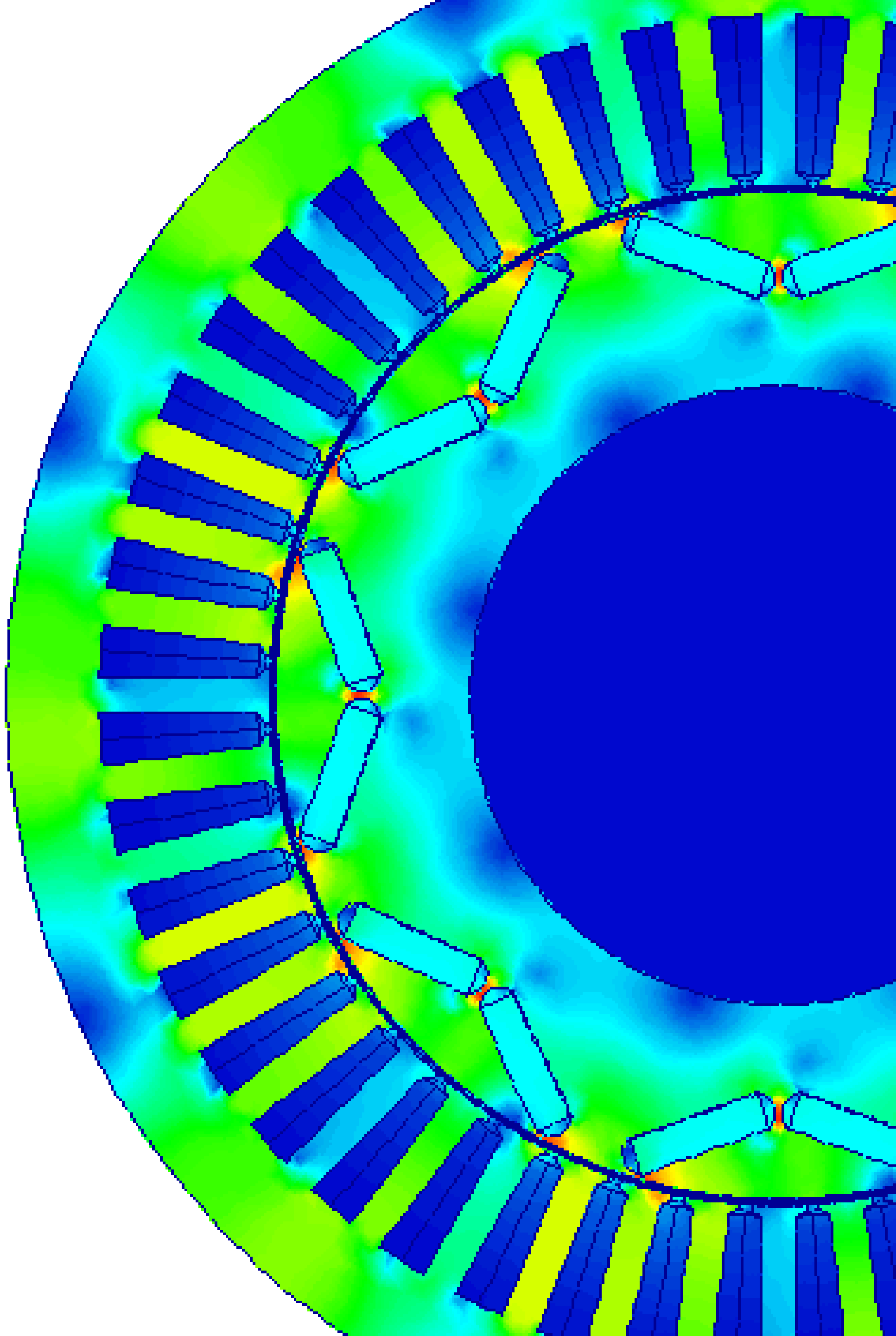
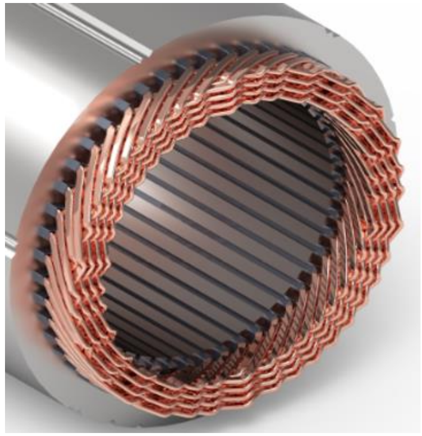


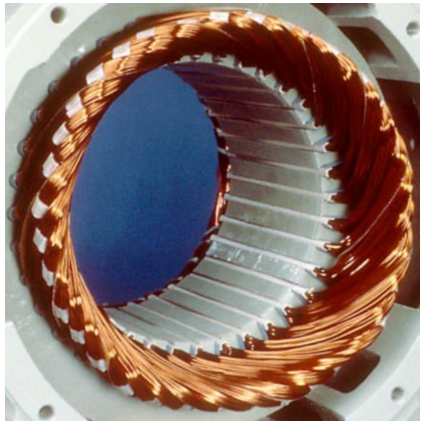
Hairpin windings

Overview

- Uses pre-formed conductors to replace random-wound copper wires in the windings [1]
- Benefits from advantages such as high fill factor, highly automated manufacturing process, etc.
- Becoming very popular in EV/HEV drive applications



Hairpin winding

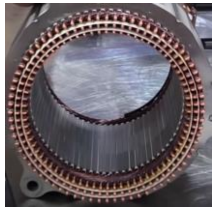


Random-wound winding

Chevrolet Volt 2nd Gen 2016

Toyota Prius 4th Gen 2015

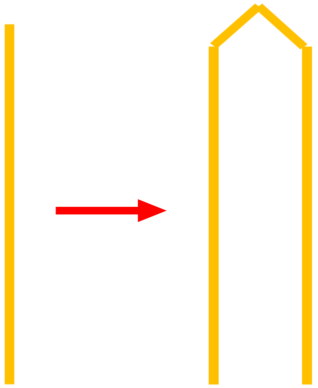
Chevrolet Bolt 2016



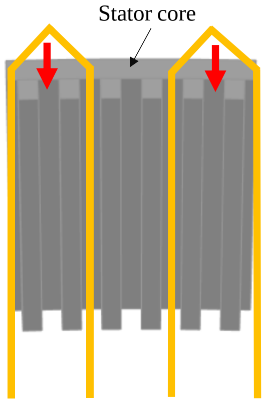
[1] W. Cai, D. Fulton, and C. L. Congdon, “Multi-set rectangular copper hairpin windings for electric machines,” U.S. Patent 6 894 417, 2005.

Production process

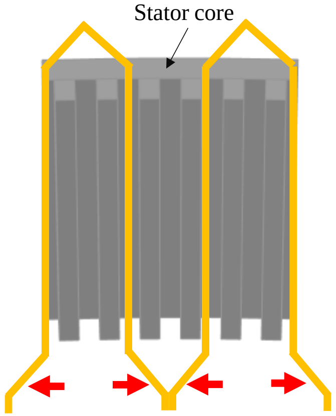
Axial-insert hairpin



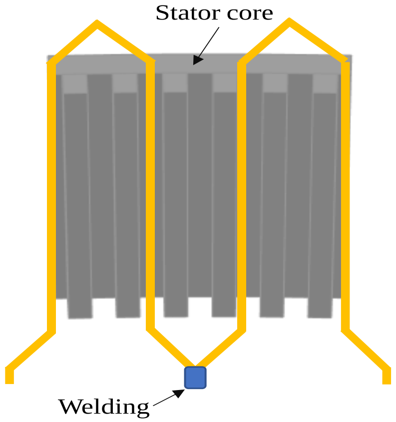
Shaping



Assembling



Twisting



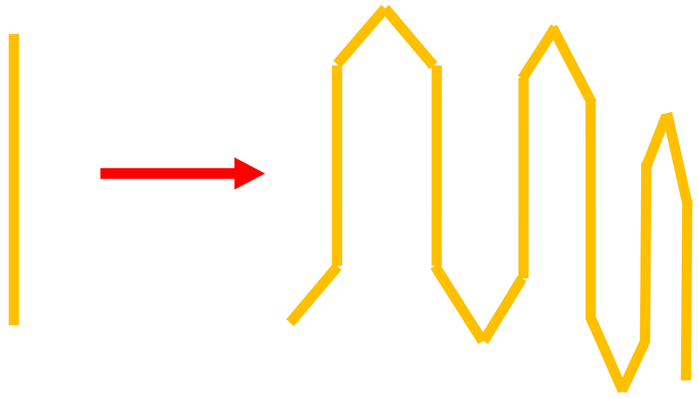
Welding

Axially inserted hairpin

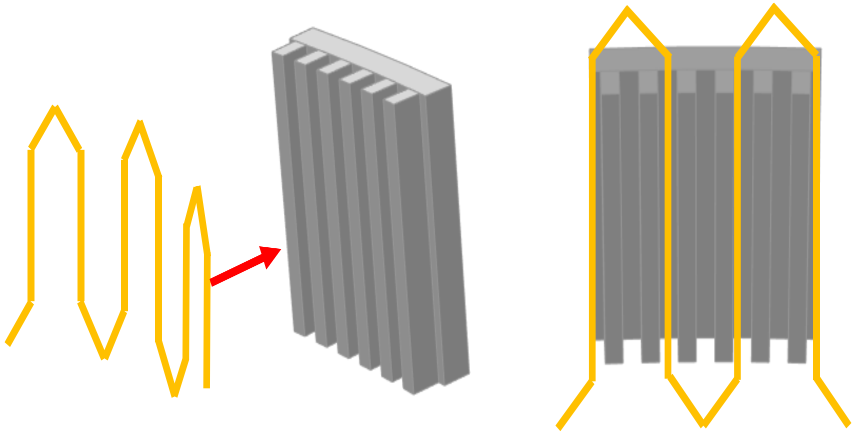
- Welding is required to connect hairpins
- The more conductors there are the more time consuming this process becomes.
- A rough maximum feasible solution is 72 slots, 8 winding layers.

Production process

Radially-insert hairpin (Continuous hairpin winding)



Shaping



Assembling

Radially inserted hairpin (Continuous hairpin)

- Welding is not required between hairpins since they are preformed
- Easier to have higher numbers of slots and winding layers, maximum around 12 winding layers.
- Open slot structure is required.

Hairpin windings

Advantages and disadvantages

Advantages	Disadvantages
• Fill factor can be up to ~0.75 • Better thermal performance • Enable a highly automated manufacturing process	• Less flexibility for winding configurations • AC losses • Higher cost

Hairpin winding modelling in Motor-CAD

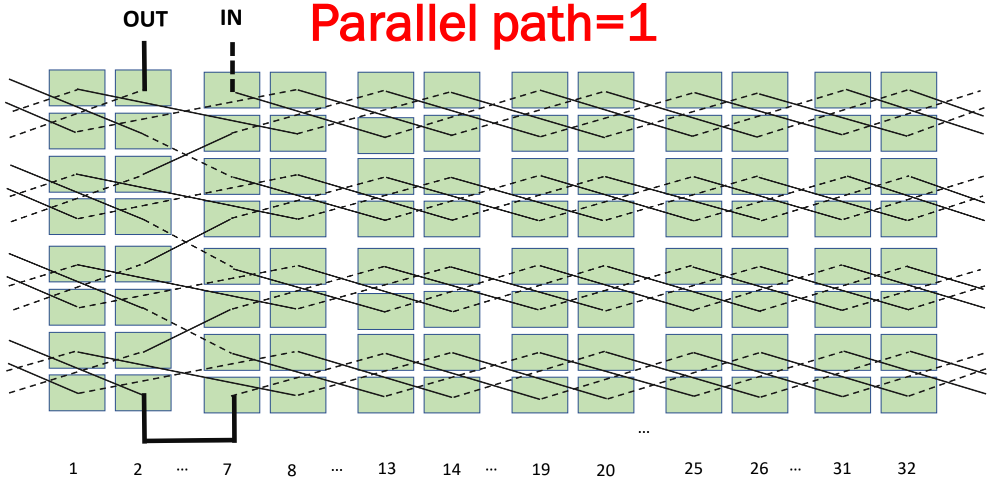
Hairpin winding design rules [1] [2]

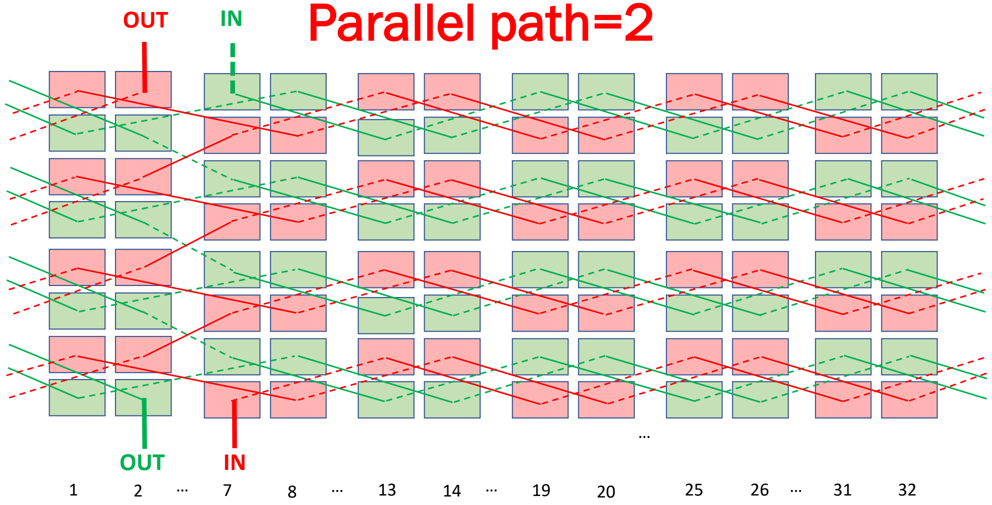
- Number of winding layers is even
- The wires that belong to the same path must cover all the layers of the slot

(Ensure same inductance for each parallel paths)

- The wires that belong to the same path must cover all the slots per pole of that phase

(Ensure same Back EMF for each parallel paths)





[1] G. Berardi and N. Bianchi, "Design guideline of an AC hairpin winding", 2018 ICEM.
[2] N. Bianchi and G. Berardi, "Analytical approach to design hairpin windings in high performance electric vehicle motors", 2018 ECCE.

Hairpin winding modelling in Motor-CAD

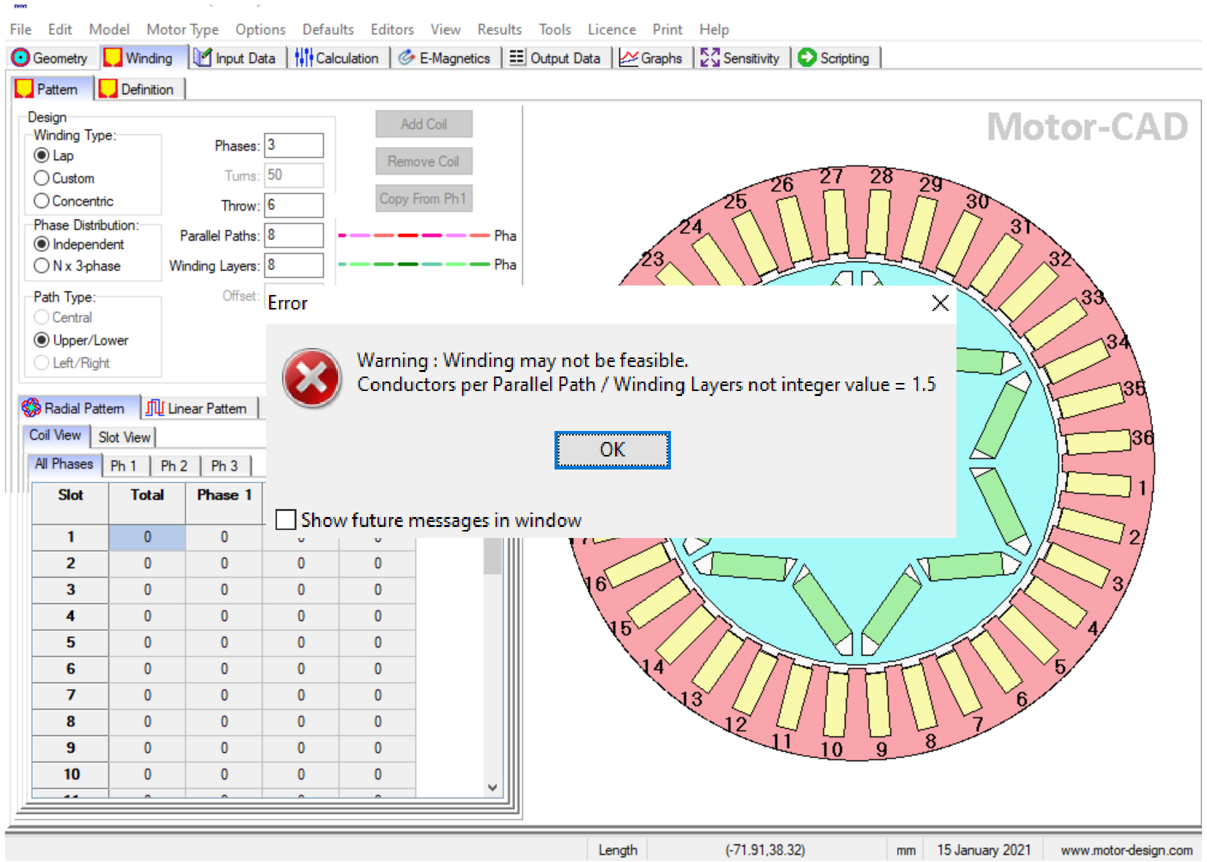
Hairpin winding design rules

Number of slots	36
Number of poles	6
Number of Parallel paths	2
Number of hairpin winding layers	8
Number of conductors per parallel path / number of layers	6
Number of conductors per parallel path / number of slot per pole per phase	24

Feasible

Number of slots	36
Number of poles	6
Number of Parallel paths	8
Number of hairpin winding layers	8
Number of conductors per parallel path / number of layers	1.5
Number of conductors per parallel path / number of slot per pole per phase	6

Not Feasible



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

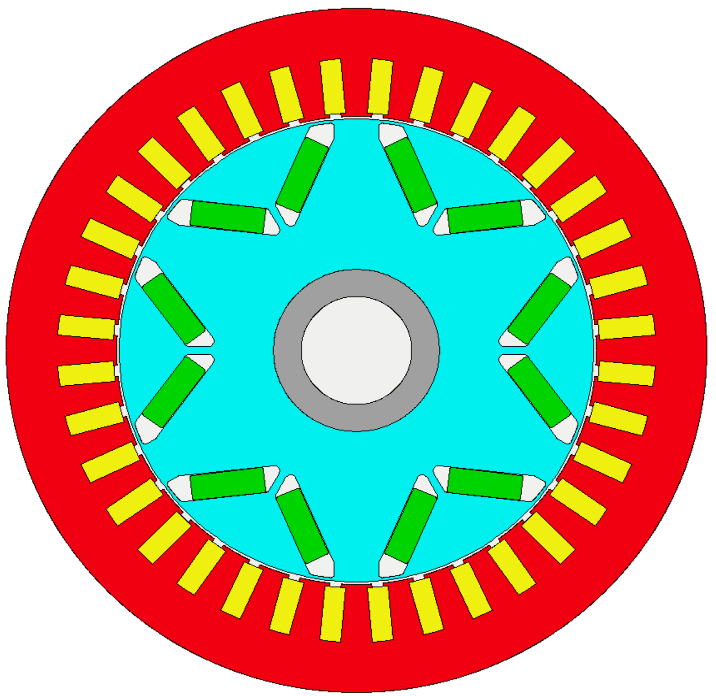
Case study

- Modelling of a motor with hairpin winding
- Analysis on the DC and AC copper losses
- Optimise the number of winding layers and conductor size to maximise motor efficiency.

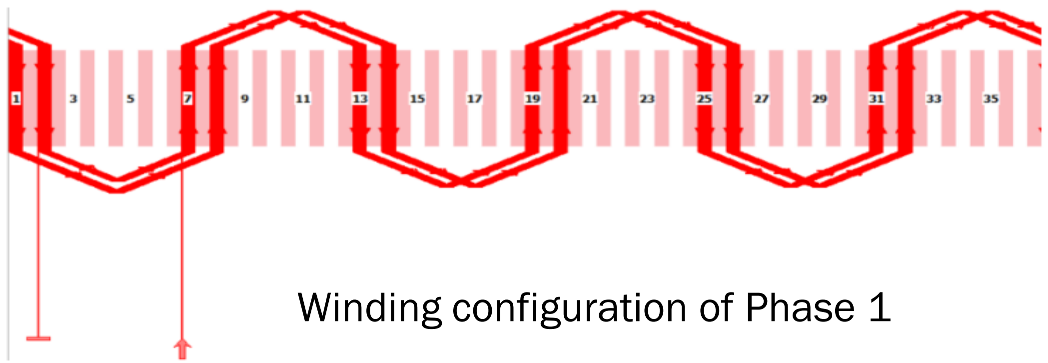
Hairpin winding modelling

The motor

Number of slots	36
Number of poles	6
Number of serial turns per phase	12
Type of the machine	V-shape IPM
Stator outer diameter (mm)	190
Stator inner diameter (mm)	130
Air gap length (mm)	0.7
Stator/Rotor lamination	NO18-1160
Magnet	N42EH
Maximum speed (rpm)	20000
Maximum current, in RMS value (A)	200
DC-bus voltage (V)	280



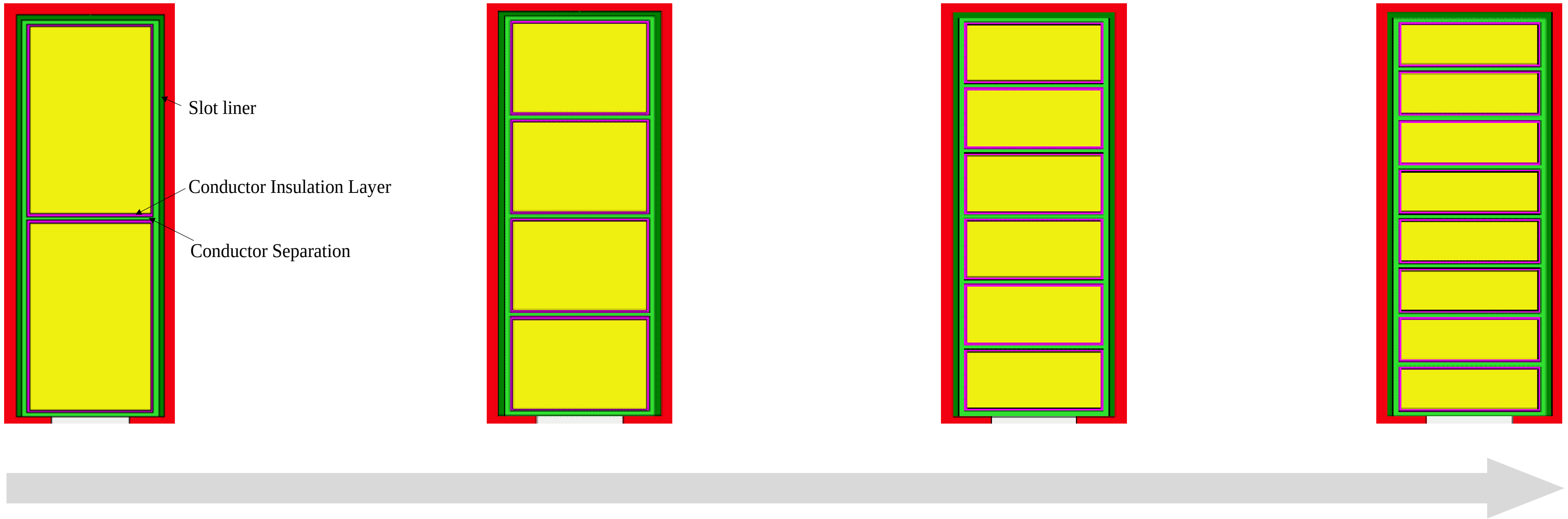
Radial view of the motor model



Winding configuration of Phase 1

Maximising the efficiency with hairpin winding

Optimisation of Number of Winding Layers



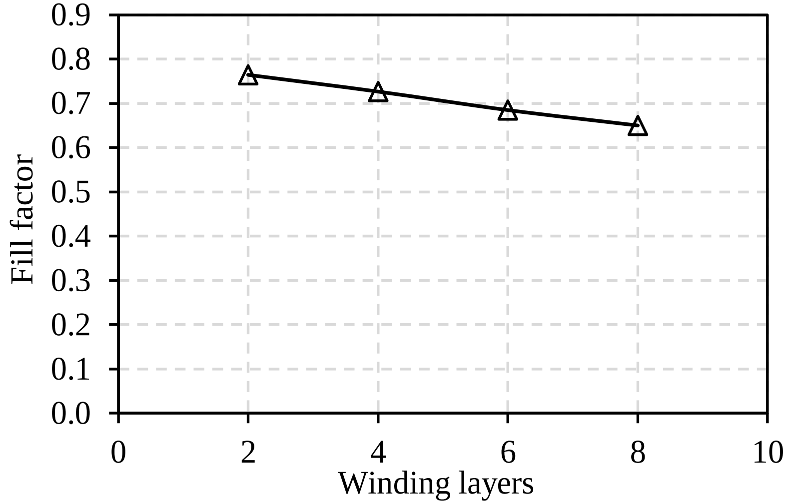
- Higher fill factor, lower DC copper loss
- Lower manufacturing cost
- Higher AC copper loss

- Lower fill factor, higher DC copper loss
- Higher manufacturing cost
- Lower AC copper loss

Maximising the efficiency with hairpin winding

Optimisation of Number of Winding Layers

Number of slots	36			
Number of poles	6			
Winding layers	2	4	6	8
Parallel path	1	2	3	4
Number of serial turns per phase	12			
Slot height (mm)	16			
Slot width (mm)	5.7			
Slot liner (mm)	0.2			
Condutor insultation layer (mm)	0.1			
Conductor separation (mm)	0.15			
Conductor width (mm)	4.7			
Conductor height (mm)	6.97	3.31	2.08	1.48
Slot fill factor	0.77	0.73	0.69	0.65

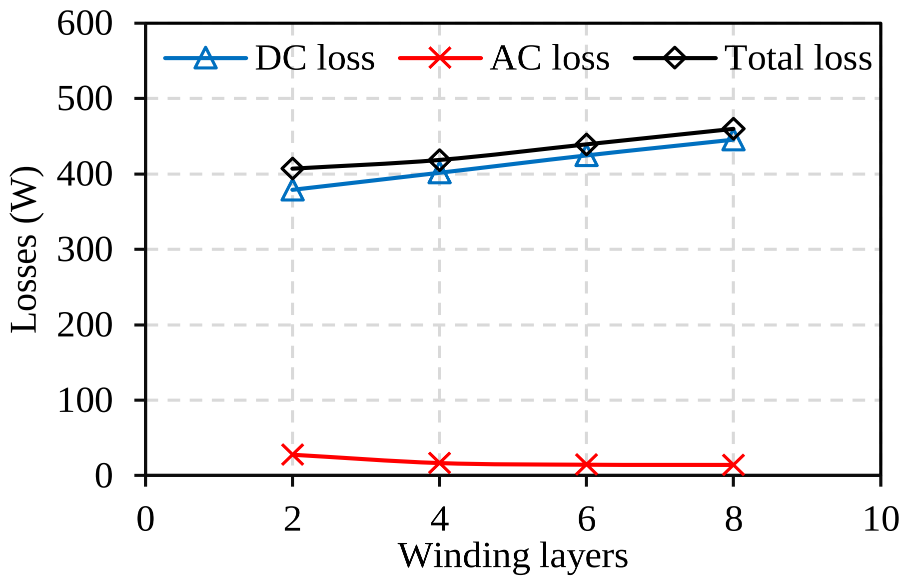


Slot fill factor

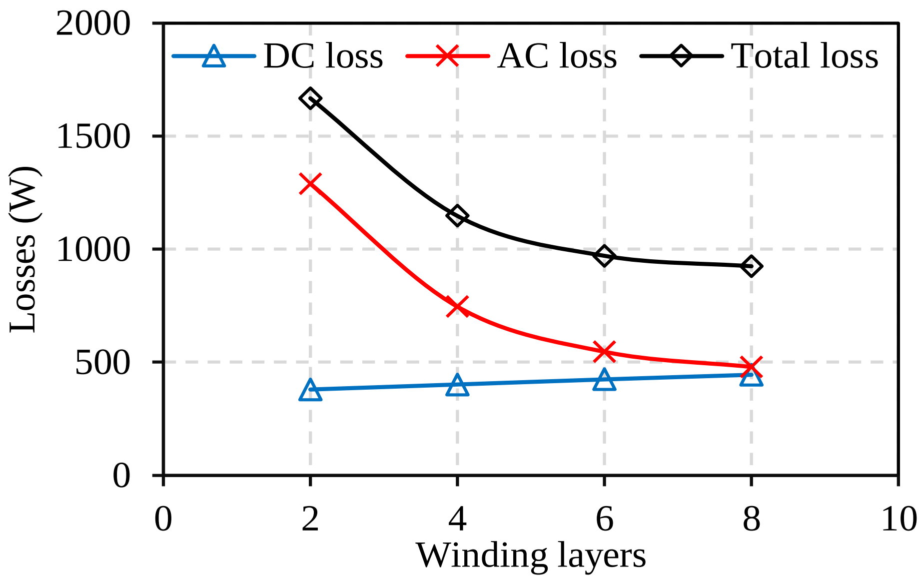
Maximising the efficiency with hairpin winding

Optimisation of Number of Winding Layers

Results at Different Operating Points



1000rpm, 200A



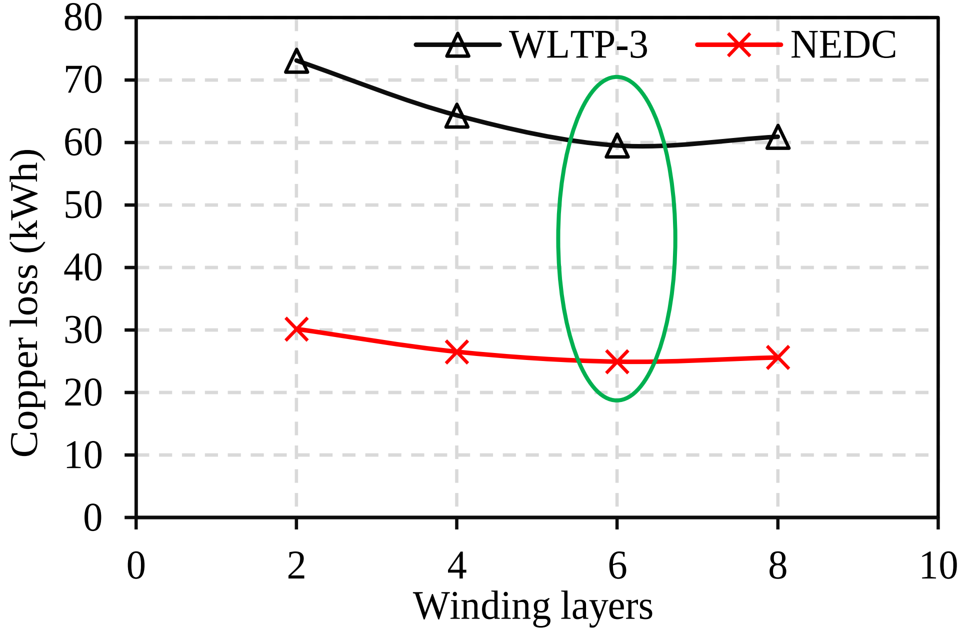
12000rpm, 200A

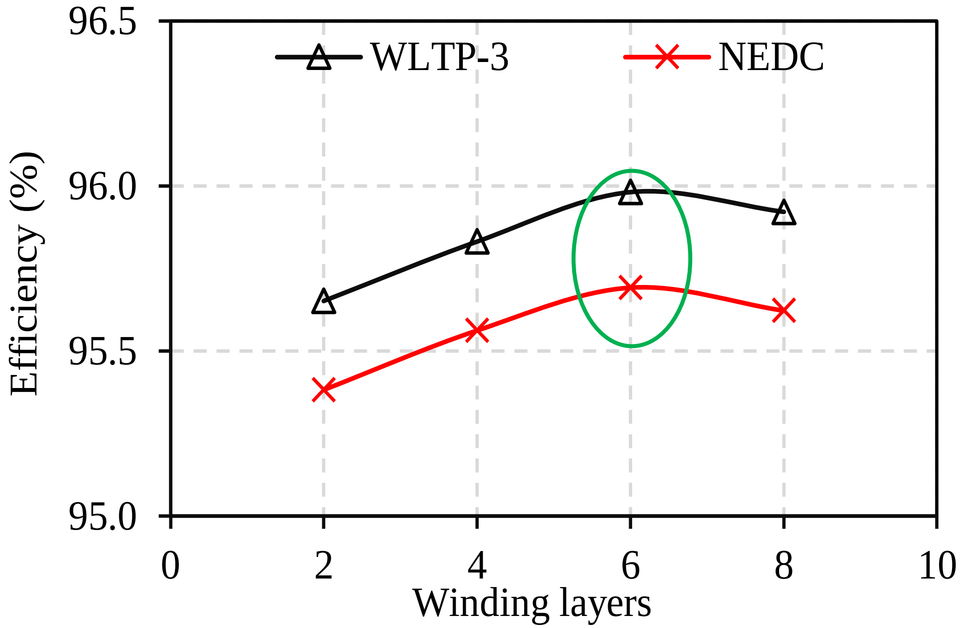
- When the speed is low, the copper loss increases with the number of winding layers
- When the speed is high, the copper loss decreases with the number of winding layers
- In order to identify the optimal number of winding layers, a comprehensive analysis considering operating points must be done

Maximising the efficiency with hairpin winding

Optimisation of Number of Winding Layers

Results for Different Drive Cycles

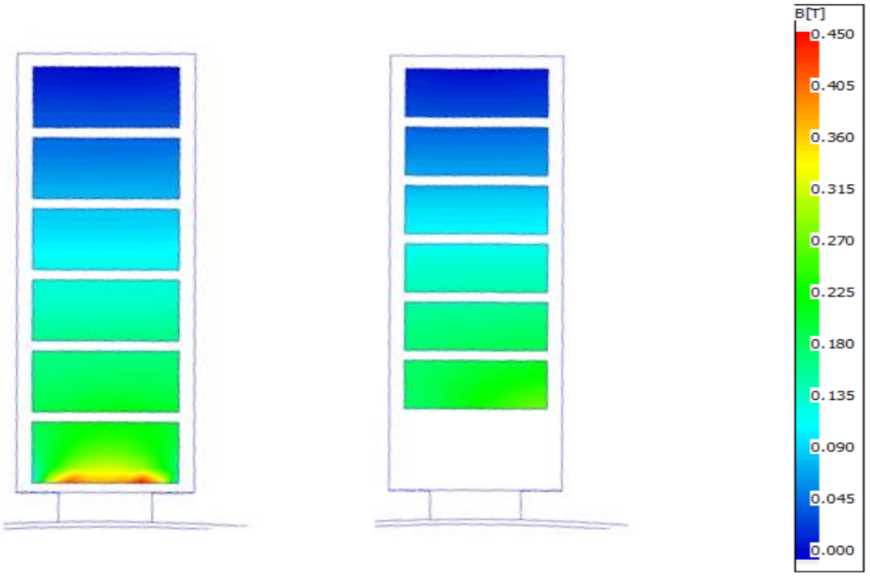




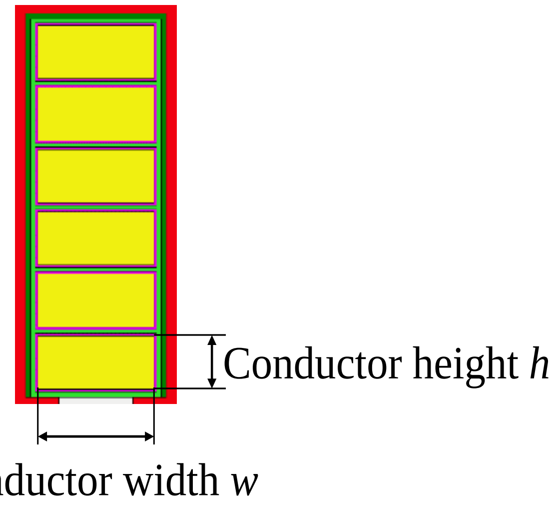
- The efficiency increases when the number of winding layers changes from 2 to 6
- The efficiency drops when the winding layers increases further from 6 to 8
- The optimal number of layers = 6 for both WLTP-3 and NEDC drive cycle

Maximising the efficiency with hairpin winding

Optimisation of Conductor Size



Flux density distribution in the conductors

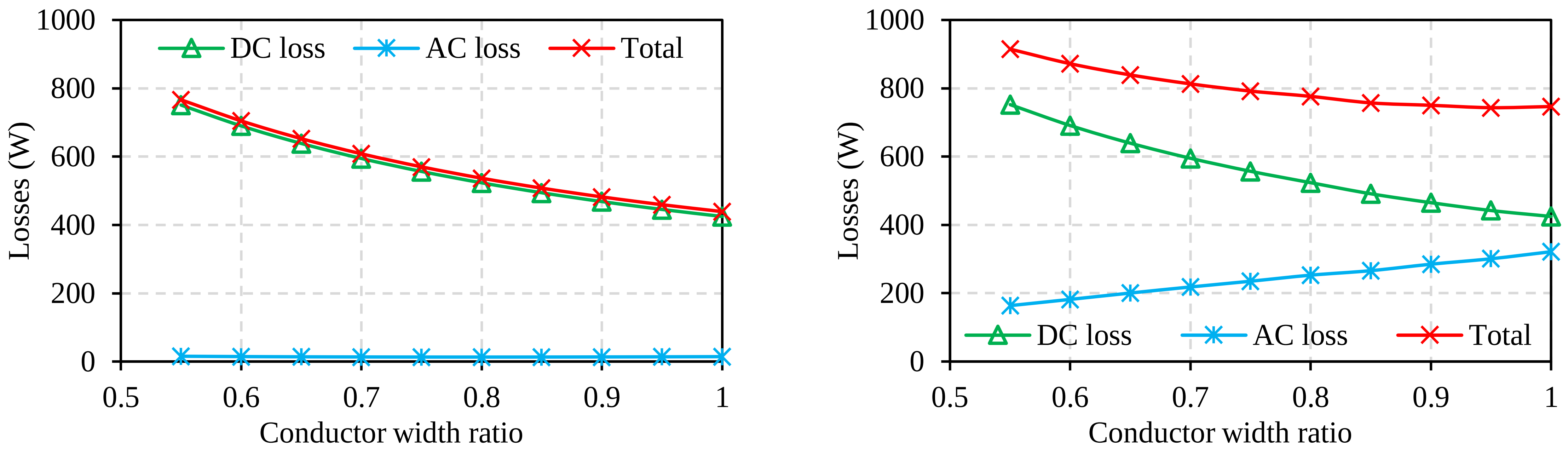


$$\text{Conductor width ratio} = \frac{w}{w_r}$$

$$\text{Conductor height ratio} = \frac{h}{h_r}$$

Maximising the efficiency with hairpin winding

Optimisation of Conductor Size



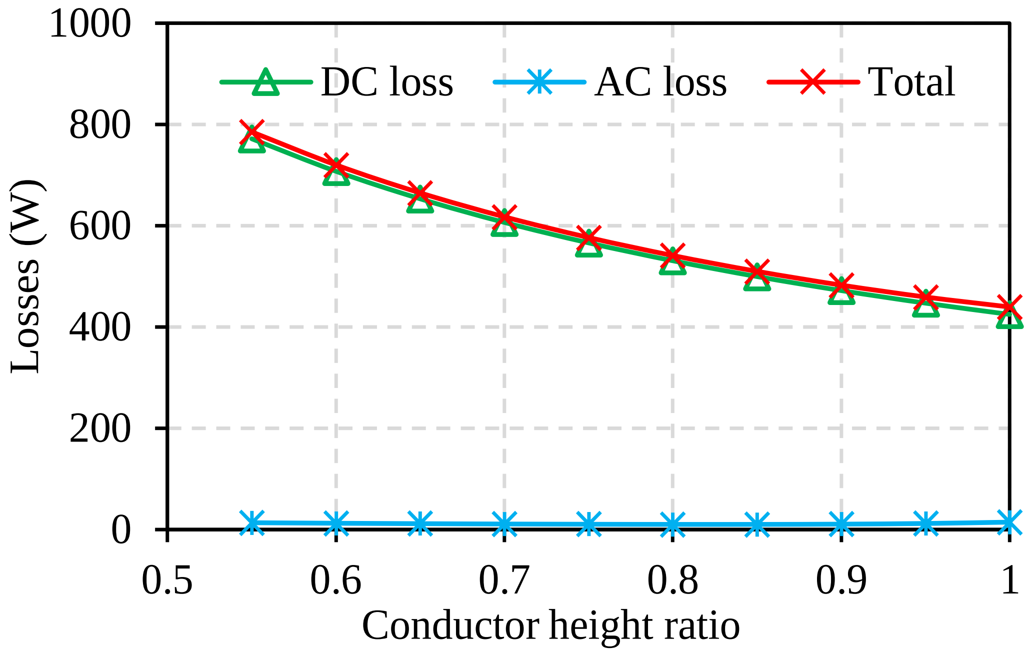
1000rpm, 200A

12000rpm, 200A

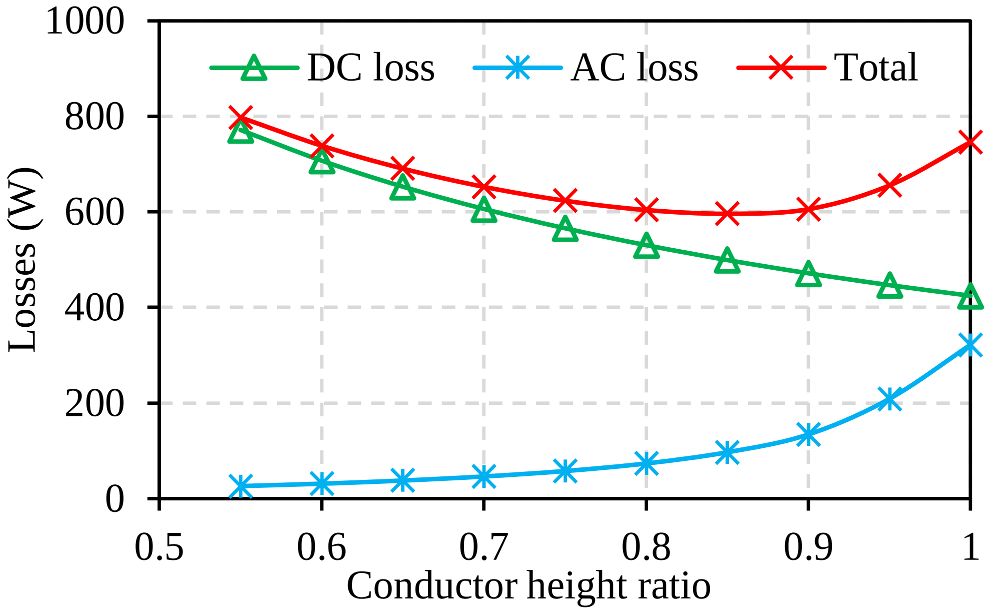
Copper losses variation with conductor width ratio

Maximising the efficiency with hairpin winding

Optimisation of Conductor Size



1000rpm, 200A



12000rpm, 200A

Copper losses variation with conductor height ratio

Results

	Original	Optimal
Parameters		
Number of winding layers	6	
Slot height (mm)	16	
Slot width (mm)	5.7	
Slot liner (mm)	0.2	
Condutor insultation layer (mm)	0.1	
Conductor separation (mm)	0.15	
Conductor width (mm)	4.7	4.61
Conductor height (mm)	2.08	1.90
Slot fill factor	0.69	0.61
Total copper weight (kg)	3.61	3.23 (-10.5%)
Performance		
Total copper loss, WLTP-3 (Wh)	59.54	52.14 (-12.4%)
Total copper loss, NEDC (Wh)	24.95	22.66 (-9.2%)
Overall effieincy, WLTP-3 (%)	95.98	96.14
Overall effieincy, NEDC (%)	95.69	95.82

Conclusions

- Using a high number of winding layers does not always result in lower copper loss
- The trade-off between DC and AC losses under different operating points and drive cycles must be considered when designing for the optimal number of winding layers
- The flux leakage in the slot opening region can cause severe AC loss in the stator winding
- Using bigger conductors to achieve higher fill factor for hairpin winding not necessarily lead to higher efficiency
- The optimal conductor size for electric motors with hairpin windings can be identified by carrying out optimizations considering drive cycles

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