Optimization of a PM assisted SR machine for electric vehicles.

L. Nguimpi-Langue - CEDRAT ; L. Chen, J. Wang - Univ. of Sheffield.

Given the economic and environmental challenges the world has to face, conventional fuel-powered vehicles will have a limited role in future transportation. Conversely, electric vehicles have the potential to provide the solution for sustainable personal mobility. Nevertheless, the road to fully-operational electric vehicles is long and winding. Among the range of electric machines, permanent magnet brushless machines seem best suited to traction applications, where energy efficiency and power density are the most important attributes. In practical terms, an EV should produce high torque, usually 3-4 times nominal value, at standstill or low speed in order to deliver the acceleration and climbing capability required. Conversely, the machine needs output peak power close to twice the rated value at medium to high speeds. Besides, in theory, efficiency must be highest at each point of the NEDC (New European Driving Cycle), and not only at and around the rated operating point as is the case for common engines.

Therefore, it is crucial to develop a viable motor design method, aiming to minimise total energy loss over the whole driving cycle.

We will outline a process to optimise a PM-assisted synchronous reluctance machine for automotive applications. This optimisation is carried out using Flux® and GOT-It, CEDRAT's finite element-based software. The aim is to enhance the energy efficiency of the machine over the whole NEDC.

Design specifications and requirements

The traction motor considered in this case is designed for the power train of a micro-sized vehicle. The NEDC shown in Fig.2 is used as a reference cycle against which the optimisation should be performed. More specific targets such as thermal and volumetric constraints can be obtained from fig1 and vehicle chassis configuration. They are summarised in Table i.

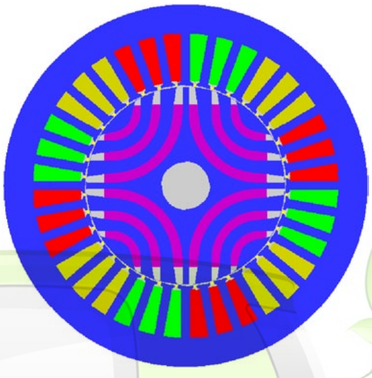

Fig. 1: Overview of the motor.

Stack length	118 mm
Stator diameter	150 mm
Rotor radius	45 mm
Stator slot depth	20 mm
Stator tooth width	4.2 mm
Remnant flux density of PM material	0.4 T

Table i: Initial geometry parameter of the motor.

Base speed	1350 rpm
Maximum cruise speed	4500 rpm
Maximum speed	5050 rpm
Peak torque below and at base speed	70 Nm
Continuous (rated) torque below and at base speed	35.5 Nm
Peak power	9.9 kW
Continuous power	5 kW
Peak power at maximum cruise speed	7 kW
Continuous Power at maximum cruise speed	4.7 kW
Maximum current limit	170 A
Maximum current density limit (rms)	20 A/mm2

Table ii: Motor design specifications.

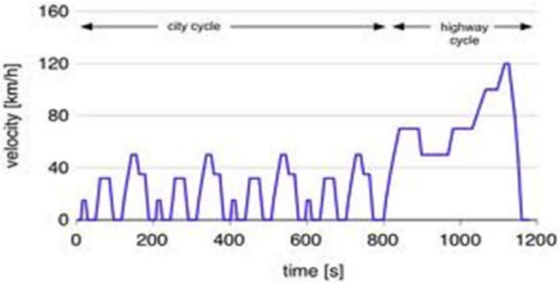

Fig. 2: New European Driving Circle: NEDC.

Preliminary optimization

Based on initial sizing, preliminary scans on geometric parameters were performed. Torque production is greatly influenced by rotor radius RR, stator slot depth SD and stator tooth width TW. These last instances are varied to maximise torque whilst copper loss is kept constant.

	Initial design	Optimized design
Rotor radius	45 mm	41.42 mm
Stator slot depth	20 mm	22 mm
Stator tooth width	4.0 mm	3.6 mm
Stator slot area	84.2 mm	115.6 mm
Rated Current	63 A	71 A
Copper loss at rated current	586 W	542 W
Iron loss at rated torque	29.40 W	28.64 W
Efficiency at rated torque	88.93 %	89.65 %
Peak current at peak torque	126 A	153 A
Copper loss at peak current	2 344 W	2 517 W
Iron loss at peak current	36.32 W	36.20 W
Efficiency at peak torque	80.45 %	79.47 %

Table iii: Comparison after the first optimization.

We notice that copper loss, torque capability and efficiency are improved at the rated point. But this only concerns the rated point when we want to obtain similar results for the whole NEDC. The optimisation for the entire cycle accounts for 600 operating points; this means it would take forever to perform optimisation using this method. From this standpoint, a computationally-efficient optimisation tool is absolutely essential.

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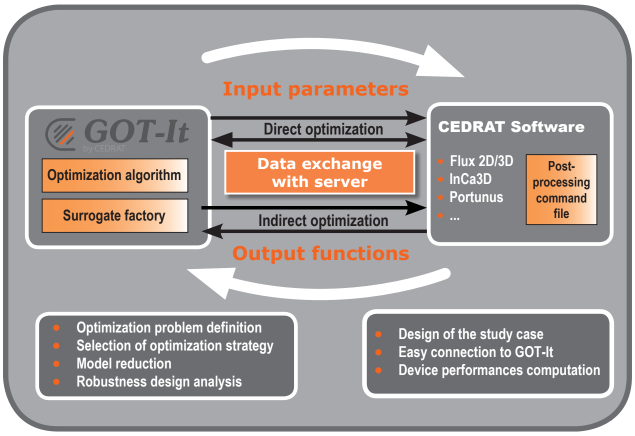


Optimization using GOT-It

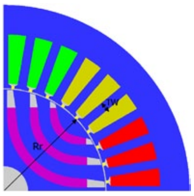
A - GOT-It overview

GOT-It is the CEDRAT's optimization tool which also communicates with the other software of the CEDRAT tools suite.

B - Our case

We previously established that a machine should be optimised according to 600 operating points of the NEDC, costing 200 hours of calculations. However, it is possible to reduce it to only 12 points. Those points are chosen by analysing the energy distribution of the vehicle over the NEDC. The total loss from the reduced map is then compared to the loss over the entire cycle and the result shows that the difference between the two is only 3%.

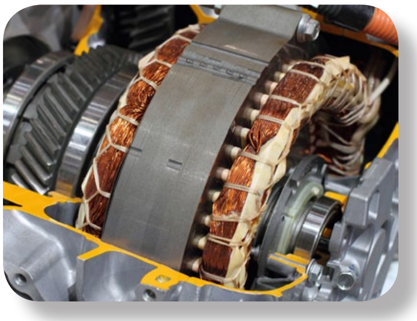
C - Process



- ***Parameters*** - For ease of mechanical integration, stator outer diameter, shaft radius and stack length are kept constant. Rotor radius and stator tooth width are selected as the parameters to be optimized.
- ***Objective*** - Maximum 12-point cycle efficiency calculated for the motor model.
- ***Constraints*** - Current and current density which governs the thermal constraint should not exceed their limits.
- ***Algorithm*** - For the global optimal result, the Sequential Surrogate Optimization (SSO) algorithm is selected. To summarise, it involves building a response surface and then using a genetic algorithm.
- ***Results***

Stack length	118 mm
Stator radius	75 mm
Rotor radius	41.42 mm
Shaft radius	13.5 mm
Split ratio	0.55
Stator slot depth	22 mm
Stator tooth width	3.6 mm

Table iv: Parameters of the final optimization.



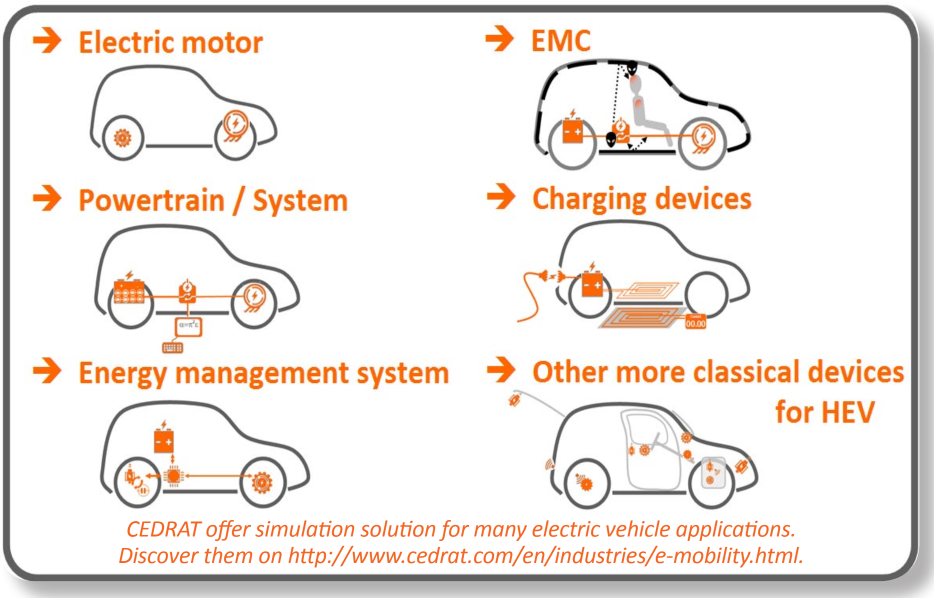
Rated torque / Base speed	35 Nm / 1 350 rpm
Rated current	71 A
Rated current density (rms)	7.60 A/mm^2
Copper loss at rated torque	542 W
Iron loss at rated torque / Base speed	28.64 W
Efficiency at rated torque / Base speed	89.65 %
Peak torque at base speed	70 Nm / 1 350 rpm
Peak current	153 A
Peak current density (rms)	16.38 A/mm^2
Copper loss at 70 Nm and 1 350 rpm	2517 W
Iron loss at 70 Nm and 1 350 rpm	36.20 W
Efficiency at 70 Nm and 1 350 rpm	79.47 %
Peak torque at max cruise speed	15 Nm / 4500 rpm
Current at 15 Nm and 4 500 rpm	68.77 A
Copper loss at 15 Nm and 4 500 rpm	508.33 W
Iron loss at 15 Nm and 4 500 rpm	165.75 W
Efficiency at 15 Nm and 4 500 rpm	91.19 %
Copper loss over NEDC	56.97 kJ
Iron loss over NEDC	15.0 kJ
Driving cycle efficiency	93.67 %

Table v: Performances of the final optimization.

It should be noted that the optimal design in the two-parameter space is achieved using only 15 calculations of cycle efficiency, thus demonstrating the effectiveness and computational advantage of GOT-It.
While the fact that the optimal design is identical to the initial design may be a coincidence in this particular example, the outcome can be explained by the characteristics of the chosen motor topology. Since ferrite magnets with relatively low remnant flux density of 0.4T are used, magnetic torque takes about 25% of total output torque. Furthermore, because copper loss over the NEDC is about 2.8 times more than iron loss, as the table shows… Thus, the preliminary optimisation result, which aims to minimize the copper loss, remains the global optimum over drive cycle.

Conclusion

It has been shown that in order to evaluate traction machine efficiency over the defined NEDC, with sufficient accuracy, enormous numbers of computations have to be performed, which inhibit any realistic optimisation process. So by employing GOT-It, the global optimisation of the machine can be performed in a very computationally-efficient manner.



➔ Electric motor

➔ EMC

➔ Powertrain / System

➔ Charging devices

➔ Energy management system

➔ Other more classical devices for HEV

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