Design and optimization of a V-type interior permanent magnets motor for EV application

Candidate: Giampiero Nitti **Supervisor**: Prof. Gianmario Pellegrino **Co-supervisor**: Ph.D. Floran Martin
Prof. Anouar Belahcen

***Abstract*—Nowadays, the interior permanent magnets motor is one of the most promising and used solutions in the electric vehicles application. This is due to the high efficiency, specific power, and constant power speed range, but also to the remarkable torque density it can achieve. For these reasons, the aim of the thesis is to design and optimize a multi V-type IPM motor that enhances these features. The working points and the traction reference of the motor have been obtained through the WLTP driving cycle. A Matlab function has been written to get all the dimensions of the motor, with a limited amount of inputs. The design part has been carried out through the development of a reluctance network for each axis of the d-q frame and, then, they have been coupled through the non-linearity of the iron core. The model has been validated by calculating the electromagnetic torque and comparing the results with the FEMM 4.2 ones, obtaining the accuracy of the tool. The model has made possible to retrieve the current-flux maps of the motor, which have been used to develop a simple open loop control, following the MTPA and MPPV laws. Finally, the Particle Swarm Optimization has been employed to get an optimal design of the motor, respecting the thermal constraint in 15 selected WLTP working points.**

I. Traction design

As first task, the main characteristics of the vehicle have been chosen. The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) driving cycle has been employed to get realistic working points of the vehicle. After that, the desired performance have been set, taking as reference a power of 60 kW, and an acceleration of 2.84 $\frac{m}{s^2}$. Therefore, the ideal torque vs speed graph of the motor has been drawn.

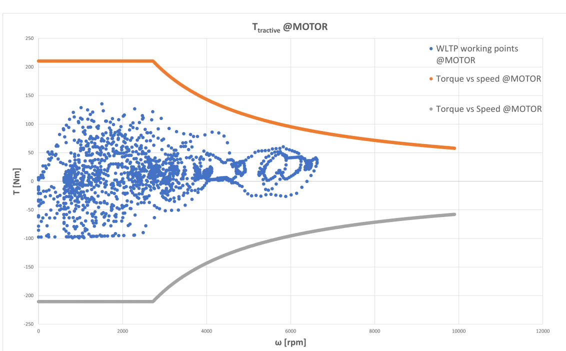

Fig. 1. Reference T-ω graph with WTLP working points.

In particular, a maximum torque of 220 Nm, a base speed equal to 2700 rpm and a maximum speed of 10000 rpm have been looked for.

II. Motor structure

The focus has been more placed on the rotor geometry, since the motor features are strongly influenced by it. It has thought to three V-type magnets barriers, by defining first the areas in which they are located. Then, with few inputs like the height and the inclination of the barriers, but also the distance between them, implementing simple geometrical relationships, all the dimensions of the motor have been obtained.

III. Reluctance network

The reluctance network method has been adopted to proceed with the design part. The aim has been to create a model of the machine through which getting results in a fast way, even though affected by a reasonable error rate.

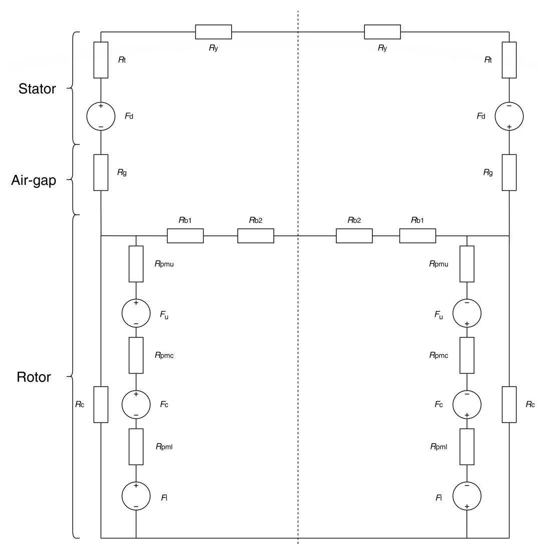

Fig. 2. D-axis reluctance network of the machine.

It has been built a d-axis reluctance network and a q-axis one, following the magnetic flux path along a pole pair. In this way, the control of the machine has been made straightforward, giving the possibility to act directly on the current components in this reference frame. The non-linear behaviour of the iron core has been taken into account. Therefore, the Newton-Raphson method has been employed to solve iteratively the circuits, getting the flux densities of the saturated parts. The non-linearity has been also used to obtain the cross coupling effect. In fact, the magnetic permeability of the bridges reluctances R_{b1} and R_{b2} is a function of the bridges flux densities calculated from both circuits. In this way, they have been coupled.

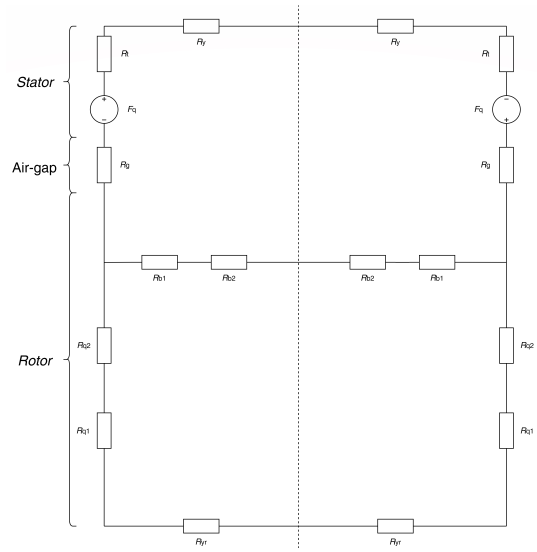

Fig. 3. Q-axis reluctance network of the machine.

Two test geometries, inspired to the Toyota Prius IPM motor, have been proposed to validate the tool. The air-gap flux density along the d-axis at no load condition and the electromagnetic torque have been the quantities compared with the FEMM 4.2 results. In the latter check, seven cases have been implemented, varying the amplitude and phase angle of the current vector. For *test 1*, it has been respectively obtained an error of 10.8 % and an average one of 20.2 %; for *test 2*, of 20.7 % and 19.5 %. Thus, the error rate of the tool ranges around the 20 %.

IV. Control and Optimization

An open loop control has been developed to follow the torque and speed references given by the WLTP working points. The MTPA and MPPV loci have been found through the Lagrange multiplier method, having considered the torque constraint for the former and an additional voltage one for the latter. The current-flux maps have been interpolated to find an expression for both fluxes to be used in solving iteratively the system. The i_d and i_q components are the outputs of the control. The optimization process has been carried out maximising the power density of the motor, taking care not to exceed the maximum temperature allowed. To do that, 15 WLTP working points have been selected and in those ones, the mean value of the objective function, of the temperature, and of the efficiency have been calculated. The particle swarm optimization has been the algorithm implemented. Starting from a population of 32 equal machines, the optimal design has been obtained in 150 iterations in each of which the thermal constraint has been respected. The table I shows the main characteristics of the optimized machine.

TABLE I
MOTOR PERFORMANCE

Stator outer diameter	[mm]	274.2
Rotor diameter	[mm]	181.4
Stack length	[mm]	50
Maximum current	[A]	300
DC voltage	[V]	750
Mean efficiency	[%]	96.2
Maximum torque	[Nm]	220
Base speed	[rpm]	5500
Maximum speed	[rpm]	14000

The structure of the motor has been drawn in AutoCAD.

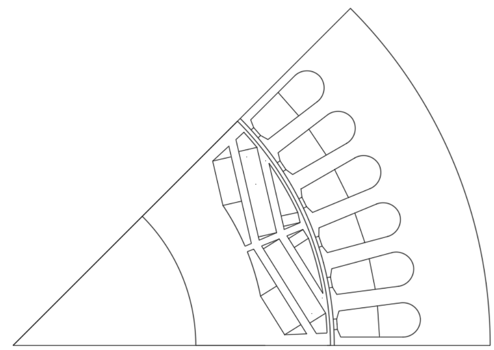

Fig. 4. Structure of the optimized motor.

The flux weakening zone in figure 5 has been obtained calculating two additional points in the MPPV locus and interpolating them, passing through the ω_{base} and the $\omega_{\max}$.

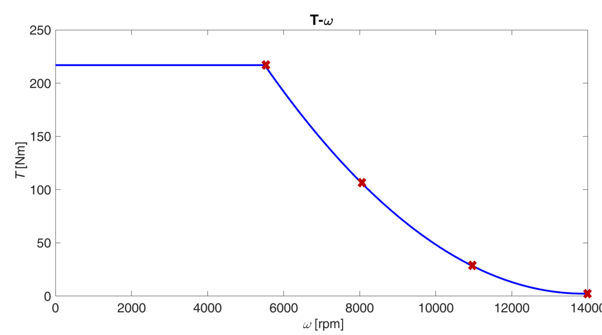

Fig. 5. Final T-ω graph of the optimized motor.

V. Conclusions

The thesis investigated the design and the optimization of a V-type IPM motor for electric vehicles purpose. The key findings are:

- The proposed method allows to get an easy control and rapidly results, although affected by an error rate of 20%.
- The torque requested is obtained, respecting the thermal constraint. The flux weakening area is smaller than expected.

VI. Acknowledgment

The Master's thesis has been carried out at the Department of Electrical Engineering and Automation of Aalto University, Helsinki, Finland.