ELECTRO-MECHANICAL DESIGN OF A MAGNETIC GEAR PROTOTYPE

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***Abstract* – A magneto-mechanical approach is proposed to design a magnetic gear prototype. Firstly, an integrated tool for electro-mechanical simulations is developed, starting from a topological parametric model of a planetary magnetic gear (PMG). Then a CAD model is realised with a progressive rise in complexity, in order to achieve quickly exchangeable configurations for different experimental tests. Three different solutions are designed with advantages and drawbacks. Finally, a block-oriented dynamic model of a PMG, inserted in a mechanical driveline, is developed in Matlab/Simulink environment using the results of magneto mechanical simulations, to virtually test the dynamic behaviour of the device.**

I. INTRODUCTION

The adoption of magnetic transmission is growing up in several industrial sectors thanks to their capability to transfer torque in absence of contact between two rotating parts, avoiding mechanical friction and necessity of lubrication and maintenance [1]. This work is presented as a quick guideline in the design of a PMG prototype, highlighting strengths and weakness of the different intermediate solutions, before converging to the optimal one. In [2] the authors have already investigated the possible adoption of a PMG in the driveline of an automotive transmission in substitution of the power split device of hybrid vehicles. The work here summarised describes the activities aimed to the design and construction of a down-scaled prototype and its test bench for investigating the dynamic of PMGs. The design process is characterised by an increasing complexity of the CAD model in order to have a high-performing and flexible device adaptable to several magneto-mechanicals studies and able to provide hints about the different mechanical and electrical technical design issues. In the following, initial requirements are described, several possible prototyping solutions are proposed and parameters of the latest release are used to dynamically test the device.

II. PROPOSED DESIGN

A first qualitative design is proposed in Figure 1. According to the main requirements, the power input is the bottom shaft connected to the inner rotor (sun) of the PMG using four orthogonal parallel keys, while the output shaft could be connected both to the middle rotor (carrier), where the ferromagnetic poles are placed embedded in a resin ring, or to the outer rotor (ring) as in the configuration reported. The device in mounted vertically in order to avoid side effects due to the gravity. One axial and three radial bearings are used to centre the three rotors each other and to support the weight of the structure.

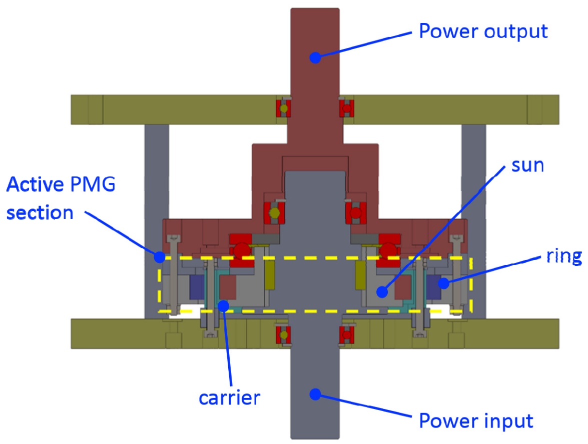

Fig. 1. First PMG prototype

In this first layout the number of auxiliary components to the PMG is relatively limited. It is possible to change the configuration connecting the middle rotor to the output shaft but in a very invasive way, since a disassembly of the prototype is necessary, losing the concentricity of the three rotors, as well. Lastly, in this configuration, the mounting of the prototype is strictly dependent on the geometry and characteristics of the adopted test bench.

These limits of the first prototype model are overcome by a second release, reported in Figure 2.

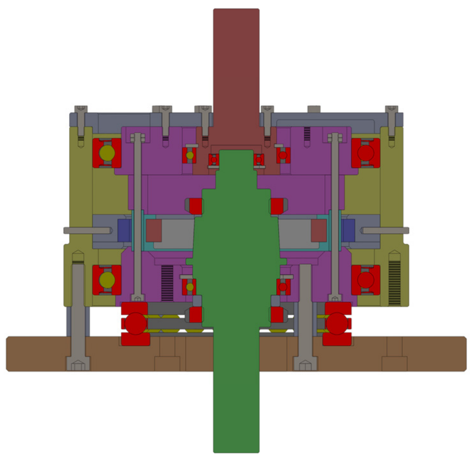

Fig. 2. Second PMG prototype

In this new layout the device assembling is completely stand-alone and independent from the test bench. Moreover, it is possible to change its configuration to have different outputs switching only some screws used to connect the bottom plate to carrier and ring of the PMG. In particular, the left part of the assembly represents the configuration with the output connected to the carrier and the ring is fixed to the bottom plate. On the contrary, on the right part the carrier is fixed, and the output is on the ring. In this way, it is possible to have two different gear ratios with the same rotational direction of the output shaft or an inverse one w.r.t the sun shaft. For precise centring of the planetary elements, a conical coupling is adopted between input shaft and PMG sun. In this new release, seven bearings are used. Unfortunately, although this configuration provides an extreme flexibility to the PMG setup, the use of several bearings introduces an increment of the mechanical dissipations.

For what concerns the active part, highlighted with the yellow dashed lines in Figure 1, two possible arrangements are proposed which are sketched in Figure 3.

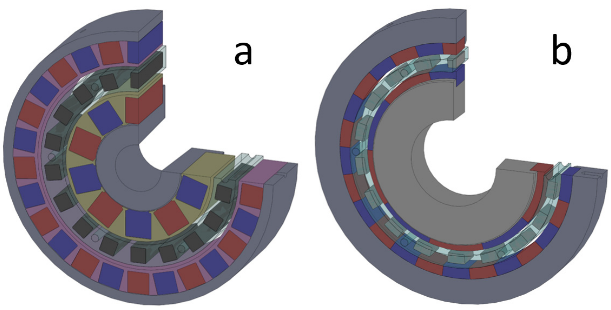

Fig. 3. Low cost (a) and high performance (b) PMG solutions

The simpler solution (a) is based on the use of commercial rare-earth permanent magnets (PMs) and a plastic material is adopted for the three rotors. This choice enables an additive manufacturing process for a rapid prototyping. The more complex solution (b) is based on the use of segmented PMs to reduce eddy-current losses [3], and laminated ferromagnetic poles. This second prototype is built in the view of high-efficiency PMG [4]. Furthermore, titanium is chosen as material for components very close to the PMG in the assembly of Figure 3. This choice is due to the good mechanical characteristics of titanium that is accompanied by a high resistivity. These are useful characteristics in the aim to minimise induced currents. Naturally, the cheapest solution is characterised by a torque density that is around 1/5 the torque density of the expensive one.

III. DYNAMIC MODEL

From electro-mechanical simulations, the values of the magnetic torques acting on the sun and ring for any possible relative position of the two rotors are evaluated. The carrier is kept fixed. In Figure 4, the free body diagrams for all the three rotors are reported.

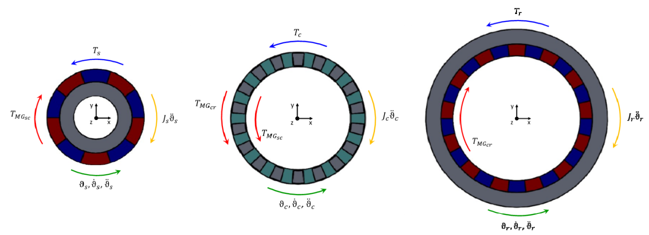

Fig. 4. Free body diagrams for the three rotors

The system dynamic equations, in matrix form, can be written as in Eq. (1), where J_s, J_c, J_r are the mass moment of inertia of sun, carrier and ring, respectively. T_s, T_c, T_r are the external mechanical torques, while $T_{MG_{sc}}$ and $T_{MG_{cr}}$ are the internal torques generated by the magnetic flux between sun and carrier and between carrier and ring, respectively.

$$\begin{bmatrix} J_s & & \\ & J_c & \\ & & J_r \end{bmatrix} \begin{Bmatrix} \ddot{\vartheta}_s \\ \ddot{\vartheta}_c \\ \ddot{\vartheta}_r \end{Bmatrix} = \begin{Bmatrix} T_s \\ T_c \\ T_r \end{Bmatrix} + \begin{Bmatrix} -T_{MG_{sc}} \\ T_{MG_{sc}} + T_{MG_{cr}} \\ T_{MG_{cr}} \end{Bmatrix} \quad (1)$$

The device is tested assigning an input torque profile, able to guarantee an acceleration phase, followed by a quite-stationary condition followed by another transition condition. Results are illustrated in Figure 5.

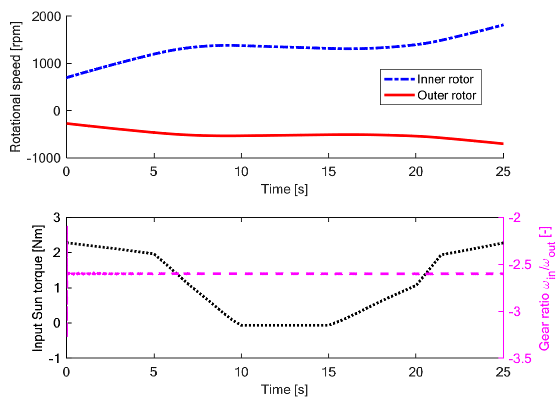

Fig. 5. Speeds (top) and torque with gear ratio (bottom) of a PMG

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