Reluctance-assisted motors

The development of reluctance-assisted external rotor permanent magnet machines could improve torque-speed ranges and further reduce the need for rare earth magnets

Until now, the main rotor technology found inside TM4's electric motors was based on surface-mounted outer rotor topology in which the magnets are glued directly to a rigid carbon steel rotor. However, in recent years, uncertainty and higher prices of rare earth magnetic materials, in combination with the demand for wider torque-speed operation ranges, have resulted in a drive to look for possible improvements in existing technology.

It is well documented that the reluctance torque in permanent magnet machines can be used to gain better performance. However, introducing this concept in TM4's outer rotor topology is a challenging task, due to the thin rotor structure found in the external rotor approach. After a thorough development process, TM4 overcame these challenges and will introduce this technology in 2015 as part of new products offered in both its Motive (light-duty vehicles) and Sumo (commercial vehicles) electric powertrain systems. Particularly of note is the design procedure used for the reluctance-assisted outer rotor permanent magnet machine, and a comparison of the new machine's performance against a surface-mounted permanent magnet machine of the same dimensions.

Normally, the advantage of an external rotor machine is its higher air-gap radius, which leads to a higher torque for the same magnetic force. This technological choice was made by TM4 when it first started working on the in-wheel motor technology developments that ultimately led to the company's creation, and was kept and improved in subsequent products. To maintain this advantage, the thickness of the rotor should be kept as thin as possible. However, in order to create the reluctance torque, significant anisotropy (saliency) should be created in the rotor magnetic circuit, which is a demanding task due to the limited available space. In addition, there will be higher eddy current losses because of the introduced anisotropy. Therefore it is not practical to use carbon steel materials to achieve this goal. On the other hand, a thin rotor made of lamination cannot support the centrifugal forces imposed at high speeds. Thus a strip of lamination is added to the rigid carbon still rotor (Figure 1 on the next page) to achieve both the required saliency and the rigidity requirements.

Reluctance-assisted external rotor permanent magnet machines can offer a greatly improved torque-speed range

The dimensions of the magnets and the rotor lamination strip have been optimized by using a stochastic optimization algorithm,

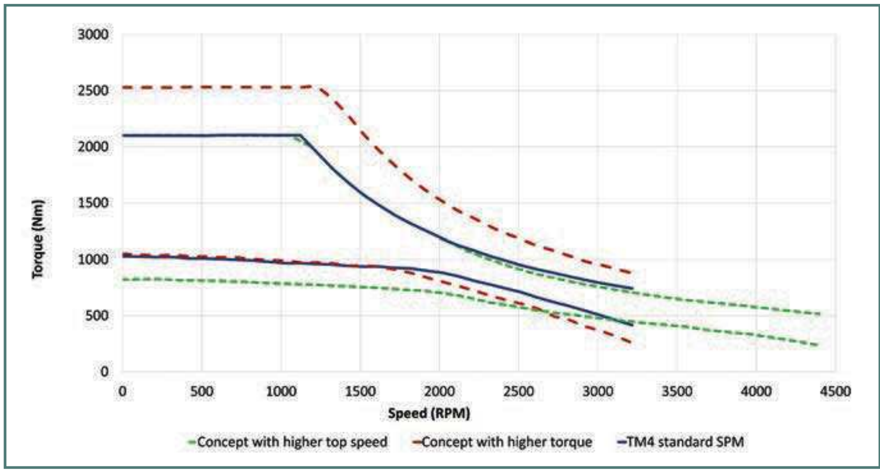

Figure 2: A performance comparison of the permanent magnet motor using the new reluctance-assisted outer rotor technology, and the original surface-mounted machine

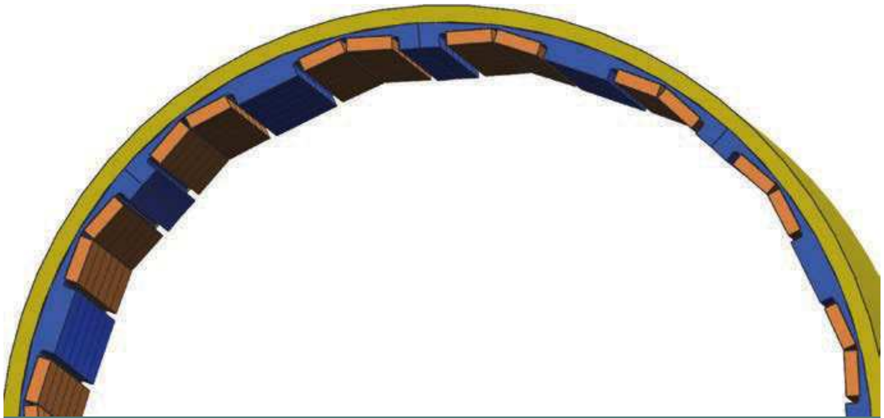

Figure 1: A strip of lamination added to the rigid carbon still rotor satisfies saliency and rigidity requirements

and by considering the design constraints typically found in automotive applications. A stochastic optimization algorithm, such as a genetic algorithm (GA), is used in combination with finite element analysis-based software to find the optimum dimensions of the rotor lamination and the magnets. The same stator dimensions of a reference SPM machine currently produced by TM4 are used in the proposed reluctance-assisted machine.

Like any other optimization problem, the first step is to define an objective function. Here, the goal is to minimize the quantity of the rare earth magnetic materials while satisfying all other constraints – such as ease of manufacturing, use of the same external envelope, lower cost, and equal or better performance. Minimizing dependency of the generated torque to the rare earth magnets indirectly leads to higher torque-to-back EMF ratio, which is an important factor in having a wide torque-speed range.

The final solution after optimization had considerably less rare earth metal in comparison with the reference surface-mounted permanent magnet machine (SPM) machine with the same dimensions – up to 60% in some scenarios.

By comparing the performances of the permanent magnet (PM) motor using the new reluctance-assisted outer rotor technology with the original surface-mounted machine, several improvements have been observed. As described previously, for a fair comparison the same stator assembly has been used in both machines for simulations. The comparison has been made for two different scenarios. In the first scenario, the maximum required torque of the new machine at low-speed condition is assumed to be the same as the SPM machine. In the second one, the maximum speed of the machine has been kept equal to the maximum speed of the SPM machine.

The results of the aforementioned comparisons, as seen in Figure 2, enable us to make a number of important conclusions.

In the first scenario, a 30% maximum speed increase has been achieved in comparison with the reference SPM machine, with around 35% less rare earth metal.

In the second scenario, maximum torque has been increased by 20% with around 15% less rare earth metal. The percentage of the torque increase in Scenario 2 is lower than the speed increase percentage in Scenario 1. This is due to the core saturation as well as contribution of the reluctance torque.

In addition to these facts, higher D-axis inductance of the reluctance-assisted machine leads to easier field weakening, lower short-circuit current and, thus, the capability to tolerate short-circuit current continuously. This means it is easier to design a fault-tolerant machine with the reluctance-assisted concept.

Finally, higher inductance means lower eddy current losses due to the PWM switching, which is a very important factor in determining the high-speed continuous power of the machine.

Approaches to tackling the problem of torque ripple and cogging torque reductions have been discussed. Nonetheless, the obtained results showed a significant improvement in torque-speed characteristics with a significantly lower quantity of magnetic materials. Further development of methods to increase the attainable saliency ratio is ongoing.

The first prototypes of these motors were tested by TM4 in the autumn of 2014, and commercially available versions will be integrated within TM4's existing product line from January 2015. TM4 is currently supplying its powertrains to several OEMs and technical centers in North America, Europe and Asia in order to drive several type of electric and hybrids vehicles. Production takes place at TM4's Canadian facilities in Boucherville and at its Chinese joint venture Prestolite E-Propulsion Systems in Beijing. Both are equipped with high-volume, flexible and automated production lines, and a large range of dynamometers and test cells, making it possible to conduct full validation and certification of electric and hybrid powertrains.