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IFAC-PapersOnLine 49-21 (2016) 322–329

Boosting Power Density of Electric Machines by Combining Two Different Winding Types

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Abstract: This paper presents a novel magnetic circuit and winding design for extreme lightweight and high torque permanent magnet electric machines. Therefore, two different types of winding are combined to boost torque sharing the same magnetic circuit. One is an air gap winding, which is mounted directly on the back iron of the stator surface using the magnetic flux field in the air gap to generate Lorentz forces acting on the winding and providing one part of the torque. The other one is a slot winding, which is fixed inside small slots of the stator back iron generating magnetic forces and contributing the second part of the torque. Overall, only a small amount of iron is necessary for this novel magnetic circuit design. This results in an extreme lightweight, efficient, dynamic and high torque electrical machines for a wide range of use in mechatronics. The paper gives a design example of a wheel-hub-motor for a passenger vehicle with an extraordinary power-to-weight-ratio.

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Keywords: Actuators, brushless motors, electric machines, electromagnetic fields, stator windings.

1. INTRODUCTION

Best efficiency, optimal controllability and a very small environmental impact are well known strengths of electrical drives. However, today additional demands appear together with rapidly growing and also completely new markets that push existing technology to its limits. First topic is *lightweight design* e.g. for all kind of mobile applications either in the area of transportation or mobile robots. Electric vehicles e.g. need to be lightweight because their electrical range is limited by battery capacity and each kg of additional weight reduces available range. A similar problem exists for mobile robots. They do not only suffer from a limited range but in addition have to carry their own drives e.g. in arms and legs which reduces their payload. Second topic is *compact design* as applications and products evolve to get more and more integrated. A very fine example for this trend is given by a wheel-hub-motor, which integrates the complete powertrain of a vehicle in its wheels. This means a big saving in parts and space on one hand but a severe demand to restrict space of the motor to fit into the rim on the other (Borchardt, 2012), (Fraser, 2011). Third topic addresses *low cost design* especially in high volume markets like automotive, E-bikes, E-Scooters etc. High benefits of optimizing design and production processes have been gained in the last years and accordingly cannot be expected to contribute with the same amount in the future.

Standard motor design today uses slotted windings, which combines a high robustness and high torque capabilities with an established production technology. The relative large amount of iron needed to build the stator back-iron is one of the drawbacks of this design. Mass and iron losses suffer from this and cooling systems are restricted and complex. As a landmark for lightweight design an experimental Siemens aircraft motor (Martini, 2015) can be used, which delivers a power-to-weight ratio of 5 kW/kg with 2600 rpm. According to Siemens this can only be done using best materials which makes the motor quite expensive. A second landmark for integration can be the Protean (Fraser, 2011) wheel-hub-motor which can be used with a 17’’ rim and delivers 1.6 kW/kg for 1500 rpm.

Air-gap winding designs generally offer a much smaller weight because they reduce the amount of iron or omit it completely. Design from Fölmli (2013) show the limits of self-supporting air-gap windings as they can carry only very small torques. To overcome this, an air-gap winding design patented by Kasper (2015) uses the stator back-iron to fix and reinforce the copper wires. Thus a very high torque can be generated and the cooling is excellent as losses in copper only have to pass a very thin (< 5 mm) slotless shell of back-iron to meet the aluminum part of the stator including the water cooling system. Fig. 1 gives an example of a designed wheel-hub motor prototype. The outer rotor carries the alternating permanent magnets in a standard way. It is attached to the hub to transmit torque to the wheel. The inner part consists of wheel bearings and a hollow shaft to lead electrical and cooling supply connections. Control unit is mounted to the inner space of stator which provides an excellent cooling for power electronics.

The wheel-hub-motor is very limited in size to fit into a standard 15’’ rim. The weight of the complete wheel including control unit but without rim is 20 kg. The nominal current is kept low to benefit on a very good efficiency. Despite these restrictions, a torque of 300 Nm can be provided over the total speed range, which goes up to 1300 rpm. The maximum power

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10.1016/j.ifacol.2016.10.576

is 40 kW, which results in a power-to-weight ratio of 2 kW/kg, which is an outstanding value for wheel-hub-motors.

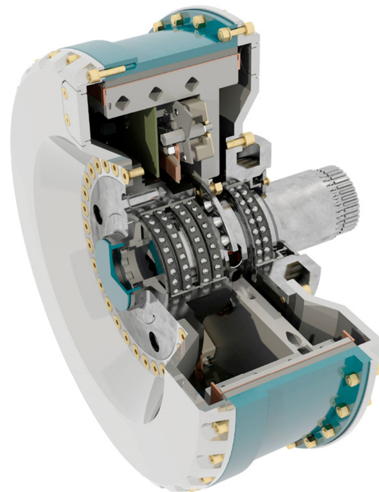

Fig. 1. Wheel-hub IMS (Zörnig, 2015)

Due to the very small inductance of air-gap windings (app. 8 µH per phase) control is a challenge. To implement field oriented control, which is standard for PSM, a very high PWM frequency above 300 kHz would be necessary. To avoid these costs a modified six-step-commutation plus control of source current was implemented.

Machines discussed so far, only provide one winding, maybe in slots of the stator back-iron or in the air gap. To achieve specific goals, it is an established method to use an auxiliary winding additionally to the main winding. A simple example is the well-known start winding to overcome starting problems of an induction motor. Another application are adaptable winding configurations to adapt motor characteristics to speed, to torque or to supply voltage. In Fei (2004) an example of a machine with switchable 4/6 pole operation to generate symmetrical forces is given. Another application is presented in Saleh (2004), where an additional winding is used to improve field oriented vector control of a SM. To maximize the electricity output of a wind turbine system, Hsiao (2014) directly coupled a permanent magnet generator having 1 kW winding and 3 kW winding with a vertical-axis windmill as a 4 kW wind power system to achieve lower cost per kilowatt.

These known combined winding solutions are neither intended nor optimized for generating a high additional torque using only the existing or a moderately extended magnetic circuit. Following this approach higher torque and power can be provided, while motor size or weight increases only moderately. This paper will present a new design concept to combine an air-gap winding and a slotted winding in the same magnetic structure. For this purpose, the existing IMS wheel-hub-motor (Borchardt, 2012), so far providing only an air-gap winding, is taken as a basis to integrate an additional slotted winding into stator back-iron. Except the stator back-iron whose height has to be increased a little bit, the active motor parts (permanent magnets, rotor back-iron, air-gap and air-gap winding remain unchanged.

2. WINDING DESIGN AND NUMERICAL MODEL

2.1 Basic design concept

In general, there are numerous possible topologies to combine several windings into one machine. A straightforward approach is starting from the given wheel-hub-motor design and provide more torque per motor active mass/volume without increasing specific losses. To have a direct comparison of technologies, existing wheel-hub motor design remains fixed. Only stator back-iron will be adapted in height to build slots in order to carry the slotted winding. This restriction in design freedom can be accepted. We will not be able to present the final optimal design in this paper, but the results presented here can be compared against the existing air-gap design which itself has been compared against several slotted machine designs.

Nevertheless, it is important to find the best way to use the B-field generated by permanent magnets in air-gap and in stator back-iron to generate maximum torque. The importance stems from high cost of permanent magnets. If the expensive permanent B-field can be used twice there is a split of cost. To achieve this, different principles of electro-mechanic conversion can be combined. As their name implies, air-gap windings are located completely in the air-gap. Consequently, they see the B-field in the air-gap. If a current i_A flows through a phase a Lorentz force acts on it generating a usable torque. After the B-field in the air-gap is used so far and no more space is left there, another winding has to be positioned into slots of the stator back-iron. Using the B-field in the stator back-iron a magnetic force acts on the slotted winding. If a current i_S is flowing through it generates an additional torque. Thus both windings benefit from the same B-field of permanent magnets while occupying their own space. Adding both torques, while sharing the active motor parts gives a very high specific torque or specific power respectively.

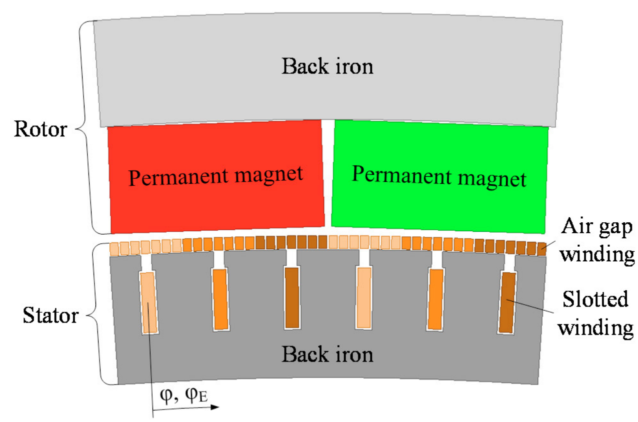

Fig. 2. Geometric design of combined air-gap and slotted winding

Fig. 2 shows a design example of such a combined winding. Because the given air-gap wheel-hub-motor has three phases, this was also chosen for the slotted winding. In general, different phase numbers are possible. Nevertheless 3-phase system

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