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MULTI-STAGE AXIAL-FLUX PM MACHINE FOR DIRECT-DRIVE RAILWAY TRACTION APPLICATIONS

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Abstract
Direct-drive traction motors devoted to railway applications must be designed in order to comply with both machine diameter restriction and achievement of very high torque density, as well as they should have substantial flux-weakening capability in order to be operated over the required constant-power speed range. Concerning to that, this paper deals with the original solutions adopted for design and construction of an axial-flux permanent magnet machine (AFPM) prototype rated 8000 N-m, 682 rev/min. For such a demonstrator machine a 4-stack AFPM structure is adopted in order to overcome the design restriction on the machine diameter, whereas very efficient cooling arrangement of the machine stator is accomplished by means of a water-cooled toroidal plate. The paper outlines the design characteristics and reports experimental results of the above-mentioned railway traction motor prototype.

I. INTRODUCTION

In railway traction applications the use of direct-drive traction motors would be desirable for reduction of the truck mass being acting on the rails, but this poses tight design requirements due to a limited diameter space being available for housing the motor on the wheel transaxle. Further to that, motor with totally-enclosed construction is mandatory and thereby motor designs resulting in both reduced power loss and very effective cooling of the machine active parts are sought.

In consideration of the high-torque operation required at relatively low speeds, it is widely recognized that permanent magnet (PM) motors designed for direct-drive applications have superior performance compared to conventional machines and among a number of novel PM machine topologies that have been investigated to date, axial-flux permanent magnet machines (AFPMs) having slotted winding have demonstrated to be one best candidate for the direct-drive motor application as they can be designed for the higher torque-to-mass ratio without loss of efficiency.

This paper describes the original solutions adopted for design and construction of an AFPM prototype rated 8000 Nm, 682 rpm. For such a demonstrator machine a 4-stack AFPM structure is adopted in order to overcome the design restriction on the machine diameter and meet the required torque rating, whereas very efficient cooling arrangement of the machine stator is accomplished by means of a water-cooled toroidal plate being sandwiched between the two halves composing the stator core of each machine stage. This paper

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outlines the design characteristics of the above-mentioned railway traction motor prototype and reports experimental results achieved from a test campaign devoted to evaluate the machine performance.

II. MACHINE LAYOUT

In AFPMs, the electromagnetic torque is mainly a function of the machine outer diameter. If the available space is too small a diameter, then the torque developed at the machine shaft can be achieved by means of a multi-stage arrangement of the machine, as schematically depicted in Fig. 1 for a 4-stack machine. In a multi-stack AFPM, if j is the number of stacks, then the machine has j stator windings and (j+1) PM disc rotors. The (j+1) rotors share a common mechanical shaft, whereas the terminals of the j three-phase windings may be connected either in series or parallel among them.

In a multi-stack AFPM the flux driven by magnets passes axially from a north-pole on one rotor to a facing south-pole on the other, as shown in Fig. 1. Thus, only the external rotor discs must be made of material with good magnetic properties (typically mild steel), since they are used to provide a path for flux. The intermediate ones, on the other hand, are used merely for mechanical support of the magnets, and so light weight non-magnetic materials can be used for their construction thus enhancing the compactness and lightness of the machine.

Being excited by permanent magnets, the machine rotors suffer no power loss and machine losses are found only in the stator. Thereby, effective cooling of the machine stator must be provided and this can actually be accomplished by means of a water-cooled aluminum toroidal plate being sandwiched between two stator core halves, as schematically depicted in Fig. 2 for a single-stack machine. In a multi-stack machine, the hydraulic circuits of the machine stacks can be connected either in series or parallel and share a common external air-to-water heat exchanger.

III. PROTOTYPE MACHINE

Consistently with the structure that has been described above, a prototype AFPM machine has been designed and built in order to verify its suitability for direct drive propulsion in railway applications. Main specifications for the machines where as reported in table 1.

These specifications led to the design of a 4-stage machine, whose design characteristic are shown in table 2, related to one stage. Specific attention in the design

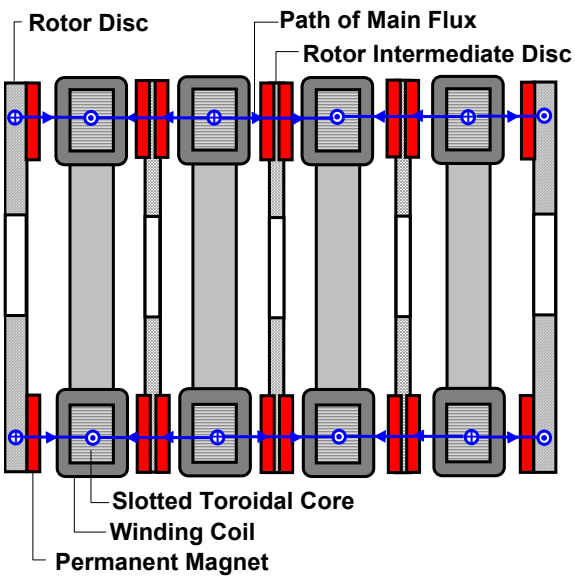

Fig. 1 – Schematic representation of a four-stage AFPM machine

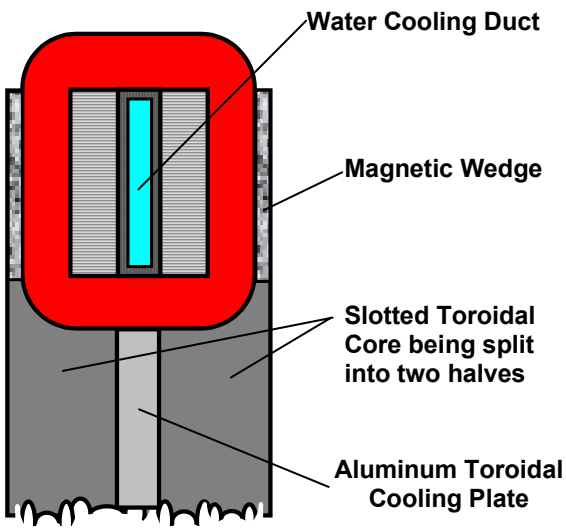

Fig. 2 – Schematic representation of the stator of a single stage

phase was paid to the problem of achieving a wide constant power speed range (CSPR), as it is commonly assumed that machines, like the AFPM; with surface-mounted PM are not suited for flux-weakening mode of operation.

Generally speaking, in fact, AFPMs, just like other surface mounted PM machines, exhibit low phase inductance value, typically in the range of 0.15-0.20 p.u. This is the consequence of the physical structure of the stator, since the reaction flux can flow in two paths that are magnetically in parallel:

i) the first one is in the airgap, the permanent magnet material and the rotor iron;

ii) the second path is entirely in the stator iron and (if present) includes the locking bars being used to close the winding slots.

In order to increase the numerical value of the phase inductance, it is necessary to decrease the reluctance of one of the two parallel paths. However, the magnetic properties of the first path cannot be changed, as it involves the main flux; the only possibility is then in changing the magnetic properties of the second path, namely of the locking bars.

To date, new syntherized magnetic materials can be shaped into wedges and used as locking bars in order to close the stator slots. These materials exhibit low hysteresis and eddy-current losses, together with good mechanical and machining properties: therefore they are suitable for the manufacturing of rotating machines. These materials have a relative permeability that, as a first approximation, is in the range between 10 and 100.

Table 1 – Main specifications

Rated power	570 kW
Rated torque	8000 Nm
Rated speed	682 rpm
Constant power speed range	3:1
Overload capability	100%

Table 2 - Design characteristics for each stage

Rated power	142.5 kW
Rated torque	2000 Nm
Base speed	682 rpm
Maximum speed	2046 rpm
Base frequency	90.9 Hz
No. of poles	16
Phase EMF (@682 rpm)	302.6 Vrms
Rated current	157 Arms
Phase resistance	57.2 mΩ
Phase inductance	2.28 mH

Use of these materials in the shape of wedges on order to close the stator slots results in a significant increase of the phase inductance.

In the case under consideration, the goal was to achieve a value for the phase inductance of about 0.67 p.u., since it can be demonstrated that this value is enough in order to achieve the desired 3:1 constant power speed range with minimum impact on the size of the inverter. At this purpose, a finite element analysis was carried out in order to optimize the design on the shape of the slot and the size of the magnetic wedge, and thus achieve the desired inductance value (2.28 mH).

After the design stage, the machine was built and assembled. Figs. 3 and 4 show the prototype during assembly and at the test bench for the experimental verification, respectively.

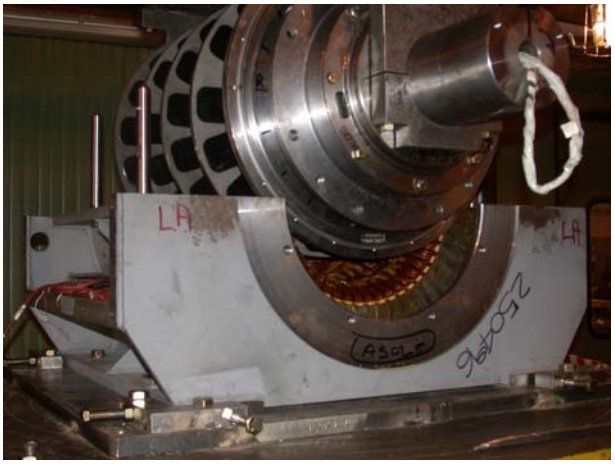

Fig. 3 – Assembly process of the machine prototype.

Fig. 4 - View of the machine prototype at the test bench.

IV. EXPERIMENTAL CAMPAIGN

An extensive experimental campaign has been carried out on the proposed prototype. Tests have been performed in order to verify design specifications, to investigate flux weakening capabilities, to identify the thermal behaviour and so on.

The layout of the experimental setup is sketched in Fig. 5, which shows the four-stage AFPM prototype coupled, through a torque meter, to a separately excited DC machine used as dynamic brake. The same figure shows also the inverter available for testing and how it has been connected to one stage of the AFPM prototype.

Preliminary tests were aimed at measuring machine parameters, so that these could be compared with the design predictions. Phase EMF, resistance and inductance were therefore experimentally evaluated, obtaining the results given in table 3. The same table shows also the rated voltage of the machine and the minimum DC link value that should be adopted in order to drive (a single stage of) the machine with an inverter, working in the linear modulation region.

Since the drive available for the experimental tests had a much lower DC link voltage (namely 440 V), we were forced to "redefine", for testing purposes and specifically in order to verify the constant power speed range (CPSR), a new set of rated values which took into account the ratio of the available and the required DC link.

This reduced scale set of rated quantities is reported in table 4. Also the rated torque had to be reduced, due to the measured EMF value, which was considerably lower than predicted in the design stage.

Using the DC machine as prime mover, it was possible to evaluate the no-load characteristics of the prototype.

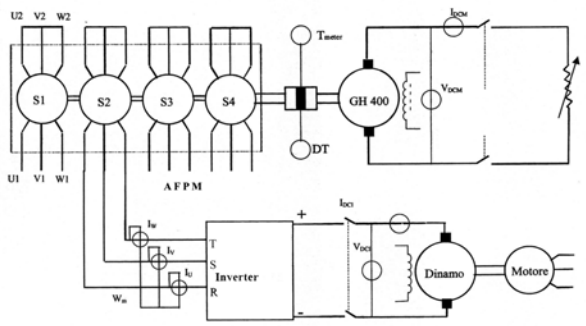

Fig. 5 – Schematic representation of the experimental setup.

Table 3 - Measured machine parameters (one stage)

Phase EMF (@682 rpm)	249.5 Vrms
Phase resistance	42.8 mΩ
Phase inductance	2.39 mH
Rated phase voltage (@682 rpm, 157 A)	327 Vrms
Rated line-to-line voltage	565 Vrms
Required DC link	924 V

Table 4 – Tested machine rated parameters (one stage)

Available DC link	440 V
(reduction coefficient)	440/924 = 0.476
Base speed	325 rpm
Base frequency	43.3 Hz
Max speed	975 rpm
Rated torque	1630 Nm
Rated power	55.5 kW

In particular, Fig. 6 presents no-load power losses as a function of speed, while Fig. 7 shows emf waveforms of the four stacks at 682 rpm. Also, Fig. 8 shows the short-circuit characteristic of the AFPM prototype, used in order to evaluate machine inductance with respect to design specifications.

After machine parameters determination, the CPSR has been verified, according to the reduced scale test previously outlined (Table 4). Fig. 9 shows some of the experimental points recorded during the determination of the mechanical characteristic of the machine, referred to one stack. In this figure it is possible to find the corner point, field weakening up to more than twice base speed and overload capability up to twice the rated torque. Comparison of experimental results with the computed theoretical values shows a very close agreement.

Finally, thermal tests have been also carried out, aimed at determining the time constant of the machine and the steady state temperature distribution inside the prototype. Specifically, from a test performed at rated torque and speed, with cooling water flowing at 2.5 l/min, it was determined that the prototype reached thermal steady state in about 2 hours and 15 minutes and that the hottest spot in the stator was at 104°C.

Fig. 10 shows the current waveform at the corner point, recorded during the above mentioned thermal tests (1630 Nm, 325 rpm).

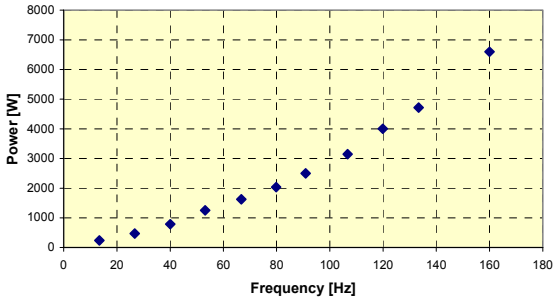

Fig. 6 - No load power vs. frequency

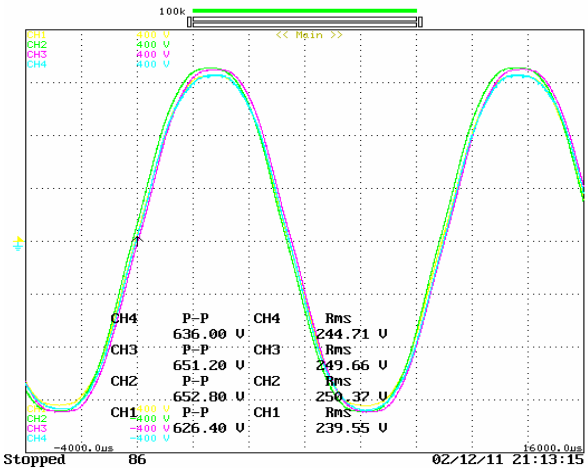

Fig. 7 - EMF waveforms of the four stages

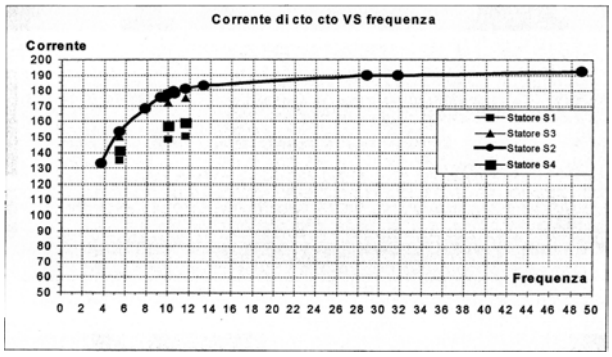

Fig. 8 – Short-circuit characteristic (x-axis: frequency in Hz, y-axis: phase current in A)

V. CONCLUSIONS

This paper has described the original solutions adopted for a multi-stack AFPM prototype devoted to direct-drive railway applications. Significant aspects of the machine design have been discussed and experimental results taken from a machine prototype have been

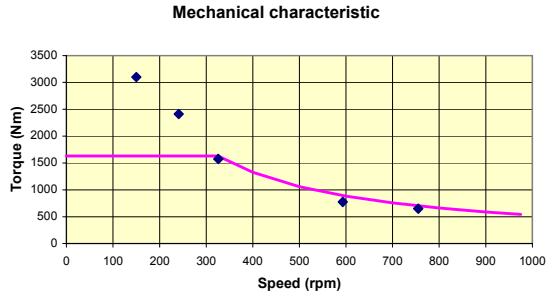

Fig. 9 – Reduced scale theoretical and experimental mechanical characteristic

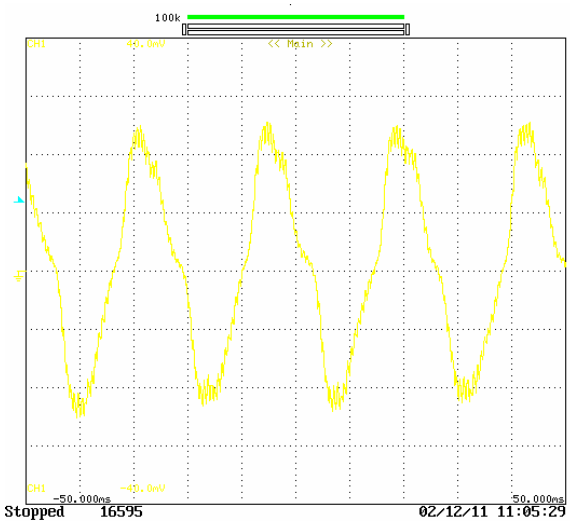

Fig. 10 - Phase current at 1630 Nm, 325 rpm (scale 100 A/div, 10 ms/div)

reported. The novel arrangement proposed for AFPMs allows machine characteristics such as very high compactness, lightness, efficiency and long-term overload capability, which are required for the direct-drive applications.

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