PERFORMANCES ANALYSIS OF AN INDUCTION MOTOR PROTOTYPE FOR DIRECT DRIVE TRACTION SYSTEM OF TRAMCAR

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Abstract. *The paper presents a special design of an induction motor used for direct drive tramcar without use of any gears. According to this design, the motor was arranged around the wheel-set within a small given space. Aspects concerning some design elements (iron sheets, open slots, magnetic wedges), structure of the data acquisition system and test results on the prototype motor are presented in the paper. Measurement results show that by special design, the induction motor proved to be a good economical solution, meting the demands of power and torque in direct drive street cars application.*

Keywords: *tramcars, direct drive, induction motor, design optimization.*

1. Introduction

The state-of-the-art light traction system of street cars (tramways, trolley lines, subway trains) consists of GTO or IGBT power inverter, feeding a.c. electric motors (cage induction, permanent magnet brushless or switched reluctance motors). An important feature of any traction motor is the rather long range of constant power. The constant torque and constant power region over wide speed range can be achieved through electronic control.

Traction motors should meet a set of requirements [1]: high instant power, high power density, high torque at low speed, fast torque response, high efficiency over wide speed and torque ranges, high reliability and robustness, low cost.

On the other hand, the direct drive system (i.e. drive of axle or wheel without use of any gears) offers many benefits [2] that must be considered: no gear energy losses; no gear maintenance; no gear noise; oil-free drive system; reduced noise of the traction motor by rather low motor speed and by inverter feeding.

Nowadays, majority of the researchers considers [1, 2, 3, 4] that the Permanent Magnet Brushless Motors are more efficient, more compact, have better steady-state and dynamic performances at low speed and are excellent motors for direct drive traction applications.

However, by special design, the induction motor proved to be [5] from the view of low-cost a good economical solution, meeting the demands of power and speed for street car application.

The aim of the paper is to prove that the induction motor can develop enough torque to perform the required speed and acceleration of a direct drive tramcar. It was decided to build a prototype in order to verify the theoretical data by measurement.

The paper presents this motor-prototype and some results of measurement by sinusoidal voltage supply, using a data acquisition and processing system.

2. Design of the prototype motor

The electric direct drive system demands from the motor a high torque level, equal with that require from the wheel axle. In consequence, these motors have bigger size that the usual ones.

On the other hand, around the wheel axle there is a small given space, limited by wheels distance and wheel diameter.

In these conditions compact motor design with low motor losses is necessary.

The limited space surrounding the axle is of a tube type, not of disk type. From this reason, electric motors showing tube shape (like induction motor [5], permanent magnet synchronous motor [2]) are much better suited for direct drive in a rail vehicle than those of disk shape (transversal flux motor, axial flux motor, etc.).

So, an induction motor for direct drive of wheel set was designed, using a dedicated computing program that finds the better motor design, with highest efficiency. For calculation, the following data was considered: rated power P_N=130 kW; poles number $2p$=10; rated voltage U_N=380 V; rated frequency f_N=50 Hz.

To ensure a tram-speed from zero to maximum 60 km/h, the motor will be supply by a power inverter, with variable voltage and variable frequency between 3÷30 Hz.

For the prototype, the mechanical design had to be performed considering stator housing, forced air cooling, and bearing concept. Only lathed parts made from massive material were used.

Outer stator from iron sheets with 60 slots was made. The laminations stack contains a usually three-phase two layer winding. From technological reason, stator winding of prototype motor with preformed copper coils was built. In consequence, the iron stack has open slots of rectangular shape that cause high order harmonics and additional stray loses decreasing the motor performances. In order to reduce the unfavorable consequence of these open slots, magnetic wedge in the stator was used.

An open slot with magnetic wedge (Figure 1 a) is equivalent with a semi closed slot (Figure 1 b). The equivalent opening $b_0^{'}$ can be calculated and is dependent on the following data: actual slot width b_0; magnetic wedge thickness h_w; magnetic wedge permeability μ; air-gap width. The magnetic wedge permeability is depending on the air-gap flux density according with the material curve provided by the manufacturer.

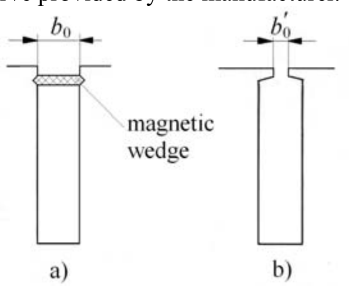

Figure 1. The stator slot: a) actual open slot with magnetic wedge; b) equivalent semi-closed slot.

On the prototype motor was mounted 60 magnetic wedges with h_w = 3 mm and μ=2,57 μ_0 that means an equivalent opening $b_0^{'}$=3,65 mm.

The inner rotor also from iron sheet was made and has a copper cage with 68 bars placed into the rectangular semi-closed slots. The rotor is fastened to the wheel-axle (Figure 2).

Figure 2. The motor prototype and actual wheel-axle.

According to this design, the direct drive motor prototype has to be arranged around the wheel-set of the bogie (Figure 3).

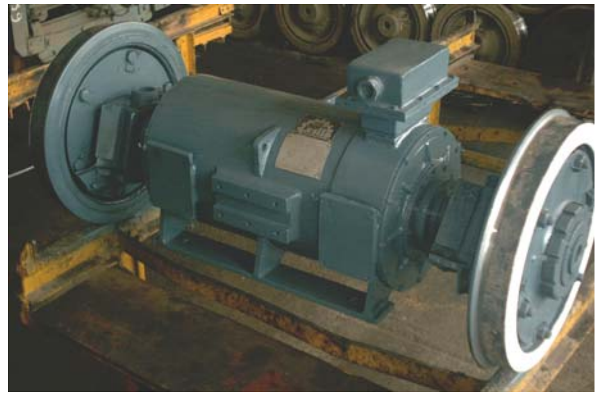

Figure 3. The wheel-set with motor prototype.

3. Data acquisition system

The bloc diagram of the Data Acquisition and Processing System (DAPS) used for testing of the motor prototype M is presented in Figure 4.

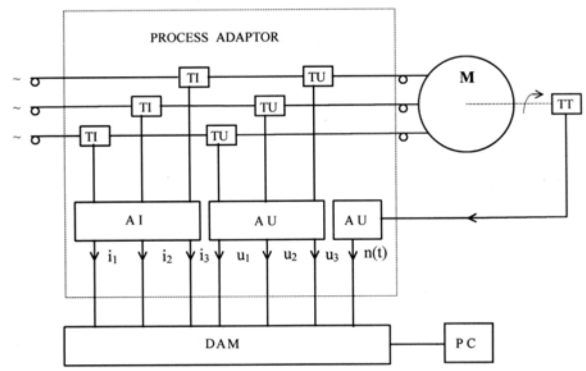

Figure 4. Bloc diagram of DAPS in a measuring circuit.

The main components of DAPS are: process adaptor module, containing the current and voltage transducers TI, TU, and corresponding adapters AI, AU. The current and voltage signals, including the signal from speed transducers TT, are transmitted to the data acquisition module DAM, and processed with the microcomputer PC.

There were designed two variants for process adapter, to achieve tests for a large type scale of electrical machines, in laboratory or in industrial environment. For current inputs the adapters have following domains: 5A, 10A, 500A, 1500A. Voltage inputs domains are 10V, 110V, 240V and 450V. For transducers, LEM type modules based on Hall effect are used. So, the adapters can be used in periodical and transient conditions, as well.

The process adapters are flexible devices, having the possibility to be used in addition with standard transducers which equipped high power machines in industrial environment. The data acquisition module was achieved with a conversion A/D module, DAS 12009 type from Analog Devices Inc.

The modules of DAPS are described in some previous papers [6, 7, 8]. For different kind of standard tests, or special type tests required from homologation of electrical machines, have been designed and achieved software packages for data processing.

This DAPS has been designed and built based on requirements of industrial customers.

4. Measurement results

4.1. No load tests

The magnetizing current dependency of the stator flux and the iron loses of an induction motor can be evaluated at a constant frequency (rated value) and a variable motor voltage.

Figure 5 show the losses measured curves of the prototype motor dependent on the motor voltage.

The phase current dependence with motor voltage is represented in Figure 6. From Figures 5 and 6 one can be seeing that at rated voltage (380 V) the no load current and loses have large values even than magnetic wedges was used. In order to reduce these values must be diminished the ratio between voltage and frequency by an automatically control of the stator flux implemented in the power inverter. The curve 2 from figure 6 show the influence of the magnetic wedges in the stator on the no load current that is of about 15% diminished. The curve 3 in figure 6 represent the calculated no load current in the suppositional case of semi-closed slots in the stator (with 3 mm opening) and without any narrow of teeth cross-section.

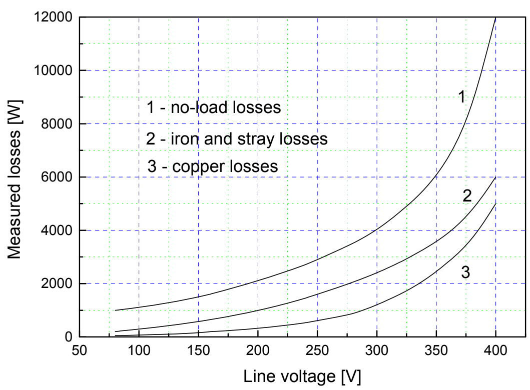

Figure 5. No-load measured loses depending on the voltage.

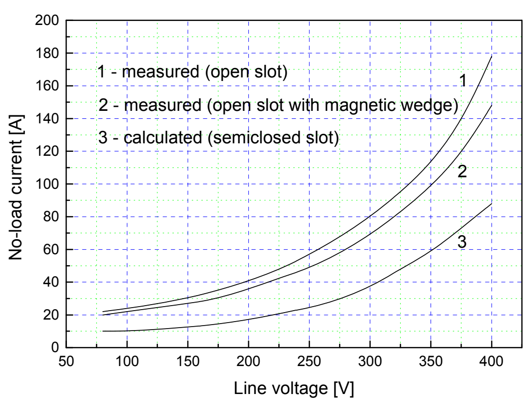

Figure 6. The voltage dependence of the no-load current.

From these tests results that the semi-closed slots in the stator is a better solution than the open-slots with magnetic wedges. But, from technological reasons for this motor prototype an open slot was used.

4.2. On load tests

In order to evaluate the load dependent stator flux optimum of the motor, load characteristics are measured at an operation with constant rated frequency in the stator and variable motor voltage.

From the load tests, input current, power factor and efficiency was measured depending on the output power and on the stator flux (i.e. ratio between voltage and frequency).

The analysis of these load motor performances shows that additional efficiency improvement is possible by controlling the magnetic flux. This can be achieved though the both voltage and frequency control of the power inverter.

In Figure 7 two curves of the current at constant output power (130 kW) as a function of the stator flux (volt/hertz) was presented: the curve 1 corresponds to the actual motor prototype with open stator slots and magnetic wedges, and the curve 2 – to the suppositional case of semi-closed slots in the stator. The current has a minimum also for other value of output power.

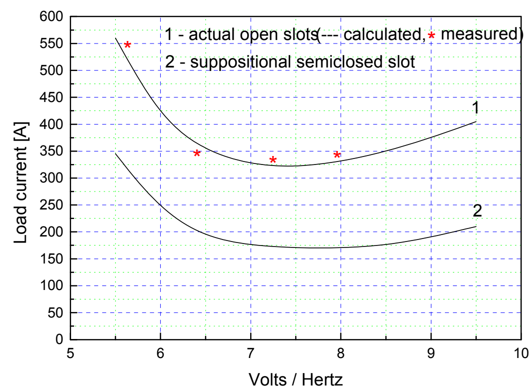

Figure 7. Load current at constant output power (130 kW) depending on the ratio between voltage and frequency.

Generally, the minimum current value determines the maximum efficiency value and, in this way, the power inverter allows for optimal control of the induction motor. Better motor performances with stator semi-closed slots can be obtained according with the calculated curve 2 from Figure 7.

4.3. Torque measurement

In the purpose to obtain the torque-speed characteristic, the motor has been tested in slowly starting conditions. Using low voltage supply, in these conditions is a good enough approximation to consider the motor is covering point by point the static torque characteristic. In this slowly start conditions the currents, voltages and the active power have been recorded.

Using the power balance method [9, 10] the torque as speed function is obtained.

In the Figure 8 is presented a comparison between experimental results and calculated torque characteristic. In the experimental results the actual influence of saturation has been considered by repeating the slowly start test at three level of voltages, at least [11, 12].

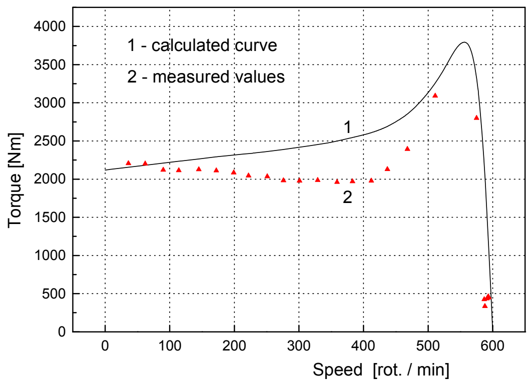

Figure 8. Torque – speed characteristic: 1- calculated curve; 2- measured values.

In the calculated curve of the torque – 1, the saturation influence on the motor parameters was not considered. Obviously, the saturation makes the difference between the two dependencies of the torque.

5. Conclusions

A gearless drive system with induction motor for light rail transit, especially for tramcar, was presented in the paper. Within the small given space around the wheel-axle a three-phase cage induction motor was designed. The direct drive traction motor which eliminate gears and hence noise and transmission losses have been performed and tested in the laboratory using the data acquisition and processing system.

The measurement results show that this motor prototype can develop enough torque to perform the required acceleration of the tramcar.

The proposed traction system including the induction motor and the power inverter with variable both voltage and frequency can be a realistic direct drive solution for modern street-cars.

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