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DIRECT-DRIVE INDUCTION MOTOR FOR RAILWAY TRACTION APPLICATIONS

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This paper deals with a new technical design for a tram-bogie with direct drive system on the axle with an induction motor. The elimination of the mechanical gearbox with gear wheels allows the layout of the induction motor on the wheel-axle. Such a direct driving system means that the electric motor develops a high torque, which is necessary in operating the tramcar axle, in a limited space by the wheels distance (wheel track) and of the wheel-axles diameter (or road clearance). For solving this problem, the authors propose an induction motor with a large number of poles, supplied with variable frequency by an inverter. In this work are shown some aspects concerning the layout of the motor on the driving bogie of the tramcar, the manufacturing, the design and the optimization of the motor and the experimental results obtained after testing the manufactured motor. From this research, it is possible to see the influence of the stator slots shape on the motor performances, unfavorable influence of the open stator slots and the favorable influence of the magnetic wedges used for the prototype. The experimental results obtained by laboratory testing of the induction machine, and the tests made with an empty tramcar on an experimental way, confirmed that the induction motor, in an appropriate shape and supplied with variable frequency, can satisfy the performances required by a driving system in electric traction.

Key words: Direct drive, Induction motor, Tramcar, Design optimization.

1. INTRODUCTION

The use of induction motors (asynchronous motors) in urban transport instead of d.c. motors allows both the mono-motor driving on the axle and the driving of each wheel in order to meet the new requirements of the traction system, especially the low floor vehicle. The main advantage of the direct driving is to avoid the mechanical gearbox. The last one becomes soon worn due to the hard working conditions.

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 both constant torque and constant power conditions on a 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 [5,6] a good economical solution, meeting the demands of power and speed for street car application. In the paper [7] the authors states that the totally enclosed a.c. induction motor is the best choice for most variable-speed applications and for some applications the direct-drive a.c. induction motor is the better choice.

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

The paper presents this work and some results concerning the motor-prototype tests by sinusoidal voltage supply, using a data acquisition and processing system.

2. SPECIFICATIONS. MECHANICAL PARAMETERS [9,10]

The design of the direct driving traction motor was made taking as start point the data of the actual tramway “Timis 2”:

– the motor wheel diameter – maximum: D_{max}= 680 mm;
– the maximum starting acceleration: a_{max}= 1.1 mm/s^2;
– axle maximum loading: 7.5 tonnes;
– maximum speed: v_{max}= 60 km/h;
– railway ramps: i = 0; 10; 20; 40‰;
– the adherence coefficient: f_a (maximum value f_{amax} = 0.33; minimum value f_{amin}= 0.2);
– the vehicle weight: G_a (maximum weight 30t; medium weight 23.25t; minimum weight 16.5 t);

The traction force of the motor vehicle, F_{0max}, is limited by the adherence coefficient and depends on the weight, G_a, as follows:

$$F_{0max}=f_a \cdot G_a \text{ [N]} . \quad (1)$$

According with last relation the traction forces for the different cases and corresponding torque are in Table 1.

Table 1

F_{0max} [N]	99 000 N = 0.33·300 000			60 000 N = 0.2·300 000			54 450 N = 0.33·165 000			33 000 N = 0.2·165 000		
$D/2$ [m]	0.34	0.32	0.30	0.34	0.32	0.30	0.34	0.32	0.30	0.34	0.32	0.30
M_0 [Nm]	8415	7920	7425	5100	4800	4500	4628	4356	4084	2805	2640	2475

The necessary force for tram starting is computed as follows:

$$F_d = \left(r_d + i\right) \cdot G_a , \quad (2)$$

where G_a is the whole tram weight, r_d is the starting tram specific resistance and i is the railway ramps [‰]. The traction forces to start the tram in the case r_d = 4, for i = 0 and i = 90‰ are presented in Table 2.

Table 2

$(r_d + i)$	4			94		
G_a [kN]	600	465	330	600	465	330
F_d [N]	2 400	1 860	1 320	56 400	43 710	31 020

For the urban and suburban vehicles, the starting and breaking are frequents and high acceleration and deceleration are presents. Therefore, an accurate estimation of the traction motor power is obtained from the heating and cooling conditions, using the formula:

$$P = \frac{1}{\sqrt{2}} m \sqrt{\nu_d^3 \frac{a_d \nu_c}{L}} \quad \text{[kW]} , \quad (3)$$

where m – the vehicle weight [t]; a_d – the starting acceleration [m/s^2]; L – the distance between two stations (the average value) [m]; v_c – the computed equivalent speed [m/s]; v_d – the speed after the starting time. It was assumed: v_d = 50 km/h, a_d = (0.8; 1; 1.1) m/s^2, L = 500 m, the stop time t_0 = 30 seconds.

The computed equivalent speed is:

$$\nu_c = \frac{L}{\frac{\nu_d}{a_d} + \frac{L}{\nu_d} + t_0} \quad \text{[m/s]}. \tag{4}$$

The values of the tram power and that of the traction motor torque in Table 3 are presented.

Table 3

a_d [m/s^2]	0.8			1			1.1		
v_c [m/s]	5.99			6.25			6.35		
m [t]	60	46.5	33	60	46.5	33	60	46.5	33
P [kW]	215	165	119	245	190	135	260	201	143
M [Nm]	1 316	1 010	728	1 499	1 158	826	1 591	1 230	875

The electric motor rotational speed must be done for the maximum wear of the bandage (D = 600 mm). So the tram should run with the maximum considered speed (v_{max} = 60 km/h).

The maximum traction force must be computed for the new bandage (D = 680 mm). So, for the same torque developed by the electric motor, the traction force at the hoop is the lowest.

The traction motor torque depends on the speed, on the railway ramp and on the assumed starting acceleration: for the motor torque on the axle of 2 100 Nm, the tram can travel at the maximum speed on rail on the sections with characteristic ramps up to 40‰; for bigger ramps, the motor overloading can be available for a short time.

The starting acceleration of the tram is computed using the formula:

$$a = \frac{M_{m\nu} - M_r}{m(1+c)r} \quad \text{[m/s}^2\text{]}, \tag{5}$$

where: M_{mv} is the motor torque developed by the traction motor; M_r is the load torque of the tram; m is the mass of the tram; r is the wheel radius; c = 0.15 is a coefficient taking in to account the masses in their rotating movement.

For a tram composed of two wagons (tram and trailer) with two bi-motor bogies there will be performed the following starting accelerations:

– empty motor tram: a = 2.29 m/s^2;
– maximum loaded motor tram: a = 1.13 m/s^2;
– maximum loaded tram and trailer: a = 0.61 m/s^2.

The maximum loaded tram and trailer reaches the speed of 60 km/h after 29 seconds along a space of 232 m and having an acceleration of 0.61 m/s.

The maximum loaded tram-car (motor and trailer) applies the brake from the maximum speed of 60 km/h up to the stopping in 26 seconds when the braking space is 213 m and the deceleration is 0.66 m/s^2.

The empty tram applies the brake from the maximum speed of 60 km/h up to the stopping point in 13 seconds when the braking space is 100m and the deceleration limit is 1.4 m/s^2.

3. THE BOGIE-PROTOTYPE PRESENTATION

One of the main disadvantages, in fact the cause of the most mechanical deficiencies, from the classic tramcar, is the driving gear of the driving axle, very important in indirect driving case of the axle for this type of vehicle.

The technical design adopted by the authors requires the mounting of the induction motor rotor direct on the wheel-axle, and the stator is supported by some spiral springs from the bogie frame.

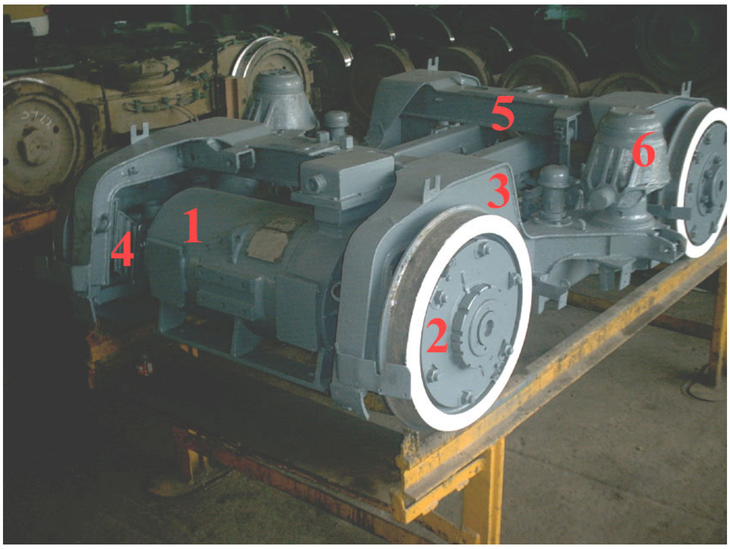

Fig. 1 – The tramcar bogie-prototype.

The tramcar bogie-prototype (Fig. 1) consists of:

1 – induction motor whose stator is fastened on the tram axle; 2 – tram elastic wheel; 3 – tram frame bogie longitudinal girder; 4 – bogie primary suspension; 5 – bogie frame traverse profile; 6 – secondary suspension element made of rubber – metal.

In Fig. 2 the layout of the induction motor on wheel-axle of the experimental tramcar is presented: 1 – induction motor; 2 – the spiral springs of supporting on the bogie frame; 3 – bogie frame traverse profile; 4 – bogie frame longitudinal girder; 5 – fastened axle.

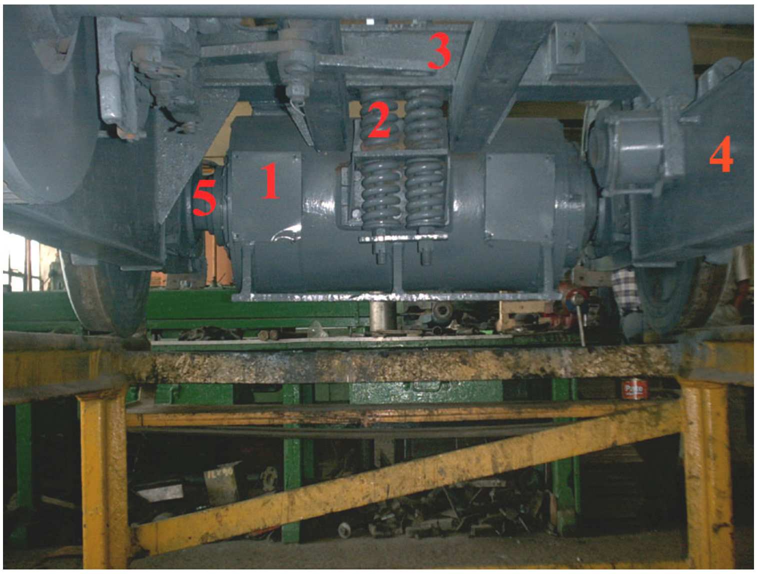

Fig. 2 – The layout of the induction motor on the wheel-axle of the experimental tramcar.

4. THE DESIGN OF THE MOTOR PROTOTYPE

The electric direct drive system demands from the motor a high torque level, equal with load torque of 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 surrounding axle space is a long cylinder type. From this reason, electric motors become a tubular shape one (like induction motor [5], permanent magnet synchronous motor [2]) being suited for direct drive in a rail vehicle than those with disk shape (as are transversal flux motor and axial flux motor).

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; frequency f_N= 50 Hz.

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

For the prototype, the mechanical design had to be performed considering stator housing, forced air cooling, and bearing concept.

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 losses 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 (Fig. 3a) is equivalent with a semi closed slot (Fig. 3b). 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 depends on the air-gap flux density in accordance with the material curve provided by the manufacturer.

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 (Fig. 4).

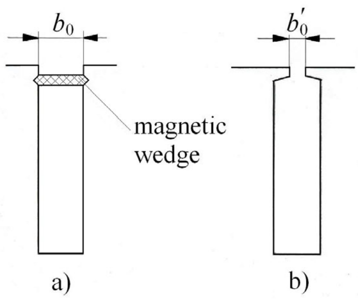

Fig. 3 – The stator slot:
a) actual open slot with magnetic wedge; b) equivalent semi-closed slot.

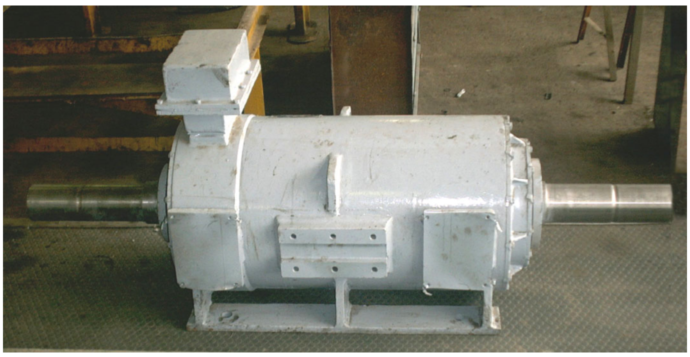

Fig. 4 – The motor prototype and actual wheel-axle.

Into the motor slots, 60 magnetic wedges with h_w = 3 mm and μ = 2.57 μ_0 were mounted, that means an equivalent slot opening $b_0^{'}$ = 3.65 mm.

According to this design, the direct drive motor prototype has to be arranged around the wheel-set of the bogie (Fig. 5).

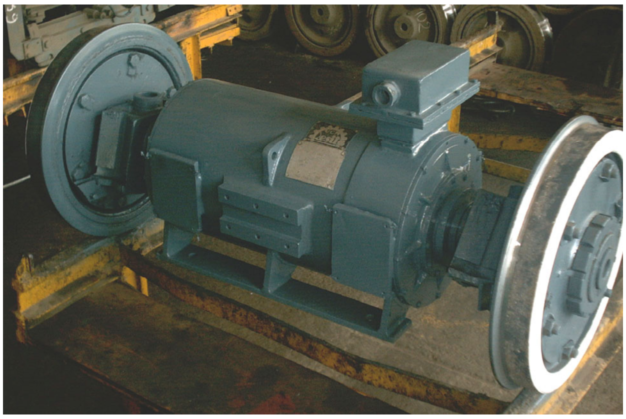

Fig. 5 – The wheel-set with motor prototype.

5. DATA ACQUISITION SYSTEM

The block diagram of the Data Acquisition and Processing System (DAPS) used for testing of the motor prototype M is presented in Fig. 6.

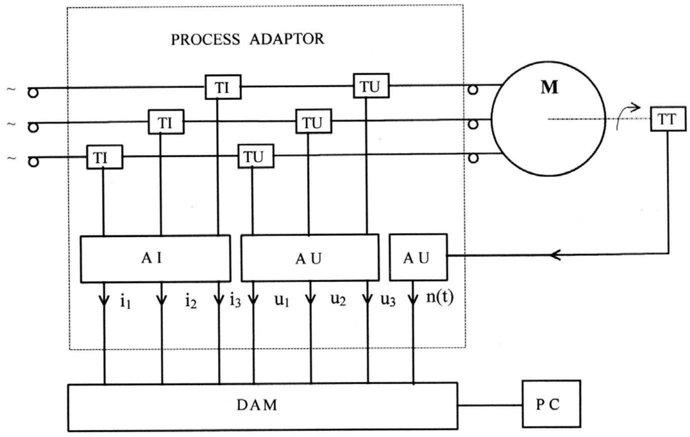

Fig. 6 – Block diagram of DAPS in a measuring circuit.

The main components of DAPS are: process adapter 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.

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, 1 500A. 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 previous paper [11]. 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.

6. MEASUREMENT RESULTS

The motor prototype (Fig. 4) was tested using sinusoidal voltage supply in the laboratory.

6.1. 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 (50 Hz) and a variable motor voltage.

Figure 7 shows the losses measured curves of the prototype motor dependent on the motor voltage.

The phase current dependence with motor voltage is representing in Fig. 8. From Figs. 7 and 8 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 Fig. 8 shows the influence of the magnetic wedges in the stator on the no load current that is of about 15% diminished.

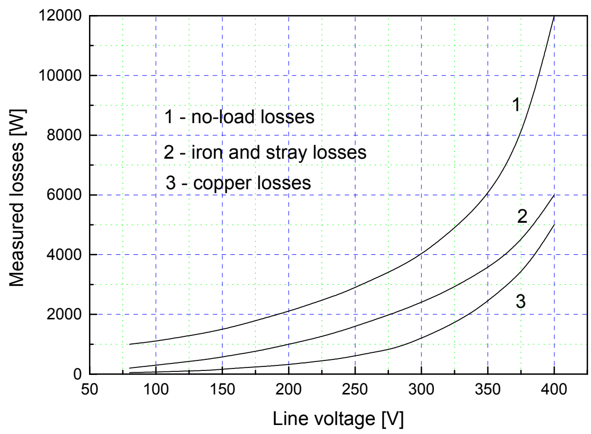

Fig. 7 – No-load measured loses depending on the voltage.

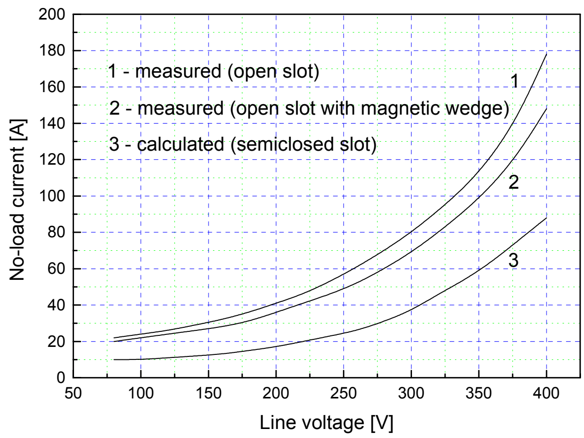

Fig. 8 – The voltage dependence of the no-load current.

The characteristic 3 (Fig. 8) means the calculated no load current in the case of semi-closed slots in the stator (with 3 mm opening) with the same teeth cross-section.

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

6.2. Load characteristics

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.

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

The curves 2 (Fig. 9) represent the calculated power factor as output power functions in the hypothetical case of semi-closed stator slots at three different supply voltage values and constant frequency (50 Hz). The tests and calculated values show that the levels of motor power factor (curves 1) are diminished because of the open slots even with the use of the magnetic wedges. It is now evident that the power factor can be significant increased if the semi-closed slots in the stator are used.

The curves 2 (Fig. 10) represent the calculated values of efficiency (semi-closed slots) as functions of output power and the curves 1 includes calculated and measured values of motor efficiency with actual open-slots and magnetic wedges.

Moreover, the analysis of these load motor performances shows that both power factor and efficiency improvements are possible by controlling the magnetic flux. This result can be achieved through the both voltage and frequency control of the power inverter.

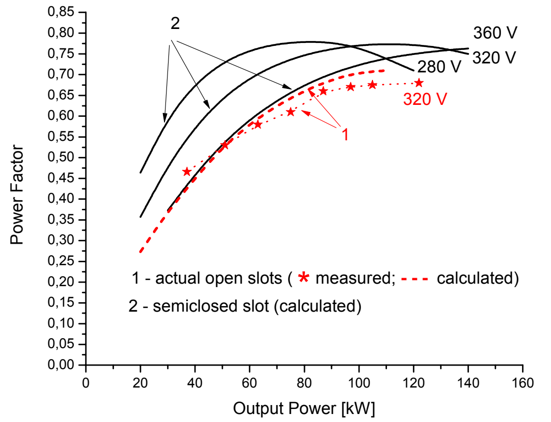

Fig. 9 – Power factor as function of output power:
1 – actual open slots (* measured values; - - - calculated values)
2 – hypothetical semi-closed slots (calculated).

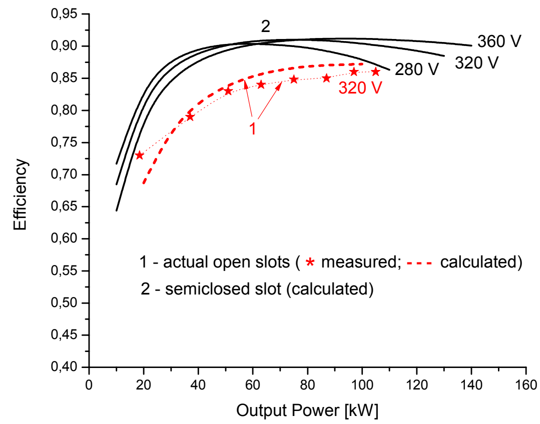

Fig. 10. Efficiency as function of output power:
1 – actual open slots (* measured values; - - - calculated values)
2 – hypothetical semi-closed slots (calculated).

In Fig. 11 two current curves at constant output power (100 kW), as stator flux (volt/hertz) functions were presented: the dashed line 1 corresponds to the actual motor prototype with open stator slots and magnetic wedges, and the dependence 2 corresponds to the case of semi-closed slots in the stator. The current has a minimum at certain value of ratio Volt/Hertz.

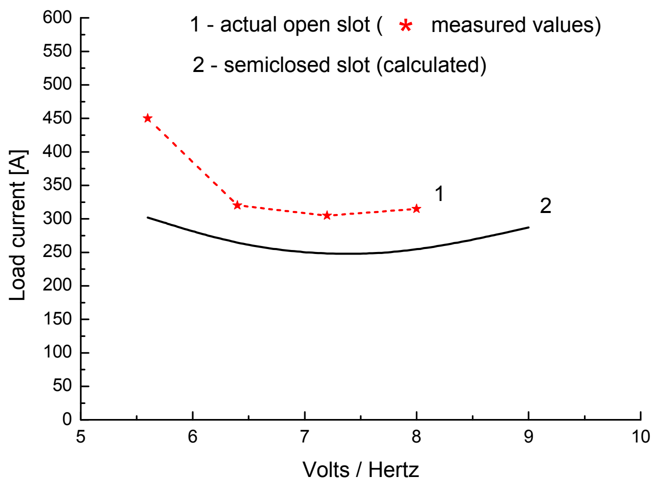

Fig. 11 – Load current at constant output power (100 kW) depending on the ratio between voltage and frequency:
1 – actual open slots (* measured values); 2 – hypothetical semi-closed slots (calculated).

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 dependence 2 from Fig. 11.

6.3. Torque measurement

In order 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 [12] the torque as speed function is obtained.

In Fig. 12 a comparison between test results and calculated torque characteristic is presented. In the experimental results the actual influence of saturation has been considered by repeating the slowly start test at three levels of voltages (less than rated voltage) according to [13,14].

At the calculated curve (1) of the torque, the saturation influence on the motor leakage inductances was not accurately considered. Obviously, because of this, there is the difference between the two dependencies of the torque.

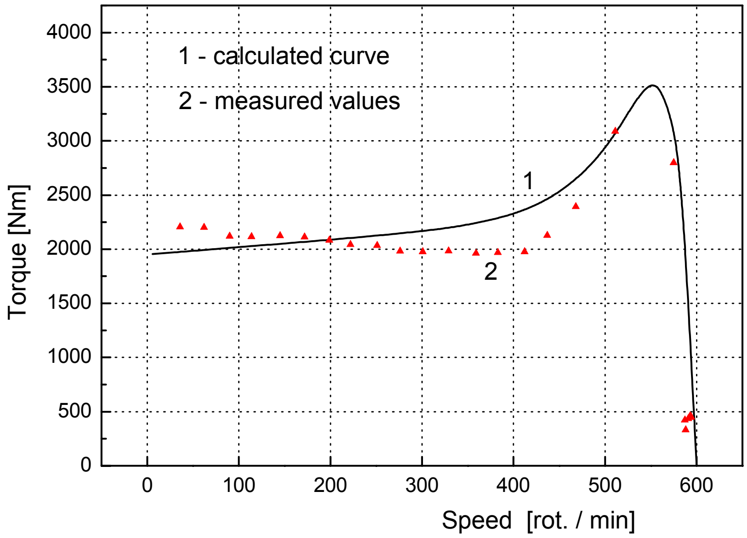

Fig. 12 – Torque-speed characteristic at 380 V, 50 Hz:
1 – calculated curve; 2 – measured (extrapolated values).

7. 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 eliminates gears and hence noise and transmission losses was performed and tested in the laboratory using the data acquisition and processing system.

In the field, the measurement results show that this motor prototype can develop enough torque to perform the required acceleration of the tramway.

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 tramways or streetcars.

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