Control of Traction Rail Vehicle with Free-wheels

Jan Čapek [1)], Petr Sýkora [2)] Václav Lenoch [3)]
[1)] VÚKV a.s., e-mail: *capek@vukv.cz*
[2)] University of Pardubice - Jan Perner Transport Faculty - Department of Electrical and Electronic Engineering and Signalling in Transport, Pardubice, Czech Republic, e-mail: *petr.sykora@upce.cz*
[3)] University of Pardubice - Jan Perner Transport Faculty - Department of Electrical and Electronic Engineering and Signalling in Transport, Pardubice, Czech Republic, e-mail: *vaclav.lenoch@upce.cz*

Abstract—**This paper is focused on the low-floor trams with free-wheels driven by PMSM motors, especially on their traction control system. The first part describes modern low-floor trams, particularly the type 15T produced by Škoda Transportation. The second part of the paper presents the simulations of characteristics operating such tram in the rail and the results of these simulations. The last part of the paper describes the mechanical construction and electrical equipment of a light experimental rail car, that will be used as an experimental base for a improvement of the control system for the tram 15T.**

Keywords—low-floor tram, free-wheel drive, gearless drive, PMSM, control system, experimental vehicle.

I. Modern low-floor trams

Tram vehicles have some specific elements in comparison with standard rail vehicles. Streetcar tracks are led through the streets of urban development, often not separated from car traffic, characterized by the presence of curves of very small radius (up to 20 m) and steep inclines. Challenging tracing of tramlines makes the construction of tram vehicles quite difficult. In addition to further tram improving it is now required a low-floor vehicle, which further increases the difficulty of the structural design of these vehicles and forces some other specifics. The use of low-floor vehicles in the public transport system allows not only convenient travel for citizens with limited mobility or passengers with wheel chairs but also significantly speeds up the exchange of passengers at tram stops.

The first low-floor tram vehicles began to be produced in the second half of the 80' of the 20th century. Since then, there was designed a large number of low-floor trams of different solutions to achieve the highest proportion of low-floor space. A high ground is considered to be a floor mounted at a height of about 600 to 900 mm above the rail, a low floor is then at a height of about 350-450 mm above the rail. The low-floor vehicles are divided into two categories - semi low floor and fully low floor. Typical arrangement of low-floor trams are illustrated in Fig. 1 and 2. The proportion of the low floor with semi low-floor trams ranging from about 15% (Fig. 1 top) to 75% (Fig. 1 below), in the case of a fully low-floor vehicles, the low floor is located along the passenger lounge.

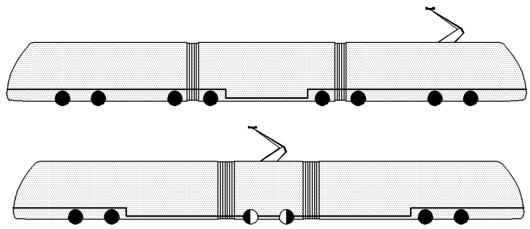

Fig. 1 Partially low-floor tram

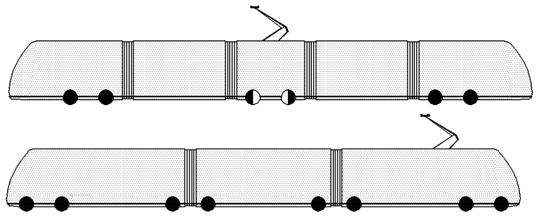

Fig. 2 Fully low-floor tram

Location of low-floor trams bogies requires the use of special bogies. For the partially low-floor tram there are often used normal (non-driven) bogies and as a drive standard chassis located above the floor in a standard height. For full low-floor trams all the bogies, including drive, are then low-rise.

A common feature of almost all types of low-floor bogies is the use of independently rotating wheels instead of conventional wheel sets. In case of drive bogie, these 'axles' are driven by a pair of longitudinally stored motors with double-sided output or each wheel is independently driven by one motor.

Behavior of independently rotating wheels moving in a dorm is different from that of conventional wheel sets. While the wheel set is used from the very beginning of rolling stock and therefore the behavior in rail is well known, independently rotating wheels on rail vehicles is relatively new element that needs to be continually examined in detail.

Using independently rotating wheels in bogies of trams was elicited from the low-platform. However, it can also be used for other important improvements of vehicles - in the case of independently rotating wheels when each of them is driven by its own motor it is possible to control each motor to improve road holding, in particular to reduce wear on wheels and rails and increase vehicle safety against derailment.

II. Tram Škoda 15T

Škoda Transportation in cooperation with Škoda Electric has designed and currently manufactures factory-type 15T trams known under the trade mark ForCity (see Fig 3). These trams - designed specifically for the Transport Company of the Capital City of Prague - had already at the design stage to meet very demanding requirements of the contracting authority. From our perspective, this is a multistage design with rotating bogies and drive on all wheel sets and at the same time the 100% low-floor vehicle without any stairs balancing of level floors inside the vehicle.

Fig. 3: Tram 15T ForCity

These requirements have led manufacturers to apply up to now seldom used traction drive concept: the wheels of the trams are no longer linked to a common wheel set in a rigid axle driven by one traction motor, tram-type 15T wheel drive was solved individually using low-speed synchronous motors excited by permanent magnets attached to wheels without the use of a gearbox, only by a flexible coupling.

The chosen drive concept enabled to meet the requirements of the vehicle when entering the contract, but later on it also brought unsolved problems. The concept of the drive using sixteen liquid-cooled synchronous motors excited by permanent magnets supplied from sixteen voltage source inverters, causes increasing complexity of the vehicles and places significant demands on the control system and data communication between its various components.

An innovation is mainly given by the absence of classical rigid wheel set in terms of roadholding. We could simply say that it is advantageous for solid axle ride in a straight line, which stabilizes the vehicle profitably, but while driving arc, however, a sweeping wheels on the rail are causing undesirable tread wear and noise. Using individual wheel drive provides in this respect a new potential and risk.

When driving it is possible to prevent an arc sweeping wheel on the rail, which can dramatically reduce both the wear of wheel and rail and noise too. In contrast, in a straight line it does not reach optimal vehicle driving, in extreme cases it can cause lower safety against derailment. All these mentioned features, however, can be influenced by appropriate management of traction drives.

Since the Department of Electrical Engineering, electronics and security systems in transport of Jan Perner Transport Faculty of the University of Pardubice participated in the development of tram traction drive 15T [1], [2], collaboration resulted in another research project, this time focusing on optimizing control algorithms mentioned on vehicles with free driven wheels.

As it would be the experimental verification of the changes effects upon the control software running on a real tram considerably complicated, we proceeded in cooperation with Škoda Electric and VÚKV to build an experimental vehicle. But the first part of the research is the simulation of the changes influence upon the control software.

III. Simulations

The MBS simulation software is used for an analysis of a rail vehicle dynamic behaviour during running on a track. In this software a virtual 3D vehicle model is created, which consists of mass elements (car body, bogie frames, wheel sets, etc.) that are connected to each other by kinematic joints (e.g. a rotational joint connecting a wheel set with an axle box) or force elements (e.g. suspension elements). After the vehicle model is created, the software builds up itself equations of motion of the mass elements and equations of the joints. The resulting system of differential-algebraic equations is solved numerically. Adams by the MSC.Software Company and Simpack by the company of the same name are the most popular MBS simulation softwares. Fig. 4 shows an example of the calculation model of a low-floor tram created in the Adams software.

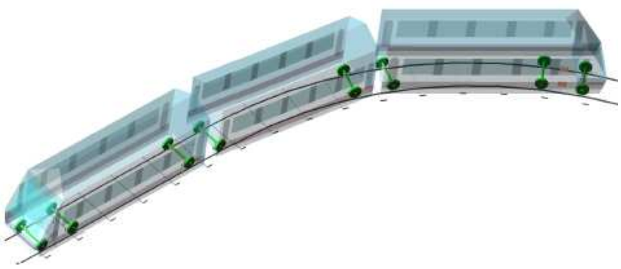

Fig. 4 Calculation model of a tram in Adams software

Nowadays, the simulations are an inseparable part of the development and research in the field of railway vehicles.

The wheel-rail joint plays an important role in the vehicle running behaviour. Thus, a mathematical model of wheel-rail contact is one of the most important and also the most complex elements in the MBS simulation software. The software enabled using of only a very simplified linear model with one point contact only in the past. Today, the simulation software contains a general nonlinear multipoint contact model. The multipoint contact between wheel and rail occurs when the vehicle is running in a curve of a small radius. Thus, such a complex model of a wheel-rail contact enables very detailed analysis of a running behaviour of tramcars even in extreme conditions, such as a vehicle run in a curve of a very small radius. Real wheel and rail profiles are considered in the calculation models – Fig. 5 shows an example of a wheel-rail contact of a tram running in a straight track (up) and in a curve of a very small radius (down), with a contact point visualisation. In Fig. 6 the two-point wheel-rail contact in a curve is clearly to be seen (a grooved rail is considered).

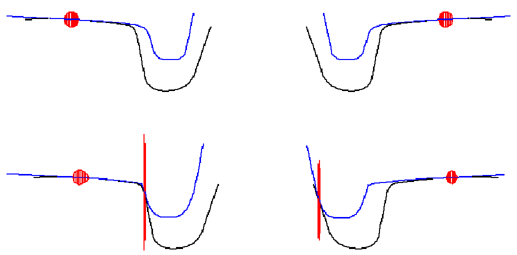

Fig. 5 Wheel-rail contact in straight track (up) and in curve (down)

With the calculation model of a tram (see Fig. 5) simulations were performed in order to compare a running behaviour of the vehicle with rigid wheel sets and independently rotating wheels. Two basic calculation cases were considered: run in a straight track and negotiation of curves of several radii.

The wheels of a rigid wheel set are forced to rotate with the same angular velocity. When the wheel set is laterally shifted in a straight track, the radii of rolling circles of the left and right wheel are different (a conical wheel profile is considered). This results in the occurrence of longitudinal slips in the wheel-rail contacts, and therefore also a pair of longitudinal slip forces. The slip forces create torque acting on the wheel set that returns the laterally shifted wheel set back to the centre of the track. Hence, the wheel set is naturally centred in a track (see Fig. 6).

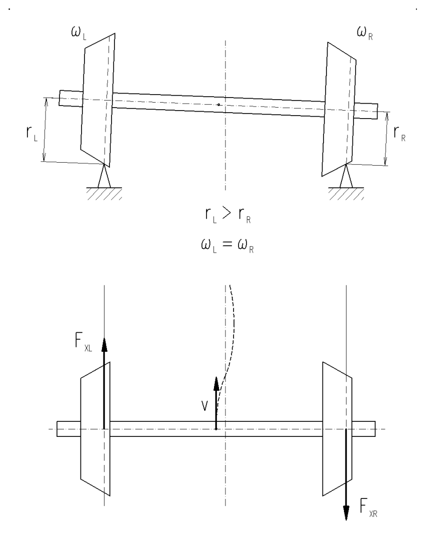

Fig. 6 Wheel set laterally shifted in a track

Independently rotating wheels are not connected in a torsion way to each other. Thus, they can rotate independently with different angular velocity. When the wheels are laterally shifted in a track, no longitudinal slip forces are generated. Hence, no forces pushing the wheels back to the central position are acting on the wheels.

Behaviour of the vehicle running in a track with irregularities show results of performed simulations shown in Fig. 7. The figure shows a dependency of lateral displacement of a wheel set (blue line) and independently rotating wheels (red line) on a travelled distance. The irregularities are on a track section from 100 to 800 m. It is obvious that independently rotating wheels move laterally with a higher amplitudes while a wheel set is forced to run in a central position in a track. The significant lateral movements are undesirable because they are associated with a higher wheel and rail profile wear. The graph also shows that after exiting the irregularities the wheel set moves to the centre of a track while the independently rotating wheels remain running laterally shifted.

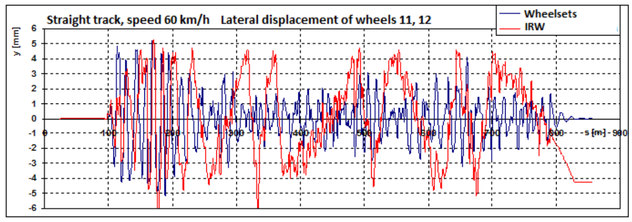

Fig. 7 Lateral wheels displacement during vehicle run in a straight track with irregularities

When a vehicle with wheel sets is running in a curve, generally three different situations may occur: 1) the wheels roll without longitudinal slips, 2) longitudinal slip force acts on the outer wheel in the curve in the direction of longitudinal movement of the wheel set, on the inner wheel in the opposite direction, 3) longitudinal slip force acts on the outer wheel in the curve against the direction of longitudinal movement of the wheel set, on the inner wheel in the opposite direction. Which one of these three situations occurs depends on the curve radius, lateral shift of the wheel set in the track, wheel rolling radii and their difference. Which one of these three situations occurs has got an influence on the size of the forces acting in contacts between wheels and rails and also on the wheel and rail profile wear. The wheel set in a curve is shown in Fig. 8.

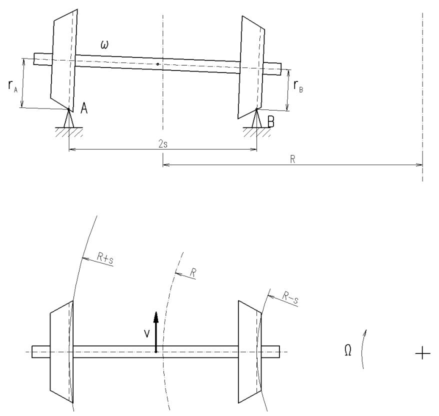

Fig. 9 Wheel set in a curve

In a case of independently rotating wheels in a curve, there are no longitudinal slip forces acting in the wheel rail contacts that would influence the wheel and rail profile wear.

Three bogie configurations were considered in the calculations: 1) a bogie with two wheel sets, 2) a bogie with two pairs of independently rotating wheels, 3) a bogie with one wheel set (in front – the first in the direction of travel) and a pair of independently rotating wheels. The results of calculations show that the lowest wheel and rail profile wear occurs for these configurations: a bogie with two pairs of independently rotating wheels in a curve of a very small radius; a bogie with one wheel set and a pair of independently rotating wheels in a curve of a large radius. Fig. 9 shows an example of calculation results – profile wear index for the three configurations of a bogie passing a curve of a very small radius.

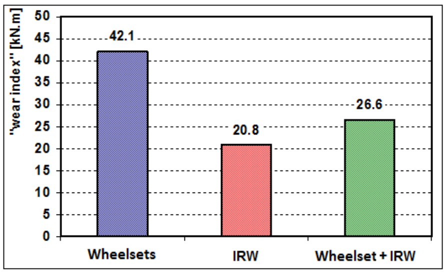

Fig. 9 Profile wear index for the three configurations of a bogie passing a curve of a very small radius

The results of the calculations can be used for designing algorithms for controlling an individual drive of independently rotating wheels. The wheel drive is currently being implemented into the calculation model and will be further developed and optimized. The results will be verified by experiments with the narrow gauge experimental vehicle.

IV. Mechanical construction of THE experimental vehicle

The vehicle is designed as a narrow gauge of 600mm. Use of this gauge allows to reduce significantly procurement costs, while offering the possibility to use as a test track Mladějov industrial railway, which is not in a regular week-long operation, moreover, this track has also a very complicated directional and vertical alignments, that are desirable for the experiments.

Further construction of the experimental vehicle has been subordinated closer to the tram-type 15T, or rather to one of its bogies. Therefore, the selected three-axle design, where the main element is a rotating bogie, where four wheels are connected by flexible couplings with four traction motors was assumed. Traction motors with the wheels are suspended from the bogie frame by conrods equipped with strain gauge sensors of operating forces - this solution will enable to measure the impact of control algorithms, the forces that act on the wheel when driving in a straight line and arc. Said wheel chassis is bound under the main frame, which is partly carried by non powered third axle, realized by standard solid wheel set.

On the main frame there is positioned first electrical switchboard, where all electrical equipment of the vehicle is located except traction motors and batteries hanging below the main frame near the third axle. . It is located on the main frame longitudinal table and after the longitudinal sides of the bench for operators. The entire vehicle is then covered with lightweight metal roof - see Fig. 10.

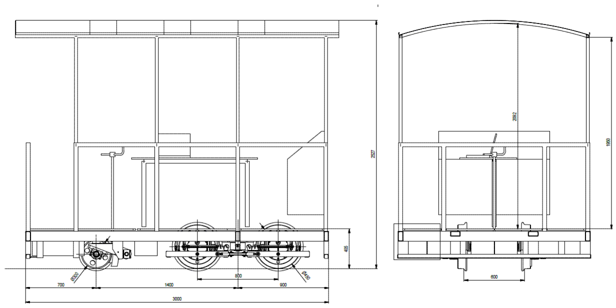

Fig. 10 Mechanical concept of experimental vehicle

The vehicle is equipped with two independent braking systems. Service brake is electrodynamic regenerative brake. Parking brake and emergency brake are hand screw, which is used for third common axle.

V. Electrical equipemenet THE of experimental vehicle

Because there is no trolley line in Mladějov industrial railway, the vehicle is built as a battery-equipped. With regards to traction drive and the estimated consumption of energy the voltage traction battery 96 V = was chosen. This battery is composed of 8 traction lead-acid batteries of the expected capacity of 150Ah@C5.

The wiring diagram is shown in Fig. 11. TBAT - traction battery is connected to the main breaker Q. It provides both safe disconnection of all electrical equipment from the vehicle battery and also serves as a emergency switch in case of an accident. As the main circuit breaker it is mounted fuse disconnector F main, staffed with 2x125A/aM fuses, followed by a DC bus to which other circuits are connected. First of all, it is through the circuit breaker FA CH (16A/C) connected traction battery charger the used type is AXIstand 96-25 from the firm AXIMA, which is a CPU-controlled fully automatic charger. Power supply of the charger is realized from the normal network 3x400 V ~ / 50 Hz.

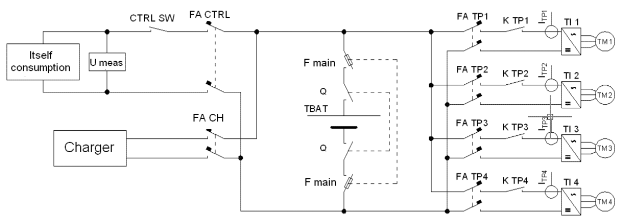

Fig. 11 Simplified diagram of the power circuits of the traction electrical equipment

Furthermore, on the DC bus the circuit of the self consumption of the vehicle is connected through a circuit breaker FA CTRL (8A/C) . In the said circuit breaker LC filter is connected together with DC-DC converters providing power supply of non-traction circuits. Through a special circuit breaker it is also connected the DC/AC inverter 96 V = / 230 V ~ 50 Hz as a power supply for computers and other devices necessary to ensure test runs.

Finally, the DC bus is connected through a circuit breakers FA TP1 ÷ 4 (25A/C) to four traction drives. These are implemented as voltage IGBT inverters. The input capacitors are therefore loaded by auxiliary relays, which are bridged after charging by contactors K 1 ÷ 4. Above the contactors there are then placed current sensors ITP 1 ÷ 4. The inverters are build by common modules from the firm. Semikron, type SK 75 GD 066 T. These modules are again over current sensors connected to traction motors type AKM 74P with integrated position sensors.

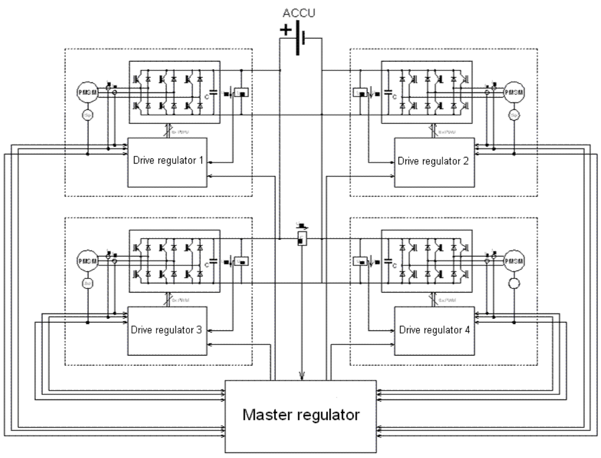

Fig. 12 Simplified diagram of the vehicle control system

Management at the level of traction drives is realized through four two-desk controllers Škoda, that evaluate the voltage and current waveforms together with the positions of the traction motor rotors and calculate individual power-switching of transistors. Connection between regulators and transistors is realized by a compact exciter Semikron SKHI 61st.

As a master controller it is used a modular control system Compact RIO from the firm National Instruments. This system provides due to its modularity imposed requirements, but it is also robust enough for use on rolling stock. Its other advantage is its programming in LabView graphical language, resulting in very efficient and intuitive creation of control algorithms including their easy modification. This system will be also used to collect data during the test runs. The structure of the vehicle control system is shown in Fig. 12.

VI. Conclusion

Currently it is done the mechanical part of the experimental vehicle and traction inverters are developed . During the year 2012, it should be the completed the experimental vehicle , so in the following year the driving tests and self-optimizing control algorithms could be done. In 2014 the results of the research should be applied to real trams. We believe that this research project will help to improve the operational characteristics of the mentioned tram as well as to fully exploit the new opportunities that this unconventional method of propulsion offers.

For more information about the simulations and experimental vehicle see [3].

VII. Acknowledgment

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