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DEVELOPMENT OF METHODS FOR ACQUIRING AND TRANSFERING MEASUREMENT DATA IN TESTING THE ELECTRIC LOCOMOTIVES

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Abstract. The paper describes procedures and methods upon which a system has been developed for testing the running behavior of new or reconstructed electric locomotives prior to release them into regular service. Special attention has been paid to precise measurement of traction currents and voltages, as well as non-electrical quantities, such as torque, longitudinal force exerted at the wheel rim, angular and linear velocity, which vary in a wide range. In addition to choosing appropriate sensors and measuring transducers, specific interface circuits were designed and manufactured, and a laboratory model for measuring electrical and non-electrical quantities of traction electric motors was developed and realised. Based on the experience and the results obtained from the laboratory model, a computerised data acquisition system for testing the electric locomotives in the field was designed from such a computerised systems as application program for simultaneous multichannel measurement of mechanical and electrical quantities, and for off-line processing of measurement results. The systems were tested during the operation on measurement and analysis of tractive capabilities, quality of anti slip regulation system, and energy consumption of a modernized locomotive.

Keywords: electric locomotive, measuring system, LabView, telemetries, angular velocity, axle torque, slip control.

1. Introduction

A recognised way of cost effective renewal of the locomotive fleet is associated with modernisation of electric locomotives. In this way, lowering the maintenance costs and increasing the locomotive function reliability in the long run is achieved. Such modernisations have been carried out in the majority of Balkan countries: Romania, Bosnia and Herzegovina, Croatia and Bulgaria in the past decade. Some series of the electric locomotives were modernised in greater numbers. The vital power converter sub-systems and some auxiliary sub-systems of these locomotives were replaced, which required revision of the original drive passport of the locomotive.

Testing the traction capabilities of an electric locomotive includes measurements of a series of electrical and mechanical quantities (IEC 61133:2003; Kostic *et al.* 2007; Kawamura *et al.* 2004; Kieβling 2001). The required electrical quantities include measurements in the power transformer primary circuit, traction drive circuit, and auxiliary circuits. The tractive force and velocity are the main mechanical properties. In addition to using these quantities to evaluate the traction capabilities of an electric locomotive, they can also be used to evaluate the adhesive potential and effectiveness of the slip control applied.

Major goals of the research presented in this paper were:

- development of methods for measuring the basic electrical quantities of the locomotive;
- development of methods for measuring the basic mechanical quantities of the locomotive;
- design and realisation of the computer based system for acquisition, processing and application of measurement data.

Based on the carried out analyses and the simulation, a laboratory model was first designed and realised, following a prototype of the system for simultaneous multichannel measurement, transfer, and acquisition of mechanical and electrical quantities relevant for evaluation of traction characteristics of an electric locomotive in service.

The proposed measurement methods were tested in laboratory conditions, on a laboratory model. After successful preparation, complex tests were carried out in the field of a modernised locomotive belonging to Serbian Railways.

The paper is divided into chapters. The principles of measuring the basic electric quantities in the primary circuit of the main power transformer and in the traction drive circuits are described in Chapter 2. Further on, Chapter 3 contains the analysis of measurements for the basic physical quantities of the locomotive. The description and architecture of the novel measurement system is given in Chapter 4. Then, the organisation is analysed in Chapter 5, and a procedure of realisation of the measurement system software support is given. The selected results are presented in Chapter 6, followed by the final chapter with conclusions.

2. The Measurement of the Main Electrical Quantities

In order to evaluate traction and service characteristics of a modernised electric locomotive it is necessary to carry out a series of measurements of electrical and physical characteristics during operation (IEC 61133:2003). This requires measuring the following electrical quantities:

- currents and voltages in the main transformer primary circuit;
- currents and voltages in power traction circuits.

Measuring the current and voltage in the main power transformer primary circuit is carried out in order to determine the degree of distortion of these quantities in the contact line, and determine the mean value of the power that the electric locomotive takes from the contact line (BS EN 50463:2007). To design the elements of the measuring system it is necessary to estimate accurately the harmonic content of the waveforms of the current and voltage, possible transient occurrences, and ranges of changes of these quantities.

Distortion of the current in the high-voltage input circuit occurs for several reasons. The degree of distortion mainly depends on the load of the drive motors, and a serial inductance on the DC link, commutation of the elements of the power rectifier and the control angle of triggering, as well as the inductance on the high-voltage side of the power supply circuit.

In the cutting edge case, which would be a completely smoothed current on the DC side of the power traction circuit, instant commutation, and distortion free supply voltage, the current input has a rectangular waveform, and can be represented by the following Fourier series:

$$i(t) = \sum_{n=2k+1} \frac{4I_d}{\pi n} \sin\left(n\frac{\pi-\alpha}{2}\right)\cos\left(100n\pi t - n\frac{\alpha+\pi}{2}\right), \tag{1}$$

where: α ($0 \le \alpha \le \pi$) denotes the control angle of the triggering of the power switching elements.

Alternating voltage of the contact line on the electric locomotive pantograph has a waveform that departs from the sinusoidal one. In the simplest case, when the section of the contact line is modeled by the chain of RL concentrated parameters in individual sections and electrical traction substation as an ideal source of alternating voltage, the voltage on the pantograph is:

$$u(t) = \left(U_m \sin(100\pi t) - \sum_k L_k \frac{di_{1k}}{dt}\right) - \sum_k L_k \frac{di_{hk}}{dt}, \tag{2}$$

where: U_m is maximum voltage of the substation transformer secondary circuit; L_k is inductance of the k-th section; i_{1k} is immediate value of the fundamental harmonic of the current in the k-th section; i_{hk} is immediate value of the distortion current in the k-th section.

Basic elements of the system for measuring the current in the primary high-voltage circuit are:

- current transformer with secondary measurement load;
- voltage measuring transformer with secondary measurement load.

Choosing measuring transformers is subject to IEC 60044 standard, based on a number of parameters, including harmonic content, peak values, level of isolation, ambient temperatures, characteristic impedances of the secondary circuit, etc.

Determining the active power and distortion factor of the current and voltage is carried out in three steps:

1. simultaneous sampling of current and voltage. Sampling rate is highly dependent of the harmonic content (1), (2) and transient disturbances;
2. multiplication of the corresponding current and voltage values;
3. averaging of the results in a predetermined time interval.

For active power calculation, instead of the classical formula valid for sinusoidal voltage/current waveforms, the following definition formula is used:

$$P = \frac{1}{T}\int_0^T i(t)\cdot u(t)\cdot dt. \tag{3}$$

Calculation of power is a post-process operation, so during the measurement, great attention should be paid to precise and simultaneous measuring of voltage and current, in order to keep the phase error of non-simultaneous measurement below 5'.

The basic elements that determine the conversion quality of power and its impact on the primary system of supply are (Mohan *et al.* 1995):

- voltage and current distortion factors;
- power factor.

Voltage and current distortion factors are given by the following expressions:

$$THD_i = \left[\left(\frac{I_{rms}}{I_1}\right)^2 - 1\right]^{0.5}; \tag{4}$$

$$THD_u = \left[\left(\frac{U_{rms}}{U_1}\right)^2 - 1\right]^{0.5}, \tag{5}$$

where: I_{rms} and U_{rms} are root mean square values for current and voltage at the input of the transformer, while I_1 and U_1 are the root mean square values of the fundamental harmonic of these quantities.

The power factor is given by the following expression:

$$PF = \frac{P}{U_{rms} I_{rms}} . \tag{6}$$

Distortion and power factors are readily calculated by applying appropriate software tools that contain program modules for FFT analysis.

In order to determine the traction and service characteristics of the locomotive it is necessary to measure currents and voltages in the traction circuits too. Currents and voltages in the traction circuit, after conversion, have a waveform that can be represented as a sum of a DC component and an AC component with a fundamental frequency of 100 Hz. In order to obtain the corresponding values of torque and force it is necessary to measure simultaneously rotor and stator currents and voltages of the traction motors. These quantities can be used to assess the torques of each traction motor, and the power transmitted by each motor.

When choosing measurement transducers it is necessary to know not only the ranges of the measured currents and voltages, but care must also be taken that the transducers could meet a series of other conditions that are prerequisites for safe measuring and obtaining of precise measurement results. We will mention a few most important requests: isolation of the measured signal from the measurement location in the load current circuit, insensitivity to external interferences, linear dependence, fast response time, and broad bandwidth.

3. The Measurement of the Torque, Angular Velocity, Acceleration, Power and Tractive Force and Analysis of Slip Control

Torsion occurs when any shaft is subjected to a torque. In Fig. 1 one such shaft of length L and radius r are presented, whose one end is fixed, and the other is acted upon by a torque T, formed by a pair of forces F–F.

The action of torque T produces torsion of the shaft by angle φ. Due to the torsion of the shaft, a line segment AB, whose length is l, is transformed into line segment AB' of length $l+\Delta l$. The relative change of the length of AB is given by the following expression:

$$\frac{\Delta l}{l} = \frac{r\varphi}{L} \sin\alpha \cos\alpha . \tag{7}$$

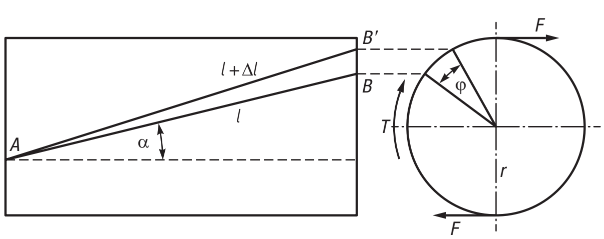

Fig. 1. Deformation of the shaft acted upon by a torque

On the other hand, it is known from the elasticity theory that the angle of torsion of a cylindrical shaft of length L and radius r acted upon by a torque T is given by the following expression:

$$\varphi = \frac{2TL}{\pi E_s r^4} , \tag{8}$$

where: E_s denotes the shear modulus of the shaft material.

Equations (7) and (8) yield the relative change of length of AB under the action of torque T:

$$\frac{\Delta l}{l} = \frac{T}{\pi E_s r^3} \sin 2\alpha . \tag{9}$$

From expression (9) it can be concluded that the relative deformation of the shaft is the largest on the surface of the shaft at the directions of angles ±45° with respect to the shaft axis, because then $\sin 2\alpha = \pm 1$.

Given that the relative change in resistance of the strain gauge is proportional to the relative elongation of the material to which it is attached, i.e.:

$$\frac{\Delta R}{R} = k \frac{\Delta l}{l} , \tag{10}$$

where: k denotes the sensitivity of the strain gauge, the largest relative change of the strain gauge resistance, and at the same time the highest sensitivity of the measurement, will be achieved if the strain gauges are placed at angles ±45° with respect to the axis of the shaft. Having in mind that in the direction of +45° elongation takes place and in the direction of –45° compression of the shaft material occurs, the gauges placed along those directions are connected with the adjacent arms of the measuring bridge (Maute, Stöckle 1986; Hoffman 1989).

Angular velocity ω of the drive axle is a parameter used for determining several important traction characteristics of a locomotive. If angular velocity is measured, it is possible to determine the values of angular acceleration by applying one of the methods of differentiating discrete signals of the angular velocity, and filtering the imminent created noise.

If the torque on the drive axle and its angular velocity are known, then it is easy to determine the mechanical power transferred from the motor to the drive axle:

$$P = T\omega . \tag{11}$$

One of the most important service characteristics of a traction vehicle is the force that drives the vehicle, it is so-called, the tractive force. Torque T and angular velocity ω are related to the tractive force F_{tr}, vehicle speed v and tractive resistances $\sum F_{res}$ through the appropriate equations. The static one is when the vehicle speed v is constant, and the dynamic one – when the vehicle speed is not constant, i.e. there is acceleration or deceleration of the vehicle.

When the vehicle moves at a constant speed, the tractive force is equal to the sum of all tractive resistances, so the following holds:

$$F_{tr} = \sum F_{res} = \frac{2}{D} T , \tag{12}$$

where: D denotes the diameter of the wheel of the traction vehicle.

Equation (12) shows that the tractive force is directly proportional to the torque on the drive axle when the vehicle moves at a constant speed.

When the vehicle speed is not constant, i.e. there is acceleration or deceleration, then the equation of dynamic equilibrium holds:

$$J\frac{d\omega}{dt} = T - \frac{D}{2}F_{tr}\,, \tag{13}$$

where: J denotes the total moment of inertia of the axis, drive wheels, and all other parts moving at angular velocity ω.

Equation (13) shows that the tractive force of the vehicle moving with acceleration or deceleration can be determined if the torque and angular velocity, i.e. angular acceleration, are known.

To achieve good tractive characteristics of the locomotive in various service conditions it is of prime importance that the locomotive has an efficient slip control system (Watanabe *et al.* 1997; Kovudhikulrungsri *et al.* 2003; Kim *et al.* 1999). The tractive force in contact between the wheel and the track is realised due to the adhesion. When, under the action of the load torque, the wheel starts to rotate, then at the point of contact between the wheel and the track, both the wheel and the track deform. If the tractive torque T is too large, slipping occurs. In order to re-establish adhesion, it is necessary to lower the torque to the value sufficient to compensate for the traction resistances.

The consequence of slipping is that the velocity of the vehicle v differs from that of the peripheral velocity of the wheel $\omega D/2$. The difference between these velocities is called pseudo-slipping:

$$v_s = \frac{D}{2}\omega - v\,. \tag{14}$$

Pseudo-slipping is zero when the tractive force is equal to zero, it is above zero when tractive force is above zero, and below zero when tractive force is negative, so called breaking mode. In practice, pseudo-slipping amounts to about 1%.

To analyse slipping, we will use the earlier given equation of torque equilibrium (13).

If within the range of adhesion the angular velocity ω increases, the rate of pseudo-slipping v_s increases, which, on the other hand, causes an increase in tractive force F_{tr}. However, the equation of torque equilibrium shows that if the tractive force increases, then the change in the angular velocity decreases, which, consequently, returns the velocity to the value prior to the change.

Within the range of slipping, when the angular velocity increases, the tractive force decreases, which would lead to further increase in the angular velocity, because $J\,d\omega/dt > 0$. If this trend continued, a series of adverse effects would ensue. Thus, it is necessary to block the occurrence of real slipping at its start and ensure re-establishing of adhesion between the wheels and tracks.

4. Elements and Architecture of the Measuring System

A computer based measuring-acquisition system was developed and realised for testing service characteristics of electric locomotives. The system has a centralised structure, and is organised around an industrial PC operating under the Windows OS. For acquisition of analogue, digital, and time signals from sensors and transducers installed on the locomotive, a multipurpose PCI compatible acquisition card and specially designed interface circuits are used. A block diagram of the realised measuring system is presented in Fig. 2.

A current transformer 300/5A accuracy class 0.2 with a secondary load of 15 VA and cos φ = 0.8 is used for measuring the current in the primary high-voltage

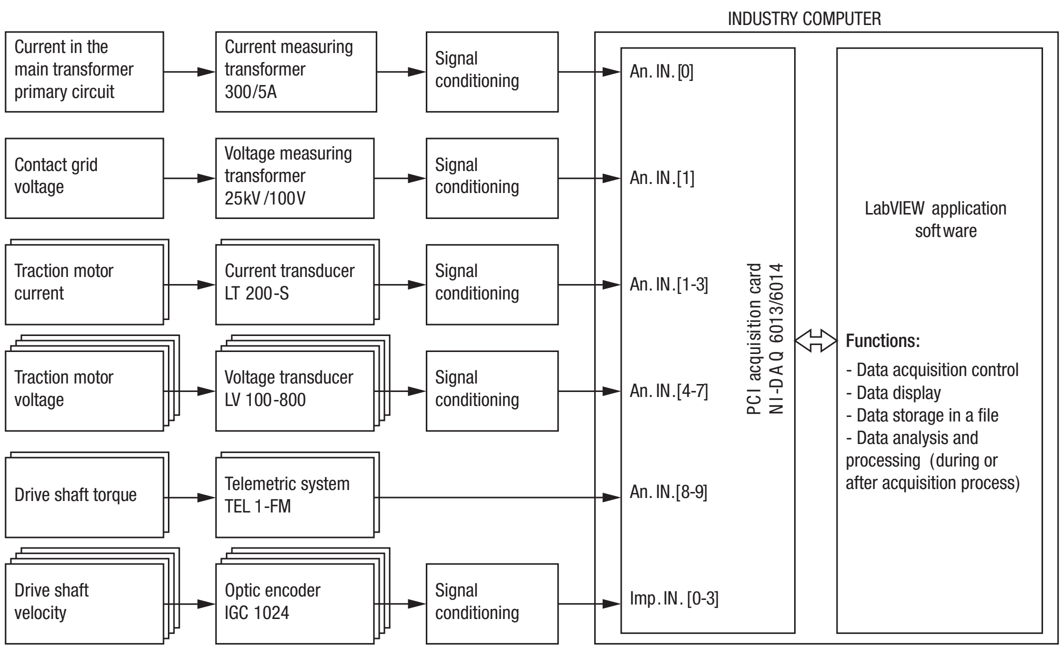

Fig. 2. Block diagram of the centralised computer based measuring system

circuit of the main transformer. By using such current transformers precise measurement of current is ensured in the range of 15 A to 300 A. For measuring voltages of the contact line in the range 19 kV to 27.5 kV an inductive voltage measuring transformer with a secondary load of 25 VA accuracy class 0.5 is used.

An isolated current transducer is used for measuring currents in the load circuit, by which current can be measured in the range 0 to ±3000 A with an accuracy of ±0.5%. The conversion factor of this transducer is 1:5000. For measuring the voltage in the load circuit an isolated voltage transducer is used, by which voltages can be measured in the range 0 to ±2250 V with an accuracy of ±0.7%. The conversion factor of this transducer is 1500 V/50 mA. Voltage and current transducers placed on the electric locomotive 444-002 during the field test are shown in Fig. 3.

The problem of supplying power to the measuring bridge and electronics can be easily solved by using an appropriate battery attached to the axle. Such a solution is the simplest and the most cost effective, thus most adequate for use in cases where no continuous extended functioning of the measuring system is required. The output voltage of the measuring bridge, which is proportional to the measured torque, is amplified and converted into frequency modulated pulses. The obtained AC measuring signal is inductively transmitted to the demodulator input, fixed near to the axle. A block diagram of the telemetric system for torque and angular velocity measurement is presented in Fig. 4.

Practical realisation of the principle in non-contact torque measurement of the rotation axles require

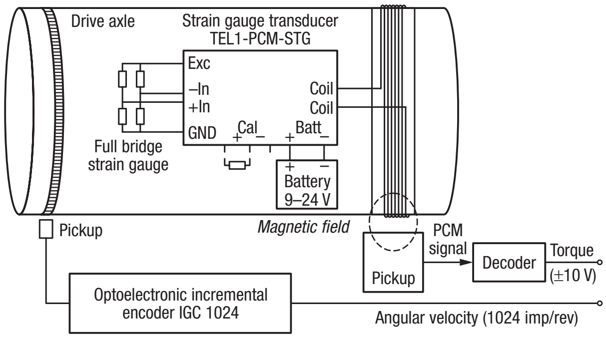

Fig. 4. Setup of elements of the telemetric system for measuring torque and angular velocity of the axle

detailed laboratory preparation. Doing this, special attention was paid to shielding against interferences and to signal processing. To avoid measurement errors that are caused by deviation of the strain gauge axes from the required directions, a premanufactured measuring bridge with strain gauges of the resistance of 350 Ω type CEA-06250US-350, by VISHAY, USA was used. For conditioning of the measured signals and telemetric transfer to the acquisition card a module TELl-PCM by KMT, Germany, was used.

Fig. 5 presents the laboratory model of the system for telemetric measurement of the velocity and torque of the drive axle.

An example of a setup measuring system elements on locomotive axle during the field test is presented in Fig. 6.

a)

b)

Fig. 3. Voltage transducer (a) and current transducer (b) in place while testing locomotive 444-002

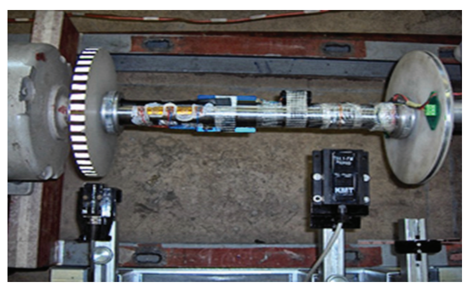

Fig. 5. Laboratory model of the system for telemetric measurement of velocity and torque

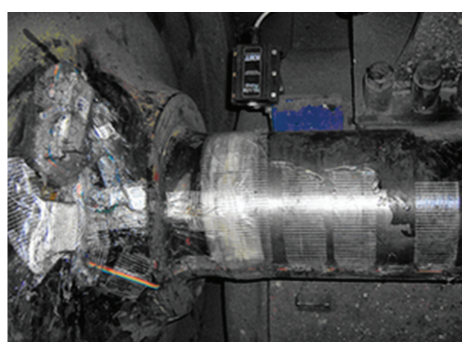

Fig. 6. Example of placing the elements of the system for torque measurement on the locomotive axle

There are several variations of inductive and optoelectronic transducers available for measuring the angular velocity (Liudvinavičius, Lingaitis 2010). The main advantages of the optoelectronic transducers over the inductive ones are that the output signal has large amplitude, which is independent on the angular velocity; they do not put extra load on the axle, and have very high resolution. For this reason, an optoelectronic incremental encoder IGC 1024 by Hubner, Germany, was used. This encoder delivers 1024 pulses per revolution, so it is possible to detect an angular displacement of 30'.

In choosing the multichannel PC compatible data acquisition (DAQ) card, special attention must be paid to the maximum obtainable sampling frequency per channel. Also, the DAQ card must be equipped with a programmable instrumentation amplifier, which allows for adjustment of voltage levels of the signals originating from different sources, in order to establish the analogue/digital conversion with full resolution.

Having in mind that the basic frequency of the AC component in the DC supply voltage is 100 Hz, and that simultaneous conversion of 10 analogue signals is handled, the DAQ card must have a sampling frequency of at least 2000 Hz. Universal acquisition cards NI-DAQ 6013 and NI-DAQ 6014 by National Instruments, USA, were used for acquisition of analogue, digital, and time signals.

5. Software Realisation

LabView program environment of National Instruments, USA, was used for providing measurement and communicational functions of the measuring-acquisition system that was realised. LabView allows for interactive development of the application program using a graphical, module structured, non-procedural programming language. Besides, visual approach to programming, integration of program routines written in classical C or Basic languages is possible.

By using LabView, an application program for multichannel simultaneous data acquisition of basic electrical and mechanical quantities of the electric locomotive was developed. Also, the realised software allows for various applications of the measured data: display on the computer monitor, transfer of data to a remote location, exchange of data with other processes, and data storage for further processing and analysis.

The realised software consists of two units: a program module for acquisition, processing and applying of the measured signals, and the second unit – a program module for post-process processing and determining of service characteristics of the traction vehicle. A block diagram of the application program is presented in Fig. 7.

Software modules for acquisition of pulsed signals obtain automatic counting from optoelectronic incremental transducer in a time interval of 100 ms. This result serves to determine the angular velocity at each of the four drive wheels of the locomotive. The software module for acquisition of analogue signals performs analogue-digital conversion of the signals with 5 voltage and 3 current transducers. In that way, the voltages and current are measured at the primary circuit of the main transformer and electromotor drive of the drive axles.

Through an appropriate instrument driver the program directly communicates with the hardware of the acquisition card NI DAQ 6013/6014 for adjusting the card parameters like sampling speed, measurement channel selection, amplification per channel, etc. For determining the service characteristics of the traction vehicle the acquired signals are processed later using library functions of LabView.

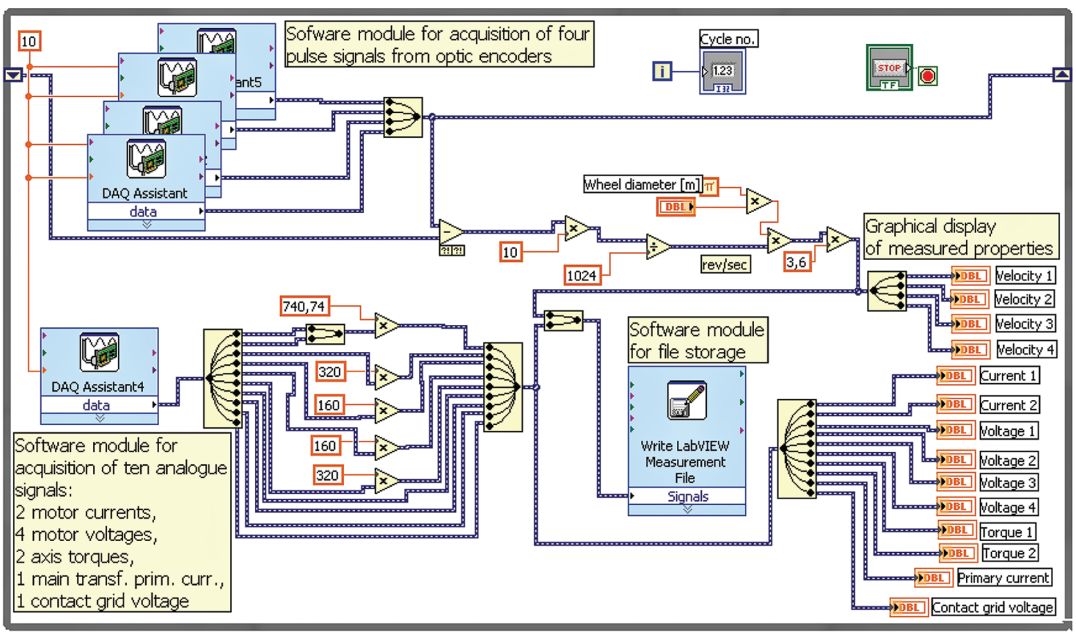

Fig. 7. Block diagram of the LabView application program for acquiring the basic electrical and physical quantities of traction vehicles

6. Results

The research and its activities which are described, enable us to develop a novel system for testing new and refurbished electric locomotives before releasing them into regular service.

The realised system was tested in field conditions, with measurement and analysis of service characteristics of a modernised electric locomotive 444-002 used by Serbian Railways.

Besides, its application in determining electrical and mechanical parameters of an electric locomotive, the realised measuring system can be used successfully in evaluating the slip control system. It should be noted that the slip control system determines the traction characteristics of the locomotive to a large extent.

The domestic electric locomotives 444-002 have a slip control system which is based on the evaluation of the longitudinal vehicle speed from data on the minimum angular velocity of the drive wheels in traction and/or maximum angular velocity of the drive wheels in the breaking mode (reference longitudinal speed). Slipping is detected by measuring the difference between the peripheral velocities of the drive wheels and reference longitudinal speed.

After detecting the slipping through sudden increase in the angular velocity (Fig. 8a) the tractive force is reduced by cutting down on the current in the electric motor group where the slipping is detected, as can be seen in Fig. 8b, where the results of measuring the torques of the drive axles and the motor currents in the starting mode are presented. In this way, slipping is prevented and adhesion between the wheels and tracks, necessary for starting the train, is achieved.

The research undertaken also included a number of investigations and actions of the slip control in the acceleration mode during maximum weight load of the locomotive. The results obtained indicate some shortcomings of the applied method of slip control, which are manifested as a lack of regulation of the tractive force upon slip detection, which can be documented by the results of these investigations.

Phenomena observed during slip control testing may lead to several adverse consequences of which we single out 'track burning' and 'rotor fly-out', which can ensue due to the abrupt increase of angular velocity caused by slipping.

7. Conclusions

1. In order to evaluate service characteristics of new electric locomotives or refurbished electric locomotives it is necessary to undertake a series of complex measurements in the field, under a range of service conditions. In the present paper, results of measurements of the main parameters of an electric locomo-

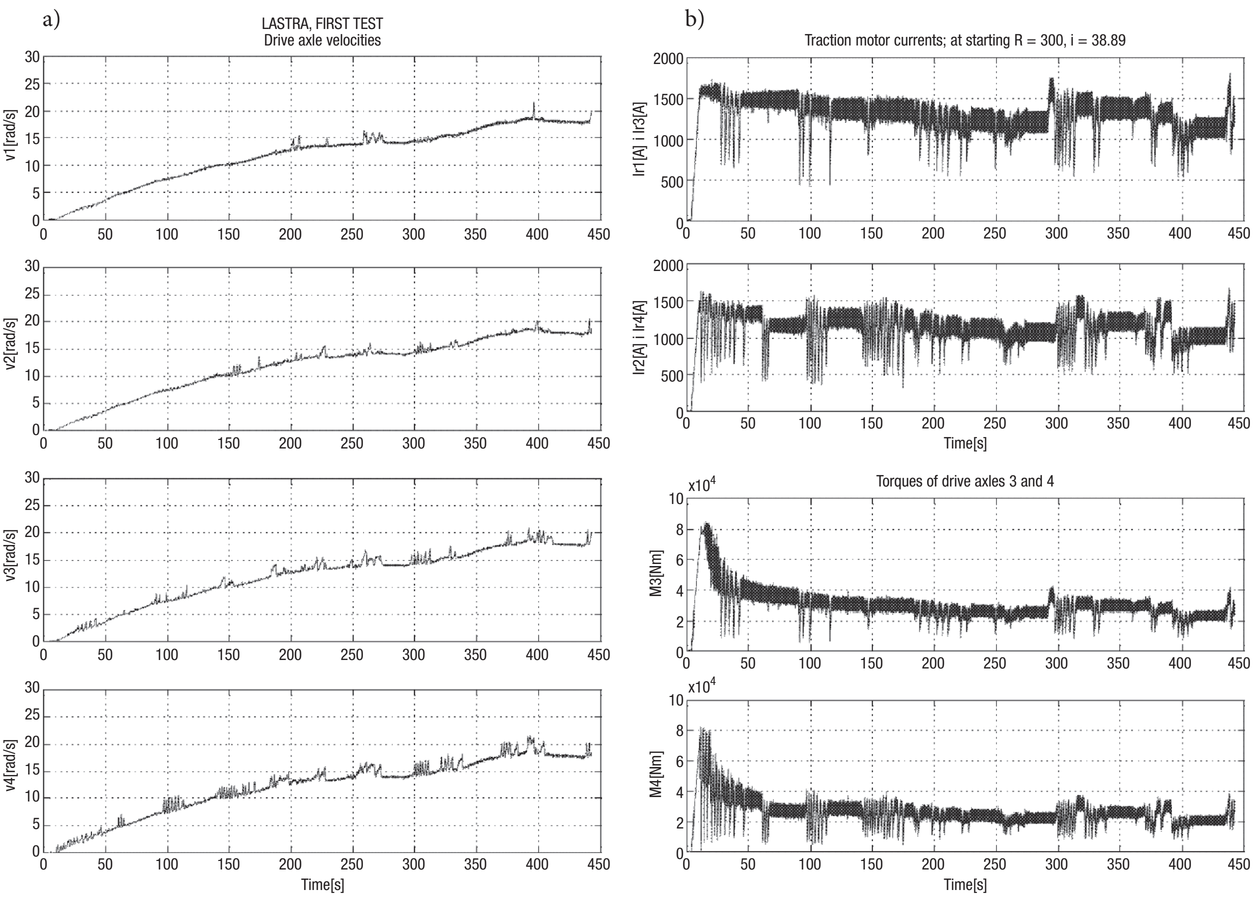

Fig. 8. Results of measuring the drive axles angular velocities on the electric locomotive 444-002, sharp jumps in velocity indicate slipping (a) and results of measuring the motor currents and torques on the axles of locomotive 444-002 (b)

tive are presented, methods of electric quantities are developed, appropriate measuring transducers chosen and available ones modified, a telemetric system developed for measurement of torque, torsion oscillations and angular velocities on the drive axles, and a novel measuring-acquisition system for testing the service characteristics of new or modernised electric traction vehicles was developed and realised.

2. Realisation of testing which laid out partly in the present paper would allow for introducing up-to-date methods and equipment in procedures of developmental, typical, and serial tests of traction vehicles. In this way, the extent and cost of traction vehicle maintenance is reduced. The presented procedures and methods can find application in other industry systems dealing with production or overhaul of generators and assemblies for traction vehicles and process industry.

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