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Simulations of electric multiple unit series 413/417 drives on the electrified tracks of "Serbian Railways"

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ABSTRACT

In the paper, the Matlab-Simulink model of simulation of operation of the ŽS 413/417 series electric multiple unit (EMU) in traction and braking mode is exposed where changes are observed: stator currents of three-phase traction motors, traction electric motor speeds and electric multiple unit, electromagnetic torque on the rotor shaft of the traction electric motor and DC bus voltage. The model allowed review of the listed parameters for: different allowed values of contact network voltage and total voltage distortion at the place of connection of the electric multiple unit to the contact network, different mechanical loads of electric multiple unit and traction electric motor and different train speeds and rotation of traction electric motors. Appropriate conclusions were made through the analysis of the simulation results obtained.

KEYWORDS

Simulations, Electric multiple unit, Serbian Railways

1. INTRODUCTION

The ŽS 413/417 series electric multiple unit (EMU) is a low-floor, four-part passenger train of "Serbian Railways" manufactured by the Swiss company Stadler. This light, fast innovative regional train (FLIRT - Fast Light Innovative Regional Train) is a specially designed electric multiple unit (EMU) of the latest generation "FLIRT 3". At the beginning of 2014, 21 ŽS series 413/417 the electric multiple units were put into service on the electric railways of "Serbian Railways", and the procurement of thirty one more is in progress, Figure 1 [1].

Figure 1: The electric multiple unit (EMU) of series ŽS 413/417

Basic technical data of the electric multiple unit (EMU) of series ŽS 413/417 are shown in Table 1 [1].

Table 1: Technical data

Track gauge	1435 mm
Max. velocity	160 km/h
Axle arrangement	Bo' 2' 2' 2' Bo'
Traction mode:	25 kV AC, 560 Hz
Maximum power on the wheel	1540 kW
Maximum starting tractive force	160 kN
Traction transformer – Main data	
Marked power	605 kVA
Maximum power per traction winding	500 kVA
Nominal voltage of traction windings	Approx. 25 kV/500 V and no load
Traction converter- Line inverter - AFE	
Input voltage	Approx. 500 VAC
Maximum input current	Approx. 1020 per AFE (2040 total)
Nominal DC-link	950 V (Under 1000 V)
Maximum output power	Approx. 525 per AFE (1050 total)
Bus capacity	85mF
Train wide AFE synchronization	6 converters - 3 EMU in multiple traction
Motor inverter - Traction three phase inverter	
Power in traction	385 kW (at wheel)
Output voltage traction	20 Hz to 120 Hz approx. from 211 V to 630V 120 Hz to 215.7 Hz approx. 675V
Output maximum current	Approx. 780 (700 Hz switching frequency)
Traction motor data	
Traction motor are three-phase asynchronous motors type	TMF 54-32-4
Continuous power	300 kW
Transmission ratio	1 : 5.9714

The traction equipment of the electric multiple unit (EMU) of the 413/417 series consists of:

- One pantograph for 25 kV AC
- One traction transformer
- Two power converters and four traction motors (2 traction motors per one power converter).
- Single-axle drive with three-phase asynchronous motors

The traction motor is installed in the motor bogie. Wheelset axle shaft, traction motor, tooth coupling and the gearbox together form an axle drive. There are two axle drives per motor bogie. The traction motor transmits the torque to the gearbox through the tooth coupling transmission ratio of 1:5.9714. The gearbox transmits the drive torque through the wheelset axle shaft to the wheels and the tracks [1]. Traction system of the train is shown in Figure 2.

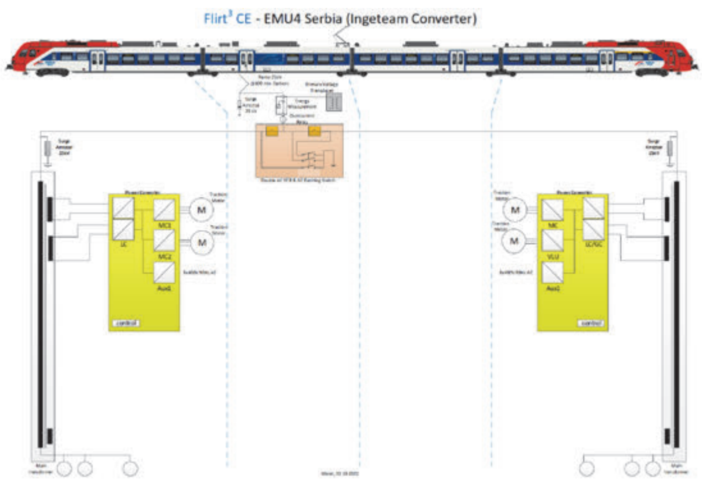

Figure 2: Principle Circuit diagram Main current of EMU

Figure 3 shows the tractive force-speed characteristics of the electric multiple unit (EMU) [1, 2].

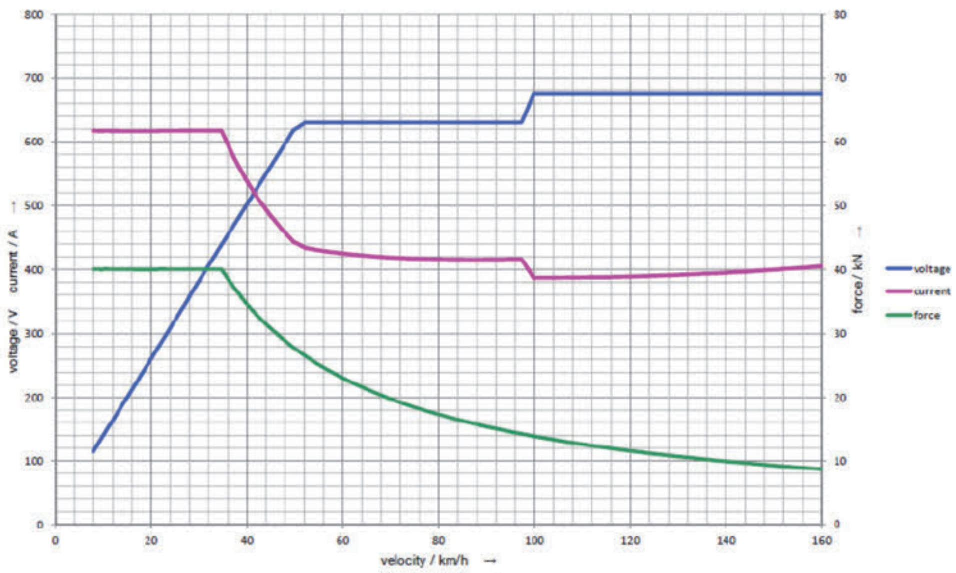

Figure 3: Traction force characteristic

Figure 4 shows the Power dependent on the line voltage of the electric multiple unit.

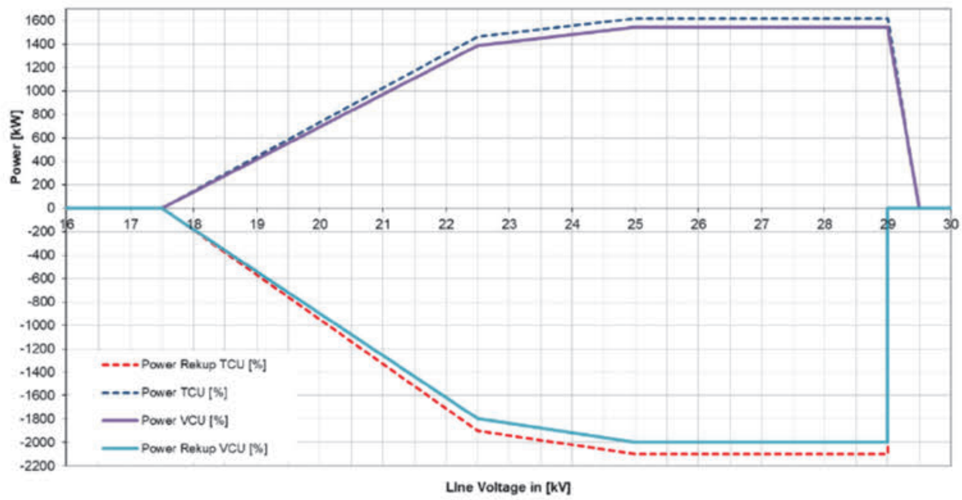

Figure 4: Power dependent on the line voltage

2. MODELING EMU IN MATLAB-SIMULINK

Modeling of EMU of series ŽS 413/417 are shown in Matlab-Simulink is shown in the Figure 5.

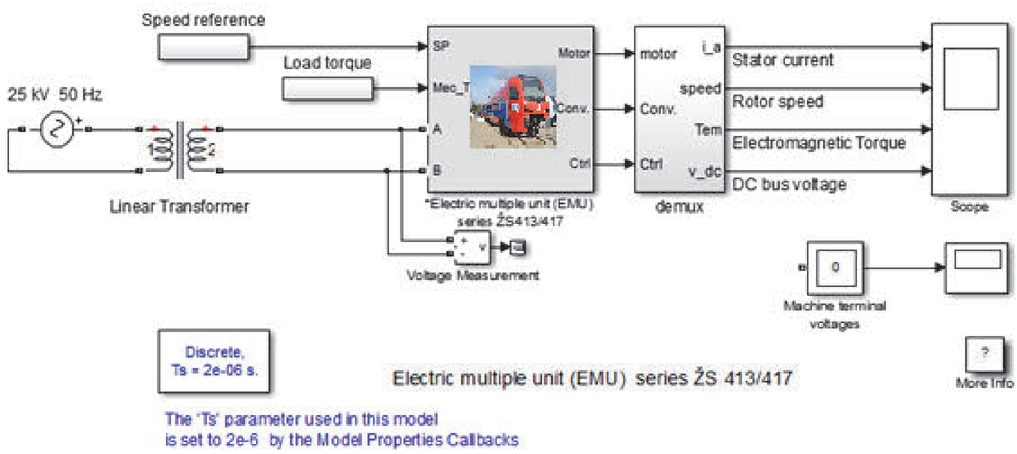

Figure 5: Simulink model of the electric multiple unit series ŽS 413/417

The high level block of electric multiple unit series ŽS 413/417 schematic shown below is built from six main blocks (Figure 6 and Figure 7). The traction transformer, the induction motor, the three-phase inverter, and the mono-phase diode rectifier models are provided with the SimPowerSystems™ library. The speed controller, the braking chopper, and the DTC controller models are specific to the drive library.

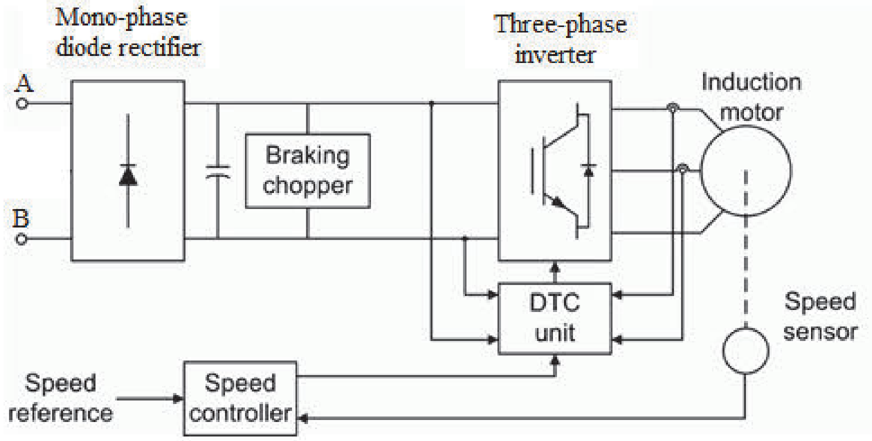

Figure 6: The high level block schematic of electric multiple unit series ŽS 413/417

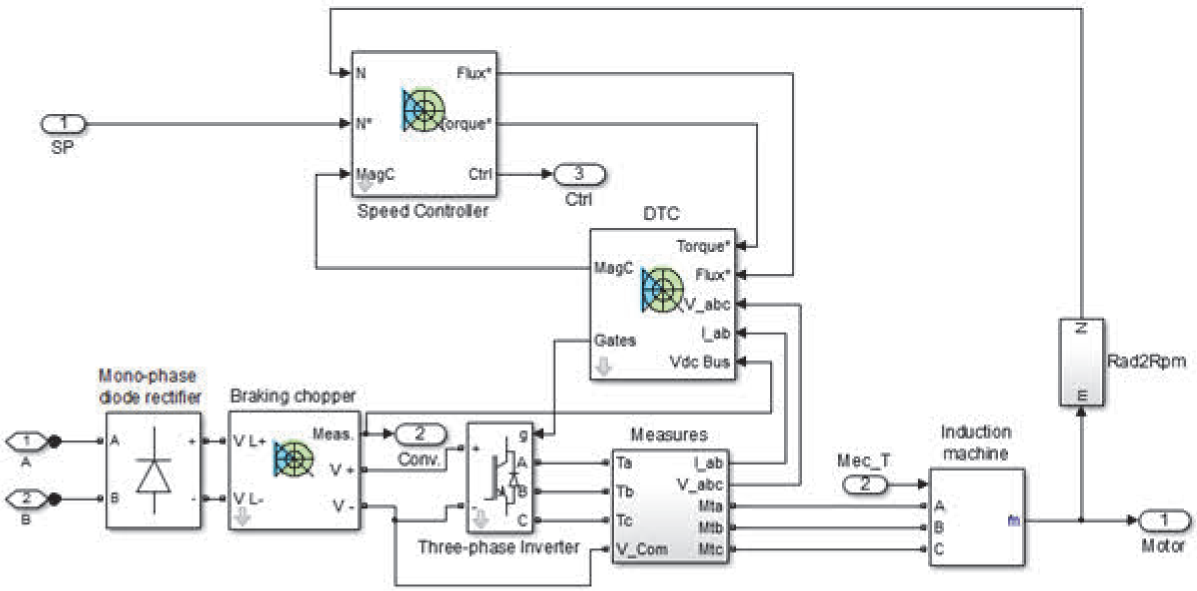

Figure 7: Simulink schematic of electric multiple unit series ŽS 413/417 built from six main blocks

2.1. Speed Controller

The speed controller is based on a PI regulator, shown below. The output of this regulator is a torque set point applied to the DTC controller block [3, 4, 5

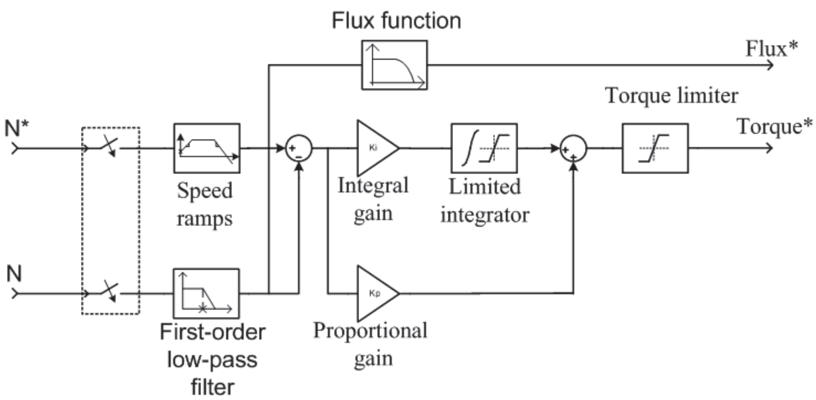

Figure 8: The high level block schematic of speed controller

Simulink model of speed controller is shown in Figure 9 [3, 4, 5].

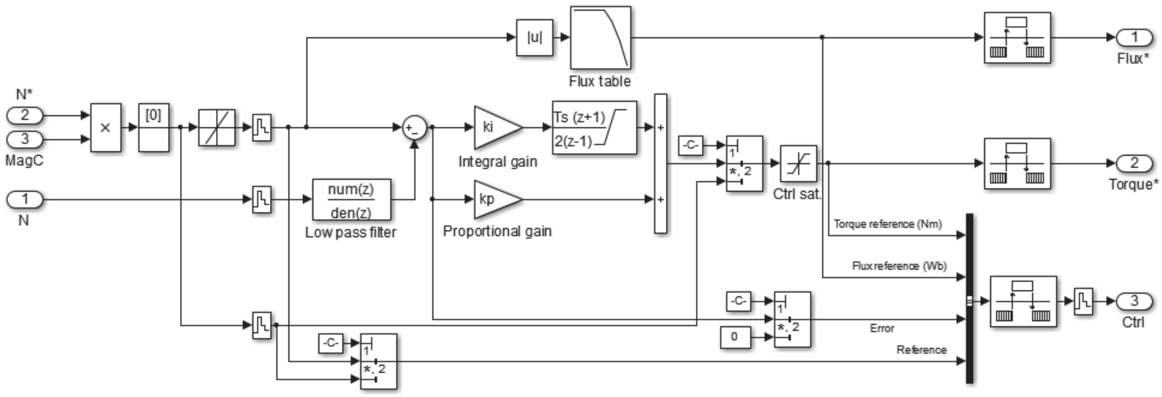

Figure 9: Simulink model of speed controller

2.2. Braking Chopper

The braking chopper block contains the DC bus capacitor and the dynamic braking chopper, which is used to absorb the energy produced by a motor deceleration. Simulink model of braking chopper is shown in the Figure 10 [3, 4, 5].

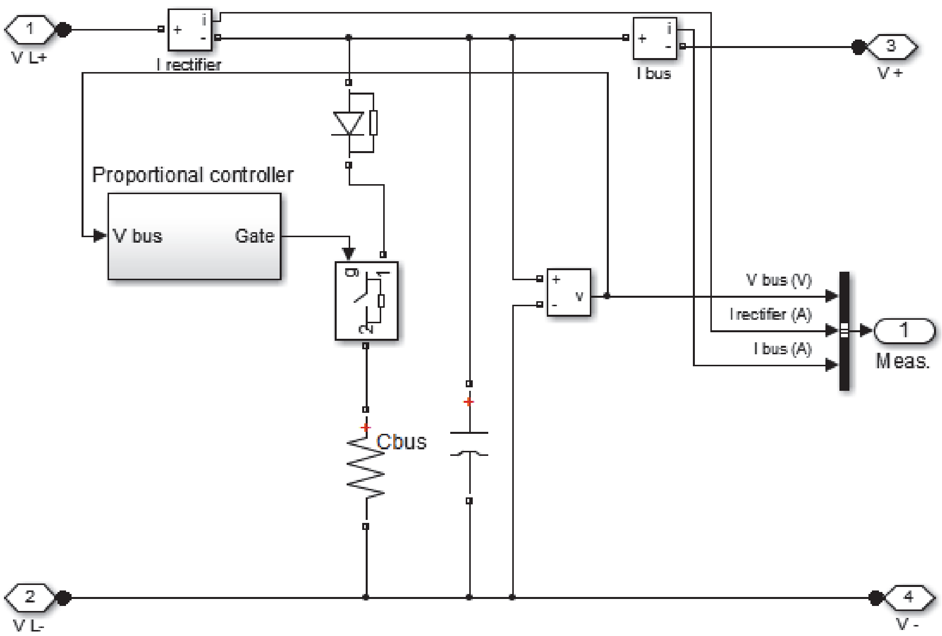

Figure 10: Simulink model of braking chopper

2.3. DTC Controller

The direct torque and flow control (DTC) controller contains five main blocks, shown in Figure 11 [3, 4, 5].

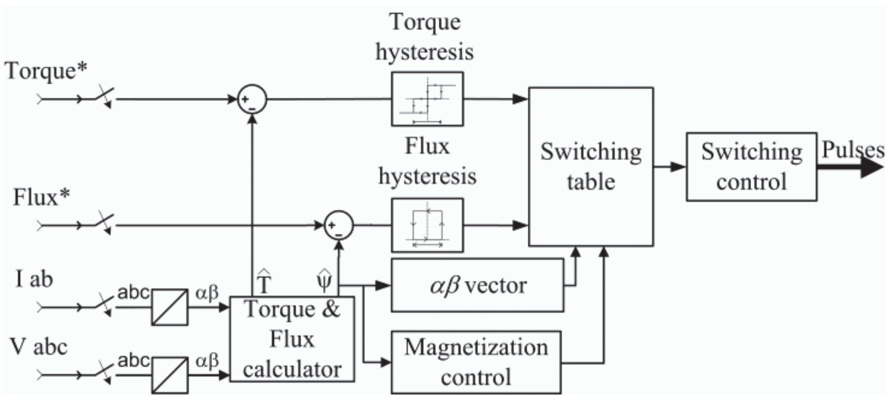

Figure 11: The direct torque and flow control (DTC) controller

The Torque & Flux calculator block is used to estimate the motor flux αβ components and the electromagnetic torque. This calculator is based on motor equation synthesis.

The αβ vector block is used to find the sector of the αβ plane in which the flux vector lies. The αβ plane is divided into six different sectors spaced by 60 degrees.

The Flux & Torque Hysteresis blocks contain a two-level hysteresis comparator for flux control and a three-level hysteresis comparator for the torque control. The description of the hysteresis comparators is available below.

The Switching table block contains two lookup tables that select a specific voltage vector in accordance with the output of the Flux & Torque Hysteresis comparators. This block also produces the initial flux in the machine.

The Switching control block is used to limit the inverter commutation frequency to a maximum value specified by the user.

Simulink model of direct torque and flux control of the drive induction motor is shown in Figure 12 [3, 4, 5].

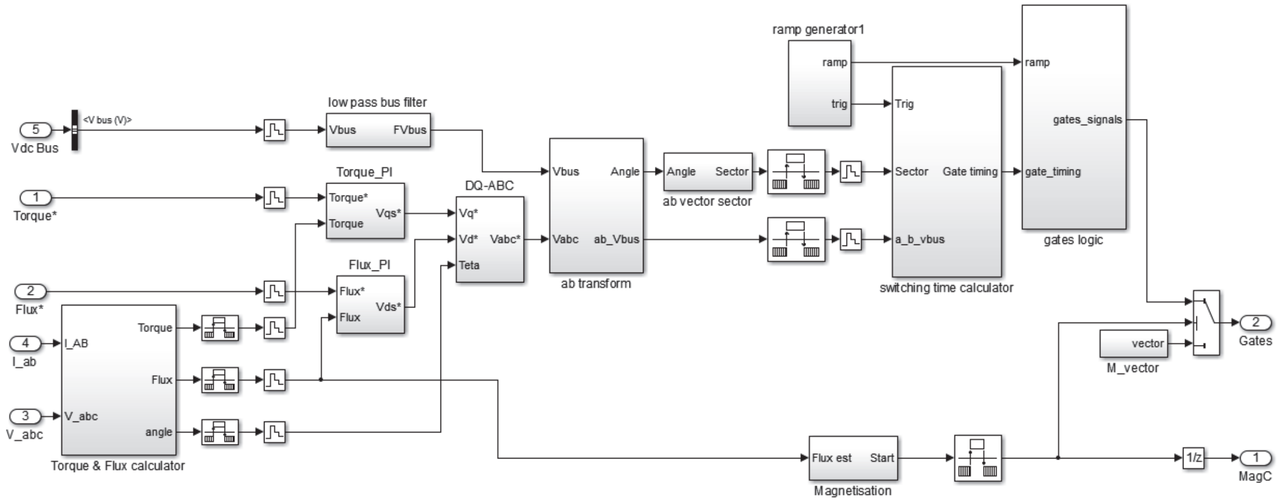

Figure 12: Simulink model of DTC (direct torque and flux control) of the drive induction motor

2.4. Measurements

In this model, the voltage of the contact network at the connection point of the EMU series ŽS 413/417 is taken as an input variable electrical quantity. This voltage can be changed within the limits of 17.5÷27.5 kV according to the provisions of EN 50163. All other parameters of the simulink model blocks are determined by the technical data of the train's devices and equipment. Electrical quantities that are measured during dynamic processes are: the stator current of the traction electric motor and the DC bus voltage converter.

The given input mechanical parameters of the model are: the desired final speed of rotation of the rotor of the traction electric motor ω_r and the resistive torque of the train movement T_m. Mechanical quantities that are measured during dynamic processes and achieving the desired rotation speed are: the reverse electromagnetic torque of the traction electric motor T_e and the change in the rotation speed of the rotor of the traction electric motor ω_r.

When calculating the reverse electromagnetic moment on the shaft of the traction electric motor T_e, the equation of the dynamic balance of the train drive train was used [6–18].

$$T_e = J\frac{d}{dt}\omega_r + F\omega_r + T_m \tag{1}$$

Wherein:

- ω_r - speed of rotation of the rotor of the electric motor,
- J - the moment of inertia of all rotating masses reduced to the rotor side of the electric motor,
- F - coefficient of viscous friction,
- T_m - resistance moments of movement reduced to the rotor side of the electric motor.

By measuring and knowing the value of the reverse electromagnetic torque of the traction electric motor T_e and the change in the rotation speed of the rotor of the traction electric motor ω_r, the traction force between the wheel and the rail F_v, i.e. the translational speed of the train *v*, is fully determined. The relationship between the rotating electromagnetic torque of the traction electric motor T_e and the traction force F_v, i.e. the rotation speed of the rotor of the traction electric motor ω_r and the translation speed of the train *v* is given by the following equations:

$$F_v = \frac{2 \cdot i \cdot \eta}{D} \cdot T_e \tag{2}$$

$$v = \frac{D}{2 \cdot i} \cdot \omega_r \tag{3}$$

Wherein:

- i - transmission ratio of the reducer (5.9714),
- η - degree of utilization of the reducer (0.94),
- D - the diameter of the EMU monobloc wheel (new/worn: 760/690mm),

In order to monitor the change in stator current, rotation speed and electromagnetic torque of the drive motor as well as DC bus voltage, a simulink measurement block was modeled as in Figure 13.

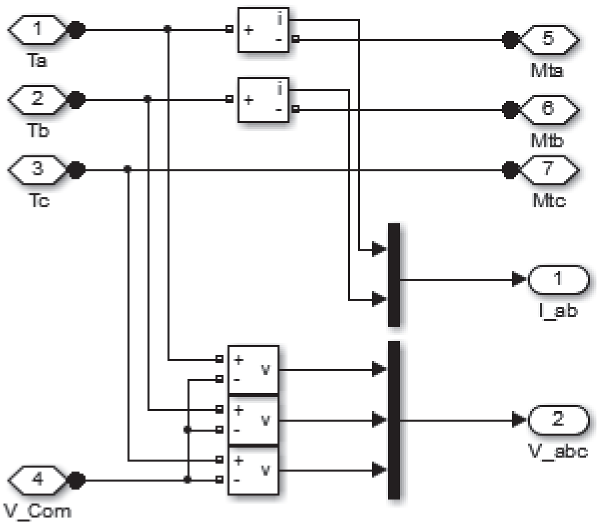

Figure 13: Simulink model of measurement

3. RESULTS OF SIMULATIONS

Assuming that the electric multiple unit (EMU):

- supplies with a stable sinusoidal voltage of 25 kV, 50 Hz,
- starts from rest at time *t*=0 s: up to the speed of the electric motor ω_r=1500 rpm (*v*=90 km/h),
- load it so that the resistance torque on the electric motor shaft is T_m=792 Nm in an interval of 0.5-1.5, and after 1.5s it is equal to T_m=-792Nm,
- starts braking from the moment *t* =1 s. and so on.

The simulation results given in Figure 14 show that the acceleration of the train up to *t*=0.5 s is achieved with a constant electromagnetic moment on the electric motor shaft of T_e=810 Nm, and when the load on the electric motor increased, the electromagnetic moment also increased to T_e=1050 Nm. The speed of the electric motor ω_r=1500 rpm (*v*=90 km/h) is reached at the moment *t*=1 when braking starts until *t*=1.75 s when the electric multiple unit stops. It is interesting to note that the speed of ω_r=1500 rpm is not reached before t=1s and if the limiters allow it even earlier. The rotating electromagnetic torque on the electric motor shaft is very small during braking in the interval from *t*=1 -1.5 s because the motor brakes due to the drag resistance of T_m=+792 Nm, and from *t*>1.5 s a negative (braking) electromagnetic is generated the moment that overcomes the inertial drag resistance of T_m=-792 Nm, bringing the train to rest. With these input parameters, the stator current of the electric motor does not exceed 1000 A, and the DC bus voltage of 800 V.

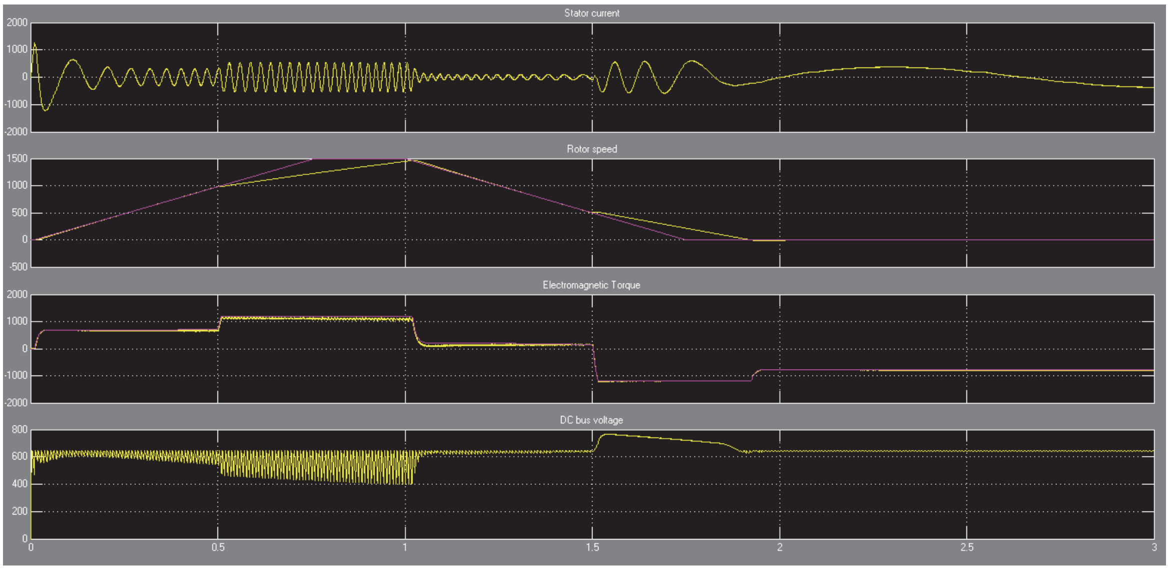

Figure 14: Changes in the stator current, rotation speed and electromagnetic moment of the electric motor and DC bus voltage of the direct current medium of the inverter EMU for ω_r =1500 rpm and T_m=±792 Nm.

If the same input parameters of the system as in the previous example are assumed, but now with a new set speed of the electric motor of ω_r =500 rpm (*v*=30 km/h), the change in the output values is shown in Figure 15.

In this case, the starting of the electric motor from rest is done with a smaller electromagnetic moment T_e=200 Nm until the moment *t*=0.5 s when the electric motor is loaded with T_e=792 Nm and increases to the value T_e=810 Nm.

The set speed of ω_r =500 rpm (*v*=30 km/h) is reached at the moment *t*=0.6 s and is maintained until the moment *t*=1 s when the start of braking is set. Braking starts with an electromagnetic torque T_e smaller than the positive resistive torque of T_m=+792 Nm and lasts until a complete stop at the moment *t*=1.5 s. For $t > 1.5$ s the electric motor remains braked due to the generation of a negative electromagnetic moment T_e that overcomes the negative resistance of T_m=-792 Nm. With these input parameters, the stator current of the electric motor does not exceed 600 A, and the DC bus voltage of 620 V.

Numerous simulations with the specified input parameters, but now with variable and permitted contact network voltage values from 19.5 to 27.5 kV and a total voltage distortion equal to or less than 8% (EN 50162) show the same or approximately the same change in output values as in Figure 14 and Figure 15.

This fact indicates a very important feature of the ŽS 413/417 series electric multiple unit, which is that the train's electric traction drive has completely eliminated the influence of the contact network voltage. Due to the mentioned fact, it can be concluded that these electric multiple unit represent a good driving railway solution.

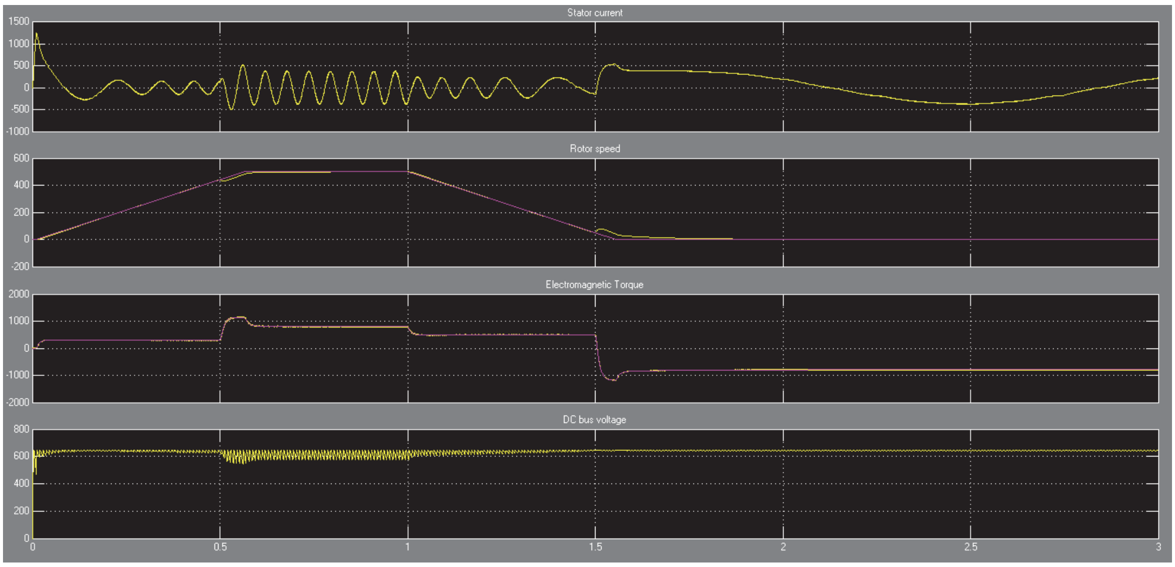

Figure 15: Changes in the stator current, rotation speed and electromagnetic moment of the electric motor and DC bus voltage of the direct current medium of the inverter EMU for ω_r =1500 rpm and T_m=±792 Nm.

The presented simulation results are fully confirmed with the experimental results presented in the literature [1]. Finally, it should be noted that the described Matlab-Simulink model of simulation of operation of the ŽS 413/417 series electric multiple unit (EMU) in traction and braking mode enables the analysis of numerous other operating conditions that can be the subject of future research.

4. CONCLUSION

The described simulation model completely objectively depicts the operation of the electric multiple unit of the ŽS 413/417 series in traction and braking mode. The model made it possible to observe the electrical and mechanical parameters of the drive three-phase asynchronous motors for: different permissible voltage values and voltage distortions at the point of connection of the multiple power unit to the contact network, different mechanical loads and different rotation speeds of traction electric motors.

Numerous simulations show a very important feature of the electric multiple unit of the ŽS 413/417 series, which is that the vehicle's automatic regulation system has completely eliminated the influence of changing voltage value and voltage distortion in the contact network on the vehicle's operation. This stability of the drive to changes in voltage value and voltage distortion in the contact network is very important in the exploitation of railway electric traction vehicles and represents a special quality of this electric multiple unit.

The results of the simulations were fully confirmed by the experimental measurements performed at the electric multiple unit of the ŽS 413/417 series.

REFERENCES

[1] "Train Description - L- 4547 Flirt 3 EMU Serbia", Document No. PR_5382875, Stadler, (2023)

[2] B. Gavrilović, Z. Bundalo, and A. Blagojević, "Regenerativno kočenje na elektromotornim vozovima serije 413/417 "Srbija voz" a.d.", Zbornik radova sa XVIII međunarodnog simpozijuma "Infoteh-Jahorina 2019", Jahorina (Bosnia and Herzegovina), 20-22 March 2019, pp. 79-83, (2019)

[3] B. K. Bose, "Modern Power Electronics and AC Drives", Prentice-Hall, New York (USA), (2002)

[4] G. Grelet and G. Clerc, "Actionneurs électriques : principes, modèles, commande", Éditions Eyrolles, Paris (France), (1997)

[5] P. C. Krause, "Analysis of Electric Machinery", McGraw-Hill, New York (USA), (1986)

[6] B. Gavrilović, "Research and analysis in the electric traction system of the Serbian Railways", Eliva Press, Chisinau (Moldova), (2023)

[7] I. Boldea and S. A. Nasar, "Electric Drives", CRC Press, Boca Raton (USA), (2017)

[8] T. A. Nondahl, "Microprocessor control of motor drives and power converters, tutorial course", IEEE Industry Application Society, pp. 7.1-7.26. (1993)

[9] W. Bolton, "Mechatronics: Electronic control systems in mechanical and electrical engineering", Pearson Education, Harlow (UK), (2003)

[10] H. Kaur, "Electric drives and their controlling techniques", Scholars' press, London (UK), (2019)

[11] N. Mohan and S. Raju: „Analysis and control of electric drives: Simulations and laboratory implementation", John Wiley & Sons, Hoboken (USA), (2020)

[12] A. Merabet, Ed. "Advanced control systems for electric drives", MDPI, Basel (Switzerland), https://doi.org/10.3390/books978-3-03943-700-9, (2020)

[13] C. Dorji, "Review of electric motor drives, machine drives and control", http://dx.doi.org/10.13140/RG.2.1.1198.6408, (2015)

[14] F. Golnaraghi, B.C. Kuo, "Automatic control systems", John Wiley and Sons, Hoboken (USA), (2010)

[15] O. V. Kryukov, D. A. Blagodarov, N. N. Dulnev, Y. M. Safonov, N. N. Fedortsov, and A. A. Kostin, "Intelligent Control of Electric Machine Drive Systems," Proceedings of X International Conference on Electrical Power Drive Systems - ICEPDS 2018, Novocherkassk (Russia), pp. 1-4, https://doi.org/10.1109/ICEPDS.2018.8571670, (2018)

[16] A. Hughes, "Electric motors and drives: Fundamentals, types and applications", Elsevier, Oxford (UK), (2006)

[17] D. Schröder, "Elektrische Antriebe – Grundlagen", Springer-Verlag, Berlin (Germany), (2007)

[18] C. Jauch, S. Tamilarasan, K. Bovee, L. Güvenc, and G. Rizzoni, "Modeling for drivability and drivability improving control of HEV," Control Engineering Practice, Vol. 70, pp. 50–62, https://doi.org/10.1016/j.conengprac.2017.09.014, (2018)