Research of the Traction Drive with Hybrid Energy Storage System

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Abstract—The paper presents the structure of the test bench of the light railway traction drive with hybrid energy storage system and results of Matlab simulation.

I. INTRODUCTION

Improvement of traffic quality and energy efficiency of the light railway transport can be reached installing the on-board energy storage systems (ESSs). The hybrid ESS along with the supercapacitor has also the accumulator battery that allows using advantages of both storage types at once.

For studying of system operation it is necessary to carry out many experiments. Full-scale experiments with a real vehicle disturb the planned traffic of passenger transport, besides such experiments demand big expenses of energy. Therefore creation of the stationary laboratory test bench [1] which is executed in a smaller power range is meaningful.

However, even 3-5 kW power range can be dangerous at the wrong choice of parameters or control methods therefore the computer model [2] of the stand by means of which it is possible to choose the most optimum configuration for physical realization is necessary. Features of research demand use of the DC traction motor as such motors are used in the Riga tram park [3]. Besides, it is necessary to provide different mechanical load of the traction machine that corresponds to different mass of a vehicle [1]. The described in [4], [5] and [6] equipment doesn’t meet these requirements therefore the new laboratory bench is developed.

II. TRACTION DRIVE TEST BENCH

A. The Block Diagram of the Test Bench

The traction drive test bench (Fig. 1) contains a DC motor, which simulates the electric vehicle traction drive, and an AC induction motor, which simulates the traction drive load. The bench is developed on the basis of laboratory stand already available in operation for electric drive study.

![Fig. 1. Traction drive test bench with load simulator](image)

The block diagram of the bench is presented on Fig. 2. The tram drive with four motors is replaced by an equivalent independent excitation DC motor which generates torque $M_{dc}$ and has the following parameters:

- $P_{dc} = 3.7$ kW – rated power of the motor;
- $r_a = 0.46 \Omega$ – resistance of an anchor circuit;
- $n_{nom} = 1370$ rpm – rated speed of the motor;
- $C_E = 0.6366$ – an electromagnetic constant.

The DC motor is connected to the 110 V DC through DC/DC converter and diode VD1 which together with the DC power supply is simulating a single-direction traction substation, with no possibility for regeneration energy return. The DC bus is equipped with a large capacitor $C_{f1}$ – equivalent to the filter capacitor of vehicle traction drive [2]. The hybrid ESS includes supercapacitor and accumulator batteries connected to the DC bus through bidirectional DC/DC converters. The voltage limiter with braking resistor $R_{br,dc}$ is necessary for overvoltage prevention on the DC bus.

B. The Load Simulator

The traction DC motor is mechanically coupled to the AC induction motor driven by frequency converter “Danfoss” VLT5022 which is connected to the 380 V/50 Hz AC network and is not equipped with a regenerative braking controllable rectifier. The AC drive operates in the braking mode as the load for the traction drive model DC motor operating in the drive mode. The braking energy produced by the load simulator is transferred to the braking resistor $R_{br}$ (chosen for long-term continuous operation). In the braking mode of the traction drive model the load simulator operates in motor mode [1]. The AC motor has the following parameters:

- $n_{AC} = 1450$ rpm – rated speed of the motor;
- $V_{AC} = 380$ V, 50 Hz – rated voltage and frequency;
- $P_{AC} = 4$ kW – rated power of the motor.

For the frequency converter control the speed control method was chosen [1]. In simplest case, accepting $M_{req} = 0$ N-m, the referred speed dependence on time $\omega_{ref}(t)$ can be expressed

$$\omega_{ref}(t) = \frac{1}{J_{eq}} \cdot C_E \cdot I_a \cdot t \cdot (1)$$

The equivalent moment of inertia $J_{eq}$ is calculated as

$$J_{eq} = \frac{d^2 \cdot k_{ws}^2 \cdot m}{4 \cdot k_{gear} \cdot k_p}, \quad (2)$$

where $d$ – vehicle wheel diameter;
- $k_{ws}$ – speed scale factor;
- $k_{gear}$ – vehicle gear box ratio;
- $k_p$ – power scale factor;
- $m$ – vehicle mass.
C. The Hybrid Energy Storage System

The hybrid energy storage system of the test bench includes the supercapacitor Maxwell BMOD-63-125 with capacity 63 F and voltage 125 V and the accumulator battery consisting of eight elements Panasonic LC-RA1212PG.

The minimum voltage on the supercapacitor is

\[ V_{\text{min}} = \frac{P_{\text{dich}}}{I_{\text{dich,max}}} \tag{3} \]

where \( P_{\text{dich}} \) – discharging power;
\( I_{\text{dich,max}} \) – maximal discharging current.

The duty ratio can be expressed

\[ D = \frac{V_{\text{min}}}{V_{\text{bus}}} \tag{4} \]

where \( V_{\text{bus}} \) – DC bus voltage.

Parameters of one element Panasonic LC-RA1212PG are:
- rated voltage \( V_{\text{bn}} = 12 \) V;
- rated capacity \( C_{\text{bn}} = 12 \) Ah;
- internal resistance \( R_{\text{bn}} = 30 \) mΩ.

Rated voltage of the battery \( V_{b} \) and internal resistance of the battery \( R_{b} \) can be expressed

\[ V_{b} = N \cdot V_{\text{bn}} = 96 \text{ V} \tag{5} \]

\[ R_{b} = N \cdot R_{\text{bn}} = 240 \text{ mΩ} \tag{6} \]

where \( N = 8 \) – number of elements.

D. DC/DC Converters

The traction drive and hybrid ESS DC/DC converters (Fig. 3) are equipped with microprocessor-based local controllers that provide control over the output parameters and safe operation of the converters [2]. The central control system coordinates the operation of all TB converters. It sends the operation mode signals and reference values to the local controllers and receives back the system state signals and the values of measured currents and voltages. The control board communicates only with the central control system.

![Fig. 3. DC/DC converters with microprocessor-based controllers](image-url)
The traction converter is loaded with a DC motor. Two motor current control loops for the running and braking modes of operation are implemented in the microprocessor firmware. The reference current and modes of operation are set by the central control system.

The control system of a supercapacitor converter is more complicated. In the charging mode it acts as a DC bus voltage stabilizer at a set value. In the discharging mode it normally draws current according to the reference value. In case of input voltage dropout it maintains the DC bus voltage at the 95V level. In both the modes of operation the limitation of supercapacitor current is activated with a set value.

Controller of the accumulator battery converter is simpler than supercapacitor converter controller. Two constant charge current values for slow and fast battery charging can be set. Discharge current is set by the central control unit.

For a choice of transistors VT1 and VT2 it is necessary to calculate the rated supercapacitor charging current $I_{cb}$ which can be expressed

$$I_{cb} = \frac{P_{DC}}{V_{bus}}, \quad (7)$$

where $V_{bus}$ – DC bus voltage.

Knowing a supercapacitor charging current, the maximum instant current of a choke coil can be calculated by (8), accepting that value of a pulsation $\Delta I_L$ doesn’t exceed 20 % of $I_c$

$$I_{L,\text{max}} = \Delta I_L + I_{cb} \quad (8)$$

The choke coil calculates for restriction of current pulsations in a range which not exceeding 20 %. The maximal inductance $L_M$ of a choke coil can be expressed

$$L_M = \frac{V_{bus}}{\Delta I_L \cdot f} \cdot D \cdot (1 - D), \quad (9)$$

where $f$ – DC/DC converter frequency.

Minimum number of windings can be expressed

$$W = \sqrt{\frac{L_M}{A_L}}, \quad (10)$$

where $A_L$ – coefficient of inductance.

III. SIMULATION RESULTS

A simplified Matlab/Simulink model of the test bench was in [2] described. The model of the traction drive simulator has been approved for simulation of Tatra T3MR trams with the following specifications:

- mass of full loaded tram 30.2 t;
- wheel diameter 0.7 m;
- gear ratio 7.36;
- rated motor speed 1720 rpm.

The calculated in [1] bench scale factors are:

$K_P = 85.5$ – power scale factor;
$K_\omega = 1.255$ – speed scale factor.

The Matlab/Simulink simulations are made in the overhead feeding mode at supercapacitor initial voltage 80 V. Acceleration, freewheeling and braking modes in time scale 1:1 were simulated. The most admissible armature current $I_{arm} = 40$ A and power scale factor $K_P = 85.5$ are used.

In this experiment modeling of accumulator batteries wasn’t applied, as the main attention was given to braking energy saving by means of the supercapacitor, as storage device most suitable for this task [7].

Fig. 5 presents single tram starting and braking processes at 12 s acceleration with maximum armature current, 10 s freewheeling followed by braking.
Fig. 6 shows the diagram of the traction motor power. The maximum generated power in the braking mode is 3 kW.

![Diagram of the traction motor power](image1)

(Apparently from Fig. 7, the ESS provides absorption of all brake energy and partially provides need of the traction drive for energy in the acceleration mode.

![Diagram of the ESS power](image2)

As it was told above, the frequency converter of the load simulator is not equipped with a regenerative braking controllable rectifier. Therefore energy generated by the load machine dissipates on a braking resistor.

Fig. 8 shows variation in time of the braking resistor power at 30 s continuous operation in the traction mode of a full-loaded tram.

![Braking resistor power](image3)

The peak power dissipated in the braking resistor is in this case approximately 3 kW.

**IV. CONCLUSIONS**

Use of on-board energy storage systems will allow increasing efficiency of passenger electrical transport by braking energy saving and its further use at vehicle acceleration.

Results of computer simulation show that the developed stand should provide correctly vehicle modeling in various operating modes.

The load simulator using gives the possibility to model vehicle operation at different mass. The braking resistor’s power of the load simulator should be at least 3000 W for maintaining a continuous operation at simulation of the traction drive’s traction mode.

**REFERENCES**


