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Specificity of Electrodynamics Braking of EP20 Electric Locomotive with Asynchronous Traction Motors

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Abstract: This article discusses comparative statistical data analysis of energy consumption by EP20, EP2K, EP1M passenger electric locomotives. On the basis of primary data, it has been established that the highest specific energy consumption is that of passenger electric locomotives with railroad trains of double-deck passenger wagons. Comparison of specific energy consumptions by EP20 and EP2K DC electric locomotives has demonstrated that the EP20 electric locomotives on flat terrain are characterized by significantly higher specific energy consumption in comparison with that of EP2K electric locomotives. Comparison of specific energy consumptions by EP20 and EP1M AC electric locomotives with single type passenger wagons has demonstrated that the EP20 electric locomotives on flat terrain are characterized by nearly the same energy consumption as that of EP1M electric locomotives. Analysis of load upon running special passenger trains for EP20 electric locomotive along Moscow–Adler line has revealed underload of electric locomotive which leads to decrease in its efficiency and, as a consequence, excessive energy consumption.

Index Terms: efficiency factor, electric locomotive, electrodynamic braking, traction motor.

I. INTRODUCTION

As was shown in [1], the passenger electric locomotives for two types of current, EP20, are characterized by the worst specific energy consumption. In another work [2] it has been established that one of the reasons is running trains of double-deck wagons which are obviously characterized by higher specific resistance to movement due to increased middle transverse section in comparison with single-deck wagons. Moreover, special tests revealed existence of other reasons related with the design of EP20 electric locomotive.

EP20 electric locomotive is equipped with two independent systems of electricity metering: for DC and AC electric traction.

a) DC electric traction.

In traction mode, activation of metering sensor makes it possible to measure the sum of energies: consumed for traction and for own needs; in the mode of regenerative braking, the energy is measure returned to electric traction network.

In the mode of electrodynamic, that is, regenerative and rheostatic braking, the energy consumed by electric locomotive for own needs is not detected and not measured.

The train energy consumption is detected by individual sensors irrespective of current and voltage sensors operating for traction and braking and is displayed adequately in all modes. b) In the case of AC traction, activation of meters makes it possible to measure the energy consumed by electric locomotive in the traction mode and the energy returned in the mode of regenerative braking as well as the energy consumed by electric locomotive for own needs in the traction mode. The energy consumed by electric locomotive in the modes of regenerative and rheostatic braking is not detected as in the case of DC traction. The connection circuit of current and voltage transformers is such that the train energy supply is adequately detected upon operation of electric locomotive in the traction mode by two sensors: sensor of traction circuit of electric locomotive operating in traction mode and sensor of train energy supply. In the mode of regenerative braking, the energy generated by regeneration is consumed for train energy supply without metering by sensors of power circuit of electric locomotive. That is, the regenerative energy consumed for train energy supply is detected only by the meter of train energy supply and is summed with the energy received for train energy supply from overhead system in traction mode. Thus, it is impossible to determine how much energy was obtained by regeneration, since its portion was returned to the overhead system and measured by regeneration meter and another portion was consumed for train energy supply and was measured by the meter of train energy supply as a part of total energy of train supply.

II. METHODS

A. General description

In order to perform reference traction and power tests, in Moscow–Adler line an EP20–043 electric locomotive was equipped with additional metering circuit (AO VNIIZhT). Signals from current and voltage sensors were measured by means of mobile measuring and computing system (MCS).

The MCS was installed on board of electric locomotive and

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connected to laptop located in test wagon by means of MC102 XL media converters and optical cable. Continuous and acceptable quality of supply voltage AC, 220 V, 50 Hz was provided by uninterruptable power system with double conversion.

Measured signals at 20 kHz were continuously recorded and stored. Signals were processed and diagrams were plotted using Microsoft Excel.

Operability of the metering system was examined during layovers in depot of Moscow Classification Yard–Ryazanskaya. The electric locomotive was near depot with lifted current collector. The overhead system was energized by DC voltage of 3 kV. In the vicinity the main track was located with running trains. Auxiliary machinery and life support systems (heating, lighting, etc.) were in standard operation state. Electricity consumption was detected during one hour by VNIIZhT MCS and standard energy meters.

B. Algorithm

The following performances were recorded during one-hour hot layover:

Energy consumption by standard locomotive instrumentation: 72 kWh;

Energy consumption by VNIIZhT MCS: 71.323 kWh;

Energy recovery by standard locomotive instrumentation: 7 kWh.

The obtained results demonstrate that the differences in energy consumption by VNIIZhT MCS and standard locomotive instrumentation are less than ±1%.

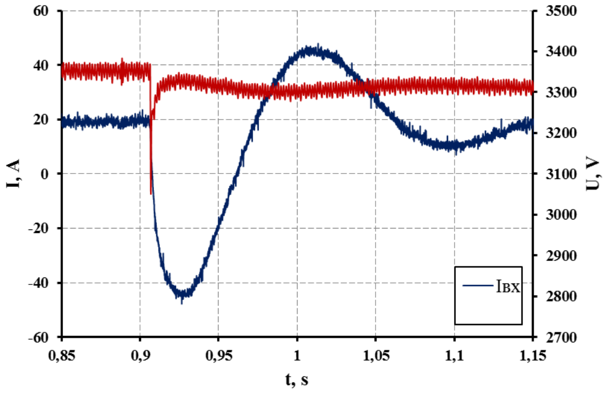

Fig. 1. DC voltage and current on collector during hot layovers of electric locomotive near depot: U_{in} min = 3,060.5 V; I_{in} min = –45.8 A; I_{in} max = 45.7 A

Energy regeneration during layover detected by standard instrumentation occurs upon sharp voltage variations in overhead system when current from locomotive passes to overhead system under the action of locomotive capacitor charged to higher voltage. Fig. 1 illustrates oscillogram of such mode. The locomotive input current of 20 A passing in steady mode from overhead system to locomotive as a consequence of voltage decrease in the overhead system from 3,300 V to 3,060.5 V started to pass from locomotive to overhead system. As shown in the oscillogram, the current reached 45.8 A. After voltage stabilization in overhead system at the new level, the current from overhead system to locomotive increased to 45.7 A, then the current was stabilized. At higher voltage drops in overhead system, the direct and inverse locomotive currents also increase. Upon voltage decrease in overhead system from 3,350 to 2,937.6 V the following current appeared: I_{in} min = -61.4 A; I_{in} max = 62.5 A.

Therefore, upon hot layover of locomotives under DC contact wire, the standard locomotive meters detected excessive (higher than actual) energy consumption and energy regeneration to overhead system, thought the traction motors were quiet and did not generate braking energy.

III. DC OPERATION OF ELECTRIC LOCOMOTIVE

The During DC operation of locomotive, the following algorithm of electric braking was determined: when brake valve handle was placed into braking position and the voltage in overhead system was below 3.6 kV, the electric circuit performed regenerative braking with energy recovery to traction circuit, as a consequence, the voltage in overhead system increased. When voltage on locomotive current collector was about U_{in}= 3.6 kV, the regenerative braking was replaced by rheostatic braking. Fig. 2 illustrates oscillogram of such mode. The power generated by traction motors P_{mot} transfers from traction circuit P_{in} to braking resistors (the oscillogram shows power in braking resistor of the first traction motor P_R1).

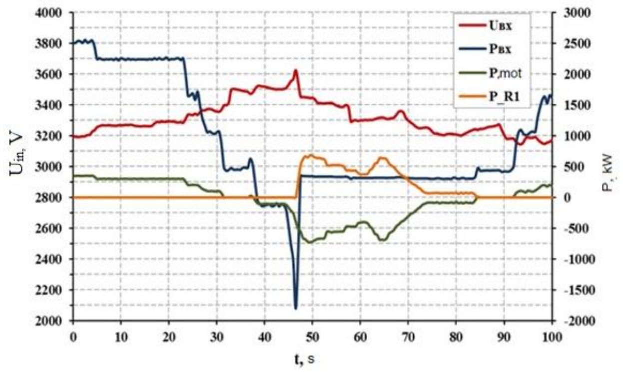

Fig. 2. Locomotive operation upon traction, regenerative and rheostatic braking. Adler–Moscow trip, March 27, 2017, Ryazan–Moscow segment. Discretization frequency during measurements: 20 kHz. Averaged data at 2 Hz (per each 0.5 s).

As a consequence of transfer to rheostatic braking, the voltage in overhead system and on locomotive current collector decreased, though, regenerative braking was not returned even at low voltages. Fig. 2 illustrates oscillogram of locomotive operation in rheostatic braking mode. The voltage on locomotive current collector decreased to 3,300 V and then to 3,200 V, however, no regenerative braking was returned, the locomotive continued to consume energy of braking resistors.

Minimum voltages in overhead system in all cases of rheostatic braking in all DC trips were analyzed (Fig. 3).

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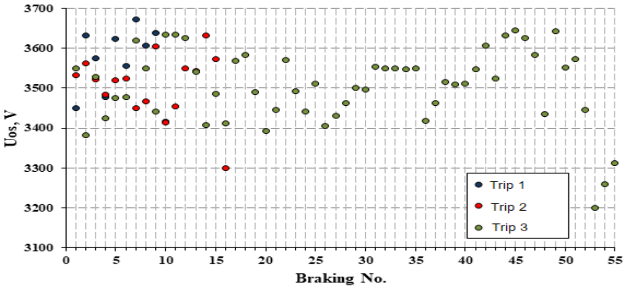

Fig. 3. Minimum voltages in overhead system after start of rheostatic braking

As can be seen in Fig. 3, upon operation in rheostatic braking mode, the voltage in overhead system was mainly about 3.5 kV. When voltage decreased to 3.3 and 3.2 kV, rheostatic braking was not replaced with regenerative braking.

In addition, voltages in overhead system at the start of rheostatic braking were also analyzed. This mode could begin both as rheostatic braking itself and as a consequence of automatic replacement of electrodynamic regenerative braking. Fig. 4 illustrates data for all cases of rheostatic braking in all DC trips. Automatic replacement of electrodynamic regenerative braking with rheostatic braking took place at the voltage in overhead system from 3,590 to 3,660 V. At voltages in overhead system in excess of 3,600 V, the rheostatic braking was initiated without regenerative braking.

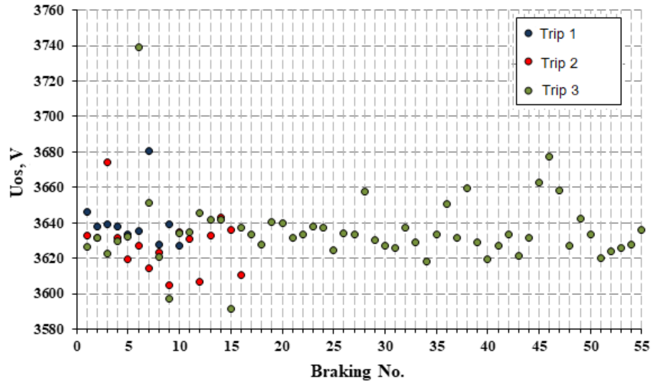

Fig. 4. Minimum voltages in overhead system after start of rheostatic braking

Table I. Relative time, %, of locomotive operation in various running modes with regard to total time of running

Moscow–Ryazan								
Trip 1			Trip 2			Trip 3		
traction	regen.	rheostat	traction	regen.	rheostat	traction	regen.	rheostat
92.5	4.4	3.1	90.8	5.1	4.1	80.4	5.0	14.6
Tuapse–Adler								
Trip 1			Trip 2			Trip 3		
traction	regen.	rheostat	traction	regen.	rheostat	traction	regen.	rheostat
			98.6	1.1	0.3	88.1	6.7	5.2
Adler–Goryachii Klyuch								
Trip 1			Trip 2			Trip 3		
traction	regen.	rheostat	traction	regen.	rheostat	traction	regen.	rheostat
			98.0	1.4	0.6	86.9	8.5	4.6
Ryazan–Moscow								
Trip 1			Trip 2			Trip 3		
traction	regen.	rheostat	traction	regen.	rheostat	traction	regen.	rheostat
90.8	6.5	2.7				81.8	6.0	12.2

The time of locomotive slowing period is shown together with the traction time.

Therefore, it has been demonstrated that significant amount of energy is consumed by braking resistors, which is accompanied by additional and, as shown above, not accounted energy consumption for cooling braking resistors. As a consequence of early (at 3.63 kV instead of 3.95 kV) replacement of regenerative braking with rheostatic braking and impossibility to return to regeneration at voltage decrease in overhead system, the time of locomotive operation in rheostatic braking mode increases with the decrease in the time of operation in regenerative braking mode. The decrease in the time of operation in regenerative braking mode leads to decrease in the energy recovered to the overhead system. As a consequence of increase in the time of locomotive operation in rheostatic braking mode, the amount of energy dissipated on braking resistors increases, which leads to increase in energy consumption for their cooling.

During the trips such mode was detected when upon decrease in intensity of rheostatic braking, the braking mode was shortly interrupted, herewith, the voltage in overhead system was lower than 3,600 V. When locomotive operator terminated the rheostatic braking mode and transferred the locomotive to short-time slowing with subsequent activation of regenerative braking mode, the locomotive was capable to recover energy to the overhead system (Fig. 5).

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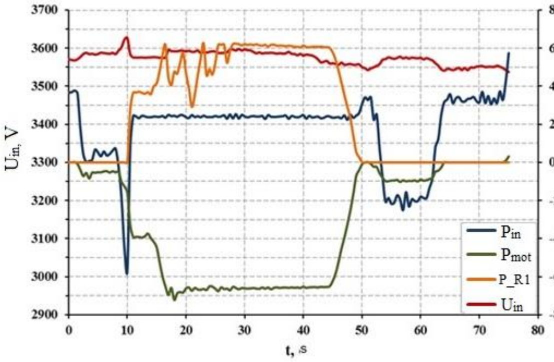

Fig. 5. Locomotive operation during traction, regenerative and rheostatic braking

As illustrated in Fig. 5, the mode starts from slowing period when the power of traction motors P_{mot} is zero. Herewith, the input power P_{in} is consumed for own needs and train power supply. Regenerative braking starts at the 2nd second. Herewith, the locomotive input power P_{in} decreases and the voltage on current collector U_{in} increases.

However, as a consequence of low efficiency of regenerative braking, the power P_{in} is still consumed from traction circuit. At the 8th second, the intensity of regenerative braking increases and the power P_{in} is recovered to traction circuit. As a consequence of power recovery to traction circuit, the voltage on current collector U_{in} increases, and after reaching 3,600 V, the locomotive transfers to rheostatic braking. In this mode, the power generated by traction motors P_{mot} is consumed for own needs (since the input power at start is lower than the locomotive input power in slowing mode) and on braking resistors P_R1. The consumed input power P_{in} from traction circuit is consumed for train energy supply. At the 50th second of operation, the power of traction motors for two seconds is zero. And only then locomotive resumes the mode of regenerative braking.

Locomotive efficiency factor and, hence, energy consumption depend directly on its operation modes. The consumed energy strongly depends on power load of locomotive.

For long time locomotive operates at low (from 0 to 25%) load and average efficiency factor for a segment is lower than the rated value, hence, during the trips, energy was consumed excessively. While detecting the reasons of increased power consumption, it is important to check if there occurs the mode when current from overhead system passes to locomotive braking resistors. During the trips long-term flow of current from overhead system to braking resistors was not detected.

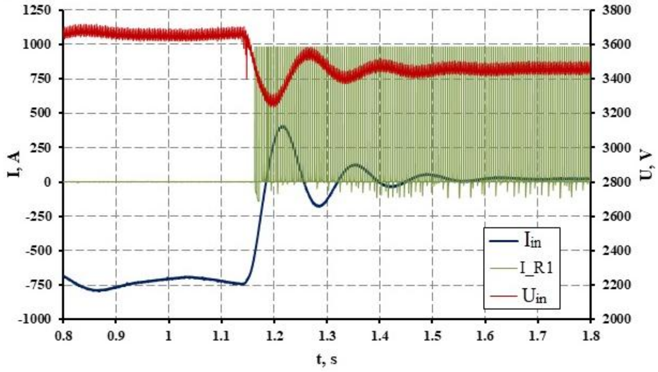

Fig. 6. Transfer from regenerative to rheostatic braking upon DC traction

However, during transfer from regenerative to rheostatic braking, the current from overhead system flows shortly to braking resistors (Fig. 6). At the 11.5th second due to voltage increase to 3.65 kV in overhead system, the regenerative braking is terminated, and after current switching to braking resistors (up to the 12.5th second) the current from traction circuit flows to braking resistors. The current can be high, however, the duration is low, about 0.1 s. During this time about 1 kWh was dissipated on braking resistors.

IV. AC OPERATION OF ELECTRIC LOCOMOTIVE

Measured During AC mode, locomotive also operated in traction mode, regenerative and rheostatic braking. Energy profitable mode of regenerative braking (Fig. 7) continued to voltage increase on current collector equaling to 28.75 kV, then braking resistors were activated and the locomotive was transferred to the mode of energy unprofitable mode of rheostatic braking. Similar to the locomotive DC operation, the voltage is underestimated (28.75 kV instead of 29.0 kV according to State standard GOST 6962). It is required to adjust preset overvoltage protection on current collector, to approve it in specifications for EP20 locomotive and to check it regularly during overall operation lifetime.

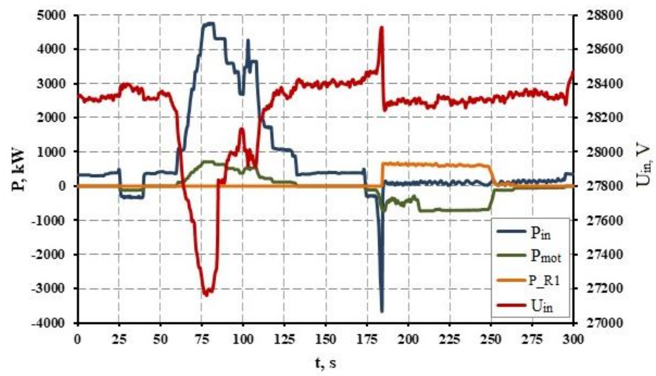

Fig. 7. Transfer from regenerative to rheostatic braking upon AC traction

The oscillogram illustrates active voltages and currents. The locomotive moved in traction mode at high voltage in overhead system: 28,300 V. At the 25th second, short regenerative braking took place at moderate power of traction motors P_{mot}.

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As a consequence of braking, the voltage in overhead system started to increase, however, due to low power of braking, the voltage in overhead system did not exceed 28,400 V, no transfer to rheostatic braking took place. The traction mode after the regenerative braking resulted in voltage decrease in overhead system. At the 175th second, regenerative braking was repeated. Power increase of regenerative braking resulted in voltage increase in overhead system, and at U_{in} max = 28,725 V, the regenerative braking was replaced by rheostatic braking. After transfer to rheostatic braking, the voltage in overhead system decreased but no return to regenerative braking took place.

Fig. 8 illustrates extended transfer from regenerative to rheostatic braking.

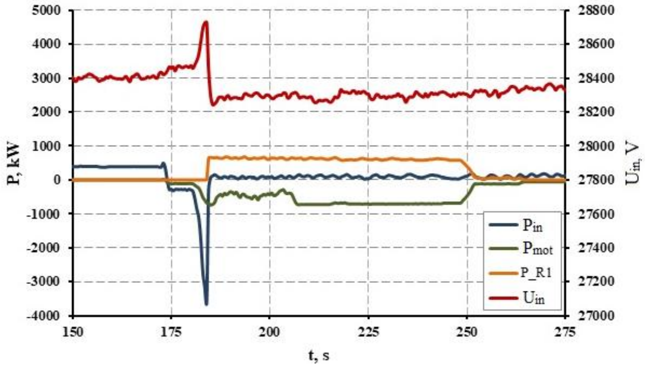

Fig. 8. Transfer from regenerative to rheostatic braking upon AC traction

It can be seen in Fig. 8 that prior to regenerative braking, when the locomotive moved in slowing mode and the power of traction motors P_{mot} was zero, the locomotive consumed input power P_{in} which was consumed for own needs and train energy supply. After start of regenerative braking, the input power P_{in} became negative, i.e. it was recovered to overhead system. Upon transfer to rheostatic braking, the input power was nearly zero, i.e., nothing was neither consumed from nor recovered to the overhead system. All own needs of the locomotive as well as train energy supply were satisfied by internal reserves of locomotive energy by decrease in energy dissipation on braking resistors P_R1 (this was the power dissipated on the first unit of braking resistors).

Fig. 9 illustrates oscillogram of instant currents of voltage of overhead system upon transfer from regenerative to rheostatic braking.

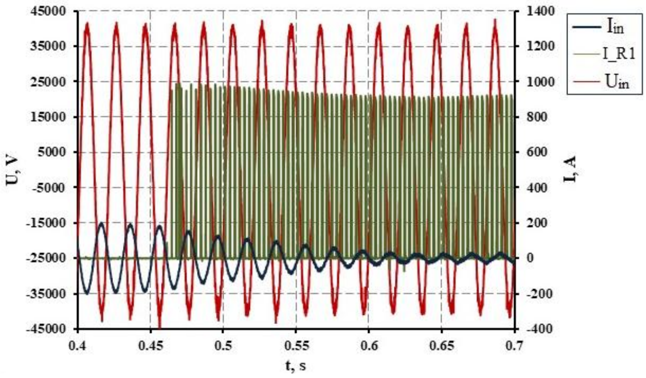

Fig. 9. Transfer from regenerative to rheostatic braking upon AC traction

The oscillogram shows that prior to transfer to rheostatic braking, the input current I_{in} and the input voltage U_{in} are in counter phase, that is, regeneration takes place with offset coefficient of about 1. When current is in braking resistor I_R1, the locomotive input current decreases.

The mode of rheostatic braking upon AC operation occurred as a consequence of high voltage in overhead system, is energy unprofitable. Despite the fact that the required braking of train is performed, the electricity generated during braking is dissipated on braking resistors. The efficiency of electric braking can be improved by recovery of active energy to overhead system.

For efficient recovery of electricity to overhead system at high voltages, it is required that the locomotive current was in advance of the voltage by preset angle φ. The advance angle φ is determined on the basis of current and locomotive variables, energy supply variables and voltage in overhead system. As shown by operation experience of Russian AC electric locomotives with reversible converters, active electric energy can be recovered to overhead system at wide range of voltage on current collector. Probably, EP20 locomotive requires for adjustment of software so that current phase offset from voltage was varied on current collector.

V. CONCLUSION

1. Reduced recovery of DC energy by EP20-043 locomotive during electric braking was detected as a consequence of noncompliance with Specifications 3TS.085.003TU-01 concerning threshold voltage in overhead system responsible for transfer from regenerative to rheostatic braking as well as non-availability of reverse transfer from rheostatic to regenerative braking at specified voltage in overhead system; in order to recover regenerative braking, termination of rheostatic braking is required.

2. Reduced recovery of AC energy as a consequence of electric braking was detected after transfer to rheostatic braking at high voltage in overhead system; locomotive with high power factor increases voltage on current collector to critical level, for instance, 28.6 kV, and transfers to rheostatic braking.

3. During hot layover of locomotives under DC contact wire as a consequence of variation of voltage in overhead system, the standard meters detect excessive (with regard to actual value) energy consumption and energy recovery to overhead system, though the motors are quiet and do not generate braking energy.

4. At the first stage it is required to provide compliance of technical state of EP20 locomotives with the valid Item 1.9.2 of Specifications 3TS.085.003TU-01 where it is stipulated that automatic replacement of regenerative braking with rheostatic braking should be initiated when the voltage in DC overhead system exceeds 3.95 kV.

5. Prior to adjustment of specifications for the locomotive, the preset DC voltage of 3.95 kV and similar preset voltage upon AC operation should be regularly verified using certified test equipment with smooth adjustment of voltage in DC and AC overhead system.

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6. Development engineers of EP20 locomotive should improve control software of converters in order to provide:
6.1. transfer from rheostatic to regenerative braking in the case of respective voltages in traction circuit;
6.2. reduced rate of voltage increases in AC overhead system, for instance, by decrease in power factor on locomotive current collector in the mode of regenerative braking.

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