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ENERGY OF STARTING UP TO SPEED OF DC TRAIN

Introduction

The proposed autonomous (off-line) mode of recuperative braking in the articles [1, 2] shows that it is more effective to start up the train using the energy which was stored in the last phase of recuperative braking by on-board supercapacitor storage system (OSSS). First of all, the off-line mode allows to save significant volume of energy for the next phase of traction mode. Secondly, it increases the traffic-capacity of overhead line. But these facts lead to the question: which energy is required to starting up the electric rolling stock (ERS) from zero to some operational speed?

The paper describes the method of energy estimation and shows the results of analysis for DC multiple unit train EPL2T.

Methodology and main formulae for energy estimation

As it was established, at the train starting the energy, which is performed by its traction motors, A_{st} consists of: 1) energy for overcoming the friction A_{fr} in the bearings of wheelpairs; 2) A_{rr} is the energy for overcoming the main forces of the train running resistance; 3) variations of stored the kinetic A_k and the potential A_p energy in the process of train acceleration; 4) ΔA_{em} is the energy of electrical and mechanical losses of system in the process of energy conversion and transmission. Therefore, the energy balance equation of train starting up is

$$A_{st} = A_{fr} + A_{rr} + A_k \pm A_p + \Delta A_{em} . \tag{1}$$

Each component of the equation is explained as follows.Firstly, we consider that the train starting carried on a horizontal straight section of track without rises and falls, so potential energy A_p is absent.The energy sum $A_{fr} + A_{rr}$ is frequently noted like $A_w(V)$. This energy is consumed on overcoming of the total resistance to train motion and is described by next equation:

$$A_w(V) = A_{fr} + A_{rr} = V \cdot t \cdot W = l_{st} \cdot W , \tag{2}$$

where V is the speed;
t is the time of starting up;
l_{st} is the distance passed in acceleration period;
W is the total resistance to train motion.

The total resistance W consists of the main running resistance W_0 and additional W_{fr}, which is based on the friction forces in the bearings of wheelpairs, so

$$W = W_0 + W_{fr} . \tag{3}$$

The absolute value of the main running resistance W_0 is determined as multiplication of the specific main running resistance w_0' on the estimated weight of the train $m \cdot g$ [3, 4]:

$$W_0 = w_0' \cdot m \cdot g \ , \text{N}, \tag{4}$$

where m is the weight of the train, t;
$g = 9{,}8$ m/s^2 is the acceleration of gravity.
Formulae for determination of the specific main running resistance w_0' are shown in [4] for most common types of main and urban railway electric transport. Generally, the formula can be written such as:

$$w_0' = a + b \cdot V + c \cdot V^2 \ , \text{H/kN}, \tag{5}$$

where a, b, c are the coefficients;
V is the train starting up speed, km/h.

The value of the additional running resistance W_{fr} at the moment of train starting up can be calculated using the formula:

$$W_{fr} = W_{fr}' \cdot m \cdot g , \tag{6}$$

where W_{fr}' is the specific additional running resistance which is calculated in accordance with the Rules of Traction Calculations [3]:

$$W_{fr}' = \frac{28}{m_0 + 27} , \tag{7}$$

where m_0 is the physical weight per one axle of rolling stock, t.

In case when the train has different types of carriages and these carriages have different axial load m_0, the coefficients m_0 and W'_{fr} should be determined for each type of carriage. That is why the resulting running resistivity is calculated by the following formula:

$$W'_{\text{fr}} = \frac{\sum W'_{\text{fr}\,i} \cdot n_i}{\sum n_i}, \tag{8}$$

where n_i is the quantity of the carriages with similar type;

$W'_{\text{fr}\,i}$ is the specific additional running resistance for i-th carriage is calculated by the formula (7).

Theoretical and experimental researches show that in formula (1) the kinetic energy A_{k} is fundamental like A_{fr} and A_{rr}. As it is known from [4], the kinetic energy which is transferred to the train weight in the process of train starting up from zero to some operational speed is given by:

$$A_{\text{k}} = \frac{m_{\text{r}} \cdot V^2}{2} = \frac{m \cdot (1+\gamma) \cdot V^2}{2}, \text{ J}, \tag{9}$$

where m_{r} and m are the reduced and physical (calculated) weights of the train respectively, kg;

$(1+\gamma) = 1{,}08$ is the rotational inertia coefficient [5].

Energy losses ΔA_{em} in traction electrical equipment consist of losses in traction electric motor (TEM), mechanical transmission, wires of power circuit, pulse converter, on-board supercapacitor storage system. The corresponding total power losses determine the efficiency of the relevant units of conversion and transmission system. Therefore, the value ΔA_{em} in the calculations of A_{st} takes into consideration the efficiencies of the next elements: TEM η_{TED}, the pulse converter η_{pc} and OSSS η_{osss}.

Abovementioned data determine the energy of train starting up by the expression:

$$A_{\text{st}}(V) = \frac{A_w(V) + A_{\text{k}}(V)}{\eta_{\text{TEM}} \cdot \eta_{\text{pc}} \cdot \eta_{\text{osss}}}. \tag{10}$$

We obtain an expression of the capacity C of OSSS which is necessary to starting up and accelerate the ERS to some speed.

As it is known, the energy which stored in the electric field of the capacitor is determined by the expression:

$$A_{\text{osss}} = \frac{C \cdot U^2_{C\text{nom}}}{2}, \tag{11}$$

where $U_{C\text{nom}}$ is the nominal voltage of fully charged capacitors.

It is not recommended to discharge capacitive storage for structural views completely to [6] and it should have some residual charge, so-called “dead volume”. Therefore, the total energy of the storage system has two components and equals:

$$A_{\text{osss}} = A_{\text{c}} + A_{\text{d}}, \tag{12}$$

where A_{c} is the exchange energy between storage system and traction motors of ERS,

A_{d} is the energy of “dead volume”.

The exchange energy can be represented as

$$A_{\text{c}} = \frac{C \cdot (U_{\text{c}}^2 - U_{\text{d}}^2)}{2}, \tag{13}$$

where $U_{\text{c}}^2 - U_{\text{d}}^2$ is the operational voltage range (charge-discharge);

U_{c} is the voltage of fully charged storage system;

U_{d} is the voltage of discharged storage system (voltage of “dead volume”).

To determine the capacity C by the energy balance of $A_{\text{st}}(V)$ and A_{c} the formulae (10) and (13) are used:

$$\frac{A_w(V) + A_{\text{k}}(V)}{\eta_{\text{TEM}} \cdot \eta_{\text{pc}} \cdot \eta_{\text{osss}}} = \frac{C \cdot (U_{\text{c}}^2 - U_{\text{d}}^2)}{2}.$$

Finally, equation above allows to get the final formula:

$$C = \frac{2\left[A_w(V) + A_{\text{k}}(V)\right]}{(U_{\text{c}}^2 - U_{\text{d}}^2) \cdot \eta_{\text{TEM}} \cdot \eta_{\text{pc}} \cdot \eta_{\text{osss}}}. \tag{14}$$

Using the expressions (10) and (14) we calculate energy for EPL2T starting up and appropriate for this storage system capacity.

Calculation and analysis results of the starting up energy of EPL2T

The multiple unit train EPL2T basically consists of 8 carriages: 2C+ 4M + 2T, i.e. 2 carriages with cabs, 4 motor carriages and 2 intermediate (trailer) carriages.

Table 1

The starting up energy of train EPL2T

V, km/h	V, m/s	$w_0^{'}$, N/kN	W_0, N	W, N	t_{st}, s	l_{st}, m	A_w, MJ	A_k, MJ	A_{st}, MJ	Capacity C, F	
										Case #1	Case #2
10	2,78	1,4667	8142,7	14471,6	3,71	5	0,074	2,36	3,04	0,517	0,414
20	5,56	1,7468	9697,7	16026,7	7,41	10	0,16	9,44	12	2,04	1,63
30	8,33	2,080	11549,2	17878,1	11,1	23	0,41	21,24	27,06	4,6	3,68
40	11,11	2,467	13697,2	20026,2	14,8	40	0,80	37,77	48,2	8,2	6,56
50	13,89	2,908	16141,6	22470,5	18,52	100	2,25	59,0	76,56	13,02	10,42
60	16,67	3,401	18824	25211,3	22,2	150	3,78	85,0	111,0	18,86	15,10
70	19,45	3,948	21919,8	28248,7	25,9	200	5,65	115,66	151,6	25,79	20,62
80	22,22	4,549	25253,6	31582,5	29,63	300	9,47	151,1	200,7	34,13	27,30

It is necessary to set the starting up speed from zero to 10...80 km/h. The formula calculation (10) starts from evaluation of the energy $A_w(V)$ which is consumed on overcoming the main forces of the train running resistance (2)-(9).

According to the experimental results [7], the main equation of the running resistivity in the range of $V = 30...130$ km/h is:

$$w_o^{'} = 1,24 + 0,02 \cdot V + 0,000267 \cdot V^2 .$$

To determine the additional running resistance W_{fr} by expressions (6) and (7) we obtain the resulting running resistance using expression (8). According to [4], the carriages of the fully loaded train have the next weights: carriages with cabs – 63,4 t, motor carriages – 78,6 t, intermediate carriages – 62,7 t. Therefore the weight of two carriages with cabs is $63,4 \cdot 2 = 126,8$ t, and values in formula (7) are $m_0 = 15,85$ t, $W_{fr}^{'} = 1,225$ N/kN. The weight of four motor carriages is 314,4 t and coefficients are $m_0 = 19,65$ t, $W_{fr}^{'} = 1,05$ N/kN. Finally, weight of two intermediate carriages is 125,4 t and coefficients are $m_0 = 15,675$ t, $W_{fr}^{'} = 1,24$ N/kN.

So the mean square value of the specific additional running resistance $W_{fr}^{'}$ in formula (8) equals 1,14 N/kN.

Then the additional running resistance W_{fr}, according to (6), is equal to 6328,94 N.

In the process of determining A_{st}, the formula (10) uses the efficiency of TEM type 1DT.003.L8U1 which is equal to 0,915 [4]. The efficiency of pulse converter [8-10] and on-board supercapacitor storage system is 0,9 [9]. The results of calculations are given in Table 1. The calculations are made for two cases: the first is for $U_c = 3960$ [V], $U_d = 1980$ [V]; the second is when $U_c = 3960$ [V], $U_d = 990$ [V]. In both cases, the starting up time is defined as $t_{st} = \frac{V}{a}$, where $a = 0,75$ m/s^2 is the train acceleration [7]. The distance passed by train in starting up period l_{st} is taken from [7] Fig. 5.4 with respect to time t_{st}.

From table 1, the train starting up from zero speed to 10...80 km/h requires the energy from 3,04 to 200,7 MJ. Practical estimation of the amount of energy was performed for EPL2T in the process of operation in the section Dnipropetrovsk-Piatykhatky of Prydniprovsk railway. These results are presented in table 2 and show the speed ranges which can be obtained after stopping.

Table 2

The starting up energy of train EPL2T

Name of the stop/station, where the train starts recuperative braking	Stored energy, MJ	The possible final speed after starting up, km/h
165 km	50,27	40
160 km	50,67	40
Dniprodzerzhynsk	69,7	45
Voskobinia	71,3	50
139 km	4,05	10
Verhniodniprovsk	38,9	35
128 km	68,62	45
125 km	69,1	45
119 km	59,52	48
114 km	42,2	35
Hranovo	94,2	55
104 km	105,1	60
Vilnohirsk	79,2	52
Zhelezniakovo	150,1	70
88 km	22,1	30
77 km	41,2	35

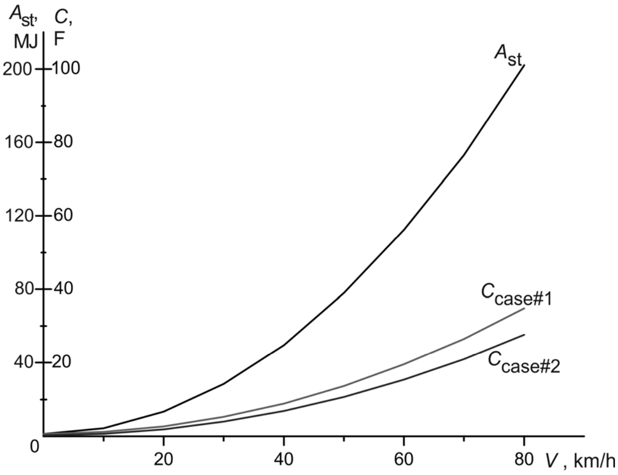

Fig. 1. Graphs of the starting up energy and storage system capacity with respect to the train speed EPL2T

Conclusions

1. Theoretical analysis shows that the additional running resistance should be taken into consideration in the calculations of starting up and acceleration energy of ERS.

2. The values of energy starting up and capacity of on-board supercapacitor storage system increase parabolically with the increasing of the moving speed.

3. The proposed autonomous (off-line) recuperative braking can be fully obtained, but the final speed of the train is different and depends on the track conditions and the quantity of stored energy.

4. The using of stored energy allows to reduce the energy consumption in traction mode on 18…25%.

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In the last 20 ... 25 years the volume of recuperated electric energy is less than 2% of the consumed by traction, while it is possible to return about 10 ... 15%. The main reason is unsatisfactory and inefficient usage of recuperated and transmitted energy to the power supply system. The paper proposes to solve this problem and induce the efficiency and the degree of recuperated energy of DC multiple unit trains by the usage of on-board supercapacitive storage system. The methods of the electric traction theory and the theory of pulse electrical engineering are used for the problem solving. The developed methodology allows to calculate the energy, which is required to starting up the multiple unit train EPL2T to some speed 10 ... 80 km/h after its stopping. Furthermore, the capacity of the on-board storage is calculated in two cases of storing recuperated energy. The novelty of the paper is the new method for estimating energy, which is required to starting up (after the stopping) the train to a certain speed. The analytical expression of the capacity of the on-board storage system was achieved and calculated for the previously estimated energy. For the first time it was found that the energy, which was saved by the on-board supercapacitive storage system, is sufficient to start up the train to some speed and reach the characteristic of full field of the traction motors. The proposed autonomous mode of recuperative braking allows, at first, to increase significantly the efficiency of energy recovery, and secondly, to reduce the weight and size parameters of on-board storage supercapacitors.

Key words: energy; resistance movement; recovery; starting up; speed; train; supercapacitor; on-board storage system; the kinetic energy.

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ЭНЕРГИЯ РАЗГОНА ЭЛЕКТРОПОЕЗДА ПОСТОЯННОГО ТОКА

За последние 20…25 лет объем энергии рекуперации электропоездов не превышает 2% от использованной на тягу, в то же время как возможно возвращать до 10…15%. Одной из причин такого состояния есть неудовлетворительное неэффективное использование электроэнергии, которая рекуперируется и передается в тяговую сеть. В статье предлагается повысить энергетическую эффективность и степень использования электроэнергии рекуперации пригородных электропоездов постоянного тока с помощью бортового емкостного накопителя. Для решения поставленной задачи использованы методы теории электрической тяги и импульсной электротехники, а также методики Правил тяговых расчетов. Изложена методика и численные расчеты электроэнергии, необходимой для разгона электропоезда ЕПЛ2Т после остановки до скоростей 10…80 км/час. Более того, выполнено оценку емкости бортового накопителя для двух случаев накопления энергии рекуперации. Научная новизна статьи заключается в том, что предложен и использован новый метод оценки энергии, необходимой для разгона (после остановки) электропоезда до некоторой скорости. Получено аналитическое выражение емкости бортового накопителя электроэнергии, необходимой для пуска электропоезда после остановки. Установлено, что накопленной в бортовом накопителе энергии достаточно для разгона электропоезда до скорости выхода на характеристику полного возбуждения. Предложенный автономный фазовый режим рекуперативного торможения позволяет, во-первых, значительно повысить эффективность использования энергии рекуперации, во-вторых, снизить массогабаритные показатели бортового емкостного накопителя.

Ключевые слова: энергия, сопротивление движению, рекуперация, разгон, скорость, электропоезд, суперконденсатор, бортовой накопитель, кинетическая энергия.

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ЕНЕРГІЯ РОЗГОНУ ЕЛЕКТРОПОЇЗДА ПОСТІЙНОГО СТРУМУ

В останні 20…25 років об’єм енергії рекуперації електропоїздів не перевищує 2% від затраченої на тягу, в той час як можливо повертати до 10…15%. Однією із причин такого стану є незадовільне неефективне використання електроенергії, що рекуперується і передається в тягову мережу. В статті пропонується підвищити енергетичну ефективність і ступінь використання електроенергії рекуперації приміських електропоїздів постійного струму за допомогою бортового ємнісного накопичувача. Для розв’язання поставленої задачі використано методи теорії електричної тяги та імпульсної електротехніки, а також методики Правил тягових розрахунків. Викладено методику і чисельні розрахунки електроенергії, потрібної для розгону електропоїзда ЕПЛ2Т після зупинки до швидкостей 10…80 км/год. Більш того, виконано оцінку ємності бортового накопичувача для двох випадків накопичення енергії рекуперації. Наукова новизна статті полягає в тому, що запропоновано новий метод оцінки енергії, потрібної для розгону (після зупинки) електропоїзда до певної швидкості. Одержано аналітичний вираз ємності бортового накопичувача електроенергії, необхідної для пуску електропоїзда після зупинки. Встановлено, що заощадженої в бортовому накопичувачі енергії достатньо для розгону електропоїзда до швидкості виходу на характеристику повного збудження. Запропонований автономний фазовий режим рекуперативного гальмування дозволяє, по-перше, суттєво підвищити ефективність використання енергії рекуперації, по-друге, знизити масогабаритні показники бортового ємнісного накопичувача.

Ключові слова: енергія, опір руху, рекуперація, розгін, швидкість, електропоїзд, суперконденсатор, бортовий накопичувач, кінетична енергія.

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