EVALUATION OF UTILIZATION EFFICIENCY OF REGENERATIVE ENERGY IN THE RIGA TRAMCAR SYSTEM

RĪGAS TRAMVAJU REKUPERĒTĀS ENERĢIJAS IZMANTOŠANAS EFEKTIVITĀTES NOVĒRTĒJUMS

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Introduction

In Riga City tramcars are equipped with regenerative braking systems arranged on the base of transistor pulse switches [1,2]. Such a braking mode is characterized with flow of energy to supply network. Utilization of the energy flow depends on number of active drive tramcars connected to the substation's link of power supply during the braking process. If current generated to contact grid by braking tramcar is fully consumed in drives of other tramcars then efficiency of regeneration is excellent. If current consumed by other tramcars is smaller than that generated by the braking then difference of currents must be dissipated in braking resistors and utilization is not fully realized. It means that efficiency of utilization depends on casual factors. Utilization should be very efficient if traction substations should invert regenerated energy to the national grid. Mostly substations are supposed only for unidirectional power flow i.e. they operated as rectifier stations. Modification of substations is connected with large capital investments and for estimation of reconstruction efficiency it's necessary to evaluate a real volume of energy regenerated and not applied in other tramcar systems i.e. volume of lost energy. Such evaluation is the main task of this paper.

Technical assumption

Volume of the energy generated by regenerative braking depends on situation in traffic intensity. Number of active tramcars by expert evaluations in Riga during a working day is presented in Fig.1.

As it is seen two expressed maximum numbers N_{rushm} of tramcars exist for rush hours in duration from 6.00 to 10:00 during five working days and from 16:00 to 19:00 in the evenings of the same days. In other hours of working days except the night hours with $N_{cn} = 0$, number of cars on line is smaller and can be expressed as N_{cm}.

Accepting that numbers N_{cm} in 12 hours and N_{rushm} in 7 hours of 5 working days are constant ones an averaged number of tramcars in day-night motion interval can be calculated as

$$N_{cwd} = \frac{7N_{rushm} + 12N_{cm}}{19} \approx 96 \qquad (1)$$

Number of tramcars operating at weekend along day-night hours are much more regular as for working days and can be accepted as 0,5 N_{rushm}.

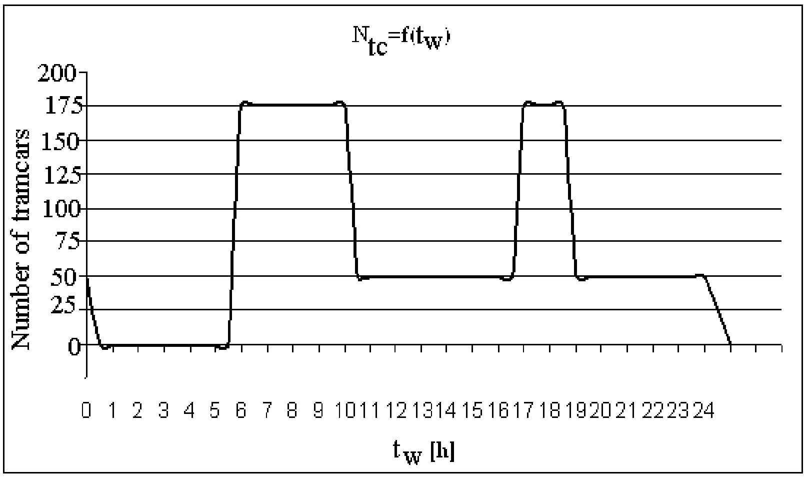

Fig.1. Total number of tramcars in Riga during 24 hours per working day

Taking into account that in Riga there is a radial network of tramlines with transit through center a number of tramcars in zone of each substation depends on distance l_c between location of substation and center. If substation is closer to the center then number of carriages connected with this substation is larger. At first approach we can accept that relative number of carriages in zone of substation is in linear declining dependence with distance l_c (Fig.2.) and this dependence is not connected with character of week's day (working or weekend) or day time.

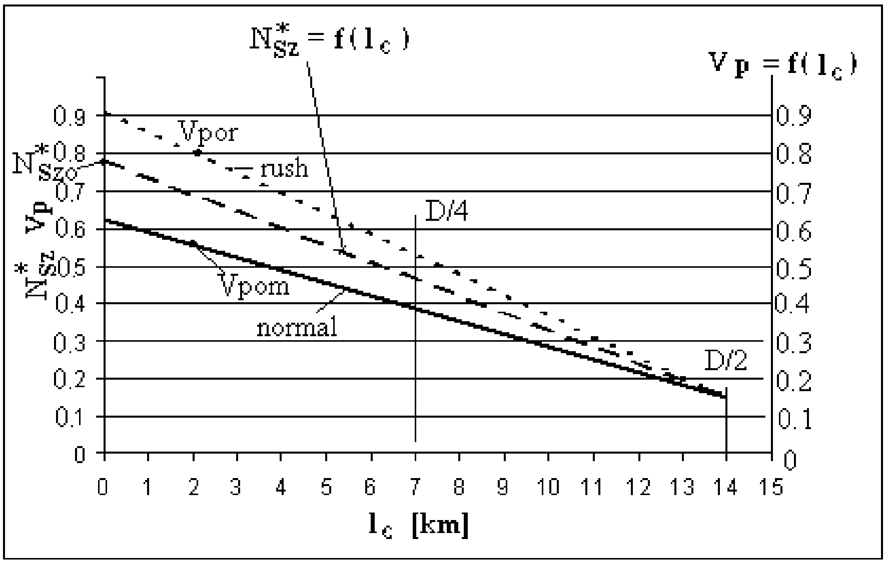

Fig.2. Relative number of tramcars N^*_{sz} for one radial line and probability V_p of absorption of recuperated energy in other carriages of the line dependence on distance l_c; D is diameter of town

Such approach defines that at each time of the day-night at distance l_c [km] from center the total number of carriages in zone of substation is

$$N_{sz} = N_{sz0}\left(1 - \frac{0.8 l_c}{0.5D}\right) \tag{2}$$

where N_{sz0} is a number of carriages at substation in very center, D is diameter of the town. At such assumption number of carriages at center of town is the largest but at suburbs – the smallest. Total number of carriages connected with all zones *z* and lines is equal to the summative of numbers of carriages for each concentrate zone

$$\sum_{m=1}^{z} N_{sz} = N_{cT} \tag{3}$$

Probability of absorption of recuperated energy in other tramcars on line depends on the number of carriages in the zone of substation. If there are more carriages, i.e. it is closer to the center then probability is higher. But number of carriages in zone is increasing with the increasing of total number of carriages in town N_{cT}. Probability factor $0 < V_p < 1$ can be linearized proportionally to the number N_{sz} of carriages in zone versus to the number of carriages and probability factor V_{po} for the very center:

$$V_p = V_{p0} \frac{N_{sz}}{N_{sz0}} \tag{4}$$

Here V_{po} depends on time of a day. At the rush hours V_{p0r} is higher than for hours of smaller load V_{pom} (Fig.2). For instance for rush hours V_{por}=0.8 but for normal traffic V_{pom}=0.6.

Calculation of recuperation parameters

Average number of carriages along one radial route:

$$N_l = \frac{N_c}{M}, \tag{5}$$

where M is a number of routes from center to suburb. If number of stops along line is S_l then averaged volume of energy recuperated by traction motors on the examined route during day-night is

$$A_{rec}^{M} = \frac{N_c}{M} S_l A_{recav} K \quad . \tag{6}$$

K is number of full passages of carriage from center to suburb in day-night. In Riga such passage from center to suburb lasts approximately 0.5 hours with 0.25 hours interrupts at suburbs. In this connection the number of passages per day for one route is $K \approx \frac{20}{0.75} = 26.6$. This number K=26 can be accepted as an average believable.

Recuperated energy A_{rec} depends on loading of carriage. It can be accepted that on working days loading is connected with number of carriages in the town. During rush hours a loading is the highest but at normal number of carriages – the smallest, i.e. averaged for working days

$$A_{recav}^{w} = \frac{A_{recr}7 + A_{rekm}12}{19} \qquad , \qquad (7)$$

where A_{recr} and A_{rekm} are recuperated energy by one tramcar during rush and normal hours [1].
If for instance on a working day $N_{rushm} = 192$, $N_{cm} = 60$, leaving from center number of routes M=15, $S_l = 10$ stopping, $A_{recav} = 0{,}15$ kWh [3], then in one route during a typical working day all carriages recuperate energy

$$A_{rec}^{M} = \frac{7 \cdot 192 + 12 \cdot 60}{24 \cdot 15} \cdot 10 \cdot 0{,}15 \cdot 26 = 223{,}47 \text{ kWh} \qquad . \qquad (8)$$

In all M routes in one working day carriages recuperate totally

$$A_{rec}^{W} = M \cdot A_{rec}^{M} = 15 \cdot 223{,}47 = 3352{,}05 \text{ kWh.} \qquad (9)$$

At weekends loading can be accepted as full, i.e. $A_{recav}^{rest} = A_{recav}$. Then annual recuperated energy in the town

$$\sum A_{rec} = WD \cdot A_{rec}^{W} + RD \cdot A_{rec}^{rest}, \qquad (10)$$

where WD and RD are annual number of working days and weekends. Approximately we can accept that WD=260 and RD=105. In its turn

$$A_{rec}^{rest} = M \frac{0{,}5 N_{rushm}}{M} S_l A_{recav} K = 3744 \text{ kWh} \quad . \qquad (11)$$

Then total volume of the recuperated energy

$$\sum A_{rec} = 260 \cdot 3352{,}05 + 105 \cdot 3744 = 1{,}264 \cdot 10^{6} \text{ kWh} \qquad . \qquad (12)$$

A part of this volume of energy can be absorbed by carriages connected with the braking ones and this absorption depends on value of averaged probability factor V_{pav}, which in its turn depends on absorption probability in very center of town V_{p0}. If probability in center at rush hours is accepted on level 0.8 (Fig.2) but at normal load as 0.6 then

$$V_{pav} = 0.6(0.8\frac{7}{19} + 0.6\frac{12}{19}) = 0.42 \qquad . \qquad (13)$$

In such case annual absorbed volume of recuperated total energy is

$$\sum A_{aps} = V_{pav} \sum A_{rec} = 0.525 \cdot 10^{6} \text{ kWh} \ , \qquad (14)$$

but inverted through substations with installed inverting equipment [4] without taking into account small losses in lines

$$\sum A_{inv} = (1 - V_{pav}) \sum A_{rec} = 0.73 \cdot 10^6 \text{ kWh} \quad . \tag{15}$$

With the current price for electrical energy 0.05 Ls/kWh such an inverting provides annual economy

$$C_{inv} = 0.05 \cdot \sum A_{inv} = 36.5 \cdot 10^3 = 36500 \,\text{Ls.} \tag{16}$$

Considerations of local efficiency of inverting

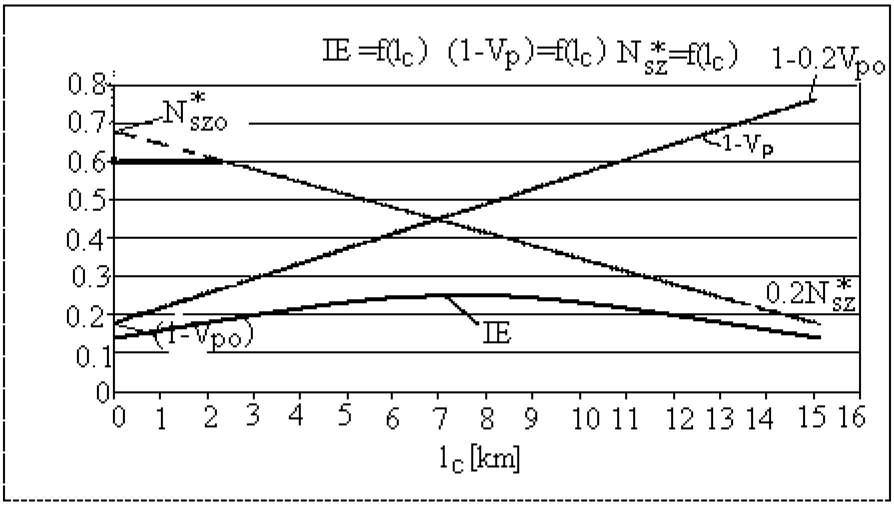

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Fig.3. Investments efficiency indicator IE , probabilities (1-Vp) and N^*_{sz} depending on l_c

Investments efficiency indicator depends on relative distance from center $\mathbf{\frac{l_c}{(D/2)} = f(l_c)}$:

$$IE = (1 - V_p) N^*_{sz} \tag{17}$$

where N^*_{sz} is a relative number of tramcars in the zone of substation. Fig.3 presents a case when probability of absorption for very center $V_{p0} = 0.8$, but $N^*_{sz0} = 0.6$, i.e. in central part of town located substations are connected with 60% of all tramcars in town.

If both $(1\text{-}V_p)$ and N^*_{sz} are in linear dependence on distance l_c then indicator of investments efficiency is

$$IE = N^*_{sz0} \left[1 - \frac{0{,}8 \cdot l_c}{\frac{D}{2}} \right] \cdot \left[(1 - V_{p0}) + 0{,}8 \cdot V_{p0} \frac{l_c}{\frac{D}{2}} \right], \; 0 \le l_c \le \frac{D}{2} \quad . \tag{18}$$

Relative distance $\frac{l_c}{0.5D}$ corresponding to the maximum of efficiency can be found as

$$\frac{l_c}{0.5D} = \frac{1.8 \cdot V_{p0} - 0.8}{1.28 \cdot V_{p0}}, (19)$$

where $\frac{l_c}{0.5D}$ must be between 0 and 1. If indicator V_{p0} for center is decreasing to 0.45, then the highest efficiency will be for central substations. If V_{p0} is 0.8, then maximum of efficiency should be at $\frac{l_c}{0.5D}$=0.62 (Fig.3). Fig.4 presents dependence of distance $\frac{l_c}{0.5D}$ at which exist maximum of efficiency on absorption probability factor V_{po} for central part of town .

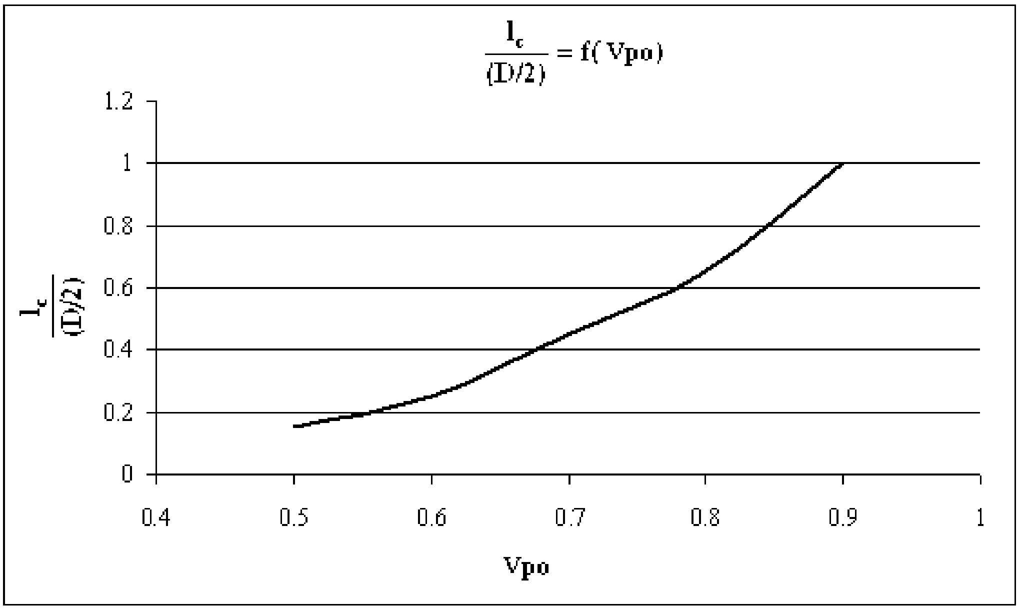

Fig.4. Dependence of relative distance from center for location of substation with maximum efficiency of investments versus absorption probability in center of town

As it can be seen maximum of the indicator of inverting efficiency corresponds to the distance close $l_c/0.5D \approx 0.5\text{-}0.6$ if probability factor for absorption of the energy regenerated by other tramcars on line in the central part of town can be accepted as 0.7-0.8 as it is in reality for rush hours on working days. It means that at reconstruction in the first stage must be developed with inverting equipment substations at a middle distance from center.

Conclusions

1. If traction substations are not equipped with inverting devices then large part of braking energy regenerated by tramcars will be dissipated as losses in additional braking resistors of tramcars.
2. Evaluation of braking energy dissipation must be provided using realistic probability factors of number of tramcars during day-night and taking into account character of a day – working or weekend.
3. Taking into account different influence parameters averaged value of absorbed by other tramcars on line braking energy can be accepted as 42% of all regenerated by total number of tramcars; 58% of regenerated energy without inverting substations is lost.
4. Most efficient as inverting substations are located at a middle distance from the very center of town and those substations must be renovated at the first stage of reconstruction.

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Raņķis I., Vītols A., Žiravecka A. Rīgas tramvaju rekuperētās enerģijas izmantošanas efektivitātes novērtējums.

Šajā publikācijā veikts Rīgas tramvaju rekuperētās bremzēšanas enerģijas izmantošanas novērtējums, pielietojot novērtējumus par ekipāžu skaitu uz līnijām diennakts laikā, kā arī ekipāžu skaita variācijām nedēļas dienu laikā. Parādīts, ka rekuperētās enerģijas izmantošanas pakāpe citos ar līniju apakšstacijas zonās saistītos tramvaju vagonos ir atkarīga gan no tramvaju skaita zonā, gan arī no attāluma līdz centram, kurā ir augstākā ekipāžu koncentrācija un lielākā izmantošanas varbūtība. Ņemot vērā visus minētos faktorus, noteikts, ka šis faktors vidēji gada laikā varētu būt 0,42, t.i., 58% no visas bremzēšanas enerģijas tiek izkliedēti bremzēšanas reostatos kā zudumi. Novērtēts, kurās pilsētas daļās būtu visefektīvāk ieviest apakšstacijās invertēšanas iekārtas. Ņemot vērā, ka pilsētas centrā ir liela varbūtība, ka enerģija tiks izmantota citās ekipāžās, bet nomalēs ir maza tramvaju intensitāte, vislielākais efekts sasniedzams vidējā distancē no centra. Doti absolūtie skaitļi par rekuperētās enerģijas izmantošanu dažādās apakšstaciju sistēmas komponentēs.

Rankis I., Vitols A., Zhiravetska A., Evaluation of utilization efficiency of regenerative energy in the Riga tramcar system.

The evaluation of utilization efficiency of the regenerative braking energy developed by tramcars in Riga is done taking into account the number of on-line tramcars during a day and its variations during a week. It is shown that the utilization of the regenerated energy by other tramcars in the same substation zone depends both on their number and on the distance from the city centre, where the maximum density of the tramcars and their maximum exploitation are observed. With all this taken into consideration it was found that the average annual utilization factor can be up to 0.42, which means that 58% of the regenerated energy (without inverting substations) is dissipated in braking resistors of tramcars as losses. It is estimated in what city districts the implementation of inverting equipment at the substations can give the greatest effect. Taking into account that in the city centre a high probability exists that the energy will be used by other cars and that in the suburbs the tramcar traffic is less intensive, the greatest effect could be expected for the medium distance from the centre. The authors present the data on the regenerative energy utilization at different substation components.

Ранкис И., Витолс А., Жиравецка А., Оценка эффективности использования рекуперативной энергии рижских трамваев.

В данной публикации произведена оценка использования рекуперативной энергии торможения, применяя оценку об количестве экипажей на линиях в течении суток, а также вариации количества экипажей в течении недели. Показано, что степень использования рекуперативной энергии на других трамвайных вагонах, связанных в зоне подстанции линии, зависит как и от количества трамваев в зоне, а также от расстояния до центра, в котором наибольшая концентрация экипажей и большая вероятность использования. Принимая во внимание все указанные факторы найдено, что этот фактор в среднем в году может составлять 0,42, т.е. 58% от всей энергии торможения распределены в тормозных реостатах как потери. Оценено, в каких районах города был бы наибольший эффект вводить оборудование инвертирования подстанций. Принимая во внимание, что в центре города большая вероятность, что энергия будет использована в других экипажах, а на окраинах малая интенсивность трамваев, наибольшей эффект может быть достигнут на средней дистанции от центра. Даны абсолютные данные об использовании рекуперативной энергии на различных компонентах подстанции.