Energy-saving tram vehicle with on-board energy accumulator

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Abstract: **Energy saving effects connected with use of energy accumulator on board of tram vehicle instead of substation are presented. Different solutions of energy on-board accumulator are presented and application of supercapacitor is suggested. Differences in results regarding weak and strong power supply system when taking into account energy losses and energy recuperation are pointed out.**

1. Introduction

Traction vehicles with ability of energy to-contact line recuperation operate effectively on lines of heavy traffic intensity. A traction vehicle simultaneously present on feeding section and consuming energy from the contact line conditions usage of recuperated energy. Energy is lost out in resistors of the vehicle if at the moment of recuperation there are no other vehicles consuming energy present on feeding section.

In case of subway, timetable may be adjusted from the point of view of recuperation efficiency. In such case energy-savings may be the highest and practically amount to 15%. On tram lines of low traffic intensity and also on railway lines as well as on tram lines of low traffic intensity and also on many lines out of rush hours probability of usage of recuperated energy decrease to several per cent.

As a solution increasing recuperation efficiency, independently on traffic intensity implementation of energy accumulators on traction substation is being proposed. Introducing vehicles with energy recuperation and accumulators on substations demand strengthening contact line (resistance decreasing). Significant is also enlarging feeding area.

It is because of decreasing of losses and also securing proper short circuit identification during recuperation. This solution increases recuperation efficiency. As regards necessity of using of accumulators and strengthening of feeding system it is an expensive solution. Introducing an on-board accumulator is followed by increase of mass of vehicle.

In this paper analysis of usefulness of available energy accumulators for application in traction vehicles was carried out. A comparison of running mode and energy charged from substation by a tram vehicle with energy accumulator and a tram vehicle without on-board energy accumulator but supplied from substation equipped with energy accumulator was carried out.

2. Solutions of on-board energy accumulators

Actually available are three kinds of energy accumulators: chemical accumulator, rotary accumulator and supercapacitor. For these accumulators it is possible to match solutions of comparable unit capacitances and similar costs. In this case significant become characteristic features of individual solution.
Energy accumulator used in tram vehicle should be characterised by:
- high unit capacitance,
- ability of total discharge of stored energy within time up to 30 seconds which demands high unit power,
- high durabiliy (at least 10 years)
- high energy efficiency of charge/discharge cycle.

In modern low-floor tram vehicles it is difficult to place elements of high dimensions. Therefore significant is ability of shaping individual dimensions of accumulator.

3. Accumulator features

Energy accumulators differ each from another in unit price (PLN/Wh), unit energy capacity (Wh/kg), durability (number of discharge/charge), energy efficiency in cycle (discharge energy/ charge energy), unit power (W/kg) connected with charge and discharge time of total energy accumulated, time of self-discharge.

These parameters are the most significant ones for application of peak energy accumulator.

Possible types of energy accumulators are described below.

3.1 Chemical accumulator

There is a number of types of chemical accumulators differing in mentioned parameters. From among below considered types of accumulators they are characterised by the most unit energy capacity, reaching 200 Wh/kg and the lowest unit price.
However chemical accumulators are characterised by long nominal time of discharge equal to several hours, independently on type of accumulator. With shortened time of charge and discharge, the efficiency coefficient strongly decreases as well as energy capacity. For improving of efficiency very large energy capacity, a few dozen more than one recuperated during a single breaking, is required. Practically efficiency of charge/discharge cycle does not exceed 70%. Low durability 500÷1000 cycles is a very negative feature. Weight of accumulator required for tram vehicle would reach over ten tons. Self-discharge time reaches one year.

3.2 Rotary accumulator

Previously applied low-rotary accumulators were equipped in wheels of big mass and diameters. Such accumulators for the sake of low energy capacity were not widespread. There is a necessity of using strong casing in order to protect the wheel in case of transport accident. This makes unit capacity even lower. Modern accumulators are characterised by low mass, but high rotary speed. Wheels are made of materials of high endurance. Applied are vaccum casings in order to decrease energy losses and special bearings. Energy capacity reaches 20 Wh/kg. Wheel is integrated with electric machine system performing as motor or generator as well. Electric machine efficiency exceeds 90% and converter efficiency reaches 90 %. Global efficiency of charge and discharge cycle reaches 70%.

Basic advantages of these accumulators are: very high durability of over ten years at practically unlimited number of cycles (several million) and a very high unit power. Charge and discharge time is equal to a few dozen seconds. Time of self-discharge is equal to over ten days.

Rotating mass requires vertical support of rotary axis for the sake of very high compensating moment at axis deviation (gyroscope effect). Rotary accumulators require maintenance in connection with necessity of oil change in bearing.

3.3 Supercapacitors

Actually being worked out supercapacitors may make up alternative energy accumulators. High capacity of such capacitors allow to accumulate up to 6Wh/kg of energy. Durability of capacitors reach 10 years enabling over 500000 cycles of charge and discharge. Capacitors are characterised by very high unit power making possible energy charging or discharging within less than 30 seconds. Efficiency of charge/discharge cycle reaches 95%. Self-discharge time is equal to several years.

It results from above presented accumulators features that in vehicles the most justified is to apply supercapacitors. For the comparative analysis an application of supercapacitors was assumed also in substation.

4 Tram vehicles and power supply system

For the comparative analysis assumed were tram vehicles:

- one recuperating energy to contact line, mass 40 Mg
- second with energy recuperation to on-board accumulator, mass 42 Mg.

Tram with accumulator has a lower efficiency of converter systems. It results from necessity of levelling the voltage difference between contact line and supercapacitor. Tram with accumulator is of enlarged maximal power by 5% to allow obtaining the same running parameters as the tram without accumulator.

Parameters of feeding substation, traction contact line for both cases are identical.

Electric traction of tram transport system is considered DC 660V with one side feeding. The feeding area of substation is divided into a number of sections supplied from individual cables (feeders). This concern only contact line while obviously rails make up one circuit with return feeders attached to it. Locations of feeders and return cables are different. Length of section is connected with short circuit current which also conditions feeder's fast breakers stings. Therefore line resistance representing catenary R_c and rail R_r resistance is summed to cables resistance which may be significant on distant sections:

$$R_s = R_c + R_r + R_f \qquad (1)$$

Another important resistance component of the vehicle feeding circuit is substation resistance (R_p):

$$R_p = \frac{\Delta U_L + \Delta U_R + \Delta U_{REC} + \Delta U_S}{n \cdot I_n} \qquad (2)$$

where: ΔU_L. and ΔU_R adequately inductive and resistive voltage drop in transformer circuit caused by nominal rectifier unit current I_n , ΔU_{REC} - voltage drop on rectifier, ΔU_S -voltage drop in supply system, caused by I_n . Consequently substation resistance value depends mainly on nominal rectifier unit power, nominal rectifier transformer power and short circuit power on AC bus of traction substation.

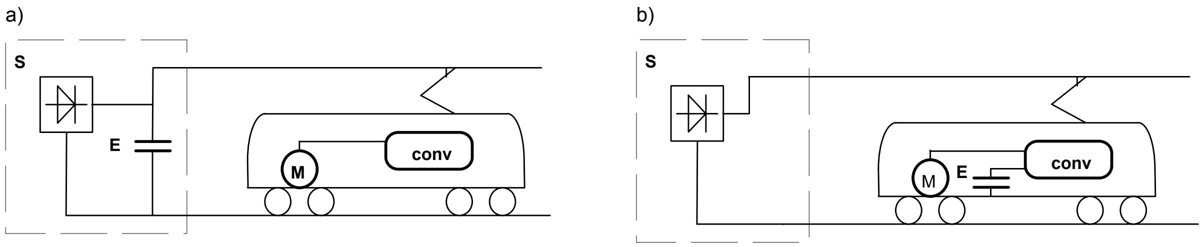

Fig. l. Analysed tram vehicles

S - feeding substation, E - energy accumulator, conv - converter unit. M - drive

a) tram without energy accumulator - accumulator on substation, b) tram with energy accumulator on board

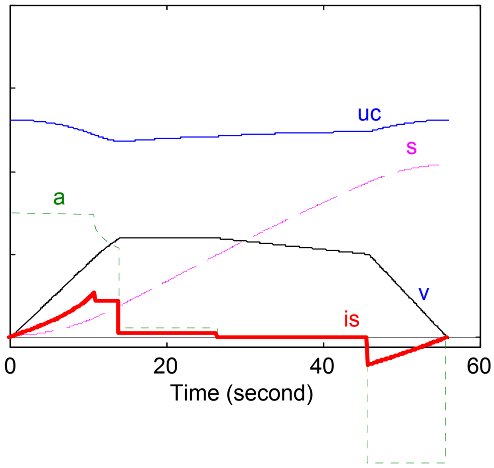

Fig.2 Schematic presentation of typical run mode. Curves: v - velocity, s - distance, a - acceleration, is - vehicle current, uc - energy accumulator voltage.

In both cases tram vehicles run according to the same run (traffic) algorithms. Fig.2 presents some run curves in case of tram vehicle without energy accumulator. Exemplary run results including delivered, consumed and recuperated energy in case of a vehicle equipped with energy accumulator and a vehicle without accumulator are presented in figure 3. Fig.4 presents maximum power depending on line resistance in both cases: with/without energy accumulator on board.

Significant parameter of power supply system is maximal load power. Maximum power taken from feeding system is reached at final phase of starting, when maximum velocity is obtained at maximal acceleration. Power taken from substation is increased by losses in feeding system. In the analysis maximum power limited only by permissible minimal voltage at current collector was assumed. Tram without energy accumulator may collect power of

1360kW (fig.4) at total feeding system resistance equal to 0.154Ω and drive power 770kW. Further increasing of resistance decreases peak power for the sake of limitation of permissible drop of voltage in feeding system. Tram vehicle with energy accumulator, independently on temporary drive power running into 800kW may charge feeding system with power of over 20 times less than in first case. Operating algorithm of tram with accumulator enables limitation of maximal power on the level below 52kW.

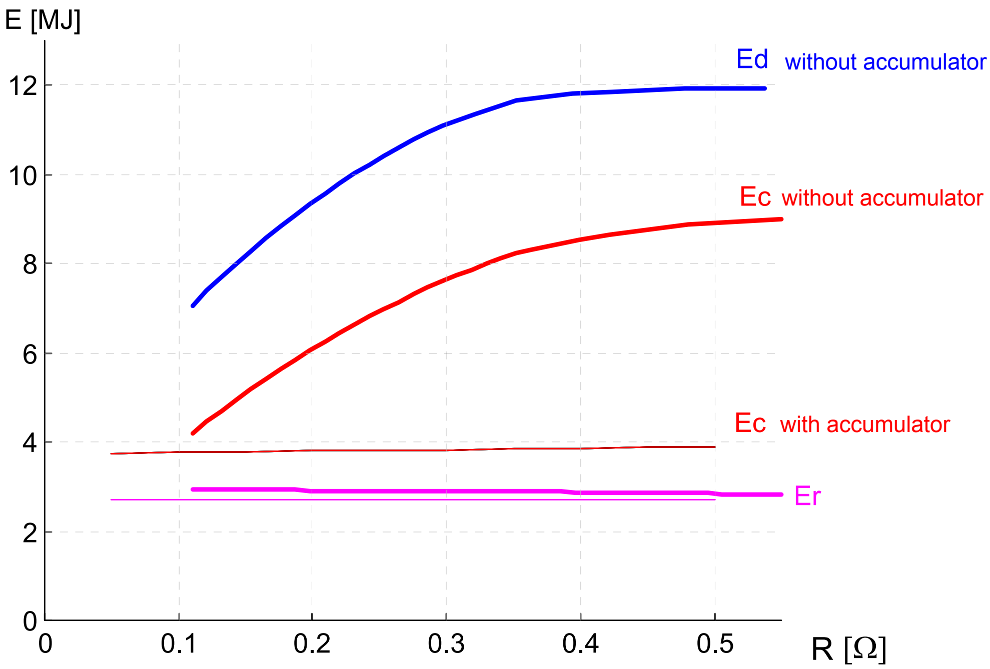

Fig.3 Exemplary run results: energy delivered (Ed), consumed (Ec) and recuperated (Er) in case of a vehicle equipped with energy accumulator (thin lines), and a vehicle without accumulator (bold lines).

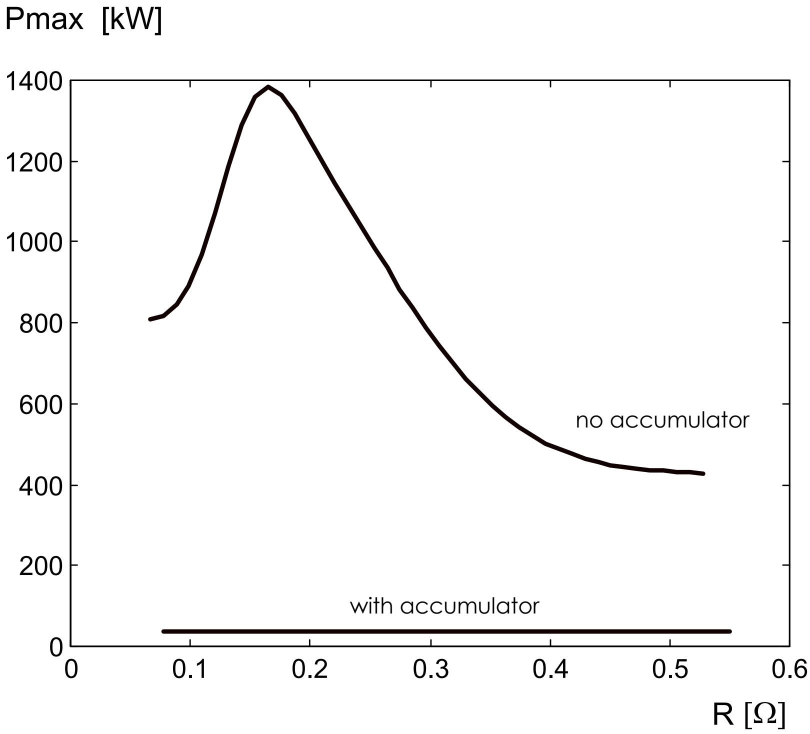

Fig.4 Maximum power versus line resistance - comparison of cases: with/without energy accumulator

5. Conclusions

Tram vehicle with on-board energy accumulator in spite of higher mass charge less energy for the run on the section between the stops, independently on type of contact line and on distance from feeding substation. The difference rises up to as much as 5 MJ for total of system resistance 0.5Ω and maximal considered distance from the substation.

For supply system of high short circuit power ("strong") with traction substation and contact line of low resistance the difference of energy change from.0.4 MJ for run near substation till 5.2 MJ for section in distance 3.km from substation. In extreme case the traction vehicle without accumulator charges 9 MJ which is by.130% more than vehicle with accumulator.

The greatest energy-saving effects connected with transfer of energy accumulator from substation to vehicle are obtained on lines where substation and traction contact line are of high resistance ("weak").

Application of energy accumulator in tram vehicle and not in substation involves extra benefits. Power supply system – traction substations, traction catenary do not have to be modernised in order to use energy coming from recuperation. Possible is introducing rolling stock of higher maximal power, increasing traffic intensity on section without a necessity of contact line modernisation. Possible is increasing average run speed. There is no necessity of use of power limitation connected with too low voltage level at the final phase of run. Maximal power returned to power supply system at initial phase of breaking is not limited with too high voltage in catenary. Tram vehicle without accumulator for the sake of voltage lower and upper limitations will cover the distance slower, and if assumed is the same run time than it will charge greater energy because starting and breaking will last longer.

If power supply area was operated only by trams with accumulators than possible would be lowering threshold of taking action of fast breakers at substation, which would increase their durability.

Presented above analysis was carried out for particular case. Only run of single vehicle was under consideration. With increase of traffic intensity energy consumption for run on equivalent distance may differ. It is connected with non-linear increase of losses in power feeding system with increase of current. This issue requires further analysis.
Tram vehicles with on-board energy accumulators could be introduced individually and immediately provide energy savings.

5. References

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