TECHNICAL BENEFITS OF TRAM VEHICLE ENERGY ACCUMULATOR

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Summary Energy saving effects connected with use of energy accumulator on board of tram vehicle instead of substation are presented. Differences in results regarding weak and strong power supply system when taking into account energy losses and energy recuperation are pointed out. Running mode and energy charged from substation by a tram vehicle with accumulator is compared to a tram vehicle without on-board accumulator but supplied from substation equipped with energy accumulator.

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.

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 [1]. 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 demands strengthening contact line (resistance decreasing). Significant is also enlarging feeding area to increase recuperation efficiency. It is because of necessity to decrease losses and also to secure proper short circuit identification during recuperation.

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 durability (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.

Energy accumulators differ each from another in unit price (EUR/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. Mentioned parameters are the most significant ones for application of peak energy accumulator.

Actually in the wide scope of implementation there are three kinds of energy accumulators available: chemical accumulator, rotary accumulator and super-capacitor. 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.

Low durability and mass of chemical accumulator required for tram vehicle rather disqualify it for potential implementation. Modern rotary accumulators are characterised by low mass, high rotary speed, wheels made of high endurance materials, vacuum casings and special bearings. Energy capacity reaches 20 [Wh/kg]. All this make rotary accumulator attractive mains of peak energy saver. However wheel is integrated with electric machine system performing as motor or generator as well. Therefore electric machine efficiency and converter efficiency both limit global efficiency of charge and discharge cycle. Moreover 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.

Super capacitors actually being worked out may make up alternative energy accumulators [3]. High capacity of such capacitors allow to accumulate energy up to 6Wh/kg. Durability of capacitors reaches 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. Conclusion here is that in vehicles the most justified is to apply super-capacitors as energy accumulators.

An analysis of usefulness of energy accumulators for application in traction vehicles was carried out. For comparison, an analysis of application of super-capacitors in substation was also carried out.

2. TRAM VEHICLES AND POWER SUPPLY SYSTEM ANALYSIS

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. A total efficiency of tram with accumulator is lower a little because of converter systems. It results from necessity of levelling the voltage difference between contact line and super-capacitor. For the sake of the analysis maximal power of tram with accumulator is enlarged 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.

Considered is DC 660 V one side feeding system. The feeding of substation is divided into a number of sections supplied from individual cables (feeders). This concerns only contact line while 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 settings. Therefore line resistance representing catenary R_c and rail R_r resistance is summed to cables resistance R_{cab} which may be significant on distant sections:

$$R_s = R_c + R_r + R_{cab}. \tag{1}$$

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

$$R_p = \frac{\Delta U_L + \Delta U_R + \Delta U_{REC} + \Delta U_S}{n \cdot I_n}, \tag{2}$$

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.

In both cases tram vehicles run according to the same run (traffic) algorithms. Fig. 3 presents basic curves describing the run on a distance between two stops. 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 Fig. 6.

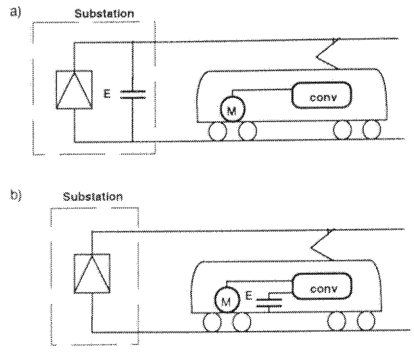

Fig. 1. Analysed tram vehicles feeding systems. E - energy accumulator, conv - converter unit, M – drive. a) tram without energy accumulator - accumulator on substation, b) tram with on-board energy accumulator

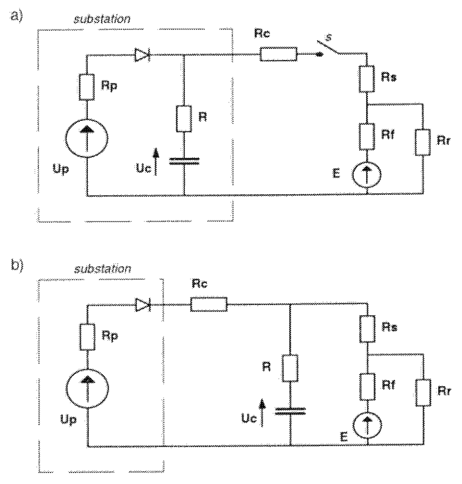

Fig. 2. Simplified substitute circuits.

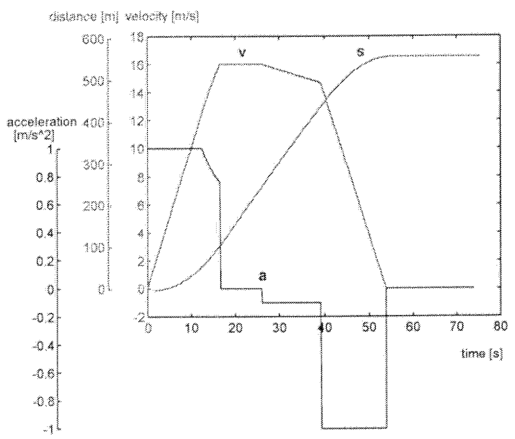

Fig. 3. Run mode described by curves of velocity, distance and acceleration in time.

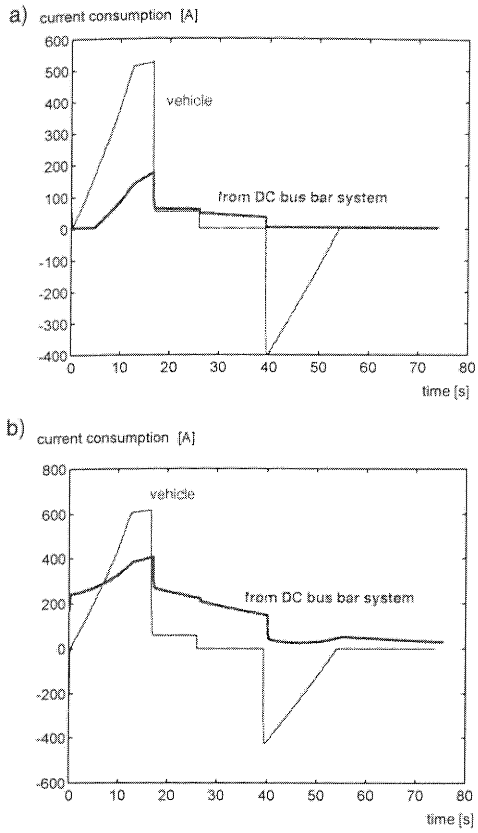

Fig. 4. Current consumption at Rc=0.1 [Ohm], and different initial values of voltage on accumulator, which correspond to fig.5 a) and b).

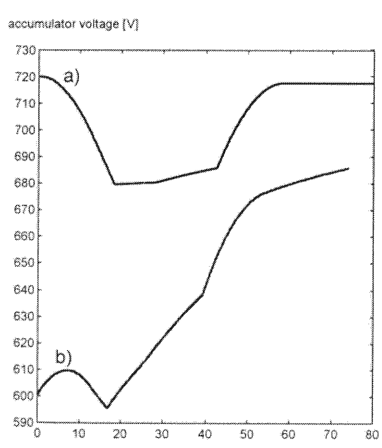

Fig. 5. Voltage on accumulator plots at different initial values for Rc=0.1 [Ohm]

Fig. 7 presents power depending on line resistance in both cases: with/without energy accumulator on board. In case of tram without accumulator this is maximal value of vehicle power for traction goals. In the case of tram with accumulator this is power which may be consumed by tram in continuous way. This power is averaged power value for running time. Passed over were auxiliary systems power losses. Then such power is less than medium ordinary tram vehicle power for the sake of much lower losses in feeding system.

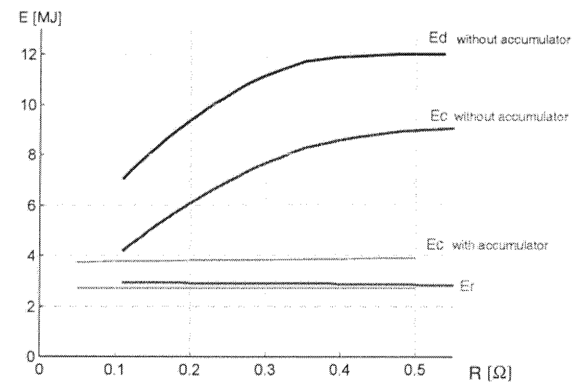

Fig. 6. Exemplary run results: energy delivered (Ed), consumed (Ec) and recuperated (Er) in case of a vehicle equipped with energy accumulator (thin lines), and a vehicle without accumulator (bold lines).

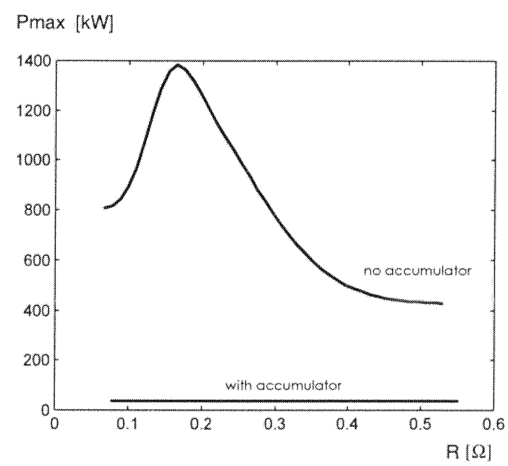

Fig. 7. Maximum power versus line resistance - comparison of cases: with/without energy accumulator

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 1360 kW at total feeding system resistance equal to 0.154 Ω and drive power 770 kW. 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 800 kW may charge feeding system with power of over 20 times less than in first case. Of course such situation is strictly theoretical. Mentioned and graphically presented values concern vehicle traction power only, while auxiliary equipment is not taken into account. However this relation shows considerably high advantage for on-board accumulator application. Operating algorithm of tram with accumulator enables limitation of maximal power on the level below 52 kW.

Tram vehicle with on-board energy accumulator in spite of higher mass charges 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 0.5 Ohm 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").

3. CONCLUSIONS

Presented analysis considered case of single vehicle. With increase of traffic intensity energy consumption for run on equivalent distance may differ which is connected with non-linear increase of losses in power feeding system with increase of current. However achieved results point out advantages for application of energy accumulator in tram vehicle and not in substation. There are some further technical 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 low level voltage at the final phase of run. Maximal power returned to power supply system at initial phase of breaking is not limited with high level 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 then it would charge greater energy because starting and breaking would last longer.

If power supply area is 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.

Some more general points for and against both solutions are listed below.

Advantages of on-board accumulator:

- Abilities of gradually introducing individual vehicles of the new type
- Low investment costs
- Ability of increasing traffic intensity without substation and/or supplying lines modernization
- Decreased consumed maximal power therefore decreased costs of power terminals
- Energy consumed significantly decreased
- Energy losses in traction catenary lowered
- At stage of mixed traffic operated with vehicles both of old and new type – ability of energy transfer from ordinary vehicles (not equipped with accumulator)
- When all rolling stock exchanged for the new type – lowered investment costs for substations and power supply systems

Advantages of Accumulator in substation:

- Possible lowering of maximal power consumed from power industry with use of the accumulator – lowering the power terminals
- Possible application of any kind of accumulator
- Making better use of accumulator capacity for existing already rolling stock

Disadvantages of on-board accumulator:

- Currently the new type of the rolling stock is not manufactured
- Increased mass of vehicles
- Application reduced to capacitor-type accumulator only

Disadvantages of accumulator in substation:

- necessity of traction catenary system strengthening
- High investment costs independent on number of vehicles
- Higher energy looses in traction catenary

Tram vehicles with on-board energy accumulators could be introduced individually and immediately provide energy savings.

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