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HYBRID ENERGY STORAGE SYSTEMS IN ELECTRIC TRACTION

Piotr Biczel
Warsaw University of Technology, Institute of Electrical Machines, Poland

Abstract
The question of the efficient recovery of braking energy is becoming increasingly important, with emphasis on improving the energy efficiency of the economy. The effectiveness of recovery in rail vehicles is limited, inter alia, by the possibility of consumption of recovered energy. One way to improve the recovery efficiency is building energy storage devices in substations, on the network and in rail vehicles. Such storage devices have to work in two modes: as a reservoir of power, compensating for the ripple current, or as a reservoir of energy, supplying vehicles for longer periods. Presently, power storage systems may be made using ultra-capacitors that have a possibility to make hundreds of thousands cycles of high current and low energy. Applications of the battery storage allows the storage of large amounts of energy, but not for high-frequent cycle. The solution to the problem are hybrid storage systems which combine the features of power and energy storage tank. They can be made on the basis of existing batteries and ultra-capacitors. The size of stored power and energy depends upon the volume designated for each part. The article explains how power and energy capacity change versus ratio of the volume destined for battery and ultra-capacitor. Another solution is to use modern LTO and LIC cell, which combine features of batteries and capacitors. The article presents a comparison of the power and energy of storage systems made from these hybrid cells. Construction of a storage tank capable of storing both power and energy and for providing high number of cycles opens the way to new supplying solutions for rail vehicles like periodical charging of the vehicle storage system.

Introduction

Nowadays, in the era of struggle for reduction of CO_2 emissions and energy consumption of economy rail vehicles with recuperation of braking energy became standard. Energy recovery involves converting the vehicle's kinetic energy into electricity again and feeding it to a traction network [10]. Ideally, this energy could be transmitted to the public distribution network or completely consumed by other vehicle. Only then the energy saving effect would be the most significant.

Unfortunately, pulses of power demand typical for rail vehicles pose a problem for operators of distribution system as they cause difficulties with voltage regulation and, above all, the emergence of voltage dips and flicker effect. This is particularly troublesome for other energy consumers.

The widespread introduction of energy recovery could increase energy savings thereby reducing the energy consumption of economy and the environmental impact of emissions, particularly CO_2. Unfortunately, in addition to the pulses of consumed power the pulses of generated power would arise when regenerated energy occurred. So now distribution systems operators defend themselves against receiving recuperation energy from railway networks. Investments in utility grid will be enforced by the deterioration of voltage quality, the increase of short circuit power in system, the emergence of two-way energy flows all enforcing a change in protection system organization.

Battery energy storage

The solution to problems at the interface between railway network and the distribution grid and the obstacle of sudden changes of voltage in a traction network may be the use of energy storage devices, the job of which is to take over power pulses load in both directions. The ideal would be the complete removal of impulse flows. The best solution would be an acquisition of energy from regenerative braking so that there is no need of using brake resistor or transmitting electricity to the grid.

The storage devices can be connected to the power traction at the traction substation, at the selected sites in network, or directly in a vehicle.

The use of energy storage in a traction substation removes only the limitation for recovery resulting from phenomena at the interface between distribution and traction networks. However, it does not eliminate problems arising in the traction, primarily voltage peaks. It can be effectively reduced by the installation of energy storage system as close to the source of pulse flows as possible, i.e. in a vehicle.

An intermediate way is to install energy storage devices at selected points of power traction.

Probably it would be best to use storage device in a vehicle. In vehicle there is usually little space which requires the installation of storage elements and converters. Integration with other systems in vehicle is necessary as well.

The installation of storage system in vehicle immediately causes willingness for using the stored energy for vehicle stand-alone operation, i.e. without power from traction. It is a very tempting prospect for security reasons (exit from the crossroads or access to depot in the event of mains failure) and because of the possibility of building railways in areas where it is difficult or impossible to build power traction (e.g. drawbridges, historical town centres). Such applications make it necessary to store large amounts of energy.

The general block diagram of the energy storage system for a DC system is presented in Fig. 1.

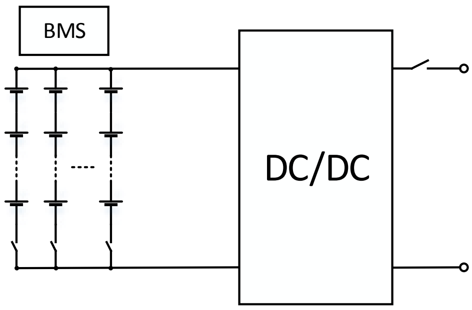

Fig. 1. Block diagram of storage device in DC system.

The storage device is connected to the DC network through power electronic converter.

The converter completes the following tasks:

- controls power flow,
- controls voltage of the storage device,
- protects the storage device against overcharging and over discharging,
- controls operation of the storage system during transient states and limits inrush current,
- limits or controls short circuit power in a coupling point of the storage device,
- performs protection features,
- introduces galvanic insulation (if applicable).

Battery or capacitor management system (BMS or CMS) controls the device's electrical and thermal operation conditions and protects them against malfunction as well as failure.

Operating conditions of energy storage system in rail vehicle

The rail vehicle in city or suburban traffic generates a lot of power pulses in the rail network – every time when vehicle accelerates there is a pulse of power consumption from traction and each time vehicle brakes it puts power pulse into the grid. During normal vehicle operation there are hundreds of such pulses a day. These are short pulses of high current rise.

On the other hand, the above-mentioned requirements concerning safety, uneven ground traffic, traffic in places where rail network cannot be built incline to design the storage device with relatively large energy capacity.

The requirements for a rail vehicle storage system can be summarised as follows:

- needs to have small volume,
- has to be able to perform dozen of thousands of cycles,
- needs to have high capacity,
- has to be able to consume and release high current peaks.

The above mentioned requirements are in conflict with one another. Modern electrochemical storage elements can either perform hundreds of thousands of deep cycles or store a lot of energy [5].

Storage element that can perform hundreds of thousands of cycles and receive currents with high slope is obviously an ultra-capacitor. However, this element has a very low energy density in the sense of volume and mass. It takes in many current pulses but can store little energy.

The secondary cell is able to store a lot of energy but the number of deep cycles is limited to from a few hundred to a few thousand.

To meet all requirements one needs to make a storage system that will have features of both. Such structures are called hybrid storage tanks [4] [8].

Hybrid energy storage system

De facto, the idea of hybridisation of storage system involves the building of two storage devices:

- one, the task of which is to take over pulse power flows with considerable high slopes of current
- second, the task of which is to store and release energy over a longer period of time.

Thus, naturally, the first subsystem contains ultra-capacitor as a storage element, the second – battery. The first should be regarded as a power storage device, and the second as an energy storage device.

Hybrid storage system can be formed as two separate subsystems (Fig. 2) or can be structurally related to each other (Fig. 3) [4] [8].

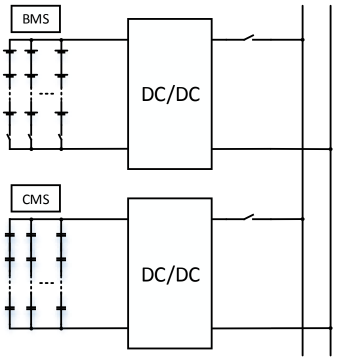

Fig. 2. Parallel hybrid storage system

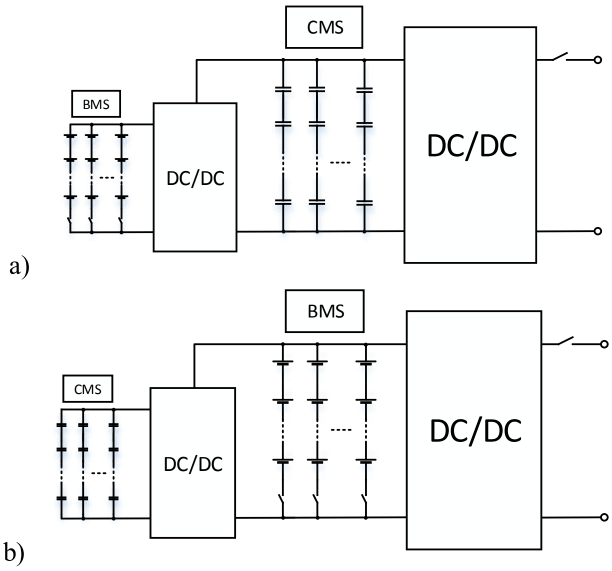

Fig. 3. Example of a combined hybrid storage system: a) with low voltage battery, b) low voltage capacitor.

In a hybrid storage system the capacity of an ultra-capacitor may be reduced because its task is to take over only the first part of current pulse. The second part should be consumed by the less dynamic storage element, which is a lithium-ion secondary battery. The battery is only responsible for long-term storage of energy. There is no need to oversize the battery capacity due to the lack of necessity of taking over steep current pulse and increasing cyclical lifetime.

An important issue is how to divide the available space between the power and energy subsystems. The specific allocation of capacity results from a given application, vehicle type, and route profile. The limitations, which should be considered from the point of view of storage elements are:

- maximum and minimum voltage,
- maximum charging and discharging current,
- maximum current rising slope,
- depth and number of cycles.

Maintaining sufficient current rise dynamic is crucial for the voltage stabilization effectiveness and storage device lifetime preservation. Forcing excessive steepness of current values rise causes the aging of components while excessive restriction – the reduction of storage system effectivity. The issue of the dynamics behaviour of storage elements is described, for example, in [1] [3] [Gent] [7] [9]. A typical waveform of pulse load of a lithium-ion cell is shown in Fig. 4 [2] and Fig. 5.

It should be also remembered that the natural dynamics of cells and capacitors will be further limited by the dynamics of converter. Thus, the converters have to be properly matched to each type of storage device and the required slope of current rise.

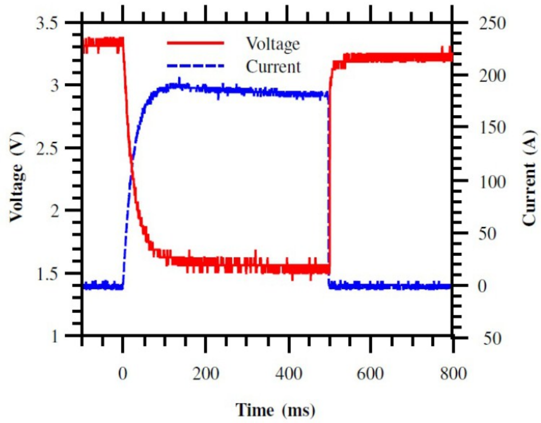

Fig. 4. Example of dynamic behaviour of a Li-Ion cell, pulse load [2].

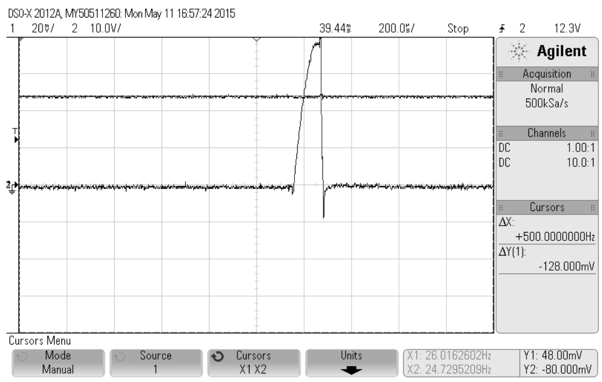

Fig. 5. Example of dynamic behaviour of a Li-Ion cell, short circuit.

Capacity of ultra-capacitor and accumulator in the hybrid energy storage

Let's consider the problem of capacity and power of hybrid energy storage. It was assumed that the both storage devices (without converters and BMS systems) can occupy a volume of 0.5 m^3. What is the total power and capacity a hybrid storage system will have depending on the ratio of the available volume for each of the two storage elements?

The calculations will be performed for a model ultra-capacitor (SC) and lithium-ion NMC type battery. These are typical modern storage elements used for cyclic operation.

It is assumed that ultra-capacitor will be discharged to a level of 50% of the maximum voltage.

It is assumed that the maximum charge and discharge current of a system is equal to the maximum continuous current declared by the manufacturer.

Parameters of both storage devices used in the calculations are shown in Table 1.

Table 1. Parameters of ultra-capacitor and accumulator used in the example

Storage device	NMC	SC
Max voltage [V]	4,1	2.7
Min voltage [V]	2.8	1.5
Capacity [Ah]	50	0.67
Max current [A]	100	1000
Energy [Wh]	185	1.4
Power [W]	370	2100
Energy vol. density [kWh/m3]	265	4.8
Power vol. density [kW/m3]	530	7190
Disch. time @ max. current [s]	1800	2,5

If the entire volume of 0.5 m^3 was designed exclusively for the ultra-capacitor or battery storage system, then at an average voltage of 600 V the storage systems would have a capacity and maximum charging current as in Table 2.

Table 2. Maximum current and capacity of the storage system of SC or NMC at average. voltage 600 V.

Storage device	NMC	SC
Energy [kWh]	132.5	2.4
Capacity [Ah]	200	4
Power [kW]	240	3600
Max current [A]	400	6000

If a given volume was shared in between the two storage elements the total power, energy, capacity, and mass of hybrid storage system would vary as a function of ratio of volume split as shown in Fig. 6-8.

Comparing the results shown in Fig. 6 with the data of Table 1 it can be seen that the energy of a hybrid storage system is determined mainly by battery, power, however, mainly by the ultra-capacitor. The number and depth of cycles also vary in accordance with the distribution of volume in between the two types of storage devices. Hybrid storage system can perform approx. 6 000 energy cycles with the energy resulting from the preconceived volume for accumulator and approx. 1 000 000 with the use of available power. For this reason, dynamic and pulse loads should be appropriately shared between both storage elements.

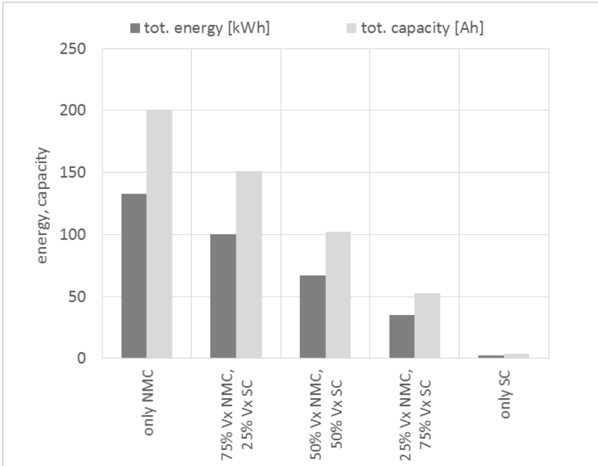

Fig. 6. Total stored energy and capacity of particular versions of hybrid storage systems.

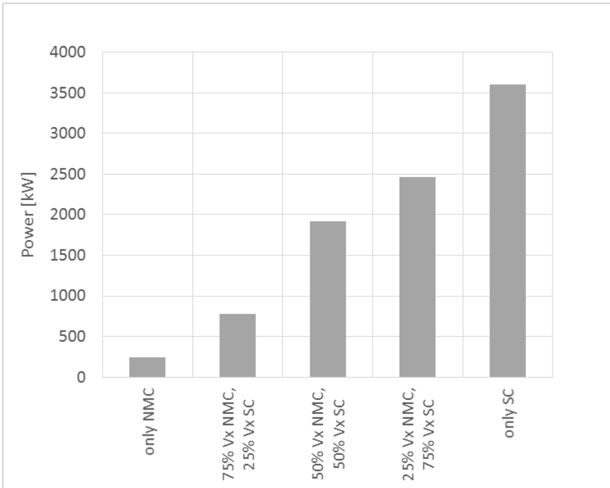

Fig. 7. Total power of particular versions of hybrid storage systems.

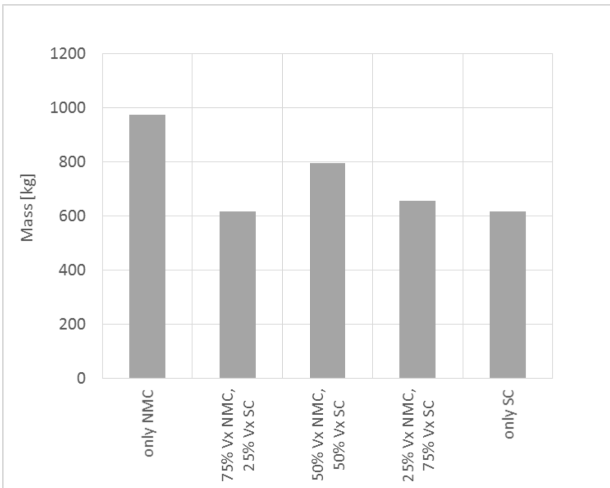

Fig. 8. Total mass of particular versions of hybrid storage systems.

Modern energy storage devices

Installation of hybrid energy storage, however, entails two problems. First, they are de facto two systems so they take more space and require the integration of the two devices. Second, in terms of the control sub storages must be correlated with each other, the vehicle system and the expected route profile.

Another solution to the problem is to use such a storage element which combines characteristics of ultra-capacitor and secondary cells. The comparison of ultra-capacitors and secondary cells gives the following conclusions:

- secondary cells have much higher energy density,
- ultra-capacitors have much higher power density,
- ultra-capacitors have significantly longer cycle lifetime than secondary cells.

Interestingly, the space of power and energy between the batteries and ultra-capacitors is free, unfilled so far by any devices.

Manufacturers of electrochemical cells went in this direction. The main motivation to search is to increase the number of cycles and discharge and charge currents of storing devices. In other words, battery design starts to resemble ultra-capacitor's properties.

Currently on the market there are two interesting devices that have these characteristics:

- lithium-ion secondary cells with LTO type anode,
- lithium-ion capacitors LIC.

LTO cell has characteristics similar to a battery but its order of magnitude has more cycles. In contrast, LIC cells have characteristics similar to ultra-capacitor but capacity is increased by an order of magnitude. Basic parameters of these cells are shown in Table 3. Both are ranked among existing devices as shown in Fig. 9. The comparison of the available number of cycles for cells NMC, LTO, LIC and SC is shown in Fig. 10.

Table 3. Parameters of LTO and LIC cells

Storage device	LTO	LIC
Max voltage [V]	2.7	3.8
Min voltage [V]	1.5	2.2
Capcity [Ah]	20	1,1
Max current [A]	400	500
Energy [Wh]	46	3,3
Power [W]	840	1500
Energy vol. density [kWh/m3]	177	15
Power vol. density [kW/m3]	3230	6800
Disch. time @ max. current [s]	180	12

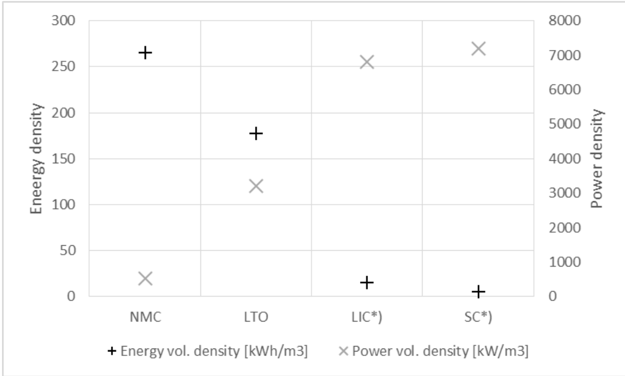

Fig. 9. Comparison of energy and power density of compared storage devices.

Fig. 11-13 shows a comparison of the basic parameters of the mentioned above hybrid storage systems with those made using LTO cells or LIC with the same volume of 0.5 m^3 and medium voltage of 600 V.

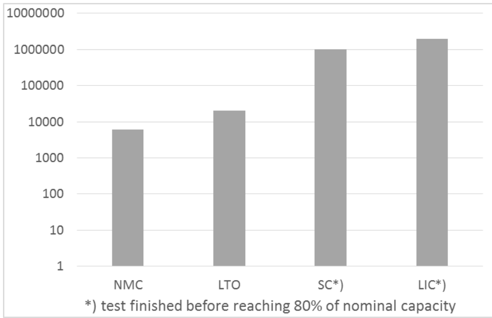

Fig. 10. Comparison of cycle lifetime of compared storage devices @ 80% DoD, 25°C.

Concept of autonomous tram with periodical supply from railway power line

Currently, most rail vehicles, capable of energy recovery, works in such a way that the energy flow is always in its entirety from or to the network. The application of ultra-capacitors' storage reduces pulse of power, but energy still needs to be constantly supplied with the grid. The use of hybrid storage system allows limiting of pulses of power and enables autonomous ride and regenerative braking energy storage to a greater extent.

Hybrid storage systems and new types of cells, such as LTO, allow for wider introduction of power supply rail vehicles with periodic charging from power line, particularly trams. This way of working is based on the vehicle is supplied only in selected areas. During the passage of a vehicle at the site of the catenary storage system is recharged. Then, in areas without network storage is discharged. During the journey power profile can be divided into two components:

- associated with charging in places where there is a traction network, and unloading a storage where it does not exist.
- associated with the collection and return of pulse energy in connection with a stop at tram stops and traffic lights.

In the first case we are dealing with cycles of energy, energy storage battery works. In the second case, power storage works, ultra-capacitor storage works.

The Institute of Electrical Machines works in the field of dimensioning and selection of storage elements of energy storage systems in these applications.

An example of a theoretical profile of the current consumed by the tram is shown in Fig. 14. It is assumed that the tram will travel underneath the line for 12.5 minutes, followed by 63.5 minutes is going to drive independently. This profile can be divided into power and energy components (Fig. 15 and 16). The power section requires a capacitor storage with a minimum capacity. $0.11I_n$ Ah, part of the energy - battery with a minimum capacity. $0.02I_n$ Ah (I_n – nominal current of the tram). The resulting rail line current is shown in Fig. 17.

Conclusions

Modern electrochemical cells and ultra-capacitors allow for flexible selection of the storage system to the demand. The constructor has a choice of different technologies depending on the nature of energy and power fluctuations that will be compensated by the storage system. Characteristically, the cyclic applications of high power is better to use ultra-capacitors, and for energy ones with fewer number of cycles, batteries.

In applications where there are two components – power and energy – hybrid storage systems should be used. It allows further customizing of the magazine to the needs. This reduces energy losses, the weight and volume of the storage system while increasing life time.

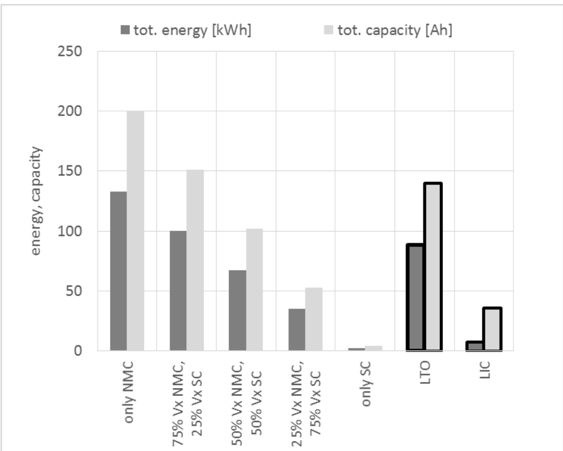

Fig. 11. Total stored energy and capacity of particular versions of hybrid storage systems compared to LTO and LIC storage.

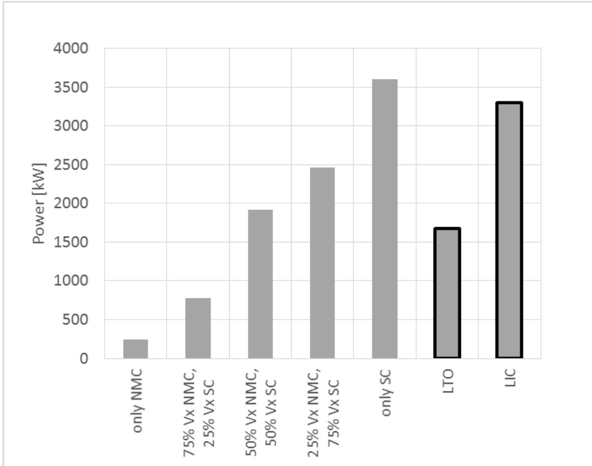

Fig. 12. Total power of particular versions of hybrid storage systems compared to LTO and LIC storage.

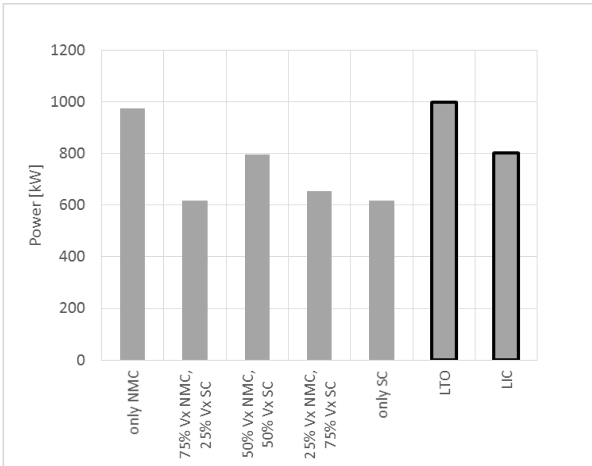

Fig. 13. Total mass of particular versions of hybrid storage systems compared to LTO and LIC storage.

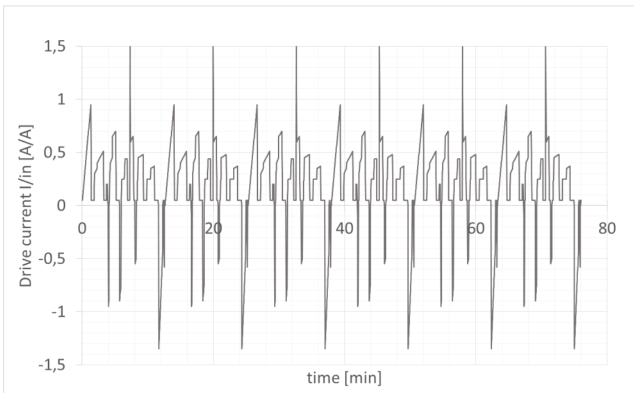

Fig. 14. An example of tram current.

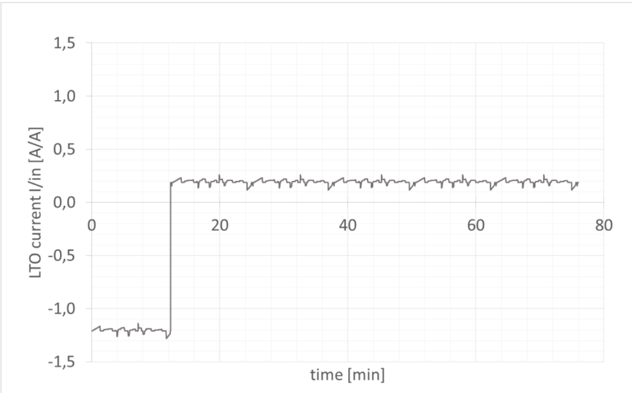

Fig. 15. Energetic component of the tram current. Battery current.

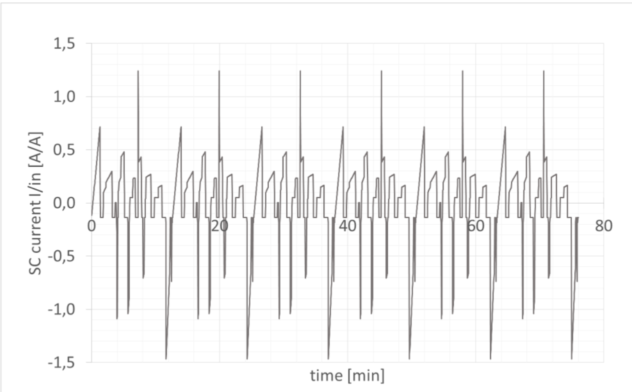

Fig. 16. Power component of the tram current. Ultra-capacitors current.

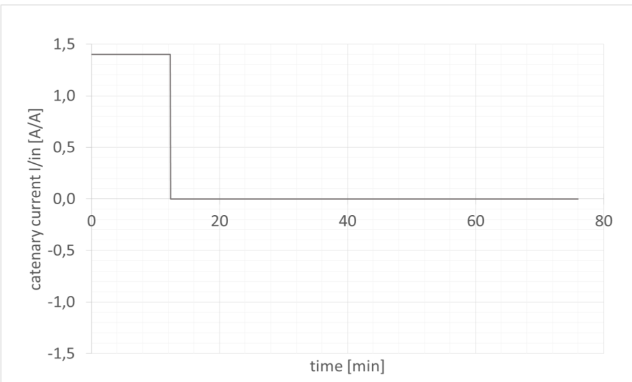

Fig. 17. Assumed catenary current

Proper allocation of capacity or available volume between the two types of storage devices is difficult. The designer must take into account the size of two components of compensated power flow – energy and power one. An important element to take into account in the planning of division of load between the two components of the storage is the slope of current rise.

Modern storage elements like LTO or LIC may replace the hybrid magazine. LTO cells are dedicated to work more as energy storage and LIC more as power storage. Both should be used in an area where cells NMC or LFP have too few cycles and power, and ultra-capacitors too little energy.

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