Energy Management and Hybrid Energy Storage in Metro Railcar

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Abstract— **This paper focuses on the use of modeling and simulation one of renewable energy.**

In this paper the results of simulation models by Matlab-Simulink for an urban-metro railcar and some newer methods for reducing the need value of capacitance for energy storage are presented. In this research was been investigated the Li-ion battery and the supercapacitor as hybrid energy storing device for the same task and its effectiveness under operation of a suitable energy control system.

The available decreasing ratio of the needed energy storage at SCAP is 25 to 40 % with this improved energy control method, which are significant values as decreasing in volume, mass and price. Mass reduction of our hybrid storage system is significant, about 50 to 60%.

Keywords- electric vehicle, regenerative braking, energy storage

I. INTRODUCTION

Energy storage devices can be used to improve the energy efficiency and the poor voltage regulation by storing regenerated energy from braking. This paper investigates the use of effectiveness of energy storage in mass transit systems, considering Budapest Metro Railway as a theoretical case study. For improving the better use of the built energy storage devices some ideas and conceptions were investigated through different way by a modeled energy management.

The effectiveness of regenerative braking is depends on the receptivity of the system. This problem can be avoided by using energy storage devices which can store regenerated energy on train board or at the track side. On board stored energy provides an additional power source for acceleration, hence reducing the magnitude of voltage sags.

II. THE MODEL OF THE RAILCAR AND ITS ENERGY STORAGE SYSTEM

Supercapacitors can be used for short-duration energy storage [1],[2],[3],[4],[5]. In comparison to standard batteries, the energy density of supercapacitor is lower by an average factor of 10, but their power density is compatible with a large range of power applications that need high instantaneous power during short periods of time. These characteristics are useful in transportation systems. The aim of my previous paper was to present how capacitive storage can be used for increasing the energy efficiency in a metro railway system and decreasing the value of needed capacitance for the energy storage. Fig. 1 illustrates a railcar model. Main railcar characteristics are: the weight without load is 34 t, while fully loaded is 44 t.

The four DC motors' total power is 200 kW, the nominal speed is 75 km/h, the maximum acceleration is more than 1 m/s^2, and the distances are approximately 800 m between stops or stations. The magnetic field of the motors is changeable here.

In previous papers [7], [8] some possibilities was be analyzed for decreasing the needed value of the minimum capacitance for store the energy from regenerative braking were analyzed. The first attained object was the 840 V the initial voltage value of supercapacitor C, which we can be calculated from the value of the capacitance C and the "beforehand charged energy" E_{Co} into C. The least voltage of C through the discharge is set for 400 V, what we set by tuning the variation of the value capacitance C by the beforehand charged energy E_{Co} and the "constant charger power" P_{Ct} from overhead line through the execution of Matlab-Simulink program.

The aim of the investigation was to determine the least needed capacitance value of the supercapacitor (C) under different conditions. Fig. 2 shows the direction of the simulation. The adequate degree of the constant charging-power P_{ct} is determined by the energy consumption of the motors. Accordingly the important aim of the investigation was to determine the adequate value of the constant charger-power

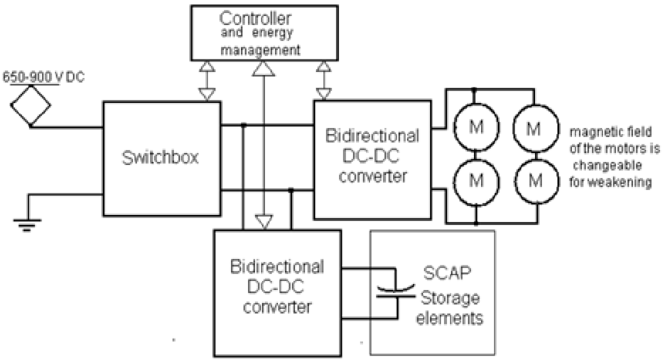

Figure 1: Railcar model with only capacitive energy storage

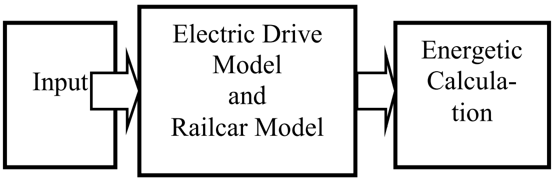

Figure 2: Aim and direction of simulation and calculations

P_{Ct} and the least possible capacitance value for C. The executions of the program were through two distances of the stations. The energy consumption of the railcar and the diverse losses were calculated by the model too. The energy consumption of motors E_{mot} are plotted also on the figure. The energy consumption is divided by the running time gives practically the approximate value of the constant charger-power P_{Ct}. In these investigations the value of *d,* voltage-ratio

$$d=(Uc_{min}/Uc_{max})100 \qquad (1)$$

was about 48 % if the Uc_{min} is 400 V.

There are some possible cases e.g. in shorter running time then the applied charged energy E_{Ct} by the method "constant charger power" P_{Ct} is lower than it is needed, so the charged energy to C is less. At this time in acceleration the voltage of C decreases under 400 V.

Instead of increasing the value of the P_{Ct} there is a novel possibility to improve this problem. If the charging power is not only a constant value but is varied by some function of the total motor power under time of traction, then the charging of the C is more rapid and the needed value of the C will be reduced. Consequently the charger power has two components, a function of motor power by a "correction factor" and a much lower "constant charging power", P_{Ct}.

Several functions were investigated for this improving method. In the first place there is a product which is directly proportional to the motor power. The applied "correction factor" to achieving this result means a proportion of the motoring power that the railcar takes down from overhead line for the motors, under controlling of an energy management.

By the method of "constant charger power" the energy mainly flows from the C and a little part from overhead line. With this newer method this rate is almost inversely. The effectiveness of this method in decreasing of the C is higher because at "correction factor" 0.4 the used energy by motors from line is in rate of 40% and from the C is 60 %. This increasing in the current from the line considerably decreases the needed value of C. The results are shown in the Fig. 3. The abbreviation "corrfact" means "correction factor". If this correction factor is zero then the improving process is out of operation. In the case if this factor varied from 0.4 to 0.6, the needed value of capacitance should be less, but at regenerative braking for storage energy the value of C is insufficient, as had be shown after some executions. The sensibly greatest value for this correction factor was selected to 0.4.

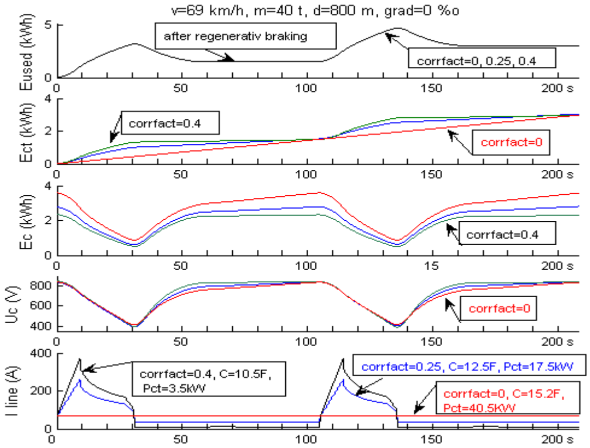

Figure 3. Various correction factor values and its effects to values of needed capacitance of energy storage

In the Fig. 3 as the same course of railcar are seen but the set of energy management is varied by value of the correction factor from 0 to 0.25 and to 0.4. As can be seen the curve E_{used} the energy consumption of the car is not varied by varied this correction factor.

The curves of charged energy E_{Ct} by the constant charger power P_{Ct} now are varied according to the value of correction factor. In lowest figure can be seen well the effects of this setting. The overhead line current curves are changed according to value of P_{Ct} and the correction factor. If this value is zero the needed P_{Ct} will be the greatest. If the value of correction factor is not zero the curves P_{Ct} are lower and under time of traction is changing according to motor power and the correction factor.

The achieved decreasing ratio of the need capacitance in our simulations is about from 25 to 35 % compared to the case of the correction factor cf=0. The charged energy E_{Ch} to storage C is composed of the correct factor multiplied by motor-power and from the constant power P_{ct}:

$$Ech=\int_0^t Pch\ dt=\int_0^t Pct\,dt+cf*\int_0^t Pmot\ dt$$

The energy management as a control task is executable with the controller by measuring the motor current and voltage, the speed, the voltage of the line. The decreasing ratio of the needed capacitance C is about from 25 to 35 % comparing to case when the correction factor is zero.

In Fig. 3 upper inset figure under the notice "after regenerative braking" is the name of a section in which the consumed energy is the lowest. The calculation of energy saving are executed from this values.

III. ANALYSIS OF COURSES

In Fig. 4 the speed is varied. Because of this at lower speeds the later points of the curves are sliding on the time axis. For keeping the *d* voltage-ratio of U_C and at the same time for increasing the mass, speed and grade, the value of C, E_{Co} and

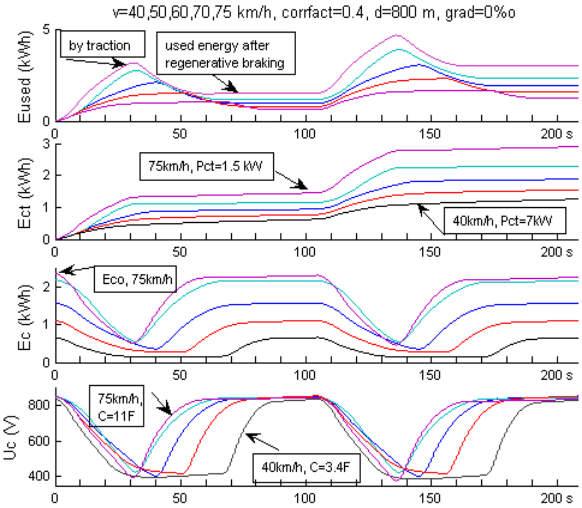

Figure 4: The speed is varied. The lowest values of needed C and P_{Ct} at corrfact=0.4 are shown and are function of speed.

P_{Ct} need to be increased too.

In Fig. 5 the correction factor was 0.4 and the grade was varied from -20 to 20 %o. The motor currents maximum value was 300 A. The current of the overhead line in this case depends on motor’s power and indirectly on grades.

The acceleration takes a longer times on 10 %o and 20 %o grades regarding the motor current maximum is only 300 A. Down below the changes of currents of overhead line under and after motoring are illustrated.

The possible lowest values of needed C and P_{Ct} at corrfact=0.4 are signed in the figure. If the grade=0 %o, the value of needed C is 10 F, but if the grad are 20 %o and -20 %o, the needed minimum value of C are 10.8 and 11 F. The alteration of the needed value of C due the 20 %o and -20 %o is very small. At the same time the energy flow provided by DC-DC converters are very different. The P_{Ct} is 48 kW at 20 %o and -42 kW at -20 %o. In the latter case it is necessary that the overhead line must be able to receive the energy from railcar. If not, this energy will be dissipated on the braking resistor**.**

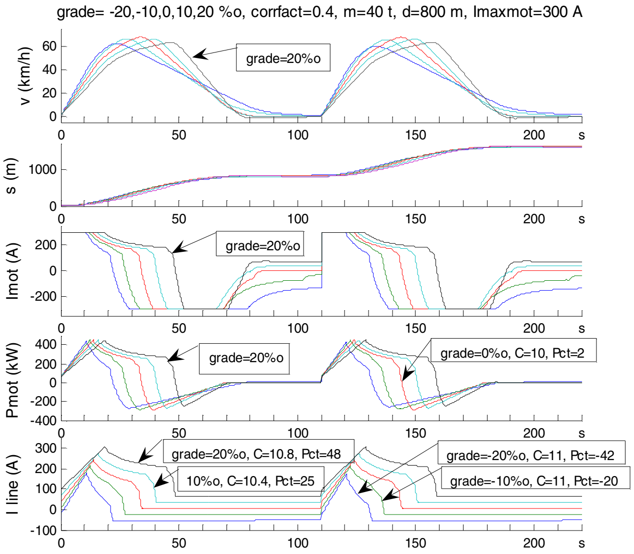

Figure 5: The grade is varied. The lowest values of needed C and P_{Ct} at corrfact=0.4 are shown

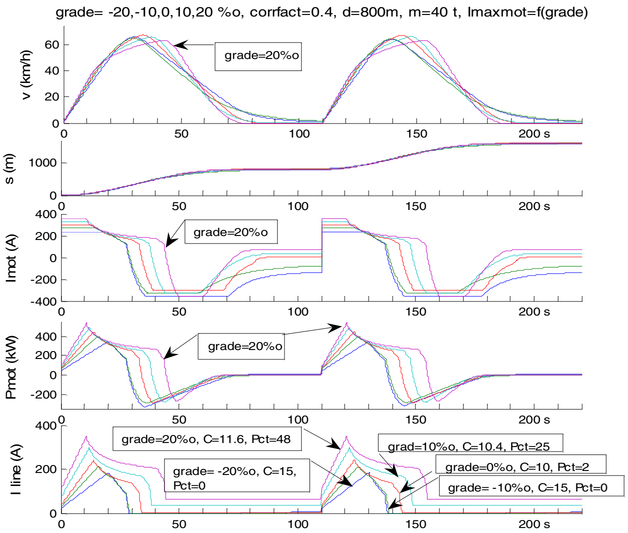

Figure 6: The grade is varied, the currents maximum are proportion to grades. The corrfact=0.4, so the current of the overhead line is not constant

For storing this energy in C, the value of capacitance needs to be increased significantly. This will be economical if this occurs frequently e.g. in more section on the traffic line.

Curves shown Fig. 6 correspond almost the same case as Fig. 5. The grade was varied from -20 to 20 %o but the change of motor currents was nearly proportions to the grade. At grade 20 %o the current is increased to 360 A from 300 A. It was needed to increase the minimum value of capacitance C from 10 F to 11.6 F at the grade 20 %o. For storing the braking energy at this section we have increased the capacitance until 15 F and this it was sufficient to storage at the grade -20 %o. At this case the negative signed “constant charging power” P_{Ct} was zero.

Fig. 7 presents the curve of the saved energy v. grade. These values are available if the traffic occurs on a constant grade. In real urban railway traffic conditions this curve is not available regarding the grades are not long generally.

The model gives possibilities to investigate any combination of uphill and downhill.

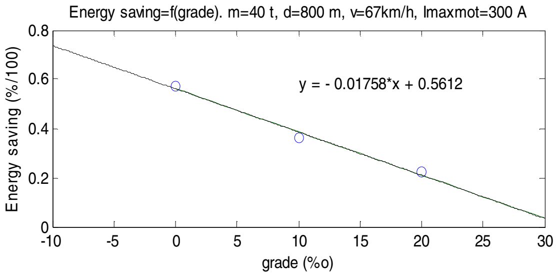

Figure 7: The saved energy v. the grade by conditions written on figure at maximum motor currents of 300 A

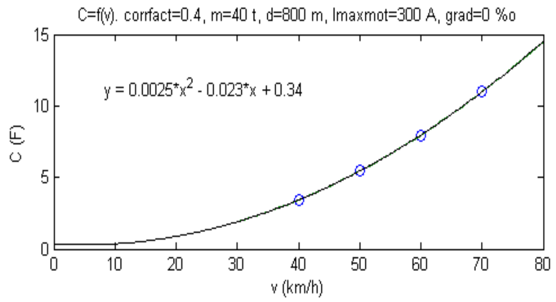

Figure 8: The needed capacitance of the energy storage v. speed under conditions written in figure

Fig. 8 presents the needed capacitance of the energy storage versus the speed in case when the maximum motor current is of 300 A, the distance between station 800 m, the mass of a car of 40 t, and the grade is 0 %o. The correction factor was 0.4.

The functions for C_{needed}, P_{Ct}, E_{C0}, E_{used}, E_{saved} v. mass, speed, distance of between stations for these from 4 to 6 values in the figures are calculated and fitted good with least square method by Matlab.

Fig. 9 shows the energy saving. v. the speed (km/h) and the distance between stations (m)

$$E_{saving}=f(\text{speed, distance}) \tag{5}$$

$$E_{saving}=Z=(9.167e\text{-}007*X^3-0.0003*X^2+0.02986*X-1.399e\text{-}007*Y^2+0.0002943*Y-0.5209) \tag{6}$$

Fig. 10 illustrates the differences between the value of C_{min} in cases corrfact=0 and corrfact =0.4 v. the speed (km/h) and mass (t)

$$C_{corrfact0} - C_{corrfact0.4}= f(\text{speed, mass}) \tag{7}$$

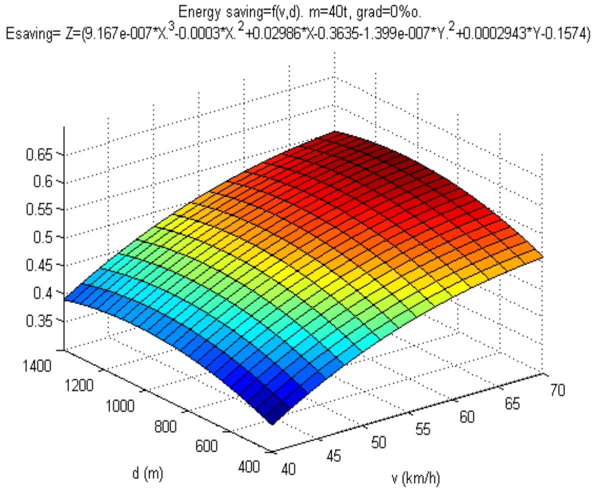

Figure 9: The energy saving v. the speed (km/h) and the distance of between stations (m).

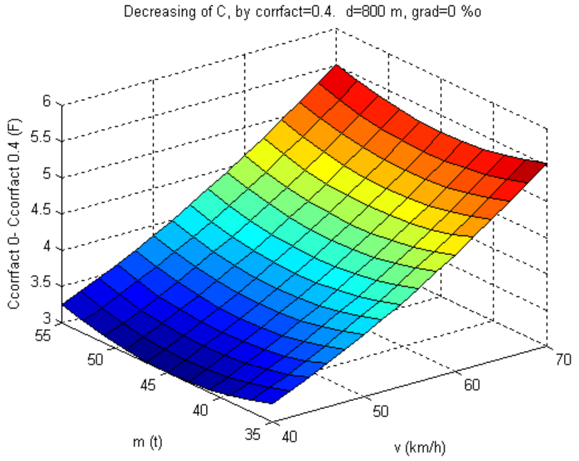

Figure 10: The decreases of the possible needed minimum values of the capacitance C_{needed} between corrfact= 0 and corrfact= 0.4.

IV. HYBRID ENERGY STORAGE BY LI-ION BATTERIES AND BY SUPERCAPACITOR

Regarding that storage capacity of newer Li-ion batteries about ten times greater then SCAP by the same weight, and those are sufficiently safe already, we investigated a hybrid storage system as like in Fig. 11 with its parameters already applicable.

Our aim is to apply a least SCAP and a possible least capacity of battery under the same conditions, for store all movement energy. The curves of Li-ion battery model are shown in Figure 12, according to the Li-ion model in newer Matlab. The curves of the battery are shown in Fig. 12. If the discharge current is low as like 40 A the discharging time is 2,25 hour and this time decreases to 8,2 minutes if the current set to 180 A.

The equations and parameters of this model prove a realistic features for all most important batteries, but there is no possibility to handle the different varieties of Li-ion batteries,

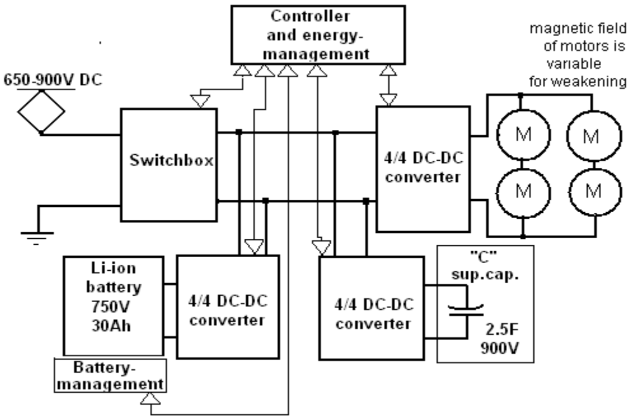

Figure 11: The model of hybrid energy storage system on a metro-railcar

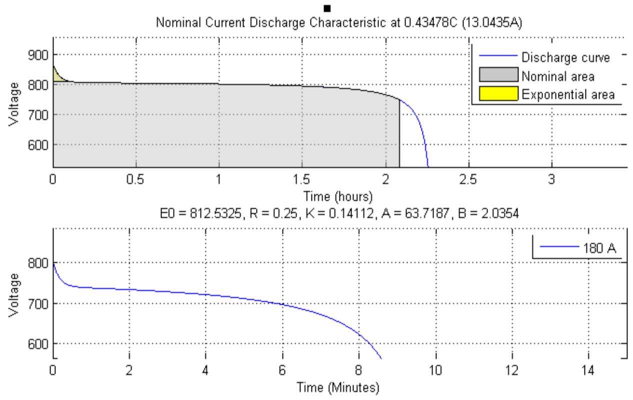

Figure 12: Discharging curves of Li-ion battery model by discharging current of 180A

for example the least inflammable iron-phosphate types. Nevertheless we think that this model approximates the real behavior of the Li-ion battery with a negligible inaccuracy.

Regarding that storage capacity of newer Li-ion batteries about ten times greater then the SCAP by the same weight, and now are sufficiently safe, we investigated a hybrid storage system as like in Fig. 11 with its parameters already applicable.

We set a railcar model according to Fig. 11, and we solved the separately variable method for handle the control of capacitive energy storage and one of the battery. After a long iteration process we got the suitable value of needed storage ability for the capacitance and for the battery. The current is limited to six times the nominal one and the current-regulator controls the surplus to SCAP. The task of energy-management is sophisticated. Speed, distance, motor current, motor power and line current shown in Fig. 13 at grade + 40%o and the same cases the battery voltage, S.O.C., current of battery,

The higher grades were between + 40 %o and – 40%o and these sections of line were repeated here five times after each other to showing the effects of the continual grade for the feature of energy-management and for the change of the energy-level in energy storage devices.

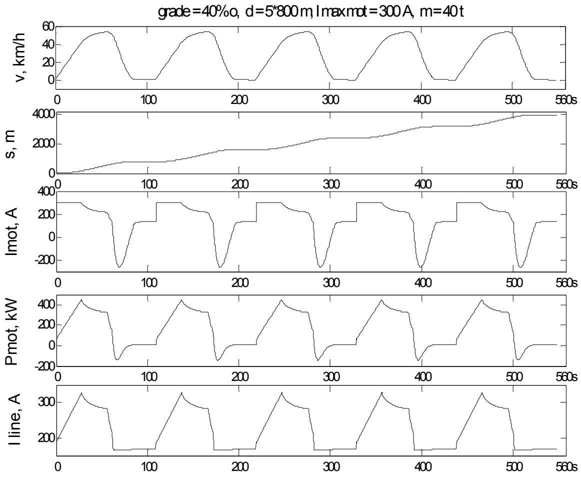

Figure 13: Speed, distance, motor current, motor power and line current. Grade = + 40%o.

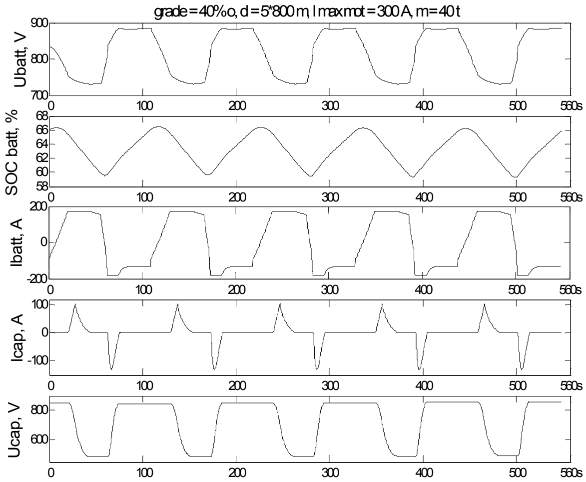

Figure 14: Battery voltage, S.O.C., current battery, current SCAP, voltage SCAP according to Fig. 14. P_{Ct}=124 kW, cf=0.271, SOCo=66 %, current limits +172, - 180 A.

The battery voltage, S.O.C., current of battery and SCAP, voltage SCAP are shown in Fig 14 according to Fig. 13. The P_{Ct}=124 kW, SOC initial is 66 %, current limits +172, - 180 A. The value of correction factor cf=0.271, must had to tuned for task, the 0.4 was too high.

In battery the state of charge, SOC was set to 50 % if in line have not any grade and even the grade was + 40 %o. The SOC was set to 35 % if the train circulated in forte slope for example -35 to -40 %o. In a realistic operation these alterations would be controllable accordingly the date of line, by from memory.

Investigations showed that the needed energy-storage ability surprisingly low both in the battery and in the capacitor.

The needed capacitance was very little by the five times repeated grades: 1 or 1.6 F at 840 V starting voltage and the needed battery was 30 Ah at 750 V nominal voltage. For managing these tasks we investigated the feature of these control-systems of these energy-storage devices.

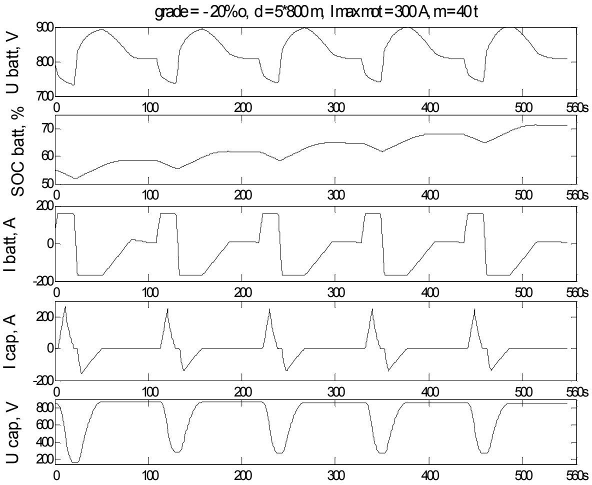

Figure 15: Battery voltage, S.O.C. , current battery, current SCAP, voltage SCAP according to Fig. 20. P_{Ct}=0 kW, cf=0, SOCo=55 %, current limits

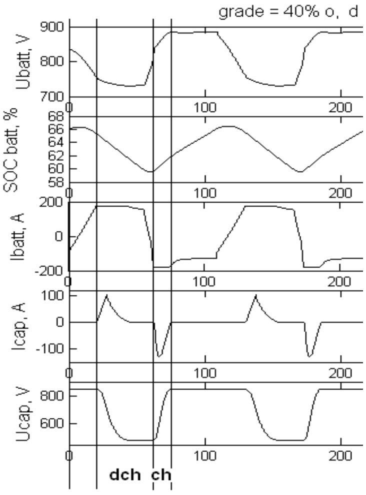

Figure 16: Grade is 40 %o by fast energy consumption in section ‘dch’ discharging and under regenerative brake the charging (ch).

It is shown that the battery current was suitable all operation cycle. When the limitation of battery current operates

a part of the need current flows to capacitor only. These current peaks are proved by the capacitor in both directions. In Fig.16 it can be shown that in time of discharging, ‘dch’ the current of capacitor begins increasing while the discharging battery current is already limited. The applied current limitations are shown on the 14-15-16 figures, in 3rd inset figures as $I_{battery}$. The change of SOC is less and the little value of supercapacitor (SCAP) here is sufficient.

In this solution realized an aim that the storage of energy is firstly stored by battery, but for giving or receiving the peak-current there is a little supercapacitor.

If the capacitance of this capacitor is a little value and the condition of operations are very varied, it is needed to a suitable fitting to the battery. In one of possible solutions we could seen that the mentioned limits for the battery current may permitted as the needed current for the capacitor if the values of this are suitable. After some tunings the good values of current limits are available. These limitations are the function of mass, speed, grades, distance of stops and the value of capacitance, respectively. The upper current limit values versus grade are shown in Figure 18. The fitted continual function line may considerable as a trend.

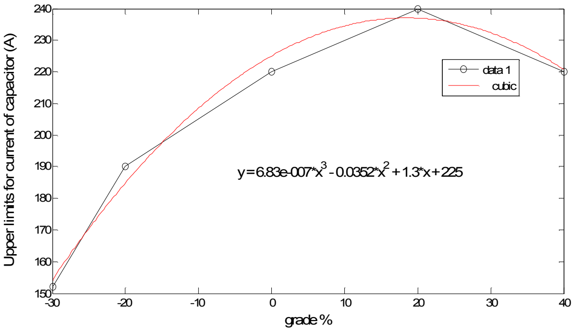

Figure 17: The applied upper current limits vs. grade

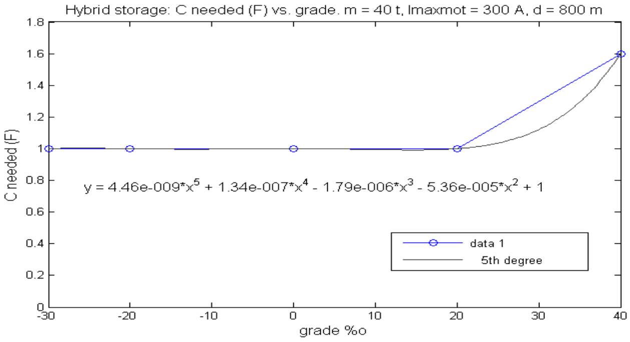

Figure 18: The needed smallest capacitance vs. grade with cooperation a Li-ion battery of 750V and 30 Ah

The needed smallest capacitance is 1 to 1.6 F, with cooperation a Li-ion battery of 750V and 30 Ah shown in Fig. 18.

For these tasks the mass of SCAP is about 1500 kg. The mass of 800 kg about with presented Li-ion battery + SCAP hybrid storage-system, without converters.

CONCLUSIONS

We presented a method to decreasing the need capacitance of energy storage device by operating a newer energy-control system.

The available energy saving in metro railcar generally is over 40 %. The available decreasing ratio of the needed energy storage at SCAP is 25 % to 40 % with this improved energy control method, which are significant values as decreasing in volume, mass and price. Mass reduction of this hybrid storage system is significant, about 50 %.

This novel process and its results are practically independent of the type of DC or AC traction motor.

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