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New Energy Management and Hybrid Energy Storage for Metro Railcar

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Abstract

This paper focuses on the use of model 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 in cooperation by a Li-ion battery 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 effectivness under operation of a suitable energy control system.
The available decreasing ratio of the needed energy storage at case 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 60%.

Keywords: *electric vehicle, regenerative braking, Li-ion, energy storage, supercapacitor, Matlab simulation.*

1 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 supposed energy management. Overall system efficiency gains can be achieved by regenerating onto the overhead line. 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.

2 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. In the Fig. 1 illustrates a railcar model. Main railcar characteristics are: the weight without load is 34 t, while the weight 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.
In the Fig.1 does not shown that the magnetic field of the motors is changeable.

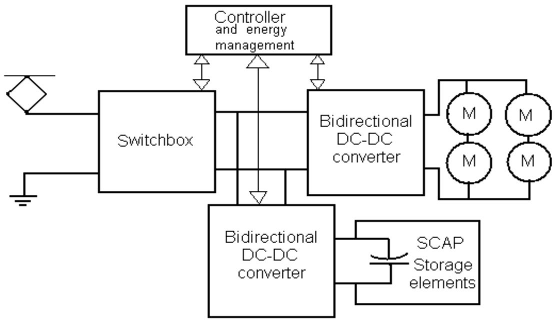


Figure 1: Railcar model with only capacitive energy storage

In the previous papers [7], [8] was be analyzed some possibilities for decreasing the needed value of the minimum capacitance for storaging the energy from regenerative braking were analysed. The first attained object was the 840 V the initial voltage value of supercapacitor C voltage, 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 charging power" P_{Ct} from overhaed 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) for different conditions. The 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 charging-power P_{Ct} and the least possible capacitance value for C.

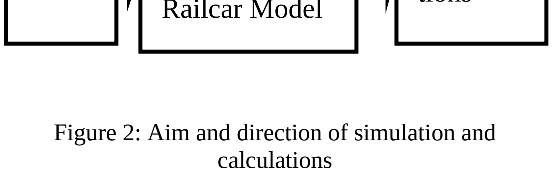


Figure 2: Aim and direction of simulation and calculations

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 figures. Practically the energy consumption is divided by the running time gives the approximate value of the constant charging-power P_{Ct}.

In the investigations the value of d voltage-ratio is

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

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 charging 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 charging power has two components, a function of motor power by a "correction factor" and a much lower "constant charging power", P_{Ct}.
Some kind of function was 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 charging 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 conciderably decreases the needed value of C. The results are shown in the Fig. 3. The abbreviation "corrfact" means the "correction factor".
If this correction factor is zero then the improving process is out of operation.
In the case if this factor is 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.
In the Fig. 3 as the same course of metro car 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.

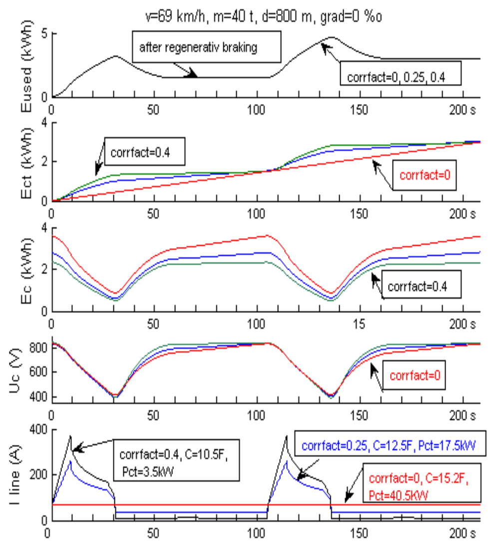


Figure 3: The changed correction factor values from 0 to 0.4 and its effects at the same traction case

The curves of charged energy E_{Ct} by the constant charging 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 charged energy E_{Ch} to the C by charger power P_{Ch} is realizes by this relation

$$Ech=\int_0^t Pch\ dt=\int_0^t Pct\,dt+corrfact*\int_0^t Pmot\ dt \qquad (2)$$

The energy management as a control task is executable with the controller by measuring the motor currant and voltage, the speed, the voltage of the line. We can calculate the motor power, and from this the value of corrfact*P_{Ct} product too.

The decreasing ratio of the needed capacitance C is about from 25 to 35 % comparing to case when the correction factor is zero.
In the Fig. 3 upper detail-figure under the notice “after regenerative braking” is the name of a section in which the consumpted energy is the lowest. The calculation of energy saving are executed by this values.

3 Analyses of courses

In the 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 P_{Ct} need to be increased too.

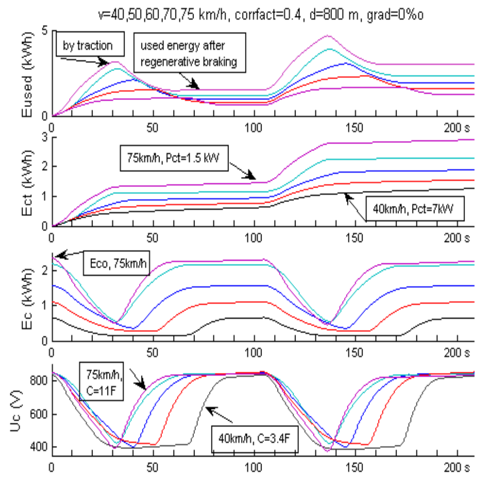


Figure 4: The speed is varied. The lowest values of needed C and P_{Ct} at corrfact=0.4 are shown and are function of speed.

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 the grade.

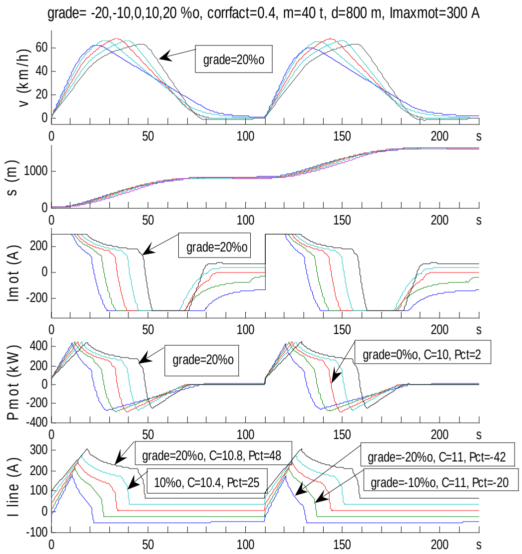


Figure 5: The grade is varied. The lowest values of needed C and P_{Ct} at corrfact=0.4 are shown

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 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**.**

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.

In the curves shown Fig. 6 are 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.

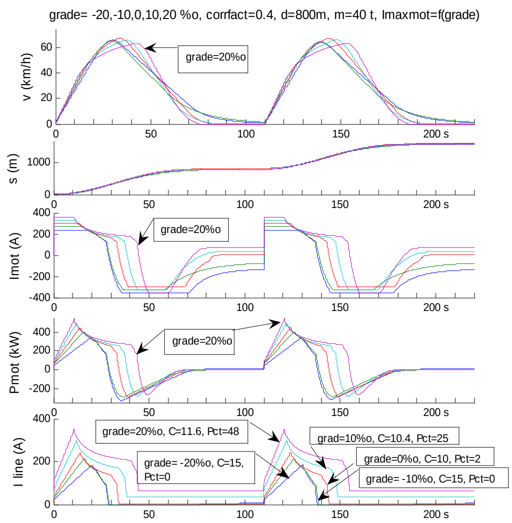


Figure 6: The grade is varied, the currents maximum are proportion to grades. The corrfact=0.4, so the current of the overhead line is not constant

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

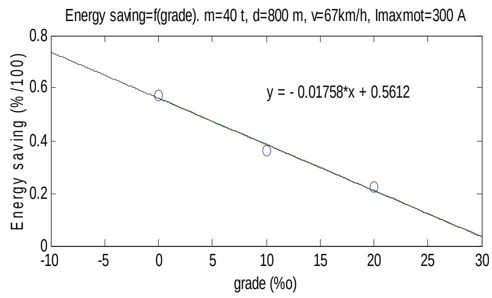


Figure 7: The saved energy v. the grade by conditions written in figure

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

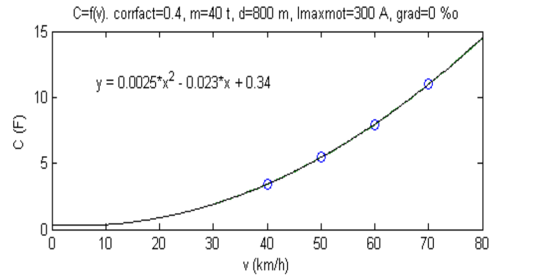


Figure 8: The needed capacitance of the energy storage v. speed under conditions written in figure

The functions for C_{needed}, P_{Ct}, E_{C0}, E_{used}, E_{saved} v. mass, speed, distance of between station 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).

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

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

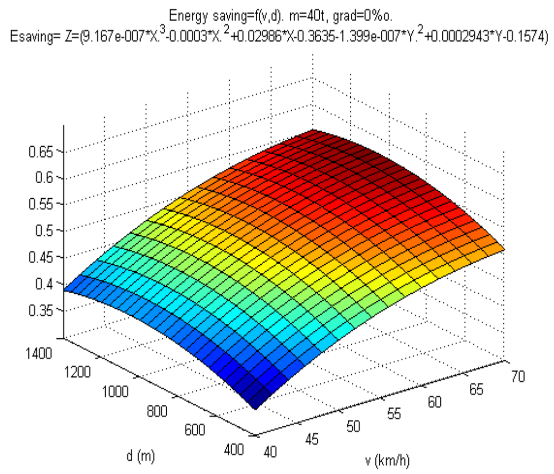


Figure 9: The energy saving v. the speed (km/h) and the distance of between stations (m).

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)

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

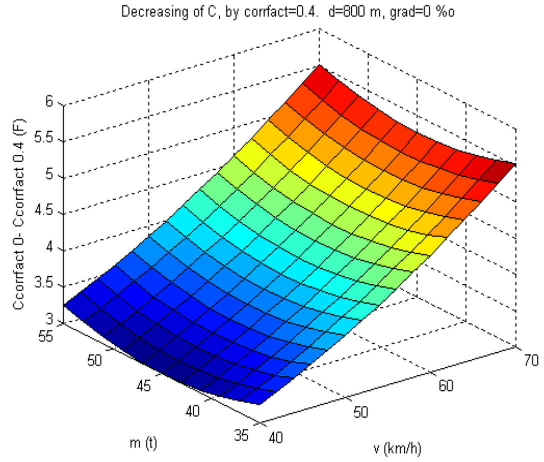


Figure 10: The decreases of the possible needed minimum values of the capacitance C_{needed} between corrfact=0 and corrfact=0.4.

4 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.

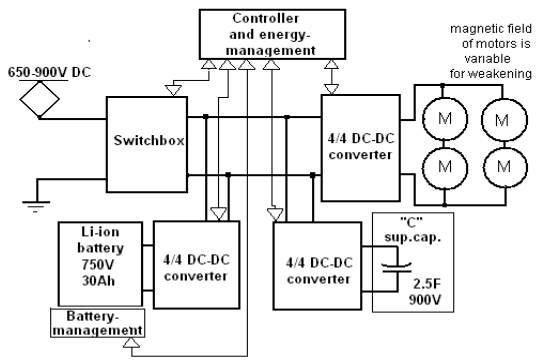


Figure 11: The model of hybrid energy storage system on a metro-railcar

Our aim is to apply a least SCAP and a possible least capacity of battery. The curve of Li-ion battery model is shown in Figure 12, according to the Li-ion model by newer Matlab.
The equations and parameters of this model prove a realistic investigation for all most imporant batteries, but theres is no possibility to handle the

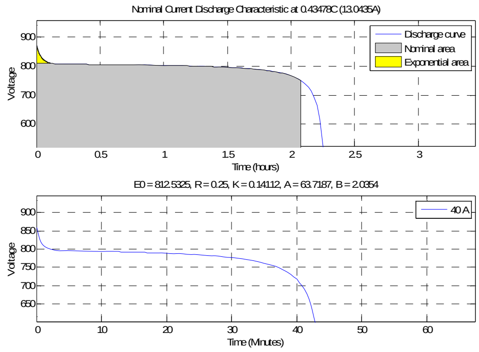


Figure 12: Discharging curves of Li-ion battery model by discharging current of 40 A

different variety of Li-ion batteries, for example the least inflammable iron-phosphate types. Nevertheless we think that this model approximats the real behaviour of the Li-ion iron-phosphate type battery with a negligible inaccuracy.

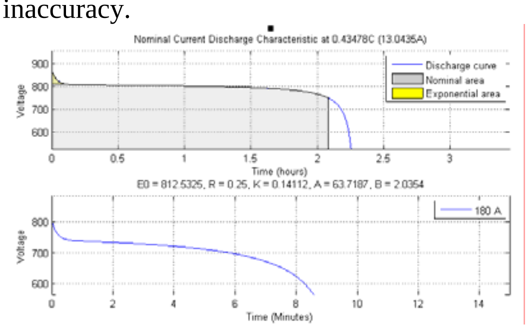


Figure 13: Discharging curves of Li-ion battery model by discharging current of 180A

We set a 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 these by a longue iteration process we got the suitable value of needed storage ability for the capacitance and for the battery.

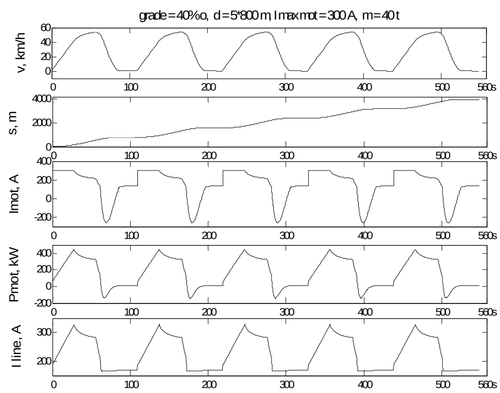


Figure 14: Speed, distance, motor current, motor power and line current. Grade = + 40%o.

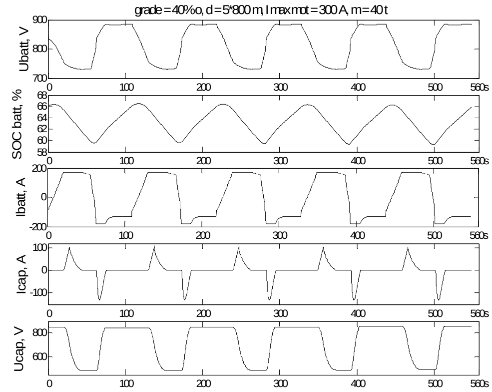


Figure 15: Battery voltage, S.O.C., current battery, current SCAP, voltage SCAP according to Fig. 14. P_{Ct}=124 kW, cf=0.271, SOCo=66 %, current limits +172, - 180 A.

At these investigations (in Fig. 14 to 23) our aims were to achiving some additional conciderations. 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 continuel grade for the behaviour of energy-management and for the changement of the energy-level in energy storage devices.

In battery the state of charge, SOC was set to 70 % if the 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 -35 %o or - 40 %o. In a realistic operation these alterations are controllable accordingly the dates of line, by from memory.

Investigations showed that the needed energy-storage ability surprisingly low both in the battery and in the capacitor. by the five times repeated grades the needed capacitance was very little :2.6 or 3 (F) at 840 V level, and the needed battery was 30 to 40 Ah at 750 V nominal voltage.

The curves of the battery shown in Fig. 12 and Fig. 13. If the discharge current is low as like 40 A the discharging time is 2,25 hour and this time decreases to 8,2 minuts if the current set to 180 A.

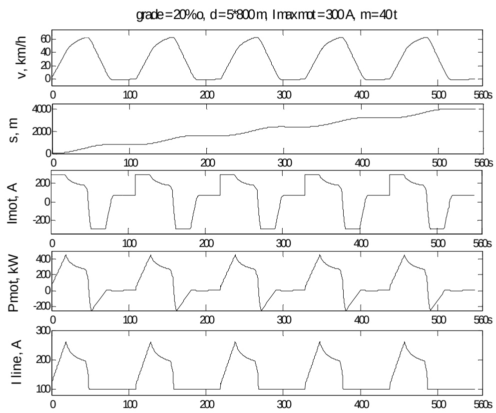


Figure 16: Speed, distance, motor current, motor power and line current. Grade= +20 %o.

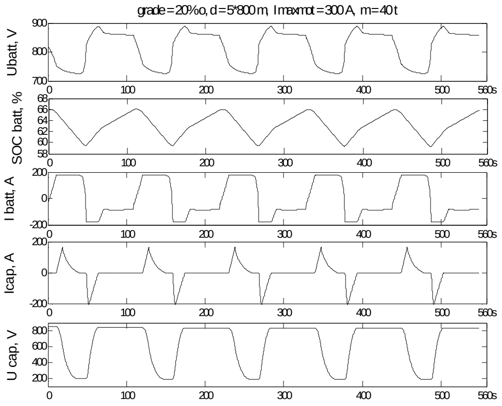


Figure 17: Battery voltage, S.O.C. , current battery, current SCAP, voltage SCAP according to Fig. 16. P_{Ct}=74 kW, cf=0.271, SOCo=66 %, current limits +180, - 180 A.

For a suitable operation it is need and available also this high value of discharge current because the time with this current are some second only as shown the later figures.

For managing all these tasks we investigated the behaviour of two control for the two energy-storage. In this model we applicate a current-limit method instead of a current control. We could show that the values of battery current are suitable all operation cycle.

When the limitation of battery current operates the part of the need current flows to capacitor only. These peaks of current are proved by the capacitor in both direction. In this solution achived an aime that the energy storage is firstly proved by battery but for giving or receiving the peak-current there is a little supercapacitor.

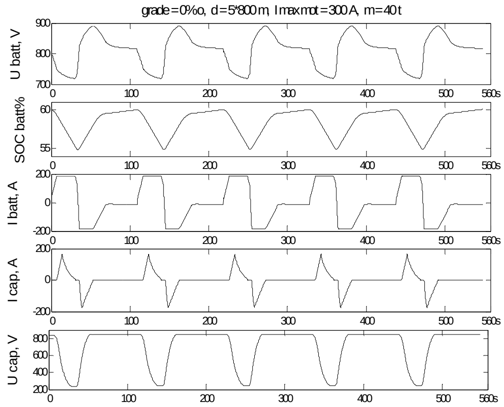


Figure 19: Battery voltage, S.O.C., current battery, current SCAP, voltage SCAP according to Fig. 18. P_{Ct}=10 kW, cf=0.4, SOCo=66 %, current limits +186, - 184 A

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 behaviour. In one of solutions we can see that the mentioned limits for the battery current may permit the needed current for the capacitor if the values of this are suitable. After some iterations the good values of curent limits are available. This limitations are the function of mass, speed, greads, distance of stops and the value of capacitance. All these considerations are achivable by a processor with an elaborated two- or multivariable function.

The applicated limitations are shown in the figures. The current is limited to six times the nominal one and the current-regulator controls the surplus to SCAP. The task of a good energy-management is sophisticated.

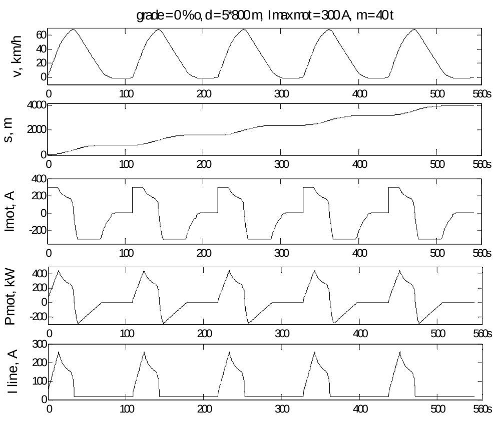


Figure 18: Speed, distance, motor current, motor power and line current. Grade = 0 %o.

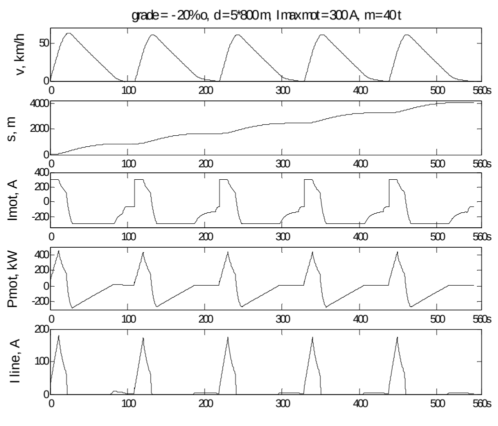


Figure 20: Speed, distance, motor current, motor power and line current. Grade= - 20 %o. If cf=0.3 then the current of line is not zero.

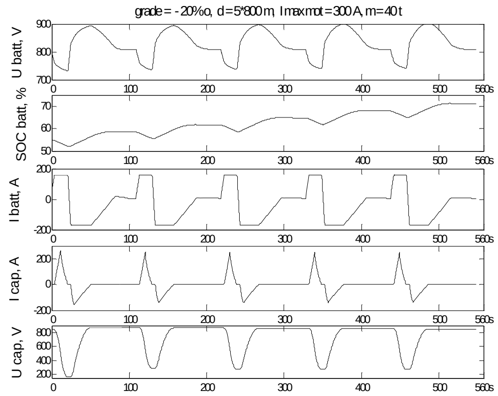


Figure 21: Battery voltage, S.O.C. , current battery, current SCAP, voltage SCAP according to Fig. 20. P_{Ct}=0 kW, cf=0, SOCo=55 %, current limits +160, - 171 A

The value of „cf" was varied for achieving these favourable results at grades between 0 and 40 %o.

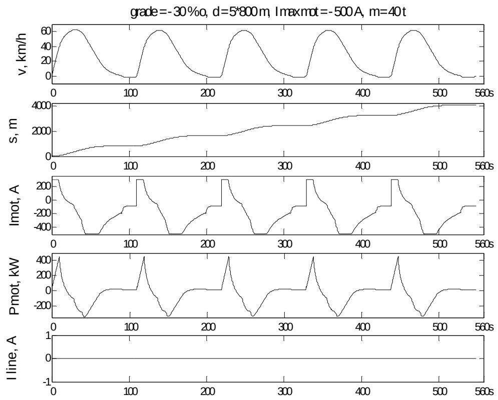
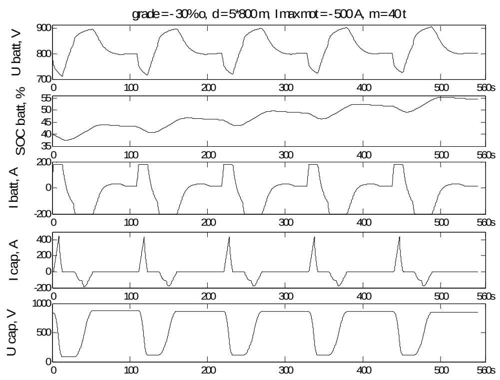


Figure 22: Speed, distance, motor current, motor power and line current. Grade= - 30 %o.



Fgure 23: Battery voltage, S.O.C. , current battery, current SCAP, voltage SCAP according to Fig. 22. P_{Ct}=0 kW, cf=0, SOCo=66 %, current limits +180, - 217 A

The currents of the battery and of the capacitor are well shown in the next figures, between the grade of 40 %o and of -30%o.

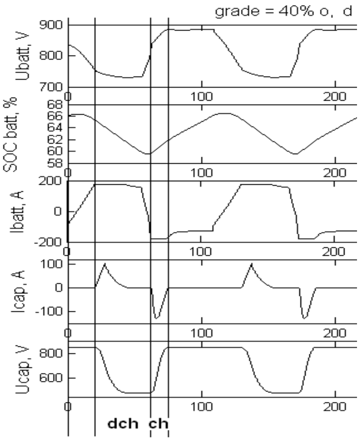


Figure 24: Grade is 40 %o with fast energy consumption in section 'dch' discharge and under regenerativ braking the charging (ch).

In Fig.24 It can be shown that in time of 'ch' the current of capacitor begins decreasing when the charging-discharging battery current is limited.

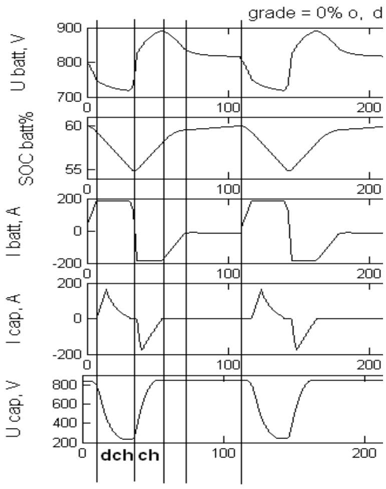


Figure 25: Grade is 0 %o. The intensity of energy consumption ('dch') and under regenerativ braking the charging ('ch') is moderate.

The current of capacitor just begins decreasing in 'ch' when the (charging) battery current is limited. It can be shown that the two storage devices are complementaries mutually.

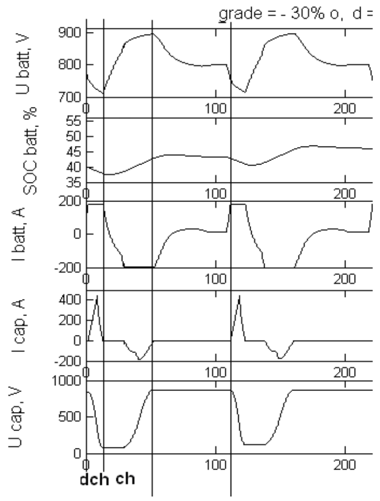


Figure 26: Grade is - 30 %o. The speed of energy consumption ('dch') is high, and under regenerativ braking at charging ('ch') is longer and moderate.

In Fig.26 it can be shown that in time of 'dch' the current of capacitor begins increasing when the discharging battery current is limited. The change of SOC is less and the little value of supercapacitor (SCAP) here is sufficient.

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.

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Conclusions

We presented the reason and the advantages of applied 'beforehand charged energy' E_{Co} and 'constant charging power' P_{Ct} in simulation.
The "correction factor" means a proportion rate of the motoring power by that the railcar gets down from overhead line under controlling of energy management.
The available decreasing ratio of the needed capacitance C with this presented improved energy control method is about from 25 % to 35 %, which is significant value.
The available energy saving in metro railcar generally is over 40 %.
We presented a method to decreasing the need capacitance of energy storage device by operating a newer energy-control system as a newer energy management.
The available decreasing ratio of the needed hybrid energy storage system at case SCAP is 25 % to 40 % with this improved energy control method, which are significant values as decreasing in volume, mass and price.
This novel process and its results are practically independent of the type of the traction motor.
The available decreasing ratio of the needed energy storage at case 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 %.

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