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Control of Energy Storage Device for Rail Vehicles

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Control of Energy Storage Devices for Rail Vehicles. (Reglering av energilagring för tåg.)

Abstract

This master thesis has been done in Berlin at Daimler Chrysler. It is concerned with research and development for electrical engines. The thesis evaluates what improvements can be achieved by using an energy storage system on a rail vehicle. Energy storage devices, like accumulators, flywheels or capacitors are currently under consideration by the rail vehicle industry. The expected benefit gained by introducing storage systems is not only reduced energy consumption but also advantages concerning reduced line peak loads, network stabilisation, improved driving performance. These devices are able to store kinetic energy during braking and to feed it back during acceleration or during max power demand. The work is divided into two steps:

- A simulation model of the vehicle's drive and energy storage system has been set up using "Matlab". Multi-objective optimisation has been applied using non-linear programming and evolutionary strategies. The results are optimised cycles for the storage operation depending on given sets of track profiles and driving cycles. These results are not necessarily combined with control laws. The problem of reduced run-time information is also not considered at this stage.
- During the second step, the results of step one have been used in a control law for the energy storage device, that is suitable for run-time implementation and that is able to deal with the mentioned reduced information. General control design principles were derived. It was evaluated what margins can be achieved compared with those of step one. Simple control laws were specified for use in the next controller implementation.

The outcome of the research work is a control law that permits to utilise in optimal way the energy storage device for a prefixed objective, like reduced energy consumption, reduced line peak loads, network stabilisation or improved driving performance. All this without knowing in advance the characteristic of the route, the brake and acceleration moment.

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1. Introduction

1.1 Overview

One of the basic customer's demands in the railway vehicle manufacturer is the reduction of energy consummation and the related costs. Because of the structure of the energy distribution network costs, the customer's tariffs are dominated by peak loads.

Energy storage devices, like accumulator, flywheels or capacitors are currently under consideration by the rail vehicle industry. The expected benefit introducing storage systems is not only reduced energy consumption but also advantages concerning reduced line peak loads, network stabilization, improved driving performance.

This devices are able to store kinetic energy during the brake time and feed it back during acceleration or during max power demand.

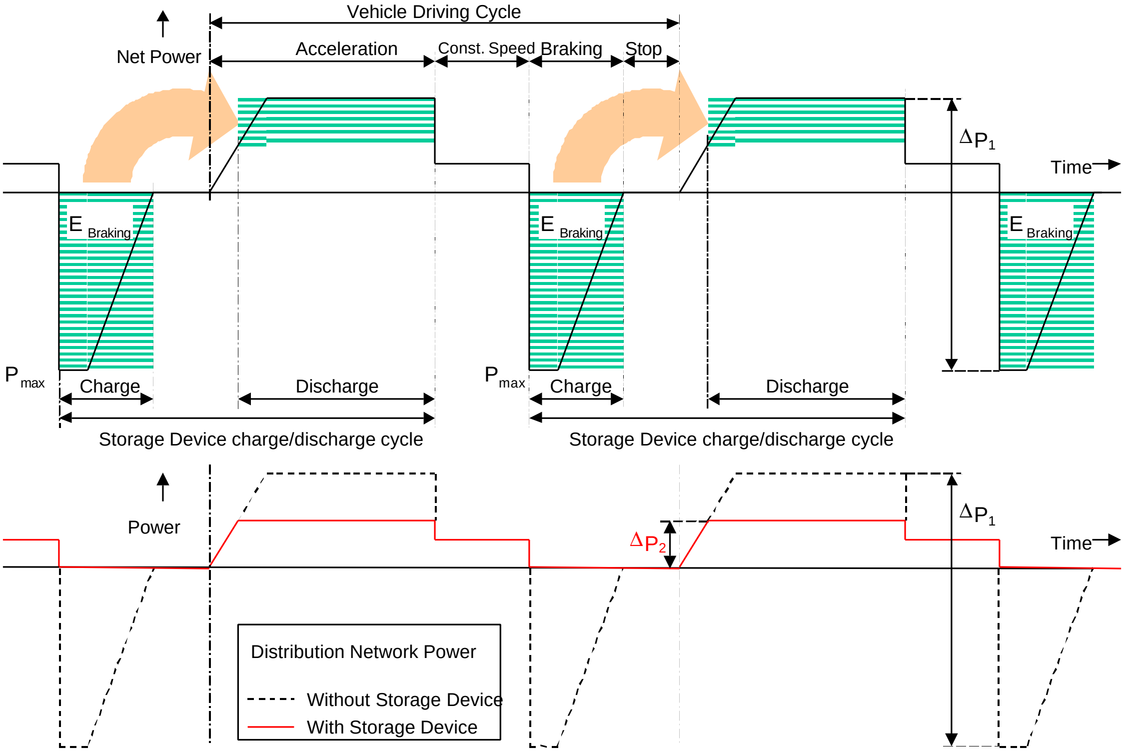


Figure 1.1

Figure 1 shows one driving cycle and two storage cycles: the green area is the brake energy saved during the braking phase and is used in the next acceleration phase.

The row below shows that the distribution network power peak DP_1 is reduced with the storage device at DP_2.

These storage devices on board of the vehicles are used because for elevate distribution network dispersion characteristics, it is not economically convenient to feed back at the electrical network the braked energy.
Consequently it is necessary to consider economic impact for investments in the new storage technology device in the rail application.
At first the storage device introduction utilizes remarkable volume for the considerable energy involved and consequently remarkable vehicle weight increment . It is necessary to do an accurate analysis between the different possible storage technology and find a compromise between volume - weight – price – technical propriety.
Second, it is necessary to know the technique characteristics of the rail vehicles, for the definitive technical choice and the correct application and uses of the storage device. The technologies characteristics for train for long distance ,like ICE, ITR,... , are very different compared with regional train vehicle or even urban vehicle. The technical factors that define the storage device choice are a lot. Data such as mass, top speed, traction effort and braking effort lead to related data like stored kinetic energy of vehicle at maximum speed and the braking time, derived from kinetic energy and braking power. The braking time of heavy rail vehicle is in the order of one minute, that of LRV (local rail vehicle), ten seconds.

	Regional Multiple Unit (EMU)	**Suburban EMU (DC, 4 Cars)**	**Diesel Multiple Unit (DMU)**	**LRV (Local Rail Vehicle)**
Mass of train (brut)	250 t	160 t	116 t	39 t
Top Speed	160 Km/h	100 Km/h	120 Km/h	70 Km/h
Drive power	4000 kW	1200 kW	875 kW	300 kW
Maximum Tractive effort	250kN	180 kN	122 kN	60 kN
Braking Power	4800 kW	3000 kW	875 kW	900 kW

Maximum Braking effort	270 kN	200 kN	56 kN	100 kN
Stored Kinetic Energy	70 kWh	16 kWh	18 kWh	2 kWh
Braking Time	50 s	15 s	70 s	9 s
Drive cycles per year	40000	100000	50000	300000
Drive cycles in lifetime (10^6)	0.8	2	1	6

Table 1.1

The data in table 1 clear the different power characteristic between the different rails vehicles family.

Consequently the economic impact for investment for this new technology is more remunerative for vehicle with low Speed, high brake cycles and short mean route. It is interesting to observe the brake power compared with the maximum tractive effort for each class of vehicle and the drive cycles in lifetime. From this table it is possible to understand how it is more remunerative to use storage device for LRV than in regional rails vehicles

1.2 Problem Description

The transport of means and goods by vehicles is always accompanied with energy consumption. Energy is necessary for acceleration, to overcome friction in components such as wheels, axles and bearings, to overcome the wind resistance and for losses in drives, converters, transformers etc. But there is the possibility to get back a good proportion of this energy: the acceleration energy is partly stored as kinetic energy in the mass of the vehicle and can be regained in the deceleration phase (braking). Although with the most modern electric vehicles, recuperation of braking energy is not perfect. In the important class of suburban and regional trains it is worthwhile to see how much energy is being saved today by recuperation and how much is available to be saved using energy storage on board of the vehicles.

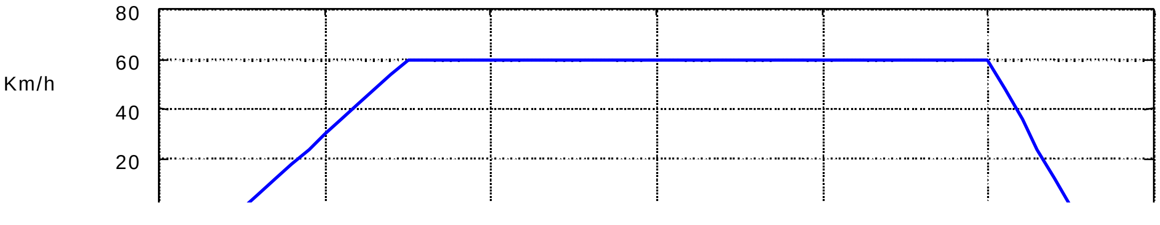
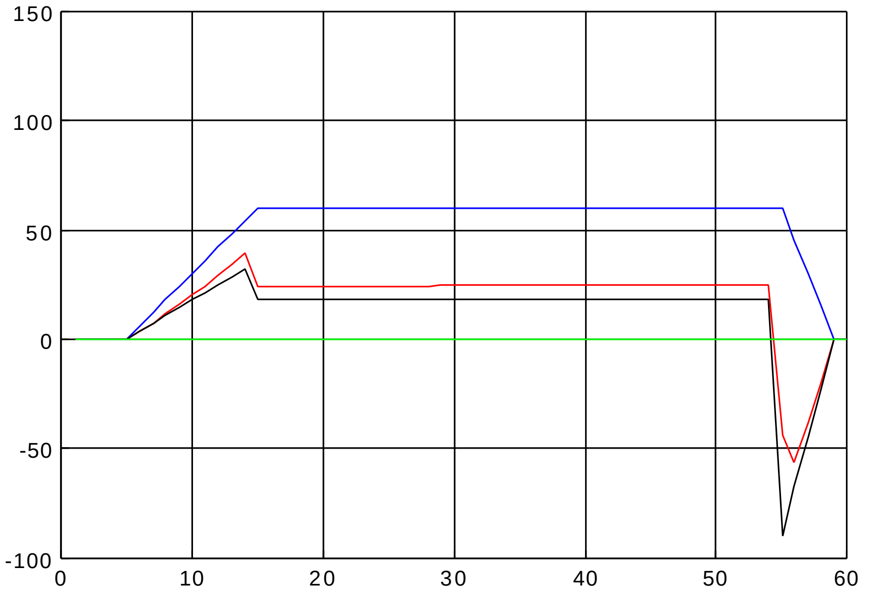


Figure 1.2

The driving cycle of a vehicle consist of four phases of operation: acceleration, constant speed (or free running), braking and standstill.



Red: PNet(t)(10^{-4}), Bleak: PTraction(t)(10^{-4}), Green: PStorage(t)(10^{-4}), Blue: v(t)

Figure 1.3

Figure 1.3 shows the net power, traction power and speed, without storage device, with the figure 1.2 Torque and speed adamant.

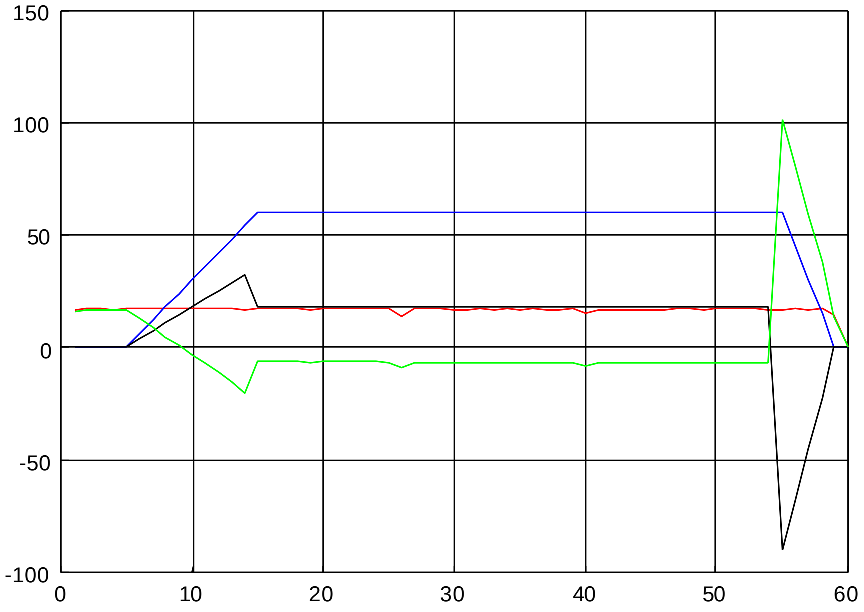
The energy in the accelerating phase has to be taken from the energy supply: from the distribution network in the case of electric vehicles or from the internal combustion engine, typical a Diesel, in the case of independently powered vehicle. This energy is partially stored as kinetic energy in the vehicle’s mass.

During the constant speed phase, the power taken from the supply is reduced, no further kinetic energy is stored. This phase is long and dominant in long distance trains and very short and negligible in urban and regional vehicles.

In the braking phase, different methods are possible. In electric vehicle, the kinetic vehicle energy flows back into the distribution network if it is able to take up the power, but this is accompanied by high losses due to the high braking power. A vehicle kinetic energy can also be dissipated by the mechanical brake without considering its energy supply. In all cases, the energy supply is inconsistently loaded and a large proportion of the vehicle’s kinetic energy is wasted.

For vehicles with frequent starts and stops it would be advantageous to store the kinetic vehicle energy in the braking phase and to reuse it during the next acceleration phase. For independently powered vehicle the energy storage system has to be on-board. This is also advantageous for electric vehicles as it avoids high energy losses in the distribution network.

Figure 4 shows the net power, traction power and speed, with storage device, with the same T and v :



Red: PNet(t)(1/10^4) Bleak: PTraction(t)(1/10^4) Green: PStorage(t)(1/10^4) Blue: v(t)

Figure 1.4

The proposal is to find power Storage control law that decides to load or discharge the Storage device, like Figure 1.4, in order to get the net power constant.

1.3 Problem Statement

Although the basic function of an energy storage device is very easy to understand, it is, however, not clear how to operate optimally the charge of the storage device under real conditions. The control strategy should take into account the mentioned objectives and the internal constraints of the storage as, e.g., maximum stored energy and allowed peak power.

The work is divided into two steps and we must evaluate what margins can, at the beginning, be achieved by the energy storage system. A simulation model of the vehicle's drive and energy storage system has to be set up. The design objectives have to be defined. Multi-objective optimization has to be applied using, e.g., nonlinear programming or evolutionary strategies. The results, at this stage, are optimized cycles for the storage operation depending on given sets of track profiles and driving cycles. These results are not necessarily already under control laws. The problem of reduced run-time information is also not considered at this stage.

During the second step, the results of step one must lead to a control law for the energy storage device that is suitable for run-time implementation and that is able to deal with the mentioned reduced information. General control design principles should be derived. It should be evaluated, what margins can be achieved compared with those of step one. Simple control laws should be specified for following next controller implementation.

1.4 Propose

Energy storage on a vehicle with frequent driving cycles has two advantages: firstly, the total energy consumption will be lower, and secondly, the load peaks of the energy supply are equalized. Therefore the maximum power of the energy supply can be reduced. In the case of electric trains this leads to significantly smaller load on the energy distribution network and, therefore, to better voltage stability and to lessen losses. Independently powered vehicles could benefit from a lighter, lower powered engine or better driving performance would be available with an existing power plant.

The proposal of the research work is to determine a control law that permits to utilize in optimal way the energy storage device in such way to center the prefixed objective, like reduced energy consumption, advantages concerning reduced line peak loads, network stabilization, improved driving performance. All this without knowing in advance the characteristic of the route, the brake and acceleration moment. The control law must be set up in Real-time context.

2. Simulation Model

2.1 Introduction

In modern railway vehicles the traction equipment mode is able to operate the drivers in motor mode for acceleration and in generator for braking. On electrical vehicles with overhead line or third rail, the feed back of the braking energy into the power supply network and the reuse of energy in other vehicles is a hardly goal because in real system, the transmission of the braking energy within the supply network is not all free of resistive losses; ordinarily an accelerating train is not along the route when the braking energy has to be feed back. For this reason the efficiency of using recuperative braking energy only has an average efficiency of about 25...35% in DC-750 V supply networks.

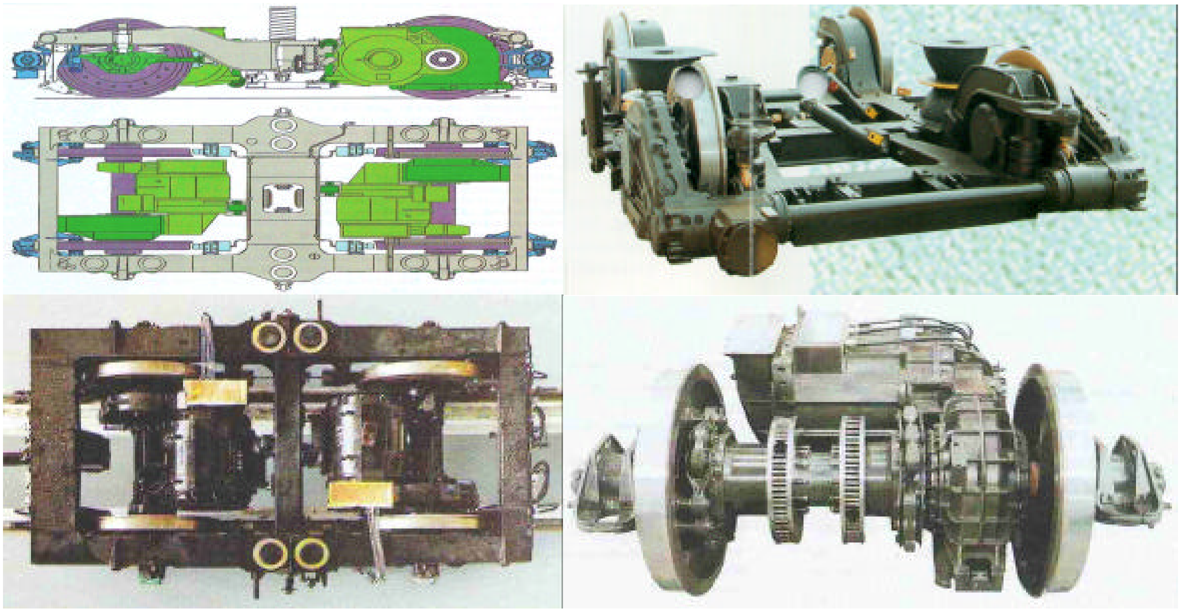


Figure 2.1

The reuse of recuperative energy can be improved definitively by storing temporarily the braking energy on the vehicle and to reuse it in the next acceleration phase. This seems to be realizable today, because of improvements in energy storage technologies within these last years. Especially the technological maturity of flywheels and super capacitors for energy storage on board of railway vehicles seem to be bases of attractive solutions.

2.2 Model Construction

The idea is to set up three simulation systems, that, with the input in the driving cycle and the storage power law for this cycle, give in output all electrical vehicle parameters, like net power, net current, converter voltage, engine current, the brake system power and all the different power losses in the engine, in the brake system, in the storage device, in the distribution network and in the input filter.

For driving cycle it means the torque moment or traction force with the respective velocity for each time, like figure 2.2.

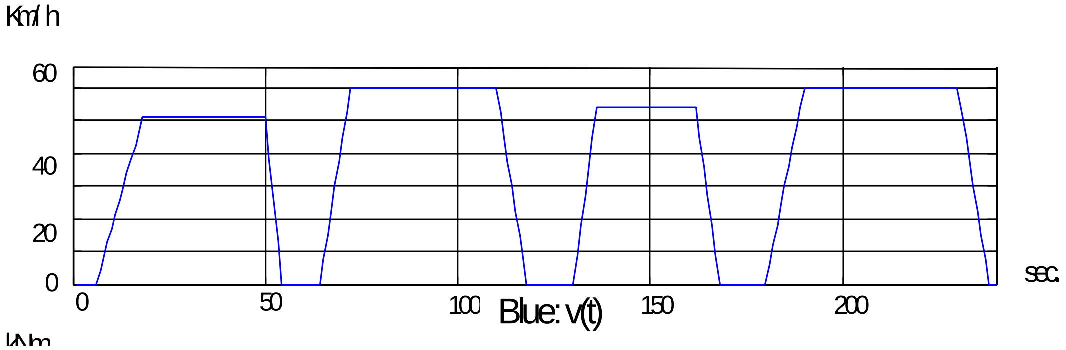


Figure 2.2

This simulation system must be set up to work with different power source with the same input and output. Energy supply could be the electric network (preferably DC) or Diesel engines with alternator.

It is impossible to feed back the brake energy with all types of supply. To represent this characteristic we have set up three different simulation models: the first where it is possible to feed back all brake energy, like figure 2.3, the second is a simulation model where it is allowed only 25% feed back of the brake energy; the third is a simulation model where it is not possible to feed back the brake energy because the current can flow only in one direction and the converter or rectifier is not bi-directional.

2.2 Model Description

The Simulation model is supposed to work in a stationary mode based on energy balances. It means that the electrical transitory are not considerated and all output variables are in electrical and mechanical equilibrium.

Figure 2.3 is an example of simulation model with energy supply electrical network at 750 V D.C. and a super capacitor for storage device where it is totally possible to feed back the brake energy.

The impedance R_N represents the distribution network line impedance. This impedance is supposed to be a function of the distance between the vehicle and the network energy supply connection.

Electrical Simulation Model

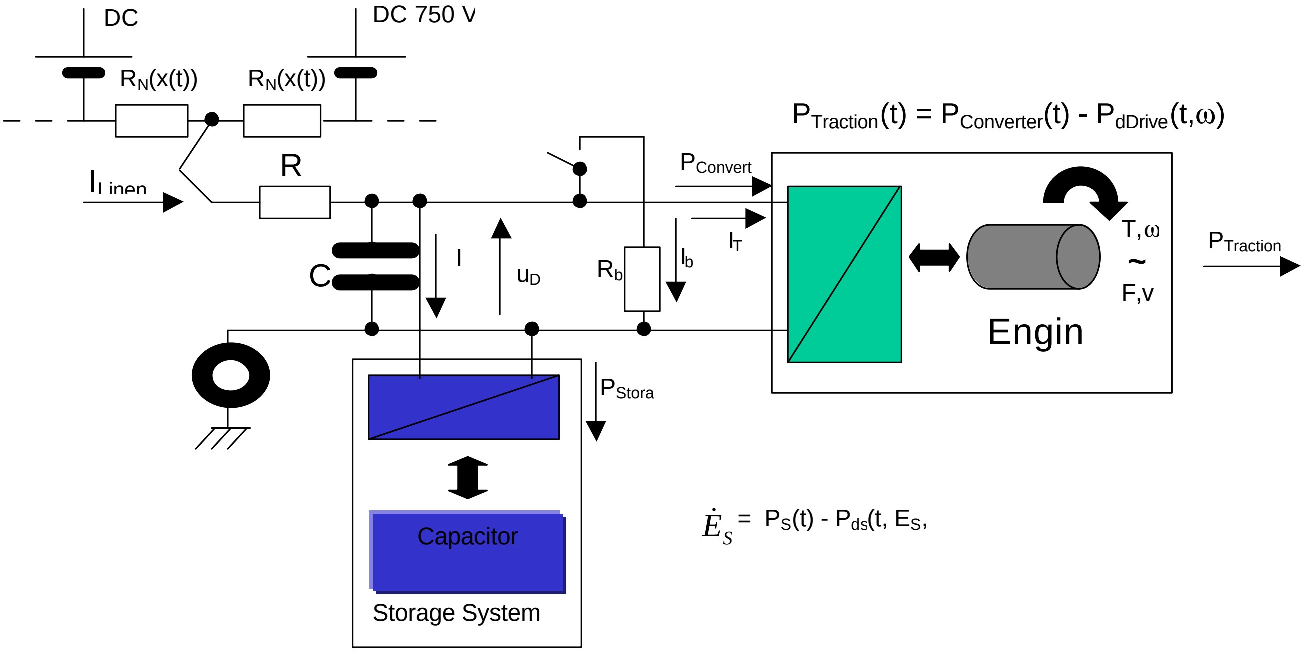


Figure 2.3

R_L and C represent the vehicle input filter. However in the electrical equation the capacitor C is negligible because its energy is too small compared with the energy in the storage device. R_B simulates the electrical brake system. During the braking phase the energy from the converter feeds back in the electrical network or in the storage device. But, if the required brake power is too much and the voltage u_{Dc} becomes too high, also the mechanical brake system begins to work and dissipates the energy with Joule effect in heat. The mechanical brake system is modeled in that way: if u_{Dc} <900 Volts i_B is 0 and if u_{Dc} >900 Volts $i_B = u_{Dc} / R_B$. $P_{Converter}$ is the converter power and it is the sum between the $P_{Traction}$ and the Pd_{Engine}. $P_{Traction}$ is the effective traction effort and Pd_{Engine} is the power dissipation in the engine and converter and it is function from the velocity and converter current.

$P_{Storage}$ is the storage device input or output power and the effective stored energy is E_S. Where E_S is the integral in the time from $P_{Storage}$- $Pd_{Storage}$. $Pd_{Storage}$ is the storage device power dissipation and it is a function from the storage energy and $P_{Storage}$.

The simulation model algorithm is written in such way that eventual changes in the electrical simulation model don't compromise the whole operation butt it is possible to add and delete new components arbitrarily.

It is possible to use for energy supply, a diesel converter, or something else similar instead of the electrical network. And it is possible to simulate that, in the same Electrical network more rail vehicles are connected and use the same energy source in the same moment. In this case it is interesting to analyze the net power distribution and how it is possible to minimize the net dissipation and to decry the peak power load.

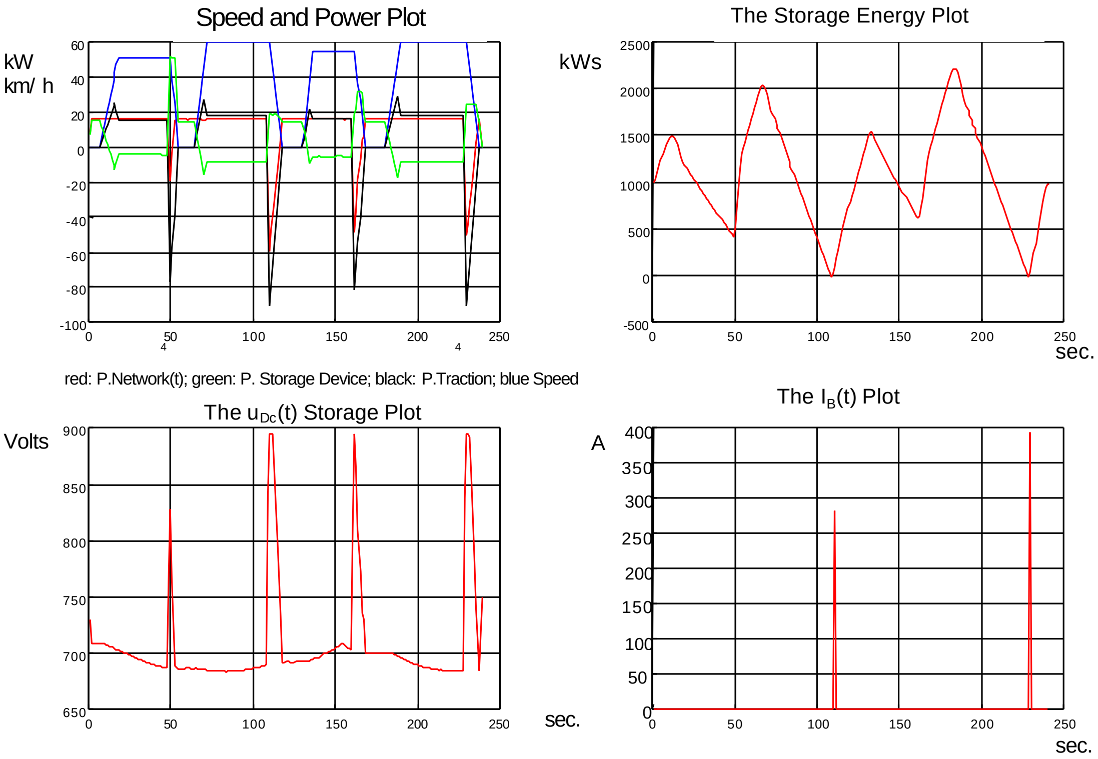


Figure 2.4

Figure 2.4 shows an example of simulation model characteristic plot with the input at the electrical model a storage power law that optimizes the network peak. In the left picture below it is possible to check that the network power is almost constant. On the right there is the storage device energy plot with the same energy at the starting and at the end of driving cycles. Down left there is the u_{Dc} voltage plot or converter voltage. By the figure down right it is possible to see that in the brake phase the converter voltage becomes relatively high and near to 900 Volts when the mechanical brake system begins to dissipate the energy.

2.3 Simulation Model Use

The electrical simulation model is used inside the optimization algorithm for the energy management: it means that in any moment the electrical simulation model should calculate the electrical variables that are used in the optimization algorithm to find the best storage power law for storage device.

The simulation model is used also to check if the implementation of the controller permits to have same result to be compared with the optimization result.

For this motivation it is necessary to be careful with the implementation from the electrical simulation model, because from it depends a good result with the optimization algorithm and to have a good controller.

3. Optimization Statement

3.1 Propose for the Optimization Step

Before setting up a control law that permits to use in the best way possible the storage system it is necessary a phase of preliminary research to understand how the different physical factor and energy parameters of the total vehicle system are affected together.

It means that it is necessary to find the correlation between the factor and parameter of the storage device and the vehicle in order to set up an empirical law that binds all together.

That's what we want to find with the optimations algorithm. The idea is to start with the eletrical simulation model and the driving cycle, with speed and traction effort for each moment, using an optimization algorithm that finds the law of the storage power to minimize one or more factors like the peak network power, the eletrical dissipation in the converter, or in the network, with a series of elementary but really important constraints, like the max energy inside the storage device should be not more his max capacity and that the energy should be positive for every time.

It is very interesting to understand which factors are possible to be changed, with the same peak network power, so to have low dissipation in the storage device, input filter, converter and network.

Another really important factor is to determinate how the peak network power increases when the max storage device capacity decreases, with the same initial conditions and same driving cycle.

3.2 Optimization Algorithm

I use the optimization algorithms inside a loop, as in figure 3.1, where, for each sampling time, are known velocity and traction power. The electrical simulation model calculates every electrical and mechanical variable from the vehicle system and from the storage device.

These parameters and variables are the input for the optimization algorithm that produces, according what we will optimize or minimize, the storage power law for the storage device with the correct constrains for the physic storage device limitations. The optimization algorithms is implemented in different way depending on what we want to optimize. If we like minimizing only the max net power the algorithm result definitively simpler than if we want to reduce the net or the vehicle converter dissipation.

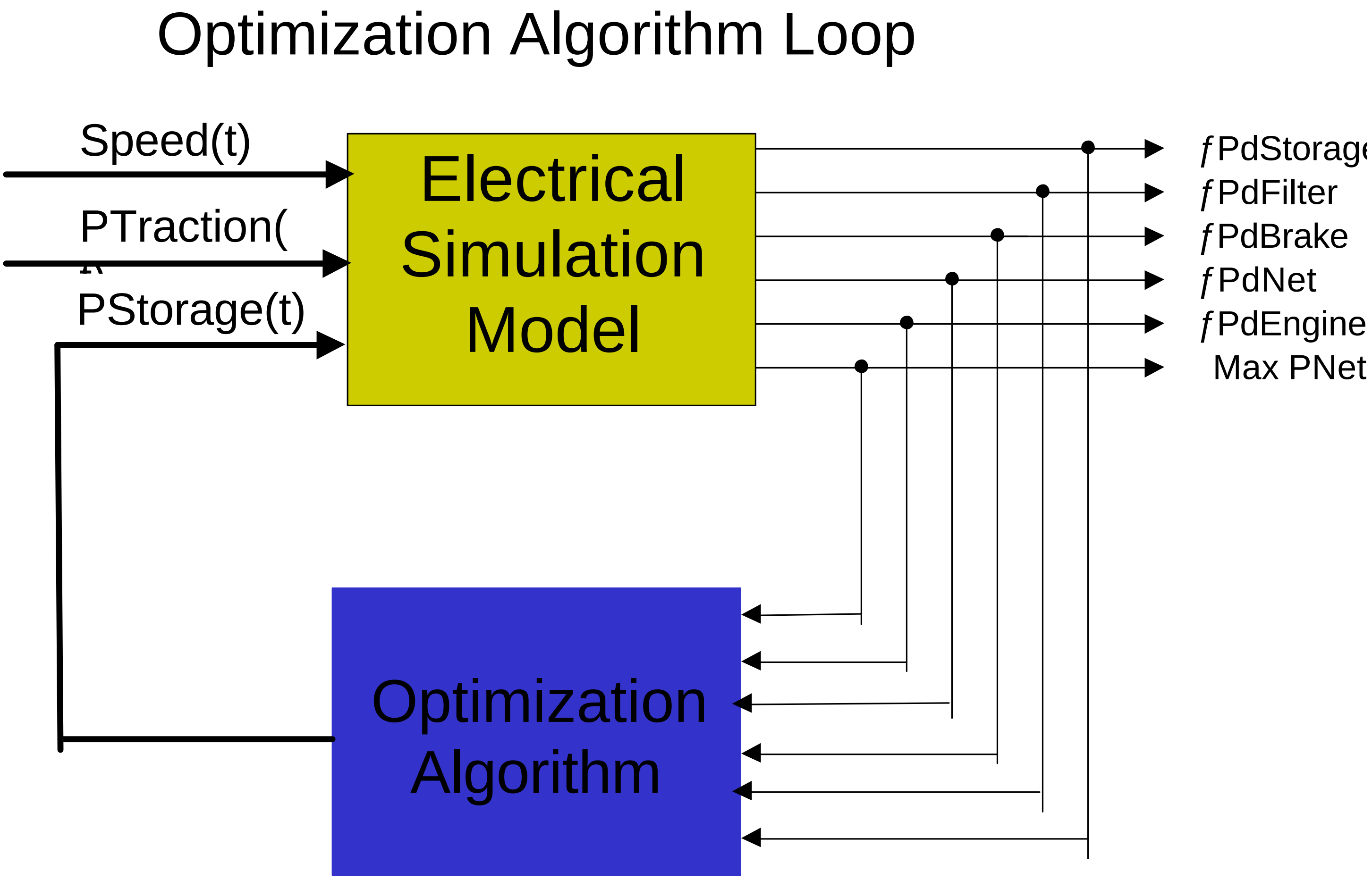


Figure 3.1

One example of optimization algorithms is in Pag. NN; this algorithm implementation is in the simulation language Matlab with the first aim to reduce the network peak power. For this application I have use the standard function in Matlab Minimax(...) applied at a network power with variable storage power that must be inside the range –max. storage power and max. storage power. The algorithm should work with the correct energy restriction like the max storage energy should be any longer the Max storage capacity and that the energy must be for each time positive.

$$\frac{\min}{PStorage}\ \frac{Max}{\{PNet\}}\{PNet\ (PStorage\ ,...)\}\ \text{with}\ \begin{array}{l} \|PStorage\| \le MaxPStorage; \\ Energy(PStorage) \ge 0; \\ Energy(PStorage) \le MaxStorageCapacity \end{array}$$

3.1

3.3 Optimization result

We have used the optimization algorithm to define which improvement is possible to find in the field of energy performance by a theoretic storage device introduced in a rail vehicle.

For the first simulation we have used data from the University in Lisbon that has supplied a 19:40 minute driving cycle and 9.018 km long. The driving cycle is from “Universidade de Caparica” to “Talamino” composed with 15 intermediate stops of 20 seconds with a real vehicle for passengers transport as in the following picture 3.2. For the experiment they have used a rail vehicle produced by Daimler Chrysler with the following technical characteristics:

Vehicle Name	**Incentro AT/6**
Mech. power at wheel (Running)	**132 kW**
Mech. power at wheel (Braking)	**350 kW**
N° of propulsion	**4 units**
Tare weight	**38,92 t**
N° Passengers	**356 units**
Max Speed	**90 km/h**

Figure 3.2

For the next following simulation we have used data from the Daimler research laboratory in Mannheim that has given us a driving cycle from two different rail vehicles.

The fist driving cycle is from a metropolitan underground train or Fast train (S-Bahn) from “Mannheim HBF” to “Käfertal BHF”, 5.150 km long, 15:10 minute and composed of 9 intermediate stops each between 15, 25 seconds. The most important vehicle technical data are in the following table:

Vehicle Name	**DB ET424**
Mech. Power at wheel (Running)	**280 kW**

Mech. Power at wheel (Braking)	**450 kW**
N° of propulsion	**8 units**
Tare weight	**110,5 t**
N° Passengers	**720 units**
Max Speed	**120 km/h**

Figure 3.3

The second Mannheim driving cycle is from a regional train for passengers transport used from the station “Mannheim HBF” to “Kurpfalzbrücke” for a distance of 54,505 km, 1:37:57 hour, with main speed 33.4 km/h and with 45 intermediate stops.
The main vehicle technical proprieties are:

Vehicle Name	**Novia**
Mech. Power at wheel (Running)	**300 kW**
Mech. Power at wheel (Braking)	**550 kW**
N° of propulsion	**6 units**
Tare weight	**90,70 t**
N° Passengers	**560 units**
Max Speed	**150 km/h**

Figure 3.4

Every driving cycle is composed of all vehicle electrical and mechanical characteristics for each sampling time. For every driving cycle parameter we have used only velocity and traction power. The rest of the data, like net current, converter voltage, brake system power, are used to check if the electrical simulation model permit to have the same vehicle characteristics.
Before starting with the simulation phase, the first step was to extrapolate the real electrical vehicle parameter and constant to have the simulation results close to reality. At the beginning we have worked without storage device to compare the result with the real rail vehicle parameters.
After we have calculated the theoretic dimension of the storage device with all energy vehicle parameters. It is possible to calculate the storage dimension with the energy kinetic equation if we know the max. speed and the full vehicle weight. The max. storage power is calculated in the brake phase from the max. brake system effort.

In the end we have used the optimization algorithm to find the storage power law and to use the storage device in the best way.

We have used the optimization algorithm in different proposals. One was to check how the max network power peak changes with the max storage capacity and with the different driving cycle, like figure 3.5.

In the figure 3.5 is possible to divide the curve in three area. The first is from 0 to 3 MWatt, where the graphic is quite flat: it means that the storage device is too small to introduce big network power peak changes, the second is between 3 MWatt and 8 MWatt, where angular coefficient graphic is quite negative: it means that for small storage device capacity increment the net power peak becomes quickly smaller, the last area is for a storage capacity bigger than 8 Mwatt: this zone is considerate as a saturation area, where big storage capacity increment reduces slowly the net power peak.

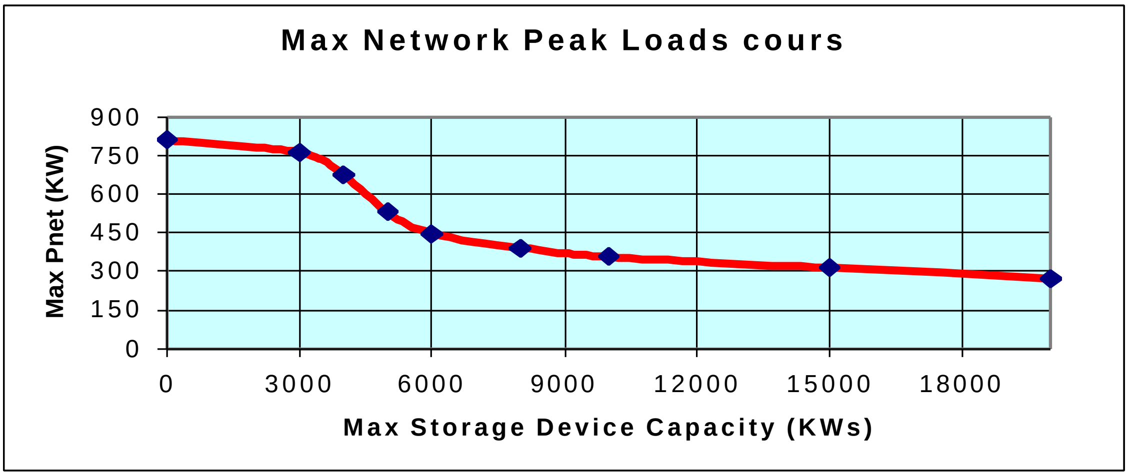


Figure 3.5

The first area represents the past when the storage device technology was too young and the storage capacity was too small to permit the increasing the technology performances.

The second area represents the present time when the storage device technology is ripe to permit to increase the performances in the rail vehicle.

The third area represents the future when the storage technology increases the dimension (kWs/m³) and the weight (kWs/kg) of the storage device permitting to work in the range from 10 MWs to 100 MWs so to better the driving performances and reduce the energy consumptions.

We have simulated different situations to find the theoretic minimum energy dissipation and the total energy reduction with the introduction of a storage device.

From different simulation results we conclude that for a reduction of 50% of the max network power peak, it is possible to reduce less than 10% of the total energy dissipation in the case that it is allowable to feed back the brake energy.

In the case that the distribution network doesn’t permit to feed back the brake energy or for vehicles with independent energy source, the total energy reduction can be bigger, between 10% to 40%.

One example that explain the different energy dissipation and the possible energy reduction with the introduction of a storage device, in the case with electrical network energy supply that allows to feed back the brake energy is in figure 3.6. This graphic is the result of the optimization algorithm with the Lisbon driving cycle and the storage device 15 MWs.

The first line shows the different energy dissipation present in the simulation model at the end of the optimization loop with storage device system. The first column is the vehicle input filter energy dissipation, the second is the distribution network impedance energy, the third is the electrical brake system energy dissipation that is zero in this case, the forth is the converter and engine energy dissipation and the fifth is the storage device dissipation energy.

The second line shows the respective energy dissipation reduction for each component listed in the first line.

Max Storage Device Capacity 15 MWs,

Power Storage 1000 kW

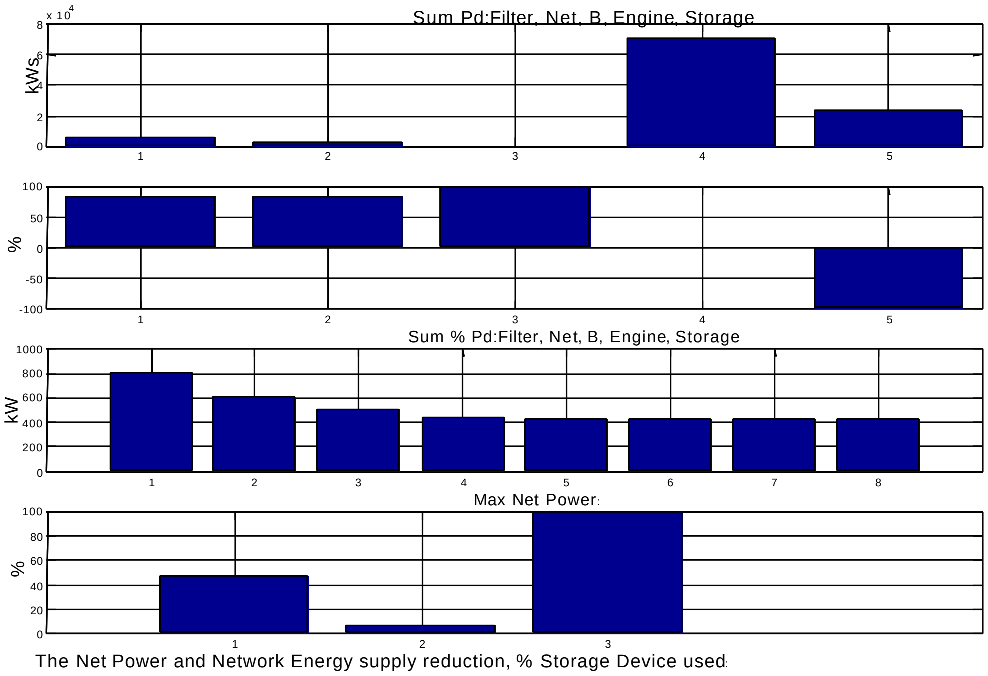


Figure 3.6

The energy dissipation in the: Input filter, Distribution network, Electrical brake system, Converter and Engine, Storage device.

It is interesting to note that the storage device introduction has reduced about the 90% the network and input filter dissipation. The brake energy dissipation is totally recuperated. The converter and engine dissipation are unchanged because the vehicle performances are the same. Of course the storage device dissipation aren’t reduced but are increased.

The third line shows the network max power peak at first without storage device 816 kW and after with the storage device 424 kW at the end of the optimization loop.

The forth line shows, in the first column, the reduction in percentage of the max power peak; the second column shows the total energy reduction from the energy supply that, in this case, is about 9-10%. The third column shows the total storage device used that is, in this case, 100%. Down, in figure 3.7 it is possible to check the electrical vehicle and energy variable from the same driving cycle used for figure 3.6.

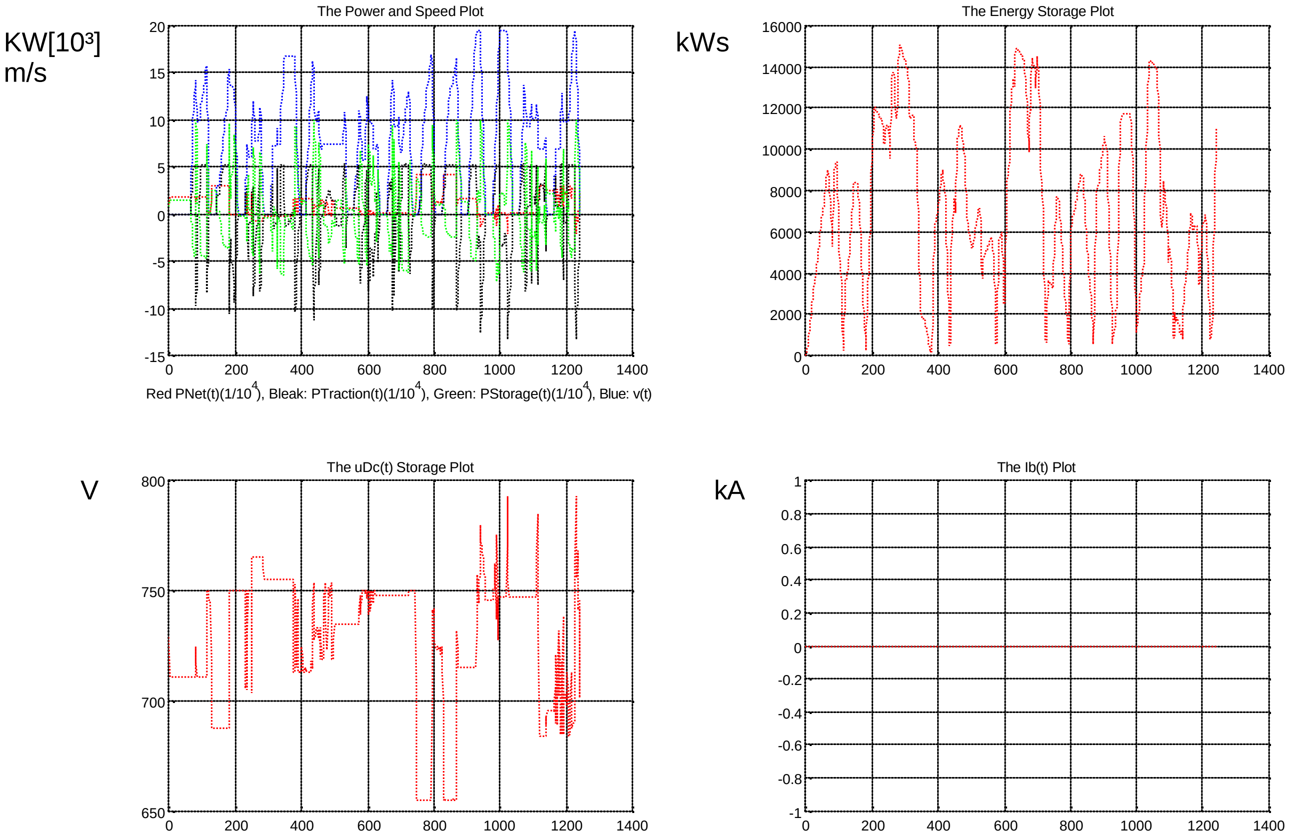


Figure 3.7

4. Control Technique

4.1 Overview

Energy supply, energy storage system and vehicle drives must operate together and therefore have to be combined and connected.

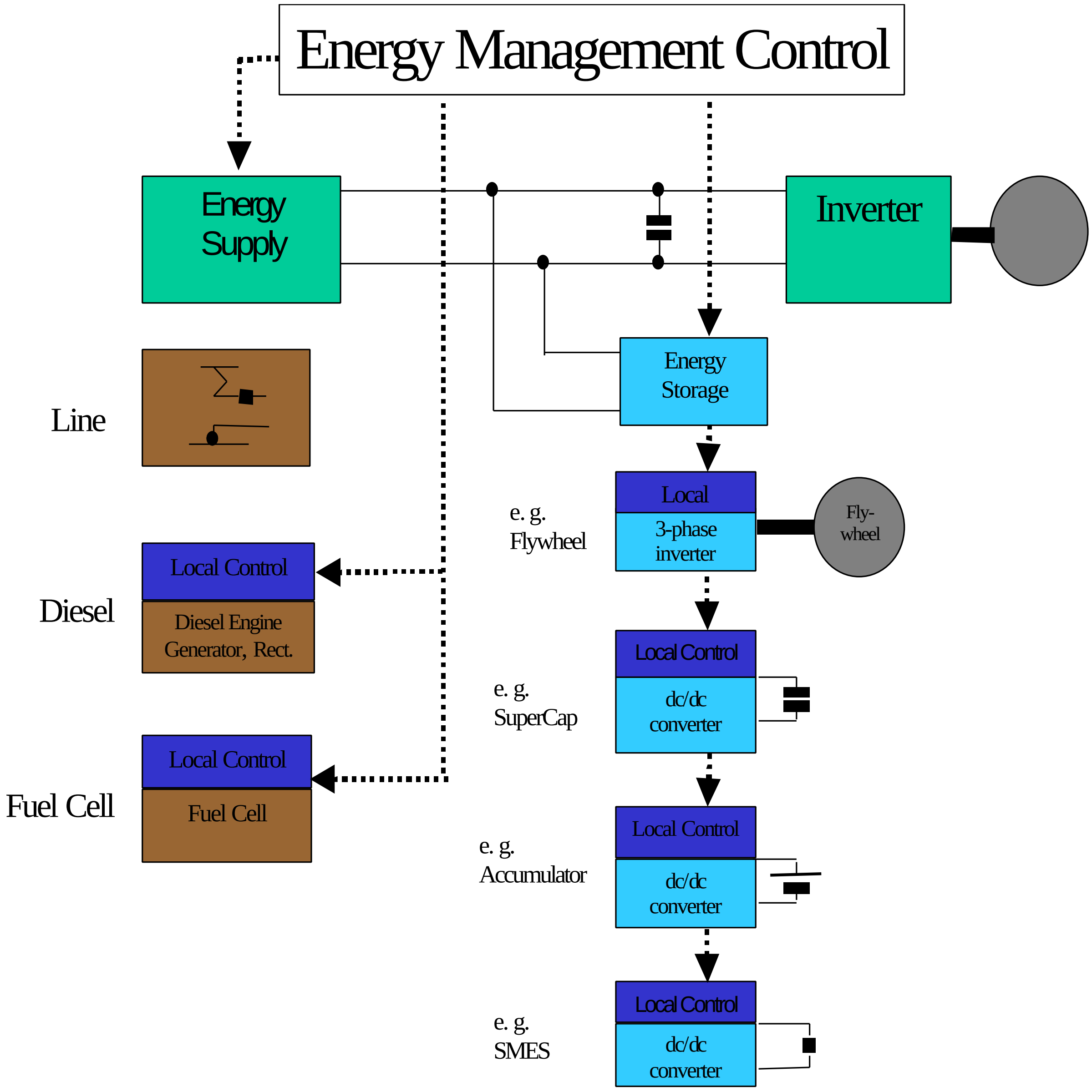


Figure 4.1

Energy supply could be: the electric network direct current with 600 or 750 volts or 15kVolts alternate current at 16,67 Hz; a Diesel engine with alternator and rectifier and with respect to future vehicles, fuels cells. Possible solutions to storage energy on-board can be flywheels, super capacitors, accumulators and SMES.

The stored energy must be controlled by means of an energy management system. The control concept is very similar for all different applications: storing all braking energy and feeding it back during the acceleration phase reduces the peak power of the supply.

The control algorithm must be set up in order to permit the vehicle, the storage device and the energy supply to work together optimizing much many factors. It could be set up to permit to have a better result to reduce the peak power but in the same time it is necessary to be careful with the total energy consumption and to use, in every moment, all storage device capacity.

The algorithm must be flexible for future alteration and evolution. If we change simulation model or storage device it should be able to work in every case with few control parameters calibration.

4.2 Control Proposals

In any case the control law should be set up around the storage device, because every storage device has different technical characteristics, but the mean idea for the control strategy should be the same. The proposal for the control law is to use as much as possible the storage capacity, because it means, in almost every situation, a relevant energy reduction. The control strategy must be robust: it means, in this case, that for different driving cycle it is necessary to have good results in the peak reduction and in the total energy consumption.

And it is necessary that with few control parameter change we aren’t far from the best solution.

The control algorithms must be able to adapt with few control parameter at the different storage device characteristics. The most part of storage device isn’t able to work at maximum power for every energy level. The flywheels can use only 50% of the energy maximum power and the supercaps can use only 70% of the total storage energy.

We can use different philosophy to implement a control law for storage device depending on which result we like to improve. For example it is possible to decide to recharge the storage device not only during the brake time but also in still stand phase or, in every case in which the traction power is under a determinate limit.

There are different methods to use the storage device. It is possible to use the storage energy proportional to the vehicle velocity, proportional to the traction effort, etc. Of course to improve the best strategy it is necessary a compromise with each other strategy.

The control law should be implemented to work in a real-time context, like figure 4.2.

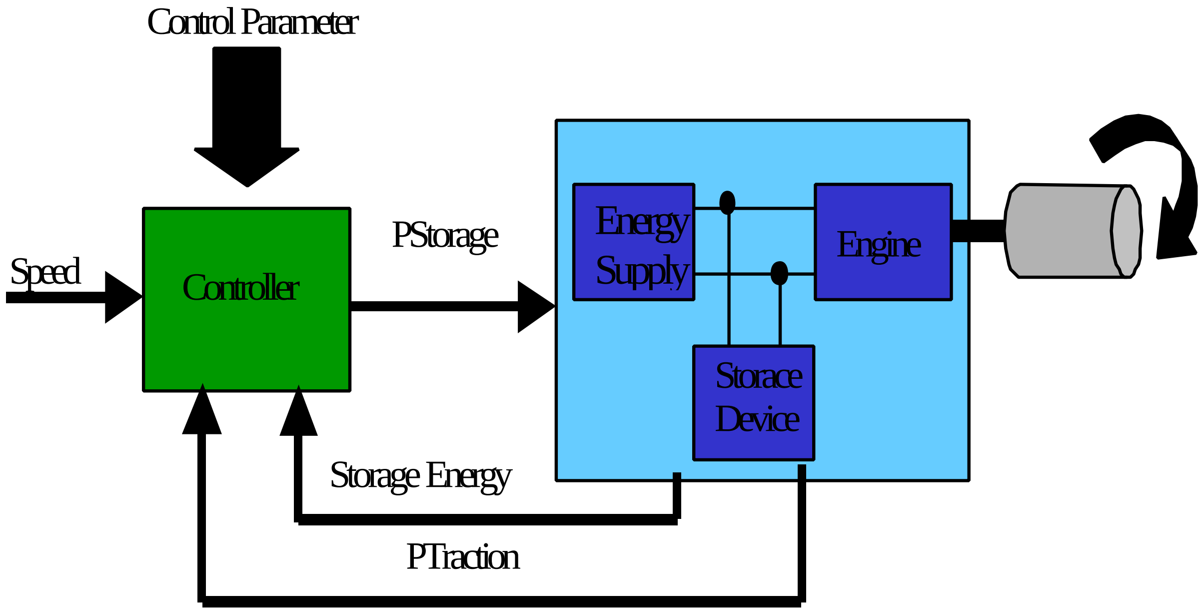


Figure 4.2

The controller should be set up to work as in figure 4.2. The reference signal, as in every vehicle, is the speed, and the feedback from the system is the traction effort and the storage energy level. This model is true for every storage device, simulation model and energy supply.

In reality the schema in figure 4.2 is too much simple, because it is not sufficient that the control signal, in this case the storage power, permit the vehicle to run with the same speed indicated in the reference signal.

To permit the vehicle to go at the same speed indicated in the reference signal it is necessary that another controller permits to have in the engine converter input a sufficient power from the energy supply that together with the energy from the storage device permit to generate the correct traction effort to advance at the velocity indicated in the reference signal.

At the moment we are not interested in studying the complicate structure that permits each rail vehicle to run at a determinate speed, but we like setting up a controller algorithms that, with the velocity in in-put, the traction effort, the storage device energy level and some control parameters, calculates for each moment the suitable storage power. However it is necessary in a real application another controller that manage the power from the energy supply.

Figure 4.3 shows the structure of the controller with the respective input and output signal. It is possible to see that for the controller are necessary different control parameters. Some control parameter could be constant and others, like driving cycle mean time, can change in the running time. In this case the controller becomes adaptive.

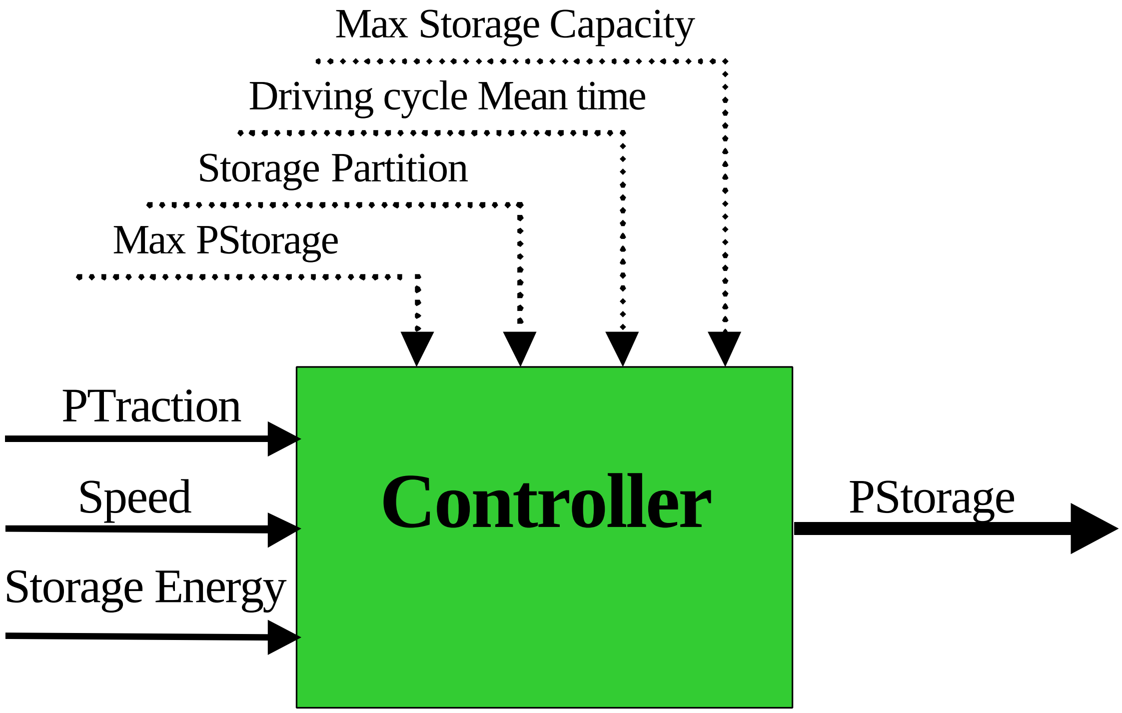


Figure 4.3

To implement the controller software in discrete time, it is necessary to follow correct real time rules to have correct efficiency. It is important that for each sampling time the delay of the control signal after the input data, is as small as possible to permit to approximate the continuos reality with discrete time signal. If this delay becomes too big, it may happen that in the moment of the control signal output, the physical condition of the system is changed and the control signal corresponds at the past of the system device and not at the present physical condition.

To reduce this delay it is necessary to implement the control algorithms with a clear structure, like figure 4.4. However a good rule is to up date all internal variables and pre calculate the next control signal after sending the present control signal.

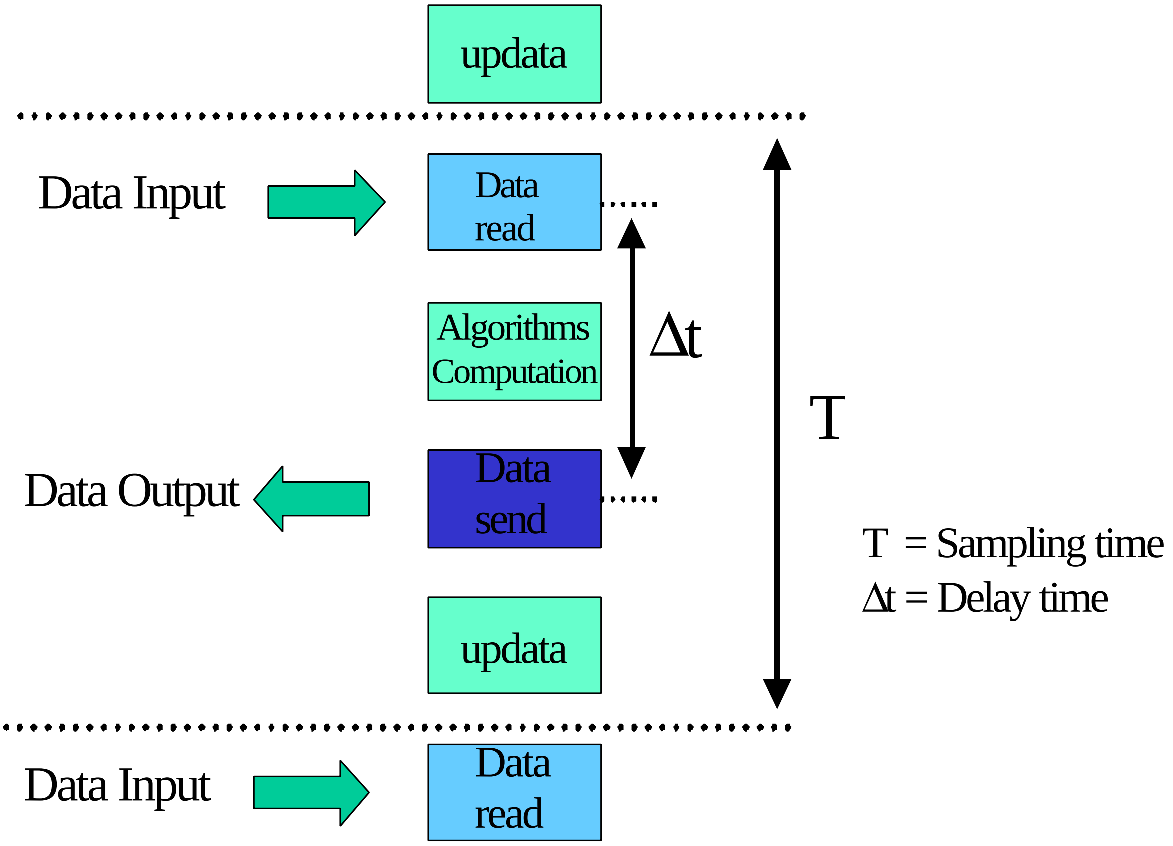


Figure 4.4

To day with the high computer performance this problem is reduced, but it remains a good proposal to implement control software in real time application in any case if there are more processes running.

4.3 Time-Rated Load Periods Curve

Before beginning to speak about the control algorithms it is necessary to introduce some important tools used by the rail vehicle engineering to understand and analyze the simulation results. In particular to analyze the electrical power solicitation we have used the Time-Rated Load Periods Curve to represent the net power characteristics. The Time-Rated Load Periods Curve are set up if it is possible to know all the net power course and to use time window with amplitude Dt smaller than the simulation time. For every time window we calculate the network power average in absolute value, beginning from time zero and shifting the time windows for dt until the end of simulation time.

In the graphic we report in y coordinate the maximum of the average in each time window and in the x coordinate the amplitude of the time window.

$$P(\Delta t) = \max_{t}\left(\frac{1}{\Delta t}\int_{t}^{t+\Delta t}\left|P_{Net}(\tilde{t})\right|\cdot d\tilde{t}\right) \qquad \textbf{4.1}$$

$$0 \le t \le Ts - \Delta t \cup 0 < \Delta t \le Ts$$

To obtain all the graphic it is necessary to repeat all the procedure with windows amplitude beginning from *dt* until TS, the total simulation time.

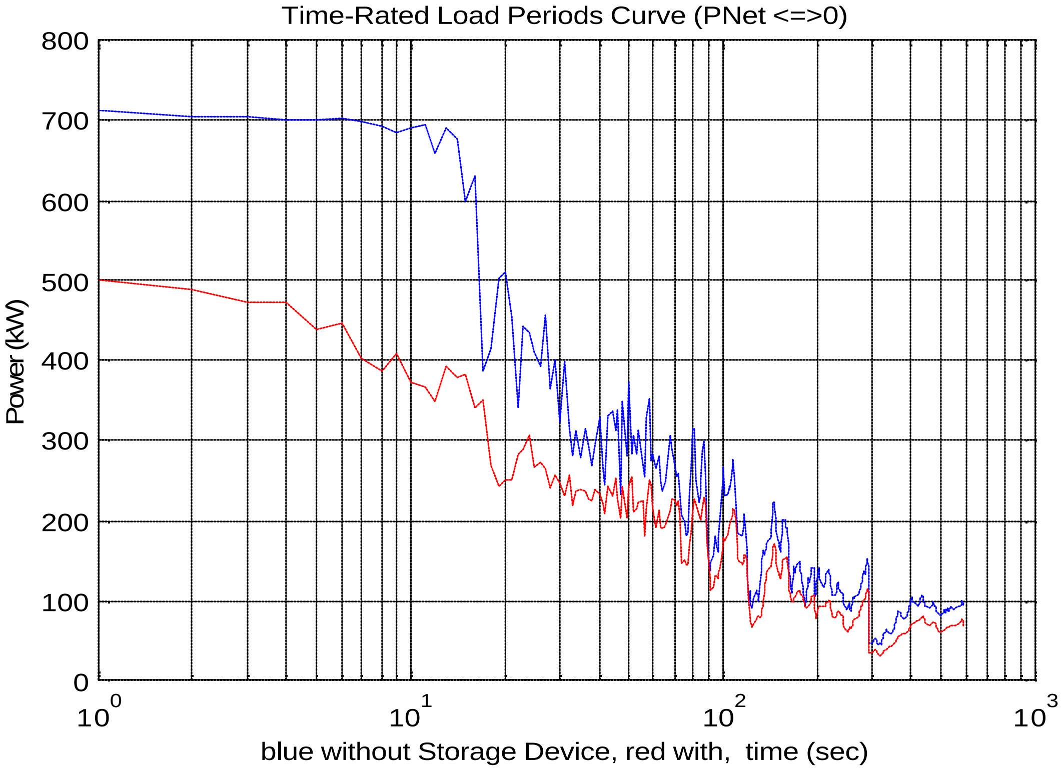


Figure 4.5

The reason why we use the absolute values of Network power because we are interested to study the electrical stress of the distribution network.

In the rail vehicle engineering this kind of graphic are more useful than other network power representation because from they simplify the study of the analysis of the results.

4.4 Control Algorithms

In order to set up the control algorithms we are starting with basic intuitive logic. The idea is to begin with a relatively easy control law and after increasing the complexity of the algorithm to obtain a better quality and characteristics algorithms and check, in every case, the strength in function of the parameter.

The first control algorithms implemented, called *Two level controller*, is composed only of two fundamental parameters: *uplevel* and *downlevel*.

The main idea is that if the vehicle traction effort is less than the *downlevel,* the storage device power becomes:

$$\mathbf{P_{Storage} = \mathit{downlevel} - P_{Trac.}} \qquad \mathbf{4.2}$$

until the storage device isn't completely full.

If the traction effort is greater than the *uplevel*, the storage device become:

$$\mathbf{P_{Storage} = (\mathit{uplevel} - P_{Trac.})} \qquad \mathbf{4.3}$$

until the storage device is completely empty.

For the storage power sign we use the convention that the output power is negative and the input power is positive, figure 2.5 and 2.6.

This algorithms structure is really simple, but it is important because it permits to understand which result may be achieved.

The strategy used is to fix the max storage capacity and then changing the two parameters until we have the maximum use of the storage device, in no case it becomes empty and, at the end of the driving cycle it should be full.

For the simulation we have used in every case real driving cycle and three different simulation models. In the first simulation model it is allowable to feed back all the brake energy, in the second only 25% of the braked energy and in the third the network is not reversible.

The results obtained with this algorithm are characterized by high influence of the parameter *uplevel.* With small change of this parameter we find completely different results. It means that the control algorithms is not robust in this parameter.

Figures 4.6 and 4.7 show the time-rated load periods curve for the same simulation model in figure 2.4 and storage device with 7 MWs capacity, with driving cycle from Mannheim HB to Käfertal HB, and different *uplevel.*

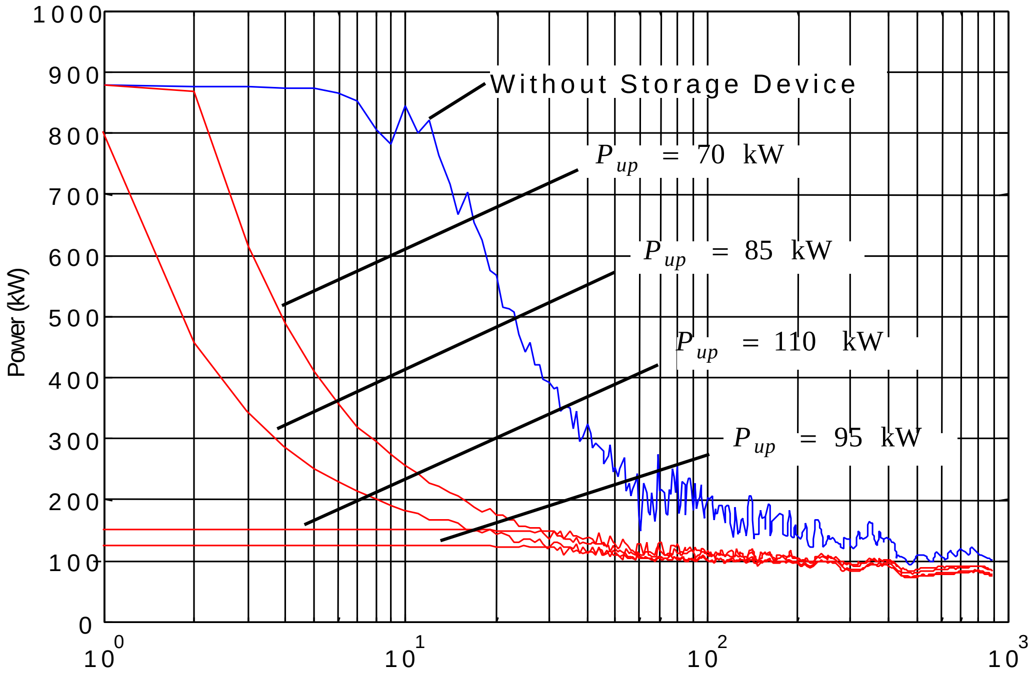


Figure 4.6

Course of the Time-Rated Load Periods Curve of the driving cycle Mannheim HB – Käfertal HB, with simulation model in figure 2.4 and Two-level controller, with different up level parameter.

With a mistake of the control parameter of about only 2% of the maximum traction of the vehicle, I have a five time network peak higher even if the energy consumed is the same.

For this reason I have implemented a new algorithms, called *Controller with energy Reserve*, that permits to have good results but it should be more robust. This new algorithm should be without the problem to be completely empty if the vehicle need maximum traction. The characteristic of the controller is that the stored energy is split in two parts and not necessarily the same. The second part of the stored energy is called reserve. In the beginning the stored energy is used with the same strategy like two-level controller until the stored energy is at the reserve level. After the reserve energy it is used with gradually like the course of a decreasing exponential, with opportune amplitude and time constant.

To calculate the time constant it is necessary to know the driving average or the average time where the traction is positive in every driving cycle. The integral of the exponential must be the same of the reserve energy.

To calculate the time constant we have considerate that in the time of three-time constants the used reserve energy should be more then 90% of the total reserve energy. To determinate the amplitude of the exponential, we have tested that the best solution is if it is linear proportional the stored energy:

$$\mathrm{P}_{\mathrm{Accu.}} = K \bullet e^{-t \cdot C}$$

$$K = -C \cdot \frac{E_{reserve}}{dt} \tag{4.3}$$

$$\int_{t}^{t+t_0} -\left|\mathrm{P}_{\mathrm{Accu.}}\right| \cdot \mathrm{dt} = \mathrm{E}_{\mathrm{reserve}}$$

This determinates that the exponential slop rate decreases if the difference between the average time with positive traction, and the time in which the reserve level is reached:

$$C = -\frac{\log(2)}{(t_{mean} - t_0)} \tag{4.4}$$

The *Controller with energy Reserve* has achieved better results for the robustness of the algorithm and energy consumption. But with the worst reduction of the peak loads, within a 50% peak reduction.

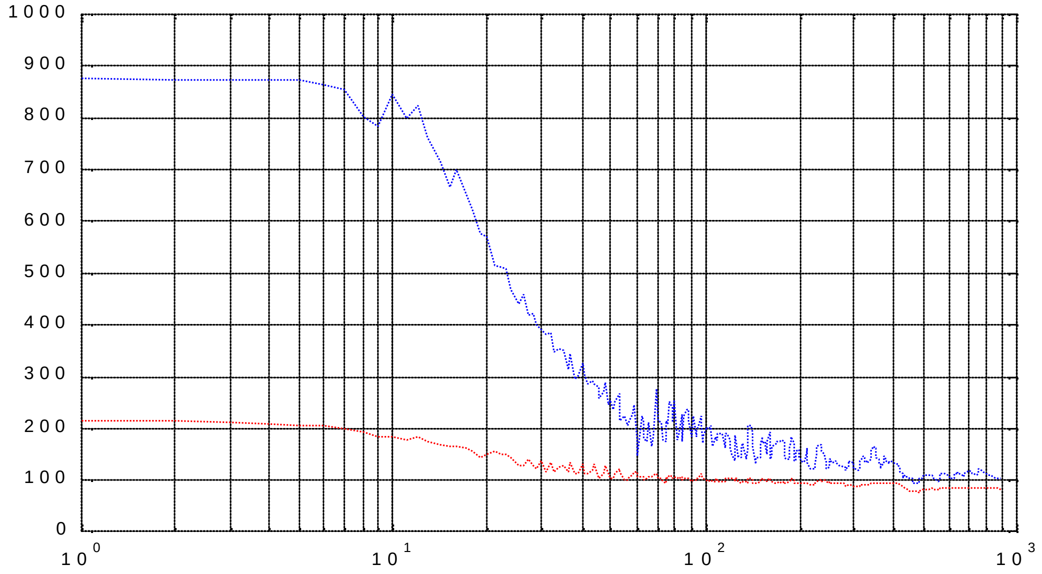


Figure 4.7

Course of the Time-Rated Load Periods Curve of the driving cycle Mannheim HB – Käfertal HB, with simulation model in figure 2.4 and Controller with energy Reserve, with uplevel =85 kW and reserve energy 30%.

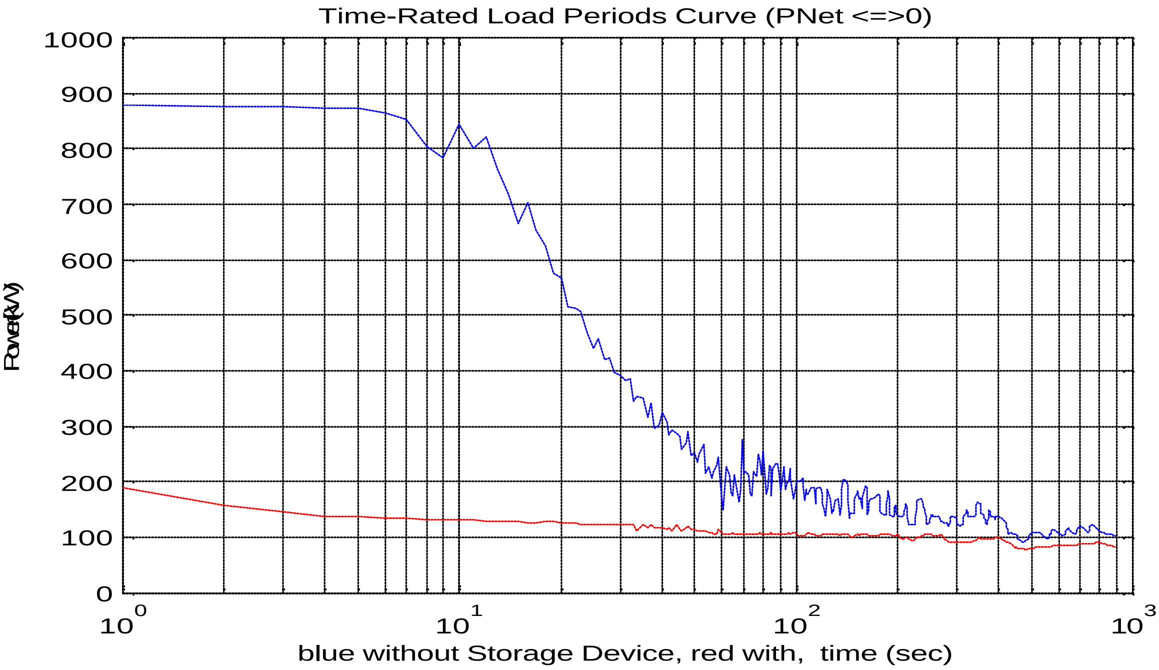


Figure 4.8

Course of the Time-Rated Load Periods Curve of the driving cycle Mannheim HB – Käfertal HB, with simulation model in figure 2.4 and Controller with energy Reserve, with uplevel =95 kW and reserve energy 30%.

The biggest problems with this controller are that it is necessary to calibrate too many parameters to have good results.

For this motivation we have tried to set up a new algorithm, that gives the same results but with fewer parameters.

The new algorithm, *Controller with additional Speed feedback*, has the same structure of *two-level controller*, but with the difference that the parameter *uplevel* and *downlevel* are not constant, and they must change with the speed and the storage energy. In this way we have implemented an adaptive controller because the parameters of the controller change during the evolution of the system.

```
x=((Energy/MaxEnergy))* ((1-Speed/MaxSpeed));   4.5
upLevel= x*MinUpLevel + (1-x)*MaxUpLevel;

x =(((MaxEnergy-Energy)/MaxEnergy)*((MaxSpeed-   4.6
   Speed)/MaxSpeed));
downLevel = MaxDownLevel *x+ (1-x)*MinDownLevel;
```

This algorithm has achieved good results depending only on few parameters. In particular it depends only on four parameters that become three while MiniDownlevel was always zero.

The parameter *MaxSpeed* and *MaxEnergy* are constant and are not free to controller design.

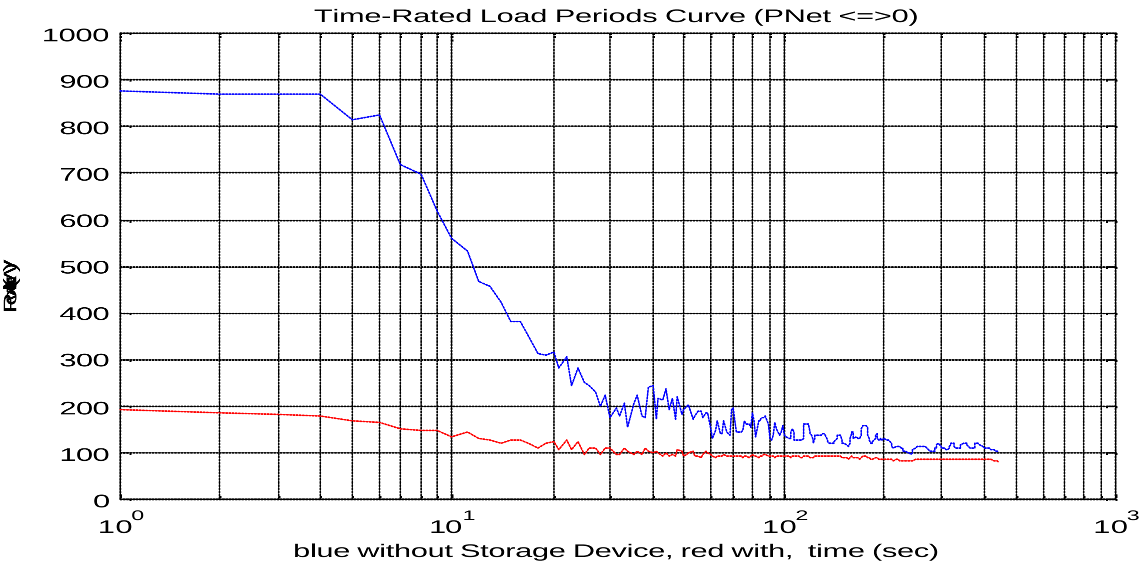


Figure 4.9

Time-Rated Load Periods Curve of the driving cycle Mannheim HB – Käfertal HB, with simulation model in figure 2.4 and Controller with additional Speed feedback, with uplevel =50-200 kW.

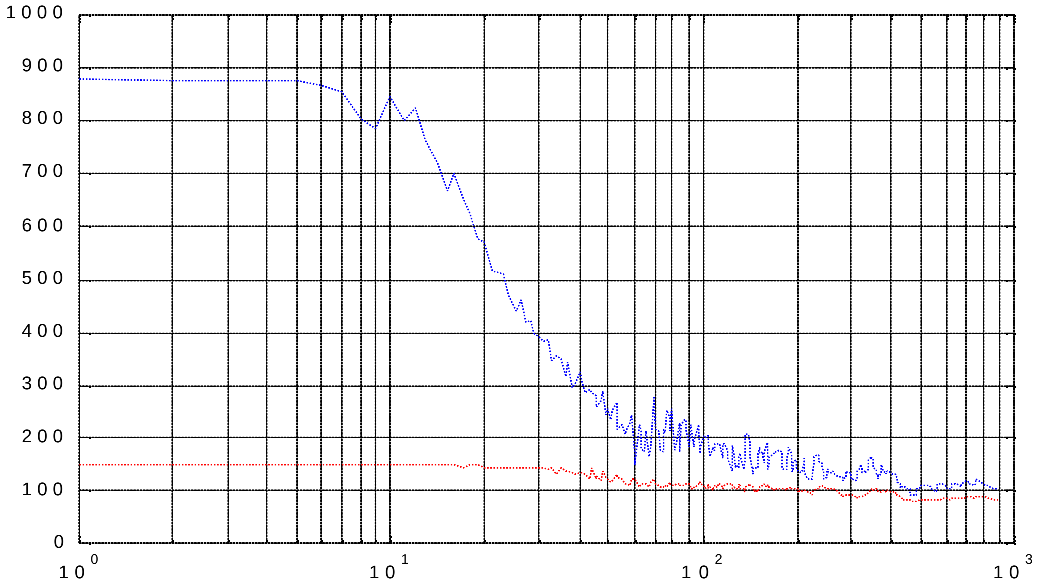


Figure 4.10
Time-Rated Load Periods Curve of the driving cycle Mannheim HB – Käfertal HB, with simulation model in figure 2.4 and Controller with additional Speed feedback, with uplevel =80-150 kW.

This Controller is much better and more robust in the parameters. From figure 4.9 and 4.10 it is possible to observe that if we change strongly the parameter, the results are in any case quite good for the reduction of the peak loads.
In figure 4.11 it is possible to observe that only half of the storage capacity is used in the most acceleration phase of the driving cycle.

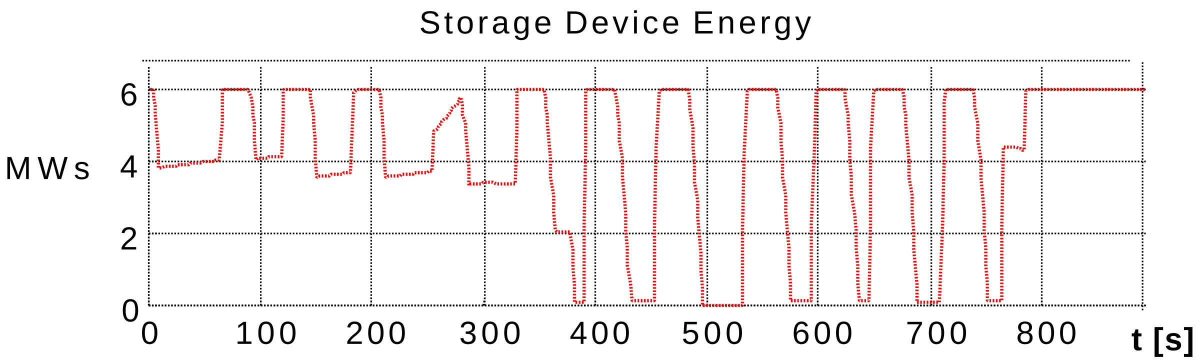


Figure 4.11

Course of the stored energy for the driving cycle Mannheim HB – Käfertal HB, with simulation model in figure 2.4 and Controller with additional Speed feedback Controller with additional Speed feedback, with uplevel =80-150 kW.

To increase the utilized energy from the storage device in the phase with low traction effort, we have improved different methods to determinate the parameter *uplevel* and *downlevel.* The best solutions are used in the *controller with nonlinear energy feedback*, where the parameters change with the square root of the storage energy and are linear with the velocity.

```
x=(sqrt(Energy/MaxEnergy))* ((1-Speed/MaxSpeed))); 4.8
upLevel= x*MinUpLevel + (1-x)*MaxUpLevel;

x =(sqrt((MaxEnergy-Energy)/MaxEnergy)*((MaxSpeed- 4.9
Speed)/MaxSpeed));
downLevel = MaxDownLevel *x+ (1-x)*MinDownLevel;
```

With this controller it is possible a higher utilization of the storage device also for acceleration phase with less traction effort, but to improve the same global results for the peak loads reduction like *Controller with additional Speed feedback*.

4.5 Result

In the implementation and simulation of the control algorithms it is necessary to considerate the optimization result as benchmark. This means that if we arrive close to the optimization result and the controller is almost robust and the parameters are quite easy to calibrate, the control algorithm is ready for the real application.

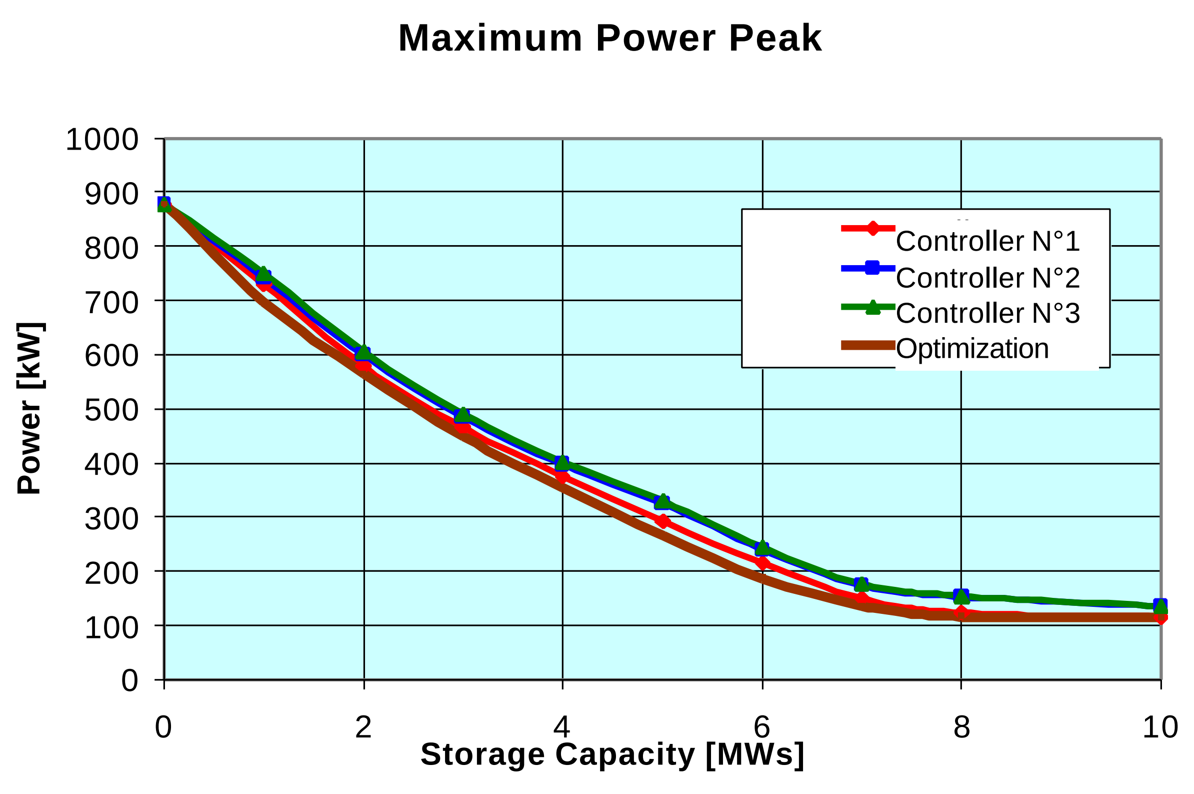


Figure 4.12

Figure 4.12 compare the peak loads result obtained with the optimization algorithm and Controller N°1to 3 for the same simulation model and driving cycle Mannheim HB – Käfertal.

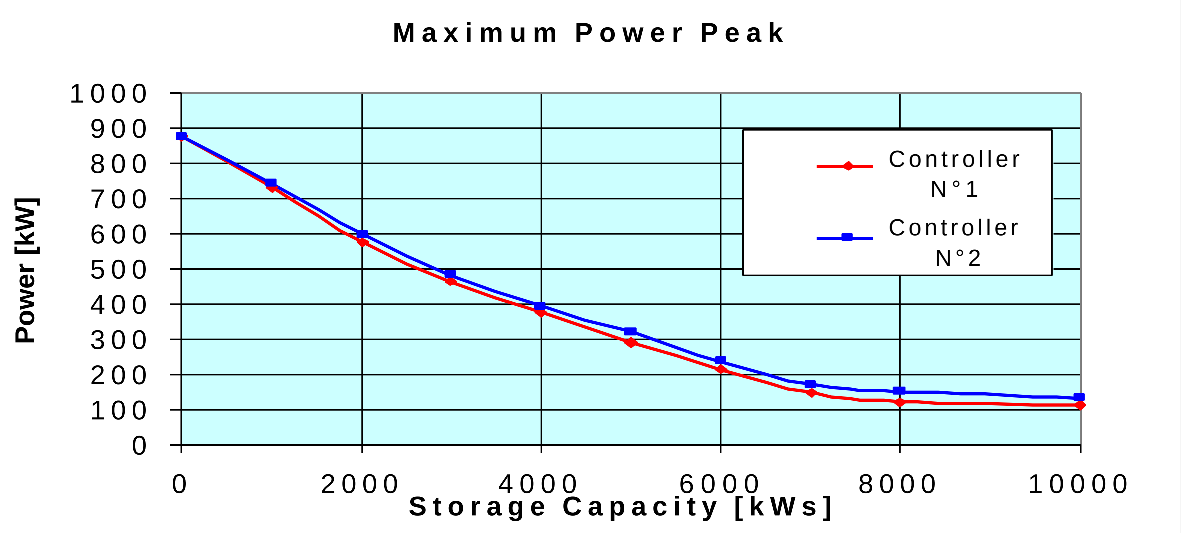


Figure 4.13

Figure 4.13 show the peak loads result obtained with the Controller N°1 and Controller N°2.

From figure 4.13 it is possible to observe that the controller N°1 permits to achieve better results, but the controller N°2 is more robust in the control parameter and easier to calibrate. With both controller strategies it is possible to achieve almost the same energy reduction.

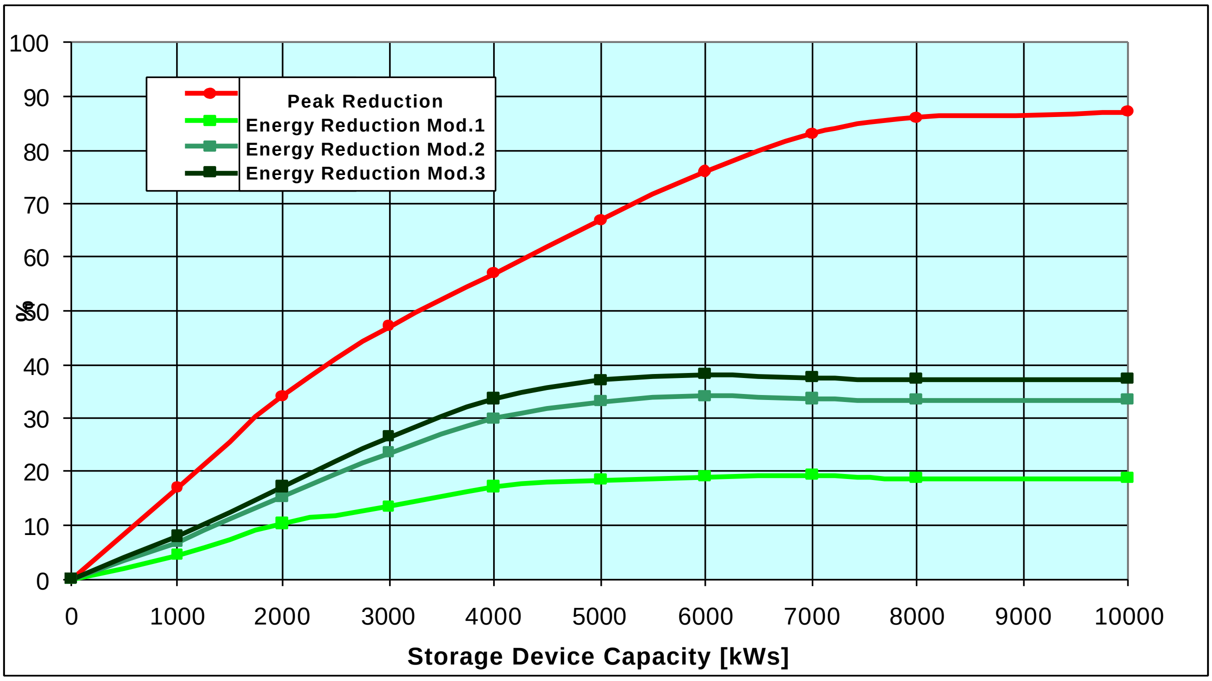
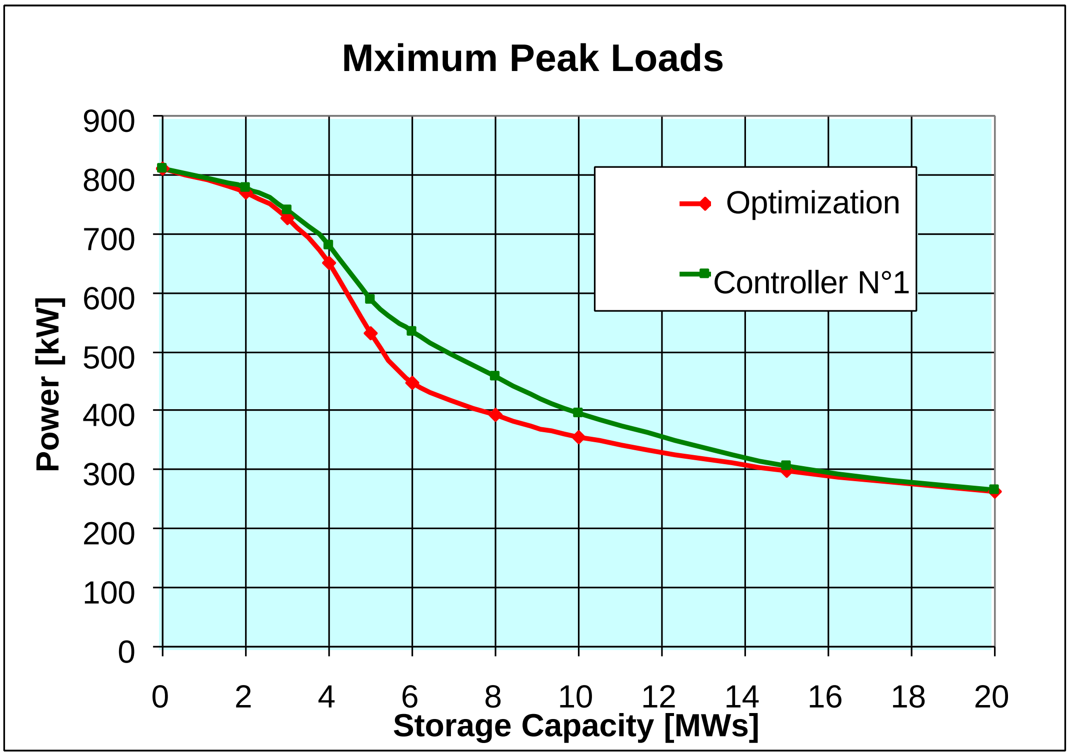


Figure 4.14

Figure 4.14 show the energy reduction for each type of simulation model and the peak loads reduction for the driving cycle Mannheim HB – Käfertal, for different storage device capacity.

Figure 4.14 illustrates the energy reduction for the three different simulation models. The figure shows that storage device greater than also 6 MWs doesn’t permit to achieve more energy reduction, but only the peak loads.

In conclusion it is possible to say that, for the driving cycle Mannheim – Käfertal, the best solution is a storage device capacity between 6 to 8 MWS.


Mximum Peak Loads
Power [kW]
900
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
20
Storage Capacity [MWs]
Optimization
Controller N°1

5. Storage Device

5.1 Overview

To set up and to implement a control low for energy management for railway vehicles it is necessary a basic knowledge of the different storage device family. Today there are on the market different types of storage device, that use different physic principles and have different technologic proprieties. It is necessary to do an accurate analysis to understand which type of device have the better characteristic for a determinate application. For each storage device family, the low power technology has improved good maturity , but not the same for the respective high power technology because they are, within the latest years, in continue evolution. Every year the market has new storage devices with more energy and power density and at low prices.

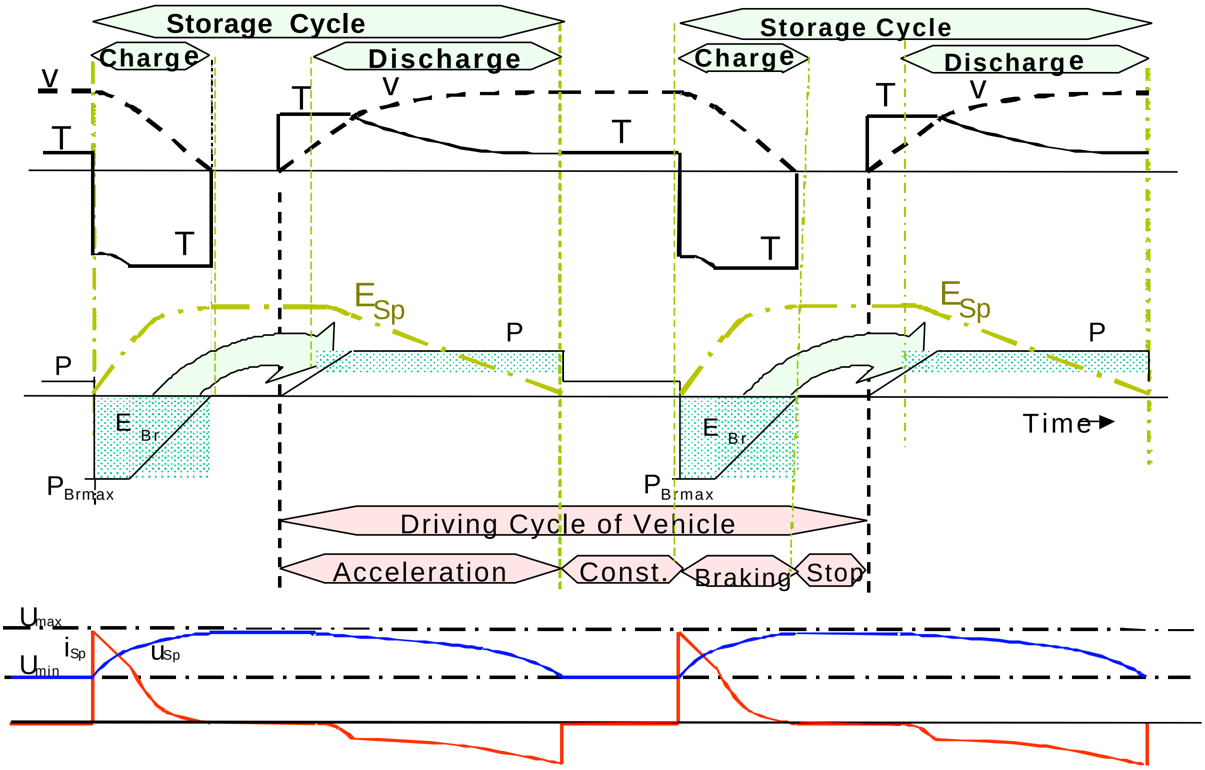


Figure 5.1

Figure 5.1 shows a driving cycle and a storage cycle: line 1 shows velocity (v) and Tractive effort (T), line 2 net power (P) *and storage energy (E), line 3 voltage (blue) and current (red) of a super capacitor as energy storage.*

The size of the energy storage system required on a vehicle is determined by the mass and top speed and by the acceleration and braking performance. These data define the quantity of energy to be stored and the power necessary to it. The braking energy and power determine the braking time, corresponding to the requested charging time of the energy storage system.

The driving and storage cycles, show the storage device changed at its max power for a long time during the charging phase. Consequently the power capability of the energy storage system, including the related power electronic converter, has to be increased, depending on the required charging/discharge power range.

	ICE	Regional Train	S-Bahn	U-Bahn	LRV
t_{Br} [s]	177	62	27	12	9
$P_{br,\ max}$ [kW]	12000	4800	2000	2000	900
E_{sp} [kWh]	410	58	8	3	1,4
U_d (U_N) [V]	2800	2800	750	750	750
$I_{d,\ max}$ [A]	4286	1714	2667	2667	1200

Table 5.1

Table 5.1 indicates the most important technical parameters for every vehicle family, to choose the opportune storage device: it means braking time, braking power, max braking energy, nominal energy supply voltage and maximal brake current.

5.2 Different Storage Device family

The criterions to chose a storage device or to define a storage family better compared to the other are manifold. A device has the better energy density and the other has the better power density. In reality, nowadays, doesn’t exist one family that is the best compared with the other storage devices. But it is necessary to find the best compromise to have, for the particular applications, high power and energy density, low storage device prices with simpler installation and control device.

Today we have different storage device families on the market, but the most important as to their best technological characteristics, are principally four: Super capacitors (or supercaps), batteries, flywheels and SEMS (System Magnetic Energy Storage). For real applications only supercaps and flywheels have improved technological maturity.

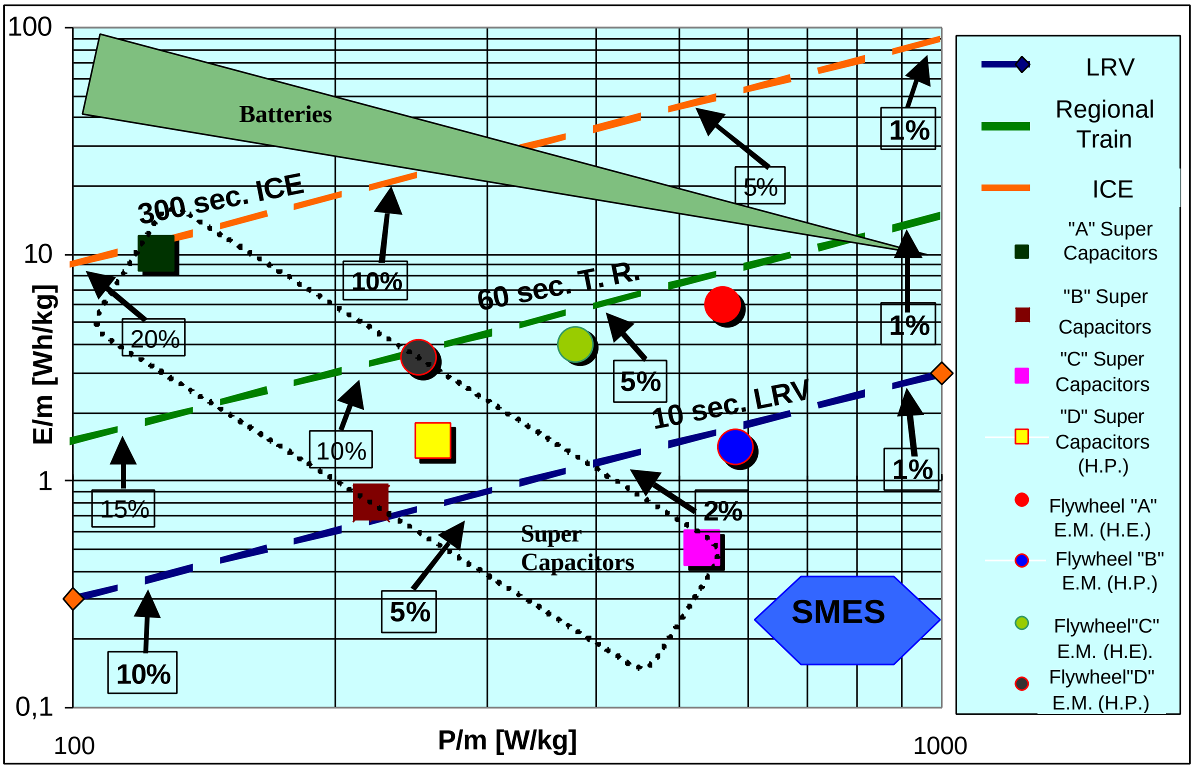


Figure 5.2

Figure 5.2 shows a Ragone diagram with energy density versus power density of Batteries, Flywheels, super capacitors and SEMS. The dotted lines indicate the power and energy density for each train family and their relative mass %.

Figure 5.2 shows the combinations of energy density and power density in a Ragone diagram for different energy storage systems. Curves of constant charging time corresponding to braking times of 300 sec, 60 sec. 10 sec. are also shown. The Ragone diagram is a means to compare different energy storage systems and to consider their adaptability on the vehicles.

On the constant charging curves is shown the percentage of the storage device mass compared with the vehicle mass for each class of vehicles.

In figure 5.3 it is possible to see the typical electrical connection to use supercaps or flywheels for different kinds of energy supply: AC 2800V. and DC 750 V. It is possible to connect the storage device in different ways to the electrical plant of the vehicle according to the type of converter and inverter used.

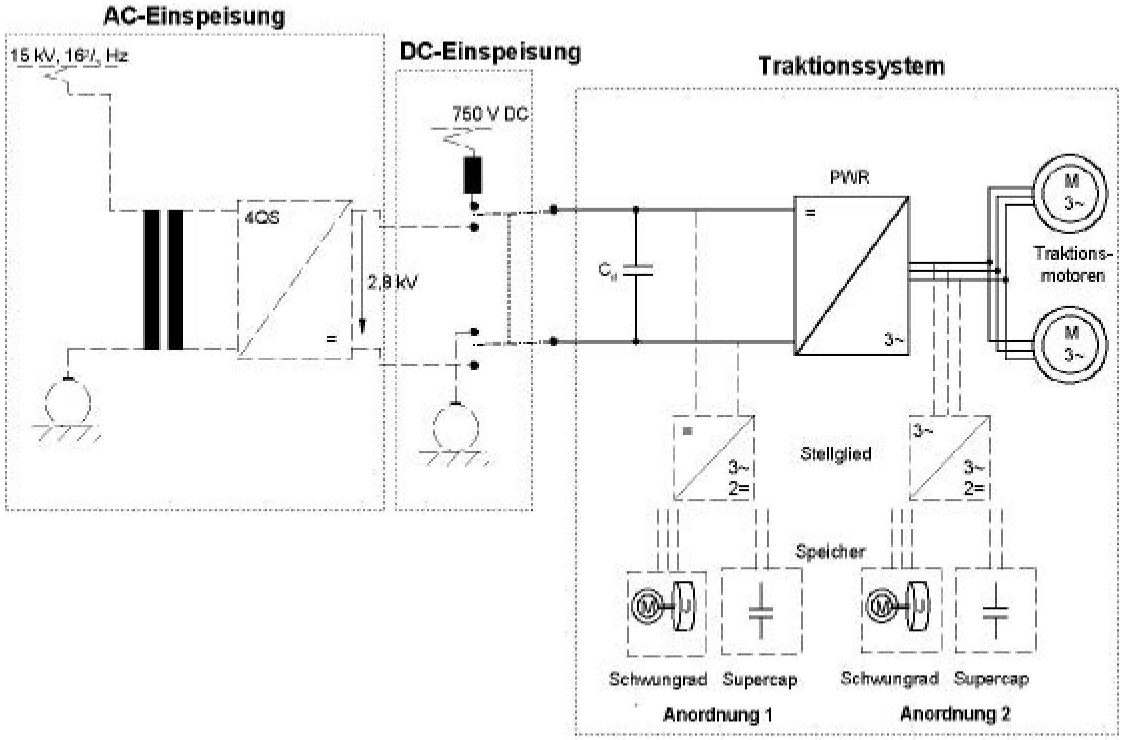


Figure 5.3

5.3 Super capacitors

Super capacitors (or supercaps), which are under intensive development, promise well for braking energy storage in the future. Several realistic products from different suppliers are displayed in the Ragone diagram (figure 5.2). The data are defined under the assumption of practical operating conditions. We have also taken into account the fact that the single supercaps cells have to be connected in series. Balancing circuit also have to be used, decreasing the power and the energy density of supercaps modules.

Available supercaps products are defined, by different charging times, from 300 to 5 sec. Of particular interest, for braking energy storage on rail vehicles, are the high energy supercaps type (HE) with charging time about 300 sec., and the high power supercaps type (HP) with charging time about 10 sec.

Supercaps and flywheels have to be coupled with electric driving system of the vehicle to allow sufficient control by electronic power of charging and discharging. In contrast with flywheels, supercaps are distributed in the vehicle and therefore the physical integration is easier. It isn’t clear how long are the limitations of the load cycles, especially on the LRV and buses.

Figure 5.1, shows the voltage and current for super capacitors under the assumption of a charge/discharge voltage relation of 2:1. At the beginning of braking at high speed, charging the discharged capacitor has to start with low voltage and high current, because of the constant power condition. Therefore it is not possible to use the full capacity of the storage, because an infinite current flows if the capacitor is fully discharged. Assuming that the used voltage range for energy storage is 0,5, the usable power is 0,5, given by maximum current and actual voltage, and the usable energy is 75%.

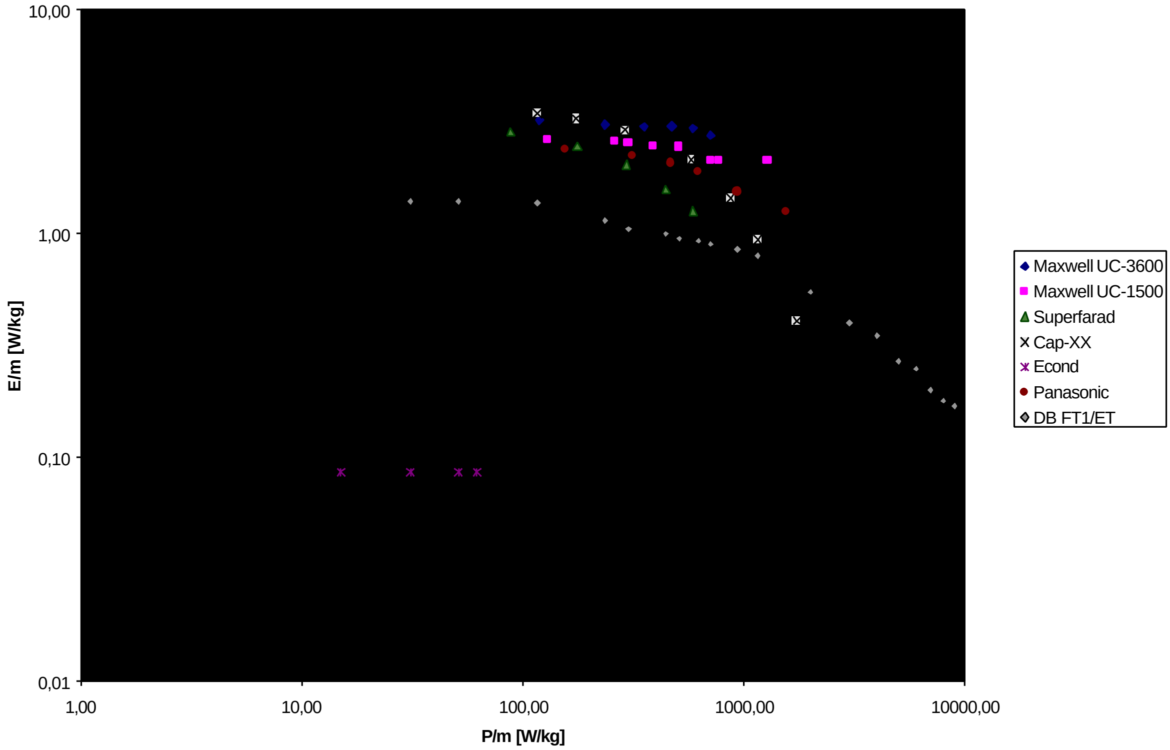


Figure 5.4

Figure 5.4 shows the energy density for different kind of supercaps in relation to power density in a linear ragone diagram.

The supercaps modules have to be connected in parallel and series, to meet the required power and energy.

Figure 5.5 and 5.6 show supercaps application on ICE rail vehicle with AC 2800 V electrical supply and on regional vehicle with DC 750 V electrical supply.

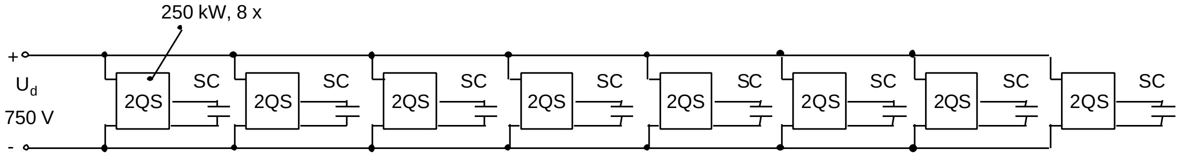


Figure 5.5

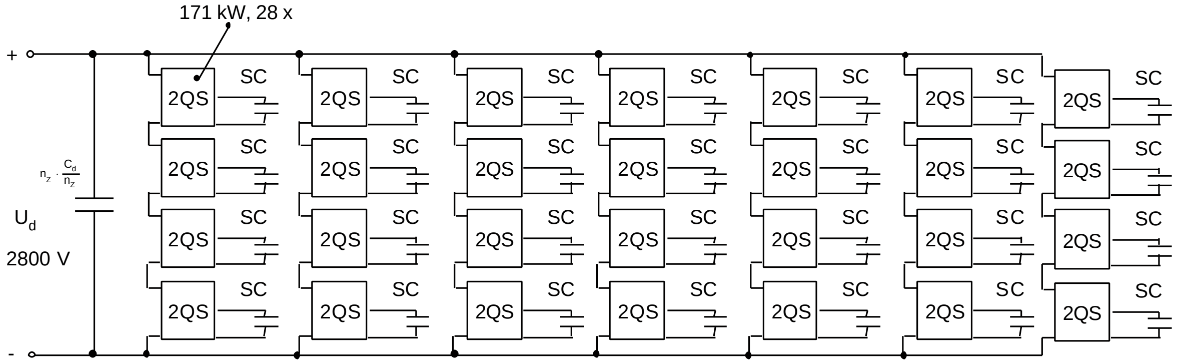


Figure 5.6

To operate with the supercaps, two-quadrant DC choppers are necessary, as previously developed for DC retrofit drives. The expenditures required for this subsystem concerning mass, volume and cost is estimated to: 14kW/kg, 10kW/l, 20,5W/Euro.

Super capacitors have to be cooled. The reason is that the internal series resistance of supercaps cannot be neglected. Forced air cooling is required to avoid too high cell temperatures because of local heat centers. The expenditure for air cooling is estimated to 5% mass and 5% volume in addition.

Figure 5.7 represents a typical power switch to permit the charging of the supercaps in the braking phase and the discharging in the acceleration phase. If L has high voltage and E low voltage then it is possible to recharge the storage device. The opposite is in the discharge phase.

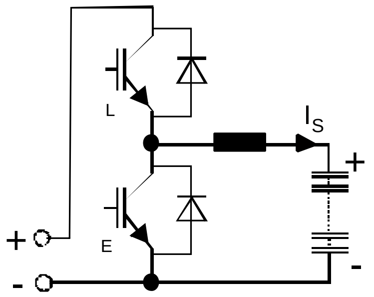


Figure 5.7

5.4 Batteries

Batteries have the highest energy density, however most batteries suffer from the low power density and the resulting high charging time. Even the newest, high power NiMe hydride batteries, with a sufficient power density, also suffer from poor load cycles. Over-dimensioning the batteries will improve the cycles performances, but the batteries life time is shorter than that of an LRV.

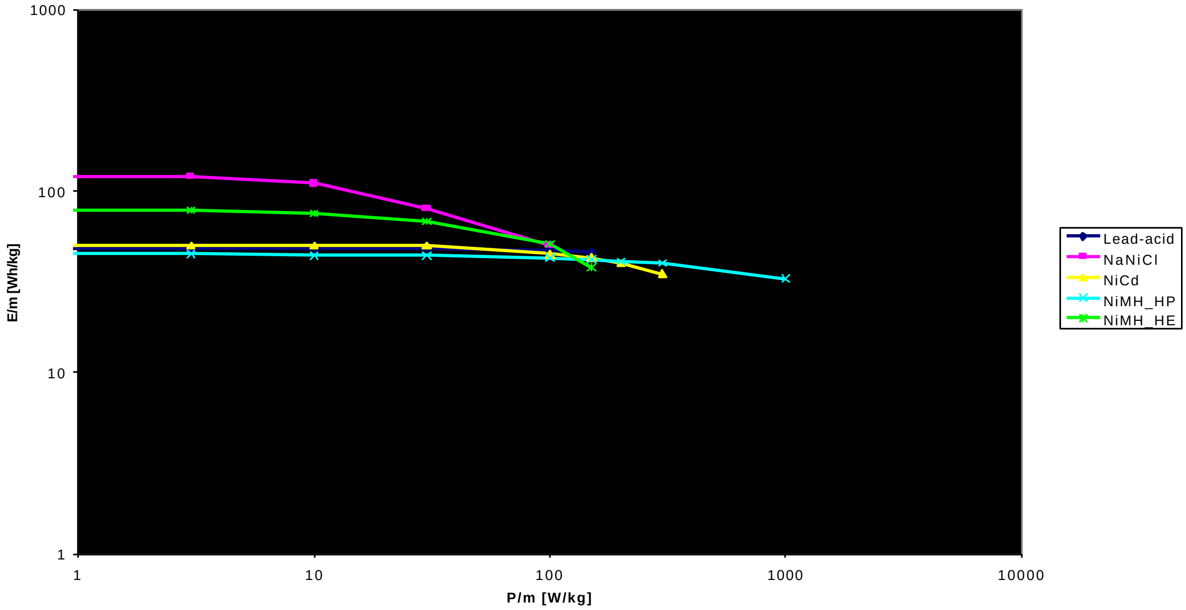


Figure 5.8

Figure 5.8 shows the density energy for different types of Batteries tested to storage device system in relation to power density in a linear ragone diagram.

The same power switch in figure 5.7 used for supercaps are used also for storage device with battery.

5.5 Flywheels

The data of typical flywheels from different suppliers are shown in figure 5.2. Flywheels meet the specifications of different rail vehicles that have about 60 sec. braking time. Shorter times (higher power, lower energy) may be storage.

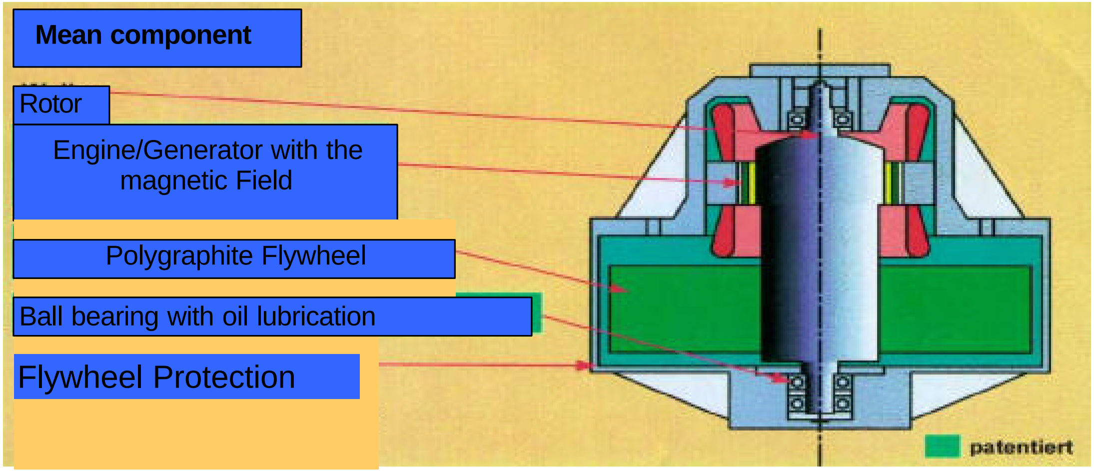


Figure 5.9

Flywheels energy storage, in combination with electrical motor/generator and inverters, is a useful method currently available from different suppliers for rail vehicle applications.

It is assumed, that the flywheels motors operate with almost full power that means in the field weakening range, where no power flowing at the lowest charging state (flywheel speed) is necessary. The range of usable energy is reduced because of the restricted operating range. With 70% of the max speed we can use only half of the total storable energy.

The flywheel motor is water cooled because a water cooling system is necessary. The cooling system of the flywheels could be integrated into the cooling system of the existing drive motors and inverters. The additional expenditure for flywheel water cooler is estimated about 10% mass and 10% volume in addition.

Every storage system need an inverter for operation, in this case the flywheel requires PWM-inverter like the traction motors, but with modified control (for permanent excited synchronous motors). The technical inverter characteristic are usually 7 kW/kg, 5kW/l, 13,5W/Euro.

As to the mechanical integration aspect, flywheels have to be as small as possible. It should not be possible to use only one heavy flywheel or one for each driven bogie, because there is no room to put it in the middle of the vehicle.

Because of the possibility to choose flywheels motors and carbon rotors in suitable size, flywheels are always able to meet the requirements exactly. Figure 5.3 illustrate a typical connection of the flywheels at the electrical plant of a rail vehicle.

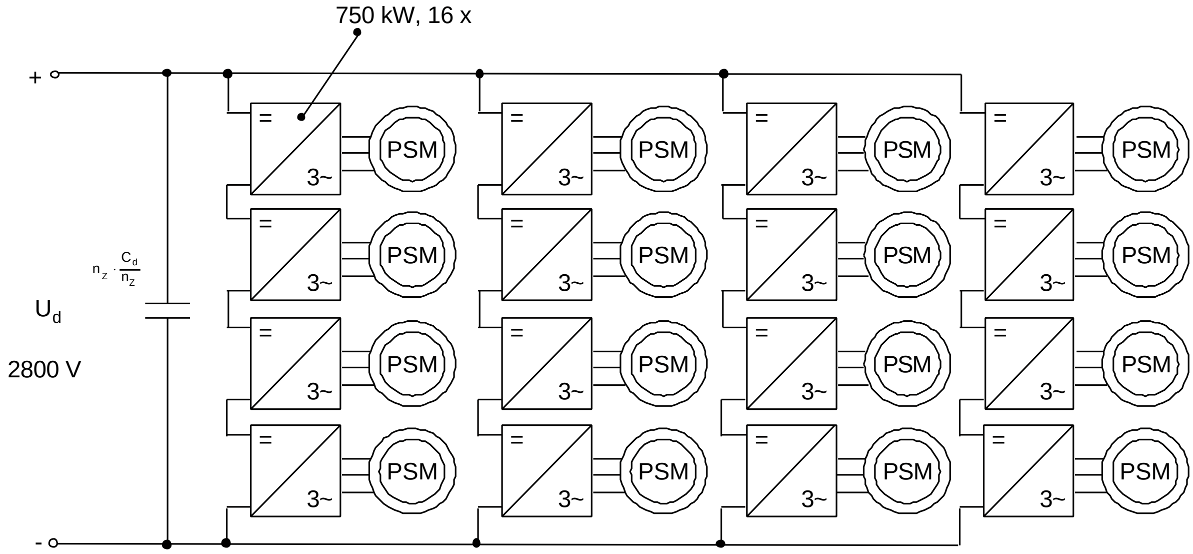


Figure 5.10

It is necessary to connect different flywheels together in parallel and series in order to have storage device with high energy and power capacity,

Figure 5.10 and 5.11 show flywheels application for ICE rail vehicle with AC 2800 V electrical supply and DC 750 V electrical supply.

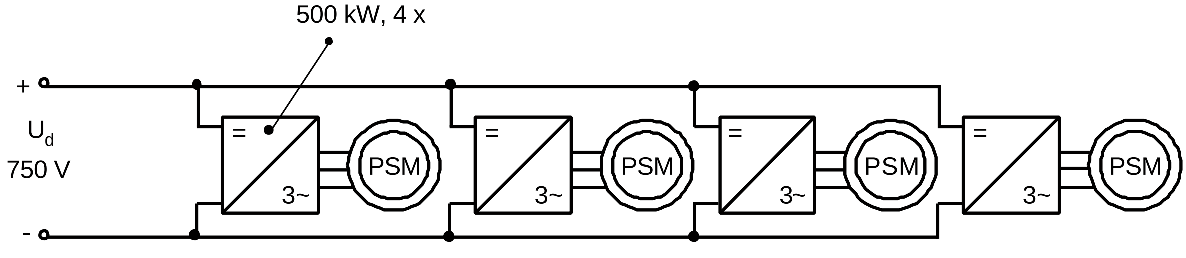


Figure 5.11

The electronic device that permits to charge the flywheels in the braking phase and discharge then in the acceleration phase is illustrated in figure 5.12 . The transistor operates in only two states way power switch. If the up transistor are on, the down transitory must be off to permit to charge the flywheels. The opposite is for the recharge phase.

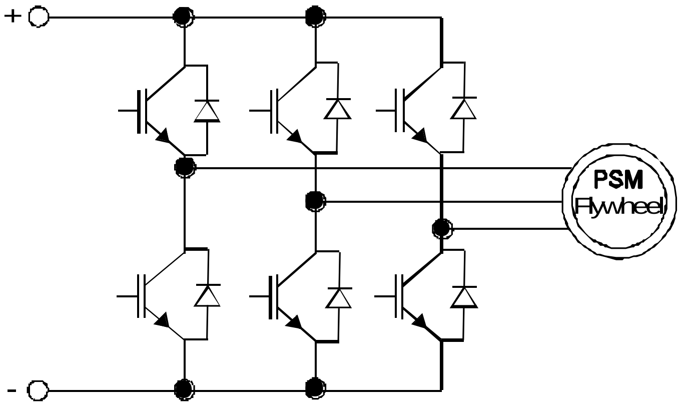


Figure 5.12

5.6 SMES

Today super conducting magnetic energy storage (SMES) is of high-power low-energy type and therefore is only suitable for power quality applications.

However, SEMS storage device results the best technical solution for the magnetic rail vehicle “TRANSRAPID”.

The SEMS results a good solution for emergency in the electrical distribution network in case of short electrical blackout.

Figure 5.13 shows the limit curve for two different electrical superconductors in relation to current density at 4,2° K. The energy is stored in the magnetic field in the air with this relation: $E = B^2 / 2m_0$. It means that for high current density the stored energy becomes lower.

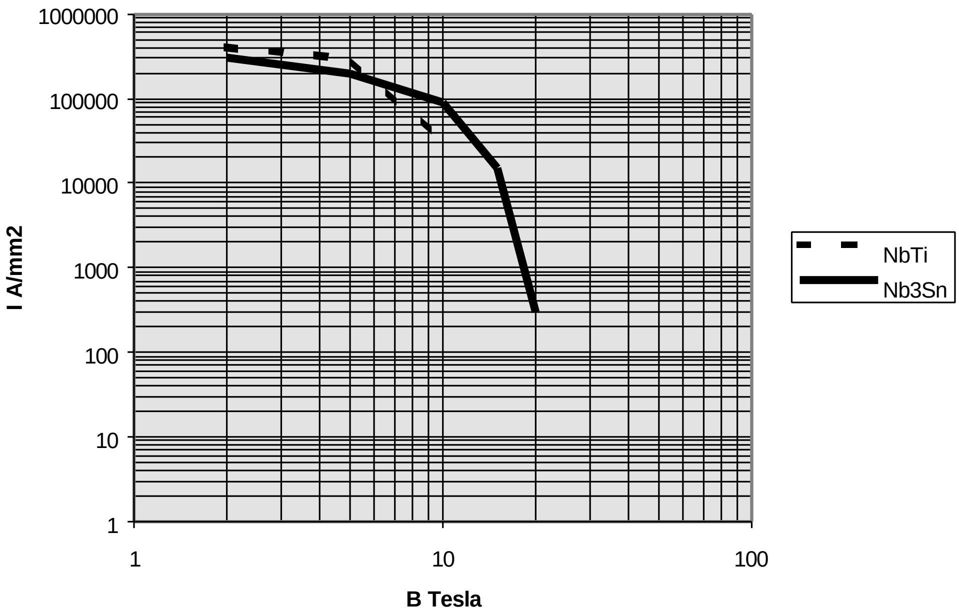


Figure 5.13

In figure 5.14 there is a typical electrical power switch that permit to charge the SEMS in the braking phase and discharge it in the acceleration phase.

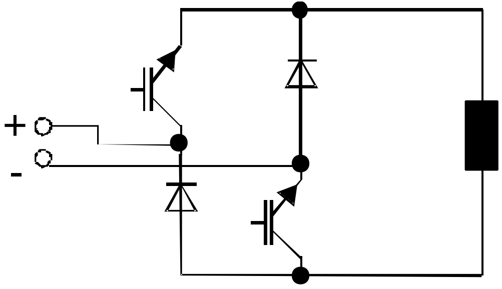


Figure 5.14

5.7 Storage Device Mass Analysis

In order to introduce the new storage device technology it is necessary to check if the actually storage device in the market permit an effective introduction of this device. For the high energy and power involved this device increases remarkably vehicle mass and volume. For this motivation it is necessary to do, at first a volume and mass analysis for the effective installation.

Table 5.2 shows the energy density, power density and the converter density for the best storage device for each storage device family.

	Battery	Flywheel	supercaps	SMES
Energy Density	101,5	8,5 Wh/kg	1,15 Wh/kg	0,3 Wh/kg

	Wh/kg			
Power Density	100 W/kg	1000 W/kg	610 W/kg	3000 W/kg
Current Converter mass	0,5 kg/kW	0,5 kg/kW	0,5 kg/kW	0,5 kg/kW

Table 5.2

It is necessary to know the energy and power involved during the brake phase to determinate the mass for each storage device. The brake energy and power change a lot for each rail vehicle family.

Rail Vehicle	Theoretic brake Energy	Effective brake Energy	Maximum power in the brake phase P_{Brake}
ICE	502,4 kWh	410 kWh	12000 kW
Regional Train	68,6 kWh	58 kWh	4800 kW
S-Bahn	8,6 kWh	8 kWh	2000 kW
U-Bahn	3,2 kWh	3 kWh	2000 kW
LRV	1,5 kWh	1,4 kWh	900 kW

Table 5.3

It is necessary to meet the minimum energy requisite and the minimum power requisite to determinate the storage device mass.

To determinate the mass with the minimum energy requisite for a Flywheel it is necessary to divide the second column in Table 5.3 for 8,5 Wh/kg to find the first column in Table 5.4. In the same way it is possible to find the second column in Table 5.4, dividing the third column in Table 5.3 for 1000W/kg.

Rail Vehicle	Mass with the minimum energy requisite	Mass with the minimum power requisite	Mass of the storage device	Mass for the current converter	Altogether mass of the storage system
ICE	**48,24 t**	12,00 t	48,24 t	6,00 t	54,24 t
Regional Train	**6,82 t**	4,80 t	6,82 t	2,40 t	9,22 t
S-Bahn	0,94 t	**2,00 t**	2,00 t	1,00 t	3,00 t
U-Bahn	0,35 t	**2,00 t**	2,00 t	1,00 t	3,00 t
LRV	0,16 t	**0,90 t**	0,90 t	0,45 t	1,35 t

Table 5.4

Table 5.4 indicate the mass for a flywheel for different rail vehicle class.

The maximum mass in the first two columns in Table 5.4 is the effective mass for the storage device. But to obtain the total mass of the storage system it is necessary to add the converter mass and the cooling device.

In figure 5.17 it is possible to see, for the different rail vehicle and for each storage device, the mass in percentage of the effective vehicle mass.

In this diagram the most compact storage system are the flywheels for every vehicle class.

The result of the comparison between Flywheels and supercaps is, that today's best supercaps have more mass in the range of 20% and more volume in the range 15%. In the future, improvements of both systems are expected, and will not change the comparison. The valuation of this fact is that a choice between flywheels and supercaps could not be done only regarding mass and volume. Other technical aspects probably will have more importance, e.g., possibility of integrating energy storage into the vehicle.

5.8 Storage Device Analysis

To compare energy storage types in different vehicle applications, the mass for braking energy storage is calculated in ratio of the total mass of each vehicle.

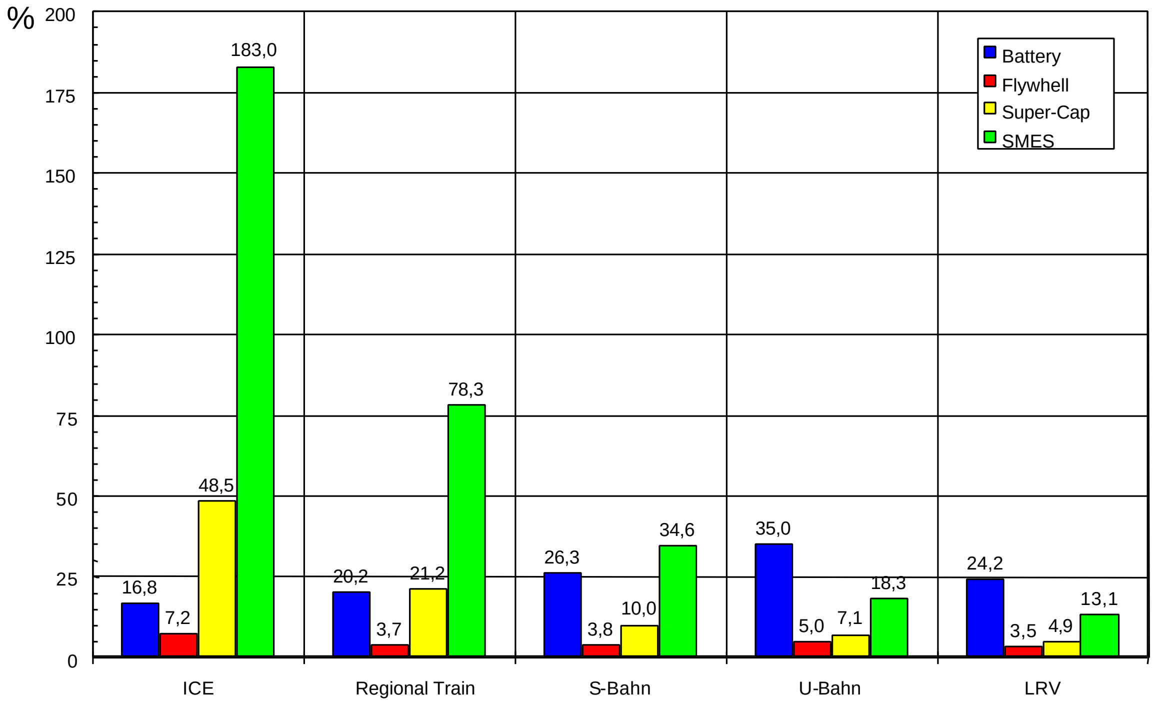
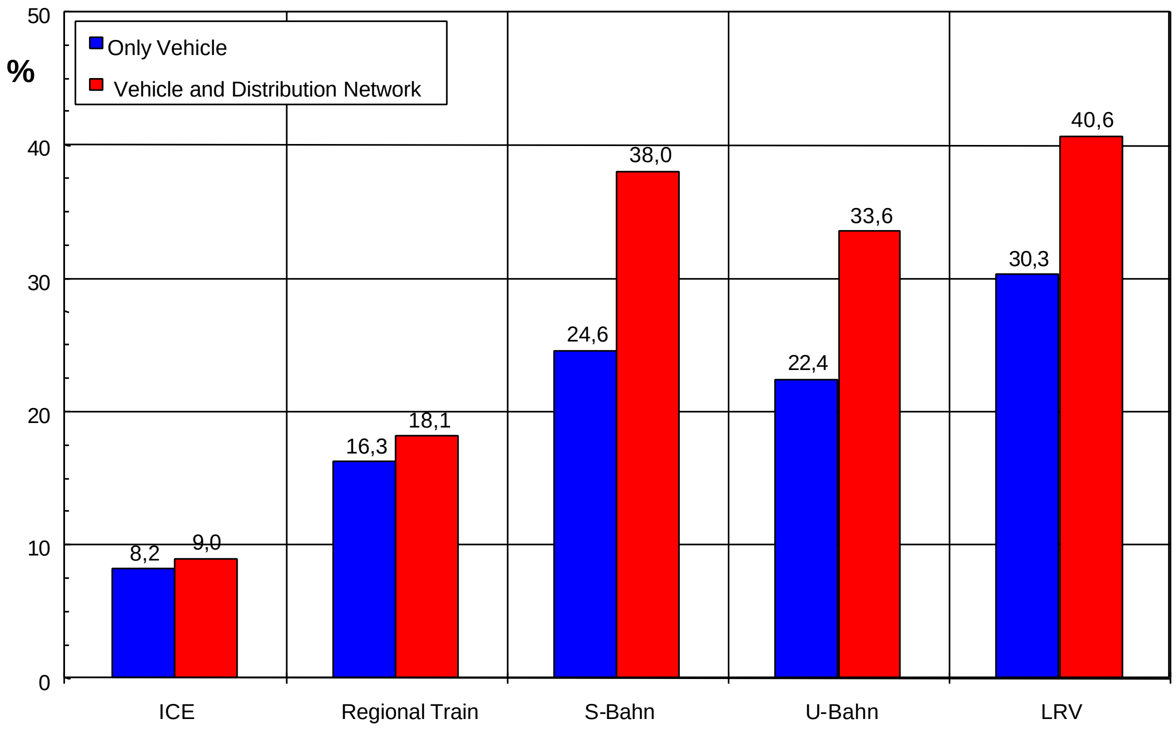


Figure 5.15

The use of flywheels in all regional and local vehicles gives the best results. At the present rate of development, supercaps are a promise for LRV applications because of low energy requirements.

Figure 5.2 and 5.15, show that there are different requirements for different applications. Every applications has its own optimum energy storage component, expressed in the different charging times in Figure 5.2. For example the supercaps A is better suited to ICE, while HP supercaps B is better used in the LRV application. The conclusion is that the manufacture of energy storage device must be able to adapt the products to specific needs of the applications.



Energy Savings by Energy Storage only Vehicle and Vehicle and Distribution Network

Figure 5.16

Energy Savings by Energy Storage for different Trains (% of total Energy Consumption)

The left block, in figure 5.16, represents energy savings only with regard to the vehicle. The right block represents the energy savings including the reduction of losses in the distribution network due to the reduced peak load (or peak currents since $P = R_{Network} \bullet I^2$). It is obvious that vehicles with 750 V DC supplies, such as suburban EMU(DC) and LRV, allow the best energy savings by utilizing energy storage. Similarly, good results can be achieved with Diesel multiple unit trains in local operation.

6. Conclusion

6.1 Economic Analysis

The energy flowing in low distance systems is rather irregular as a result of frequent acceleration and braking operations. The result is, that it is necessary to oversize the energy supply of the vehicle and of the fixed installation in relation to the mean power. The results are high energy loss and large voltage variation.

It would be advantageous to smooth the energy flowing by an adequate energy storage in the vehicles.

In this project it is planned to evaluate the advantages of energy storage in light railway vehicles with respect to energy saving (-20%) and costs of the total system. The elements influencing the dimensions of the energy storage are the traffic line (distance between stops, number of stops, gradient of the line, maximal speed, permissible brake acceleration) and the operating program. Without extending fixed installations it is possible to support more efficient vehicles with energy storage for a more attractive urban traffic.

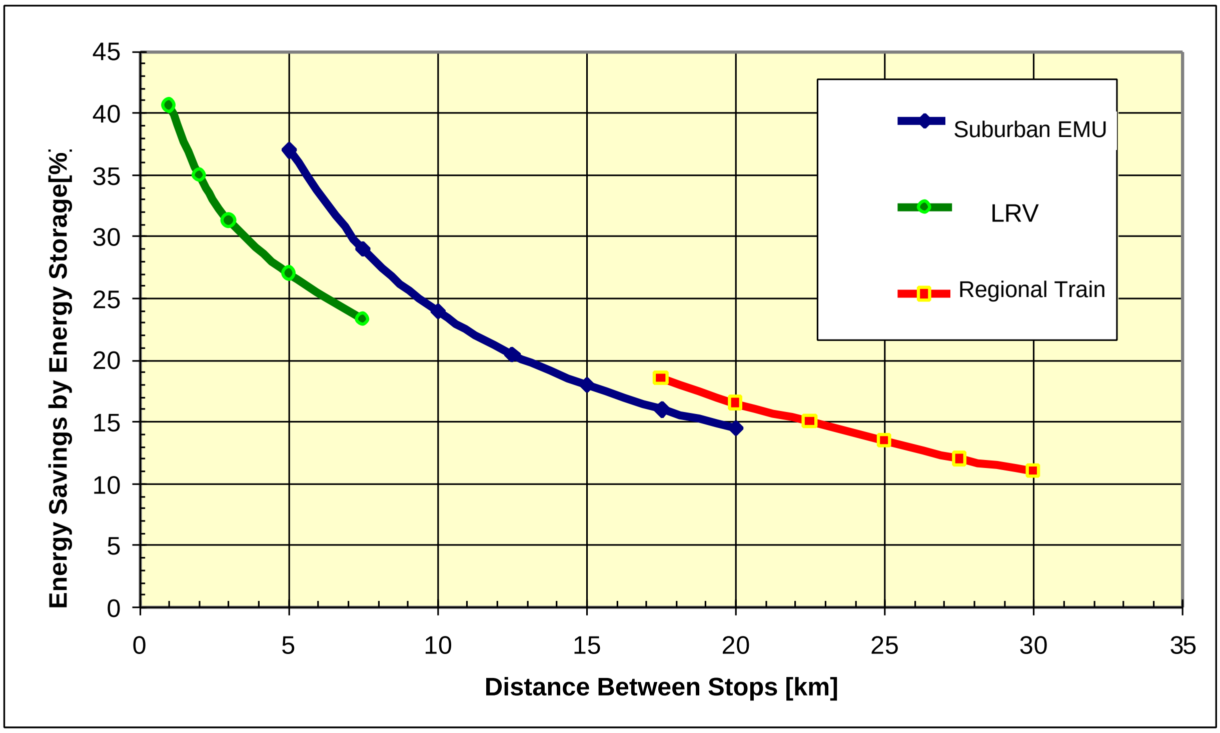


Figure 6.1

Figure 6.1 displays the dependence of energy savings on frequency of stops for different rail vehicle family.

The benefits of energy storage have been identified in energy savings and in reduction of the power supply, but the same benefits are smaller because of the expenditure into the storage system and its operation. The prospective savings in running costs must be balanced against the fixed investment costs. Credit balance as a function of time is calculated by taking into consideration the predictable costs (saved energy, storage equipment, maintenance, etc.), the financial conditions (rate of interests), reliability related costs (repair) and costs due to the additional mass.

In figure 6.2 the typical credit balance over lifetime is shown with respect to LRV, suburban EMU's and DMUs equipped with flywheels or with supercaps.

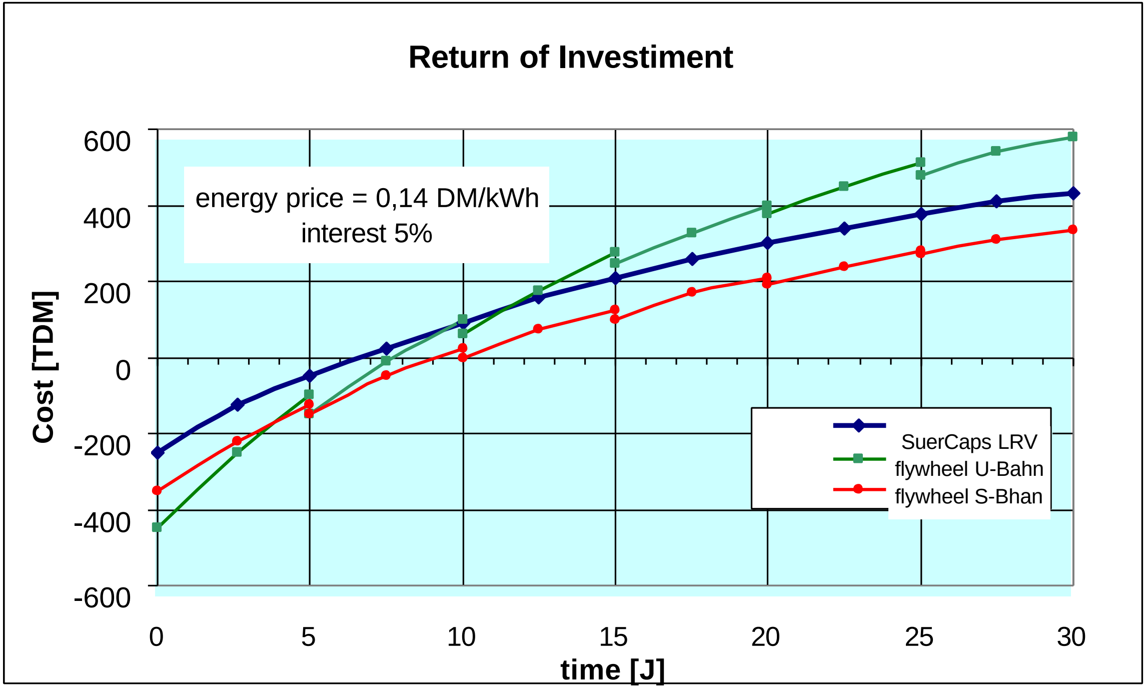


Figure 6.2

The return of investment of energy storage system is in the range 10 to 30% of the lifetime of the vehicles, depending on the vehicle type and on the type of energy storage. It will be influenced by further development of the storage technology, with respect to mass, volume, reliability, availability, safety and price.

For local trains and light railway electrical vehicle or Diesel supply, on-board energy storage will become a suitable method for energy savings to reduce the life cycles cost. On–board energy storage allows reuse of the braking energy in the subsequent acceleration phase and could therefore significantly reduce the energy consumption of these trains about 35%. Reducing power peaks will lead to reduction of network losses especially for DC trains. The installed power on trains driven by energy supply, such as Diesel engine, fuel cells could be reduced up to 45%. Reduced emission and increased economy of diesel engines are further advantages. Life cycle costs due to energy savings and smaller investment by downsizing the energy supply.

Up to now, it has not been possible to make a final choice of the storage medium between flywheels and supercaps. Both energy storage methods will have their own applications in the near future. It is important to recognize that different applications need a suitable storage. Supercaps, as upcoming technology, have very good potential future.

Today, the return of investments for energy storage could be in the range of 3 to 10 years in case of regional and suburban EMU's and DMUs. Energy storage could be turned into products, when the total life cycle costs are beneficial for the individual application.

Each individual product project has to take into account: higher investment costs (to be paid by operator), suitability into the application, savable energy (individual load cycles), future expected energy costs(influence of open energy market) and reliability of system and components (repair and failures).

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