Hybrid Locomotive

SUSTRAIL

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CONTENTS

1. INTRODUCTION

Task 3.2.1 started in month M6 and ran to month M36. The main objective of the task is to provide guidelines for future freight locomotives. The first part of the project was devoted to a literature study and overview of different technologies available on the market. The results provided by the WP2 will be used as the input requirements for the vehicle dimensioning.

As a result of the literature review, based on the vehicles propulsion system, four different locomotive topologies have been identified. The conventional diesel-electric locomotive equipped with one combustion engine, usually running on diesel, connected to a generator. A second type is the electric locomotive that requires a grid connection. The third type is the dual mode locomotive, which can take advantage of the electrified railways but it can also run on diesel where that is necessary. Finally, the fourth type is the hybrid locomotive that, in relation to a dual mode locomotive, is equipped with energy storage as well, in general a battery or a super capacitor.

Based on the initial review the next phase in the project is a closer analysis and dissemination of the information provide in WP2 and in WP2.4 “Future vehicle performance requirements” in particular. Furthermore, a closer definition of the project and a specification of the main requirements, such as acceleration, tractive effort, power demand etc. will be performed. In the following step, attention will be focused on two topologies, a dual mode topology and a hybrid electric topology. Part of the investigation will also include the possibility of having a number of smaller combustion-engine-generator (genset) units rather than having one big genset unit.

Within the SUSTRAIL project a number of different lines have been chosen that will represent the different railway lines around Europe. The following routes have been chosen as typical routs;

- The Mediterranean Corridor in Spain, which is a mixed traffic electrified line in the east of Spain
- The Bulgarian route from the Serbian border to Turkey, an intermodal connection which is part of the European “Corridor 10” project
- Two key intermodal freight routes in the UK, from the ports of Southampton and Felixstowe to the North West of England, part of Network Rail’s “Strategic Freight Network”.

Some information about the freight train operation on these routes are provided by SustRail Deliverable D1.5 *Route summary: Logistics, local freight market and whole system economics*. Furthermore some additional data about the routs is given by deliverable (D1.2) *The sustainable freight railway: Designing the freight vehicle – track system for higher delivered tonnage with improved availability at reduced cost.*

1.1 Historical perspective of electric railway traction and electrified railways

The modern railroads of today have evolved through a long history. The wooden rails called “Wagonways” were used in Germany as early as in the middle of the 16th century. They provided an easy way for horse driven wagons or carts in contrast to the muddy and dirty roads. In the end of 18th century the wooden rails were replaced by the iron rails and somewhat later the horse pulling power was replaced by the mechanical power.

1.1.1 First locomotives

The first locomotives developed in the end of 18th century and in the beginning of 19th century were equipped with external combustion engines (ECE). The ECE is a heat engine where the internal working fluid is heated by combustion in an external source, through the engine wall or a heat exchanger. During the expansion, the pressure force is created which acts on some component of the engine and thereby produces motion and usable work, typically steam engines.

Over the next hundred years the steam engines together with the drive chain or propulsion system have been further developed and refined. In the middle of 20th century the steam engine hade several drawbacks compared to the locomotives propelled by the internal combustion engines. One of the main drawbacks was the operation availability as the steam engines need to be taken out of duty for cleaning and maintenance at least once a day.

1.1.2 Internal combustion engine

Although the first types of Internal Combustion Engines (ICE) dates back to early 16th century (1508) when Leonardo Da Vinchi sketched a gunpowder machine with the intention to raise heavy weights, the first practical and effective ICE was developed by Nicolaus Otto in the second half of 19th century (1876). Internal Combustion Engine (ICE) is a type of engine where the combustion of the fuel occurs in a combustion chamber that is an integral part of the working fluid flow circuit. The expansion, due to the combustion, applies a direct force to some component of the engine, e.g. a piston or turbine blades, etc. The engines are typically two-stroke or four-stroke engines.

The Otto cycle machine in a similar way as the gunpowder machines uses a separate plug to ignite the ”air-gas” mixture and thereby starts the combustion process. In the end of the 19th century (1893) Rudolf Diesel presented another type of ICE which in contrast to Otto-cycle machines uses heat of compression to start the combustion process.

In 1913 General Electric company (GE) in United States designed the first commercially successful ICE-Locomotive. These locomotives were equipped with the Otto cycle ICE. However, these locomotives did not make a huge success as they could not compete with the steam engines in terms of efficiency. Furthermore, these locomotives suffered from poor conversion of the engine output power into the useful tractive force over the whole speed range.

1.1.3 Electrification of the railways

Meanwhile there was another technology that was gaining in popularity especially in urban areas, where the electricity was readily available. Many of the existing horse lines become electrified and run with an electric street car instead. Soon the electric cars were to operate outside city borders on interurban railways.

The electric propulsion seemed as a very attractive alternative to steam power. The benefits with the electric propulsion, however, were restricted to the electrified railways only. Hence, the high efficiency diesel engine coupled with an electric generator looked as very attractive solution.

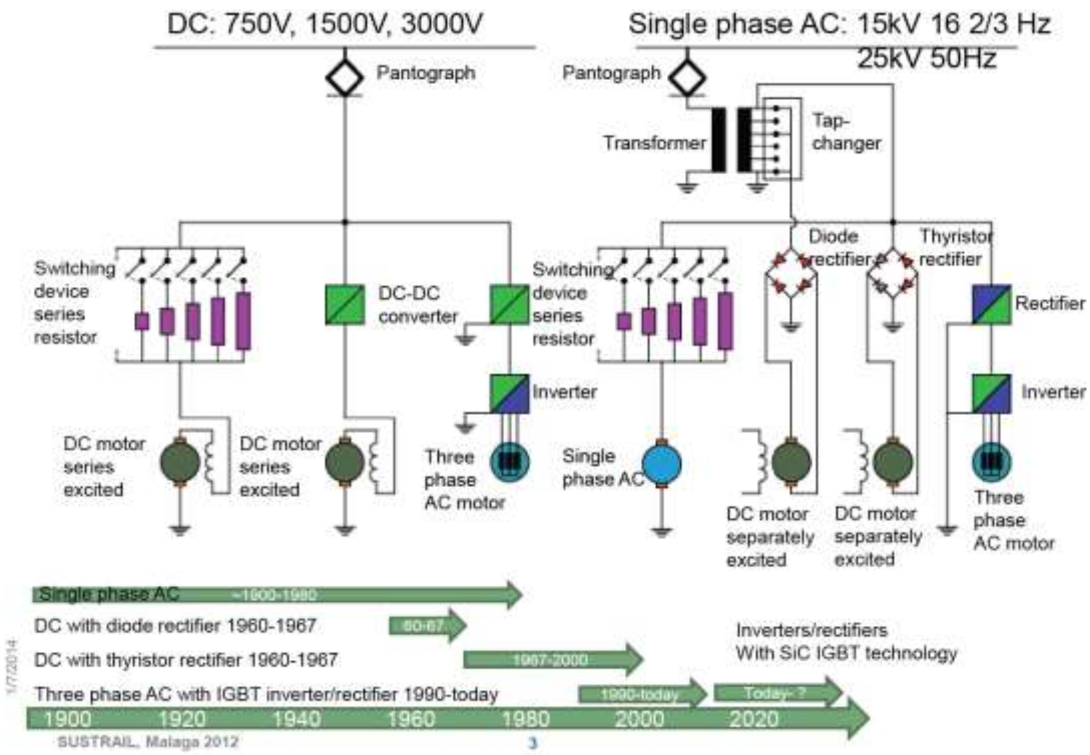


Figure 1 Electrification progress [1].

1.1.4 Existing technologies of today

Most of the locomotives today are powered by electricity. The source of electricity is either an overhead line alternatively a third rail or a diesel electric generator.

1.1.4.1 Diesel locomotive

Diesel locomotive is a type of locomotive where a diesel engine is used to provide the necessary tractive power. The breakthrough for this type of locomotives was during 1950’s which in turn implied the end of steam locomotive technology. The size of the diesel engine was considerably smaller compared with the early built machines and at the same time the efficiency of the machine was improved drastically. Hence, the diesel engine became more cost efficient and required less maintenance which resulted in lower operating costs for these types of locomotives. In comparison to the electric locomotives, diesel locomotives have usually approximately the same tractive force per axel whereas the power to weight ratio is much higher for electric locomotives.

Prior Steam engine propulsion system

1876 Nicolaus Otto; first Internal Combustion Engine running on gasoline also used for locomotive propulsion.

1893 Rudolf Diesel; develops diesel engine using pressure to start the combustion

1912 First diesel powered locomotive

1917 GE develops diesel electric propulsion system (DC-generator and DC-traction motor)

1960 Introduction of semiconductor devices. DC-generator being replaced by AC-generator

2005 Genset locomotives (a huge diesel engine and a generator is replaced by several smaller gensets)

The diesel locomotives may be divided into two categories diesel electric and diesel hydraulic.

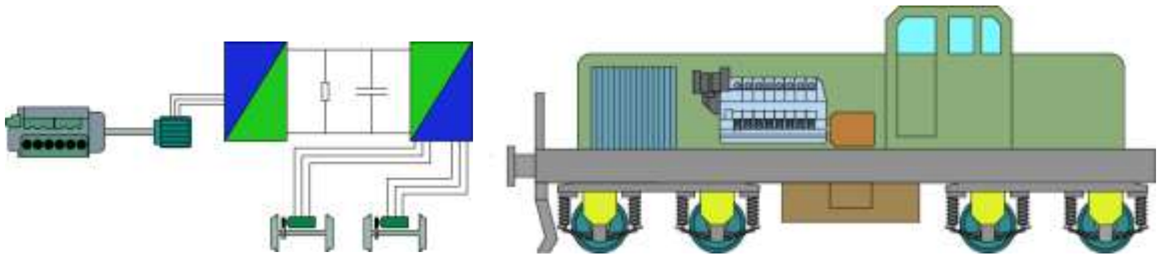
1.1.4.2 Diesel hydraulic locomotives

Two types of hydraulic-transmissions systems can be identifies; hydro dynamic and hydro static. They will not be dealt with further in this report.

1.1.4.3 Diesel Electric locomotives

In diesel electric locomotives the diesel engine output shaft is connected to an electric generator. These types of locomotives are also the most common type of diesel locomotives. The energy from the diesel combustion engine is converted into electrical energy before it reaches the wheels. Hence, there is no mechanical coupling between diesel combustion engine and the wheels. The generator and or traction motors are either producing/consuming alternate current (AC) or direct current (DC).

The dc traction motors were more common in the past owing to its simple control. However, due to the commutator brushes, the control of the motors becomes difficult at lower speed. Modern diesel electric locomotives are mostly propelled by AC motors, in general three phase induction motors.



a) b)

Figure 2 Diesel electric locomotive a) schematic view of the driveline b) diesel electric locomotive.

AC motors can be designed for higher maximum speeds, thus a smaller torque and volume for a given power rating. They are also produced in larger volumes and as a consequence AC motors are more cost effective.

Yet another contributing aspect is the rapid development of the control equipment such as the converters which offers better control even at lower speeds. Usually these types of locomotives are equipped with one huge diesel engine, one main generator and an auxiliary generator attached to the same shaft. Problems associated with these types of locomotives are huge starting currents. Hence, the battery must be dimensioned accordingly. Locomotives in shunting load conditions and cold weather are therefore left to run in idling just to prevent the freezing that may cause a huge damage to the locomotive.

1.1.4.4 Genset locomotives

In order to improve the efficiency of the locomotive some manufactures are starting to look at a solution that is commonly known as a *genset*. It means that instead of having one big diesel combustion engine coupled to a big electric generator, the electric power is provided by several smaller units that are connected in parallel. Thus, when the locomotive is in idling and only a fraction of electric power is needed, i.e. to maintain some vital function in the vehicle like air conditioner or heating of the drivers' cabin, this can be provided by only one small unit. Hence, the losses in the vehicle are kept at a minimum. When the maximum power is needed all genset units are operated simultaneously and provide the rated power.

Typically these loco- motives are perfectly suited for shunting or switching operations with intermittent operating conditions. The drive cycle during one day requires very low mean power with high peak power levels and long idling intervals.

1.1.4.5 Dual mode locomotives

Dual mode locomotives can take advantage of the electrified line through a catenary or a third rail but also run on non-electrified railways.

Dual mode locomotive should not be considered as hybrid vehicle as they do not have a large energy storage unit, typically a battery. A huge energy storage capability like the batteries can booth be considered as an advantage and as a dis- advantage at the same time.

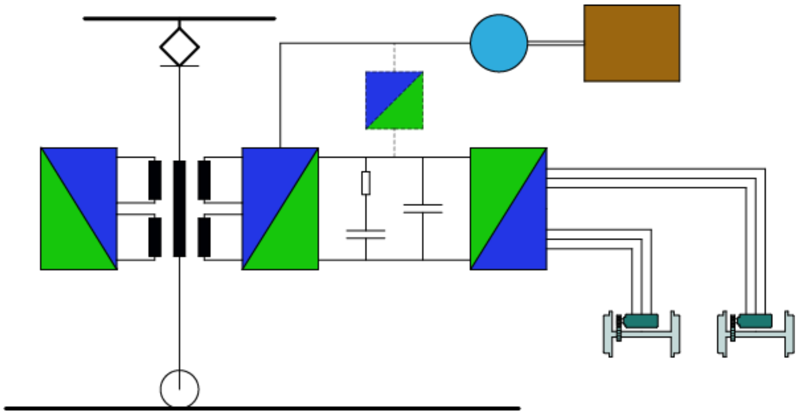


Figure 3 Schematic view of a dual mode locomotive.

From the operational point of view the batteries give an additional flexibility to the vehicle as the transient power requirement can be covered by its stored energy. Hence, the combustion engine can operate in a high efficiency area or even in a most optimal efficiency point. Whether the combustion engine can operate in a smaller efficiency area or at an optimal point strongly depends on the size of the batteries. On the other hand, introducing a battery into the system implies a more complex system, and what is more important much more costly.

a) b)

Figure 4 a) Vossloh EURODual for freight purposes comes with three different diesel options: 700 kW, 1400kW and 2800 kW. Electric traction 5000 kW. b) Bombardier ALP-45DP for freight and passenger service (Line between New Jersey and Montréal). Electric traction 4000 kW, diesel traction 3134 kW.

a) b)

Figure 5 a) Class 38 traction power1500/780 kW b) ED1600 traction power 1600/560 kW

1.1.4.6 Hybrid locomotive

The definition of a hybrid vehicle given by UN is:"A hybrid vehicle" is a vehicle with at least two different energy converters and two different energy storage systems (on-board the vehicle) for the purpose of vehicle propulsion." [2]

Hybrid vehicles can be classified in many different categories depending on the definition, like; mild hybrid, power hybrid etc. However, there is more prominent classification of the hybrid vehicle that are used today and those are: Series Hybrid Electric Vehicle; Parallel Hybrid Electric Vehicle; and a combination of those, Series-Parallel Hybrid Electric Vehicle.

1.1.4.7 Series Hybrid Electric Vehicle SHEV

In a series hybrid electric vehicles there is no mechanical connection between the combustion engine and the wheels. Thus, all energy must be converted to electrical energy before it reaches the wheels. This topology fits very well with the drive train which is equipped with other types of energy converter sources than the conventional combustion-engine-generator unit, like fuel cells or the Free Piston Energy Converter. A schematic view of a series hybrid electrical system can be seen in Figure 6.

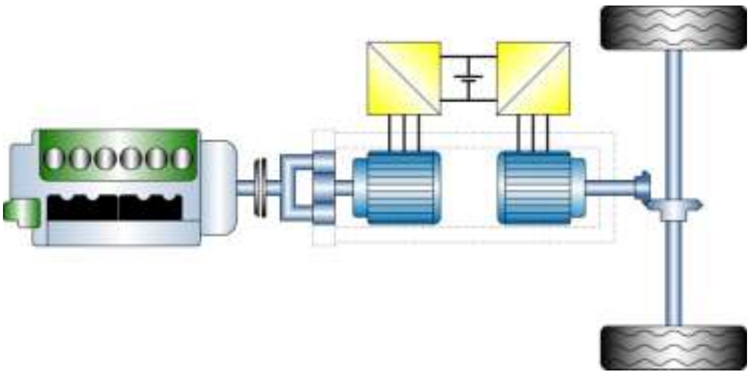


Figure 6 Schematic view of Series Hybrid Electric Vehicle (SHEV) [2].

The advantage with this topology is that the combustion engine can be downsized and to some extent optimized to work only in the most operating efficient point. Whether the combustion engine can operate in only one point or not, is strongly depending on the size of the battery storage and its dynamics.

1.1.4.8 Parallel Hybrid Electric Vehicle PHEV

In the parallel Hybrid Electric Vehicle the combustion engine is directly connected to the wheels and provides thrust.

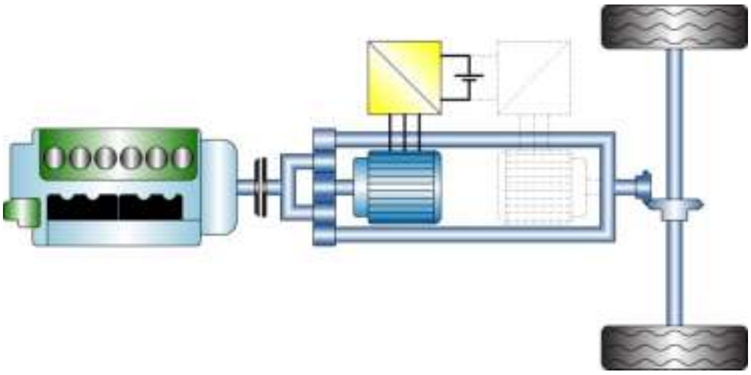


Figure 7 Schematic view of the Parallel Hybrid Electric Vehicle (PHEV) [2].

The electrical machine in the system is used booth as a motor and as a generator. In the motor operation mode it provides additional torque to the wheels i.e. in a steep climb or during acceleration. It operates in the generator operation mode when there is a need of charging the energy storage unit or during the regenerative breaking. Schematic layout of the topology can be obtained in Figure 7.

As the electrical machine can only be used as a motor or as a generator at a time the system cannot achieve the maximum torque operation mode and charge the energy storage at the same time. Compared to the SHEV topology the combustion engine is now obliged to work in different operation points with lower efficiency. However, this topology has an advantage compared to the SHEV when there is a need for constant power demand during a longer period of time. As there is no need for additional energy conversion to the electric energy before it reaches the wheels the efficiency of the system becomes higher.

1.1.4.9 Series Parallel Hybrid Electric Vehicle

Series Parallel Hybrid Electric Vehicles is as the name indicates it is a combination of the two topologies above. It can be operated as purely electric vehicle, or as a conventional vehicle, or as a combination of those.

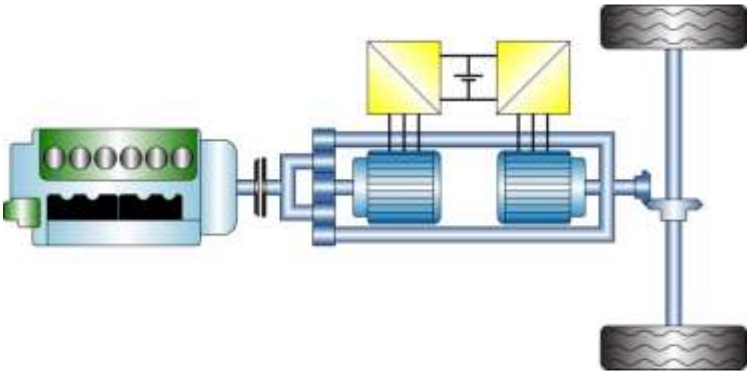
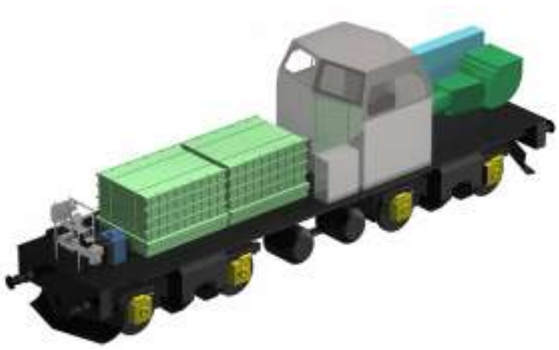


Figure 8 Schematic view of Series Parallel Hybrid Electric Vehicle (SPHEV) [2].

One of the key components in this topology is the planetary gear. This topology is equipped with the two electrical machines, one used as a generator and the other one used as the motor. This topology tends to be complex and expensive but can take full advantages of booth the previously described topologies above. A schematic view of the topology is shown in Figure 8.

1.1.4.10 Swedish Experience with hybrid system

In Sweden a feasibility study has been carried out into incorporating hybridlocomotives in switch yards.



a) **b)**

Figure 9 a) Prototype T43H b) schematic view of the prototype.

The study was performed in collaboration with "Svensk Tågteknik AB" and some other partners. Within this project a prototype hybridlocomotive was buildt and tested. The portotype is shown in Figure 9.

The prototype was designed according the "Green Goat" and the performance data of the prototype vehicle is shown in Table 1. Instead of a large combustion engine and a generator unit the prototype was equped with a smaller combustion engine and generator unit plus a large battery storage system.

Table 1 Technical data of the original T43 and the rebuilt T43H [3]

Technical data:	T43	T43H
Weight	72 tonnes	78.7 tonnes
Maximum Power	1063 kW	893 kW
Starting tractive effort	212 kN	230 kN
Displacement of combustion engine	136 litres	8.3 litres

The weight of the battery was not seen as a problem. The test result showed a huge potential in energy savings between 30-80% depending on the usage and the load cycle. Another advantage was highly reduced exhaust emission of the NOx particles, up to 90% improvement. A drawback was the inability to charge the battery storage from the grid and also the limited range and the speed of the locomotive.

1.1.4.10.1 The Green Goat

The driveline architecture of the Green Goat is similar to a SHEV. The locomotive was designed for only one shift, but was being used for longer service. As a result of that several of the units

Figure 10 The Green Goat prototype [3]

were caught fire and were destroyed. Another contributing factor to failure was a poor battery management system that failed to prevent battery shorts [4].

2. OVERVIEW OF THE ROUTES

2.1 UK route

The UK route is one with most diversity regarding the electrification of the lines. There are mostly non electrified routes but there are also electrified parts of the route. There are two different systems of electrification; 750 V DC (from a third rail) and 25 kV, 50 Hz, AC line from an overhead catenary system.

A sligthly more detailed description is given bellow:

The first part of the line is between Felixstowe and Nuneaton

- Length 256.6 km
- Maximum axle load 22.8 tonnes
- Electrified Mostly not (the first 30 km is under 25kV AC overhead catenary)
- Typical line speed 120 km/h

The second part of the line is between Southampton to Nuneaton.

- Length 211.2 km
- Maximum axle load 25 tonnes
- Electrified Mostly not (the first 48 km is electrified under 750V DC)

- Typical line speed 160 km/h

The lines described above meet at Nuneaton where they join the West Coast Mainline which continues further to Warrington via Crewe. The last part of the line in England is between Nuneaton and Crewe:

- Length 101.6 km
- Maximal axle load 22.8 tonnes
- Electrified Yes (25kV AC overhead)
- Typical line speed 120 km/h

2.2 Bulgarian route

The Bulgarian route stretches between Kalotina in the west and Svilengrad in the east. The line is a mixture of an electrified part west of city Plovdiv, which lies approximately in the middle of the route, and a non-electrified part of the route to the east. System of electrification is 25 kV, 50 Hz, AC with a maximum permissible current of 500 A.

- Length 374.9 km
- Maximal axle load 22.5 tonnes
- Electrified Mostly (220 km between Dmitrovgrad an Krumovo 25kV, 50Hz, AC overhead)
- Typical line speed 75 km/h

2.3 Spanish route

Spanish route is situated on the east coast between the Castellbisbal and Silla. Castellbisbal lies just south of Barcelona and Silla lies close to Valencia. The route is electrified throughout the whole distance. The system of electrification is 3 kV DC. The line described below stretches between Valencia and Tarragona which was originally taken as a part of the investigation. This was later on extended from Castellbisbal to Silla.

- Length 272 km
- Maximal axle load 25 tonnes
- Electrified Yes (3 kV, DC)
- Typical line speed 100 km/h

3. VEHICLE PERFORMANCE

Some of the vehicle's performance parameter are governed by the track specifications. Thus it is important to have a good knowledge of the route the vehicle is going to operate. One of the key specifications is actually the maximum allowable axle load.

3.1 Tractive power

The tractive force required by a train is given by

$$F = m_a \cdot a + D \tag{eq 1}$$

The equation above describes the force required for the train to accelerate; at constant speed the force is equal to the total running resistance D. In the equation above m_a is the train's equivalent dynamic mass and a is the acceleration.

3.2 Running resistance

The running resistance is the resistance a locomotive needs to overcome in order to keep a constant speed. The running resistance can be broken down to four different components:

- Rolling resistance (D_r)
- Aerodynamic resistance (D_a)
- Curve resistance (D_k)
- Gradient resistance (D_g)

3.2.1 Rolling resistance

The rolling resistance depends on many different factors, just to mention some; friction in wheel bearings, irregularities on tracks and on wheels etc. An approximate value of the rolling resistance can be obtained from the expression below

$$D_r = m \cdot (c_1 + c_2 \cdot v) \tag{eq 2}$$

Where m is the vehicles mass and $c_1 = 0.01 - 0.02\ \left[\frac{N}{kg}\right]$ and $c_2 = 0.00015 - 0.0003\ [s^{-1}]$.

Rolling resistance is strongly dependent on the running properties of the vehicle and on the quality of the track. It will increase with poor quality of the track and poor quality of the running resistance of the vehicle.

3.2.2 Aerodynamic resistance

Aerodynamic resistance is a part of the resistance that has high contribution to the total resistance of the vehicle. However, as it is speed dependent the largest impact will be at higher speeds. The aerodynamic resistance can be written as following:

$$D_a = \frac{1}{2} \cdot \rho \cdot v_{rel}^2 \cdot A \cdot C_D(\beta) \tag{eq 3}$$

where ρ is the density of the air (1.3 $\left[\frac{kg}{m^3}\right]$), v_{rel} is the relative wind speed $\left[\frac{m}{s}\right]$, and A is the train´s front area $[m^2]$. $C_D(\beta)$ is an aerodynamic drag constant which is a function of the wind´s angle of attack β, which is given by equation bellow:

$$\beta = \tan^{-1}\left(\frac{v_w \cdot \sin\vartheta}{v + v_w \cdot \cos\vartheta}\right) \tag{eq 4}$$

The value of the relative wind speed can be calculated by the following equation:

$$|v_{rel}| = \sqrt{v^2 + v_w^2 + 2 \cdot v_w \cdot \cos\vartheta} \tag{eq 5}$$

3.2.3 Curve resistance

Usually the wheels on a wagon are connected by a rigid axle, thus wheels traveling in a curve will not cover the same distance where the outer wheel will have to travel a larger radius. As the wheel-set is fixed in a boogie there will be a certain slippage and friction between the rail and the wheels thereby causing a certain resistance

$$D_k = \frac{m \cdot 6.5}{r - 55} \qquad \text{(eq 6)}$$

where m is the mass of the train, r is the radius of the curve and factor $6.5\left[\frac{m^2}{s^2}\right]$ is valid for ridged bogie. For a soft bogie this factor can be lowered to 2.0.

3.2.4 Gradient resistance

$$D_g = m \cdot g \cdot \sin\theta = m \cdot g \cdot \frac{S}{1000} \qquad \text{(eq 7)}$$

Using the approximation "$\sin\theta = \theta$" in the equation above for small angles, which is always the case in the railway context, the equation can be further simplified. Where S the gradient is expressed in per mille, m is the mass of the train and g is the constant of gravity.

3.2.5 Total resistance

Total resistance that needs to be overcome by the train is the sum of all resistances described above and is given in equation bellow

$$D = D_r + D_a + D_k + D_g \qquad \text{(eq 8)}$$

3.3 Definition of different vehicle masses

- m total static mass of the train.
- m_w mass of one car.
- m_a equivalent dynamic mass of the train. The dynamic mass of the train is typically 5-10% higher than the static mass.
- m_α adhesive weight of the train. It is the sum of all axle weight of all driving axles. For the freight train, usually there is a locomotive which provides all tractive effort required, hence the adhesive weight is often the same as the weight of the locomotive provided that all axles are driving. If there are several locomotive this is the same as the sum of the weights of all of the locomotives.

$$m_a = m + \sum_{i=0}^{n_w} \frac{J_i}{r_i^2} \qquad \text{(eq 9)}$$

$$J_i = k_g^2 \cdot J_i + J_w \qquad \text{(eq 10)}$$

m is the static mass, n_w is the number of wheel sets, J_i is the total moment of inertia per wheel set, r_i is wheel radius, k_g is gear ratio, J_m is inertia of the rotor, J_w is the wheel-sets and gears moment of inertia.

4. POTENTIAL HYBRIDIZATION

A question is how to design a vehicle with best performance. The first step is to look at the performance requirements in form of acceleration, maximum speed; maximum torque etc. next step is to consider other requirements such as maximum weight of the locomotive; efficiency and finally the cost.

Today one of the important factors that takes the next step, in the development of the technology, are the legislations in terms of the efficiency, exhaust emissions etc. provided by i.e. the European Union, but also by some governments on a national level. The need for a new function of the equipment is also something that imposes a technology development.

Whether the higher efficiency can be achieved with the hybridization of a system is a very relevant question. As mentioned earlier, different types of hybrid systems suits better for some applications and are less suitable for some other. In other words the efficiency of the system strongly depends on the load cycle.

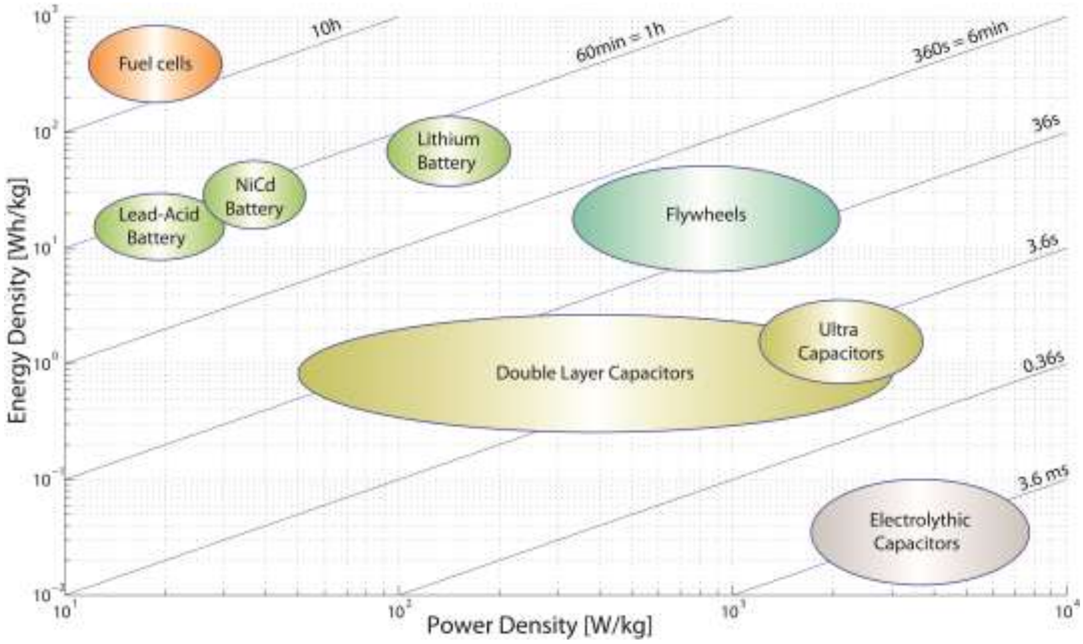


Figure 11 Ragone plot of different energy storage units.

One way to find out the possible benefits of the hybridization of the vehicle is to look at the power demand during the vehicles operation cycle. The ratio between the maximum power demand and the average power demand during a load cycle can be used as an indicator for a possible hybridization benefit. In equation form this could be defined as following [5]:

$$\boldsymbol{PHP = 1 - \frac{P_{ave}}{P_{max}}} \qquad \text{(eq 11)}$$

Where PHP stands for *Potential for Hybridization in Power*, P_{ave} is the average power during the load cycle and P_{max} is the maximum power demand during the cycle. In order to avoid mathematical irregularities there are some restrictions that has to be imposed on, $PHP \in [0,1]$. This is with regard to $P_{ave} < 0$ and $P_{max} < 0$, thus in these cases the $PHP = 1$.

Apparently the value of PHP is varying between 0-1 where 0 is low suitability of hybridization and 1 is the maximum suitability for hybridization. However, while this value indicates a possible benefits of hybridization it does not give any answer to the storage capacity which strongly influences the size of the system and eventually the price.

Variations in power demand from the load cycle will have a direct impact on the size of the energy buffer required. The energy is given by the integral of the power over a time period, thus in a high frequent power demand the required energy buffer will tend to become smaller compared to slow varying cycles. It should be pointed out that this implies an optimal system design.

Based on *PHP* only, it might be difficult to see the complete potential in hybridization of a system, thus the *Potential Hybridization in Energy* (*PHE*) can be introduced as a complement [6]. The energy in the system is calculated according to the following equation:

$$\boldsymbol{E_s(t) = \int_0^t \left(P(\tau) - P_{avg}\right) d\tau} \quad \text{(eq 12)}$$

where $P(\tau)$ is the variation in power demand during a load cycle and P_{avg} is the average power of the complete load cycle. Using equation (eq 12) above the useful energy is then calculated by:

$$\boldsymbol{E_u = \max E_s(t) - \min E_s(t)} \quad \text{(eq 13)}$$

Finally the potential hybridization in energy PHE can be defined as:

$$\boldsymbol{PHE = \frac{P_{max}}{E_u}} \quad \text{(eq 14)}$$

However, booth *PHP* and *PHE* indicators need a well-known or well defined load cycle in order to calculate these indicators. In reality this is usually not the case, the load cycle are not known in advance. Hence, the design procedure needs to be performed in a different approach.

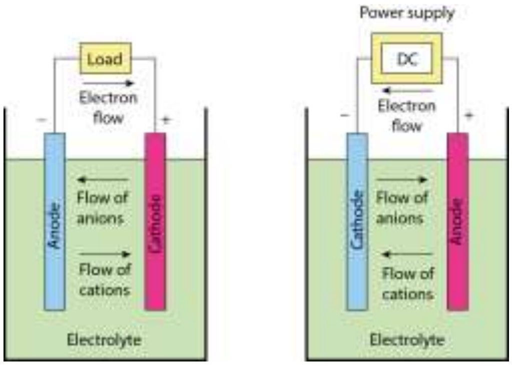
In order to be able to calculate and size the energy buffer there needs to be certain demands and requirements. They can be of different kinds of nature; physical size, weight but most probably of energy size and dynamic response. In [7] the requirements were set on the energy buffer where the vehicle should be able to run at least 10 km purely on electric propulsion. The dynamic response will have a direct impact on the acceleration performance on the vehicle thus the boundary for the performance of the vehicle are well defined in the traffic regulations. Based on the information in the regulations the requirements can then be exactly defined.

4.1 Energy Storage

When it comes to the energy storage, there are many different options in the way this can be accomplished, falling weight, mechanical deformation (spring), compressed air, etc. However, not all of them are interesting when it comes to hybridization of the modern rail vehicles. There are three different ways that are more distinguished compared to the others; battery, super capacitors and flywheels. The electric energy in the battery, which is one of the most common ways to store energy, is stored through an electrochemical reaction. An alternative way of storing electric energy is the capacitor, which opposed to the battery stores the energy as a static charge. Flywheel stores energy mechanically rather than electrically.

4.1.1 Batteries

As mentioned above, batteries transfers, through the electrochemical oxidation-reduction reaction, chemical energy into the electric energy. Usually the voltage obtained through the reaction process is limited to a couple of volts. Hence the battery often consists of a number of cells that are connected into series or in parallel to provide a desired voltage or energy capacity.



a) b)

Figure 12 Principle operation of a battery cell during a) discharging and b) charging process [8]

The principal operation of a battery is shown in Figure 12. There are many different types of batteries and, generally speaking batteries are usually considered as high energy density storage units.

However, recent development has been focused on batteries that can provide high power rather than an increase in their energy density [9]. A lot of this research has been driven by different automotive companies searching for improvements in the efficiency of the vehicles.

One solution is to replace the conventional drive line with a battery for energy storage and electrical motors for the propulsion purposes. These types of vehicle are usually abbreviated as Electric Vehicles (EV). As the battery is the main energy source, usually the batteries are deeply discharged before recharging from the electricity grid. The cycle life time becomes an important issue during the design stage whether the battery is going to meet the minimum requirements. Another important issue is the range requirement that the battery needs to meet, which by using an appropriate load drive cycle, can be calculated by looking at the energy consumption. It should be mentioned that in most cases the battery pack is able to provide the required peak load once the energy capacity is met. The battery power considering the efficiency is:

$$\boldsymbol{P_{battery} = \eta \cdot (1 - \eta) \cdot \frac{V_0^2}{R}} \qquad \text{(eq 15)}$$

where V_0 is the nominal voltage of the battery (open circuit) and R is the inner resistance of the battery and η is the required efficiency. Actually the battery peak power is obtained from (eq 16) i.e. when the efficiency of the battery is 50%. There are several reasons why the efficiency of the battery is considered, one is of course the efficiency of the total system. However, one of the main reason is the energy losses in the battery which needs to be cooled. Although the size of the battery, considering the peak power demand, can be minimized allowing for lower efficiency the cooling system on the other hand would increase.

$$P_{peak} = \frac{V_0^2}{4 \cdot R} \quad \text{(eq 16)}$$

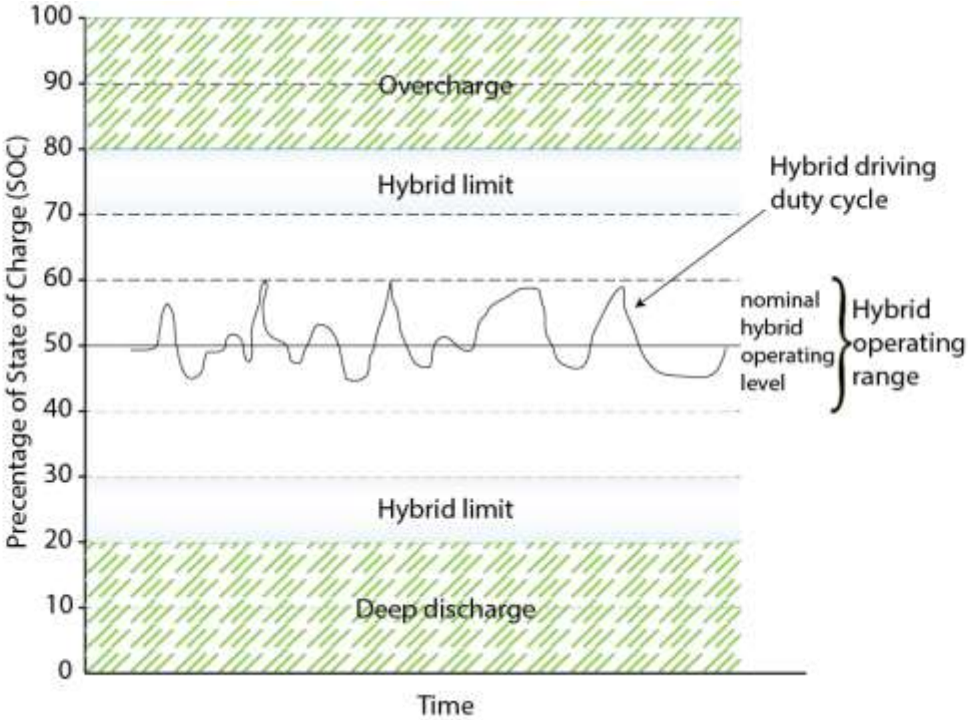


Figure 13 State-of-Charge consideration for battery operation in hybrid electric vehicles [10].

Another possible solution is to assist the conventional drive line with a secondary auxiliary power source. This solution comes in various configurations, some of them described in earlier sections. In addition to the energy recapturing during the breaking of the vehicle, this solution also offers the possibilities of downsizing of the conventional combustion engine and running the combustion engine at the most optimal efficiency.

The size of the battery storage unit can vary from very small sizes, in so called power assist hybrids, to large sizes with equal sharing of power in so called full hybrid vehicles. However, using the battery as auxiliary power source implies very tough requirements and demands on the battery. To optimize the lifetime of the battery it should operate around 50% of its state of charge and spend minimum of its time in the overcharge and over-discharge [10]. This is illustrated in Figure 13.

As mentioned, one reason to keep the battery ”*State Of Charge* (SOC)” on 50% level is to increase the battery life but another reason is to be able to regenerate the energy during the decelerations of the vehicle. Thus the battery will be able to deal with large current spikes without been overcharged. This relatively low SOC level will however bring down the useful capacity of the battery, in other words the size of the battery needs to be doubled in order to meet the energy requirement. Depending on the chemistry properties of the battery it can also react differently on charging and discharging currents. Some batteries are able to tolerate higher charging currents compared to the discharging currents and vice versa. This is something that needs to be taken into consideration during the design stage and the size of the battery has to be adapted accordingly [6] [10].

4.1.1.1.1 Modelling of the battery.

Modelling of the batteries in an accurate way is important for developing the control strategies of hybrid electric vehicles through simulations studies [11]. Numerous different models have been developed and reported in the literature. In its simplest for the battery can be represented by a voltage source with a constant resistance connected in series, as shown in Figure 14.

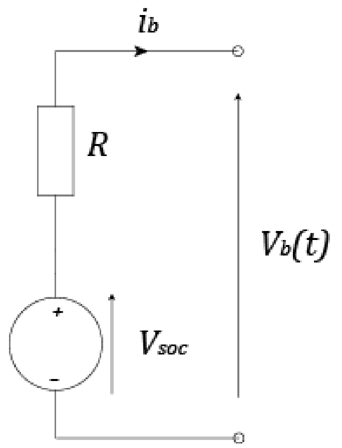


Figure 14 Simple battery equivalent model.

Battery equivalent models can be summarized in different categories: electrochemical models, mathematical models and electrical models [12]. Among those, electrical models are the most intuitive ones. These models can in turn can be divided into: Thevenin models, impedance models and runtime based models [13].

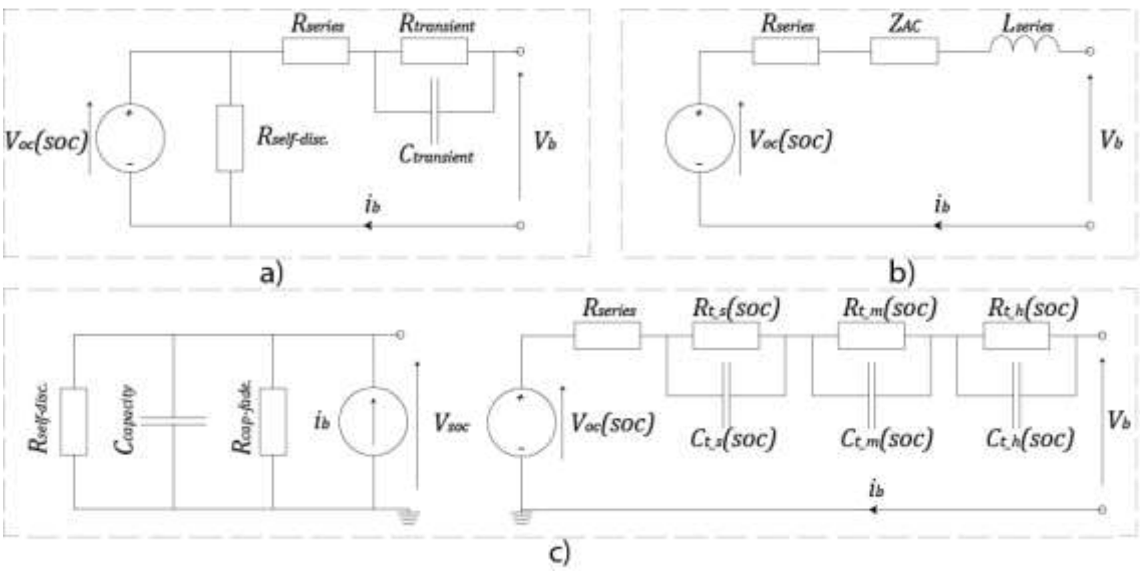


Figure 15 a) Thevenin- b) Impedance- and c) Runtime-based electrical battery model.

These models are shown in Figure 15. The impedance based model shows good agreement between measured and simulated results [14].

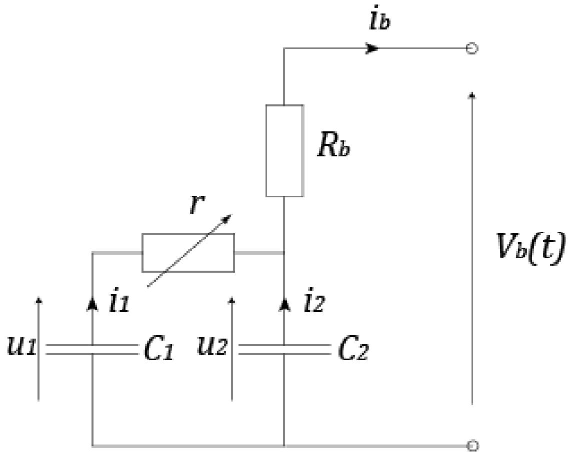


Figure 16 Lithium ion battery equivalent model

By using the electrochemical impedance spectroscopy the value of the impedance Z_{AC} is determined. The method however is somewhat complicated. The Thevenin model assumes a constant open-circuit battery voltage $V_{OC}(SOC)$ which does not take into consideration the steady state battery voltage variation. Thus, in order to improve the model a nonlinear capacitance is used. The runtime-model uses a couple of different networks, where the first part is taking care of the capacity and SOC level in the battery and the second part is taking care of the transient response [12] [13].

All models have their strengths and weaknesses. A more detail description of a battery model used and implemented in a Matlab/SIMULINK environment [7] is given below.

In the equivalent circuit above the resistance r is the non-linear resistance, while the internal voltage drop is represented by the linear resistance R_b. The capacitance C_1 is given by:

$$\boldsymbol{C_1(u_1) = A_1 \cdot e^{-B_1 \cdot (u_1 - u_{M1})^2} + A_2 \cdot e^{-B_2 \cdot (u_1 - u_{M2})^2}} \qquad \text{(eq 17)}$$

where A_1 , B_1, u_1, and u_{M_1}, and A_2, B_2 and u_{M_2} are parameters dependent on the cell current and the temperature. The capacitance C_2 is given by:

$$C_2(u_2) = \frac{D_0}{2} \cdot (1 + \text{erf}(u_2 - u_E)) \text{ för } 0 \leq u_2 \leq 4.1$$
$$C_2(u_2) = D_0 \cdot (u_M - u_2) \text{ för } 4.1 \leq u_2 \leq u_M \qquad \text{(eq 18)}$$

In the equation above, parameter D_0 also depend on the cell current and the temperature. u_E and u_M are the boundary values of the voltage interval, which also gives a hint about the technology that is being used within the cell. In [7] these values have been put to 2.7 V and 5.0 V respectively.

The total capacity of the battery, due to the conservation principle of charge, is given by:

$$Q = \int_{3.05}^{3.9} C_1(u_1)du_1 + \int_{3.05}^{3.9} C_2(u_2)du_2 \qquad \text{(eq 19)}$$

Where the limits of integration are given for deeply discharged and fully charged cells i.e. 3.05 and 3.9 V respectively [7].

$$V_b(t) = u_1(t) + R_b \cdot i_b(t) \qquad \text{(eq 20)}$$

Current dependent parameters:

$$A_1 = a_{11} + a_{12} \cdot \log_{10}(1 + \frac{i_b}{i_0}) \qquad \text{(eq 21)}$$

$$A_2 = a_{21} + a_{22} \cdot \log_{10}(1 + \frac{i_b}{i_0}) \qquad \text{(eq 22)}$$

$$B_1 = b_{11} + b_{12} \cdot \log_{10}(1 + \frac{i_b}{i_0}) \qquad \text{(eq 23)}$$

$$B_2 = b_{21} + b_{22} \cdot \log_{10}(1 + \frac{i_b}{i_0}) \qquad \text{(eq 24)}$$

Coefficients a_{11}, a_{12}, a_{21}, a_{22}, b_{11}, b_{12}, b_{21}, b_{22} and i_0 are temperature dependent. For the nonlinear capacitance C_2 and the nonlinear resistance r the equations are given below:

$$C_2 = d_1 + d_2 \cdot \log_{10}(1 + \frac{i_b}{i_0}) \qquad \text{(eq 25)}$$

$$r = r_1 + r_2 \cdot \log_{10}(1 + \frac{i_b}{i_0}) \qquad \text{(eq 26)}$$

Where d_1, d_2, r_1 and r_2 are temperature dependent. The value of the current i_0 is represented by the following equation:

$$\boldsymbol{i_0 = i_{01} \cdot log_{10}\, T(t) + i_{00}} \qquad \text{(eq 27)}$$

As mentioned, in order to model the battery cell in an accurate way the temperature dependency of the battery cell needs to be taken into consideration. From the test data it was shown that the linear temperature dependency of the coefficients gave satisfactory results. However, the coefficient a_{21} was the only coefficient that showed a nonlinear behavior with the temperature and has a quadratic depends of the temperature [7]. The temperature dependency of the coefficients are given in Table 2.

Table 2 Temperature dependent coefficients [7]

$a_{11} = a_{111} \cdot T(t) + a_{110}$	$b_{11} = b_{111} \cdot T(t) + b_{110}$
$a_{12} = a_{121} \cdot T(t) + a_{120}$	$b_{12} = b_{121} \cdot T(t) + b_{120}$
$a_{21} = a_{212} \cdot T^2(t) + a_{211} \cdot T(t) + a_{210}$	$b_{21} = b_{211} \cdot T(t) + b_{210}$
$a_{22} = a_{221} \cdot T(t) + a_{220}$	$b_{22} = b_{221} \cdot T(t) + b_{220}$
$u_{M1} = u_{M11} \cdot T(t) + u_{M10}$	$r_1 = r_{11} \cdot T(t) + r_{10}$
$u_{M2} = u_{M21} \cdot T(t) + u_{M20}$	$r_2 = r_{21} \cdot T(t) + r_{20}$
$d_1 = d_{11} \cdot T(t) + d_{10}$	$R_{b0} = R_{b01} \cdot T(t) + R_{b00}$
$d_2 = d_{21} \cdot T(t) + d_{20}$	$R_{b1} = R_{b11} \cdot T(t) + R_{b10}$
$R_b = R_{b1} \cdot T(t) + R_{b0}$	

Table 3 shows the constant which are needed for calculating the coefficients described above. As can be noted there are different constants for charging and discharging of the battery. The constants given below are considered for a new battery cell and they need to be somewhat modified along the lifetime of the cell.

Table 3 Constant coefficients for a lithium ion cell [15]

Parameter	*Discharge*	*Charge*	*Parameter*	*Discharge*	*Charge*
a_{111}	385	385	b_{210}	76.75	76.75
a_{110}	95500	95500	b_{221}	-0.089	-0.089
a_{121}	-400	-400	b_{220}	7.8	7.8
a_{120}	33750	48300	r_{11}	-0.0004	-0.0004
a_{212}	25	0	r_{10}	0.051	0.051
a_{211}	-710	300	r_{21}	0.0002	0.0002
a_{210}	139250	142000	r_{20}	-0.016	-0.016
a_{221}	-79	-385	R_{b11}	0.00004	0.00004
a_{220}	-6500	23750	R_{b10}	-0.0001	-0.0001
d_{11}	-340	-340	R_{b01}	-0.0046	-0.0046
d_{10}	91500	91500	R_{b00}	0.0185	0.0185
d_{21}	221	221	i_{01}	-2.638	-2.638
d_{20}	-21550	-21550	i_{00}	12.47	12.47
b_{111}	-0.102	-0.102	u_{M10}	3.84	3.85
b_{110}	9.1	9.1	u_{M11}	0.0005	0.0025
b_{121}	-0.0028	-0.0028	u_{M20}	3.56	3.645
b_{120}	0.83	0.83	u_{M21}	-0.001	-0.0027
b_{211}	0.61	0.61			

4.1.2 Capacitors

Like a battery a capacitor can store electric energy. However, the working principle behind is quite different. While a battery store electric energy through an electrochemical reaction the energy in the capacitor is stored electrostatically in an electric field.

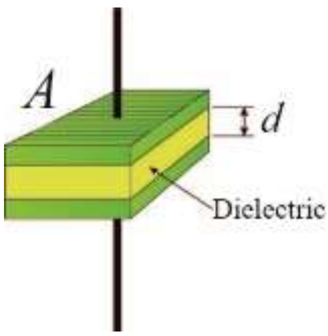


Figure 17 Schematic view of a capacitor.

The capacitance of the capacitor is given by (eq 28), where C is the capacitance given in Farad, ε is the permittivity of the dielectric material, A is the area of the plates and d is the distance between the two plates.

$$C = \varepsilon \cdot \frac{A}{d} \quad \text{(eq 28)}$$

According to the equation the capacitance can be increased by varying the physical size of the capacitor i.e. increasing the area A of the conductive plates in the capacitor or by decreasing the distance d between the plates. Another way to affect the capacitance is to change the properties of the insulating material. Depending on the dielectric material capacitors can be divided into different categories where ceramic, Aluminium and film are among the best known. Based on requirements, such as temperature or size, different types are used in different applications.

The energy stored in a capacitor is given by: [16].

$$\boldsymbol{E = \frac{1}{2} \cdot C \cdot V^2} \quad \text{(eq 29)}$$

where V is the voltage between the plates. The breakdown voltage of the capacitor is strongly related to the electric properties of the dielectric material.

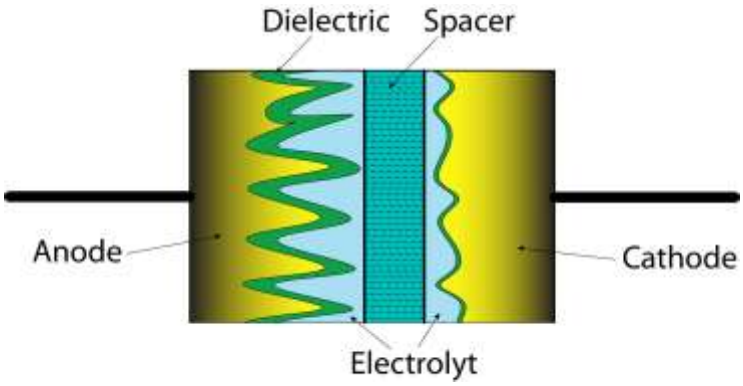


Figure 18 Schematic view of a Super capacitor.

As mentioned, one way to increase the capacitance is to increase the area of the plates. In special types of capacitor called electrolyte this is done by roughening the surface of the plates by etching. The surface of anode, which consists of very high purity aluminum, is etched through either a physical or an electrochemical process. Furthermore, the anode is subject to a process called forming in order to create an insulating layer of oxide. This is achieved by placing the anode in an electrolytic solution which allows the oxide layer to grow.

In order to preserve the oxide layer during its lifetime the spacer of the capacitor is soaked into the electrolyte. Thus, these types of capacitors have a fixed polarity, reversing the voltage on the terminals will damaged the capacitor due to the gases from the chemical reaction of the electrolyte.

4.1.2.1 Super capacitors

Super capacitors; also known as *Ultra capacitors* or *Double layer capacitors* have been known for quite some years. The first patent dates back as long as 1957 [17]

Super capacitors have much higher power density compared to the batteries. They can deliver power much faster and has a much longer lifetime, up to 500000 charge/recharge cycles have been reported [18].

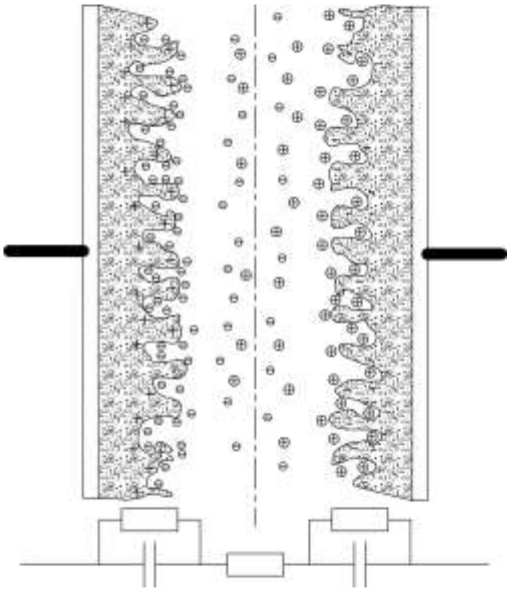


Figure 19 Super capacitor in it charged state [18].

Compared to conventional capacitors they have much higher energy density. However, there are certain drawbacks, one of them is the non-uniform nominal parameters. The low operating voltage might imply some implementation problems [19]. The breakdown voltage is depending on the type of electrolyte and the small charge separation distance. Thus the low operating voltage is inherent in the principal operation of the super capacitor with a typical value between 3 and 4 volts.

The maximum power that can be obtained from the capacitor is given by: [18]

$$P_{max} = \frac{V^2}{4 \cdot R} \qquad \text{(eq 30)}$$

where V is the nominal voltage of the capacitor R is the equivalent series resistance (ESR) in ohms. The equation above is derived from the matched resistance of the load this means that the efficiency of the charged and discharged power will be about 50% [16]. Hence, if the super capacitor should deliver high amount of power there will also be huge amount of losses that needs to be taken care of which will require cooling system of considerable size. Therefore it is important, not only from the size of the cooling system, but also from efficiency point of view, to have another approach in determining the size of the capacitor bank. The charge/discharge power as a function of the efficiency is:

$$\boldsymbol{P = \frac{9}{16} \cdot (1 - \eta) \cdot \frac{V_o^2}{R}} \qquad \text{(eq 31)}$$

where V_o is the rated voltage of the super capacitor.

4.1.2.2 Modelling the super capacitors

To perform a simulation study, super capacitors needs to be modeled as an equivalent circuit. In the literature different models have been proposed and analyzed. In [20] an approximate schematic circuit diagram is given, see Figure 20.

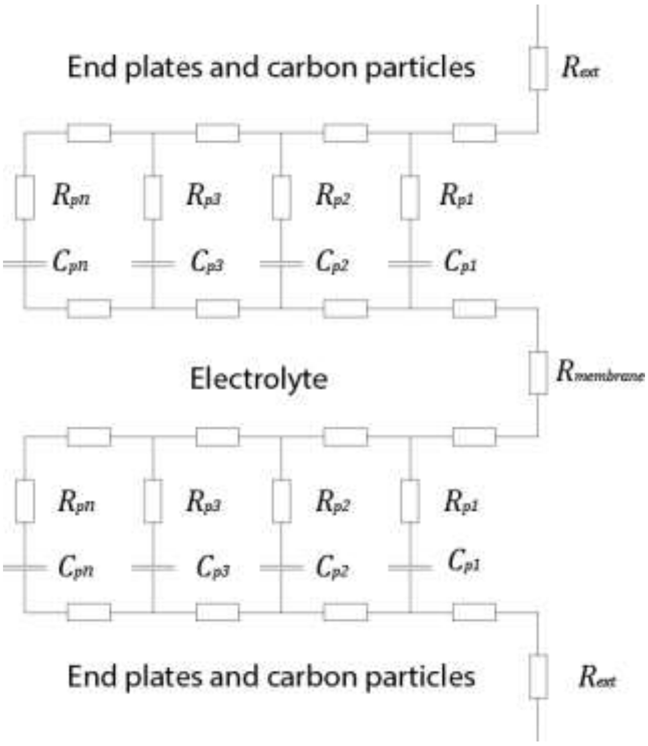


Figure 20 Approximate equivalent RC-circuit of a super capacitor [21].

This diagram tries to describe a millions of tiny pores in the capacitor that are connected in parallel. As these pores varies in size so will the capacitance of each pore, furthermore each pore is accompanied by a resistance which will be dependent on the size of the pore and its position in relation to the external circuit. Due to the existing symmetry on both sides of the membrane, two equal circuits can be connected in parallel through a resistance $R_{membrane}$.

The resistance $R_{membrane}$is a function of the porosity of the membrane, and as such it can be determined through the measurements. $R_{external}$ is the resistance of the external circuit, thus it can easily be determined and controlled. Because of many capacitances and resistances, the circuit described above is useful for understanding and theoretical discussions. However, it is very difficult to model the circuit, thus there is a need for simpler model with good enough accuracy.

In [22] a simplified model, with only one branch consisting of R and C in series, was investigated and compared with the measurements. The simulation results and the results obtained from measurements were not in satisfying agreement to each other, mostly because the self-discharge component of the capacitor was not modelled in the equivalent circuit [22]. In order to improve the model, a resistance was added in parallel to the capacitance. After tuning of the circuit parameters, this model was found to have good enough accuracy. However, the model lacks some dynamic properties of a super capacitor.

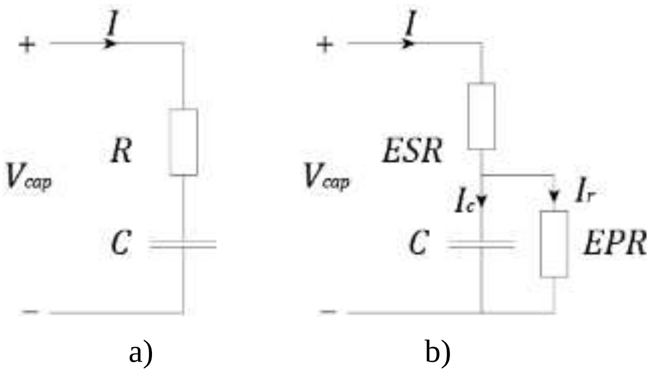


Figure 21 Simple equivalent models of a super capacitor, a) simple model b) model with equivalent series resistance (ESR) and equivalent parallel resistance (EPR).

In [23] two different models are described, one which is quite similar to the R-C model already mentioned. The capacitance however, is not constant, instead it varies linearly with the voltage. Thus if the dynamic response is not of high importance and the problem consider only the amount of energy stored in the capacitor, this model is suitable.

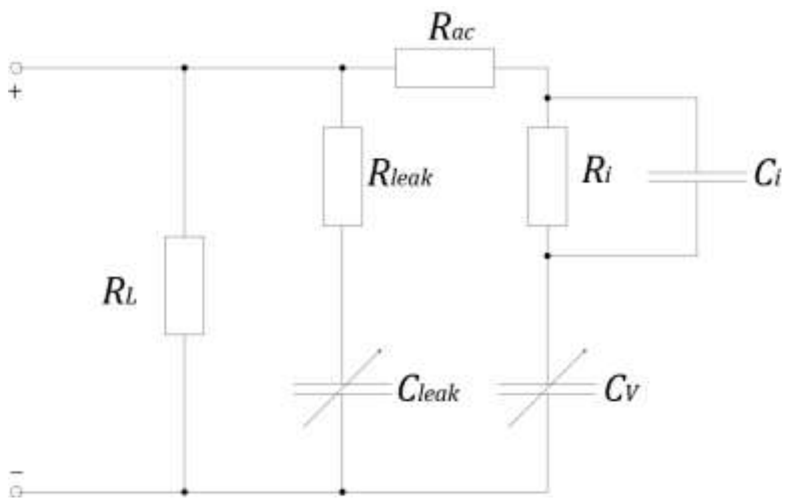


Figure 22 Lumped parameter model of the double layer capacitor (super capacitor) [23].

The second model described, takes into account the frequency dependency, including AC resistance and redistribution of the charge within the super capacitor.

This model allows for the self-discharge of the capacitor as well. The input parameters to the model, that allows adaptions of the circuit to a real double layer capacitor, are given below. These parameter are either obtained from the measurements or can be based on the known approximations related to a typical double layer capacitor:

V_{dc}: rated voltage of the capacitor.

C_{dc}: capacitance rated voltage.

k_c: voltage dependant capacitance (F/V)

R_{dc}: DC resistance

R_{ac}: AC resistance

f_{ac}: AC resistance crossover frequency

I_L: leakage current

r_{cleak}: leakage capacitace as a ratio of total DC capacitance

t_{leak}: time constant of short-term leakage effect

The voltage dependent capacitance in the model is divided into two components, the leakage component C_{leak} given by:

$$\boldsymbol{C_{leak}(v) = k_{leak} \cdot V_{dc}} \qquad \text{(eq 32)}$$

and the C_v which represents the main component and:

$$\boldsymbol{C_v(v) = C_0 + k_v \cdot V_{dc}} \qquad \text{(eq 33)}$$

In the equations above k_v and k_{leak} constants are related to the input value k_c and are calculated from the following equations:

$$k_{leak} = \frac{C_{dc} \cdot r_{cleak}}{V_{dc}} \qquad \text{(eq 34)}$$

$$C_0 = C_{dc} - k_c \cdot V_{dc} \qquad \text{(eq 35)}$$

$$k_v = k_c - k_{leak} \qquad \text{(eq 36)}$$

The resistance R_{leak} together with the leakage capacitance C_{leak} represents the short term leakage behavior, where leakage resistance is given by:

$$\boldsymbol{R_{leak} = \frac{t_{leak}}{C_{leak}}} \qquad \text{(eq 37)}$$

From Figure 22 it can be observed that the resistance R_i, which is the difference between the DC and AC resistances, is in parallel with the capacitance C_i, which in turn is in series with the resistance R_{ac} and the main capacitance C_v. Hence, for high frequencies the capacitance C_i will act as a short circuit and for lower frequencies the AC and DC resistances will add to each other. The R_i and C_i are given bellow.

$$R_i = R_{dc} - R_{ac} \qquad \text{(eq 38)}$$

$$C_i = \frac{1}{2\,\pi \cdot f_{ac} \cdot R_{ac}} \qquad \text{(eq 39)}$$

Table 4-Parameters for two super capacitors [23].

DC capacitance	C_{dc}	2600 [F]	1500 [F]
Rated voltage	V_{dc}	2.5[V]	2.5[V]
Voltage-dependant capaci.	k_c	250 [F/V]	150 [F/V]
DC resistance	R_{dc}	0.6 [mΩ]	1 [mΩ]
AC resistance	R_{ac}	0.33 [mΩ]	0.47 [mΩ]
AC crossover freq.	f_{ac}	5 [Hz]	10 [Hz]
Leakage current	I_L	5 [mA]	3 [mA]
Leakage capacitance factor	k_l	1/20 [-]	1/20 [-]
Leakage time constant	t_{leak}	33 [s]	33 [s]

The resistance R_L account for the DC-leakage current and is given by the following relation:

$$R_L = \frac{V_{dc}}{I_L} \qquad \text{(eq 40)}$$

For some typical super capacitors the parameter data is given in Table 4 above.

4.1.3 Flywheel

A flywheel energy storage, that stores energy mechanically, is an alternative to the electrical energy storage. It has been used for decades in various applications and in recent years in electromechanical applications in order to smooth the electric power demand. In [24] a flywheel has been suggested for a hybrid locomotive application. However, the flywheel is out of the scope for this report and will therefore not be considered and described in more detail in the following.

4.2 Combination of a super capacitor and a battery.

Recently a lot of research has been performed on combining batteries and ultra-capacitors [25] [26] [27]. The idea is to bring the best features of booth technologies together where the ultra-capacitor could take care of the short frequent and high power requirements while the battery could compensate for the less frequent and more steadily power requirements.

4.2.1 Connecting the battery and super capacitor

The simplest solution is to connect the battery and a super capacitor in parallel without any additional power control devices. This is illustrated in Figure 23. There are certain benefits with the connection shown in Figure 23, a certain reduction of the transient currents in and out of the battery [27] is obtained and the circuit solution is simple.

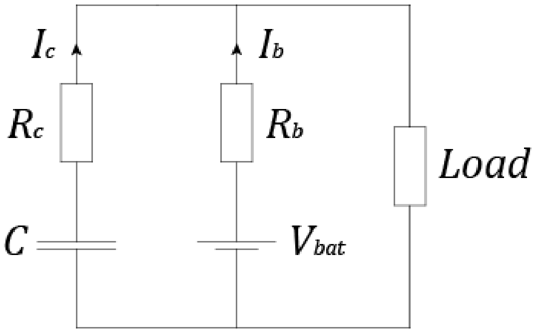


Figure 23 Parallel connection of super-capacitor and battery without any power control devices.

However, there might arise some problems, due to the physical operation principles of batteries and of super capacitors. The voltage of the super capacitor is directly proportional to the state of charge (SOC) and varies almost linearly from full charge to zero charge. Hence, the voltage of the capacitor and the voltage of the battery will vary in a different way as illustrated in Figure 24. As the voltage varies in a different way some of the energy will be transfered from the battery to the super capacitor causing additional losses. The best way to utilize the super capacitor is to combine it with a power control device like a DC/DC converter.

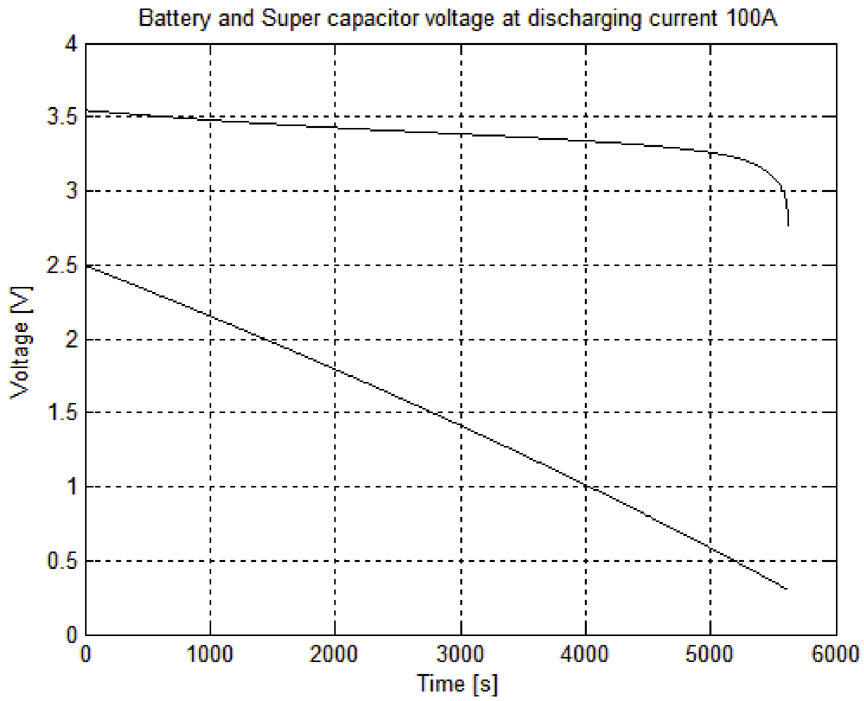


Figure 24 Simulation results of voltage variation of super capacitor and a Lithium-ion battery at constant discharge current of 100 A.

Eventually one can identify four different possibilities in the design layout of a hybrid vehicle equipped with both super capacitor and a battery, as illustrated in Figure 25 [28]. As mentioned in earlier chapter, one way is to connect the battery and the super capacitor directly to a DC-bus bar, as shown in Figure 25 a), without any control possibilities in energy/power flow from each of them. A second option is to connect either the super capacitors, Figure 25 b) or the battery, Figure 25 c) to a DC-bus through a DC/DC-converter. Lastly and the most flexible solution is shown in Figure 25 d), where a DC/DC converter is connected between the DC-bus and booth the battery and the capacitor.

The solution with two DC/DC converters is the most flexible one giving the opportunity to control the power flow booth from the battery and the super capacitor. In addition it will decouple the DC-bus voltages from the battery and the super capacitor voltage respectively.

The voltage of a single battery cell or a capacitor cell is quite low, thus in order to achieve a desired voltage a number of cells has to be connected in series. High DC-bus voltage is desirable as it will affect the sizing of other electrical components such as the electrical machines. For the same power rating, electrical machines with higher voltage will become smaller in size. With a DC/DC converter the sizing of the battery storage system will add another degree of freedom and the battery can solely be optimized for the energy and power requirements.

From the efficiency point of view it is beneficial to have as few energy conversion steps as possible, every conversion of energy implies some energy losses that results in a system with a lower efficiency. Thus, from the efficiency point of view adding the DC/DC converter may be seen as a disadvantage. However, the efficiency of the converter is relatively high, so the final efficiency of the system will not be affected too much.

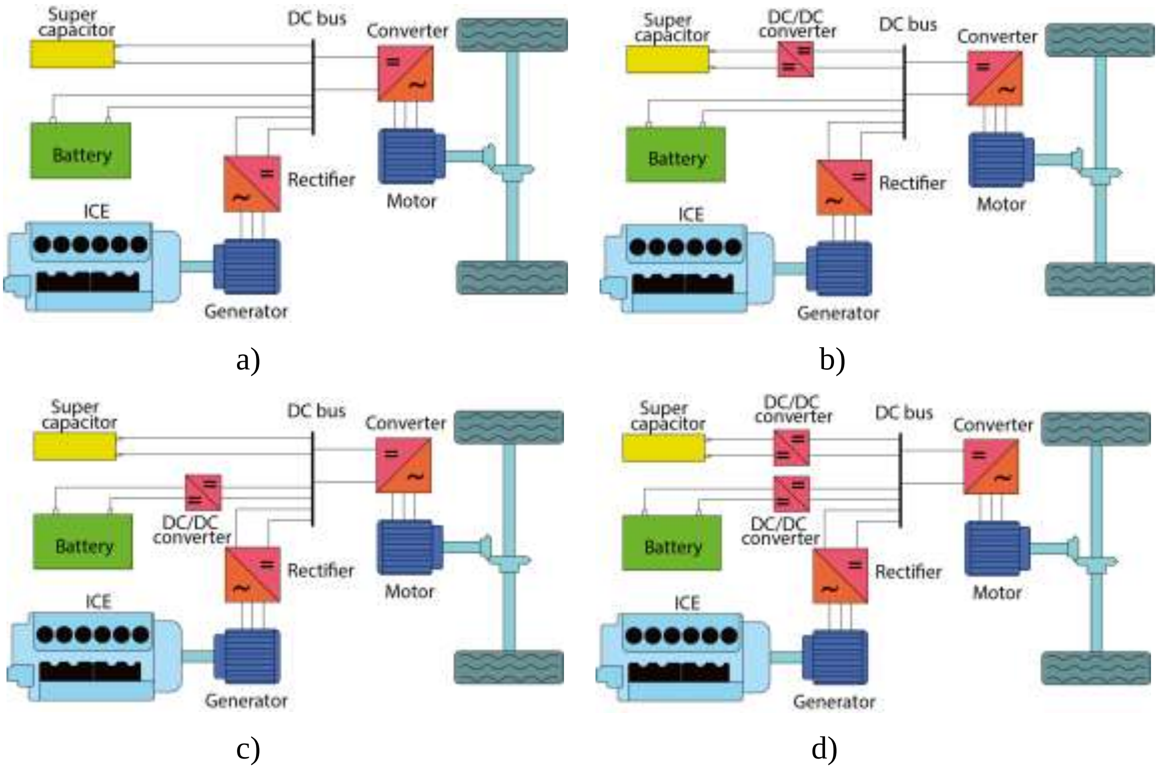


Figure 25 Different hybridization topologies with both the battery and the super capacitor incorporated.

Due to the reason discussed above, a solution with only one DC/DC converter may be considered as a useful compromise and as a suitable choice. However, one important question is where the DC/DC converter should be placed; between the battery and the DC-bus or between the super capacitor and the DC-bus. As the battery has more constant voltage across the operation interval the most suitable option is to place the DC/DC converter between the super capacitor and the DC-bus. In this way the utilization of the super capacitors would be increased.

4.2.1.1 Control strategy: Splitting Frequency

From the Ragone chart we can define the frequency response for different energy sources according to the expression:

$$f_p = \frac{\rho_p[\mathrm{W/kg}]}{\rho_e[\mathrm{J/kg}]} \qquad \text{(eq 41)}$$

where ρ_p is the power density and ρ_e is the energy density of an energy source [5] [6]. This is illustrated in Figure 26.

As mentioned in earlier chapter, the idea behind a combined energy storage with batteries and super capacitors is to let the super capacitor take care of the short frequent and high power demands and thereby letting the battery work with a more steady power demands. Thus, the power demand from a certain load can be filtered with the help of information in figure below.

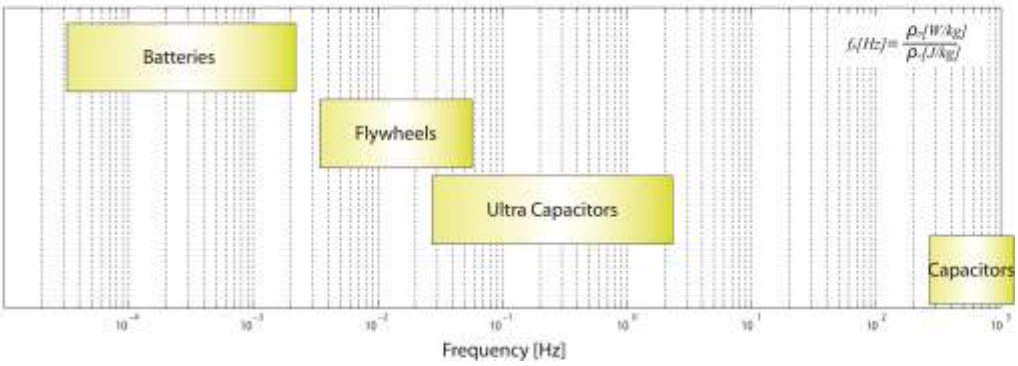


Figure 26 Frequency characteristic of different energy storage technologies [5].

A schematic view of a frequency splitting strategy in a locomotive is shown in Figure 27. Besides the energy storage consisting of super capacitors and a battery the locomotive is also equipped with a smaller ICE providing the power P_{ICE}. P_{LOC} is the power requirement from the load, which is processed through a low pass filter and split into, P_{SC} which is the power demanded from the super capacitor and P_{BAT} which is the power demanded from the battery.

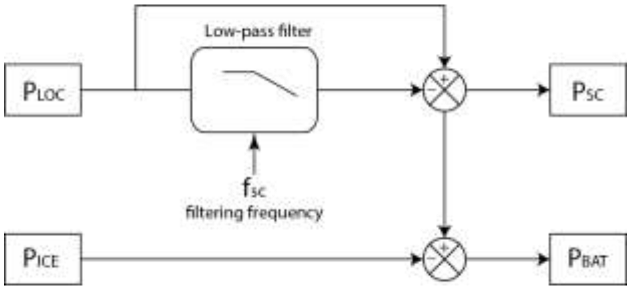


Figure 27 Schematic view of the frequency splitting energy management [24]

5. Simple analysis of the locomotive

Based on the data of the track provided in chapter 2 it can be noted that the Bulgarian route is the one that permits the lowest axle weight. The mass of the locomotive can be calculated if the number of axis is known:

$$m_{loco} = m_{axle} \cdot n_{axle} \qquad \text{(eq 42)}$$

where m_{axle} is the maximum axle load allowed on the track and n_{axle} is the number of axles on the train. Assuming that all axels in the locomotive are driving the adhesive mass then is the same as the locomotive mass.

$$m_{\alpha} = m_{loco} \qquad \text{(eq 43)}$$

Unlike passenger trains, where a low mass of the vehicle is an important issue this is not of any concern for a freight locomotive. Moreover a higher weight of the locomotive is actually desirable as the tractive force is directly proportional to the adhesive weight:

$$F = \alpha \cdot m_{\alpha} \cdot g \qquad \text{(eq 44)}$$

α in (eq 44) is the adhesion coefficient which depends on several factor. One is the available friction between the rail and the wheels and the other one is the slip control system of the vehicle. For modern vehicles with advance slip control, assuming dry conditions, this coefficient typically is in the range of or above $\alpha = 0.3$. In wet conditions the rail becomes more slippery, thus this coefficient becomes considerably lower. Generally speaking α is varying between 0.1-0.35.

Assuming the adhesion coefficient to be $\alpha = 0.3$ and the constant of gravity $g = 9.81$ Table 5 summarizes the tractive force with respect to different number of driving axles. It should be mentioned that the lowest permissible value for the axle load on the track has been used, i.e. for the Bulgarian track 22.5 tonnes.

Table 5 The usable force in a locomotive with different number of driving wheels.

n_{axle} [ ]	2	4	6
F [N]	132435	264870	397305

The force in the table above is the useable force in a locomotive, i.e. although the tractive system of the locomotive could provide even higher force it would only result in spinning of the wheels. According to the equation (eq 1) the force produced by the propulsion system should be high enough to overcome the running resistance but also to provide enough force for acceleration of the train. The acceleration of the train is then given by:

$$a = \frac{\alpha \cdot g \cdot m_\alpha - D}{m_a} \quad \text{(eq 45)}$$

5.1 Acceleration

According to the Deliverable in Work package 2.4 there is no exact requirement on the acceleration performance of the freight train. Instead the regulation from each country should be followed where the speed and acceleration requirement are well defined.

5.2 Traction motors

Electrical motors can be divided into several different types. The first classification is DC and AC motors depending on the voltage they are connected to. One of the big differences is that the DC motors require a mechanical commutator with copper segments and brushes applied to these segments. The commutator is exposed to substantial wear and thus a related maintenance cost.

5.2.1 DC motors

DC machine were very popular as a traction motor in early years of electrified railways. The most important reason is the simplicity of the speed control.

Figure 28 An example of a DC-machine with a commutator and brushes shown inset in the top right corner.

However, with the introduction of power electronic converters the control issues of the electrical machines started to become relatively easy even for AC machines. Hence, the induction machine started to gain in popularity as traction machine.

5.2.2 AC motors

There are number of different topologies for AC machines, among them the most interesting ones for traction purposes are induction machines and permanent magnet synchronous machines (PMSM).

5.2.2.1 Permanent magnet synchronous motors

Permanent magnet machines are, as the name indicates based on permanent magnets. These types of machines are recognized for high efficiency and high power density. The rotor of the machine rotates synchronously with the rotating magnetic field, thus the machine is sometimes called as synchronous permanent magnet machines.

Usually the magnets are mounted on the rotating part, in order to avoid any brushes, which is the case when the current needs to be transferred to a rotating part. Depending on the application the rotating part can be more conventional inner part, inner rotor machine but also the outer part as outer rotor machine. Both types have certain advantages and disadvantages, cooling capabilities of the machine as well as the centrifugal forces acting on the magnets are some of the issues.

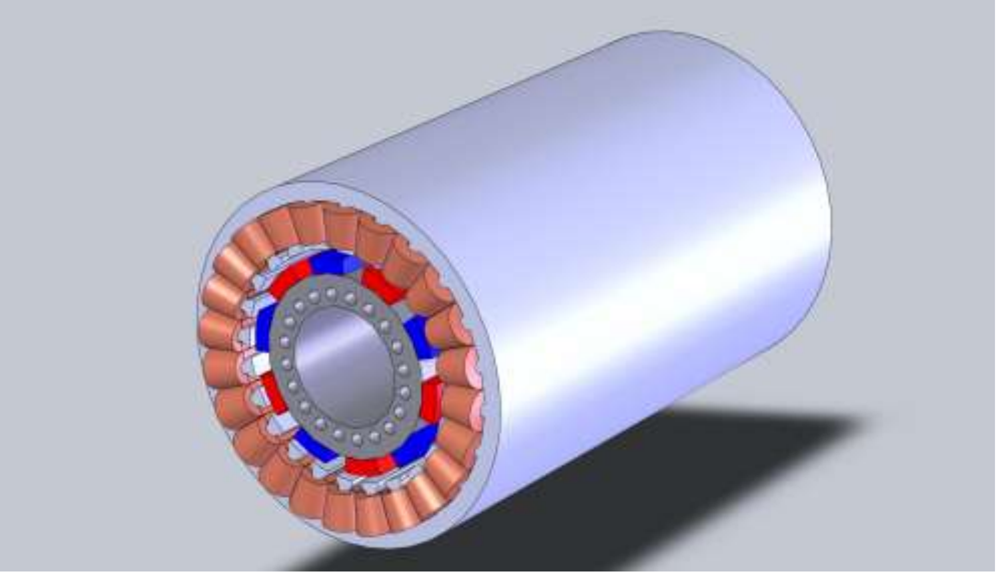
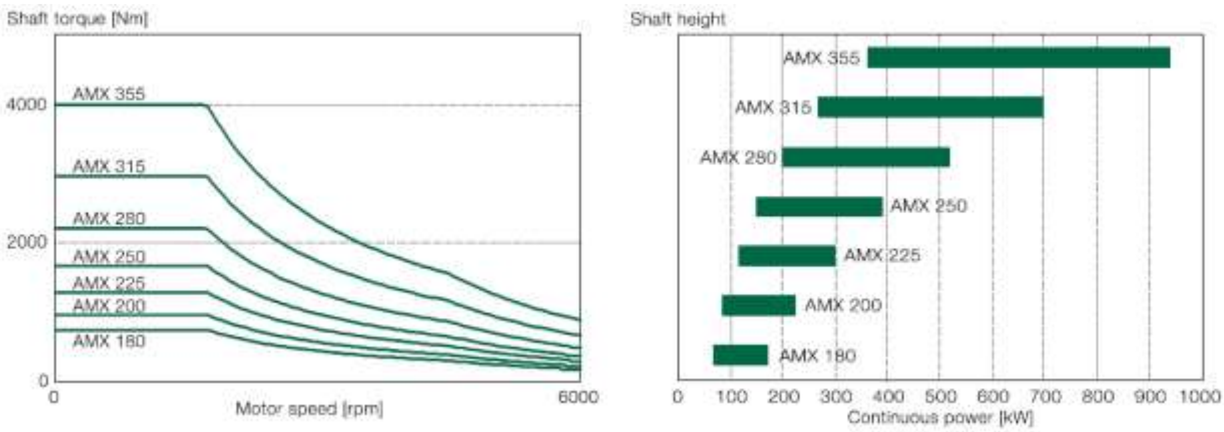


Figure 29 Permanent magnet machine with surface mounted magnets and concentrated winding design.

5.2.2.2 Induction motors

The secret of the induction machine lies in the operational principle, a magnetic rotating field created by the stator voltage induces voltages in the rotor that enables the current flow and thereby the torque production. The speed of the rotor always lags the speed of the rotating field, otherwise there will be no torque production, and it is also sometimes referred to as an asynchronous machine. Compared with the permanent magnet machines it has lower efficiency and lower force density; however it is less expensive and more robust.



a) **b)**

Figure 30 ABB modular induction traction motor [29].

Generally the motors can be design according to the specification on nominal torque, voltage and operational speed in order to meet the requirements in the best possible way. However, this will usually result in a higher cost. Another possibility is to use more standardized components provided by different manufacturers. Figure 30 shows an example of a modular induction traction motor available on the market.

Based on the information from the figure a simple analysis can be performed in order to choose a suitable traction motor.

As mentioned earlier the maximum desired speed of the prescribed future locomotive is 140 km/h, which corresponds to approximately $v_{max} = 39$ m/s. This speed corresponds to the maximum speed of the traction motor divided by the gear ratio. Looking at the Figure 30 a) it can be observed that the maximum speed of the machine is $\omega_{maxmotor} = 6000$ rpm. The maximum speed of the wheels can be calculated according to:

$$\omega_{maxwheel} = \frac{v_{max}}{\pi \cdot D_{wheel}} \cdot 60 \qquad \text{(eq 46)}$$

where $\omega_{maxwheel}$ is the maximum rotation speed of the wheels, D_{wheel} is the diameter of the wheel and v_{max} is the maximum speed of the locomotive. The suitable gear ratio then is:

$$k = \frac{\omega_{maxmotor}}{\omega_{maxwheel}} \qquad \text{(eq 47)}$$

The torque that can be obtained at the wheels is calculated from:

$$T_{wheel} = n_{axle} \cdot k \cdot T_{motor} \qquad \text{(eq 48)}$$

And finally the tractive effort, that is the tractive force of the locomotive is found as:

$$F = \frac{T_{wheel}}{\frac{D_{wheel}}{2}} \qquad \text{(eq 49)}$$

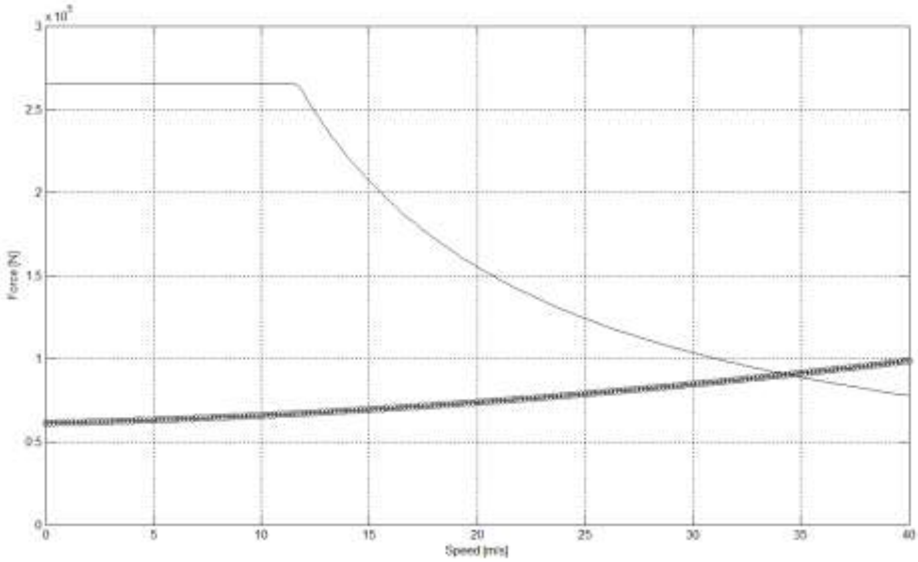


Figure 31 Force-speed profile for a locomotive based on a BoBo configuration with all axle's powered $m_a = 940$ tonnes, locomotives front area $A = 12$ m², side wind speed $v_w = 4$ m/s and a gradient of $S = 5$ ‰.

In the figure above the solid line represents the tractive force of the locomotive while the line with the circle markers (-o) represents the running resistance at a gradient of 5 per mile. The total power of the traction motors is approximately 3.1MW. As seen from the figure, the locomotive will not be able to run at maximum speed at this gradient.

It should be mentioned that the gradient resistance is the major contribution to the total running resistance for freight trains. If the requirement is that the locomotive should be able to run with maximum speed at this gradient, the power rating of the traction motors needs to be increased.

5.3 Dimensioning of the battery

An important issue when designing the battery is the voltage. If a DC/DC converter is used the voltage can be chosen relatively freely. However, too low voltage would result in big and bulky DC/DC converter. Generally the voltage levels of a DC bus in hybrid vehicles can be used as guide target. The voltage levels lies between 250- 600 V.

Another approach would be DC-voltage levels available in electrified railways. Choosing a voltage corresponding to the grid voltage could benefit the system as it makes it possible to reduce the number of components. The grid voltage could be connected directly to the DC-bus without any converter in between.

As described earlier DC-voltage levels of 750 V, 1500 V and 3000 V exist in Europe. The 3000 V level is not suitable as the battery would need many cells in series and become large and bulky. Generally, levels above 1000 V are classified as high voltage and requires thicker insulations, thus there probably exist fewer standardised components on the market. BY choosing a voltage of 750 V, and considering lithium-ion batteries, the number of cells in series will be:

$$n_{cellb} = \frac{750}{3.6} \qquad \text{(eq 50)}$$

Where the 3.6 is the cell voltage of a lithium-ion battery cell at 50% of SOC level. The next step is to make sure that the battery can provide the adequate power to the system. Using (eq 15) and rearranging it, the total resistance of the battery can be obtained as:

$$R_{totb} = \frac{P_{battery}}{\eta \cdot (1-\eta) \cdot V_0^2} \quad \text{(eq 51)}$$

The number of parallel strings can then be obtained from:

$$n_{parallelb} = n_{cellb} \cdot \frac{R_{cellb}}{R_{totb}} \quad \text{(eq 52)}$$

For the example above where the power is 3.1MW we would need 208 cells in series and 13 in parallel assuming battery efficiency of 90% and with the cell inner resistance of $R_{cellb} = 0.001$ ohm.

Here it should be mentioned that the sizing procedure described above is quite simple and have assumed that the battery charging and discharging capabilities are the same. This is however, not true for all battery models, thus a more advance method then has to be applied.

5.4 Dimensioning of the super capacitor

When designing the capacitor, it is assumed that the capacitor is connected to the DC-bus through a DC/DC converter. Thus, the voltage of the capacitor is chosen to 500 V. The voltage level will determine the number of cells that needs to be connected in series and thereby it will indirectly determine the size of the whole capacitor energy storage. In addition the size of the capacitor will also be affected from the power requirement which will determine how many cells that needs to be connected in parallel. The number of super capacitor cells in series is given by:

$$n_{cellsc} = \frac{500}{2.5} \quad \text{(eq 53)}$$

Using (eq 31) and after some rearrangement gives:

$$R_{totsc} = \frac{16}{9} \cdot \frac{P_{supercapacitor}}{(1-\eta) \cdot V_o^2} \quad \text{(eq 54)}$$

The number of cells in parallel is then given by:

$$n_{parallelsc} = n_{cellsc} \cdot \frac{R_{cellsc}}{R_{totsc}} \quad \text{(eq 55)}$$

From (eq **53**) we can see that there will be 200 cells in series and after insertion of $R_{cellsc} = 0.0006$ ohm and a power demand of 3.1MW it is obtained that only one string of super capacitors is needed. However, if there is an energy requirement as well, this needs to be investigated further.

5.5 Simple Simulink model

In order to illustrate the frequency splitting approach a simple Simulink model was developed and used. The Simulink model is shown in Figure 32.

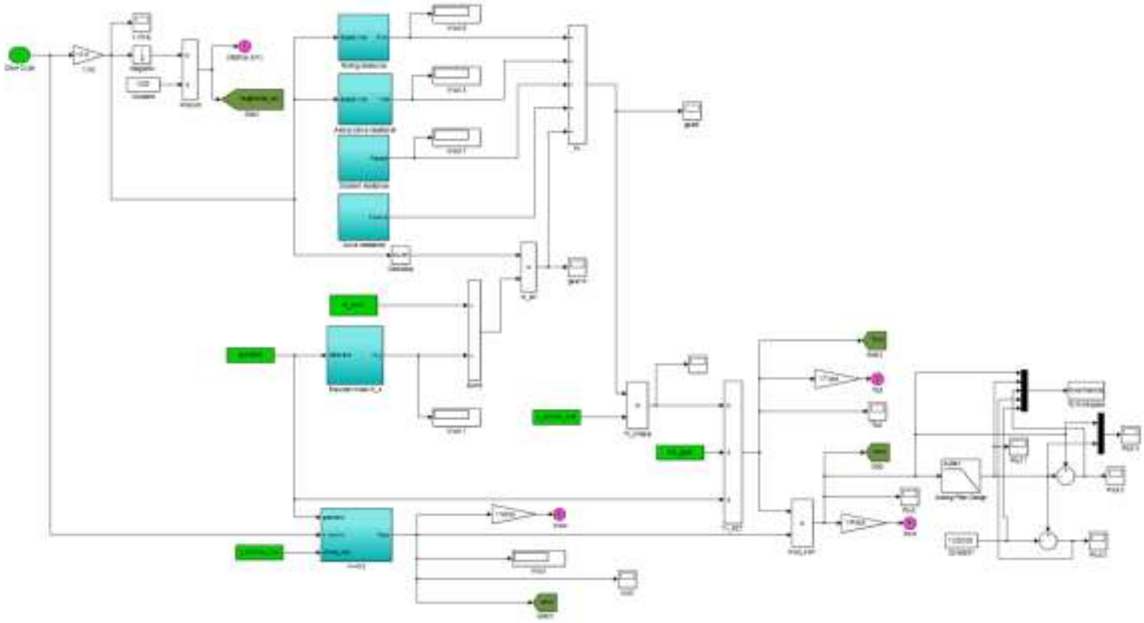


Figure 32 Simulink model on Vehicle performance BoBo configuration with all axle driving.

Due to the lack of information regarding the specific load speed profile, the load speed profile, FTP 72, shown in Figure 33, has been studied. FTP 72 is normally used in the car industry.

Thus, the acceleration demand and thereby the power demand will be way off the requirements that are used for the freight locomotive. However, the results obtained are still good for better understanding and for highlighting some of the issues.

As shown in Figure 34, power requirement reaches up to 15 MW with a slope of 1 ‰ and $m_a = 940$ tonnes.

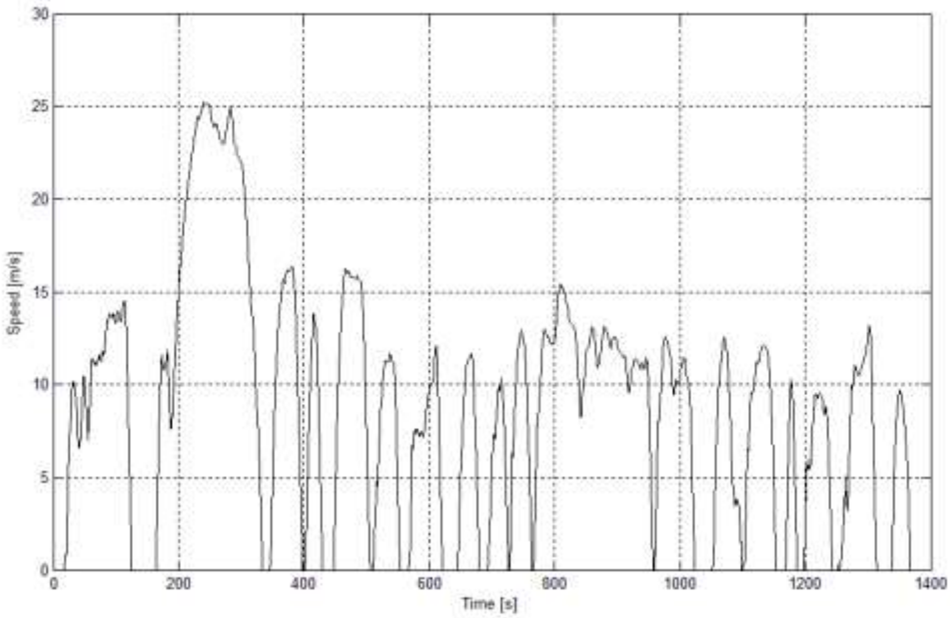


Figure 33 FTP 72 speed-time profile.

As mentioned these figures are only for purposes of better understanding and do not represent the actual case. The power demanded by the load cycle, goes through a low pass filter with a cut of frequency corresponding to the battery response shown in earlier chapters, which is approximately 3-4 mHz. It should be mentioned that the cut of frequency is quite low, a more careful analysis need to be performed in the future.

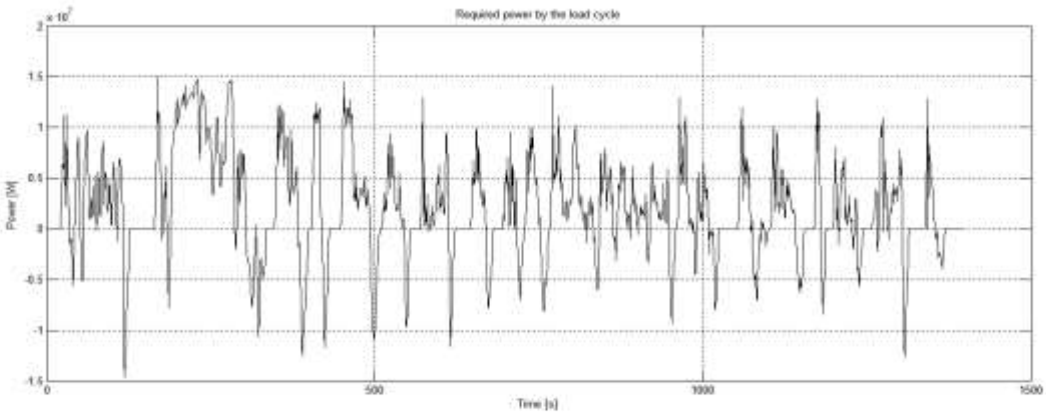


Figure 34 Power demand from FTP 72 load cycle.

Figure 35 shows the power demanded by the three different sources the ICE, the super capacitor and the battery. The ICE operates continuously with a rated power of 1 MW while the rest of the power will come from the battery and the super capacitor.

For the simulations, only simple control method has been used. In a more realistic case the control method needs to consider the battery and the super capacitor SOC-level and adapt the frequency cut of frequency accordingly. Another issue is the phase shift of the power demanded by the battery caused by the low pass filter.

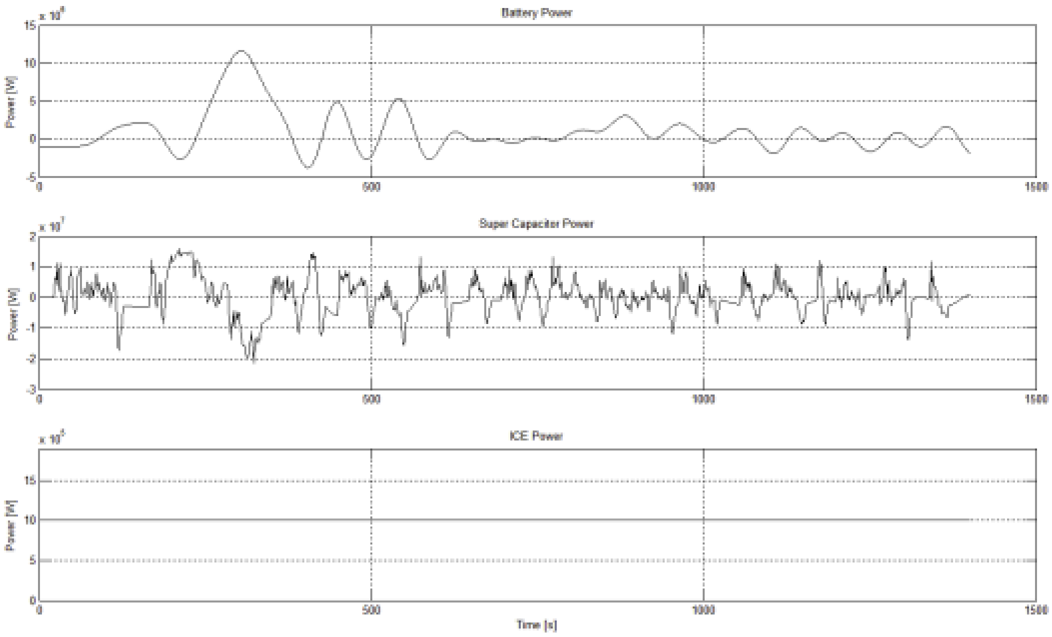


Figure 35 Splitting the power demand between the ICE, the Super Capacitor and the Battery.

An advantage with hybridization of the vehicle is the possibility to downsize the ICE as the peak power demands will be covered by the battery or the super capacitor. However, the size of the ICE and a generator in a diesel electric locomotive is quite substantial leaving the space for yet another step. Instead of having only one ICE- generator unit, they can be split into several smaller units. This is already done in so call Genset locomotives described earlier. Figure 36 illustrates a hybrid locomotive with several smaller ICE-generator units.

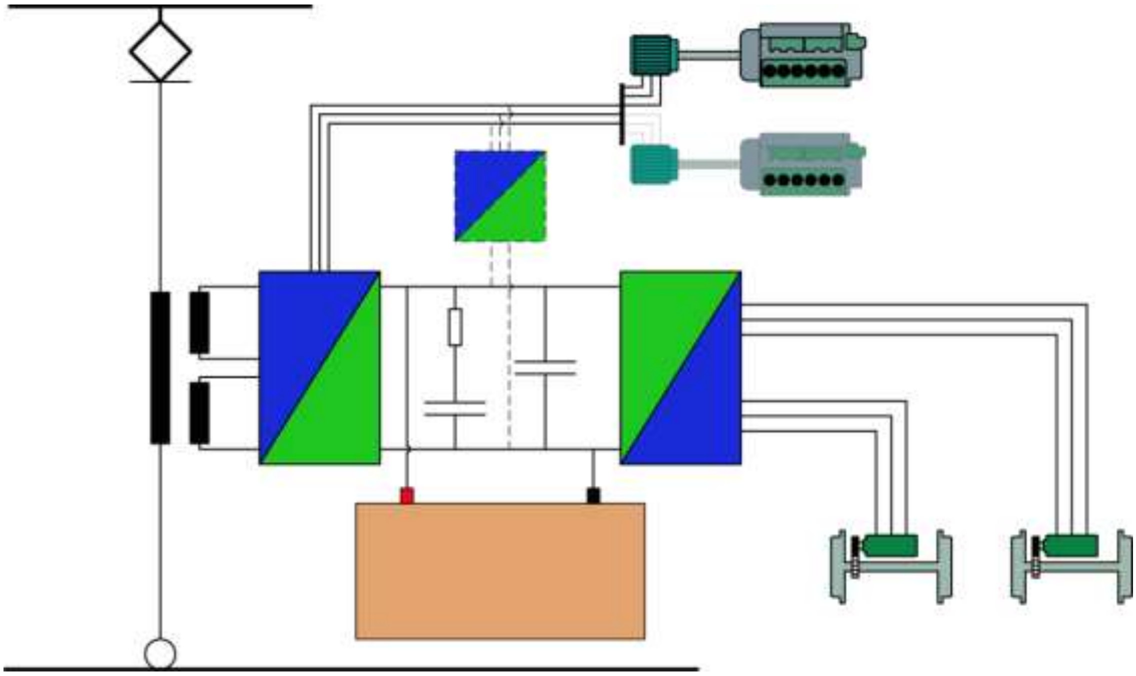


Figure 36 Several smaller ICE-generator units in a hybrid locomotive.

An advantage of having smaller units is that more standardized ICE:s could be used most likely truck engines. As the genset units already shows some improvement in the efficiency this would be a benefit. Furthermore this would probably result in a less expensive and more flexible system. However, this would certainly require a more sophisticated control method which may be seen as a drawback.

The maintenance intervals of truck diesel engines are much shorter than those for trains but on the other hand maintenance is simpler and less expensive. Since the trains are supposed to use electric power for substantial parts of their operation the time between maintenance can be kept acceptable.

The simple design procedure can be summarized according to the following flowchart.

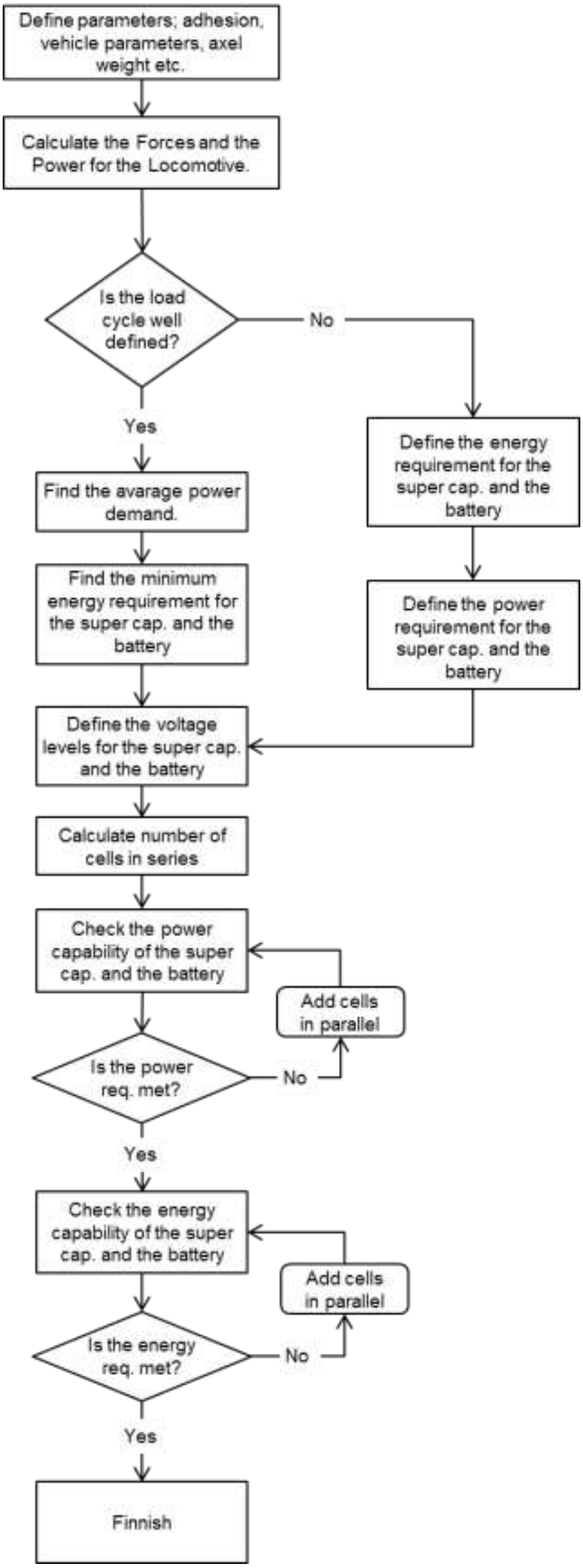


Figure 37 Flowchart diagram.

6. CONCLUSIONS AND FUTURE WORK

When it comes to hybridization of a certain vehicle the obvious question is do we need to do it and what are the benefits? What are the challenges and what is the cost? There are several reasons that are pushing for the development, governmental legislations but also the competiveness of the market just to mention some.

For a freight locomotive a higher efficiency is definitely an issue, as for other types of hybrid electric vehicles, the issue whether the efficiency can be increased or not is strongly related to the load cycle and the way the locomotive is operated.

In lack of a real load cycle usually there are well defined test cycles which are used for benchmarking and comparison of different technologies. In [30] different test cycles were evaluated and compared to the real measurement data, where a large discrepancy was found between the results in field and the results obtained from the load cycle. This indicates that optimization of a vehicle is difficult and more detailed specifications needs to be defined in order to make an appropriate design.

The modular approach where the super capacitor and the battery and genset unit (ICE+generator) are of the same physical size could be a solution to some of the issues. In this way if the locomotive is going to be used as a switcher a more suitable design would be with higher battery power/energy rating and lower rating of the Gen-set units. However, if the locomotive is going to perform more as a main line freight locomotive covering larger distance with relatively constant power requirement would require several more Genset units and less batteries and super capacitors. A modular approach would also benefit from the use of more standardized combustion engines used e.g. in heavy trucks.

Genset units have already shown good results and are available on the market today. However, these locomotives are primarily used as a switcher units with lot of idling and it is not evident how they would perform as more profiled freight locomotives with more constant power demand.

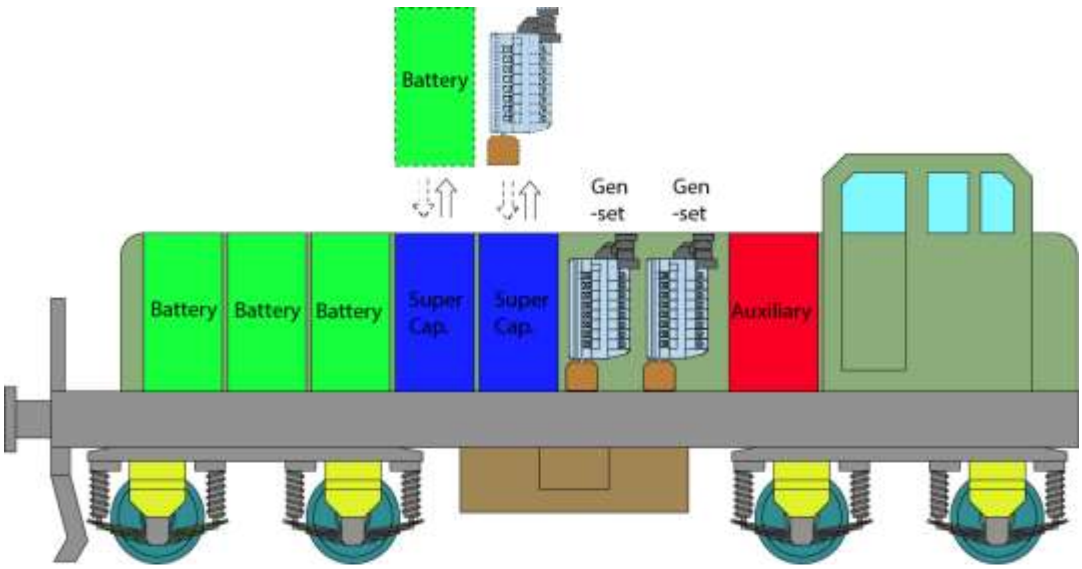


Figure 38 Schematic view of a locomotive in a modular design approach.

In this case, within frame for a modular approach, a couple of smaller Gen-set units could be replaced by a bigger one.

Concerning the maximum speed of the freight train there is a desire to increase the speed from typically 120 km/h to 140 km/h. One of the reasons is to harmonize the freight traffic with the passenger traffic which usually operate at higher speeds. This would be of a great benefit to the line operators as they could utilize the track more effectively. Yet another benefit is of course an increase in capacity of the freight traffic, thus making the railway freight more competitive compared to other solutions, especially compared to the roads.

6.1 Future work

Find a realistic solution in terms of size and weight of the battery and super cap. In this report only some simple analyses are performed in terms of power and energy rating. For future work it is evident that booth the physical size and the cost has to be investigated as well.

Further investigations on benefits of using several smaller diesel engines instead of having only one are necessary. Some load cycles, i.e. where the railways are not electrified, may require higher and more constant power demand. An interesting question is what would be more efficient several genset units or one big unit.

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