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# Practical Application of Electrical Energy Storage System in Industry

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## 1. Introduction

### 1.1 Industry application of ESS

Storing of energy allows balancing of the supply and demand of energy. Today, the energy storage system (ESS) in commercial use can be broadly categorized as mechanical, electrical, chemical, biological and thermal. In further we will discuss electrical and partly mechanical system. Accumulation of electrical energy presents a big problem solved by a lot of specialists and scientists. Many ways of accumulation has been put into practice (for example: systems using flywheel, battery, supercapacitor etc.). Today commonly used vehicles of light traction (trams, trolleybuses) are not able to accumulate their kinetic energy. Saving of this energy is possible only by regenerative braking. This method is possible when another tram starts up on the same part of trolley line. Nowadays electrical energy storage system can be found in transport vehicles and in power engineering systems. In general the energy-storage devices charge during low power demands and discharge during high power demands, to provide energy boost when needed.

Carbon emissions, the depletion of natural resources by fast consumption, traffic congestion and the rising costs of fossil fuels are all issues pushing the world to search for alternative means of transportation. Mass-transit buses, fleet vehicles, long-haul trucks and other heavy-transportation vehicles such as trains, light rails, trams and subways, all benefit from the using of a hybrid power drives in relation to the energy storage system. The global number of vehicles around the World will triple in the next 50 years (Chan & Wong, 2004). Thus, methods of improving fuel economy have gained worldwide attention. The efficiency and all-electric range (AER) of hybrid electric vehicles (HEVs) depend on the capability of their energy-storage system (ESS), to store large amounts of energy and release it quickly according to load demands.

In transport ESS allows accumulation of the braking energy in conventional vehicles and special racing vehicles such as Formula 1. The kinetic energy is accumulated into the ESS during vehicle braking. This energy can be used to the vehicle acceleration again. It is important to save the energy in the vehicles accelerating very often such public transport vehicles (we can think about stabile or mobile version according to the local specific conditions).

Heavy transportation vehicles - such as trains, trams and subways - place particular demands on energy storage devices. Such devices must be very robust and reliable, displaying both long operational lifetimes and low maintenance requirements. Further, the devices must operate efficiently under harsh conditions including handling peak currents, high duty cycles and frequent deep discharging.

ESS can absorb and store all kinetic energy from a braking system, depends on total energy designed in ESS. The emission-free stored electrical energy in ESS is then available to assist in acceleration, to reduce fuel consumption and accompanying emissions or energy drain, as well as drive the air conditioner, operate power steering or perform other electrical functions. As an added bonus, regenerative braking takes most of the mechanical brakes load off, reducing brake maintenance and replacement expenses.

Very important area of ESS is power engineering where the ESS covers small to large rated power range, including active PFC used to set the appropriate power factor and harmonic emission to the power grid.

The important characteristics of ESSs include energy density, power density, lifetime, cost, energy storage time and maintenance (see Fig. 3 and Fig. 4). Currently, batteries and ultracapacitors are the most common options for vehicular ESSs. Batteries usually have high energy densities and store the majority of onboard electric energy. On the other hand, ultracaps have high power densities and present a long life cycle with high efficiency and a fast response for charging/ discharging (Burke, 2007; Khaligh & Li, 2010; Zhang et al., 2008; Lu et al., 2007). A fuel cell (FC) is another clean energy source (Fig. 1 and Fig. 2); however, the long time constant of the FC limits its performance on vehicles. Very perspective ESS shows the flywheel system with low cost benefit and high energy density. However using flywheel in the transport is a bit disputable due to gyroscopic effect. Nevertheless for stationary systems the ESS with flywheels presents perspective topology with respect the low energy storage time (Fig. 4), this system cannot be used as back up power source as batteries and ultracaps.

Fig. 1. City bus powered by Fuel Cells (TriHyBus.cz, 2008).

Fig. 2. Detail on fuel cells, the ESS is composed of Li-ion battery and supecapacitors (TriHyBus.cz, 2008)

As design engineers have found, batteries have high-energy capability while the ultracapacitors have high power capability. In an optimal hybrid alternative drive system, both technologies could be combined in a way that maximizes the benefits of both. In general vehicles have batteries to provide energy back up for control systems, start engine etc.
The ESS of most of the commercially available HEVs is composed of only battery packs with a bidirectional converter connected to the high-voltage dc bus (the Toyota Prius, Honda Insight, and Ford Escape).
Start-stop technology enables the engine in conventional, electric or hybrid-electric delivery trucks and refuse vehicles to shut down when they come to a stop at a red light, picking up or dropping off passengers, or when sitting in traffic. ESS then provides a short burst of energy that restarts the motor. ESS can save millions of barrels of oil over conventional gasoline-only powered vehicles.

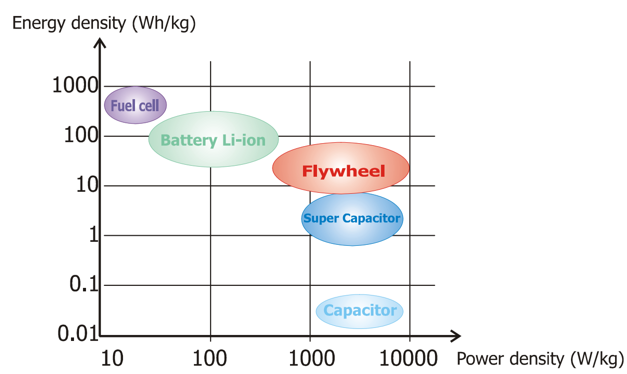


Fig. 3. Comparison of several ESS due to energy and power density

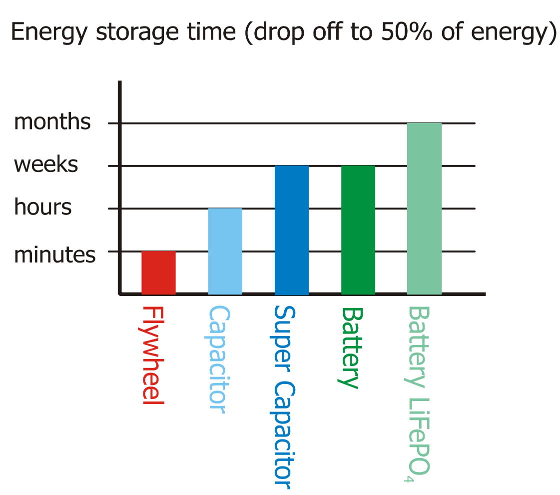


Fig. 4. Comparison of Energy storage time of several ESS

## 2. Battery

Batteries have widely been adopted in ground vehicles due to their characteristics in terms of high energy density, compact size, and reliability (Lukic et al, 2008).
The Batteries have a very wide field of applications in systems for the electrical ESS. They are used in stationary systems, as short time power sources (eg UPS).The other applications are in transport, used as the main source (eg, full-electric vehicle), or as the secondary sources (for covering of peak powers combinated with FC) - the main advantage is their

ability to accumulate electrical energy during braking. The batteries bonus proprieties are high energy density, excellent energy storage time and reliability. There must calculated with the fact that batteries are limited by operating temperature and exhibit the lower power density compared to the other electric ESS. Very important parameter of the battery is the price, that depends closely on the battery type. Among the other monitoring proprieties (batteries used in industry) there are charging and discharging currents, life time / cycles.

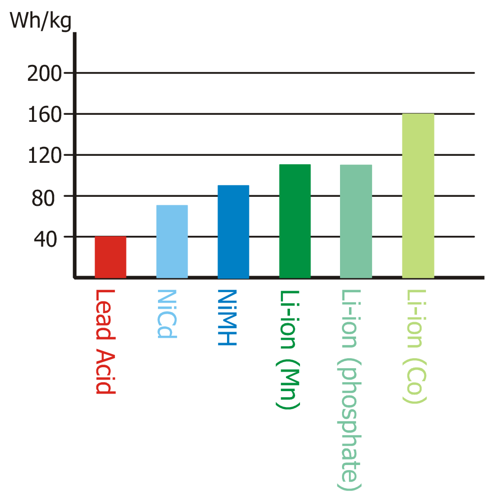


Fig. 5. The dependence of Energy density on battery weight

*The basic types of batteries used in industry and their specifications are:*

**Lead–Acid Batteries**

These types of batteries are composed of the spongy lead works as the negative active material, lead oxide is the positive active material, and diluted sulfuric acid is the electrolyte. During discharging, both materials (positive and negative) are transformed into lead sulfate (Williamson et al, 2005). The lead–acid battery presents several advantages for HEV applications. They are available in production volumes today, yielding a comparatively low-cost power source. In addition, lead–acid battery technology is a mature technique due to its wide use over the past 50 years. However, the lead–acid battery is not suitable for discharges over 20% of its rated capacity. When it operates at a deep rate of state of charge (SOC), the battery would have a limited life cycle.

These batteries are still one of the most popular for its low price. The disadvantage of this battery is using of toxic lead and very low charging currents for ESS.

**Nickel–Metal Hydride (NiMH) Batteries**

The NiMH batteries use an alkaline solution as the electrolyte. The battery is composed of nickel hydroxide on the positive electrode and the negative electrode consists of an alloy of vanadium, titanium, nickel, and other metals. The components of the battery are harmless to the environment; moreover, the batteries can be recycled. The advantages of these batteries are long lifetime, wide operating temperature ranges and the resistance to over charge and over discharge. The batteries should not be repeatedly discharged by high load currents, because the lifetime of battery is reduced to about 200 cycles. Another disadvantage is the battery memory effect.

**Lithium-Ion Batteries**

These types of batteries are characterized by high energy density and low memory effect. The Li-ion battery uses an oxidized cobalt material as a positive electrode, the negative electrode is made of a carbon material and lithium salt in an organic solvent is used as the electrolyte. The advantages of these batteries are high energy density of 120 Wh/kg, high power density of 300 W/kg, long battery life of 1000 cycles, low memory effect and environment harmless. The main disadvantage of this battery is still the high price and questionable availability in the future.

**Nickel–Zinc (Ni–Zn) Batteries**

Nickel–zinc batteries have high energy and power density, low-cost materials, and deep cycle capability and are environmentally friendly. The operation temperature of Ni–Zn batteries ranges from −10 ◦C to 50 ◦C, which means that they can be used under severe working circumstances. However, they suffer from poor life cycles due to the fast growth of dendrites, which prevents the development of Ni–Zn batteries in vehicular applications.

**Nickel–Cadmium (Ni–Cd) Batteries**

These types of batteries are characterized by long lifetime and can be fully discharged without damage. The specific energy of Ni–Cd batteries is around 55 Wh/kg. The disadvantage of these batteries is using of cadmium. These batteries can be recycled, but the cadmium is a kind of heavy metal that could cause environmental pollution if not properly disposed of.

A summary of the batteries properties used in industry can be seen in Table 1, or in detail (Buchmann, 2011).

| | Lead Acid | NiCd | NiMH | Li-ion (Mn) | Li-ion (phosphate) | Li-ion (Co) |
|---|---|---|---|---|---|---|
| Energy density (Wh/kg) | 30 – 50 | 45 – 80 | 60 – 120 | 100 – 135 | 90 – 120 * | 150 – 190 |
| Cycle life (80% of nominal capacity) | 200 – 300 | 1500 | 300 – 500 | 300 – 500 | 1000 – 5000 * | 300 – 500 |
| Self discharge per month | 5 % | 20 % | 30 % | low than 10 % | low than 3 % * | low than 10 % |
| Nominal voltage per cell | 2 V | 1.25 V | 1.25 V | 3.6 V | 3.3 V * | 3.6 V |
| Load current – peak –continuous | 5 C<br>0.2 C | 20 C<br>1 C | 5 C<br>0.5 C | 30 C<br>10 C | 20 C *<br>5 C * | 3 C<br>1 C |
| Operating temperature | -20°C to 60°C | -40°C to 60°C | -20°C to 60°C | -20°C to 60°C | -20°C to 60°C | -20°C to 60°C |
| Safety | Thermally stable | Thermally stable, fuse recommended | Thermally stable, fuse recommended | Stable to 250°C protection circuit recommended | Stable to 250°C protection circuit recommended | Stable to 150°C protection circuit mandatory |
| Toxicity | Toxic lead and acids, harmful to environment | Highly toxic, harmful to environment | Relatively, low toxicity, should be recycled | Low toxicity | Low toxicity | Low toxicity |

* For the Li-ion (phosphate) battery it is necessary to know the type and used material

Table 1. Comparison of selected types of batteries usable for ESS

One of the main indicators of the battery quality is energy density (Wh/kg), Fig. 5 and Table 1 show that the best batteries are based on lithium-ion technology. In terms of safety and lifetime are today come to the fore a very advanced lithium-ion batteries with phosphate and that are widely using in electric traction. The leading manufacturers of these batteries are Valence Technology ($LiFeMgPO_4$) and Winston Battery Limited ($LiFeYPO_4$). In the data from the manufacturers can be found other important information about the batteries. Such as:

- Cycle life (80% of nominal capacity) depends on operating temperature Fig. 6.
- Discharge voltage behaviour (operable capacity) depends on temperature Fig. 7, Fig. 8.
- Discharge voltage behaviour (operable capacity) depends on load current Fig. 9.
- Battery self discharge behaviour per one year Fig. 10.

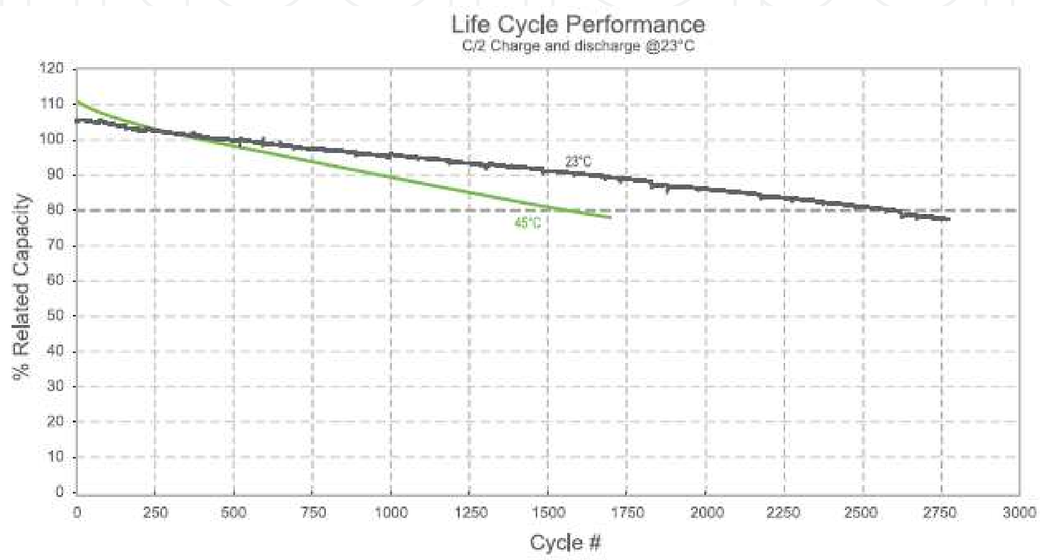


Fig. 6. Battery cycle life depends on operating temperature ($LiFeMgPO_4$) (Valence Technology, 2010)

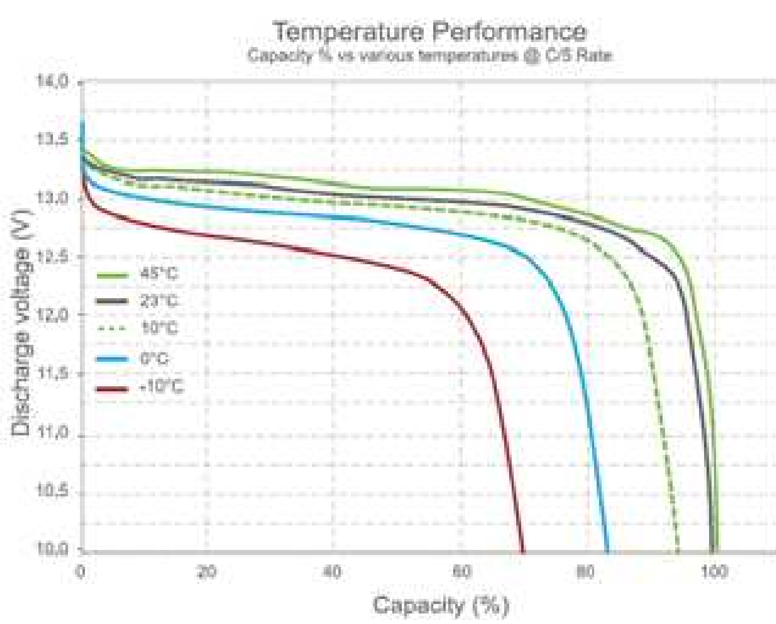


Fig. 7. Discharge Voltage depends on operating temperature ($LiFeMgPO_4$) (Valence Technology, 2010)

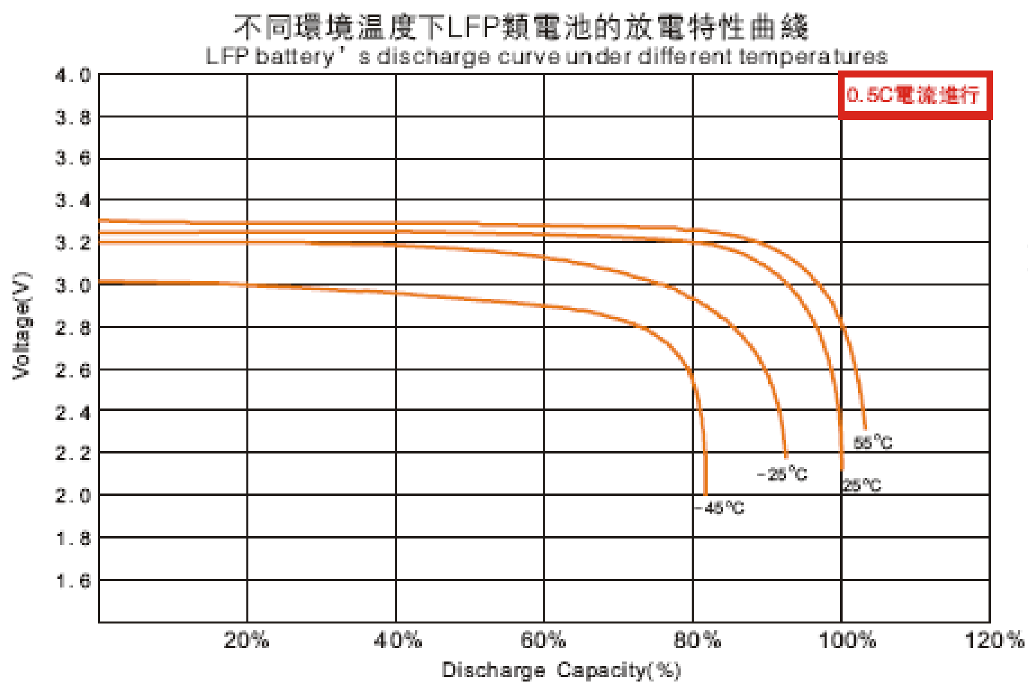


Fig. 8. Discharge Voltage depends on operating temperature (LiFeYPO4) (Winston Battery Limited, n.d.)

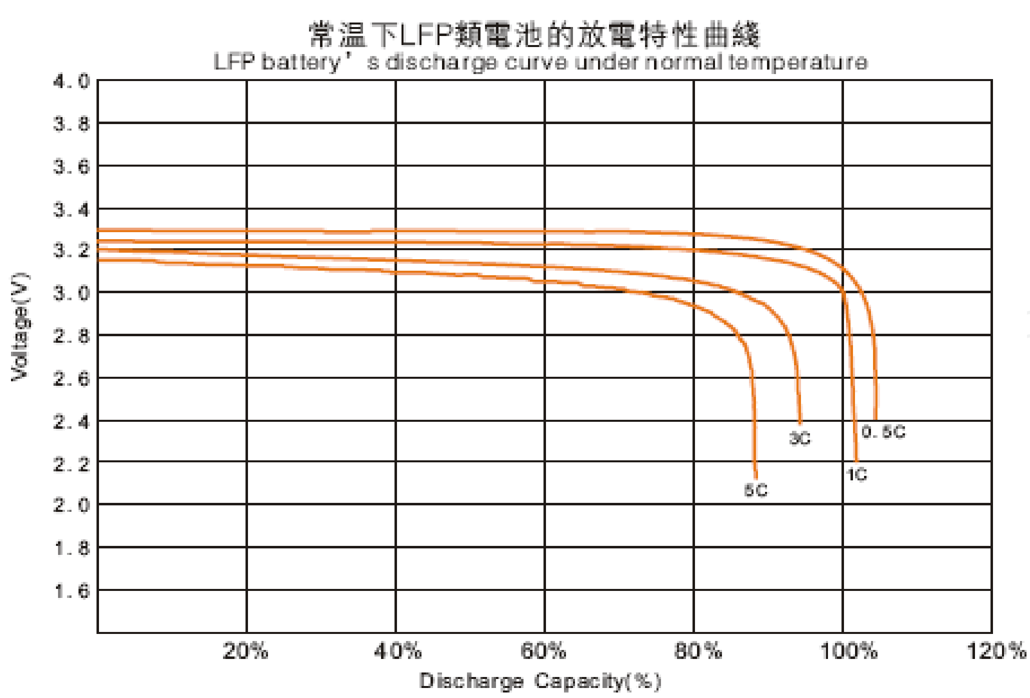


Fig. 9. Discharge Voltage depends on load current (LiFeYPO4) (Winston Battery Limited, n.d.)

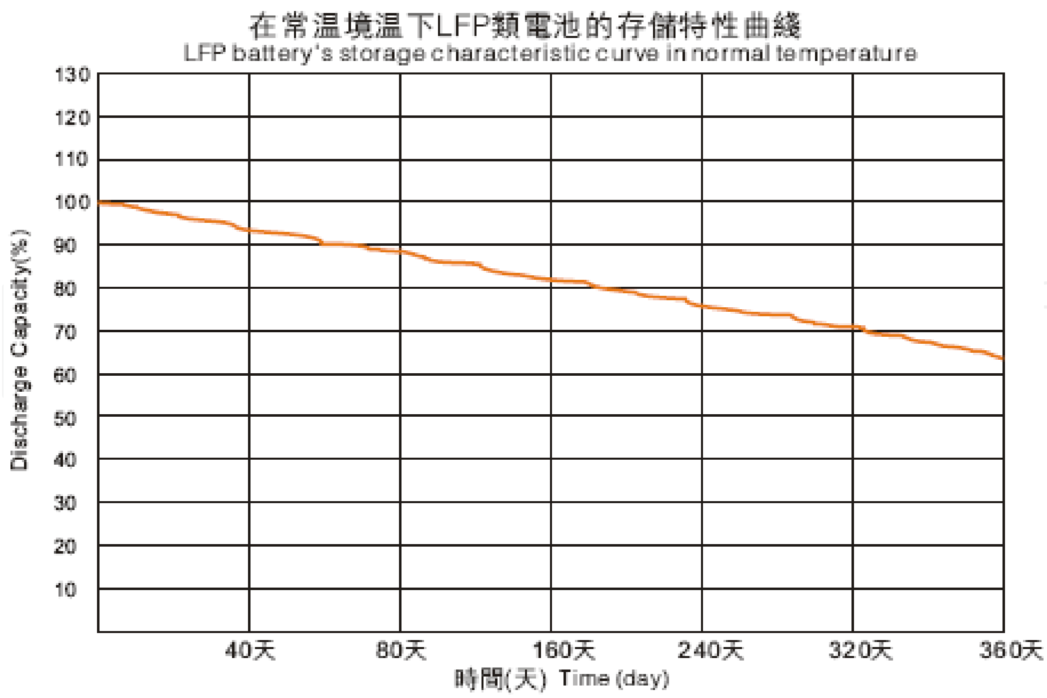


Fig. 10. Battery self discharge behaviour (LiFeYPO$_4$) (Winston Battery Limited, n.d.)

The electrical ESS based on battery must contain the special electric circuit, that ensures the battery charging and discharging at the specified limits. The basic topology is depicted in Fig. 11, battery cell is connected to load/source via buck/boost converter. The battery voltage is lower than DC-link voltage and for charging the battery is used the buck converter (T1, D2 elements). During discharging of battery cycle the voltage should be increased by boost converter (T2, D1 elements). This topology is simply and very often used at electric traction and at back-up system for example (Drabek & Streit, 2009).

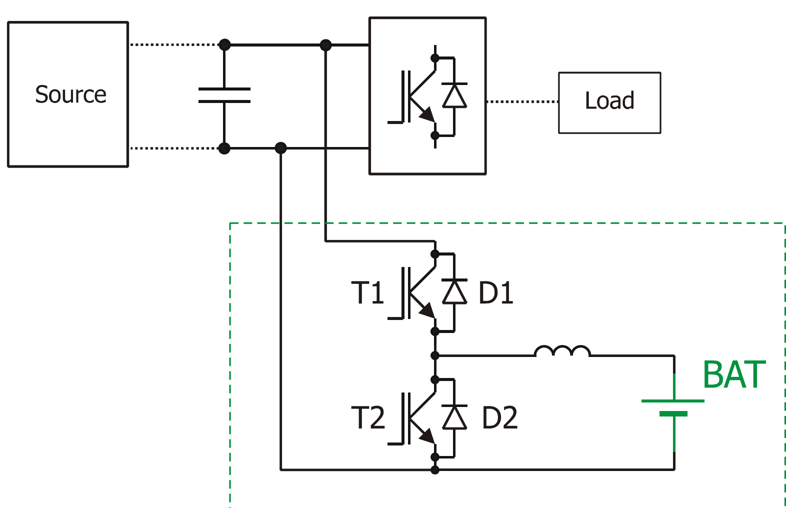


Fig. 11. The basic power circuit for ESS based on battery (standard buck/boost converter)

Sophisticated topology uses the N-phase buck/boost converter. The principle is similar as the previous one, only the current is divided into three parallel branches, that are controlled by shifted carriers in PWM.

The advantage of this topology is in reducing of the current ripple caused by shifted carriers PWM control. The example of three phase buck/boost converter is shown in Fig. 12.
This type of converter is practically used e.g. for photovoltaic systems (Lin et al., 2010), where is pressure to reduce converter losses. Another common use is at electric traction, where the reducing of the filtering inductor weight and size is welcome.

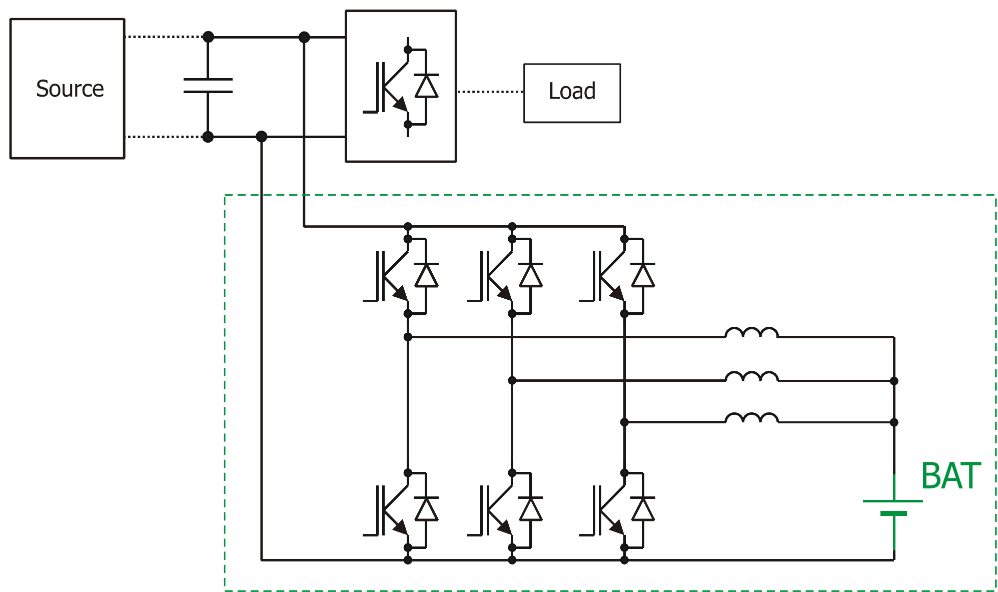


Fig. 12. The three-phase buck/boost converter for ESS based on battery

The modern power circuit topologies for electrical ESS based on battery is the bi-directional DC/DC converter with transformer binding for example Fig. 13. This type of converter is typically used for PV systems, because in relation to soft switching technology it has high efficiency (Shengyong et al., 2010).

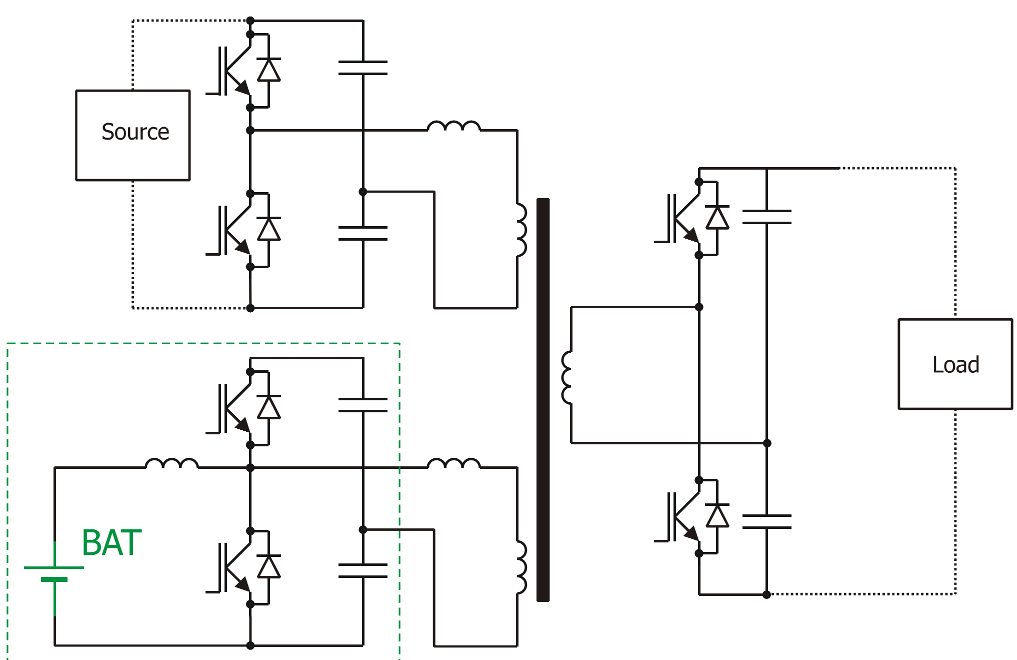


Fig. 13. Traction topology of ESS based on supercapacitors – high voltage version

The Fig. 14 – Fig. 16 show several transport vehicles powered by battery ESS.

Fig. 14. Battery scooter (Vectrix Corp, 2010) Battery: Li: LiFeP04, 30Ah capacity

Fig. 15. Battery car (CODA Automotive, 2010) Battery: LiFePO4, 728 cells (104s7p)

Fig. 16. Battery bus (Zhongtong Bus Holding Co, (n.d.) Battery: Li-ion, 540 Ah capacity

## 3. Supercapacitors (ultracapacitors)

Supercapacitors (SC) are electrochemical capacitors with an unusually high energy density compared to common capacitors, typically thousand times greater than a high-capacity electrolytic capacitor. They are based on a structure that contains an electrical double layer (anode (aluminium foil) – active carbon – separator – active carbon – cathode (aluminium foil) - it is shown in Fig. 17) and therefore they have the high capacity. The carbon nanotubes have very large surface area. One gram of this carbon presents surface area about 2000m2/g. The SC stores energy by physically separating positive and negative charges. The charges are stored on two parallel plates divided by an insulator. Since there are no chemical variations on the electrodes, therefore, UCs have a long cycle life but low energy density. The power density of the UC is considerably higher than that of the battery; this is due to the fact that the charges are physically stored on the electrodes. Low internal resistance gives UC high efficiency but can result in a large burst of output currents if the SC is charged at a very low SOC.

There are five UC technologies in development: carbon/metal fibre composites, foamed carbon, a carbon particulate with a binder, doped conducting polymer films on a carbon cloth, and mixed metal oxide coatings on a metal foil. Higher energy density can be achieved with a carbon composite electrode using an organic electrolyte rather than a carbon/metal fibre composite electrode with an aqueous electrolyte (Lu et al., 2007).

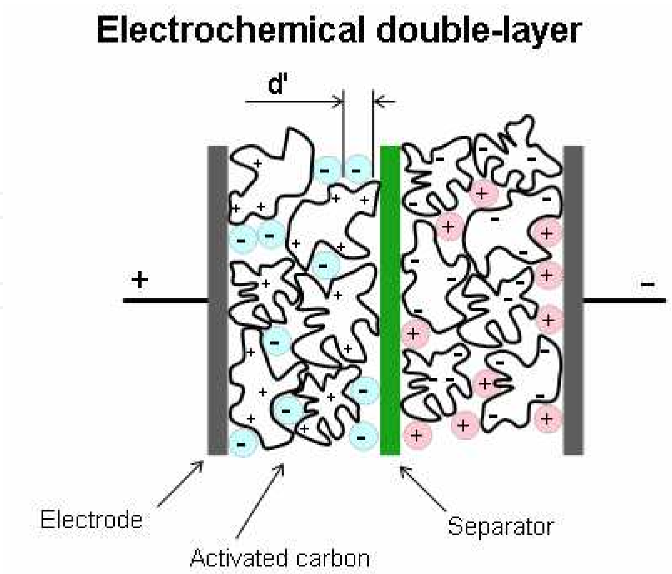


Fig. 17. Principle of supercapacitor (EPCOS AG, 2011)


Fig. 18. Typical structure (layers) of supercapacitor (EPCOS AG, 2011)

Fig. 17 shows charge distribution in SC. Large surface area of carbon nanotube can soak up a lot of charge, therefore SC presents the high capacity. SC fills the gap between common capacitors and common batteries as you can see in the Fig. 3.
Ultracapacitors quickly capture energy from braking and then use that energy to provide a short burst of power during acceleration and to dramatically reduce the use of fuel in a conventional internal combustion engine or electrical energy drain in an all electric or hybrid system. Generally used ultracapacitors in transportation are compact, high-performance, have exceptionally long-life and fulfil many of the functions of batteries but with dramatically higher reliability and they are virtually impervious to any climate condition.


Fig. 19. The hybrid bus with supercapacitors (Maxwell Technologies, 2011)

Supercapacitors are made in different modules and packages. Because the voltage of one cell is only two volts, the cells must be connected to series connection for increase of the voltage. Large industry SC has a nominal voltage of 125V. This 125V transportation module is shown in Fig. 20.


Fig. 20. 125V Transportation Module (Maxwell Technologies, 2011)



Fig. 21. SC on the roof of Scania bus (Green Car Congress - BioAge Group, 2010)

Features of 125V Transportation module:
- More than 1 million of charge - discharge cycles
- Operating temperature -40° C to +65° C
- Nominal capacitance 63F
- Internal resistance 18mΩ
- Constant current 150A
- Peak current 750A (1s 10% duty cycle)
- Energy about 100Wh (discharging to half voltage)
- Weight 59,5kg
- Size 619 x 425 x 265 mm

In principal the configuration of DC/DC converter should be following:
- Classical buck/boost converter (two-quadrant converter – one voltage polarity with current reversal) – Supercapacitor voltage cannot be higher than voltage in DC line due to diode (Fig. 22)
- Two buck/boost converters (two-quadrant converter according to $C_{SC}$ – one voltage polarity with current reversal) – Supercapacitor voltage can be higher than voltage in DC line (Fig. 23).

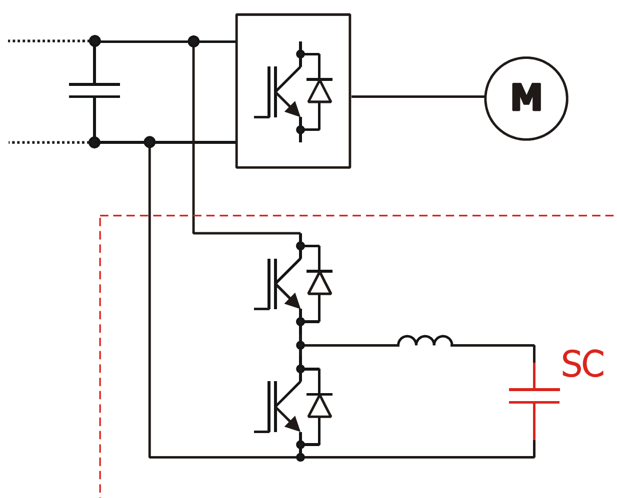


Fig. 22. Traction topology of ESS based on supercapacitors – low voltage version

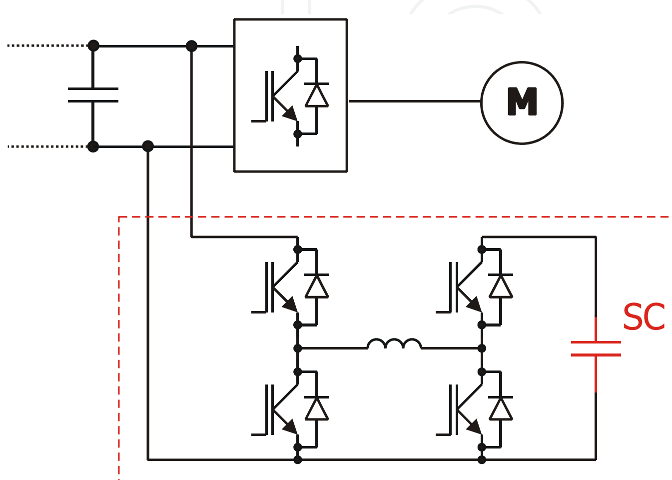


Fig. 23. Traction topology of ESS based on supercapacitors – high voltage version

*Example of using SC in light rail*

Fig. 24 shows principle schema of energy storage system with supercapacitors. This topic is described in the (Drabek & Streit, 2009).

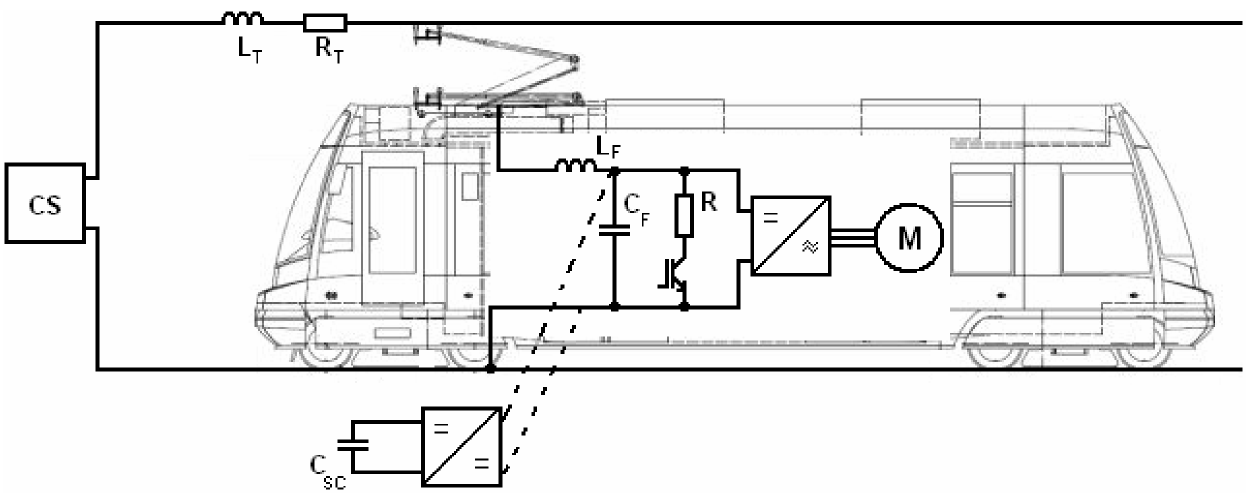


Fig. 24. Topology of energy storage system in light rail vehicle

The Energy Storage System is created with the DC/DC converter and with the block of supercapacitors. Charging of supercapacitors (braking of vehicle) and discharging (acceleration of vehicle) is controled by DC/DC pulse converter.

Voltage of supercapacitors corresponds with quantum of accumulated energy. It is necessary to connect SC by DC/DC converter to set voltage of SC independent of DC circuit of traction converter voltage. Controlling of DC/DC converter ensures using SC in right time. Energy accumulation during braking vehicle and using of the energy by first accelerating request appears as the best way of controlling idea.

Transferring of kinetic energy to the SC (means charging and discharging) can be done by appropriate control strategy of Buck/Boost converter. This accumulated energy can be used for acceleration of the vehicle. PI controller ensures current from ESS (Energy Storage System) as an equivalent with current of traction converter. It means that PI controller controls trolley line current to zero. This idea saves a lot of energy needed for repeated accelerations.

Simulations have been provided for a tram vehicle with rated power of 348 kW, weight 22t. Block of supercapacitors 125V, 63F by MAXWELL (Fig. 20) was chosen. We have used block of 4 supercapacitors - that means 500V and 15,75F (nominal voltage of trams is 600V and due to used converter in Fig. 22 it is necessary to use ESS with low voltage).

Basic settings for control of DC/DC convertor:

- $U_{CS}$ has not exceed level of 500V and decrease under level of 250V (it depends on manual of SC MAXWELL, the common minimum voltage is 50% according to the lifetime cycles).
- ICS has not to exceed level of 750A (it depends on manual of SC MAXWELL according to the lifetime cycles).

It is possible to use few ways to control energy storage system. Firstly, to control voltage $U_F$ to nominal value of trolley voltage (e.g. 600 V) – to discharge SC at lower voltage of UF and charge SC at lower voltage of $U_F$. The control of charging and discharging according to driving cycle of the vehicle (braking – charging, acceleration – discharging). The second method is used for described system.

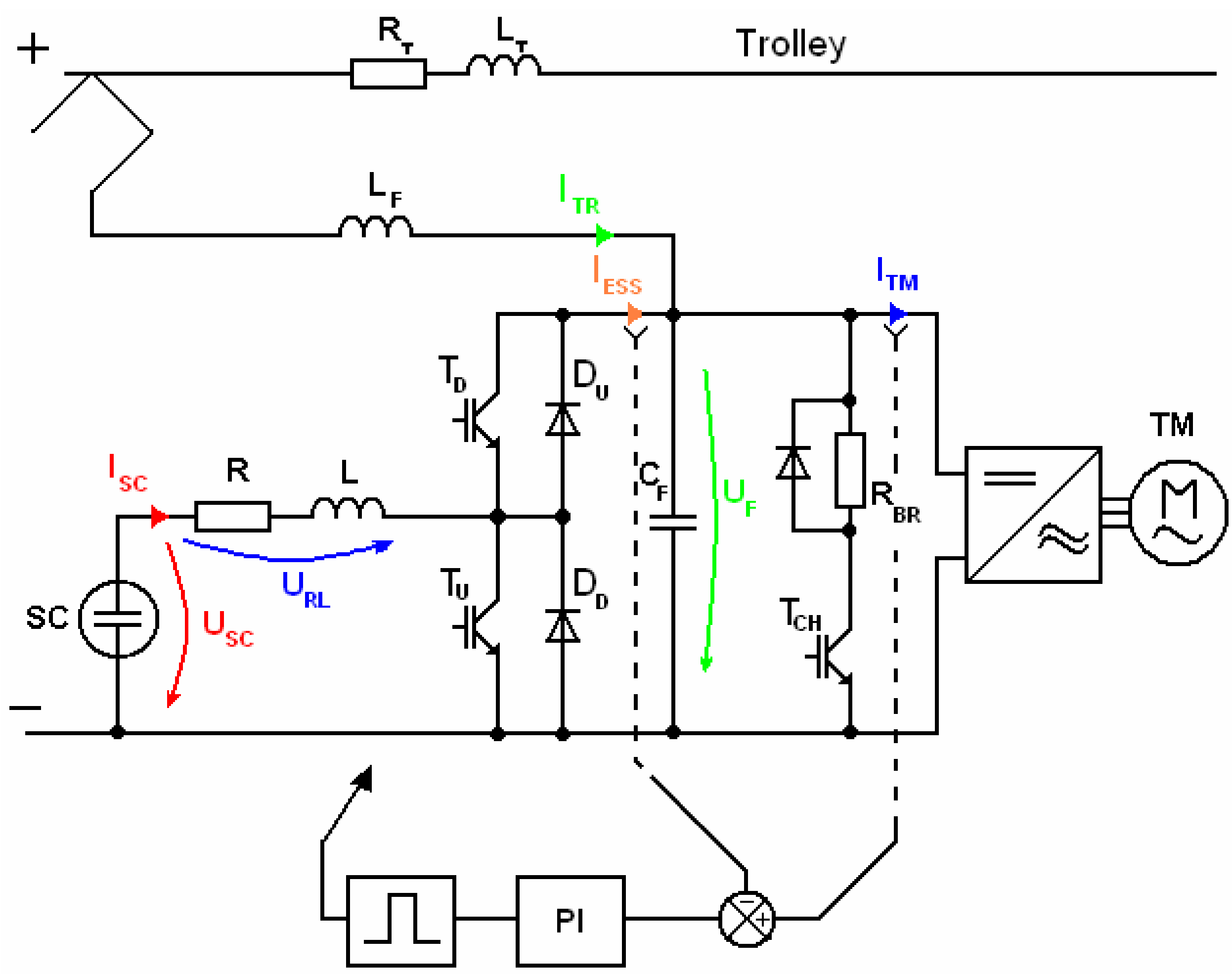


Fig. 25. Light rail topology - Buck (TD)/Boost (TU) convertor for SC

Proposed control strategy:

- Firstly to discharge SC by every request for acceleration and prepare SC for charging during braking.

Fig. 26 shows behaviour of energy storage system for chosen grading of track. Shown values correspond to schema in Fig. 25. Current is filtered to better view. In time period 1-2s current of traction motor is fully supplied by energy storage system SC as you can see in Fig. 26. In time 6s supercapacitor is fully discharged, therefore current for traction motor is fully supplied by trolley line. SC is charging by first braking in time 10-13s and it is discharging by next accelerating in time 14-17s. In time 23s SC is fully charge and redundant energy is taking out by braking resistors $R_{BR}$ (if the recuperating to the trolley line is not possible due to over voltage).

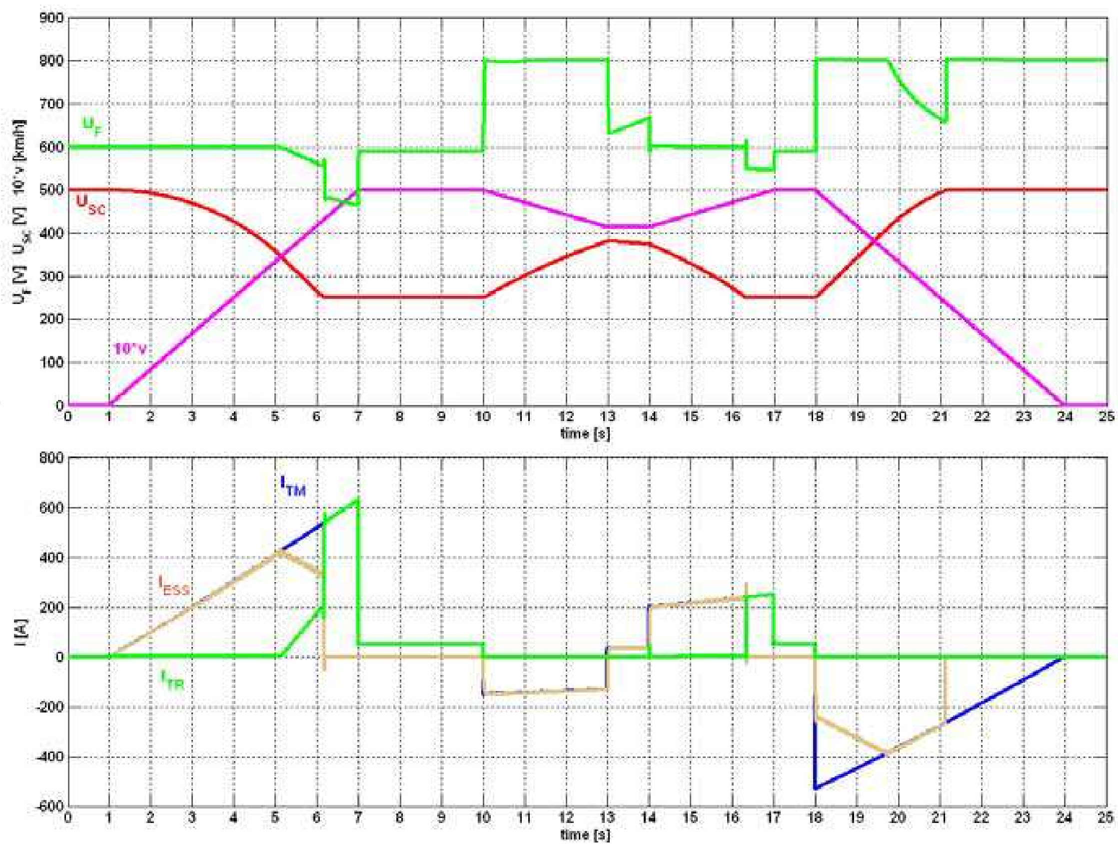


Fig. 26. Application of energy storage system for grading of track

## 4. EES with flywheel

Interesting energy storage system used in industry is flywheel. It is a mechanical ESS, which is again interesting for use in electric traction vehicle, as well as stationary ESS. The flywheel is a rotating device, this device accumulate kinetic energy as:

$$E = ½ . m.v^2 \quad (1)$$

Same as

$$E = ½ .J\omega^2 \quad (2)$$

E...energy [J]
m...weight [kg]
v...speed [m.s$^{-1}$]
J... moment of inertia [kg.m$^2$]
ω...angular velocity [s$^{-1}$]
The quantity of kinetic energy, that is accumulated by flywheel directly depends on the rotor moment of inertia, also it square depends on angular velocity. Therefore, it is advantageous to adjust the flywheel for high speed as possible. The aspect of the saving weight with maximizing of the flywheel energy is especially important in traction vehicles. Nowadays the well-known application is in the racing cars Formula 1, the system ESS is called KERS (Kinetic Energy Recovery System - Fig. 31).

As a perspective electric drive in ESS with flywheel is used the switching reluctance motor (SRM), that brings advantages in simple motor design, low cost, robust construction. On other hand it needs advanced control system (Talla & Stehlik, 2008). The energy storing and removing from flywheel can be done by mechanical means (Flybrid Systems, 2010), or by electrically Fig. 27.

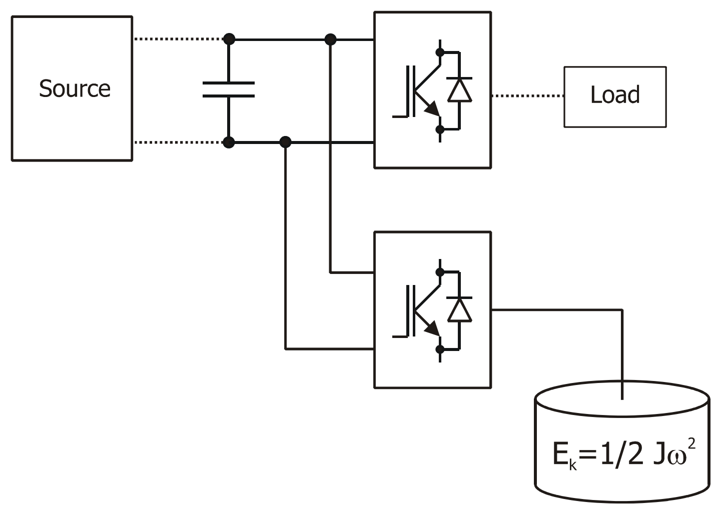


Fig. 27. Flywheel energy storage done electrically

The Fig. 28 shows a complete ESS device with flywheel and Fig. 29 shows the configuration of the flywheel as a presented by VYCON company (VYCON, 2011).

Fig. 28. Flywheel energy storage systems (VYCON, 2011)

A summary of the flywheel properties can be seen in Table 2, or in detail (AutoSpeed - Web Publications Pty Limited, 2011; Cibulka, 2009)

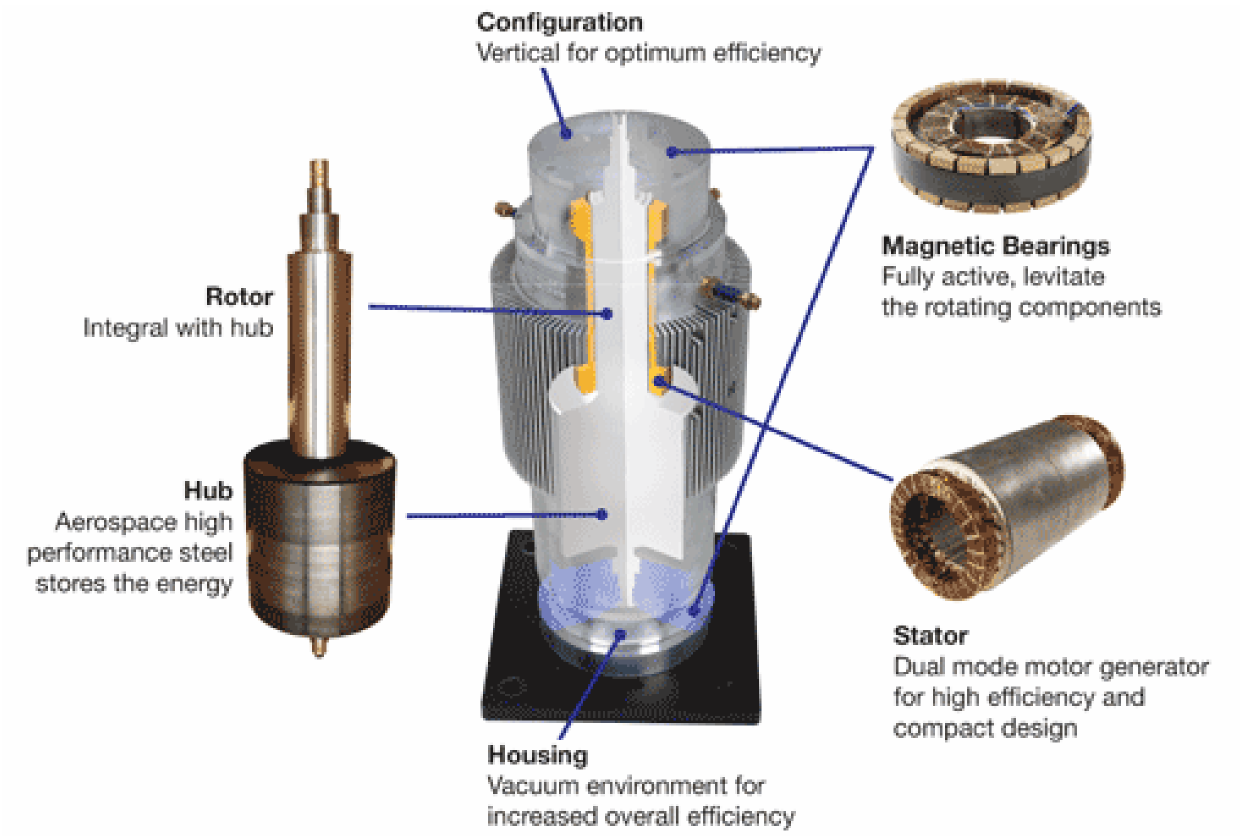


Fig. 29. The flywheel composition (VYCON, 2011)

| | BATTERY $LiFePO_4$ | SUPERCAPACITOR | FLYWHEEL |
|---|---|---|---|
| Energy density (Wh/kg) | 90-120 | 1-4 | 40-60 metal<br>140-350 composite |
| Cycle life | 500-1500 (3000)* | 1 000 000 | 5 000 000 |
| Self discharge | lower than 10 % (3%)* per month | 50% of initial voltage per month | 2-5% per minute |
| Operating temperature | -30°C +60°C (-45°C +85°C)* | -40°C +65°C | -40°C +150°C |
| Safety | + | + | - |
| Toxicity | - | + | + |

* For the Li-ion (phosphate) battery is necessary to know the type and used ingredients (donated)

Table 2. Comparison of ESS used in industry

**Flywheel advantages and disadvantages**

| + | - |
|---|---|
| High reliability | Gyroscopic effect |
| Very low maintenence | High energy losses (2-5% per min) |
| High temperature range | Special (expensive) bearings |
| High power density | Dangerous if failure |
| No capacity decreasing in time | Vibration (producing and sensitive) |
| Enviromental friendly | Complicated control |
| Unneeded cooling | |
| Long lifetime | |
| Easy energy remaining information | |

In Fig. 30 - Fig. 33 are shown different flywheel devices used at modern road vehicle.

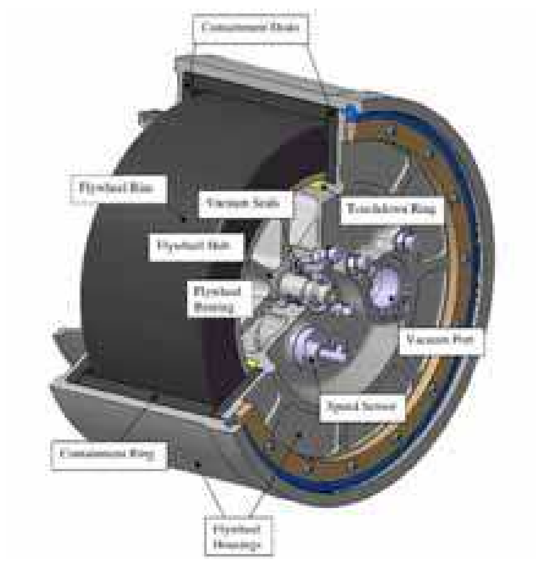

Fig. 30. Flywheel construction (Flybrid Systems, 2010)

Fig. 31. The original CVT based Formula One KERS (Flybrid Systems, 2010)

The next practical using of flywheel is at light traction vehicle as a tram. The fig. 34 presents hydrogen train using flywheel for energy storage.

Fig. 32. The Jaguar flywheel module with integrated vacuum and lubrication pumps (Flybrid Systems, 2010)

Fig. 33. The Flybrid Flywheel Capacitor (Flybrid Systems, 2010)

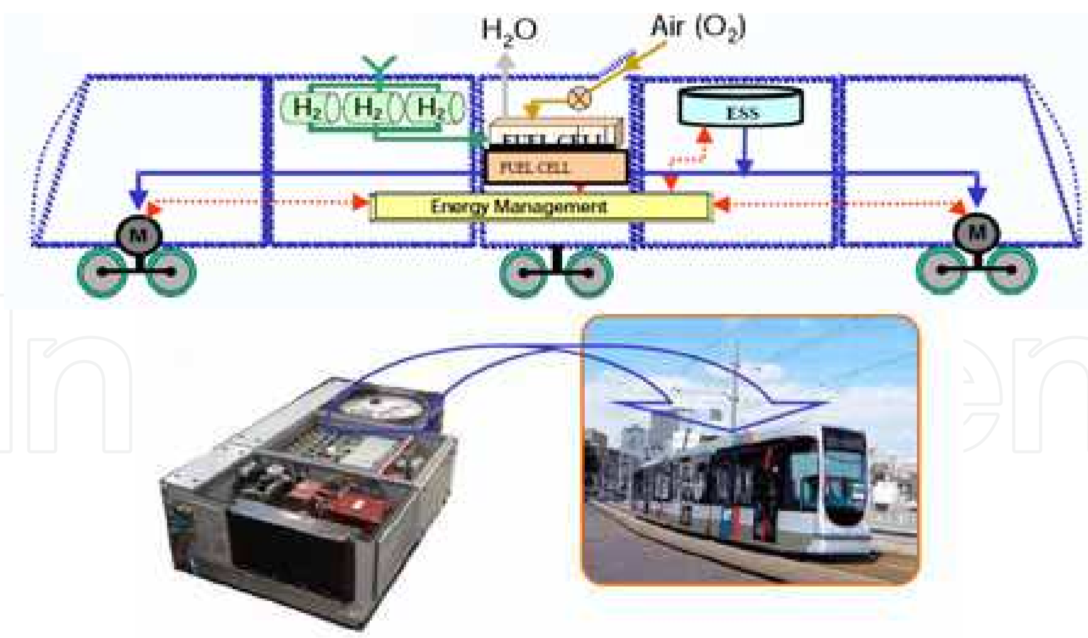


Fig. 34. Hydrogen train (ALSTOM, 2011)

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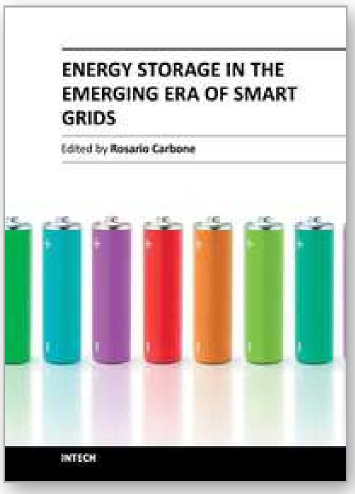


**Energy Storage in the Emerging Era of Smart Grids**
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Reliable, high-efficient and cost-effective energy storage systems can undoubtedly play a crucial role for a large-scale integration on power systems of the emerging â€œdistributed generationâ€ (DG) and for enabling the starting and the consolidation of the new era of so called smart-grids. A non exhaustive list of benefits of the energy storage properly located on modern power systems with DG could be as follows: it can increase voltage control, frequency control and stability of power systems, it can reduce outages, it can allow the reduction of spinning reserves to meet peak power demands, it can reduce congestion on the transmission and distributions grids, it can release the stored energy when energy is most needed and expensive, it can improve power quality or service reliability for customers with high value processes or critical operations and so on. The main goal of the book is to give a date overview on: (I) basic and well proven energy storage systems, (II) recent advances on technologies for improving the effectiveness of energy storage devices, (III) practical applications of energy storage, in the emerging era of smart grids.



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