Functional analyses and application and discussion regarding energy storages in electric systems

Karol Bednarek, Leszek Kasprzyk
Poznań University of Technology
60-965 Poznań, ul. Piotrowo 3a, e-mail: {Karol.Bednarek; Leszek.Kasprzyk}@put.poznan.pl

The current paper focuses on functional properties of energy storages as well as looks at their application in electric power systems. Moreover, the work thoroughly analyzes and compares the parameters and functional properties of batteries and supercapacitors, as frequently used power storages. The discussion has been employed in the functional analyses regarding storing of power in guaranteed power supply systems, as well as power systems used in electric or hybrid cars. The opening chapters of this paper concern the importance of the discussed issues and also feature brief descriptions of the most popular power storages. Next, functional properties and parameters of batteries and supercapacitors are presented. They have also been subject to a comparative analysis as well as an analysis of their application in power systems (illustrated with the example of the UPS EVER SINLINE and power transmission system of a passenger car).

1. Introduction

Electric power is the most popular form of energy because it is easy to produce, process (change its parameters), send and convert into other kinds of energy. Usually it is delivered to receivers through a power network. However, there are many cases where this power has to be accumulated for future use in certain conditions. This is a situation when storage items or devices are applied.

Electric power storages are systems that allow to accumulate power in any form (by changing electric power into other kind of energy or collecting it inside of a magnetic or electric field), and then, processing the accumulated power and delivering it at any moment in form of electric energy of given parameters [1-6]. Using energy storages is predominantly connected with issues of the correctness of electrical power system (especially in cases where renewable sources of energy are involved), with functioning of guaranteed power supply systems (that comprise mostly UPS devices), with powering of mobile systems, such as data communication systems, portable medical devices, consumer electronics as well as modern technologies of powering used in motor industry.

Energy storages in power industry make it possible to collect power in periods of its excess in the production-distribution system and then its effective utilization when a power shortage or receiving overload occurs. Moreover, they can be used as emergency sources during failures or momentary but intensive power fluctuation. They can also work together with ecological sources (photovoltaic, wind, etc.) as power buffer in stochastic operation conditions and also when these sources are overloaded. Therefore, it can be said that energy storages play the role of power supply system stabilizers in the power industry [1, 6].

Power supply interruptions can be not only inconvenient to the receivers due to lack of electricity and impossibility of using certain devices, but may also have serious consequences, such as loss of data in IT systems, device damage, as well as the impossibility of providing heating in commercial premises (especially in winter). What constitutes a good solution to this type of issues is application of guaranteed power supply systems, such as UPS devices. In the stand-by operation mode (engaged in case of no mains power supply or incorrect parameters of the supply voltage) the electric power that has been accumulated in the storages is used in order to power secured receivers (most often the ones of very crucial importance). The functional properties of the energy storages influence the quality and effects of the guaranteed power supply systems' operation, which, in turn, impacts safety and conditions in which the receivers operate.

Accumulating power is also relevant for power systems used in electric or hybrid vehicles. The discussion about such systems needs to include the following issue: the storages used in these vehicles have to provide high power density (that is high dynamics of receiving and returning of the electric charge) and, at the same time, they have to ensure high energy density (that is high efficiency or, in other words, the source's capacity).

The paper examines possibilities of storing energy, with particular attention drawn to functional properties and comparison of batteries and supercapacitors. The analyses have been focused on application of these devices in guaranteed power supply systems (UPS) and in the motor industry. The analysis has been based on the functional properties of the following devices: UPS EVER SINLINE in battery module version and Evolution (with super capacitors) as well as the drive system of an electric car.

2. Systems of energy storages

Energy can be stored in various forms and physical systems. The choice of the appropriate method and desired physical solution depends on many factors, such as operation conditions, the amount of accumulated energy, environmental conditions, size, mobility needs or stationary nature of the energy storage. Accumulating energy involves using certain physical and chemical phenomena. The processes that take place inside energy storages include: transformation of electric power into chemical or mechanical energy and the other way round or accumulation of electric power inside a magnetic or electric field. The following are considered to be energy storages [1-10]:

- kinetic energy storages – energy of rotating masses,
- pneumatic energy storages – storages with compressed air,
- pumped-storage hydroelectricity plants – water energy,
- superconductive magnetic energy storages – accumulating energy in the magnetic field,
- supercapacitors – accumulating energy in the electric field,
- electrochemical secondary cells – batteries (battery energy storages).

Kinetic energy storages

Electric power in kinetic energy storages is converted into mechanical energy and is accumulated in the rotary motion of massive impellers. The rotating flywheel consumes electric power in order to gather and keep its angular velocity, and then (in periods of intensive needs for energy or power supply interruption) the mechanical energy accumulated in the flywheel is converted into electric power of given parameters (with the use of generators and power-electronic converters) [1, 4, 5, 7-9]. Slow-running (up to 10000 turns/min) and high speed (up to 100000 turns/min) systems are used. High-speed systems feature composite impellers that rotate in vacuum on magnetic bearings. They have a very high power density but lower energy density. What is more, this kind of impellers is very efficient (over 90%) and long-lasting (their life-span is about 20 years) but their maintenance is very costly.

Pneumatic energy storages

In these systems, energy is stored in form of compressed gas (air at the pressure of 100 atm) and next is converted into electric power (by means of generators and power-electronic converters). Application of storages with compressed air depends on the existence of natural underground bodies (such as caves, pits, and caverns) which have appropriate air tightness. They enable accumulation of huge volumes of energy and operation at big changes of power consumption. Their efficiency is about 60 ÷ 80%, whereas their life-span is about 20 ÷ 40 years. What may constitute an issue here is the relation between pressure and temperature. This type of storage is considered to be an alternative to pumped-storage hydroelectricity plants in electrical power-engineering systems [1, 4, 5, 9].

Pumped-storage hydroelectricity plants

In this kind of plants electric power (in periods of excess of power in relation to demand) is converted into potential energy of water that is pumped from the lower container to the upper one. Then, during periods of maximum load, the water mass energy is converted in the generator into electric power. These systems store huge amounts of energy, with consumption of big volumes of electric power being possible (between dozens and hundreds of MW). Additionally, the charging-discharging time is between several hours to several days. The efficiency of these systems reaches about 80%, whereas their lifespan is estimated to be 30 ÷ 50 years. Their applications strongly depend on the hydro-geological conditions of the area. What is more, such plants are very expensive [1, 4-6, 9]. They are used for optimization of power management in electric power systems.

Superconductive magnetic energy storages

What this group of storages bases their functionality on is the ability to collect energy within a magnetic field of induction coils made of superconductors. These systems can handle very high loads of electric current (of the order of kA) since their operation takes place in very low temperatures (below the temperature of liquid nitrogen), thanks to which power losses in the winding are very small. Their efficiency is very high (up to 95%) as well as their expected life-span is very long (up to 30 years). They are capable of transferring big amounts of power (of the order of MW) but they have low densities of energy. In practice, they are used rather rarely due to high costs of superconductive elements and cooling, that is necessary for their proper operation [1, 4, 5].

Batteries and supercapacitors

Batteries are the most popular energy storages (also outside electric power industry) but supercapacitors are a very interesting and promising solution that becomes more and more advanced. Due to their accessibility, functional properties and area of application, it is these two energy storages that will be discussed more thoroughly in the following chapters of the current paper.

3. Functional properties of secondary electrochemical cells (batteries)

In batteries (that is, secondary electrochemical cells) energy is collected in the form of chemical energy. Electrodes and electrolytes participate in the occurring chemical reactions, which results in changes of the technical parameters and limits durability of the batteries.

There are various kinds of secondary electrochemical cell constructions, among which we can list the following batteries: [4, 5, 9, 10]:

- lithium-ion and lithium-polymer (high: power density, energy density and efficiency, expensive technology and difficult maintenance),

- zinc-bromine (high: power density, energy density, expensive maintenance, include toxic and easily corroding materials),
- vanadium (high: power density, energy density, expensive technologies, difficult standardization, designed for big applications),
- nickel-cadmium and nickel-metal-hydride (high mechanical resistance, long operation time, high energy density, expensive technology, include toxic materials),
- sodium-sulfur (high efficiency, high power and energy densities, but technologically expensive, require high operating temperature),
- lead-acid, etc.

The lead-acid batteries are a widely used solution due to the good price-capacity ratio, simplicity of the charging system and possibility of applying short-term loads of high electric current in vehicle powering systems and guaranteed power supply systems (UPS),. They have a relatively high energy density, that is the unit amount of collected electrical power represented volumetrically or in terms of mass (about 100Wh/kg). They reach efficiency of about 70%. The biggest disadvantages of lead batteries as energy storages are: [2, 3-5, 9, 10]:

- low power density (about 100 W/kg),
- long times of recharging energy (between several and a dozen hours),
- short life-span represented in charging-discharging cycles (less than 1000 cycles),
- relatively heavy,
- significant dependence of parameters (SEM, internal resistance, capacity and durability) on temperature.

Low power density means that the dynamics of receiving and returning the electric charge is low, which, in turn, results in limitation of practical currents' value. Long-term high charging and discharging currents significantly decrease the durability and capacity of batteries. If the operating temperature is higher than recommended (20°C), the active material of the electrodes gets damaged whereas the grillwork corrodes. As a result, the operation time of the battery is shortened (by 50% at each lasting increase of the temperature by about 10°C) and, analogically, its capacity is lowered, whereas the battery's self-discharge process becomes faster. Low temperatures cause the battery's source current to drop, increase the internal resistance, and impair its starting-up ability as well as the ability to receive current.

The fact that batteries include liquid electrolyte is a disadvantage because this creates a possibility of leakages and the necessity to refill the electrolyte.

In order to improve their functional properties, batteries are often made in maintenance-free versions (SLA type – Sealed Lead Acid, or VRLA – Valve Regulated Lead – Acid). They are produced in two technologies [1-6,9,10,12]:

a) gel batteries (where the water solution of sulfuric acid mixed with silicon dioxide gives a substance of gel consistency that plays the role of the electrolyte),
b) AGM batteries (Absorbed Glass Mat – where the electrolyte is absorbed in a separator made of porous glass veil).

Gel batteries are inferior to AGM in terms of limitations regarding discharging by means of high currents, thus, they are less often used in high power systems.

Thanks to reducing the necessity of maintaining the devices (therefore, lowering maintenance costs) and elimination of the possibility of electrolyte leakages, it is maintenance-free batteries that are most often used. Example parameters of such batteries have been presented in Table 1.

Table 1. Parameters of maintenance-free batteries [16, 17]

Parameter	Symbol and unit	EVER GREEN POWER EGP 12-90	MYBATT MH12150
voltage	U [V]	12	12
electric capacity	C_n [Ah]	9	150
internal resistance	R_W [mΩ]	18	14
charging current	I_L [A]	0,9 (max 2,7)	15 (max 45)
power density	P/m [W/kg]	71	97
energy density	A/m [Wh/kg]	34,4	36,4
operating temp. range	T [°C]	0 ÷ 40	0 ÷ 40
no. of charging cycles	n [-]	1 000	1 000
charging time	t_L [h]	14	16

4. Supercapacitor – functional properties

What constitutes an alternative to energy storages are systems involving collecting energy in electric field (where no chemical reactions occur), that is, condensers. They usually collect a small amount of electric current, that is, low energy density.

Supercapacitors (also called ultracondensers) are electrolyte condensers of a specific construction [3-6, 9, 12]. Their functioning consists in collecting electrical charges within an electric double layer – ELD, which occurs on the boarder of electrode – electrolyte mediums (Fig. 1).

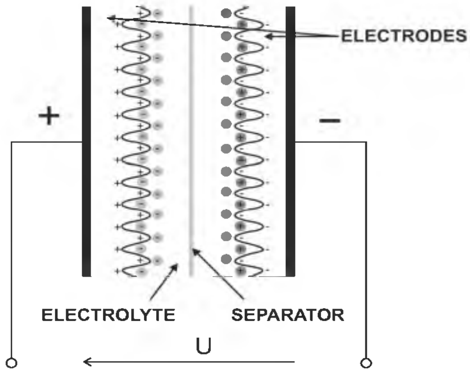

Fig. 1. Occurence of double layers in a charged supercapacitor

Advanced nanotechnologies allow electrodes to be produced in the form of multi-wall carbon nanotubes, which helps to achieve their huge specific area surfaces (which can exceed as much as 2000 m^2 per 1 gram of the electrode) and their immense capacities. Organic electrolytes are used as electrolytic substances, which results in higher values of working voltage – about 2,7 ÷ 2,8 V (and higher energy density) or water electrolyte (working current is then limited to 0,7 ÷ 0,8 V in order to avoid electrolysis).

Tabela 2. Parameters of supercapacitor modules [12]

Parameter	Symbol and unit	LSUM 050R4P 0166F EA	3 x LSUM 033R6P 0250F EA
voltage	U [V]	45 (max 50,4)	90 (max 100,8)
internal resistance	R_W [mΩ]	6,5	14,4
charging current	I_L [A]	150	150
power density	P/m [W/kg]	400	514
energy density	A/m [Wh/kg]	3,42	4,00
operating temp. range	T [°C]	– 40 ÷ + 65	– 40 ÷ + 65
no. of charging cycles	n [-]	1 000 000	1 000 000
charging time	t_L [h]	0,013	0,011
condenser's capacity	C [F]	166,6	83

Supercapacitors feature:

- very big electric capacity (up to several thousand farads),
- very high power density (possibility of taking high energy input within short time, thus, charging and discharging with high currents – fast renewal of electric charge) – about as much as 10000 W/kg,

- lower energy density (capacity of the charged source, that is, the ability to store energy) of about 10 Wh/kg,
- short battery refill time (several minutes),
- low internal resistance value (less than 0,3 mΩ), thus, small internal power losses,
- high efficiency (sometimes even higher than 95%),
- very high durability (represented both in operation time estimated to be 20 years as well as in the number of charge-discharge cycles – about 1000000),
- small degradation of functional properties despite multiple charging and discharging
- possibility of operating in a wide range of temperatures (– 40°C ÷ 65°C),
- low damage to the environment.

The biggest disadvantage of supercapacitors is their very high price, which may change along with the rapid development of nanotechnologies.

More detailed information regarding functional properties and technical parameters of supercapacitors has been included in works [1-5,12]. The most important technical parameters of some supercondenser modules (used in applications described in the following chapters) have been presented in Table 2.

5. Comparison of batteries and super capacitors

So far it is electrochemical batteries that have been the most popular sources of stored electric power (apart from applications in electric power systems). Basing on the materials that were included in the previous chapters (regarding functional properties and technical parameters of analyzed sources), it can be postulated that a supercapacitor is one of the most promising types of energy storages [1-6, 9-15].

Their biggest advantage is a very high power density – up to 10000 W/kg. It shows that the dynamics of receiving and returning of the electric charge is very high, which translates into the possibility of taking huge amounts of power from these sources in a very short time as well as the possibility of applying very high charging and discharging current (often significantly limited by the parameters of other systems connected to them). It also contributes to quick refilling of the collected energy (several minutes) which means that the battery needs very little time to be ready to work again after being discharged. These parameters are much worse in batteries where the power density is about 100 W/kg. They can be loaded with high currents only for a short time (for example, during combustion engines starting-up). Applying high charging and discharging currents for longer periods results in irreversible changes in their structure (permanent bastardization of plates, losses of the electrodes' active mass), which leads to a significant drop in durability and capacity of the electrochemical sources. The recommended charging procedures say that the starting charging current should not exceed the empirical value of 0,3 C_n [A], where C_n is the nominal electric capacity of the battery represented in [Ah]. For the capacity of 40 Ah, this current is 12 A, whereas supercapacitors can handle currents of kA. The most often recommended value of the charging current in batteries is 0,1 C_n [A], which gives 4 A for the aforementioned electrochemical source. In batteries used in UPS devices, these currents have even lower values because these solutions have lower capacities. Low values of charging directly result in long charging time (refilling of energy) of electrochemical sources – between several and a dozen hours (depending on the battery level). It also should be mentioned that it is not advisable to use up all electric power collected in a battery since such discharge leads to decreasing its durability and electric capacity. Supercapacitors do not have such limitations – the extent to which they are discharged is only the result of the current's threshold value (which drops during discharging), at which receivers still can be powered. Durability of batteries (even in recommended conditions of usage) is considerably lower than in supercapacitors. It is represented in the number of charge-discharge cycles (in condensers it is about 1000 times higher) or in years of operation (in batteries this number is several times lower).

The advantage that batteries have over supercapacitors is the energy density parameter. In secondary electrochemical cells it is 100 Wh/kg, whereas in ultracondensers it is about ten times lower. This is a very important parameter because it shows what energy collecting capacity of the source is – a very significant aspect in power supply systems.

Supercapacitors are more efficient than electrochemical cells. They reach the value of about 95%, whereas in batteries they are in the area of 70%. This difference results from lower internal resistance (less than 0,3 mΩ, in batteries it is between several and a dozen mΩ), which contributes to smaller internal losses and results from the fact that no chemical reactions occur in supercapacitors.

What is also very important is that ultracondensers have a wider operating temperature range (– 40°C ÷ 65°C) than secondary electrochemical cells (0°C ÷ 40°C) and, unlike in batteries, their parameters hardly depend on temperature changes. The recommendations of use for batteries include information that their operation time is relevant for the temperature of 25°C, however each lasting increase of temperature of about 8 ÷ 10°C causes the battery's durability to drop by 50% (for example, using a battery in 41°C shortens the operation time to 25% of its original durability). In case of supercapacitors, degradation of the functional properties over time and due to environmental factors is negligibly small. What also argues for the use of supercapacitors is their free-maintenance nature, low operation costs and small harmfulness to the environment [4, 5].

This comparative analysis shows that functional properties of batteries and supercapacitors are often complementary (especially in respect of such important parameters as power density and energy density). Their hybrid operation would be an interesting and functionally optimal solution – supercapacitors could be used in operation of high dynamics of energy transmission (both giving away and storing the electric charge), whereas batteries could be applied as the main power source during stable operation. However, it should be kept in mind that most functional parameters of supercapacitors are better than the ones in batteries and that the dynamic development of technologies used in their production may soon make them the most effective energy storages in every respect.

6. Applications of energy storages in UPS devices

What is very important in many cases of electric powering of devices is ensuring continuity of power supply and providing power of very good parameters. It is especially crucial for strategically important devices, where stoppages or failures of power supply result in big economic losses or cause danger to human health, life, and general safety. This is when guaranteed power supply systems UPS are used.

The energy storing component constitutes a very important part of UPS systems. So far, it is batteries that have been the most popular energy storages featured in these devices. Dynamic development of nanotechnologies convinced the most prominent UPS makers to use supercapacitors as the energy storages in their systems.

UPS EVER SINLINE in EVOLUTION version (Fig. 2) is an example of such a solution [16]. This is a feeder whose output apparent power is 2000 VA (active power is 1650 W) and which features supercapacitor module 3 × LSUM 050R4P 0166F EA (whose technical parameters can be found in Table 2). The SINLINE XL 2200 feeder with battery 4×EGP 12-90 has similar parameters (functional parameters of the batteries have been presented in Table 1) – its output apparent power is 2200 VA, whereas its active power is 1540 W.

a) b)

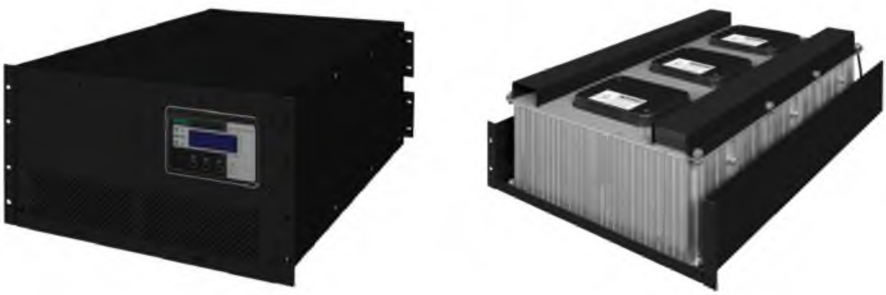

Fig. 2. UPS EVER SINLINE in EVOLUTION version (a) and supercapacitor module (b)

A great advantage of the UPS EVOLUTION over solutions with maintenance-free lead acid batteries is a very short charging time - 3 ÷ 5 min (in the XL 2200 version it is over 300 minutes). Such differences are attributed to the value of charging currents of the energy storages – the value of this current in the supercapacitor module is 150 A, whereas in case of batteries it is recommended that the current is 0,9 A and does not exceed 2,7 A. A very high number of charging cycles (over 1000000 – more than 1000 times higher than in batteries), the number of years of operation, which is 3 times bigger than in electrochemical cells, as well as about 5 times lower power losses in supercapacitors that result from the differences between these energy storages show that the high original investment costs of the solution will be compensated for by low maintenance costs. One of the most important functional parameters during operation of guaranteed power supply systems is the time of power support during battery operation (during voltage drops and occurrence of incorrect parameters of the mains voltage). Times of power support in UPS EVER SINLINE: XL 2200 (with the battery module) and EVOLUTION (with supercapacitors) depending on the power of the connected load can be found in Fig. 3. (in the form of characteristics).

The graphs show that in the range of smaller loads (up to 1000 W) longer power support time is provided by a UPS with the battery module, whereas at bigger loads (over 1000 W) it is feeders with supercapacitors that ensure a slightly longer stand-by operation time. This fact is connected with the difference in efficiency of these energy storages. The amount of load influences power losses – an aspect in which battery energy storage do not deliver as well as supercapacitors.

Extending the time of power support in some UPS solutions is achieved by parallel connection of additional external battery modules (which might be done by the user who can decide about investment costs and functional properties of the system).

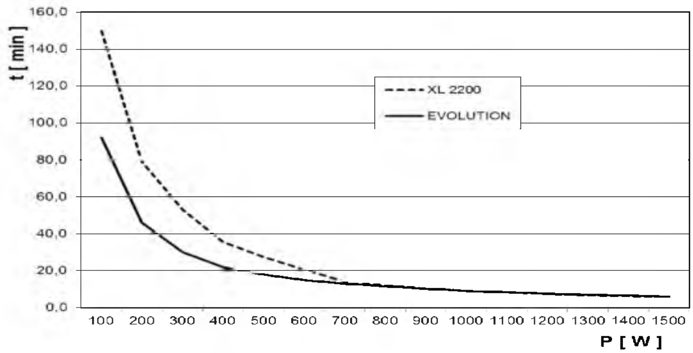

Fig. 3. Comparison of power support times in UPS EVER: SINLINE 2000 EVOLUTION and SINLINE XL 2200 at various power loads

It should be kept in mind that the life and available energy of batteries depend on the conditions that these devices operate in (used currents, temperature of operation, etc.). One of the elements that illustrates functional parameters of batteries is their discharge characteristics represented by currents in given thermal conditions. EVER GREEN POWER EGP 12-90 battery in the temperature of 20°C has been used as an example of a battery discharge characteristics that can be found in Fig. 4. [16].

At the initial stage of discharge, changes in voltage on the battery clamps are linear and then an intensive (non-linear) drop of voltage value takes place during discharge. The non-linear nature of the characteristics increases with the increase of the battery discharge current.

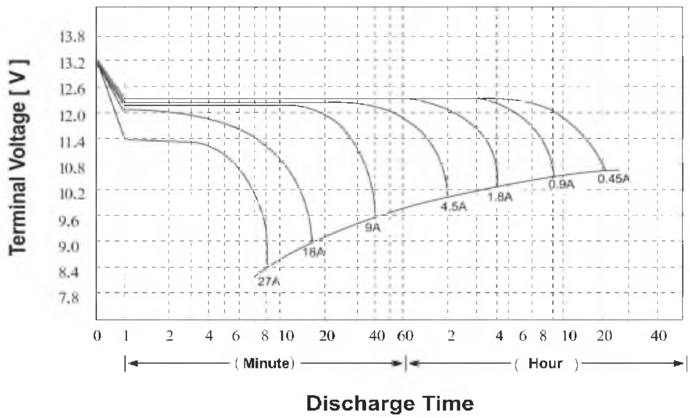

Fig. 4. EGP 12-90 battery discharge characteristics in the temperature of 20°C [16]

7. Applications of energy storages in electric and hybrid vehicles

Basic parameters that energy storages in electric and hybrid vehicles should have are: high capacity of collecting energy, ability to return and receive high volumes of power, as well as small weight and size. Currently it is lead acid batteries that are most often used in drives. However, their power density is several dozen W/kg, which is not enough in dynamic states such as rapid acceleration or regenerative breaking. Also the limited number of charging cycles (usually up to 1000) shows that traditional batteries may quickly wear out and that the cost of their replacement will make the vehicle uneconomic [5, 10, 11, 12, 13, 17].

Taking into consideration the number of charging cycles and the ability to transfer high volumes of power, supercapacitors seem to be the best solution since their power density is several thousand W/kg and the charging cycles number is several million. It should be emphasized that they have a low internal resistance (less than 1 mΩ) and are able to transfer currents of up to 1000 A. Also their durability (up to 20 years) makes them a better energy storage for electric or hybrid vehicles. However, it should be noted that supercapacitors have a low energy density – between several to several dozen times lower than in batteries. This is why complete elimination of traditional batteries is unjustified when the possibility to collect energy is taken into consideration. Using both mentioned energy storages is a kind of compromise. Supercapacitors, thanks to their properties, would be used during transferring (returning or receiving) high powers, whereas batteries would operate in periods close to nominal conditions.

In order to explain the operating conditions of power transmission systems and relating electric parameters of energy storages used in the aforementioned vehicles, an analysis of power and energy demands of a 1000 kg passenger car has been conducted. An average resistance to motion (rolling and aerodynamic motion) for an average passenger car going at the speed of 60 km/h is at the level of 250-300 N. Taking into consideration additional resistance on transmission gears and bearings at several dozen N, the total resistance to motion used for the analysis was 375 N. This was the basis for setting the power necessary to keep constant speed of 6,25 kW.

For further discussion it has been assumed that the system will be powered with a 84 V voltage. The choice of the voltage was influenced by the fact this voltage is safe (up to 120 V in normal conditions) and is often used in electric vehicles. Next, the value of the current consumed from the energy storages while running at a constant speed of 70 A was established for the set power value and at the set voltage of batteries. Assuming that the vehicle should cover 60 km at the given speed (60 km/h), the travelling time is 1 hour – the travelling section is an average distance covered daily by passenger cars in the city. The established running time and calculated power demand were the basis for the required electrical power – about 6,25 kWh (which is equivalent to about 104 Wh/km) as well as the load – 74 Ah. Taking into consideration the efficiency of the powering system and the fact that the battery would not operate in nominal conditions, as well as bearing in mind possible reserve of energy for a longer travelling section, batteries of a two times bigger capacity (150Ah) were chosen. In order for the battery module to achieve the given operating voltage, 7 batteries of MYBATT type MH12150 were put together. They were made in AGM extended life version (in nominal conditions the designed durability is estimated to be 10-12 years – however it should be remembered that even slight changes in the operation temperatures or increases of charging and discharging currents significantly lower their durability) [5, 15, 17].

It is necessary to increase the capacity to protect the life-span of the batteries that (even in good conditions) have a low number of charging-discharging cycles, as well as due to technical reasons, since it is not possible to use up all energy collected in storages but only up to 60-70 % of it. This is especially important in case of batteries because excessive discharging may lead to warping of the plates (especially at high charging and discharging currents), which, in turn, results in losses of active mass and bastardization of the plates – this causes the durability and capacity of batteries to decrease.

In practice, what also should be taken into consideration, is the demand for short-term peak power at 20 kW – necessary for driving comfort and safety of traffic – which is usually used in a period below 1% of the whole driving time. This requires over three times bigger current, which creates the necessity of using energy storages that have higher power density, such as supercapacitors. Hence the suggestion of applying three condenser modules of the LSUM 033R6P 0250F EA type connected in series as a storage operating together with the batteries. Theoretically, the energy accumulated in such a condenser (113 Wh) would be enough to gather speed from 0 to 60 km/h on a vehicle weighing 1000 kg three times or to recover all energy during braking – such energy is 38,5 Wh.

Using the same batteries in order to provide the energy required in dynamic states (for example, during accelerating and braking in city traffic, etc.), would create the need to obtain several times bigger capacity of battery modules, which could prove very costly. This, in turn, would multiply the weight and volume of the batteries, which is one of the most important issues in today's electric vehicles designed to cover long distances. The cost analysis of such systems is an important and interesting aspect. This is why, on the basis of the demand for the energy needed to cover the set distance (6,25 kWh), it was estimated that the cost of the electric power needed to cover that distance was about 2,5 PLN– assuming that the storages would be charged from an individual electrical power mains (at home) – which constitutes about 0,04 PLN/km.

Acceleration and braking as well as natural topography (going up or down a hill) in electric cars does not influence the total consumption of energy that much due to the possibility of recovering it. It is, however, connected with efficiency after converting energy so the resulting additional cost should be taken into consideration – thus the total cost of covering the distance was finally estimated to be 0,06 PLN/km. Moreover, the costs of buying the batteries (6,000 PLN) and a supercapacitor (about 10,000 PLN) should be kept in mind. The operation time of supercapacitors is up to 20 years, whereas in normal operating conditions typical for powering systems of electric cars, the batteries should be replaced every 2 years. Thus, 48,000 PLN should be invested during 10 years of using the vehicle that during this time will cover 300,000 km.

The cost of petrol for a car that on average uses up 7 liters of petrol per 100 km would be about 115,000 PLN, excluding the cost of replacing filters, oil, etc.
A preliminary analysis shows that maintenance costs in 10 years are lower in electric cars by about 58 %. However, it should be stressed that what constitutes more than 70 % of the outlined maintenance costs of an electric vehicle is the accumulator's battery, whose cost depends mostly on its capacity. This means that if the distance to be covered without charging the battery was increased to, for

example, 200 km, with the 10-year mileage at the same level, the maintenance costs would drop to about 90,000 PLN (depending on the reserves of power and energy) and would constitute about 78 % of the costs of a diesel car petrol.

The conducted research shows that electric vehicles are economic especially in city traffic, where the vehicle covers short distances within a day (without charging). Undoubtedly, the low maintenance costs of electric vehicles are a big advantage but despite many car makers offering more and more electric cars which are able to cover 400-500 km without recharging, their purchasing cost as well as lowered electric parameters of batteries in winter deter most consumers from choosing this eco-solution.

8. Summary

The choice of energy storages for operation in electric systems is mostly dependent on the kind of application, especially on the demand for energy, which is completely different in, for example, electric power systems and in mobile devices and vehicles. Another factor that has a big influence on the choice of the energy storage is the load character – the likelihood of intensive fluctuation of demanded power as well as the ability to collect energy within a given time. Also investment and maintenance costs as well as weight and size may prove crucial. In some cases, even localization may play a significant role (natural topography, hydrogeological aspects, etc.).

When it comes to the possibility of transmitting and receiving energy in a possibly short time, supercapacitors become very effective energy storages. It can be especially important during operation in difficult thermal conditions such as in rooms without air-conditioning and exposed to sun, mines or electric and hybrid cars. Due to the construction of batteries and the way they work, application of traditional batteries for operation in such conditions entails the necessity of their frequent replacement (as often as twice a year), which creates significant investment costs (the cost of buying the batteries) as well as running costs (replacement, maintenance, etc.). In such situations it is necessary to ensure appropriate operating conditions, for example, by using air-conditioning in the rooms where the batteries are located, which is also very costly. This is why condensers are more and more frequently used instead. They are much more resistant to difficult conditions (their operation temperature range is -40 to +65 °C), and their operation time is much longer.

On the basis of the power analysis as well as investment and maintenance costs of the electric vehicle in question, it was shown that supercapacitors can also have an application in the motor industry. They do not have as good capabilities of collecting energy as batteries, however, due to the high power density and considerably bigger number of charging cycles, supercapacitors can be used in vehicles as additional energy storages together with traction batteries. Application of such a hybrid storage in an electric vehicle allows for better interaction with the drive because it provides both good energy collecting capability (the battery used mostly in preset operation conditions) as well as a great capability of providing big power (supercapacitor used mostly in dynamic states – during dynamic acceleration as well as regenerative braking). Thanks to the application of supercapacitors it is possible to substantially lower the total maintenance costs of the car, especially in a long-term perspective.

Analogical benefits can be achieved by using these two energy storages in guaranteed power supply systems (UPS).

Application of a hybrid system of energy storage that consists of batteries and supercapacitors constitutes a modern and optimal solution of an energy buffering system which is highly capable and suitable for dynamic exploitation of sources and which improves the general efficiency and durability of powering systems.

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