Study Of Sustainable Transportation System with FESS Flywheel Energy Storage Systems and Ageing Process of Lithium-Ion Batteries

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Abstract: - On the development way to a low-carbon emission, vast advancements in energy storage are being done. However, for the use case of sustainable transportation, only a handful of technologies can be considered, as solution. These technologies must be reliable, economical, and suitable for transportation applications. All transport sectors are embarking on a trajectory to zero emissions by 2030 thus increasing the demands for, and on batteries and broadening their range of applications. This paper describes the characteristics and aging process of well-established and commercially available technology named Lithium-Ion batteries in the context of public transit buses along with FESS (Flywheel Energy Storage Systems). Beyond the obvious use case of onboard energy storage, stationary buffer storage inside the required fast-charging stations for the electric vehicles is also discussed. The main affecting parameters related to energy storage ageing are analyzed in detail.

Key Words: ***Energy storage system, FESS, charging and discharging current, ageing, transport, CO2 reduction, cost-benefit analysis, life cycle analysis, E-mobility, battery, charging station, renewable energy storage.***

I. INTRODUCTION

One of the fastest-growing economic sectors is road transport; which contributes up to 25 percent to the carbon dioxide emissions.

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A possible strategy to reduce local emissions is to increase the share of zero-emission electric vehicles. In last 10 years, especially energy storage, has proved to be the bottleneck. Despite intensive research activities, mobile energy storage is still the limiting factor hence limiting the success of hybrid and electric vehicles.

Since the direct storage of electrical energy can be realized by the coils, indirect storage methods prevail. This means that in a first step, the electrical energy is converted into another form of energy and subsequently stored for later reconversion into electrical energy. In Figure 1, a short classification into mechanical, electrochemical, chemical, electrical and thermal energy storage systems is given. When energy storage is discussed in the context of sustainable transportation, the first topic that comes to mind is electrochemical batteries for electric vehicles (EVs). Battery in electric vehicles without a doubt play an important role in our path towards zero-emission mobility.

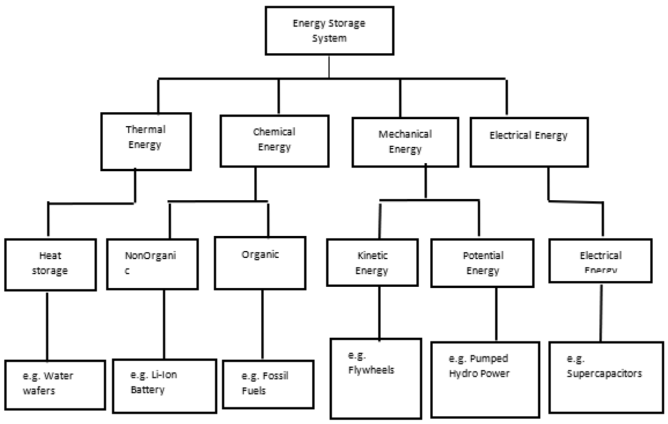

Fig.1.Classification into mechanical, electrochemical, chemical, electrical and thermal energy storage systems

II. Properties Of Different Energy Storage Systems

To give an overview, Table1 shows general technical and economic properties of the storage technologies.

Table.1. General characteristic and economic properties of different energy storage technologies relevant to different transport applications.

Energy Storage Technology	Specific Energy (Wh/kg)	Specific Power (kW/kg)	Temp. Range (°C)	Cycle life (-)
Mechanical Energy Storage				
Flywheel Energy Storage Systems (FESS)	10–100	>10	−30 °C to +70 °C	limitless
Chemical Energy Storage (only Li-Ion Batteries)				
Lithium Iron Phosphate (LFP)	90–120	4	−20 °C to +60 °C	5000–6000
Lithium Titanate LTO	60–80	1	−30 °C to +75 °C	>15,000
Lithium Nickel Cobalt Aluminum oxide (NCA)	200–300	1	−20 °C to +60 °C	500
Lithium Cobalt Oxide (LCO)	150–200	1	−20 °C to +60 °C	500–1000
Lithium Manganese Oxide (LMO)	100–150	4	−20 °C to +60 °C	300–700
Lithium Nickel Manganese Cobalt oxide (NMC)	150–280	1–4	−20 °C to +55 °C	3000–4000
Electrical Energy Storage				
Double Layer Capacitor (DLC)	5–10	>10	−20 °C to +60 °C	1 million
Hybrid Capacitor	10–20	>10	−20 °C to +60 °C	>50,000

III. Battery

Li-Ion batteries are one of the mature technologies that have been used in various fields of application since the beginning of the 21st century. However, due to developments in recent years, Li-Ion batteries have become the energy storage device of choice for most transportation applications. Because of their popularity, a lot of scientific and industrial, literature (provided by manufacturers) exists, which can be used to assess certain properties, such as cycle life, aging, etc. This paper will, hence, give only a short overview and primarily focus on the lesser-known properties of Flywheel Energy Storage Systems (FESS).

When it comes to “usable/achievable lifetime”, a metric is necessary to ‘measure’ the state of health of batteries. Typically, capacity and/or internal resistance are used in datasheets of cell manufacturers, giving some indicators to define the end-of-life (EOL) condition, e.g., a decrease of capacity by 20% or increase of internal resistance by a factor of two compared to the begin-of-life (BOL) values [6]. In reality, those limits depend on the actual application, and the datasheet’s lifetime values need to be scaled accordingly. Many applications allow a much higher decrease in capacity than defined by the manufacturer. This slightly increases initial costs and weight, but tremendously extends service life, e.g., a typically used value of 33% decrease of capacity results in a BOL to EOL capacity ratio of 1.5 compared to 1.25 for the manufacturer’s 20% value. In this case, battery they would weigh (=cost) about 20% more. However, the lifetime would increase by about 65%. In other words, the battery would weight (=cost) less for a given lifetime and reach a higher over-all energy throughput. Only small benefits are gained by pushing it even further. Especially in transportation applications, the initial increase in weight is the limiting factor. The achievable lifetime and performance of batteries depend on many parameters, with temperature as the dominating influencing factor [6]. Even though the values are given in Table 1suggest a wide operating temperature range, a closer look into actual datasheets reveals the problems within temperature must be kept below a certain value in order to reach the highest cycle life. Low temperatures increase the internal resistance and thereby have a detrimental effect on the performance of the system as well. However, charging is often no longer allowed by the manufacturer. Finally, at the low end of the operating temperature range, the discharge performance of the cell is typically less than 10% compared to 20o C values, e.g., References. Due to this severe decrease in performance, it is often necessary to heat up the cells before the system is put into operation. The primary significance of high temperature is the decrease of the cell’s lifetime, both calendar and cycle life. As a rule of thumb, one can assume that the calendar life is reduced by a factor of two every 10o C increase in temperature (actual values taken from datasheets vary between 7 and 15oC) [9]. The continuous operation at the maximum allowed temperature would reduce the lifetime to just a few months, or a year at most. An additional factor influencing the achievable lifetime is the cell voltage, and in the case of batteries also cycle count, depth of discharge (DOD), as well as charge and discharge current rates. Additionally, cycling the battery reduces its lifetime. There is no simple correlation between charge/discharge cycles and occurred damage. As mentioned before, it not only depends on the cycle count, but among other factors, also state-of-charge (SOC), DOD and charge/discharge rates. Still, a few basic and generally valid statements can be made: Just like calendar life, cycle life is influenced by cell temperature, but not necessarily with the same temperature coefficient. The calendar life temperature coefficient is 10oCper half/double lifetime, but for cycle life, the coefficient is 14o C. Increasing charge/discharge rates reduce cycle life. High cycle life values, as shown in Table 1, are typically obtained by utilizing low charge or discharge rates, e.g.1 C (1 h charge/discharge rate) or even lower. Increasing these rates, as often necessary for high-speed charging or other heavy-duty applications, reduces lifetime. Especially when the cell is optimized for high specific energy content, which is mainly the case for most batteries used in electric vehicles, where weight is of major interest.

IV. FLYWHEEL ENERGY STORAGE SYSTEMS (FESS)

4.1 Background Information

Prices of Lithium-Ion batteries are decreasing on the global market and energy densities have reached reasonable values, allowing EVs to travel 200 km and more on one charge. However, there are still significant technical challenges, which need to be solved, or alternatives need to be found. One of the major drawbacks of chemical batteries is limited cycle life, which was described in Section 2.1and will be discussed in particular in this paper. Flywheel Energy Storage Systems (FESS) has experienced a revival in recent years, mainly due to some of their interesting properties. Like, an unlimited number of charge/discharge cycles, no capacity fade over time, power and energy content are independent of each other, operation at low or elevated temperature is easily possible ,operation at low or elevated temperature is easily possible, precise state of charge (SOC)/state of health (SOH) determination, precise state of charge (SOC)/state of health (SOH) determination, no risk during transportation/uncritical deep-discharge (flywheel stands still, no risk during transportation/uncritical deep-discharge (flywheel stands still),no toxicologically critical/limited resources necessarily required. Due to the above-listed properties, FESS are increasingly used for grid stability or fast charging.

4.2 FESS Working Principle

In a FESS, energy is stored in kinetic form; the working principle is based on the law of conservation of angular momentum. In electromechanical FESS an external torque is applied to a rotor by the use of a motor/generator, hence only an electrical and no direct mechanical connection for power transmission is required. In order to charge the FESS, the applied torque accelerates the spinning mass (rotor). If the spinning mass decelerates, energy is taken out of the system, and the motor acts as a generator. Electrical energy from the grid or other sources can be converted into kinetic energy charging the FESS. In the case of discharge, the motor/generator decelerates the spinning mass converting kinetic energy back to electrical energy. The amount of stored energy is defined by the rotor's moment of inertia and the rotational speed, according to Equation (1).

$$E_{KIN} = I * \omega^2/2 \qquad (1)$$

E_{KIN}=Kinetic Energy in J

I = Mass Moment of Inertia of the Spinning Mass/Rotor in kg*m2

ω = Angular Velocity in rad/s

Around 89% of the total kinetic energy of the FESS is usable when the system is operated between 33 and 100% of the maximum permissible speed. For that reason, FESS usually operate within a certain decelerate down to standstill during regular operation.

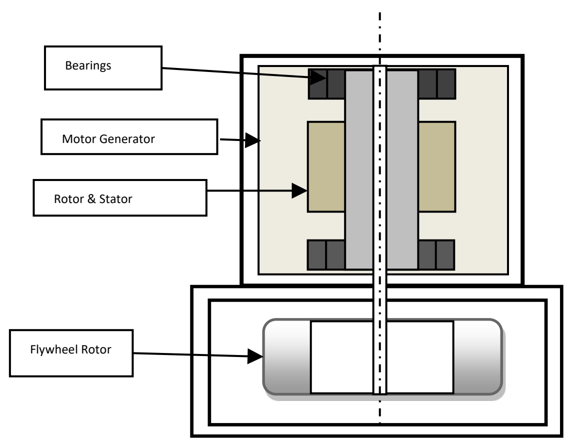

Fig.2. Schematic of flywheel energy storage system

(III) . Self-Discharge of FESS

Losses have an important influence on the suitability of this technology for different use-cases. The following paragraph gives a short introduction to this topic, starting with the three main causes of FESS self-discharge Air drag; Bearing torque loss; Power consumption of peripheral components [2]. Air drag losses during operation are crucial for FESS with high specific energies. Circumferential speeds beyond the speed of sound are common and exceed 1 km/s in some cases, which would cause enormous air drag during operation. This air drag would result in losses and eventually be dissipated into heat, which causes thermal issues leading to system failure. In order to reduce these losses, FESS are usually operated in a vacuum atmosphere, and pressure levels down to 1 μbar are common. At such low-pressure levels, air drag losses play only a minor role. The power consumption of the vacuum pump and other peripheral components must be taken into account when analyzing the overall system losses. FESS service life > 25 years is feasible with only minor maintenance effort.

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V. CONCLUSION

According to various aspects described in above sections, in order to measure any energy storage device, the predictability of the duty cycle is important. To be more precise, the case of fully electrified buses with on-board energy storage. In total each bus travels approximately around 0.5–1 million kilometers during its expected lifetime of 10–15 years. A 12-m-bus were derived based on experiences gathered by the operator, and are shown in Table.2Pune in India is used as an example.

Table.2. Average Values Used as Reference Based on a Representative Bus Route

Daily Mileage per Bus	150-200 Km	Typical Round-Trip Duration	1 h
Expected Lifetime	10-15 years	Average Energy Consumption	1.5kW/ Km
Typical Round-Trip Distance	12 km	Energy Consumption Per loop	18kWh

Operating time during a whole day is around 16–18 h, so around 300 kWh storage would be needed to drive a whole day without any charging stops. For the most part of the day, there are six buses on the route simultaneously. Therefore, a bus arrives at the ‘end-stop’ every 10 min and (depending on traffic) a few minutes are left before it has to leave again. This time (0–5 min) could be used as a ‘charging-window’. Assuming a 2-min charging window at the 10 min end stop (The actual duration of the end stop may vary depending on traffic; hence, a minimum of 2 min is assumed for charging.), an average power of 540 kW would be needed to transfer the previously calculated 18 kWh.

VI. SUMMARY

Within this study, energy storage for sustainable transport applications was investigated with respect to service life. The theoretical background of different energy storage systems, as well as different use-cases were described in detail. For exemplary energy storage comparison and benchmarking, the use-case of a fully electric transit bus operating in urban public transportation was selected, whereas onboard energy storage and buffer energy storage inside the fast-charging station were considered. From a great variety of options, established and feasible energy storage systems were chosen for a more detailed analysis. For energy storage inside the fast-charging station, it was shown that high demand on cycle life and other requirements, such as short storage time, high power and long targeted service life clearly favour flywheel energy storage systems (FESS) over super capcitors or batteries. However, fewer load cycles and long-time storage onboard the transit bus calls out for state-of-the-art Li-Ion batteries rather than super caps or FESS. Hence, which energy storage technology is most suitable strongly depends on the envisioned use-case and consequently the actual duty cycle. In this context, the great potential of FESS was shown. It is to be expected that in future some of the major advantages of FESS will be exploited, e.g., nearly unlimited cycle and calendar life, easy state of charge determination, independence from limited resources, etc. FESS-specific drawbacks, such as self-discharge, weight and cost may be detrimental to mobile (onboard) applications, but can be mitigated or neglected in some stationary applications, such as EV charging stations. Hence, FESS represent a valuable contribution to the energy revolution by increasing grid stability and facilitating the integration of renewables into the grid.

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