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Review of Mechanical, Electrochemical, Electrical, and Hybrid Energy Storage Systems Used for Electric Vehicles

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Abstract

The population rate in the world is increasing rapidly. Depending on the population, the need for transportation increases at the same rate. Traditional vehicles, which provide great convenience in transportation, have some disadvantages. For example, the fossil fuels used in conventional vehicles create greenhouse gasses such as CO_2 and N_2O. This has a negative impact on global warming. To eliminate these negative aspects, interest in electric vehicle (EV) and hybrid electric vehicle (HEV) technology studies has recently increased. Some problems have arisen with these technological studies. The range problem in vehicles is the biggest of these problems. Therefore, various solutions are sought for energy storage problems in vehicles. In this article, studies on HEVs and energy storage in EVs are examined. According to the data obtained from this examination, the performance analysis of the Energy Storage Systems (ESS) was made. The performances of the electrochemical batteries used in HEVs and EVs were compared. In addition, a flywheel energy storage system was investigated in HEVs and EVs to recover the energy lost due to braking.

Keywords: Battery, Electric vehicles, Energy storage, Hybrid electric vehicles, Regenerative braking systems

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1. Introduction

Greenhouse gasses which have become a part of everyday life, have many negative effects on the global climate and air quality. Greenhouse gasses are becoming more threatening because of these atmospheric emissions [1]. The transport sector is the second largest producer of CO_2 from fossil fuel combustion. This makes the transport sector the second most influential factor in global warming [2]. According to the International Energy Agency's 2020 report on EVs, the introduction of EVs was crucial for reducing air pollution and greenhouse gas emissions [3]. EVs have higher energy efficiency than conventional internal combustion engine–based vehicles [4, 5]. It has been determined that a traditional internal combustion engine can use only 18–25% of the energy it produces from fuel, and a vehicle with an electric motor and battery can use 46% of the energy it receives from the socket [6]. In addition, EVs recover most of the kinetic energy lost during deceleration by using the electric motor as a generator [7]. However, the problem of insufficient driving range in EVs remains. This is an important factor limiting the rapid development of EVs [8, 9]. Therefore, high–performance ESSs are required to power EVs. As ESSs are the most important part of EVs, there is an urgent need to improve battery technology. There are three types of batteries that stand out in EVs. These are Lead–Acid (LA), Nickel Metal Hydride (Ni–MH), and lithium–ion batteries. In addition, there are metal–air batteries such as Lithium–air (Li–air) batteries for large energy requirements [10].

The demand for greater distance between charges limits future perspectives of Ni–MH batteries in fully battery powered EVs. Currently, much research is being conducted on Ni–MH batteries to fill the energy density gap in the United States (USA), Europe, Japan, and China. More than 10 million HEVs used Ni–MH batteries for propulsion applications in 2018 [11, 12].

Recently, a lot of work has been done on the compound brake control strategy to increase the range and braking performance of EVs [13]. In one of these studies, a battery and flywheel hybrid energy storage system was built using regenerative braking. For example, the Flywheel Energy Storage System (FESS) has been integrated into 500 busses in London. As a result of this application, 20% fuel savings were achieved [14]. It is emphasized that this hybrid system in EVs has a critical effect on economic and dynamic properties. The application of such hybrid methods in the ESSs of EVs not only increases the cruise range of the EVs but also extends the service life of the batteries [15–17]. In another study, a flywheel was used in the regenerative braking system of a bus [18]. The energy obtained from this system is stored in the flywheel. Because of the study, it was determined that the fuel consumption of the bus decreased by 30%.

In a simulation study, the energy storage efficiency of $LiFePO_4$ batteries compared with that of supercapacitors (SC) was investigated [19]. As a result of this study, $LiFePO_4$ batteries and SCs were found to store regenerative energy with an efficiency of approximately 67% and 97%, respectively [20].

HEVs have distinct advantages over single–energy vehicles in terms of increasing system operating efficiency, extending battery life, and reducing pollutant emissions [21]. Fathabadi [22] applied a hybrid vehicle with a weight of 1880 kg and a fuel cell/supercapacitor. Because of this experiment, the vehicle achieved a power efficiency of 96.2% at a speed of 158 km/h. He also determined that the distance traveled was 435 km.

In this study, the effects of ESSs used in EVs and their working principles, power and energy densities, cycle life, charge–discharge times, and temperature on their efficiency were investigated. The obtained results were compared and analyzed.

2. Energy Storage Systems Used in HEVs–EVs

ESSs emerged using energy in a specific form. These systems can be classified as mechanical, electrochemical, chemical, electrical, and thermal [23]. In the selection of ESS to be used in EVs, features such as energy density (Wh/kg), power density (W/kg), cycle efficiency (%), self–charge–discharge characteristics, and life cycles are considered [24].

2.1. Mechanical energy storage systems

Three mechanical storage systems are commonly used to generate electricity in EVs. These include compressed air energy storage (PAES), pumped hydro storage (PHS), and flywheel energy storage (FES) [25]. FES is used as an energy storage system at a significant level in the automotive industry [26].

FESS, which stores energy according to the rotating mass principle, consists of three main parts. These are the bearing system that supports the rotor, the rotor system to store energy, and the generator/motor system that performs the energy conversion [27]. These systems have their own specific tasks. FESS has a high–speed rotating mass of up to 50,000 rpm [28, 29]. Since FESS depends on the square of the rotor speed according to Equation (1), it is clearly seen as an important parameter in the energy storage system [30]. In addition, flywheels have high power density, little environmental impact, a long–life cycle, high cycle efficiency (85%), and long operating life [31]. They can also store energy in megajoules (MJ).

$$E = \frac{1}{2}\, I \quad \omega^2 \qquad (1)$$

In equation (1), ω(rad/s) is the angular velocity of the flywheel, E (J) is the amount of energy stored by the flywheel and I $(kg\ m^2)$ is the moment of inertia [32].

FESSs in ESSs are a system with higher efficiency (90–95%) than other methods [33]. In EVs and HEVs, the flywheel is used to store energy. This energy can also be used for sudden acceleration of a vehicle on steep slopes [31, 34]. Braking energy is stored by FESS in a short time in the regenerative braking mode [32].

Erhan and Özdemir [14] presented the topology in Figure 1 regarding the integration of FESS into a hybrid system. In this topology, charging the FESS was defined as the deceleration mode and discharging it was defined as the acceleration mode. In addition, a brushless direct current motor was used in the motor/generator (M/G) unit where the FESS was located. In the first case, the kinetic energy of the FESS was increased and stored in the flywheel. In the second case, this stored energy was transferred to the M/G unit. In this study, a recovery efficiency of 56% was achieved. In addition, it was determined that FESS was 30% lighter, 60% less volume, and 50% inexpensive than traditional CVT (continuously variable transmission). In addition, it was emphasized that FESSs require less maintenance and have fewer moving parts than CVTs.

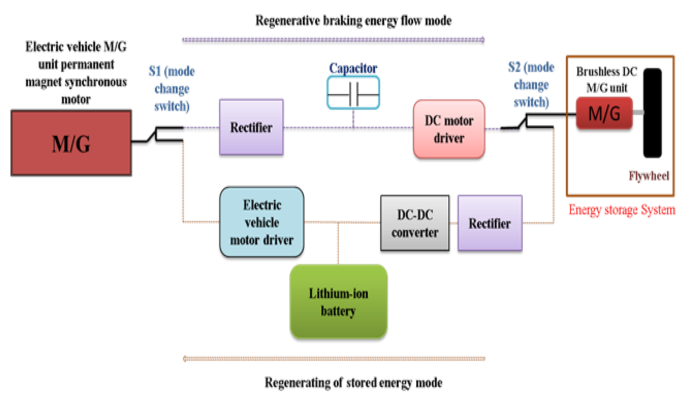

Fig. 1. Diagram of a hybrid electric vehicle with FESS

2.2. Electrochemical energy storage systems

References should be listed at the end of the paper in font 9. They should be numbered consecutively and referred to square brackets. Electrochemical energy storage systems can be classified into three parts: electrochemical capacitors, batteries, and fuel cells. Batteries work by converting chemical matter into electrical energy [35]. There are two types of electrochemical storage [36]. They are classified as primary and secondary batteries. Secondary batteries with higher specific energy and power are used in EVs. These batteries have advantages such as a flat discharge profile, high specific energy, low resistance, high power density, negligible memory effect, and wide temperature performance range [37]. In today's EV applications, nickel metal hydride batteries, lithium–ion batteries, and lead acid batteries are mostly used [38].

LA batteries were the first battery technology to appear approximately 130 years ago [39]. The most widely used battery type in internal combustion vehicle applications [40]. In addition to this use, they are used in many areas because of their robustness, safe operation, temperature tolerance, and low cost [41].

$$PbO_2 + H_2S0_4 \rightarrow PbSO_4 + H_2O + ½O_2 \qquad (2)$$

$$Pb + H_2S0_4 \rightarrow PbSO_4 + H_2 \qquad (3)$$

In the lead acid batteries in Equation (2) and Equation (3), where the electrochemical reactions are given, lead dioxide (PbO_2) is used as the positive electrode, lead (Pb) is used as the negative electrode and, sulfuric acid (H_2SO_4) solution is used as the electrolyte [42]. Figure 2 shows the chemical properties of the lead–acid batteries during charging and discharging. To generate power, the electrodes immersed in an electrolyte consisting of a diluted solution of H_2SO_4, and during discharge, H_2SO_4 combines with sponge Pb and PbO_2 to form lead sulfate ($PbSO_4$) and water [43]. During the discharge process, the electrolyte becomes increasingly diluted. Thus, during the charging process, the H_2SO_4 density in the electrolyte increases [44, 45]. Its rated voltage is higher than 2.00–2.25 V. Moreover, its power density is 250 W/kg, its specific energy is 35–40 Wh/kg, its cycle life is 1500–5000, and its total service life is 15 years [46].

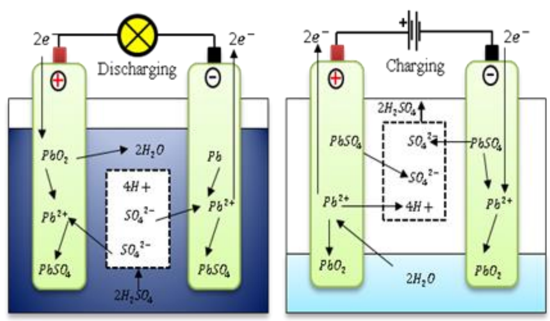

Fig. 2. LA battery chemistry a) During discharge b) During charging

Nickel metal hydride batteries are based on a hydrogen storage electrode in a hydroxide solution [47]. These batteries have 1.5–2 times higher energy density than Ni–Cd [48, 49]. Although their energy densities are low compared to lithium–ion batteries, they have advantages such as high–power capacity, overcharge/discharge tolerance, environmental compatibility, and safety. Because of these advantages, they are more suitable for portable EVs and HEVs [50]. Lithium–ion batteries are a serious alternative to the Ni–MH batteries used in most HEVs [51]. One of the battery types frequently used in EVs is Ni–MH batteries [52]. Additionally, as of 2017, 85% of the batteries used in the listed HEVs were based on Ni–MH batteries [53]. However, with the rapid market development of HEVs, it was concluded that extensive research is underway to improve the cycle life of Ni–MH batteries and their energy density.

2.3. Electrical energy storage systems

Supercapacitors (SC) are also electrochemical capacitors [54]. When voltage is applied to the capacitor, opposite charges accumulate on the surface of each electrode separated by the dielectric [55]. This allows the capacitor to store electrical energy, as shown in Figure 3 and Figure 4 SCs are divided into two groups: Pseudocapacitor and electrochemical double–layer capacitors (EDLCs) [56]. The EDLC consists of conductive porous electrodes. Capacitors whose capacitance depends on the electrostatic absorption of electrolyte ions on the surface area are EDLCs. These capacitors are based on energy storage from reversible redox reactions at the electrolyte/electrode interface [57].

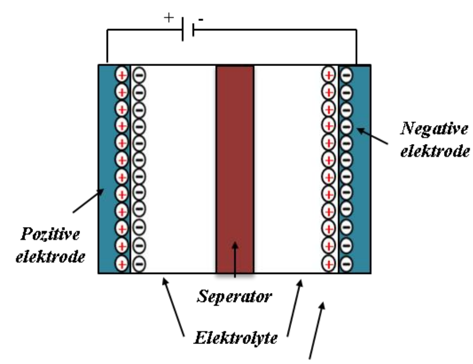

Fig. 3. EDLC schematic diagram of supercapacitors

Pseudocapacitors, unlike EDLCs, involve a reversible Faradic redox reaction. This rapid reaction occurs at the electrode of the capacitors. When potential is applied, charges begin to be generated. These charges are then transferred through the double–layer formation of the EDLC [58]. As in batteries, so–called capacitors also involve the addition and separation of charges. However, in terms of power density, using an electrolyte makes pseudocapacitors more efficient. Here, the capacitance is in an electrochemical form and largely depends on the active sites present. Faradic charge is stored in the electrodes of these capacitors [59].

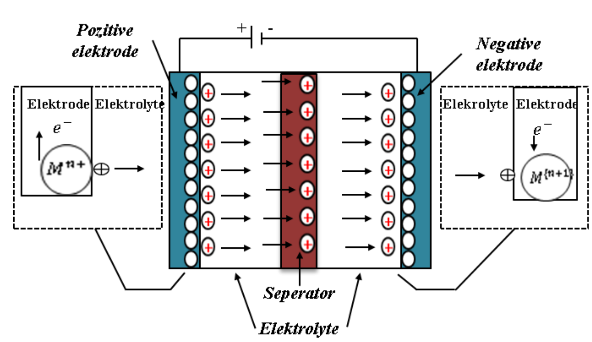

Fig. 4. Pseudocapacitor (M represents metal atom)

Supercapacitors can directly accumulate electrical energy because of the electrochemical double layer effect. At the same time, supercapacitors can be charged and discharged at a very high specific current (A/kg), 100 times greater than that of a battery [35].

EDLCs and redox/pseudosupercapacitors are limited to practical applications because of their low energy density [60]. Therefore, typical SCs are used because of their high specific power (W/kg) [35]. It is also very interesting in energy storage because of its high energy density, fast charge/discharge rate, and ability to operate for a lifetime without requiring maintenance [61]. Other reasons for using SCs in EVs are their stable electrical properties and wide temperature range [62]. However, SCs have low specific energy densities. Therefore, they are not suitable for long–distance driving as an independent energy source.

The best application of SCs would be in plug–in (rechargeable) HEVs (PHEV) and EVs. It is suitable for use in combination with batteries designed for long cycle life, high energy density, and low cost [63]. High currents can be produced by the motor because of regenerative braking. SCs can capture and store this energy efficiently [64]. Improvements can be made in the overall efficiency of the system when this application is implemented. Simultaneously, SCs greatly reduce the dynamic stress on the batteries and peak currents, which also extends the battery life [63].

Since 2013, HEA or EV automotive manufacturers have developed prototypes using UCs instead of batteries to increase the efficiency of the powertrain and store braking energy [65]. Today's HEA technology increases the efficiency of EVs, improve the environmental perspective, and reduce the cost [66, 67].

Typically, SCs are used because of their high specific power (W/kg) [35]. However, the specific energy of current commercial SCs is lower than that of most batteries. In Figure 5, the energy–power density change of various energy storage systems is given [62].

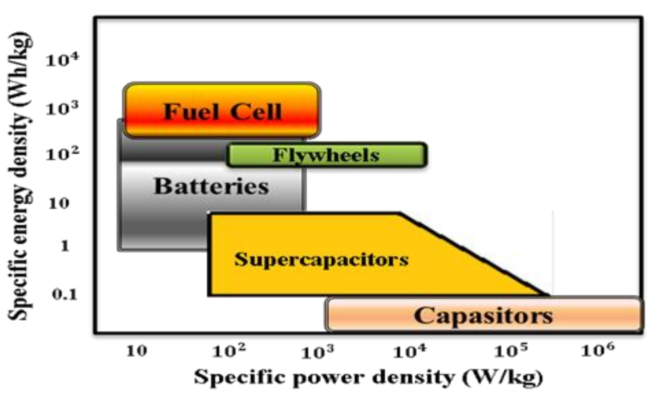

Fig. 5. Power density by the energy density of various energy storage systems [68]

3. Hybrid Energy Storage Systems

If the battery is used as the sole energy source of an EV, the power and economy of vehicles will be greatly limited [69, 70]. The battery pack is generally recognized as the most expensive single component in an average configured EV. This accounts for approximately 35–45% of the total production cost [71]. In addition to their high cost, battery performance, driving range, power output, cycle life, safety, etc. affect the overall performance of EVs. However, finding the perfect battery chemistry is also not easy. Therefore, hybrid ESS is promising, and it is a widely used solution where the battery is expensive [72].

HEVs can be expressed as the integration of more power sources (internal combustion engine, fuel cell, etc.) on the vehicle. In other words, an HEV consists of two or more energy sources (battery, flywheel, etc.) [73]. For example, Arslan [74] obtained electrical energy by driving a linear generator with an internal combustion engine to solve the range problem of small EVs.

In the FC/battery/SC topology, FC is the main energy source. Batteries and supercapacitors are used as two auxiliary energy sources [75–77]. For example, in HEVs, different energy sources such as batteries, SCs, or FCs can be used to power the electric drive system. However, only a portion of the energy exchange capacity of SCs can be used in the SC/battery configuration [78]. In addition, a hybrid FC/SC/battery configuration provides the longest battery lifetime [79, 80].

Yi et al. [81] created the hybrid vehicle model consisting of a battery and capacitor, as shown in Figure 6. In this model, the distribution of power between energy storage devices was examined. Additionally, the in case of developing an energy management strategy, reducing power consumption in EVs and thus extending battery life has also been investigated.

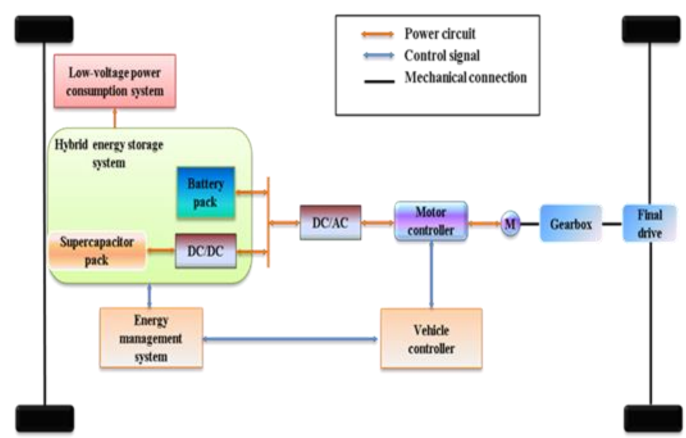

Fig. 6. HEV block diagram

Batteries are insufficient to store the current that occurs during short–term regenerative braking [82]. Depending on the size of the selected FESS, battery fatigue can be reduced by up to 30% with the hybrid system topology [83].

Alpaslan et al. [84] emphasized that meeting the energy demand and achieving the desired vehicle range depend on the selection of FECV components, and the vehicle' curb weight and operating conditions should also be considered. In addition, they also stated that the selection should be made according to the rotor–stator type of the electric motor (brushless and permanent magnet), current type (AC or DC), and energy or power rate of the storage unit (e.g. Lithium–ion battery, NiMH battery and SC).

Yildiz and Özel [85] investigated the energy consumption performance of topologies in power transmission systems and the usability of minimized electric motors in hydrogen fuel cell electric vehicle models. In this work, a 68 kW Proton Exchange Membrane (PEM) fuel cell and a supercapacitor with a maximum storage energy of 7 kWh were used as the two main energy sources. The supercapacitor was preferred as the main energy source for regenerative braking. Based on the New European Driving Cycle (NEDC) and Federal Test Procedure (FTP–75) drive cycles, the state–of–charge ratios of the supercapacitors were also compared. As a result, it was found that the miniaturized electric motor structure can recover more energy than other structures.

Boyacıoğlu et al. [86] stated that PEM fuel cells, which use hydrogen as fuel, will be widely used in EVs in the future. Accordingly, it has been stated that it will lead to increased use of EVs and increased hydrogen fuel production. In addition, it was emphasized that the use of PEM fuel cell electric vehicles contributes greatly to the reduction of greenhouse gasses in the transportation sector.

Kurtulmus and Karakaya [87], in their study on the use of FESS in regenerative braking systems of EVs, compared the amount of energy obtained at the maximum and minimum angular velocities of two flywheels with the same radii and different masses. The energy difference between the two flywheels was found to be 23% and 13% at maximum and minimum rpm, respectively. In addition, the power obtained from the flywheels at maximum and minimum rpm was determined to be 23% and 3%, respectively.

4. Conclusions

With the development of various technologies, reducing costs, and finding ESS solutions, HEVs and EVs will be widely used technologies in the future. In this article, the main issue is different energy storage technologies and HEVs used for EVs. At the same time, the regenerative braking systems used in HEVs and EVs are also discussed. Because of these investigations, it was determined that the energy released when the vehicle goes downhill or in case of sudden braking can be stored with higher efficiency.

Flywheels had high power density, a long–life cycle, long operating life, little environmental impact, and 85% cycle efficiency. Therefore, it has been observed that the energy generated because of regenerative braking can be stored to a large extent by the flywheel system. According to this result, the range problem can be minimized by using FESS, and accordingly, the service life of the batteries can be extended. In addition, it has been determined that the lowest–cost $LiFePO_4$ battery among lithium batteries is frequently preferred in EVs. However, $LiFePO_4$ batteries store energy with an efficiency of 67%, whereas supercapacitors store it with an efficiency of 97%.

Other than the lithium batteries used in HEVs and EVs, other batteries are also used. The use of Ni–MH batteries in 85% of HEVs has been found to be a serious alternative to lithium batteries. In addition, more than 10 million HEVs in 2018 saw the use of Ni–MH batteries for propulsion applications.

Generally, an average configured battery pack is the most expensive single component in an EV. It has been determined that this constitutes approximately 35–45% of the total production cost. Also, not only cost but also driving range, power output, safety, cycle life, etc. It affects the overall performance of EVs in various ways. It is also not easy to find the perfect battery chemistry. Therefore, it was concluded that hybrid ESS should be used instead of a single source.

Various topologies have been developed for the use of fuel cells, which are high–energy densities and clean energy sources, in EVs and HEVs. According to these topologies, the range problem in electric vehicles can be overcome with fuel cell vehicles. By using various ESSs, hybrid designs can be developed to develop high–efficiency, low–cost, and long–range vehicles.

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Conflict of Interest Statement

The authors declare that there are no conflicts of interest in this study.

CRediT Author Statement

Zeyneb Nuriye Kurtulmuş: Conceptualization, writing, editing, and data curation
Abdulhakim Karakaya: Data curation, supervision, and validation

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