Hybrid Battery Technologies with Battery Management System in Power and Energy Sectors

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***Abstract*—As an energy storage device, battery technologies had evolved over the years from using a simple nickel-iron to the later superior technology of lead-acid. Furthermore, as the needs of the battery to store a large amount of energy grows, the manufactures of batteries have been compelled to manufacture superior hybrid batteries by combining different technologies with efficient battery management system. The hybrid battery technology using high-quality power electronics combines different but complimentary individual battery technologies into a single pack. However, there is a need to understand the individual characteristics of these batteries. This will not only make the battery to be safer, cost-effective, and more reliable but also predict accurately the condition of the battery units. By comparing their technical properties such as cost, efficiency, and life cycle, this paper discusses the overview of existing hybrid of battery technologies and how they can be managed in power and energy sectors.**

***Index Terms*—Battery Electrical Vehicles (BEV), Battery Storage Technologies, Battery Management System (BMS), Electric Vehicles (EV), Hybrid Energy Storage System (HESS).**

I. Introduction

The quest for ensuring a cleaner environment and sustainable natural resources, with a focus on reducing the emission of greenhouse gasses (GHG) has been the major focus of many researchers and energy experts. Other reasons which are to reduce energy over-dependence on coal, oil and to store energy etc. for transportation, and powering of the utilities, had necessitated the research into the application of battery. Therefore, the application of battery as energy storage has become important domain in ensuring a sustainable and feasible development of an efficient electric grid system, as well as efficient clean transportation electrification for Electric Vehicles (EVs). It is predicted that by the year 2020, the EVs clean market will be dominated by full Battery Electrical Vehicles (BEV) models (Young et al. 2013). Currently, batteries in the Transport Vehicles (TVs) applications are conventionally used either as Starting-Lighting-Ignition (SLI) or as Energy Storage Source. The batteries used in the TVs have different requirements such as high amount of current to enable initial ignition of the vehicle and are not designed to perform deep discharge frequently as compared to another application usage where they are used as motive power, auxiliary power, or as traction. The designer of this later requires the deep discharge of about 80% Depth of Discharge. The operation mode of SLI batteries requires high state-of-charge (SOC), with shallow cycling, while full discharge is never achieved [16]. Hence, SLI batteries must satisfy the requirements such starting function or startup Internal Combustion Engine (ICE). Their service function, for example, must ensure an electrical buffer function between the production and consumption (air-condition, radio, lightning etc.). Due to the continuous supply of power peaks needed by the traction drive, more stress is applied to the battery to satisfy that mentioned requirement. Consequently, the lifespan of the battery is reduced. Therefore, the topology that could offer improvement in terms of cost, efficiency, and lifespan is a hybridization of the different battery technologies.

Lead-acid batteries (LABs) have been the power source of choice for the automobile electric system since the early years of 20th. Currently, 12V LABs are often the first choice for SLI batteries, due to low cost and availability. With the increase in load demand in the automobile electric system, LABs are failing to meet the demand of the electric system. Therefore, research works are extensively focusing on the development of an efficient, reliable, and safe Hybrid Energy Storage System (HESS) using a different combination of batteries technology such as Lead Acid batteries (LABs), Lithium-ion (Li-ion), and Super-capacitors. The aim of this hybridization is to produce HESS with the capability to deliver power and energy within the wide range and requirements expected in the Internal Combustion Engine (ICE) vehicle battery application. The HESS which would meet the demand of electrical systems of TVs, and EVs; must be able to effectively adapt to either long-term or short-term usage, as well as a specific way of recharging. It must also be able to determine the charging/discharging current, voltage, State of Charge (SOC), State of Health (SOH), End-of-Life (EOL) and operating temperature. However, recharging of each type of battery is important, as each battery requires a different mode of charging due to its chemical compositions.

Since the LABs are failing to meet the demand of electric system in TVs and other useful functions in power and energy sectors, there are needs to have HESS as an alternative. Furthermore, with many other problems which remains in many electrical power systems, such as instability in power quality because of sag, distortion of voltage, fluctuation of frequency response, high peak demand, large-scale renewable power flow introduction of renewable energy based microgrid, energy storage, etc., had necessitated the urgent need for hybrid energy storage system (HESS) [19]. Each battery technology requires different ways through which it needed to be treated hence; this work is aimed at providing a review of the existing battery technologies and their management strategies. This also includes their advantages, characteristics, and usage.

In this work, the review of current battery technology is provided. Also, it highlights the characteristics of each battery technology in combining to form HESS. As a contribution of the paper, different charging characteristics, methods and battery technologies have been compared and inferences regarding their applications have been derived.

The organization of this paper is as follows; Section II discussed the existing battery technologies, HESS is discussed in Section III, battery management and characteristics are discussed in section IV. Section V discussed different battery charging methods, while section VI is the conclusion.

II. Battery Technologies

The battery is a device that contains one or more cells connected in series or in parallels, which chemical energy is converted directly into electricity by means electrochemical oxidation-reduction (redox) reactions. The cell consists of electrodes which are a positive electrode which holds a higher potential and negative electrode which hold a lower potential, electrolyte, terminals, and container [17]. Battery technologies have evolved over the generations as seen in Table I. Table I further examine various developmental attributes of battery technologies. Each of these energy storage technologies contains both advantages and disadvantages which made them suitable or unsuitable for specific application in energy storage device. Therefore, in choosing a battery for a specific purpose, factors such as State of Life (SOL), State of Health (SOH), State of Charge, (SOC), safety, protection, Open Circuit Voltage, (OCV), as well as cost, etc. must be carefully considered. Furthermore, there is a specific way through which each battery technology must be treated. Failure to do show will not only shorten the lifespan of such battery but can lead to both human injury and appliances damage such as an explosion.

The Lead-acid batteries are the oldest type of rechargeable batteries. Although has a superior quality as compared to other battery technologies, however, lead-acid batteries are associated with poor depth of discharge. Lithium-ion batteries have been the most promising batteries used in electric vehicles. However, it is limited due to its working mechanisms such as low chemical reaction speed, high C-rate charging and discharging rate. Normally charge and discharge at high C-rate operation inspire the serious polarization phenomenon of battery, which limits the discharge capacity and leads to the tinier driving range. Thus, the high workload affects the health of the battery, which will accelerate the ageing and shorten cycle life of the battery. At any moment, lithium-ion batteries deteriorate in performances, this consequently reduces the life of lithium-ion batteries.

Super-capacitors are developing to a promising field in energy storage technology. The super-capacitor also which is also known as ultra-capacitor is made of double capacitors, an electrode, an electrolyte, a collector, and a diaphragm. Its advantages include stable electrical characteristics and its operating temperature range is relatively wide. They are normally used to supply high current at ranges that are considered harmful to the conventional battery in TVs, and EVs. Super-capacitor also has high power density, longer lifespan, wider operating temperature range, and completely free maintenance. Other examples of battery technologies are discussed in Table I for comparison.

There is no single battery technology that can meet all the requirements of all energy storage applications. Thus, critical analysis and comprehensive evaluation of each battery technologies must be carried out before choosing a battery for various purposes such as in electric vehicle, green mobile cellular, etc [2]. The Table I summarizes performances characteristics and compares the existing battery technologies. Furthermore, based on Table I, each battery technology's characteristics can be assessed against the requirement of the applied systems.

III. Hybrid Energy Storage Systems (HESS)

With the increasing prices of gasoline and continuing breakthroughs in the battery technology, the HESS combines advantages of different batteries into a single pack controlled by battery management system (BMS). Using HESS, the battery is prevented from surge current or high-rate charge and discharge that might severely reduce the lifespan of battery [20]. The authors of paper [20] therefore proposed using Model Predictive Control (MPC) model that was based on energy management method to achieve hybridization. This was realized using the advantage of each battery technology to complement each other. The super-capacitor use with the battery in this HESS has the following advantage [22]:

- Improve vehicle acceleration
- Improve overall drive efficiency, thereby increasing the driving range.
- Reduce life cycle costs by extending the battery life
- Reduce capital costs by direct replacement of some batteries.
- Increase the energy and power density of HESS

TABLE I. COMPARISON OF EXISTING DIFFERENT ENERGY STORAGE DEVICES [2] [7] [9-10].

Storage Technology	Energy Rating (MW)	Quality	Discharge Period(h)	Capital Cost ($/kWh)	Cycle Cost ($/kWh) output	Life Cycle (y)	DOD at 80% cycle of life	Percentage Efficiency (w/o power electronics) (%)	Advancement Stage	Security issues	Disadvantages
Pumped hydro	10 MWs to GWs	Very good	> 8.0	80–200	0.001–0.02	30	20,000–50,000	70–85	Commercial	Exclusion area	Special geological and geographic requirements
Superconducting magnet energy storage	10 MWs	Good	0.25	10,000	0.4–1.70	30	1000–10,000	90–95	Commercial	Magnetic field	Before a full commercial storage level can be reached, the additional long loop is required
Compressed air energy storage	10 MW to GW	Very good	0.1–15.0	50–110	0.03–0.06 (with gas)	30	9,000–30,000	60–79	Demonstration stage with limited commercial	Pressure vessels	Special geological and geographic requirements
Flywheel energy storage	1–100 kWs	Slow	0.1–1.0	300–5,000	0.05–0.4	20	> 20,000	> 90	Commercial	Containment	Low energy density and efficiency
Supercapacitors	5–100 kWs	Good	0.02–1.0	82,000	0.03–0.4	low	10,000–100,000	> 95	Commercial	—	It has a low level of energy density and discharges itself quickly
Thermal energy battery or storage	MW to 100 MWs	Slow	1.0-45.0	$500/kW	0.035–0.16	20	4000–10,000	60	Commercial	Risk of the explosion because of temperature rise	Large initial capital is required to build the initial infrastructure
Lead-acid batteries	kW to 10 MWs	Fast	0.1–4.0	350–1500	0.40–1	5–10	200–1500	70–76	Commercial although, not is bigger appliances or systems.	There is a high risk of hydrogen explosions	It is associated with bad performance in the handling of deep discharge
Sodium sulphur batteries	0.1–100’ MWs	Fast	1.0–10.0	300–950	0.09–0.5	5–10	210–4500	85–90	Commercial stage	High temperature operation. Potential fires	Poor thermal cycling
Lithium-ion batteries	KW to 100 MWs	Fast	0.1–1.0	850–5,000	0.3–1	5–10	5,000–7,000	> 90	Commercial, but not in large scale appliances.	Potential fires and explosions (require advanced monitoring and control)	High cost
Flow batteries	Between kW–100 MWs	High	1.0–20.0	180–250	0.06–0.2[a]	> 10	5,000–14,000[b]	75–85	It is almost at the full commercial stage.	It is associated with leakages as well as poor chemical handling	It has low-medium energy density compared to other technologies

a. *Decreases with increasing energy to power ratio. Possible reduction by partial refurbishment.*
b. *Up to 270,000 cycles reported for All-Vanadium Redox Battery by Sumitomo Electric Industries, Japan.*

The main advantages of LABs, in this HESS, are due to their low self-discharge and are not expensive thus, make LABs a good choice to reduce the cost of HESS. Their disadvantages are short lifespan, low power and energy density. Therefore, is advisable to use with them with other materials such as Li-ion or super-capacitor where the LABs will be used for low frequent demand. However, using the Li-ion, Nickel and super-capacitor in HESS will increase the cost of the EVs.

Currently, BMS for the HEVs greatly in the reduction of fuel, while other merits are highly dependent on the energy management strategy used. One of the main challenges facing this BMS is to make the correct decision on power split. The early energy management controllers mostly use heuristic approaches inspired by the preferred behaviour of the propulsion system [21]. The main advantage of the heuristic approach is that it can be implemented easily in real time driving mode. However, heuristic strategies do not guarantee the desired performance under different conditions. This problem can be solved using systematic model-based optimization methods with significant performance or objective functions [19].

Hybrid batteries have certain advantages compared to a normal battery technology. With each technology advantage, HESS can achieve high power capabilities and large energy storage at the same time with a smaller size or weight in comparison to using batteries only to form HESS. The HESS with super-capacitor also increases battery cycle life through peak power shaving, improved dynamic performance, and thermal burden relief [25]. According to [23], SCANIA buses are using HESS of super-capacitor, where super-capacitor is used to handle the charge/discharge cycles expected in an HEV. HESS is used to increase the lifespan of battery by allowing the super-capacitor to handle the high peak charge and discharge currents during rapid acceleration or deceleration of the HEV, while the battery is used to supply the substantially lower average load current. [24] it shows an example of HESS in a Chevrolet Volt car. In the summary, the advantages of using HESS in TVs and EVs, HEVs, and plug-in hybrid electric vehicles (PHEVs) are:

- HESS improve the battery storage capacity consequently meet the demand of electric system in vehicles. The batteries can be connected either in parallel or series according to the desire of demand of vehicles.
- Have higher power and energy density compared to a normal battery.
- HESS has a longer lifespan; the batteries technology will not be subjected to frequent deep charging.
- HESS reduce the lifespan cost
- HESS improve vehicles efficiency and range.

IV. BATTERY CHARACTERISTICS AND MANAGEMENT

As earlier stated, the need for proper energy storage management is crucial in any application where the storage is required. A typical example of the need for proper energy storage management can be found in renewable energy system integration, and in electrical vehicles (EVs). Both require a storage device or battery that can store energy and discharge accordingly from few seconds to several hours. In terms of renewable energy integration, battery technologies such as Li-ion, flow battery, and Sodium-Sulphur (Na-S) have been used due to their advantages as summarized in TABLE I. EVs can be classified into three different classes [1]. These are battery EVs (BEVs), hybrid EVs (HEVs), plug-in hybrid EVs (PHEVs). It should be noted that PHEVs as well as HEVs contain battery energy storage and combustion engine internally, but, a rechargeable battery option is used in BEVs. This is employ for propulsion of electric motor power [3].

It is important to understand the system behaviour to be able to develop a full and quite accurate model of each subsystem components. Battery Management strategies help in making a decision that allows for the effective design of the energy management system. The BMS is designed to meet two objectives. The first objective is a constant monitoring of the HESS states to determine the ability of the HESS to deliver its specified output and to prolong its useful lifespan. Secondly, the BMS ensure that the HESS operates efficiently and at the safe range, such that the battery is not damaged by ensuring an accurate dimensioning of batter's characters such as State of the Health (SOH), State of Life (SOL), State of Charge (SOC), and the Remaining Useful Life (RUL) [18].

BMS also promote the lifespan of a battery in a safe way. Although most batteries contain inbuilt electronic control protection circuit against high and low voltages, this cannot be the main substitute for the role or function of BMS, which is to increase the safety and efficiency of a battery. This makes BMS be crucial in development and control of the battery.

Generally, batteries that are used in power and energy sector are typically characterized by high energy density as well as low power density. Low power density is a major limiting factor in improving the performance dynamics of many EVs. Thus, the background information on these batteries is essential to the way through which a battery can assess its power ability. Furthermore, the frequency of operating for charging and discharging of each battery differs because of internal resistance, and amplitude [26]. According to [27], the lithium-ion batteries have internal resistances that could maximize directly as the frequency of operation increase. Peukert equation is used to model the ampere-hour capacity of batteries as it affects the current rate of discharge [27]. Therefore, both current and state of charge (SOC) are non-linear of charging and discharging of internal resistances of batteries [28-29]. Other battery's characteristics are summarized as follows;

- A battery cell, Battery module, and Battery pack: A single battery cell is the combination of cathode and anode electrodes, separated by a liquid electrolyte in a case. The battery module is a combination of two or more battery cells in a single case. By and large, a case of battery pack contains different battery modules for better heat energy management. Thus, a single EV can contain many battery packs.
- Battery Volumetric Energy Density: Volumetric energy density can be defined as the unit volume of a specific energy of a battery. It is also referred to as battery energy density. The SI unit is Wh/l [1] [12].
- Power Density: The zenith power of a battery at a specific volume is known as its power density. Its unit is represented by W/l [1] [12].

- Gravimetric Power Density: Gravimetric power density, otherwise called specific power is the summit battery power at a specific mass unit [1] [12].
- Battery Gravimetric Energy Density: The gravimetric energy density of a battery can be described as the total amount of energy which a battery can retain at a specific unit mass. It is also known as battery specific energy. The unit of battery specific energy kept in a battery is Wh/kg [1] [8] [12].
- Ampere-hour Capacity: In a fully charged battery, the total amount of charge that can be withdrawn from it is known as its Ampere-hour capacity, under normally specified working conditions. This working condition is often predetermined by the manufacturer during the production of the new battery [1] [5] [12].
- Charge or Discharge Rate: Total amount or rate of charge that can be taken or stored in a battery per hour is called the significant capacity rate. This is used to know the rate at which a battery can hold or release a charge [1] [12].
- Internal Resistance: The total collective corresponding resistance in an enclosed battery is known as its internal resistance. It is, however, dependent on activities of the battery such as charging, discharging, and operation modes [1] [12] [15].
- Peak Power: Peak power can be described as the stage where lag voltage value is equal to the two-thirds of the input voltage within a circuit [1] [12-15].
- Battery Cut-off Voltage: The lowest permitted to empty a battery, designed by a manufacturer is known as cut-off voltage. This is the point at which the batteries can no longer discharge any further [1] [12-15].
- State of Charge (SOC) of a Battery: This is a very significant attribute of a battery, because, it helps to determine the safety mode of the battery and ensure its good working condition. Battery state of charge can be defined as a critical condition of a battery which is determined by the load current, temperature, and other working condition. Accurate measurement of SOC help to determine the number of charges left in a battery [1] [12] [15].
- State of Health (SOH) of a Battery: The state of health of a battery is the comparison between the highest number of charges a battery can hold when it was manufactured newly to and the highest number of charge it can hold when it is old. SOH can also be defined as the ratio of the maximum charge capacity of an aged battery to its maximum charge capacity when the battery is new. SOH is a significant factor to determine the age of a battery as well as its leftover lifecycle. [1] [12].
- The Depth of Discharge (DOD) of a Battery: A parameter that is used to estimate the total percentage of the number of charges that had been taken away from a battery during operation is known as the depth of discharge. Each battery at deep-cycle has a different percentage of discharge as indicated in TAB I [1] [12].
- Number of Cycle: Total estimated cycle capacity that a battery has at any value of DOD before it fails to discharge or charge, is its number of cycle, also known as cycle lifetime. The value of cycle life which is its operating life is often estimated to be 80 % of the DOD. The cycle life is inversely related to the DOD. Thus, DOD of smaller value is often used during active operational mode to achieve bigger cycle life [1] [15].
- Calendar Life: This is the expected period of a lifetime of a battery when it is subjected to specific conditions such as temperature and SOC [1] [15].
- Battery Reversal: This is a condition that occurs in a battery when it is made to work when the value of the voltage of the negatively charged cathode electrode is higher than the voltage of positively charged anode electrode. When this condition is prolonged over a long period of time, the weaker cell is subjected to a force which made it reverse its voltage and continues to supply current to the circuit. This often damaged the cell of the battery permanently [1] [12] [15].
- Thermal Management System (TMS): Protecting the of a battery against the rise in temperature is important. Failure to do this causes explosion and fire outbreak in most batteries. Therefore, TMS is implemented in EVs to guide against high temperature within a battery pack. Thus, prolonging the life cycle of a battery. Cooling is often adopted in most simple batteries; however, the cooling liquid is employed in many advanced technologies [1] [12].

Therefore, from the battery management angle, the BMS can be generally delineated as the integration of computation hardware, controllers, sensors, and communication, combined with designed software algorithms, to estimate the capacity of charge/discharge current as well as the time taken for the calculation of charge rate, depth of discharge, state of charge and state of health of the battery pack. As already mentioned, important features such as SOH estimation, SOC estimation, battery safety and protection, accurate cell balancing, and charging control, are a great deal in BMS' operation.

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V. Conclusion

This review had been able to present a substantial background information on current battery technologies and their usage informing HESS. It has also been able to compare the currently available battery technologies as well as the methods of charging. This had helped to identify the progress that had been made, and some of the knowledge gap such as the ecological factors in deposing these worn-out batteries. Since the application of batteries in storing energy will increase, so will their negative impact on the ecological system. Thus, the impact of batteries on the environment should be considered, to avoid environmental pollutions. Also, along with all the advantages of using BMS in hybridization of different battery technologies, the importance of cost-effectiveness cannot be overemphasized. Electronics control mechanism or device for BMS is an open research that needs to be considered as well as a policy to ensure harmful or pollution of the environment is prevented.

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