Comprehensive Analysis of EV and Fuel Cell Technologies for E-Mobility Applications

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Abstract -- **One of the main reasons for the present acceleration in the development of hybrid electric vehicle technologies is the depletion of fossil fuels and their detrimental effects on global warming. The current literature on energy applications in electric vehicles (EVs) and power conversion topologies and storage systems is compiled in this study. For an EV to reduce the amount of time it takes to charge, it needs sources that are very powerful and energy efficient. The several power conversion methods and energy storage technologies that can be used with electric vehicles are described in this article. Benefits and drawbacks of several power conversion designs, including DC-DC converters, DC-AC inverters and AC-DC rectifiers are discussed. This study also looks at the performance characteristics of a number of energy storage devices, such as fuel cells, super-capacitors and batteries. The paper also projects future developments in this field and addresses the difficulties and possible advantages of integrating these technologies into EVs. The conclusions of the paper are supported by other research studies.**

Keywords: *Batteries, Electric vehicles, Fuel cell, Ultra-capacitor, Hybrid electric vehicles*

I. INTRODUCTION

ELECTRIC vehicles (EVs) are growing in popularity because of their superior performance, low maintenance costs and reduced emissions. Nonetheless, EV dependability and efficiency are significantly impacted by energy storage and transmission systems. Advantages and disadvantages of various energy storage and power conversion topologies for electric vehicles are covered in this article [1], along with reviews and comparisons. Based on current research articles and technical reports [2], the review offers a comprehensive summary of the most innovative developments in this industry. The primary objective of this paper is to provide an in-depth overview of the many power conversion and energy storage alternatives for plug-in vehicles (EVs) so that engineers and researchers can make informed decisions while developing new EV technologies. Due to their advantages for the environment and the economy, electric vehicles have recently attracted a lot of attention [3]. Electric vehicles (EVs) are incredibly effective, affordable to operate, and ecologically friendly modes of transportation since they run on battery energy. However, the energy storage systems and power converter topologies employed have a big influence on how reliable and efficient EVs are.

When discussing EVs, the term "power conversion topologies" refers to the electrical circuitry used to transform battery-stored DC power into the AC power needed to run the electric engine [4]. The range, acceleration and energy economy of an EV can all be significantly impacted by the power converter designs' efficiency and performance [5]. Energy storage devices in EVs are batteries used to store electrical energy for the electric motor. The range, power output, and general performance of the EV can all be significantly impacted by the characteristics and functionality of the battery.

Scientists and engineers are working on novel energy storage technologies and power converter topologies to improve the efficiency and reliability of EVs [6]. Through a comparative analysis of these disparate technologies, scientists and engineers may make informed decisions in the development of new electric vehicle technologies. This overview article aims to provide a thorough examination of the energy storage and power conversion topologies now available for EVs, along with an assessment of their benefits and drawbacks. The review will offer a thorough overview of the most advanced technologies in this subject, based on current research publications and technical reports. The most promising energy storage and power conversion topologies for the creation of new EV technologies will be chosen with the help of this study.

The two primary types of EVs are hybrid electric vehicles (HEV) and all-electric vehicles (AEV). AEVs can be powered by a variety of electrical energy sources, including solar, fuel cells, UC and batteries. Since road transportation accounts for about 28% of GHG emissions, the development of AEVs and HEVs is primarily driven by the desire to minimize greenhouse gas emissions [7]. Encouraging the usage of electric vehicles may be one of the best ways to reduce GHG emissions and protect the environment because the transportation industry is a significant source of emissions. In 2017, the benefits of using electric vehicles became apparent to people all around the world, and as a result, over a million of them were sold [8].

Currently, there are more than three million electronic cars on the road globally, a 50% increase from 2016.

II. CLASSIFICATION OF ELECTRIC VEHICLES

The main generator that is most frequently utilized is the internal combustion engine (IC) engine, showcasing proven technologies for both passenger and commercial vehicles. Currently under development is a hybrid automobile, sometimes known as a hybrid electric vehicle or HEV, which is powered by an EM coupled with an internal combustion engine. Consequently, the vehicles can be simply categorized as ICEVs, HEVs, or AEVs. While hybrid electric vehicles (HEVs) use a variety of power sources to propel their vehicles, internal combustion engines (ICEs) running on gasoline power ICEVs. AEVs, on the other hand, are totally powered by electricity. When ICEVs and AEVs are combined in the simplest possible way, an HEV is produced. HEVs, which combine an electric motor and internal combustion engine to increase fuel efficiency, and Fuel Cell Electric Vehicles (FCEVs), which generate electricity using hydrogen fuel cells, are two other categories of EVs. In addition, EVs are divided into groups according to their size and function, such as electric trucks, buses, and cars, which reflects the wide range of uses for electric propulsion in the transportation industry. Electric bikes and scooters are examples of micro-mobility solutions that are becoming common.

Battery Electric Vehicle: A battery-electric vehicle (BEV), or simply an electric car, is a vehicle that runs solely on electricity. It is powered by rechargeable batteries, which are typically composed of lithium-ion cells and an electronic engine. Compared to traditional gasoline-powered cars, the battery electric car is a more environmental-friendly choice because it produces no pollutants while in operation. The production of the battery and the electricity required to charge it, however, may have a negative impact on the environment. Batteries have advanced to the point that longer travel distances and faster recharge periods are now possible. As a result, more people now consider electric cars to be a sensible option for transportation.

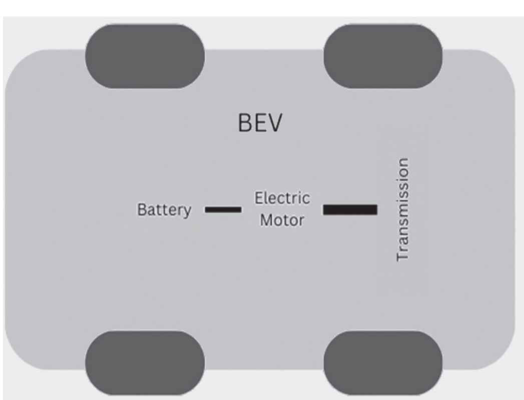

Figure 1. Basic structure of BEV.

Hybrid Electric Vehicle

Series Hybrid Electric Vehicle: It powers its electric drive train using energy from a tiny ICE that also turns the wheels. The primary functions of the ICE, which is not physically attached to the wheels, are powering the electric motor and charging the batteries. Here, the electric motor—which is propelled by the ICE and doubles as a generator to charge the batteries—is the main source of motion. To optimize economy, the ICE operates at a constant speed and is not instantly coupled to the wheels. During regenerative braking, the electric motor can also function as a generator, transforming kinetic energy into electrical energy and storing it in the batteries.

Parallel Hybrid Electric Vehicle: It combines an ICE and an electric motor. The gearbox connects the electric generator and ICE in a parallel HEV so they can cooperate to move the car forward. Here, both the electric generator and internal combustion engine are connected to the transmission and can cooperate to power the wheels. A variety of engine designs, including ones with one or more motors, can be made. An ICE and an electric motor are often connected in a single motor configuration.

Series-Parallel Hybrid Electric Vehicle: It combines components of parallel and series hybrid vehicles, called SPHEV. Both an electric generator and an ICE can power SPHEV.

There are three different ways to operate the car:

- When the car is in electric-only mode, its battery and electric motor are its only sources of power.
- In hybrid mode, the vehicle moves using both an ICE and an electric generator.
- ICE-only mode: The electric motor is deactivated and the vehicle exclusively runs on the ICE. In this configuration, additional power is provided to the ICE during acceleration by the electric generator, which may enhance fuel efficiency.

Plug-in Hybrid Electric Vehicle (PHEV): It comprises an electric generator, rechargeable battery cells, and a gasoline engine. A gasoline engine must be utilized to power the car after a short while for PHEVs. The term "plug-in" hybrid was created because a PHEV may have its battery cell recharged by plugging the car into an electrical outlet. For a set amount of time, usually between 20 and 50 miles, this allows the car to run entirely on electricity, depending on the battery's capacity and the state of the road. When the vehicle's electronic range is exhausted, the gasoline engine will fire up to provide it more power and a longer range. Compared to traditional gasoline-powered cars, PHEVs provide a number of benefits, such as increased fuel economy, reduced emissions and cheaper maintenance. They also have the benefit of allowing battery cells to be recharged at home or at public charging stations. Some users might find the electrified range insufficient, and

PHEVs can cost more than traditional gas cars. The energy source that is used to charge the battery is another aspect of PHEVs' environmental friendliness; depending on the location and time of day, this energy source may change.

Fuel Cell Hybrid Electric Vehicle (FCHEV): It is a hybrid car with an electric engine that is fueled by batteries and fuel cells. Because of their high efficiency and minimal emissions, FCHEVs are usually regarded as one of the most promising alternatives to traditional gasoline-powered cars. The only byproducts of the electrochemical process that the fuel cells in FCHEVs use to transform hydrogen gas into energy are heat and water vapor. The vehicle's fuel cells can generate enough energy to run the electric engine or store it in the battery for later use. A large-capacity lithium-ion battery that may supply additional power when required, like during propulsion or hill climbing, is frequently seen on an FCHEV. Compared to traditional gasoline-powered vehicles, FCHEVs have a number of benefits.

TABLE 1-- COMPARISON OF HYBRID ELECTRIC VEHICLES

Characteristics	*Propulsion*	*Energy system*	*Energy source and infrastructure*	*Advantages*	*Disadvantages*	*Important issues*	*References*
ICE vehicle	IC engine-based drives	Fuel tank	Products made of petroleum (crude oils) with refuelling station	Better performance, easy operation, completely commercialized, trustworthy, long-lasting	Poor fuel economy, hazardous emissions, and rather large size.	Non-renewable, emits toxic gases, is reliant on crude oil, and uses up fuel.	[17,18]
BEV	Electric motor drive	Battery, ultra-capacitor	Electric grid charging	Zero emission, independence on petroleum products, short driving range (200-300 km), commercially available.	High-performance propulsion, significant upfront costs, and charging infrastructure	Grid effect from battery pack weight, size, and ICE, as well as infrastructure for charging stations, are all factors.	[19,20]
FCHEV	Electric motor drive	Fuel cell, battery, ultra-capacitor, flywheel	Hydrogen, fuel	Zero emission, high efficiency, independence on crude oil, high driving range	Fuel processor, fueling system, and hydrogen cost are considerable.	Cost of H_2, H_2 storage infrastructure, refilling station, cycle life, and dependability	[11]
HEV	Electric motor drive and IC engines	Battery, ultra-capacitor, ICE generating units	Gasoline station, infrastructure for grid charging facilities	Low emission, commercially available, long driving range	dependent on battery size, driving cycle, and crude oil, greater cost	Battery pack weight and size, component integration, and power management for multiple input energy storage sources are all important factors.	[12,13]
Plug in HEV	IC engine, EPS-based drive	Fuel tank, battery, ultra-capacitor	Electrical energy with charging facilities	Energy efficient, petroleum products with charging station,V2G or G2V capability gradually commercializing	Higher complexity, impact on grid, poor dynamic response	Infrastructure for charging stations, power flow management, and battery pack weight and size	[15,16]

HEV Energy Sources: HEVs use a combination of energy sources to power their motors. The main energy sources are:

- ICE: An ICE uses a standard patrol or diesel engine to power the vehicle. The engine, which is often smaller than that of a regular car, is utilized to supplement the electric drive when extra power is needed or when the battery is becoming low.
- Wheel Power: An electronic engine powers the wheels of the car. When moving, it is powered by an internal combustion engine (ICE) or recharges a battery through regenerative slowing.
- HEV's battery is its primary energy storage component. Regenerative braking and the electric motor generate energy that is stored for when the engine needs electricity. (Regenerative braking is a technology that harnesses the kinetic energy of a stopping vehicle to provide power to a battery. This extends the vehicle's range and reduces the amount of energy lost when braking).
- Fuel Cell: A fuel cell is another energy-producing component of some HEVs. Water is the only byproduct of a fuel cell's usage of oxygen and hydrogen to produce energy. This provides the vehicle with a dependable and effective electrical source.

Fuel Cell: In an electrochemical device called a fuel cell, an oxidant and a fuel react chemically to produce energy. It is made up of a fluid, a cathode and an electrode. The anode receives the fuel, which is typically hydrogen and the cathode receives the scavenger, which is typically oxygen. An electrical charge can be produced by ions moving through the electrolyte between the electrode and cathode.

$$E_{cell} = E_0 + \frac{RT}{2F} ln \frac{P_{H_2}\sqrt{PO_2}}{P_{H_2}o}$$

This formula, also referred to as the Nernst equation. Here *R* is the universal gas constant, *F* is Faraday's constant, and P_{H_2} and P_{H_2O} are the partial pressures of hydrogen and water respectively, E_0 is the internal hydrogen/oxygen chemical process' standard potential. The total voltage of FC could be stated as follows, accounting for the "double layer effect" and ohmic overvoltage:

$$V_{fc} = E_{cell} + V_{act} + V_{ohm}$$

where V_{act} is the activation overvoltage in an electrical domain that exhibits the "double layer effect," and is the ohmic overvoltage caused by the membrane resistance. Transportation, mobile power generation and fixed power generation for residences and commercial buildings are a few possible uses for fuel cells. Unfortunately, these technologies are still too expensive to be widely used and there is currently no infrastructure for hydrogen.

Battery: The energy storage component known as the battery is used in relation to EVs and HEVs to power the vehicle's electric motor or motors and other electrical components. An EV or HEV's battery is usually a rechargeable lithium-ion battery, while some models may also use lead-acid or nickel-metal hydride batteries.

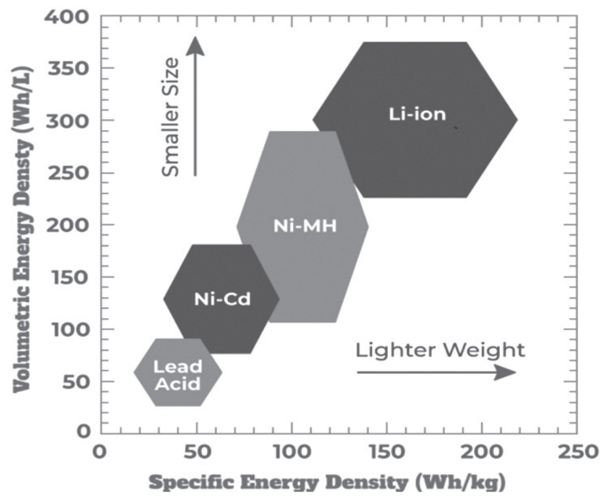

Figure 2. Energy density for different batteries.

Because it affects the vehicle's range, propulsion, and other crucial operational factors, the battery is essential to its entire operation. In contrast to an EV, which just has its battery as a power source, an HEV's battery powers the car in conjunction with a gasoline engine. Kilowatt-hours (kWh) are the unit of measurement for battery capacity, and a larger battery often has a longer operating range. Owners of EVs and HEVs should also examine the charging method and battery life. All things considered, the battery is crucial to the operation of both electric and hybrid vehicles, and the automotive industry is actively focused on improving this sector through research and development.

Ultra-Capacitor: Super-capacitors, sometimes referred to as electrochemical capacitors, are long-lasting, efficient devices with appropriate energy and power density. Because of the charge storage technique, it can withstand millions of filling and discharging rounds. The porous carbon electrodes used in ultracompact capacitors (UCs) have a very small spacing (around ten) and a large surface area (1000 m^2/g) with the electrolyte. Normal capacitors, on the other hand, consist of two electrodes that are spaced apart by a dielectric material. Compared to conventional capacitors, which measure capacitance in millifarads (mF), microfarads (F), and picofarads (pF), UC capacitors measure capacitance in a comparatively greater number of Farads, (F).

$$W_{\max} = \frac{1}{2} \cdot C_{\text{total}} \cdot V_{\text{loaded}}^2$$

The energy that may be stored in a capacitor is W_{max} . Because of their large capacity, higher operating temperature, and high efficiency (>90%), UCs can be used in a variety of applications in place of batteries. Production of UCs with higher capacitance values has been made feasible by noteworthy developments in nano-material technology. The technology's commercialization has advanced and manufacturing costs have decreased due to the growing use of UCs in transportation-related applications.

Fly Wheel Energy Storage: A flywheel is a mechanical battery that can hold rotating kinetic energy. It is a device for mechanical and electrical energy storage. Flywheel Energy Storage Systems (FESS) are widely used in applications such as hybrid electric vehicles, trains, ships, spaceships, wind turbines and hybrid power generation systems. The three main components of the FESS are the machine, which consists of a generator, motor and inertia wheel; the rotor bearing; and the power electronic circuit or interface. A flywheel's stored kinetic energy (EK) is equal to the product of square of its spinning speed and moment of inertia.

Furthermore, FESS finds uses in enhancing power smoothing, power quality, power system stability and facilitating the incorporation of renewable energy sources. There are two types of FESS: low-speed FESS and high-speed FESSs. Each of these types has distinct physical traits and ways of using things. A low-speed FESS structure does not require a vacuum enclosure, while a high-speed FESS structure does require magnetic bearings, composite discs and vacuum enclosures. Most applications of the high-speed FESS are in space technology. Formula One cars frequently use magnetic flywheels because of its various advantages, which include high energy density, fast speed charging, and low losses.

Motors in Electric Vehicle: Rather than using an internal combustion engine to generate power, EVs use one or more electric engines. The size, weight, and intended use of an electric automobile are some of the parameters that influence the type and location of the motors. Below are some illustrations of electric car engines and the related reading materials:

- Permanent Magnet Synchronous Motors (PMSM) are a popular choice for electric vehicles because of their high-power density and efficiency. They use a stator with windings and a stationary magnet rotor to generate power. Two EVs that use PMSM are the Tesla Model S and Model 3.
- Induction motors (IMs) are another type of AC motor that is utilized in electric vehicles. They are less costly and have a simpler design than PMSM, but their effectiveness is lower. Certain electric vehicles, including the BMW i3 and Nissan Leaf, use induction engines.
- Brushless DC motors (BLDC) and PMSM motors are similar in design, although BLDC motors have a different control system. They have a high power-to-weight ratio, which makes them suitable for lightweight electric vehicles like scooters and e-bikes.
- Switched Resistance Motors (SRM): SRMs are a type of motor that generates power by utilizing the iron core's resistance. They are inexpensive, have an easy-to-understand construction and run quickly. Two EVs are the Audi e-tron and the Jaguar I-PACE.

III. CHALLENGES AND POSSIBLE OPPORTUNITIES

The automobile industry releases a new electric vehicle (EV) model with a new technological advancement almost every day. Electric vehicles still need to prove they are a competitive option to internal combustion engine (ICE) vehicles, even if there are ever more of them on the road. Before EVs can be widely used and proven in terms of design and employment, a number of technological and financial challenges need to be addressed.

The following is a list of the challenges:

- Why EVs are comparatively more expensive and have limited dynamic capabilities and short driving ranges because they rely on a single energy source.
- Why there are only a limited number of hydrogen filling stations and plug-in recharge stations available for FCHEV vehicles.
- ESS takes up a lot of space.
- Issues with the disposal of batteries and FC due to the hazardous elements they contain after usage.
- Dependability issues with the system brought on by the faulty EM, FC stack, power converter, battery, and storage device
- *Range Anxiety:* Some customers worry that they will run out of battery power before arriving at their destination because the range of electric vehicles is shorter than that of conventional gasoline-powered automobiles. This problem can be remedied by developing more efficient batteries and a dependable recharge mechanism.
- *Charging Infrastructure:* For electric cars to become widely accepted, a stable and accessible infrastructure for charging them must be established. Now, charging outlets are few and not usually in convenient locations.
- *Battery Technology:* One of the main barriers to the widespread adoption of electric vehicles is the continued high cost of batteries. The development of new and more efficient battery technologies is necessary to reduce the cost of electric cars and increase their efficiency.
- *Production costs:* Compared to vehicles powered by normal gasoline, the production of electric cars is more expensive. The high cost of battery production and the lack of industrial economies of scale are contributing factors behind this.

- *Supply chain:* Finding supplies for rare earth metals, which can have detrimental impacts on the environment and create unstable political situations, is just one of the many steps in the convoluted supply chain required to make electric automobiles.
- *Consumer Education:* Despite the fact that electric automobiles require less maintenance, emit less pollution, and operate more quietly, many consumers are still unaware of these benefits. Increasing the penetration of electric cars can be achieved through educating consumers about their advantages.

In view of the aforementioned difficulties, the following options are apparent: Research possibilities exist in battery technology for much higher specific power and energy that offer longer working range.

- Building new infrastructure along highways to facilitate hydrogen refuelling and battery charging at regular intervals, which will stimulate infrastructure investment.
- The development of cutting-edge technologies with better cost- and reliability-effectiveness for power converters, batteries, storage devices, EM, and FC stacks.
- Public-private cost sharing and government-issued clarifications about control over Electric Vehicle Supply Equipment (EVSE) service providers might expedite the implementation of initial infrastructure.
- Using renewable energy sources, including solar power, to boost dynamic performance. Local governments can enforce new, improved EVSE designs by offering incentives for EVs or by making significant changes to local rules and regulations.

Intelligent infrastructure can be implemented through the collection and exchange of data from research projects and demonstration projects.

High voltage and high energy usage systems are required for energy storage systems that store energy from renewable sources like solar and wind power. These gadgets can be used to supply backup power during periods of high usage or when renewable energy sources aren't available.

IV. CONCLUSION

Electric cars are more in demand as they reduce dependency on fossil fuels and greenhouse gas pollution. However, a major disadvantage of electric cars is their short range, necessitating the development of effective energy storage and power conversion technologies. For electric vehicles, numerous power conversion topologies and energy storage technologies have been developed, each having pros and cons of its own. Bidirectional converters, DC-DC converters, and DC-AC inverters are some of the most widely used power conversion designs. In a similar vein, batteries, fuel cells and ultra-capacitors can all be used as energy storage devices in electric cars. Factors like power requirements, operational range, cost and efficiency are considered when choosing the best power converter design and energy storage system for a certain electric car application.

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