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# HYBRID ELECTRIC VEHICLES: A COMPREHENSIVE SURVEY

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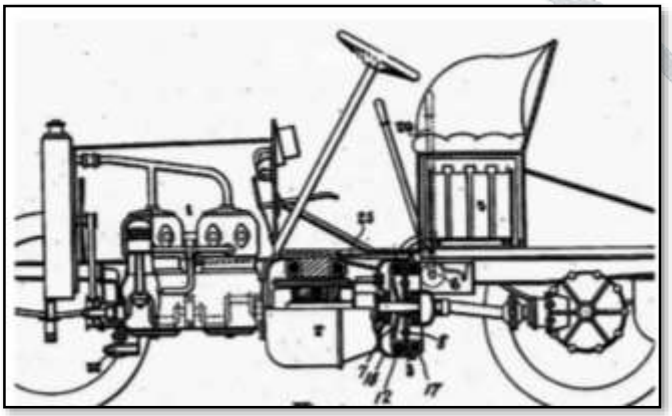
***Abstract:*** "Green Technology" is highly emphasized upon since last few decades, with the objective to promote "Clean Environment". With the serious environmental issues caused due to exponentially increasing transportation, Hybrid Electric Vehicles [HEVs] are in great demand as a promising solution. This research study presents a comprehensive survey of the various types, characterizations, energy models, energy management strategies and few examples of in HEVs. Research developments, issues and challenges in the reported literature of HEVs are also highlighted in this study along with a brief note about recent advancements and the latest models of HEVs.

***Index Terms*: Hybrid Electric Vehicles, Energy Management**

## I. INTRODUCTION

"Transportation" in the current and upcoming days has witnessed a substantial paradigm shift. While in earlier days it took more than few months to travel across distant places, today it may just take a few hours or a few days at most. Considering the serious limitation of fossil fuel-based vehicles, Electric Vehicles are now emerging as entities of paramount importance in this astonishing modern vehicle revolution [1]. Electric Vehicles [EV] use the electricity in conjunction with another energy source. Hybrid Electric Vehicles [HEV] power its wheel using a combination of internal combustion and electric motor leading to fuel efficiency, whereas the EV restricts to a single source to power its wheels. EV thus mark relatively lower emissions when compared to HEV. Figure 1 depicts a mere representation of long revolution in the Electric Cars. First Electric Car was developed in Scotland, somewhere in 1839. The present modern day showcases a fast-growing Hybrid SUV [2].



The first electric car is reported to have been developed in Scotland in 1839 [3]

BMW X3 plug-in hybrid fast-growing EV SUV segment ( Stephen Edelstein January 19, 2022 [4]

Fig. 1: First EV and Modern HEV

## II. RELATED LITERATURE

Year 1834, has a special mention in the history of Electric Vehicles because the first electric vehicle – a Tricycle was built by Thomas Davenport which attracted the attention of the researchers, manufacturers and Environmental thinktanks. Later on, after around 1990s EV started gaining popularity and were considered as potential solution to clean environment. HEVs have evolved from their nascent stage and are reported to offer better fuel efficiency and operate in favor of environment. They have continuously attracted the interests of manufacturers as most promising technology and thereby demanding continuous research to explore the energy resources, various devices and technologies, power and energy management strategies, propose various configurations, explore the optimization techniques, switching techniques to ultimately enhance the acceptability, utility and performance of the HEVs. The market witness some of the excellent contributions from Toyota and Honda. [5]

HEVs utilize two or more energy resources like an engine, battery, ultra-capacitor and Fuel cell [6]. One of the power source is derived from power of the Internal Combustion Engine [ICE] while other one is chemical batteries and/or electric motor drive. Recent advances have also marked use of photovoltaic / solar cell as a potential energy source in HEVs [7]. Various software simulators are also exhaustively utilized for validating various sizes and speeds of the designed motors. One such software widely used is 'Advanced Vehicle Simulator [ADVISOR]'. Autorickshaw – a popularly preferred mode of transport in India & other Asian and Plug-in HEVS were analyzed for their performance, fuel efficiency and emissions. MATLAB / SIMULINK is also a popularly used simulation tools for such experimentation and rigorous performance analysis [8].

Next few sub-sections present the developments and related literature on HEVS.

### 2.1 Categories of HEVs:

Based on the energy sources used, HEVS are broadly classified in the following four Categories [9]:

Mild Hybrids: Along with electric power they additionally utilize, a small boost to gasoline engine of the vehicle. They do not have to be plugged in and the recharging of the batteries is through regenerative braking.

Full Hybrids:

Full hybrid vehicles, like mild hybrids, have both a gasoline engine and electrical components. A complete hybrid vehicle's electrical components, on the other hand, can handle far more workload than a mild hybrid vehicles. At certain distances, most full hybrids can be operated entirely on electricity. Two major types of Full HEVs are categorized as Parallel and Series types, however with the recent advancements in the technology, a combination of both the typical types, namely, Parallel and Series is also evolving and being practically deployed using a computerized set-up to decide the mode.

Plug-In Hybrids:

Unlike Mild and Hybrid HEVs, that depend only on the internal means to charge their batteries, Plug-In Hybrids use external charge along with the internal as well. This results in obvious yield to greater electric ranges and come close to fully Hybrid and fully electric vehicles.

Electric Vehicles with Range Extender Hybrids

Some HEVs are equipped with a small gasoline engine to offer extra power when required. When an electric vehicle runs out of battery power, it must be recharged before it can be used again. Such range extender hybrids use their gasoline engine to charge the battery or power the electric motor. Depending on the size of the gasoline engine, the range may extend from few dozen to few hundreds of miles.

### 2.2 Classification of HEV

Earlier HEVs were typically classified as either series or parallel based on their mechanical connections. As depicted in Figure 2, in series type of HEV, the Engine [E] and Generator [G] are coupled together. Electric motor is responsible for the propulsion of electricity and the engine is used to recharge the battery. In parallel type both the Engine and the Motor are coupled via a transmitter. In a series/parallel HEV, however recent advancements in technology present few HEVs offering advantages of both series and parallel. Series-Parallel and complex hybrid structures of HEV are therefore very common these days that use an additional planetary gear set is used [10].

Classification of HEV is also based on various possible configurations of Ultra Capacitor [UC] and battery. They depend on the various ways to connect and interface a battery and UC as listed below [7]:

- Passive battery / UC
- Passive cascaded battery / UC
- Active cascaded UC / battery
- Active cascaded battery/ UC
- Active cascaded configuration with two DC/DC Converters
- Multiple DC/ DC converters
- Multi- input DC/DC converter

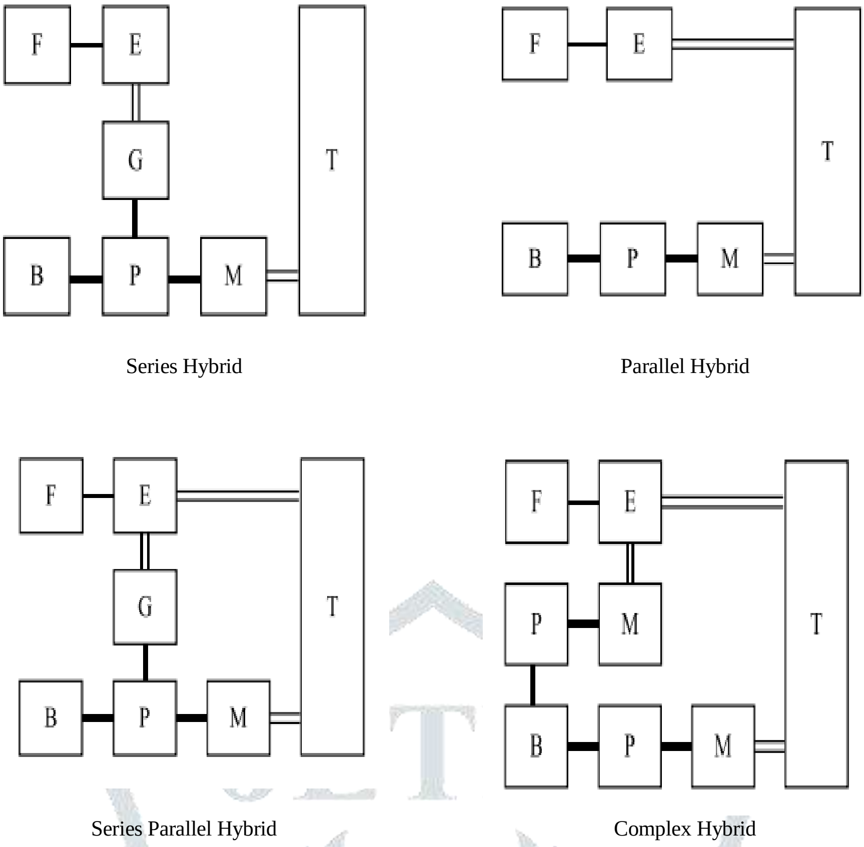



Fig 2: Classification of HEVs [10]
(B: Battery, E: Engine, F: Fuel Tank, G: Generator, P: Power Converter, Transmission, —— Electric link : bidirectional, ▬ Hydraulic link : unidirectional, ═ Mechanical link : bidirectional )

### 2.3 Types of HEV

Hybridization Factor, HF is defined as ratio of PEM and (PEM + PICE) where, PEM is the Peak Power of the Electric Motor and $P_{ICE}$ is the Peak Power of the Internal Combustion Engine ICE [8].

HEVs are categorized in the following types considering the HF as the criteria:

- Micro HEV (HF < 0.1) use limited power and saves the fuel consumption of the fuel.
- Mild HEV (HF < 0.25) are not capable of driving vehicle alone but saves fuel consumption.
- Power Assisted HEV (0.25 < HF < 0.5) can be turned in fully electric mode and become zero emission.
- Plug-in HEV (HF > 0.5) uses battery as a storage device

### 2.4 Energy Sources in HEV

Battery model, Fuel Cell [FC] model, Solar Cell Energy model are very commonly used renewable source to power the hybrid vehicles. A brief comparison of the energy sources is presented in the Table I.

Table I: comparison of the energy sources

| Energy Model | Principle / Approach used | Advantages | Disadvantages |
|---|---|---|---|
| Batteries | Chemical reaction to Electrical energy | High Power Density | - Low Energy density<br>- Have limited life cycle that depends on operating temperature |
| Fuel Cell | Chemical reaction for production of DC Electrical Energy | Can be used for transportation applications | - Slow dynamic properties<br>- Need secondary sources |
| Solar energy model Photovoltaic | Convert sunray to electrical energy | Low production cost | Suitable for vehicles with weight less than 300 kg (light electric vehicles) |

### 2.5 Energy Management Strategy in HEV

Energy Management Strategy [EMS] is a key aspect of HEV, which decides the fuel efficiency and emissions of the vehicle. Some of the popularly reported EMS are dynamic Programing, non- linear model predictive control, Bilevel model and equalization consumption minimization strategy [11]. These strategies are compared and detailed in the appended Table II.

Table II: Energy Management Strategies

| EMS | Advantages | Remarks |
|---|---|---|
| Dynamic Programming [12] | Achieves globally optimal results | Requires prior knowledge of the entire driving cycle (speed Road slope) |
| Pontryagin's Minimum Principle (PMP) [13] | Minimize the Hamiltonian function at each instant to optimize the power | Needs information of the future driving conditions to achieve optimal EM |
| Nonlinear Model predictive control [MPC] [14] | Obtained synergy in Adaptive Cruise Control ACC and EMS | Gear shift commands, torque distribution and hybrid dynamics needs to be considered |
| Bilevel MPC [15] | Improve fuel economy in eco-driving application | |
| Equivalent consumption minimization strategy [11] | Utilizes flexible torque request, promising fuel efficiency | Other configurations like complex parallel, series parallel needs to be explored. |

### 2.6. Hybrid Cars v/s Zero Emission Vehicles [ZEV]

While the idea and the driving force behind the invent of HEVs was clean environment and zero emission, unfortunately the new generation of hybrid cars are not as eco-friendly as expected and do not comply to its purpose. The hybrid cars are designed to support both the modes of operation i.e., Battery and Gasoline. In battery operated mode, hybrid cars do not emit exhaust or harmful emission and are therefore ecofriendly. However, in hybrid mode of operation, even the latest HEVs like TESLA are reported to emit harmful emissions although they are relatively still less than the conventional vehicles. The Hybrid Cars although projected as zero emission cars may not necessarily be always capable of achieving that standard [16].

## III. Discussion and Conclusion

Environment friendly transportation is dire need of the society due to limitless hazards caused by the conventional vehicles. Considering the available energy sources, Electric Vehicles [EV] are reported to have limited driving range and power capacities. In near future, HEVs are expected to offer encouraging solution and dominate the automobile industry. Various system configurations are being researched by exploring electric machines, sensor-less control, high power semiconductors, switching topologies. Research and subsequently, the manufacturing community is all geared up to design, develop and deploy the motor drives, power units, energy sources, adaptable and flexible energy management strategies, various hybridization factors and other components required for HEVs, they are not yet fully experimented on all the types and configuration of HEVs. Moreover, while encouraging results in terms of 'Zero Emission' are obtained with battery operated mode of HEVs, it is still an issue and remains unresolved, when it comes to hybrid mode of operation. This issue is of paramount importance specially in the regions of extreme climatic condition. This is because, the HEVs are programmed to switch to gasoline mode in extreme cold / hot weather and switching to hybrid mode which leads to emission and leaves carbon footprints. Adaptive cruise control which is a preferred choice of drives demands extra energy leading to further switching of modes. HEVs are thus practical and sustainable solution for Super-Ultra-Low Emission Vehicles [SULEVs]. Battery operated EV [BEV] and Fuel Cell – EV [FCEV] are Zero Emission vehicles [ZEV] [10]. A comparison showcasing the characteristics of each are presented in table III.

AI is playing a crucial role in the EV industry, with applications like as autonomous driving, user behavior monitoring, and smart navigation systems. It can be utilized for a variety of safety applications, including equipment predictive maintenance, driver behavior monitoring, and vehicle security. Artificial Intelligence is being used by a variety of organizations in their vehicles; some are using it to replace present transportation systems with self-driving services, while others are using it to improve the battery power of their electric vehicles.

Table III: Comparison of HEVs, BEVs, FCEVs

| | HEV | BEV | FCEV |
|---|---|---|---|
| Range | Long | Short | Medium |
| Cost | Medium | High | Very High |
| Emissions | SULEV | ZEV | ZEV |
| Maturity | Mature | Immature | Immature |

Government of various countries is promoting the deployment of HEVs and Electric Vehicles. Schemes like Faster Adaption and Manufacturing of Hybrid & Electric Vehicles (FAME) are promoted and numerous initiatives at state level are undertaken in India. Few States exempt the road fees for the EV while other states like Delhi, Maharashtra, Meghalaya, Gujarat, Assam, Bihar, West Bengal, Rajasthan, and Odisha provide subsidies ranging from 5K to 30 K [17]. Regardless of untiring efforts by the Government, research community and the manufactures, the acceptability, safety, driver comfort, reliability, performance and cost of the HEV is still limited and has a long way to go.

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