A SYSTEMATIC LITERATURE REVIEW ON HYBRID ELECTRIC VEHICLES

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Abstract:
The urgent need to reduce fossil fuel consumption and environmental harm has sped up advancements besides fuel-efficient vehicles. Hybrid electric vehicles, or HEVs, have come to be seen as an effective remedy for these problems. Better fuel efficiency, fewer pollutants to meet environmental standards, and a safety net versus rising petrol prices are all made possible by HEVs. The performance of these cars was affected by the architecture and components used, which combined the power of an internal combustion engine and an electric motor. The number of HEVs has increased significantly due to technological developments and governmental policies. This in-depth analysis of the literature on HEV architecture, control strategies, parts, and energy storage systems gives a complete picture of the state of the research. It also investigates the different energy management systems (EMS) and strategies employed by HEVs. The review identifies the existing literature's constraints, difficulties, and knowledge gaps. These results shed light on areas that require further investigation to address issues and fill in knowledge gaps in the domain of hybrid electric vehicles. Finally, this literature review contributes to a better knowledge of HEVs by analyzing their architecture, control strategies, parts, and energy storage systems. It also provides details on the various EMS and HEV-specific procedures. The results of this review highlight the significance of ongoing research to overcome obstacles and improve the field of hybrid electric vehicles.

Keywords: Hybrid Electric Vehicle, Battery, Energy Management System, Architecture, Storage System.

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1. Introduction:

Air pollution is the second greatest risk to human health after climate change, according to the World Health Organisation. The air that nine out of ten people breathe poses serious threats to their physical well-being. Additional lab-tested results indicate that CO2 emissions have multiplied throughout the European region. Additionally, CO2 emissions from fossil fuels keep rising. Transportation is by far the main contributor to this pollution, which results in unsustainable energy consumption and is predicted to increase to 50% [1] in 2035 from the current level of 25% global CO2 emissions. [2] hypothesize that by lowering CO2 emissions, EVs (electric vehicles) could contribute significantly to vehicle decarbonization. Electrical vehicles are those that are wrought by one or more electric motors. It can be powered by a generator or fuel cell system that converts fuel to energy, a battery periodically recharged by solar panels, a collector system that draws electricity from extravehicular sources, or any combination of these options. Among the many types of electric vehicles are electric boats, planes, and even spaceships [3]. [4] It has been proposed that countries impose strict restrictions to set a limit on the selling of ICEVs. Norway & the Netherlands have set a deadline of 2025, and France has set a target of 2040 to promote EVs and end the sale of ICEVs. The growing number of electric vehicles significantly impacts the distribution infrastructure. The distribution system traditionally supported a unidirectional flow of electricity from centralized power plants to customers. However, because EVs need infrastructure for charging and use the grid for power, their widespread adoption creates a new dynamic. The distribution system has both opportunities and challenges due to the rise in demand for electricity brought on by EV charging. On the one hand, EVs can operate as mobile energy storage devices and aid in grid stabilization, making it possible to integrate renewable energy sources like solar and wind. On the other hand, concentrating EV charging in certain locations may put pressure on regional distribution systems, causing grid congestion and jeopardizing grid resilience.

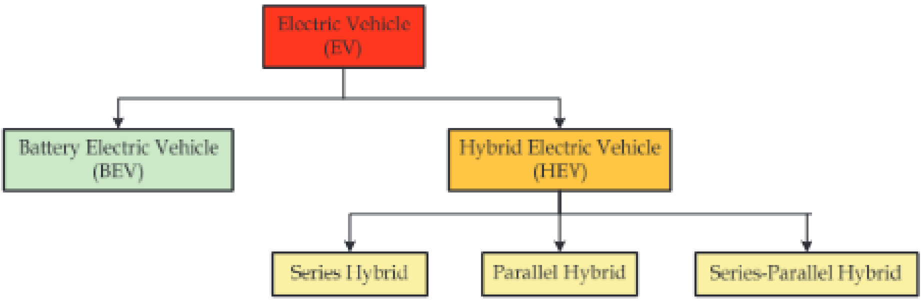

Figure 1 General Classification of Electric Vehicle

When the number of electric vehicles produced increases thanks to the efforts of car companies and academic institutions throughout the world, a more comprehensive classification system for these vehicles is likely to emerge. There are two main categories for describing energy converters, with the most common one shown in Figure 1. Both hybrids and BEVs (sometimes known as pure EVs) fall within this category. Batteries in BEVs store energy exclusively utilized by one or more electric motors to supply mechanical power in the absence of an internal combustion engine (ICE). In hybrid electric vehicles, the combined efforts of the electric motor & internal combustion engine (ICE) provide propulsion. According to the Society of Automotive Engineers [5], a hybrid vehicle includes two or more energy storage devices that must function together or autonomously to power the propulsion system. The minimum number of energy converters and storage systems required of a hybrid vehicle is two, same as in the case of light-duty hybrid cars. The performance, environmental benefits, and speed of electric vehicles are combined with the high degree of autonomy provided by conventional vehicles equipped with spark ignition engines, compression ignition engines, fuel cells, and solar panels to create a hybrid electric vehicle (HEV) [6]. In addition to the poor energy density of batteries, pure electric vehicles often have a shorter range than their internal combustion engine counterparts. Between 60 and 75 kilometers can be driven with no emissions, while the full range of possible autonomy is between 800 and 1000 kilometers [7]. Recent developments in automobile technology have made such journeys possible. Plug-in commercial vehicles are more popular because of their larger battery capacity and quicker charging times compared to regular hybrids [8-9]. Onboard energy storage typically consists of Li-ion batteries with a capacity of 13 to 18 kWh.

On the other hand, recharging durations for electric vehicles are frequently lengthy. However, quick and ultra-quick recharging technologies have emerged, enabling recharge periods of only approximately 30 minutes [10]. However, there are still few of these kinds of facilities.

Furthermore, many nations need a sufficiently extensive charging station network. These restrictions have hampered widespread use of pure electric vehicles. However, it is anticipated that this tendency will alter soon. HEVs are considered a strong replacement for pure electric vehicles in this situation. Technology related to batteries is always evolving. For large-scale electric storage, new technologies are created every generation [11–14]. Current HEV models still have the traditional combustion arrangement in addition to the electrical component of an HEV. Future HEVs are anticipated to have a crucial role in overcoming the drawbacks of all-electric vehicles by utilizing combustion components. In this way, enhancing the autonomy provided by the electric counterpart still requires the combustion system.

Additionally, the price of electricity is still extremely high in many nations and is rarely competitive with traditional fuels. Vehicle makers and researchers have created a variety of setups for linking both systems in this situation. The fundamental obstacle to developing HEVs is managing power flow between petrol and ESS, which causes vehicle motion. The need to lessen petrol intake and output emissions is at odds with the ESS's limited energy source. It is challenging to find a solution that satisfies the constraints and the needs at the same time, and trade-offs are typically necessary. The problem is exacerbated by the desire to avoid a drop in vehicle performance. Regardless of the HEV type, the selected EMS will significantly impact the vehicle's performance in terms of fuel efficiency and tailpipe emissions [15]. There are several studies from the past ten years and even more recently that have previously helped to compile reviews of HEV from different writers. However, the author thinks that as technology develops and more approaches are introduced, interest in EMS for HEV will continue to rise and appeal to fresh ideas for many years. This review paper's primary goal is to increase awareness of optimization approaches, the author's main area of research interest, and add to the increasing list of talks about recent proposals for HEV. In actuality, very few references are currently available on the configuration in question; hopefully, our work fills that gap.

The research project will proceed as described below. The present state of hybrid electric vehicle research is discussed in Section 2. Section 3 reviews the common HEV configurations that are currently under consideration. This section will explore the power electronic topologies utilized in EVs. Section 4 covers the various motor types used in EVs. The energy management system for HEVs and various control strategies are also explained in this section. A detailed explanation of recent trends in energy storage systems utilized in HEVs is provided in Section 5. Section 6 details how a comparative analysis is made based on the goals, uses outcomes, and research opportunities found in previous literary works. The limits and research gaps identified in the published literary works will be covered in Section 7. The conclusion section will provide a concise summary of the review paper and value-added material from the literature, followed by a list of references.

2. Related Works:

Hybrid electric vehicles have received much interest in the transportation sector as a means of reducing fuel consumption and greenhouse gas emissions. Numerous studies and research projects must be conducted on the various elements of hybrid electric vehicles. Existing important HEV-related works include these. Using both human energy input and photovoltaic solar energy, this research suggests designing and building a hybrid electric vehicle for experimental purposes. The primary positive elements, energy-related problems, and experimental findings are given.

To store and supply electrical energy, HEVs rely on energy storage technologies, which are commonly batteries. Research has been conducted on several forms of battery technology, such as lithium-ion, nickel-metal hydride, and solid-state batteries, to improve their functionality, energy density, and lifespan. The subject of research has been the effectiveness of battery management systems (BMS) in tracking the battery pack's temperature, health, and charge. These solutions aid in safety, safety optimization, and battery life extension. [17] Two methods are used to study the proposed supercapacitor method for storing photovoltaic energy. Earlier, a summary of the use of supercapacitors in solar energy conversion systems was given.

The cutting-edge topic of hybrid energy storage devices was summarised in [18]. A hybrid energy storage system (HESS) is the advantageous combination of two or more energy storage systems with different operational characteristics. In this study, we provide the principal approach for power flow decomposition utilizing peak shaving and double low-pa filtering, and we briefly address typical HESS applications, energy storage coupling topologies, core energy management ideas, and popular HESS uses. There have been demonstrated efficiency gains in energy storage systems for EVs [19]. The advantages of a battery and ultra-capacitor based hybrid energy storage system are discussed.

To increase fuel efficiency and minimize emissions, the models and management of the vehicle need to be more accurate. The kinematic or reverse approach, the quasi-static or forward technique, and the dynamic approach are the three main methods of vehicle modelling that have been studied in the academic literature. The kinematic method takes into account the vehicle's speed and the road's gradient as input variables. The driver model used in the quasi-static method of HEV modelling balances the real speed profile of the vehicle with the target vehicle speed (drive cycle speed) to provide a profile for the power demand necessary for matching the speed profile of the target vehicle. Richard Bellman is credited with developing the dynamic programming methodology. Depending on the optimization criterion, choosing a decision from a limited set of decision variables at each time step resolves discrete multi-stage decision problems. When the beginning circumstances of a vehicle's performance are known, DP operates effectively. Additionally, DP requires some post-processing process, such as neural network-based processing or a comparable technique, to finalize the results. Finding the best answer is made even more challenging by this. [20] the parallel hybrid powertrain's design, operation, and control scheme for the driving and braking systems were examined. The results of their analysis indicate that using an altered Indian driving cycle improves fuel efficiency; however, no statistics have been presented that compare the alteration or enhancement of emissions when compared with the basic data.

Energy management systems greatly influence the performance and efficiency of HEVs. Researchers have developed various control systems to effectively manage the energy flow within the hybrid powertrain, including rule-based, optimization-based, and model-predictive control algorithms. Studies have concentrated on real-time control algorithms that optimize energy use and reduce fuel consumption by considering variables, including traffic circumstances, road gradients, and driver behavior. [21] claims that driving cycle recognition will aid in more effective energy management of HEVs after thoroughly analyzing the various bibliometric-based HEV energy management systems. The primary components of the most popular energy management systems used in HEVs, together with their advantages and limitations, are statistically analysed. A work on adaptive energy management for HEVs through driving pattern recognition has been published [22]. In [23], we have reports of the verification of a parallel HEV and of a full longitudinal quasi-static model. In another study, the validated model and the New European Driving Cycle were used to examine the impact of an early gear-up change on fuel consumption as a whole. This approach was deemed preferable since it reduced fuel use in real time without significantly impacting the battery's final charge. According to [24], when the parallel HEV's performance was compared to that of real-world conventional vehicles and typical driving cycles, the HEV outperformed them in terms of fuel and engine efficiency.

A crucial similarity between all the research declared above is that the method used aimed at the optimal design is for the component sizing or the control strategy, whereas an additional variable is kept fixed. According to certain studies, it depends on the fuel consumption or emission metric. The energy redistribution and efficiency change of the key vehicle components before and after optimization still needs to be considered, even when both are considered. In contrast, a vehicle's component sizing and control strategy work together to deliver the greatest performance in real-world conditions. As a result, to create a hybrid electric vehicle using a design that is both decreased regarding fuel use and emissions because of the implementation of an appropriate control strategy, component sizes, and control strategy parameters must be simultaneously optimized. Significant research on EMSs for vehicle applications has been conducted over the previous ten years, with only minor differences in categorization. More than 50 different fundamental algorithms have reportedly been utilized in numerous investigations and presented in several papers, according to earlier literature. Studying these techniques' applicability, dependability, appropriateness, and efficacy for online applications would be interesting because most have yet to be successfully applied in FCHEV EMS optimization. The ability to compute extremely complex and multidimensional configurations, as well as the integration and fusion of various EMS control strategies aimed at enhancing overall performance, could all be achieved by researching some of these emerging algorithms. Heuristic techniques like the one presented in [25], which largely focuses on using the Artificial Bee Colony (ABC) algorithm-based approach to HEV optimisation, have been the focus of recent breakthroughs in heuristic controller research. This method uses the Basic ABC (BABC) algorithm to determine the best action for simultaneously optimizing component sizes and an HEV control technique. Another theory by [26] uses a pheromone-based technique with a shorter computing time than the prior theory. Both of these solutions used the simple ABC optimization technique, which has the problem of discovering and exploiting throughout the quest for the best solution. Exploitation is the ability to build new, better solutions utilizing the knowledge of earlier, successful solutions, and exploration is the ability to investigate the many unknown parts in the solution that is provided space to find the overall optimum. [[27] used the particle swarm optimisation fuzzy algorithm, the original fuzzy algorithm, and the quantum chaotic pigeon-inspired optimisation (QCPIO) algorithm to fine-tune the membership function of the fuzzy logic controller. They looked at the SOC of the power supply and emissions under different conditions of operation.[28] used particle swarm optimisation to pick the vehicle's overall energy cost as the optimisation objective, hence increasing the threshold of the rule-based approach. The driving cycle was then used to evaluate the online control efficiency of this method.

Because of its superior global search performance and low algorithm complexity, the genetic algorithm (GA) used in evolutionary computing has become one of the most widely used algorithms in modern optimisation. The genetic algorithm, inspired by natural selection, uses a random search strategy called global searching to eventually arrive at the best possible solution. These benefits are ideal for improving the effectiveness of the EMS's rules, parameters, or evaluation criteria [29]. Natural processes, such as genetic variation, are used as models to solve the optimisation problem. While GA can be employed in EMSs to find globally optimal solutions, it is more effectively viewed as an offline optimisation method that helps researchers choose the most appropriate HEV parameters (such as engine size and battery capacity) due to its time-consuming and resource-intensive nature. [30] Using GA, the optimal configurations were discovered, and the topic of energy management in fuel-cell hybrid electric vehicles was explored. These are only a few examples from the extensive research on hybrid electric vehicles that have been conducted. The corpus of research on this subject is growing as researchers aim to improve hybrid vehicles' functionality, efficiency, and sustainability and hasten their adoption in the automotive industry.

3. Most Typical configurations for HEVs:

Depending on how the power sources are combined and integrated inside the vehicle, hybrid electric vehicles (HEVs) can be set up in various ways. Here are some of the most prevalent HEV configurations:

3.1 Automobile Hybridization Level Categorization

The goal of the hybridization theory is to reach the point when HEVs are regarded fully electric. The level of hybridization determines the relative significance of the HEV's electric and combustion systems. Therefore, the importance of the electric system increases with the level of hybridization. Two alternative perspectives could be used to conceptualize the hybridization of an HEV [31]. Propulsion system hybridization: This category includes vehicles with a heat engine (often a combustion or compression engine) and an electric traction system operating simultaneously. As a result, both systems can move the car forward, alone or in tandem. An electric motor in a hybrid vehicle's propulsion system is only utilised to get the car going and keep it going slowly for short distances. Incorporating hybrid systems into the electrical grid: One or more cars in this scenario could run entirely on electricity. These setups have potential as either production or storage facilities. An electric motor is a minimum requirement for this configuration. When the electric batteries in the tractor system run out, the heat engine will automatically begin recharging them. The hybridization system and power supply combine an electric system with fuel to boost autonomy. This framework can also be applied to fuel-cell electric vehicles, which generate power by using fuel cells to directly convert hydrogen into electricity [32].

There are three subcategories that can be created from the above grouping: as illustrated in Figure 2, according to [33]. In that regard, once a hybrid vehicle achieves a substantial level of hybridization, the electric component in the vehicle is enhanced.

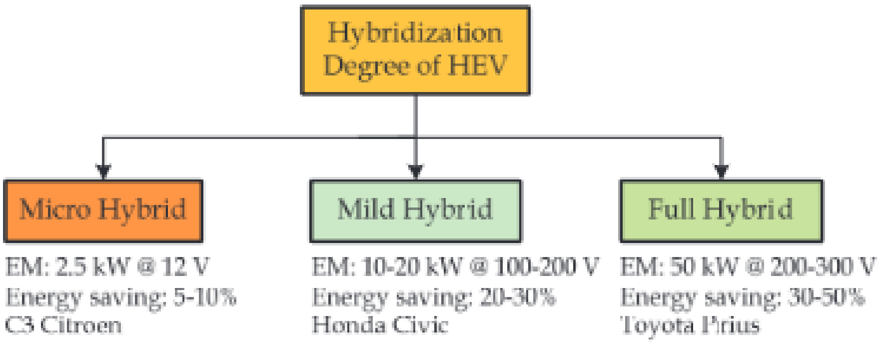

Figure 2 Classification of HEV according to Hybridization degree

This classification measures the degree of hybridization of the HEV. It demonstrates the importance of the electric motor's influence on how a car travels. A 12 V, roughly 2.5 kW electric motor is used in micro-hybrid vehicles. The EM supports only the start-and-stop maneuvers that are crucial for city driving. Especially when using this driving mode, energy investments range from 5% to 10%.

This is a dreadful economic climate because of the three major problems of fossil fuel dependence, urban air pollution, and greenhouse gas emissions. The Citron C3 is a good example of this. Mild hybrids have an EM of 10-20 kW at 100-200 V. Between 20% and 30% more energy can be saved than was predicted. Commercially available vehicles are the Honda Civic and Honda Insight. Mild HEVs could not be a solution even if they were widely adopted, according to the aforementioned triad, given the target global CO2 reduction and, what is worse, if one considers that the global fleet (which is primarily made up of ICE vehicles) is growing as more and more consumers are created in developing nations. Mild HEVs may appeal more to consumers than ICE equivalents because of their greater initial cost due to fuel economy. For instance, in Brazil alone, the fleet of passenger vehicles has doubled during the past ten years. The last car in this lineup is a full hybrid with an EM of roughly 50 kW at 200–300 V, which is capable of conserving 30%–50% of energy while driving in cities thanks to sophisticated control algorithms that only use the ICE when necessary and always at its most effective setting while diverting any excess energy to batteries. Moreover, the battery and supercapacitor store the energy gained from coasting and regenerative braking. If the truth be known, this household should have the Toyota Prius. While full hybrids can be a useful ally in the fight against the triad, their effectiveness is limited compared to that of purebreds for the same reasons.

3.2 Classification by Architecture

Different architectures result from the various ways that hybridization can happen.: series hybrid, parallel hybrid, series-parallel hybrid.

A series hybrid setup, such as the one depicted in Figure 3, uses an ICE solely for electricity generation. Since it is not physically tied to the wheels, the ICE can operate more effectively. The vehicle's electric motor is then powered by the electricity produced. The hybrid series configuration operates as follows: The ICE runs continuously to produce power. The electric motor, which powers the vehicle's propulsion, receives the electricity. The battery, which the ICE or regenerative braking may recharge, contributes electricity to the electric motor. The wheels receive torque from the electric motor to move the vehicle ahead. The hybrid series configuration has several benefits, such as increased fuel efficiency due to the ICE operating at peak performance. Providing electric power for stop-and-go or low-speed driving situations, lowers pollution and fuel consumption in cities. The mechanical complexity is reduced because the ICE is not mechanically connected to the wheels.

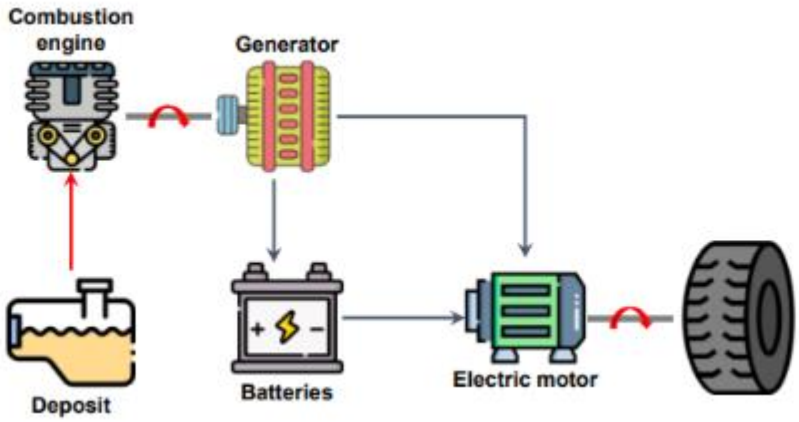

Figure 3 Series Hybrid HEV

The parallel hybrid system shown in Figure 4 allows both the ICE and electric motor to generate propulsion power, and they are both mechanically connected to the wheels. The powertrain management system decides the power distribution between the ICE and the electric motor based on the driving circumstances and energy requirements. The parallel hybrid design operates as follows: When there is a low demand for power or a low desire for speed, the vehicle can run entirely on electricity. When there is a great demand for power, like during acceleration or ascent up a steep incline, the ICE helps. The electric motor can run independently when necessary or in concert with the ICE to boost power. When braking with regenerative energy, the electric motor can act as a generator, producing electrical energy that can be utilized to recharge the battery. The advantages of the parallel hybrid system include increased performance and power due to the combined strength of the ICE & electric motor. Power delivery flexibility enables the best power distribution dependent on driving circumstances. The energy normally wasted during deceleration or braking is captured and stored using regenerative braking.

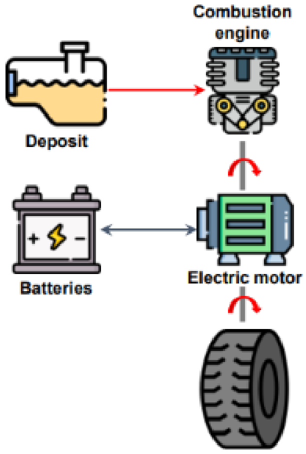

Figure 4 Parallel Hybrid HEV

With a high degree of flexibility and efficiency, the power-split hybrid arrangement in Figure 5 includes components from both series and parallel hybrids. It enables the vehicle to run in several modes depending on the needed power and efficiency. Planetary gear sets and clutches effect together to provide the powertrain's different power distribution pathways in the power-split hybrid system. Power from the engine & electric motor may be divided and integrated in various ways to increase efficiency and performance. In parallel mode, the engine and electric motor work together directly to drive the wheels. In series mode, the engine powers a generator, which in turn feeds electricity to the electric motor. Based on the current driving conditions, battery charge level, and power demands, the powertrain management system chooses the optimal power split. The power-split hybrid configuration offers a variety of advantages, such as increased efficiency from the use of multiple power channels and power split optimization following operational circumstances. The combined power of the engine and electric motor results in increased power and performance. Regenerative braking enhances overall efficiency by assisting in capturing and storing energy.

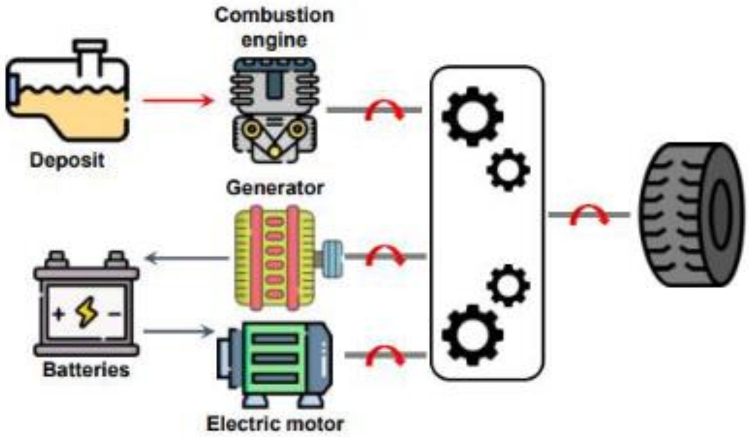

Figure 5 Power-Split Hybrid HEV

3.3 Classification by market segment

The vehicle market is divided into several categories (or segments) in a final classification for HEVs, largely based on prices [34]. Figure 6 shows the five segments that were found. The second-tier family car segment's hybrid electric vehicles (HEVs) are optimised for short commutes and local trips. When ICE is the primary source of energy in cities, the overall impact is negligible. Propulsion driven solely by an electric motor, on the other hand, has the potential to attain high levels of efficiency and efficiently address the three interrelated problems of fossil fuel use, air pollution, and greenhouse gas emissions. To put drivers' minds at ease about the possibility of running out of electricity, the ICE (with its petrol tank) may serve as a range extender. Although this category has previously been used to describe HEVs, it is exciting to use it because, as was just indicated, the latter can significantly help lessen problems in urban areas and combat climate change.

The family's main vehicle will frequently fall into the intermediate car category. It must function well on roads and be appropriate for urban use. In this market, the Toyota Prius is a competitive option. HEVs with high-end vehicles are not suitable for city use. They offer optimum comfort in addition to outstanding technical and road performance. Of course, excellent technological performance ignores the environment's perspective. The small delivery vehicle market is mostly designed for urban use. However, vehicles in the first family car class must be able to move a lot of relatively short-distance excursions every day, unlike those in the second family car segment. Therefore, great efficiency would be acceptable from the perspectives of the environment, the climate, and fuel economy. The category for city buses is devoted to urban public transportation, which includes urban tourism transportation. Vehicles in this group have a driving range of about 250 km and a moderate speed.

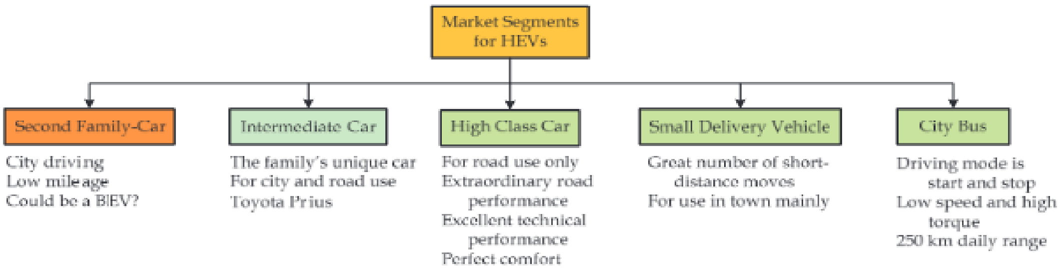

Figure 6 Classification of HEV by market segment

4. Control and component system of HEV

Hybrid electric vehicle control besides component system uses a variety of parts and control techniques to regulate power flow, maximize energy efficiency, and improve overall vehicle performance.

4.1Components of HEV:

- **Internal Combustion Engine (ICE):** The ICE serves as the main power source in an HEV. It offers mechanical power to power the wheels directly or indirectly via a generator; runs on petrol, diesel or another fuel source.
- **Electric Motor/Generators:** To provide electric propulsion, support the ICE, and enable regenerative braking, HEVs integrate one or more electric motors/generators, as seen in Figure 7. When the ICE is driving a generator to charge the battery or during regenerative braking, these motors can function as generators to transform mechanical energy into electrical energy.

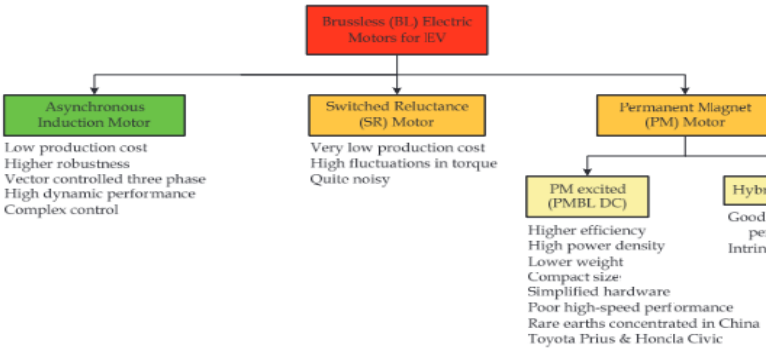

Figure 7 Electric motors for HEV

- **Battery Pack:** The electric motor(s) and regenerative braking are powered by electrical energy stored in the battery pack. Lithium-ion (Li-ion) and nickel-metal hydride (NiMH) batteries are two common battery chemistries in HEVs.
- **Power Electronics:** In an HEV, energy flow between the power sources and loads is managed by power electronic converters [35]. They include DC-DC converters and inverters that switch from DC to AC power, as seen in Figure 8. Motor controllers, which control speed and torque of the electric motor(s), are another power electronics component.

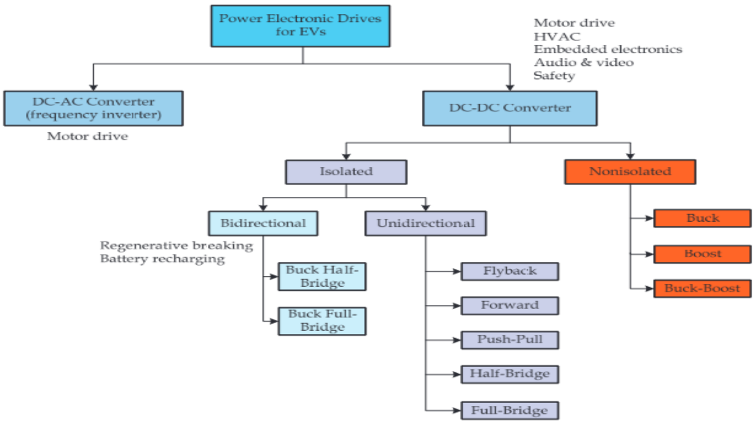

Figure 8 Power Electronics Topologies Used in EHV.

- **Transmission:** The ICE and electric motor(s) in HEVs may transport power to the wheels through a specialized gearbox arrangement. A standard gearbox or a continuously variable gearbox (CVT) that provides effective power distribution can be used as the gearbox system.
- **Energy Storage and Management System:** An energy management system (EMS) oversees battery incriminating and freeing as well as the flow of energy between the power sources (ICE, battery, electric motor(s)). Based on driving conditions and efficiency standards, it ensures energy is used as efficiently as possible.

4.2Control Strategies in HEV:

The key to a successful EV design is control. Control engineering has improved over the years and relies on sophisticated hardware, including integrated development environments, digital signal processors, and microcontrollers. Engineers and researchers continue to face challenges with "efficient" control of EVs despite the availability of many powerful tools and techniques. The fact that this subject is among the most well-covered in technical literature is not a coincidence. Researchers and automakers utilize cutting-edge digital control techniques like fuzzy and optimum control to try to improve the behavior of EVs.

HEVs use various control techniques to enhance energy management and overall vehicle performance. Typical control methods include:

- **Power Split Control:** The control scheme determines how much power is distributed between the ICE and electric motor(s). It chooses when to use the ICE alone when to utilize electric power alone, or when to mix both power sources according to the driving conditions, the battery's charge, and energy efficiency considerations.
- **Regenerative Braking Control:** During acceleration or braking, kinetic energy is captured by regenerative brake control and transformed into electrical energy. The control system regulates amount of regenerative braking force, maximizes energy recovery, and manages changeover concerning regenerative and friction braking.
- **Energy Management Control:** The energy management control strategy optimizes the power distribution between the ICE and electric motor(s) to achieve the intended vehicle performance and fuel efficiency. Choosing the best power distribution and operating modes considers the driver's needs, road conditions, battery state of charge, and powertrain parameters.
- **Hybrid Mode Control:** The hybrid mode control lets you choose the vehicle's operating mode, such as an all-electric, series, parallel, or power-split hybrid. The control system selects the appropriate mode based on several factors, such as the driving environment, battery condition, and power requirements.
- **Vehicle Stability Control:** Vehicle stability control systems are incorporated into HEVs to improve stability and safety during cornering and acceleration. These systems adjust the power delivery, braking, and steering based on data from the vehicle dynamics, wheel speeds, and driver inputs to keep the vehicle stable.

An HEV's control and component system needs highly technical algorithms, sensors, and actuators to optimize power distribution, energy economy, and vehicle performance. To create a balance between fuels, the components and control methods cooperate.

5. Hybrid Energy storage and optimization techniques

5.1Energy storage system:

Several factors [36] influence the selection of an ESS, such as charging rate and energy density, lifespan, cost, weight, and size. Currently, batteries and Ultra Capacitors (UC) are the two most popular ESS options [37]. Batteries have a high energy density and low cost per watt hour, however they have a limited cycle life and poor specific power. In contrast, UCs have low energy density, high cost per watt, low efficiency, and high peak power [38, 39]. The UCs have almost limitless cycle lifetimes and can withstand extremely dynamic and robust power profiles [40]. The UCs are also accountable for reducing sulfation in EVs' lead acid batteries. While batteries are best suited to low-frequency needs, UCs supply both high-frequency and high-magnitude power. The needs can't be met entirely by an energy storage device.

Nevertheless, combining two can help overcome their drawbacks. The UCs can withstand rises during battery operation and sustain the DC-bus voltage while the batteries preserve the SOC of the UCs. The outcome of combining these two is that the system as a whole will be very stable. In order to protect them and increase their longevity, UCs are added to EV batteries. The batteries may be used as efficiently as possible because the UC absorbs the sudden variations in load. A UC is added to transform it into a HESS, and one resistance capacitor (RC) and numerous RC branches can be used to represent the batteries. A critical challenge is influencing how big they should be in determining the optimal power distribution between the battery and a UC.

5.2 MPPT used in HEVs

In response to the growing need for converting to renewable energy sources, PV technology is advancing faster than other alternatives. Its ease of use, lack of noise, lack of pollution, resistance to direct contamination, and lack of complexity all add to its appeal. The most well-known algorithm for tracking this MPP has been constant voltage tracking, although it has limitations when the temperature fluctuates. The most widely used methods to get around them are incremental conductance (IC) and perturb and observe (P&O).

Popular MPPT algorithms like the P&O algorithm constantly adjust the operating point of the solar panel by a small amount while monitoring variations in power output. In reaction to the detected change, the algorithm alters the operating point to boost power production. This iterative process is repeated unless the maximum power point (MPP) is reached. The Incremental Conductance method constantly monitors the derivative of the power-voltage curve to determine the MPP of a solar panel. It compares the immediate and incremental conductance to determine the optimal voltage that maximizes power generation. Based on the comparison outcomes, the algorithm modifies the operating point. Using the solar panel's open circuit voltage (Voc), the fractional open circuit voltage algorithm calculates the MPP.

The operating voltage is adjusted by computing the open circuit voltage percentage corresponding to the maximum power point. This approach is straightforward and uses a small amount of computing power. An enhanced control method that can be utilized for MPPT in HEVs is model predictive control. It forecasts the power output at various voltage levels using a mathematical model of the solar panel. The voltage that corresponds to the algorithm's estimated maximum power output is then chosen. MPC can optimize the power output while considering dynamic environmental changes and various system restrictions. Neural network-based MPPT algorithms use artificial neural networks to learn the correlation between input parameters (such as solar irradiance, temperature, and voltage) and the associated optimal operating voltage. These algorithms can deliver precise and effective MPPT performance while adapting to shifting environmental conditions. Several variables, including the characteristics of the renewable energy source, the particular needs of the HEV system, and the available computer resources, influence the choice of the MPPT algorithm. The algorithm's choice should depend on the individual application and performance needs of the HEV because different algorithms have different benefits and drawbacks.

A simple charging method using P&O MPPT for HEV applications was suggested for MPPT control techniques without current sensing devices [41]. This method can calculate the MPP using the PV voltage plus converter switching duty ratio. A tiny PV cell and additional hardware components were employed [42] to achieve high efficiency while reducing power loss and cost to a minimum. HEVs could use a solar-thermoelectric hybrid system using P&O-based MPPT, according to [43]. This technique can track the worldwide MPP with less expensive equipment. In addition, the PVHEVs' own ANN-based MPPT was implemented. The reference voltage for the feed-forward loop can be estimated in real time using an offline ANN trained using the backpropagation and gradient descent momentum approaches. It is recommended in [44] that the P&O method be used when parking a HEV, while the voltage-based MPPT algorithm be utilised when driving one. A boost converter is used in this technique to extract the maximum amount of energy from a given supply. When charging, the algorithm instructs the converter to operate in constant current and constant voltage mode. Also, in [46], the P&O algorithm for HEV was created. In order to offer a fast transient reaction with high stability for fluctuations in solar irradiation, a modified P&O algorithm has been developed. P&O and IC-based techniques allow for regulation of the sun's varying irradiance. They offer the best answer and a practical example of driving conditions. Distributed MPPTs (DMPPTs) benefit greatly from voltage balancing management since it allows each MPPT to operate from its own power supply.

It is crucial to remember that several variables, including the properties of the renewable energy source, the particular needs of the HEV system, and the available processing resources, influence the choice of the MPPT algorithm. The algorithm's choice should depend on the individual application and performance needs of the HEV because different algorithms have different benefits and drawbacks.

5.3 Optimization Techniques

Whenever you want to get the most out of your available resources, optimisation is the way to go. Optimising entails finding a value for a variable that maximises or minimises the objective function while still conforming to the constraints. Particle Swarm Optimisation [47-50], Genetic Algorithm [51-53], and Simulated Annealing [51-53], as well as integer algorithms like mixed-integer linear programming and Mixed Integer Programming, are the major three heuristic optimisation approaches employed in the study of EV charging stations. There are many optimization techniques in the literature.

According to the authors of [54], the parking deck functions as an ESS. A non-sequential Monte Carlo simulation method has been developed to calculate its potential contribution. Researchers utilised the available electricity from wind turbines (WTs), photovoltaic (PV) systems, diesel generators, and parking decks to improve the resilience of the advanced distribution system during the outage event. To account for the unpredictability of renewable energy sources, they also implemented stochastic modelling. The authors provided a comprehensive optimisation model for sizing PV and WT Battery Energy Storage System (BESS) units, as well as EV charging stations, while accounting for total loss in the distribution system. This approach is supported by two real-world distributed systems, the Alibeykoy and Hamikoy feeds [55]. The authors additionally consider the load's changing profile over time. The widespread adoption of EVs and RES in the energy industry contributes to the formation of a novel economic model. The authors recently proposed a cutting-edge bi-level model for EV parking lots in a renewable energy distribution system [56]. In order to optimize the profit for the owner of the EV parking lot, the suggested model is constructed in two stages using stochastic programming. The authors of [57] suggested using the PSO and Voronoi diagram in combination with a suitable allocation and sizing for a fast-charging station and public parking lot to reduce the annual cost of the total PEV charging station.

The authors of [58] suggested using ESS in rapid charging stations to lower the operating expenses of a fast charging station to diminish its adverse effect on the power grid during peak hours. The optimal BESS capacity is the output of the proposed architecture's mixed-integer linear programming model. During off-peak hours, network energy is stored by the BESS and then delivered to EVs. The purpose of the suggested approach is to determine how much of a BESS a fast-charging station needs in order to cut down on the station's energy cost (SEC) and storage cost. The authors of [59] utilised EV storage capacity to mitigate grid operation costs and the intermittent nature of wind power supply. In order to reduce grid operation costs, the proposed stochastic security constraints unit commitment model (SCUC) suggests coordinating the use of electric vehicles (EVs) with the production of wind power on an hourly basis. Mixed integer programming (MIP) was utilized due to the grid complexity and mobility of V2G. Using the IEEE-6 bus and specialised IEEE-118 bus testing equipment, the proposed method is verified. The writers did not rely on the BESS; rather, they made use of the available space in the vehicle. Furthermore, constant charging and discharging shortens the battery's life in an automobile. The authors of [60,61] created a three-tiered Energy Management System (EMS) with primary, secondary, and tertiary levels to reduce the price of energy exchange between the grid and micro-grid.

6. Comparative analysis of Energy Management Strategies

[62] suggests a method based on fuzzy logic that can be used with hybrid and electric vehicles. The EMS uses the battery reference current & transient currents managed by the UCs to distribute power while considering the energy characteristics of each power source. [63] combined two separate SoC & acceleration inputs with a PI controller and fuzzy logic to predict driving behavior. The vehicle employed a pseudo-spectral rule-based method. [64] using a HESS application that modifies power output according to component voltage and temperature. To choose the optimum EMS controller topology, [65] combined the k-control optimization strategy with a rule-based technique, particularly filtering. The findings demonstrated that a rule-based approach performs better in almost all driving cycles and a restricted SC range. A dynamic programming framework for optimization was established at [66], and HESS would self-adapt to provide the rated power without going over a lower threshold determined by the current speed and needed power. An overall 4% improvement in the status of health (SOH) conditions was made. A DP-based predictive control system should be able to anticipate road conditions to produce a sufficient power split scheme with few losses. In order to avoid costs, switching/conduction losses, & current plus magnitude changes, neural networks were trained and managed using the dynamic programming technique [67].

Real-time optimization utilizing two distinct methods is advised by [68]. both the Genetic Algorithm-based method and the Gamma-based approach with fixed coefficients. At high speeds, both methods were evaluated and found to utilize more than 20% less energy. A Genetic Algorithm method to choose the proper power splitting ratio among energy storage devices as defined in [69]. The system's mass, price, and volume were to be cut, but the battery life was to be extended.

An additional field of research in energy management is adaptive model control techniques. [70] created an adaptive sliding approach to track control and block switching frequencies. Our system achieved operational stability for HESS safety and efficiency while handling load changes 37% faster. In order to determine the best power combinations, various inputs are evaluated extraordinarily rapidly and simple enough. This reduces velocity tracking errors and promotes regenerative braking. At the same time, knowing the road grade is crucial for maintaining battery capacity for later use.

Generally, fuzzy logic controllers perform better while reducing life cycle costs and battery degradation [71]. Of course, there are examples of different strategies being blended and put side by side in literature. At [72], a more workable real-time control technique using an EMR-based PI controller was used. The switching and frequency techniques were applied exactly as specified. With a lower maximum battery current, the frequency approach appears to be more reliable and recovers more energy [73]. An online power management technique is put forth [74] that uses the KL rate to calculate the likelihood of each driving circumstance on individual trips. Compared to a rule-based strategy, the method is automatically updated based on the value, lowering energy losses by 0.5–1%. Similar to the method described above, it provided a field-based power distribution method that includes a compensator that controls cut-off frequencies and dc-link voltage fluctuations, leading to a 15% decrease in battery aging [75].

Table 1 summarizes the prior review of EMS for HEV based on recent publications.

Table 1 Summary of a recent publication in the literature review

Reference number	Author/year	Methodologies used	Findings
[22]	Shuo Zhang & Rui Xiong, 2015	pattern recognition-based adaptive energy management	The simulation results demonstrate that compared to the baseline and conventional dynamic programming-based control systems, the proposed energy management technique improves fuel economy.
[23]	Wisdom Enang et al., 2015	Dynamic programming	Over the Japan 10-15 driving cycle, fuel savings of up to 19.07% can be made.
[26]	Long, VT, 2015	Multidisciplinary Design Optimization (MDO) & pheromone-based Bees Algorithm (PBA)	With identical optimization goal results, the new version, PBA, demonstrated a convergence speed gain of 20–25% compared to the Basic Bees Algorithm (BBA).
[27]	Pei J et al., 2017	quantum chaotic pigeon-inspired optimization (QCPIO) algorithm	Compared to the traditional fuzzy EMS and the PSO_Fuzzy EMS, EMS significantly improves fuel economy.
[28]	Chen Z et al., 2015	fuzzy control	Fuzzy control can reduce energy loss by up to 5.99% and extend the Charge Depleting (CD) phase by up to 4.45%.
[30]	Zhou, S. et al., 2019	Genetic Algorithm(GA) is combined with Advanced Vehicle Simulator (ADVISOR)	HEVs can cut their overall fuel usage by 17.6% and 9.7%, respectively.
[42]	Ahadi A, Liang X (2017)	Cost optimization net present cost method	A more effective alternative for energy storage is a battery and hydrogen combo.
[[63]	I. Yahia et al., 2016	Control speed strategy using fuzzy logic	creates a maximum speed reference for an EV for various battery charge levels and acceleration. convey competence
[64]	J.Q. Li et al., 2017	Logic threshold control strategy(LTCS)	The ideal LTCS can greatly lower battery energy loss and improve the efficiency of high-specific power ultra-capacitors.
[65]	A. Castings et al., 2015	An optimization-based strategy (λ-control) and a rule-based strategy (filtering)	While filtering performs well for low supercapacitor voltage ranges, -λcontrol is better suited for high supercapacitor voltage ranges.
[66]	S. Zhang et al., 2016	dynamic programming (DP)-based novel analysis method	Control strategies can increase system effectiveness in a variety of situations.
[67]	J. Shen et al., 2015	dynamic programming, intelligent online implementation, realized based on neural networks	Online energy management controllers can outperform rule-based control strategies by extending battery life by over 60%.
[68]	J. Shen et al., 2016	neural network	Compared to a battery-only energy storage system, the battery SoH is reduced by 31% and 38%, respectively.
[69]	H.H. Eldeeb et al., 2019	wavelet transformation and split power ratio	produced a HESS with a smaller cost, volume, and weight than those described in the literature.
[[70]	B. Wang et al., 2017	estimator-based adaptive sliding-mode control	The existing modification to deal with the load variation yields a settling-time improvement of over 37% and 50% with the ASMC method.
[74]	R. Xiong et al., 2018	reinforcement learning (RL)-based real-time power-management strategy	Reduce the energy loss effectively, and the percentage drop in overall energy loss can be as high as 16.8%.
[75]	Y. Wu et al., 2020	artificial potential field with a compensator	The artificial potential field strategy guarantees state-of-charge constraints for supercapacitors and decreased battery capacity loss compared to current real-time power allocation systems.

1.**7. Limitations, Challenges, and Research Gaps**

The range of an HEV is comparatively small. Given that an HEV should only use a small amount of ICE energy, the distance traveled per charge is modest. Regarding this variable, improvements have been made. Furthermore, it takes an HEV at least 30 minutes to charge completely, compared to only 5 minutes for a regular car to fill up completely. Because of the sophisticated design of HEVs, significant maintenance costs are incurred, as well as increasing demand for highly experienced mechanics and technicians. Batteries The energy storage battery has been a point of controversy for hybrid and electric vehicle (HEV) technology for quite some time now. Due to their great energy density, lithium-ion batteries are the standard in HEVs. The downsides of these batteries include their high environmental sensitivity, their bulk, and their price. When compared to an ICE, a battery is more cumbersome and sensitive to temperature changes. The battery was constructed with harmful components, contradicting its claim to be a green technology and adding icing to the cake. The greater risk of electrocution from HEV batteries raises the risk of human life in the event of an accident.

Optimization technologies have substantially improved the performance and efficiency of hybrid electric vehicles (HEVs). However, some restrictions, difficulties, and research gaps still need to be filled. Here are a few:

Using sophisticated optimization techniques in HEVs can add complexity and raise the price of the vehicle. System complexity, calibration, and cost-effectiveness issues might arise from the addition of sophisticated control algorithms, cutting-edge sensors, and other components. Optimization approaches rely on precise real-time data for optimal functioning, such as traffic situations, road grades, and battery parameters. Although this information is crucial to the success of optimisation algorithms, it can be challenging to acquire and interpret in real-time. Accurate mathematical models of the vehicle, engine, and environmental elements are frequently required for optimization strategies. In turn, the optimization techniques' performance might be impacted by variances in real-world conditions, uncertainty in model parameters, and dynamic changes in system behavior. Multiple competing goals, including fuel efficiency, emissions reduction, and performance, are involved in HEV optimization. Finding the best trade-off between these goals is a difficult undertaking. An ongoing research problem is to create sophisticated multi-objective optimization methods that can manage these competing objectives successfully and effectively. The performance and efficiency of HEVs are significantly impacted by battery deterioration over time. Optimization methods must consider battery degradation impacts and devise plans for extending battery life while preserving optimal vehicle performance.

Further difficulties in maximizing environmental effects and resource consumption arise when the complete life cycle of the HEV, including battery production, use, and recycling at the end of its useful life, is taken into account. Research is still being done on how to incorporate renewable energy sources like solar cells and wind turbines into HEVs. Key problems include maximizing the use of these erratic energy sources, assessing their effects on system effectiveness, and creating plans for efficient power management and storage. Although individual HEV parts and systems have been optimized, more comprehensive system-level optimization strategies are required. This entails considering the interactions and synergies among various components, control algorithms, and optimization methodologies headed for obtain the best overall execution and efficiency of the entire HEV system. For the interoperability and seamless integration of various optimization technologies in HEVs, it is essential to design standardized interfaces, communication protocols, and data exchange formats. Standardization activities are required to promote the adoption and interoperability of optimization approaches across various vehicle models and manufacturers. By addressing these restrictions, difficulties, and research gaps, hybrid electric vehicle optimization technologies will progress and improve, resulting in more effective, economical, and environmentally friendly transportation options.

8. Conclusion

Introducing HEVs into the market is considered as crucial in bringing attention to environmentally friendly autos in light of the impending energy crisis caused by the depletion of world fuel sources and worsening environmental circumstances. It is a tried-and-true technology that is already available. As the rate of adoption continues to rise and automakers devote more resources to the field, the price per unit of functionality decreases. Improvements in EMS layout and the adoption of HEV technology have set the region on the path to success. HEV is the link between today and a future of emission-free autos. This work emphasizes limitations, challenges, and research gaps in the previous literature. These areas of concern offer insightful information for future HEV study and development. Researchers can help overcome obstacles and advance the field of hybrid electric vehicles by solving these problems. Overall, by looking at HEVs' architecture, control strategies, parts, energy storage systems, and optimization methods, this literature study helps to comprehend them better. However, it is hoped that more study and comprehension of car technology will eliminate these shortcomings, increasing the likelihood that it will become the preferred design for manufacturers and customers.

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