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A Review on Fuel Cell based Hybrid Electric Vehicles

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Abstract
This paper presents an overview of Fuel Cell technology and the Fuel Cell Hybrid Electric Vehicle which is a growing and upcoming technique in automobile sector for providing one of the best substitutes of Internal Combustion Engine. This vehicle emits no harmful and poisonous gases and prevents the atmosphere from greenhouse gases emitting from vehicles which contributes a lot in polluting the environment. In this paper the working of a fuel cell has been explained and the methods to be implemented in designing a vehicle based on fuel cell. The energy management strategies have been studied also for proper utilization of fuel for attaining maximum efficiency. A number of literatures have been reviewed too for making this technology to be practically viable and feasible.

Keywords
Fuel Cell, Proton Exchange Membrane (PEM), Energy Storage Device, Power Converters, Energy Management Strategy

I. INTRODUCTION

The global problem faced by the world today is ever increasing population, consequently leading to rise in energy demand. Energy is a prime mover for the wheel of life, and its requirement is increasing with change in life style, comfort level, and faster urbanization/ industrialization. The earth is having limited energy in various forms, which is being consumed at an alarming rate. Nowadays fossil fuels are largely consumed for electric generation and vehicle propulsion. Energy crisis and environmental degradation due to the combustion of fossil fuels has led to the development of new energy technologies that can efficiently optimize the energy usage, thus limiting the consumption of available resources besides protecting the environment from noise and emissions [1]. The major offender of all these ill effects is the transport sector. The transport sector itself contributes to 14 % of the greenhouse gases whereas road transport emits 16 % of CO2 [2]. Reduction in the resource consumption leads to reduction in CO2 emissions and this is possible by using hydrogen. In addition to fuel consumption, the

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pollution level in the atmosphere is also increased to a certainly high level that leads to the major focus on renewable sources. Henceforth, the hunt for alternate sources and new conversion technologies for converting the non-conventional energy in disposable form is getting dominant.

In order to reduce the large amounts of toxic emissions from the automobiles, electric vehicles provide a prominent solution. Electrification of automobile can be regarded as one of the encouraging technology for upcoming imperishable transport system. Electric thrust of automobiles comprise of an option universally considered to design zero emissions transportation. Electric vehicles through the use of modern electric storage systems have shown its reliability and technical feasibility. Fuel cells (FCs) are portrayed as the new emerging energy source. They consume hydrogen gas as the primary fuel and are able to generate electrical power with high efficiency, low operation noise and no emissions. Even though hydrogen is not an energy source but a carrier of energy, it can store and deliver energy in usable form when produced from some other compound that contains it. The most commonly used methods for producing hydrogen is reformation of natural gas and methanol reforming from fossil fuels. Hydrogen has many advantages for which it has been chosen as an alternative fuel to protect the environment like high specific energy, high thermal efficiency, high octane number, high auto ignition temperature (580^0C), low noise during energy conversion, no carbon emissions and requires less space as compared with batteries.

Efforts are being made by various governments, academic institutes, oil industries and automobile industries for making an emission free vehicle to provide clean environment. For promoting the use of hydrogen in automobiles the initiative has been taken by government of India named as Green Initiative for Future Transport (GIFT). It aims to develop and demonstrate hydrogen-based IC Engine and Fuel Cell based vehicles. Fuel cell electric vehicles are the emerging technology and gradually will capture the automobile market.

II. LITERATURE REVIEW

The basic principle of Fuel Cell is to convert chemical energy from fuel directly to electrical energy. This happens when an ion passes from anode to cathode and electrical work from electrons is obtained. As the voltage obtained from one fuel cell is less than 1 V, therefore to generate higher voltage a number of fuel cells are attached to form a stack [2]. Proton Exchange Membrane or Polymer Electrolyte membrane (PEM) is a type of fuel cell, which is developed mainly for vehicular transport applications [3].

The PEM fuel cells (PEMFC) employ hydrogen and oxygen from the air to produce electricity, water and heat. The PEMFC is supplied with hydrogen and air at the inlet and flow fields, and then diffuse through porous media to the polymer membrane. The membrane in the middle of a cell contains catalyst both with the anode and cathode. The catalyst layer on the anode separates hydrogen molecules into protons and electrons. Thereafter, the membrane allows transfer of protons and enables the electrons to flow through an external circuit before recombining with protons and oxygen at the cathode to form water. This migration of electrons produces electricity. The basic operating principle of Fuel Cell is shown in Figure 1 [4]. The electrochemical reactions carried out at the anode and cathode is given as

At anode,

$$H2 \longrightarrow 2H^{+} + 2e^{-}$$

At cathode,

$$4H^{+} + O_2 + 4e^{-} \longrightarrow 2H_2O$$

The combination of above two equations gives:

$$2H_2 + O_2 \longrightarrow 2H_2O$$

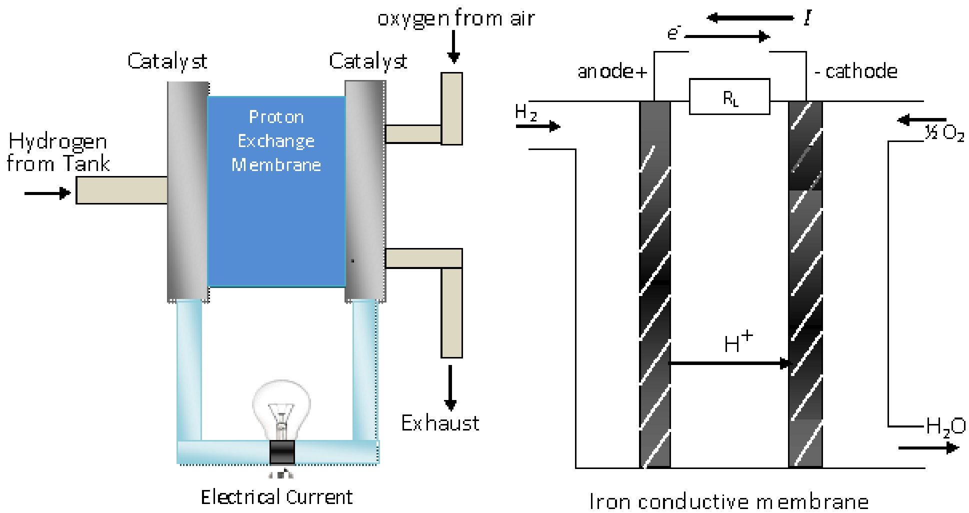

Figure 1: Basic Operating Principle of Fuel Cell

Among the available FC technologies, polymer electrolyte membrane or proton exchange membrane FCs (PEMFCs) are considered to be most suitable for electrical vehicle applications due to their several attractive features, such as low operating temperatures, relatively low cost and quick start up, simplicity, viability, and high efficiency.

There are many advantages of considering PEMFC in the automobile sector to extend the vehicle autonomy with zero emissions is PEMFC such as high-power density, high current density causes the weight and stack size to reduce, good transient power response, no starting problem, advantageous for automotive applications because their tank can be filled in short periods of time [5]. In addition to this the electrolyte is a solid material that reduces the corrosion and electrolyte management problems having an operating temperature in the range of80^{0}C-100^{0}C [6].

However, certain points have to be considered before its utilization in the automobile sector, such as sensitive to fuel cell impurities and cost of electrolyte. Also, it requires careful control of the moisture at the anode and cathode streams to operate efficiently because the electrolyte being used gets saturated with water. The other types of fuel cell with their operating characteristics are given in Table 1 [7].

Table 1: Different Types of Fuel Cells

Type	Electrolyte	Catalyst	Operating Temp (^{0}C)	Efficiency	Use
Alkaline Fuel Cell (AFC)	KOH	Platinum	80-120	40-50	Automotive, military, aerospace engg.
Polymer Electrolyte Membrane Fuel Cell (PEMFC)	Solid Polymer	Platinum	50-100	35-45	Transport, portable or stationary, medium or small
Phosphoric Acid Fuel Cell (PAFC)	H_3PO_4	Platinum	150-220	35-45	Medium stationary areas
Molten Carbonate Fuel Cell (MFC)	Molten carbonate salt	Nickel	650	50-60	Large utility areas
Solid Oxide Fuel Cell (SOFC)	Ceramic	Perovskites	800-1000	45-55	Small auxiliary power units

III. FUEL CELL TECHNOLOGY IN AUTOMOBILE SECTOR

The fuel cell vehicles are better alternative than the battery driven electric cars because they are light in weight, smaller in size, offers supply of power for a long time, easily replaceable fuel cell cartridges and no self-discharge with time [8][9][10]. Fuel Cell Vehicle (FCV) can be made compact and hence improve the packaging of power trains in vehicles. It is quite simple and contains very few or no moving parts. The fuel cell technology offers low noise and vibration free operation even in high acceleration period when the fuel demand is high [11]. Due to the reaction time of the air compressor, the FC system time response is quite slow compared to vehicle traction power dynamics. Therefore, hybrid electric vehicles (HEVs), i.e., hybridization of fuel cells with one or more energy storage unit (ultra-capacitor/ super capacitor or battery) improve the system performance. The performance of the fuel cell can be increased by adding additional auxiliary sources of power supply known as hybridization. Hybridization of the fuel cell stack, dc/dc converters and ESS helps in managing the power demand and prevents the fuel cell from transient loading. Due to this fuel cell technology is able to achieve high efficiency by distributing the peak power demand from the it [12][13].The major issue for the development of FCV is the proper coordination between the multiple energy sources and converters. The control of power flow in the process is another prime concern in the fuel cell technology [14]. Hence, the utilization of a proper control or energy management strategy (EMS) in the FCV is very much necessary for its efficient operation.

Also, a control strategy is very much essential for the efficient operation of fuel cell vehicle. A control strategy is an algorithm which controls the working of the vehicle drive train. The control strategy receives the input signal in the form of speed, acceleration, torque by the driver, the type of road, traffic conditions and so on. The output is obtained in the form of signals to turn ON/OFF certain components or change the operating region.

The main objective of the EMS is to fulfil the driver's demand [15] for the traction power, charging of energy storage system, minimum fuel consumption, optimizing the fuel efficiency and reducing emissions. The main function of control strategy is to design an algorithm to obtain the proper division of power between the motor, fuel cell and energy storage devices by considering the constraints such as drivability, charging and discharging of energy storages, gradeability and reliability of components so that the fuel consumption and emissions are minimized. The power required in fuel cell is in the range of 0.5 kW- 2 MW depending upon the type of vehicle [16][17].

IV. ELECTRICAL TOPOLOGY USED IN FUEL CELL HYBRID SYSTEM

The electrical topology of Fuel Cell Hybrid System (FCHS) consists of fuel cell system, hydrogen storage system, energy storage system, power electronics devices, electrical machine, battery and super capacitor [18]. The role of each of these components are discussed in the below sections.

Fuel Cell System

Apart from fuel cell stack the PEMFC system having various components, such as air delivery system, hydrogen delivery system, thermal and water management system [19]. The air delivery system provides oxygen to the electrochemical reaction using compressor and hydrogen delivery system used for pressurized gas storage. A thermal and water management system used in PEMFC system to handle temperature and humidity during the operation.

Hydrogen Storage System

The hydrogen is required in the operation of FCHS which is stored on board in the vehicle itself. The hydrogen is stored in the compressed form at a pressure of 350 bar or 700 bar [20].

Power Electronics Devices

The power electronics devices used in the FCHS are motor controller, dc/dc converters, and inverters. The power electronics devices basically regulate the output voltage of fuel cell by providing a mask to the output voltage variation of the fuel cell stack. The power electronics converters process and control the electrical power flow among the fuel cell, battery, super capacitors and the electric machine [21]. The motor controller regulates the power to the motor and dc/dc converter converts unregulated dc to regulated dc. This voltage is then used to power the vehicle's auxiliary loads such as lighting, windshield wipers, and the radio too. In addition to this, the inverters convert DC power from the fuel cell, battery or super capacitor to alternating current to power the electric machine. The FCHS is connected to the DC bus through a step-up power converter (Boost converter), whereas the energy storage system (ESS) is connected to the DC bus through a bi-directional power converter (Buck-Boost converter). This converter acts as a "switch" that allows the regulation of the energy flow between the ESS and the dc bus. The load is fed through a DC-AC inverter [22].

Electric Machines

The electrical machine is another important component of FCHS. It receives the alternating current from inverters to provide traction to the wheels of vehicles and allows propulsion [23].

Energy Storage System

In order to operate the fuel cell in a vehicle application, the fuel starvation problem needs to be eliminated. The fast energy demand causes a high voltage drop in a short time which is being treated as a fuel starvation phenomenon and as a result of this the performance of fuel cell degrades [24]. Therefore, an energy buffer is needed to improve the vehicle performance when the dc bus demands high power in short time i.e., during acceleration [25]. The energy storage system helps in improving reliability, stability, power quality etc. The two different types of energy storage system can be used in the FCHS operation, such as batteries and super capacitor. The performance of the battery and super capacitor can be assessed from pulse power test.

- *Batteries*

Batteries are electrochemical devices that convert electrical energy into potential chemical energy during charging and convert chemical energy into electric energy during discharging [20]. Batteries have largest energy density i.e., more energy is stored per weight. They have slow charging time limited by charging current. The role of the battery in a fuel cell hybrid vehicle can be summarized as given below.

- Acts as a source of energy electric vehicular devices.
- An energy storage device during regenerative braking.
- Electrical energy storage device that is generated from the fuel cell at low load.
- Assists the fuel cell power at higher load.
- Main energy supplier when fuel cell system operates at low load.

Various types of battery are under development. The factors in selecting a battery for vehicles operation are specific power, specific energy, life-cycle and cost. The cycle efficiency of batteries is around 80 %.

- *Super capacitors (SC)*

Electric double-layer capacitors, also known as super capacitors, electrochemical double layer capacitors (EDLCs) or ultra-capacitors are electrochemical capacitors that have a very high energy density as compared to common capacitors. An ultra-capacitor is an innovation in the field of capacitors. The main difference between a capacitor and an ultra-capacitor is that- it uses a very small charge separation distance that is literally equivalent to the dimensions of the ions within the electrolyte. Due to the carbon technology, these capacitors are able to create a very large surface area. Thus, it has a very high capacitance than an ordinary capacitor. They are quite beneficial for hybrid vehicles. The cycle efficiency of SC is around 95 %. SC has high charging time depending on high charging current (power), available from main source. The super capacitors having the followings advantages as an energy storage device in fuel cell vehicles [25].

- High energy storage compared to conventional capacitor technologies.
- Low Equivalent Series Resistance (ESR) compared to batteries hence providing high power density capability.
- Low Temperature performance
- Fast charge/discharge since they achieve charging and discharging through the absorption and release of ions.

Working of fuel cell hybrid system

Fuel Cell Hybrid Systems (FCHS) are a combination of a primary power source i.e., the fuel cell and an energy storage system (a battery or super capacitor bank) that supports to supply the load power demand [26]. Hence, the load power due to the power supplied from the fuel cell system and energy storage system is given by

$P_{load}(t) = P_{fcs}(t) + P_{ess}(t)$ for all t

where, $P_{load}(t)$ is the power supplied to the load, $P_{fcs}(t)$ is the power supplied from the fuel cell system and $P_{ess}(t)$ is the power supplied from energy storage system.

Figure 2 indicates the power flow in a Fuel Cell Hybrid System (FCHS).The power converter connected between ESS and the DC bus plays an important role in the implementation of the energy management strategy in the hybrid system. Also, the converter connected between the FCS and the dc bus allows the regulation of the power flow from the FCS to the output.

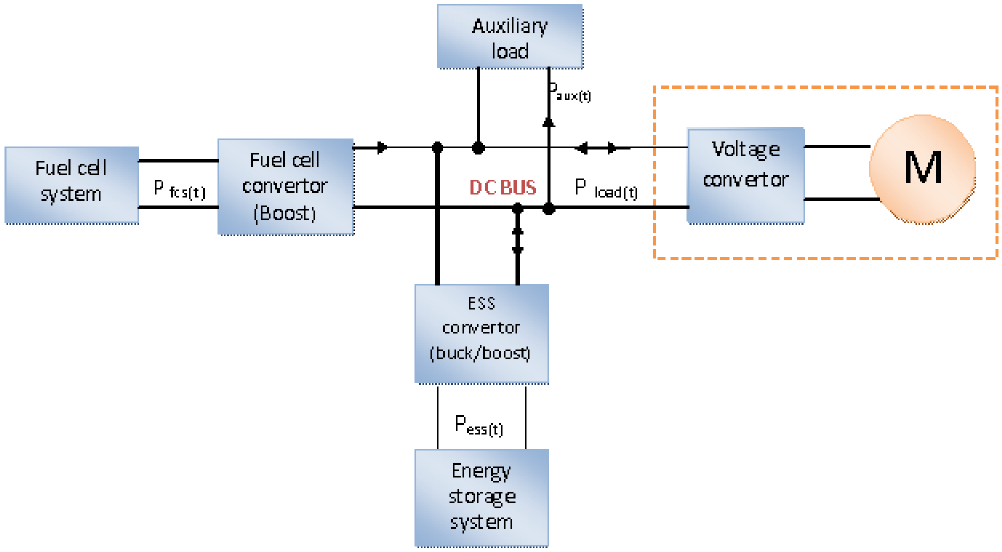

Figure 2: Diagram showing the electrical topology and the power flow in a Fuel Cell Hybrid System

V. ENERGY MANAGEMENT STRATEGIES

To guarantee the efficiency and performance of FCHEVs, a relevant Energy Management Strategy (EMS) plays an important role. An EMS defines the power sharing between the different energy sources in the system to fulfill the power demand. In order to maximize the fuel economy a supervisory control strategy needs to be developed on the basis of the driving cycles. It has to ensure that constraints on the operation of the fuel cell system and storage are not violated, without compromising on the drivability of the vehicle. EMS is based on a dynamic classification which focuses on distribution of the global power between the sources to the vehicles.

The EMS are the algorithms which determine at each sampling time the power generation split between the Fuel Cell System (FCS) and the ESS in order to fulfill the power balance between the load power and the power sources. Depending on how the power split is done minimization of the hydrogen consumption can be obtained. To find a global optimal solution, control techniques where a minimization problem is resolved needs to be studied. The energy management control strategies are basically divided in two categories: Rule based control strategy and Optimization control strategy. The functions to be performed by the EMS of a hybrid vehicle are to provide the power demanded by the system and the driver, control and maintain the State of Charge of Battery and Super Capacitor, recover the braking energy during regenerative braking as much as possible, to operate each component of the vehicle with its optimum efficiency.

For this, different approaches for EMS were found in literature. In [16], the proposed strategy was based on the regulation of the DC link voltage by controlling two power converters, and, thus, the fuel cell operates in almost steady state conditions. In [27], three heuristic strategies were compared using a FCHV model. In contrast, other publications propose the strategies based on optimization techniques. One of the most relevant was the method presented in [28], based on a control strategy called Equivalent Consumption Minimization Strategy (ECMS). The base of this strategy consists in converting all the power flows in equivalent hydrogen consumptions. But the practical implementation of the fuel cell technology in the vehicular technology is still not commercialized and lot of efforts is required.

Then [29] studied the different control strategies for energy management of the HEV with pros and cons of each. He studied about the rule-based control strategy and also optimization-based control strategy, Fuzzy and deterministic rule-based strategy. Out of these, fuzzy rule based is most popular. The deterministic rule-based methods are the heuristics which utilize deterministic rules on the basis of power flow analysis. He studied the characteristics and approach of optimization method also and found that these management strategies play a crucial role in working and performance of vehicle. He also compared the different global optimization methods on the basis of computation intensity, robustness, real time approach, analytical solution and its complex structures. Also, he concluded that the comparison of these methods can be made under various heads like robustness to modeling uncertainties, robustness to driving situation variations, computational complexity, and adaptation to more complex structures, predictive control etc. [15] studied a stochastic control strategy for HEV. Out of the different control strategies fuzzy and static optimization were used for power split. Also, deterministic dynamic programming (DDP) was used to find optimal solution but had certain drawbacks like it optimizes only for a specific driving cycle and the rule extraction process is time taking. To overcome this, Lin proposed a stochastic dynamic programming optimization method and Markov chain modeling. It is a time invariant state variable feedback and is directly used in real time. He performed a simulation on continuous time standard driving cycle in SIMULINK and compared the performance of SDP with previous driving cycles and better results were achieved over most of driving cycles when compared with rule-based methods. This infinite horizon SDP governs or controls the engine and battery operations.

[30] studied the power management strategy for a FCHEV in offline and real time system and concluded that real time system consumes more hydrogen but improves system durability. The real time system was optimized using genetic algorithm whereas two offline techniques– dynamic programming and Pontryagin's minimization principle were used and compared too. [31] described about two different control strategies for FCHEV named as offline and online strategy with the objective of minimization of hydrogen consumption. Offline control strategy depends on dynamic programming and online strategy depends on fuzzy logic controller.

Offline strategy aims at optimum distribution of power split between sources i.e. fuel cell and battery bank for a driving cycle already known whereas in online strategy predictive information is not available hence four different modes or states are considered based on state of charge (SOC) of battery. SOC is defined as the ratio of capacity remaining to fully charged capacity. A fully charged battery has 100 % SOC and fully discharged battery has 0 % SOC. For Electric vehicle and hybrid vehicles energy capacity plays a more important role than coulometric capacity (Ahs) since it directly associates with vehicle operation.

[32] Studied about the main objectives of HEV to make it practically commercial and the different EMS i.e. rule based and optimization control strategy. In[18] the design and analysis of fuel cell hybrid system oriented to automotive addressing the advantages of this kind of power systems was studied and also focused on the technique allowing the improvement in efficiency of FCHVs. Also, FCHVs electrical structures and the electrical topology comparing two types of energy-storage devices (batteries and SCs) are analyzed and addressed. It was concluded from the paper that SCs seem one of the best technical alternative because FCHVs require storage systems with high specific power and high cycle durability. [33] set up a hybrid test bench having two sources (fuel cell and battery) because among different architectures parallel configuration is the best possible combination of hybrid vehicular system with two different driving cycle patterns i.e., staircase and Amman cycle. In both patterns, fuel cell alone and fuel cell with battery was compared and results were better in case of fuel cell with battery.

In [34], it was proposed that an energy management of a hybrid vehicle by considering multi objective cost function based on power flows with an economical oriented model predictive control approach. But it needs effort in the improvement of control model along with the efficiencies of different components by considering all relevant behaviors. The [35] studied the power control of an electrical system having a PEMFC and boost converter for controlling the speed of servomotor for vehicle application. The output voltage and motor speed control is performed with adaptive sliding mode control even in presence of uncertainties. The [36] proposed a complete detail of the different energy management strategies using various methods of optimization for achieving minimum fuel consumption and also the detail of optimization techniques used and available. The paper [37] used a fuzzy subtractive clustering approach to develop a real driving pattern database representing traffic condition and also designed an adaptive fuzzy logic controller with particle swarm optimization algorithm to make a recognition algorithm for traffic condition for different traffic conditions attaining 9-17 % improvement in fuel consumption.

VI. CHALLENGES ASSOCIATED WITH FUEL CELL TECHNOLOGY

There are various methods for the production of hydrogen, such as by biological wastes, renewable energy, clean coal gasification, chemical water splitting route. But, the depository of hydrogen is big task in a fuel cell technology. There is some method for storing the hydrogen are compressed hydrogen, metal hydride, liquid phase i.e., cryogenic storage at -2530C, Carbon nano- structures. Moreover, the cooling of fuel cell system is also a challenging issue in the motor application.

The fuel cell electrical characteristics depend on curve which shows relation between voltage and current density known as polarization curve [4]. The response of fuel cell turns on on the complex dynamics of heat and mass balance within and outside the stack. This limitation is overcome by the combination of energy storage systems (ESS) in the PEMFC.

The dynamic response of FCS for quick energy demand is slow even if it has good energy to weight ratio therefore to meet instantaneous power demand it is must to combine some external energy source in parallel. This causes the cost and weight of the system to increase but reliability can be achieved in vehicular system. The variation in the power level of FCS needs to be considered which requires the study of the system efficiency.

In [22] an extensive review of the architecture of the disparate types of electric vehicles was proposed. He focused on the present and future issues along with technical difficulties related with the commercialization of these vehicles. [2] also concluded that an auxiliary source of power must be there in order to avoid fuel starvation problem which results in lack of reliability and lifetime of power sources. In [19], the authors studied the topological overview, architecture and configuration of Hybrid Electric Vehicle (HEV) and FCV. They studied about the different combinations of the HEV vehicles like series, parallel, combination of series-parallel along with battery and also about FCV and Fuel Cell Hybrid Vehicle (FCHV) for limiting the emissions from the vehicle. Also, they studied about the working of Fuel Cell for passenger car as well as fuel cell powered transit bus for heavy duty. In [38] it was focused on the size of fuel cell system along with ESS, the effect of driving cycle and the driving constraints of vehicle so that hydrogen consumption is lowest. This is achieved with proper secondary source of energy, to assist the power of FCS and the necessary algorithm for control in power management strategy. He considered two driving constraints- grade ability and acceleration. The algorithm based on global optimization, he calculated an optimum solution for distributing the power between FCS and ESS for minimization of hydrogen consumption.

VII. CONCLUSION

The growing concern is to protect and conserve energy and environment resulting into the hybrid fuel cell based vehicles development. The commercial development of the fuel cell vehicles is day by day becoming a dream come true. The hydrogen fuel used for fuel cell based vehicles, is inherently in pure form and is clean since the hydrogen consumed by either combustion or a fuel cell emits only water as its by-product. But, the hydrogen cost is too high as compared to other fuel options and dangerous to handle so, it is likely to play a major role in the economy if the cost goes down by doing certain changes and improvements in the existing technology. For vehicular applications, it is found that fuel cells have considerable high efficiency than IC Engine. Also, it is quiet in nature and also reduces environment pollution. In this paper, we find that PEMFCs have proved to be one of the most attractive options among the fuel cell available. Also, we studied the areas which can be improved to enhance the performance of vehicles. There are many challenges that still have to be met before a fuel cell power system can achieve the cost, performance and reliability in order to guarantee successful commercialization of fuel cell vehicles. The things still required on the commercial scale in market is the introduction of hydrogen refueling stations for FCEV. The research in the field of fuel cell provides improvement in cost and performance both. The shortcomings of FCVs are being reduced in recent years because the power density and cold start issue is not a show-stopper anymore.

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