Comparison of Fuel Cell, Fuel Cell Battery, and Fuel Cell Ultra-Capacitor Vehicles

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Abstract— Fuel cell automobiles are the vehicles which use fuel cell as an energy source rather than traditional lead batteries. However, fuel cell cannot be used for bidirectional flow of power. So, fuel cell has to be used with batteries or ultra-capacitors. Battery has high density of energy and ultra-capacitors have high density of power. So, in this survey we will review model of batteries used with fuel cell, and model of ultra-capacitors have been used with fuel cell. However, batteries have low life because of charging and discharging cycles and ultra-capacitors have high reliability due to numbers of charging and discharging and high value of specific voltage than battery but it will take long time for startup so in this survey we will review how system will behave after combining these two terminologies with fuel cell. Moreover, in this survey we will compare these powertrain terminologies on the bases of element sizes, control tactics and reliability of fuel cell automobiles because elevated global warming associated to indicate the need of replacement of internal combustion engine (ICE) vehicles.

Index Terms— Minimum 7 keywords are mandatory, Keywords should closely reflect the topic and should optimally characterize the paper. Use about four key words or phrases in alphabetical order, separated by commas.

1 Introduction

Due to global warming and depletion of fossil fuels is being predicted we are in the need of replacing internal combustion engines (ICE) with other non-combustible fuel which has low greenhouse gases emission So to resolve this problem fuel cell automobile are best substitute. Fuel cell has capability of generating high electrical power with low operational noise but there are many limitations in getting fuel cells on the way, reliability of fuel cell because fuel cell has high cost per unit, low transient performance and can't allow bidirectional flow of power. Therefore, it is necessary to use fuel cell with energy storage system (ESS) like batteries and ultra-capacitors which will be advantageous for long time period. Batteries have high specific energy density but ultra-capacitor usually have high value of specific power than batteries and more reliable because of withstanding capacity by means of number of charging/discharging cycles.
A number of researches has been done in the past by researchers using fuel-cell with the batteries as an ESS and fuel-cell with ultra-capacitor as an ESS. Batteries have low life because of low charging/discharging cycles and ultra-capacitors have high specific power and numbers of charging/discharging cycles but it takes long time for startup.

Therefore, the best solution model mounted by the researchers is to use batteries and ultra-capacitors as ESS with the fuel-cell. An analysis of the quality has been performed to get best cartography which is based on cost efficiency and weight of the system.

In a fuel-cell automobiles fuel-cell module provide base power for constant driving and ESS module provides peak power for acceleration and braking energy. Moreover, the cost of system reduced, efficiency and transient performance of system increased.

From recent researches it has been shown that system with combination of Batteries and Ultra-capacitor has superb performance. All types of automobiles use DC to DC converter for raising the produced voltage of the fuel cell to match the provided voltage at input side of motor controller. This design is useful because it allows to use small voltage and therefore less expensive fuel cells. The ultra-capacitor and batteries used in series is limited to the number cells. Usually, a DC to DC converter can be used for each Energy storage system which is battery or ultra-capacitor. Techniques that we are discussing bidirectional converter to reduce weigh, costs and dropping power mean of losses. The control strategy of this research is to use ultra-capacitor to meet the transient/ transitory power demand. Therefore, battery has been used with DC to DC converter so that losses connected with the converter operator are often less common in the cycle of driving. An important feature of this strategy is to ultra-capacitors to abolish battery life, as batteries are reduced to capacity conditions with over cycles of charging and discharging. Fuel-cell can be use with the battery, ultra-capacitor, and combination of both. The comparison of models of these techniques is shown in the next sections.

2 Background

Fuel cell is an open thermodynamic technology. it is one of best efficient among the non-conventional sources which generate electricity and heat with the help of chemical reactions between oxygen and hydrogen and also it has only water in byproduct [1]. More to basic the fuel of fuel cell is hydrogen fuel and hydrocarbon fuel is used and now it is the best substitute to fossil fuel for proving the energy to backward areas. moreover, fuel cell has many types e.g. "direct methanol fuel cell, alkaline fuel cell, phosphoric acid fuel cell (PAFC), molten carbonate fuel cell" etc. from these classified types of Fuel cell PAFC is best and reliable among these types due to its higher operating temperature [2]. But there are many limitations that kept the fuel cell in the limit.

3 PROBLEM STATEMENT AND PROPOSED SOLUTION

There are many limitations in obtaining fuel cells reliability of batteries and fuel cell introducing a new substructure that will reduce the cost of vehicles. So, it is difficult to design the optimal solution for battery, fuel cells and cost. Ultra-capacitor usually has high value of specific voltage than batteries and more reliable because of withstanding capacity by means of number of charging/discharging cycles. So fully controlled and plant parameters must change accordingly due to the coupling demand. This survey compares the near optimum framework for the topography for fuel cell automobiles with ESS as battery, fuel cell automobiles with ESS as super capacitor and combination of both power storing devices mounted with fuel cell. The main purpose of research in this field is to minimize the fuel cost of the automobile and enhance the efficiency of the vehicle. The automobile models include the model of all DC to DC converters with detail work, that was designed in engineering software (MATLAB) for custom parameter studies. This document aims to connect to the system controller correction upon the fuel cell modeled with battery, the fuel cell mounted with ultra-capacitors and the fuel cell with combination of both (battery ultra-capacitor) automobile. This paper will give a compact correlation between all three categories.

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4 FUEL CELL MODEL

Research that has been described by 'M.kazerani' and 'J.Bauman' have main attention on the outage character that are (I vs V and V vs I curves) for getting on his line of fuel-cell model the researcher has to evade the complications that have been coming in the way of modeling of fuel-cell e.g. Mass of cell that has been mounted, material of that cell, and weigh of blower. Typical efficiency curve and I vs V curve that has been shown in following based on HYPM fuel-cell. [3]

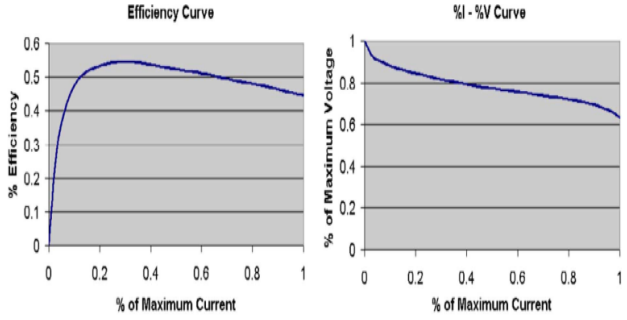

Fig. 1 Fuel-cell efficiency curve and %I–%V curve[4]

Scanning of scales assumes that the size of the efficiency curve and I-V dimension of curve remains fixed as the percentage of maximum current curve and percentage of maximum voltage curve. So, that the same relative curves can also be used for different sizes of fuel-cell for running each simulation model. On the basis of latest and real request to the fuel-cell, the voltage and efficiency of the fuel-cell can be found from these curves. (%I–%V and %I–efficiency) [3]. The energy of the hydrogen consumed can be found in term of "gasoline gallons equivalent (gge) and miles per gasoline gallon equivalent (mpgge)" as follows:

$$E_{H2}(t_{final}) = \int_0^{t_{final}} \left(\frac{P_{fc}(t)}{\varepsilon_{fc}(t)} + \frac{P_{aux}}{\varepsilon_{avg.}}\right)dt \ldots(1)[3]$$

$$gge = \frac{1}{3600}\frac{Wh}{joule} * k\frac{gge}{Wh} * E_{H2}(t_{final}) \ldots(2)[3]$$

$$mpgge = \frac{miles}{gge + \left(\frac{E_{SOC} * k}{\varepsilon_{path}}\right)} \ldots(3)[3]$$

Basically fuel-cell could not allow bidirectional flow of power. In the hybrid fuel cell powertrains Fuel cell can provide the base energy for constant level of drive so energy storage device is necessary to attach with fuel cell model to increase the reliability and efficieny of that system so hybrazization degree can be defiend as[4]

$$H = \frac{P_{ESs}}{PESS + P_{FC}} [4]$$

Fuel cell vehicle operates on pure hydrogen and availability of refueling pure hydrogen is not a suitable option therefore fuel cell vehicles must have one energy storage device from which it is possible for optimizing the advanced control strategies of the automobile's fuel economy, drivability, and emissions,[5][6].fuel cell system has been dominated by temperature and demand of fast energy will effect in drop of the voltage for short instant of time therefore fuel-cell system has energy storage system so that the fuel cell is the main source of energy and then ESS can be used as the backup energy device[7]. Batteries have high density of energy and low density of power so far then ultra-capacitors have high density of power and low density of energy therefore using both powertrains can compromise of a high density of power and high density of energy with ESS and from which our system will be small light weight and highly efficient and reliable [3][8]. Therefore, sufficient size and weight of system's energy storage devices is and major facing issue to obtain an appropriate system [9]. So, from the researches it is definite that fuel cell with an energy storage device has high reliability and superb performance.

5 ULTRA-CAPACITOR MODEL

The model of super-capacitor used by the 'J.burker' 'M.kazerani' and 'J.Bauman' is typical Maxwell supercapacitor that six cells are mounted in their researches that have been simulated in series to get high voltage. It has simulated cell balancing for balancing of cell and sturdy packaging. Super-capacitor is mounted with HV bus directly in topology that has been selected by these authors in their researches, so that it can get maximum amount of the voltages. In these techniques authors also simulated the super-capacitors in parallel to get high voltage same as 'wenzhong Gao'. The voltage of used super-capacitors can be calculated by using this equation that has been described by 'J. Marshall and M. Kazerani' as follow [3][5].

$$v_{uc}(t) = v_{uc}c(0) + \frac{1}{C}\int_0^t i_{uc}(\lambda)d\lambda \text{ [25]}$$

here C is uc-p based total capacitance. It also included the line drop voltages and line losses that has been caused by the internal resistance of the system [25]. Cost of Maxwell super-capacitor that has been used for high volume of production is 85$ per cell that is much higher than the typical battery cell Which means that weigh of that Maxwell cell is approximately same or lower than the battery cell. so, when we talk about the balancing of the system, we have to use same weigh of battery in that system for balancing of mass [26]. Cycle tests that have been performed by 'J.burker ,E. Schaltz, and A. Khaligh' shown that the super-capacitor is much durable than the battery cell even after 500000 cycles Maxwell super-capacitor losses only less than 20% of its capacitance C [3][10]. In other case of 'E. Schaltz, A. Khaligh and P. O. Rasmussen' The ultra-capacitors are mounted as a series connection of a capacitor and resistor with the DC to DC converter which converts the power between bus and ultra-capacitors and this model has efficiency of 0.95 furthermore when he ultra-capacitors are overrated then from high pass filter energy will be consumed and if battery is attach with it will never effect the charging and discharging of the battery [12]. Different converter technologies are used for power electronic interface in fuel cell system between ESS and the high voltage dc bus which depend on the application of required power in system. In these two cases a classical boost converter is used as a fuel cell converter "which is commanded to draw a specific amount of current from fuel cell" [13] [14]. Furthermore, the ultra-capacitor can handle fastest energy change in the system that's why ultra-capacitor is the fastest energy source and it can achieve a dc voltage regulation by supplying the energy to system [8]. Moreover, fuel cell is main source of energy and it also supply energy to the energy storage device to be charged and ultra-capacitor can regenerate braking by using its high specific power density [15]. The ultra-capacitor and fuel cell current loops are provided from two reference signal one is from ultra-capacitor "Iuc" and other is from the fuel cell "Ifc". "Which is produced from the dc bus voltage loop and ultra-capacitor voltage regulation loop." as state variable for dc bus voltage loop it consumes dc capacitive energy and energy as a command variable is produced by super-capacitor for linear transfer function of system" [8]. Furthermore, to ultra-capacitor strategy the negative ultra-capacitor current generated by dc voltage link if load power's magnitude taken as negative. Furthermore, the dc bus voltage regulation produced positive magnitude of ultra-capacitor current if density of load power is higher than rated fuel cell power [16] also dc bus voltage causes an increase decrease in load power when ultra-capacitor cause increase decrease in current [8]. Moreover in

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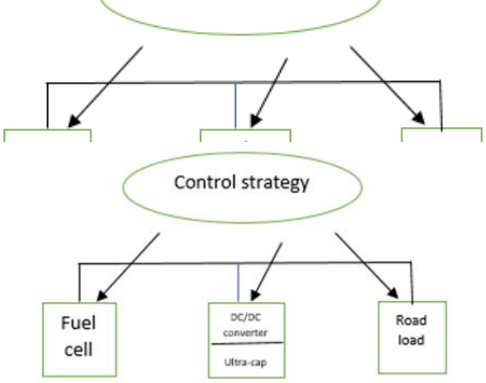

Fig. 2 Fuel cell hybrid Ultra-capacitor powertrains [5]

In another case the super-capacitors have been simulated with dc bus having source of 2 quadrant dc-dc converter and one inductor is also used. The purpose of using inductor is energy transfer and filter. The size of inductor is enough for rippling of current and for switching frequency. The current that flows through the storage device is either positive or negative that allows power to move in bidirectional [17].

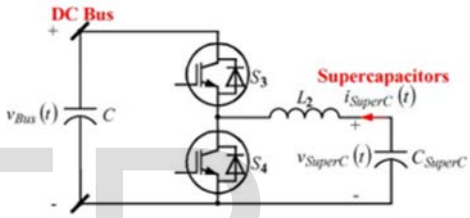

Fig. 3 Quadrant ultra-capacitor converter [17]

6 BATTERY MODEL

"There are many types of batteries but Lithium-ion batteries are now generally accepted as the optimal choice for energy storage in electric vehicles over lead-acid or nickel-metal-hydride batteries due to their superior power and energy densities"[18].'J.Burker' also preferred to use lithium ion battery in his research instead of typical batteries due to its high density of power[18], this battery is preferred on typical used batteries due to its high efficiency cost efficient and better life of cycling [5][19][20].these cells can be used in parallel as well as in series to get better efficiency by comparing the V vs SOC curves with other models. Similarly fuel cell used in series gave the maximum of its voltage that compared with other models used in series by comparing V vs SOC curve. The estimated efficiency of this model is 95% [21].

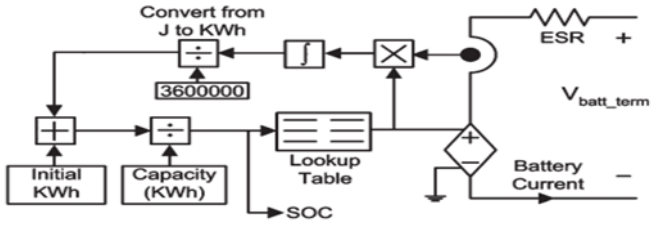

Fig. 4 Basic diagram of the battery model [3]

The basic method of finding power of the battery is multiplying the calculated current with calculated voltage of battery in kilowatt that can sum up with input or output power of battery. To get better SOC power of the battery have been divided with total capacity of batter this is reliable method to get better SOC [22]. For getting the constant voltage of batteries the cells of batteries are connected in series to get better cycles of charging and discharging without interrupting motor working. For Energy storage system two quadrant of dc to dc converter has been used between HV bus and battery and the level of voltage of battery is lower than the HV bus. Cost of each battery cell is 19.31$ including packing or cycling cost which is lower than the super capacitor. Peak current limit of the battery cell is 70A but its capacity has been decreased from charging and discharging of cycles. these level of charging and discharging has been more decreased when it is under operation of vehicle now it has threat that its consequences could be worst when it has to deal with higher level of current or system [3] [12]. As we know that battery has density of energy and lower density of power but has been leading to fuel cell five-time higher density of power but less than super capacitor but lifespan of battery is lower due to cycles of charging and discharging or due to carry the higher level of current. The nonlinear function of the current and state of charge is cycling of charging and discharging [18]. In this research the author presented the Simulink proved two cases of using the batteries with fuel cell. In the first case 25 cells of lead acid batteries are used whose peak power is 86.35KW but the weight of system is 1380kg. In the second case the number of batteries has been doubled (50 module) whose peak power is 172.8KW and the weight of system is 1655kg [5]. But the sufficient sizing of powertrains batteries or ultra-capacitors should be balancing the mass of system and "W.GAO" proved from his research that the combination of both powertrains batteries and ultra-capacitors system has superb performance and most efficient [5].

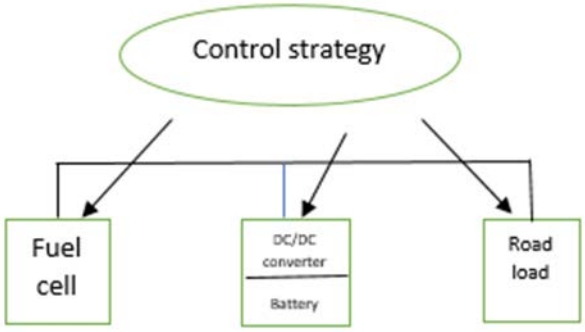

Fig. 5 Fuel cell hybrid battery powertrain [5]

7 MAJOR RESULTS

The main objective of the research is to maximize the facts related to the performance measured by high-speed acceleration, fuel economy and power costs. The cost of the fuel cell inversely proportional to the size of cells. Since the cost of the primary obstacle in the refueling battery is more expensive, it is therefore important to perform a high efficiency and work less than that of the maximum power. Even for the fuel cell battery ultra-capacitor, it seems that the maximum number of battery cells in the connection of the series obtains an essential objective. The ultra-capacitors are more efficient because they provide the best transmission power compared to the other two. Because of the high running costs and cost reduction, the main advantage of the fuel cell battery is the main advantage of life.

TABLE 1
Parametric study variables and bounds [3]

Vehicle Type	Variable	Lower Bound	Interval	Upper Bound
Fuel Cell-Battery(FC-B)	fc_kW	35	5	75
	batt_p	1	1	8
	filter(T)	1	2	18
Fuel Cell Ultra-capacitor (FC-UC)	fc_kW	35	5	75
	batt_p	5	1	16
	PI time constant	.0002	.0002	.0012
Fuel Cell-Battery Ultra-capacitor (FC-B-UC)	fc_kW	35	5	75
	batt_p	1	1	6
	batt_s	45	10	75
	uc_p	1	1	6
	filter(T)	1	2	18

TABLE 2
Selected optimization results [18] [24]

Vehicle Parameters (Fc_kW=40)	Acceleration Time(s)	Fuel Economy (mpgge)	Cost (USS)	ESS Cost Breakdown (USS)
FC-B batt_s=105 batt_p=3	10.267	51.362	$23468	Batteries $6032
FC-B-UC batt_s=75 batt_p=4 uc_p=2	10.161	51.792	$29335	Batteries $5745 Battery DC/DC $1564 Ultra-capacitor $4590

4 Conclusion and Discussion

This document provided a detailed comparison between the near-optimum fuel cell system with battery, the fuel cell system having ultra-capacitor and fuel cell mounted with combination of both these power trains automobiles. Parametric studies have been performed on a scale to determine the dimensions and the high component controllers for the top of the selected vehicle. Time of Acceleration, fuel cost efficient and cost-purpose function have been included in this research. The model included details of the power electronic converter to enhance the accuracy in the results. Different simulation models produce the following result that can be applied to fuel cell automobiles.

- Because of the current and expected future prices of fuel cells in comparison with cells of battery and ultra-capacitor, Maximum size of fuel cells has the maximum power demand to operate extremely fast and support vehicle systems.
- Fuel cell ultra-capacitor powertrain is the highly efficient than the battery but it is least desirable due to its high cost, low fuel economy and high weight of the automobile.
- From the recent advancement in the powertrains defined that ultra-capacitor has low density of energy as compared to batteries.
- Automobile having battery as ESS or Automobile having super capacitor as an ESS are close contestants.
- The life span of the fuel cell mounted with battery is low due to charging and discharging cycles and less costly but ultra-capacitors are high costly and high mass powertrain.
- Fuel cell vehicle having both powertrains have superb performance and reliable because it will be high fuel efficient and it will enhance lifespan of battery due to less battery stress of charging and discharging cycles. So, it is the best powertrain for the future vehicle.

Acknowledgment

I wish to thank to my Almighty Allah and my parents for Being so helpful and showing strength in me.

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