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Emerging Technologies for Hybridized Energy Storage System for Electric Vehicles

Diwakar Singh*, V.K. Giri*, and Shekhar Yadav*

Abstract –*The biggest problem of modern era is pollution, which is continuously increasing and has become a great cause of concern for the world. Every government of today's world is putting its best effort to overcome this problem. It has been observed that a major cause of pollution is excessive use of the internal combustion (IC) engine vehicles. Hence, to reduce the pollution, the idea of Hybrid Electric Vehicles (HEV's) is becoming more popular day by day because they cause comparatively less pollution. The increasing demand of HEV's has raised the demand of energy storage system (ESS). Here, renewable energy sources have to be used to make it more eco-friendly but these ESS have a huge problem of low efficiency hence, the range of HEV's decreases. Hence more than one ESS's are hybridized to form a hybrid energy storage system (HESS) which can overcome the problems faced in ESS. In this paper different kinds of HESS's such as battery-fuel cell, ultra capacitor-fuel cell, ultra capacitor-battery, fuel cell-battery-ultra capacitor have been studied and a comparison is made on different criteria such as energy efficiency, robustness, pollution effect, battery life etc. This paper will help in developing HEV's with enhance performance*.

Keywords –Battery, Fuel Cell (FC), Electric Vehicle (EV), Hybrid Energy Storage System (HESS), Ultra-Capacitor (UC).

1. INTRODUCTION

In The standard of living is increasing every day due to increase in the facilities and new inventions which aid in our day to day life, along with it the pollution is also increasing. The major cause of the pollution is excessive use of IC engine vehicles which is contributing a lot in greenhouse effect due to its large emission rate [1]. The fossil fuel driven engines are causing nearly 25% of the CO2 emission of the world [2-5]. The IC engine driven vehicles also have very low efficiency of energy conversion which is up to 20%. The research of EV suggests that it has intimating energy transforming efficiency which can be up to 60%. It is also prognosticated that by year 2050 the passenger vehicles are likely to become 100% nil-emission vehicles [6]. The electric vehicles (EV's) have different devices for energy storage such as ultra-capacitor, battery, fuel cell [7] which are eco-friendly. These EV's are modified by combining the energy resources to develop hybrid electric vehicles (HEV's). Such combination enhances the performance of EV and also helps in providing continuous supply of power to the vehicle. It also increases battery life; longevity of FC's can be found easily [8]. The advantages of HESS in comparison to ESS in EV applications are given in [9] Combining UC with any other storage system helps in reducing its work load by supplying power during transient phase of the power requirements. In case of HESS for HEVs it helps in decreasing the stress of FC and battery, taking in account that whole operation should run under a defined state of charge (SOC) level according sources used and topology considered, sometimes it is used as a tactic to control, considered converters of the system. In recent period many control strategies such as PI controller [10], model predictive control (MPC) [11], wavelet based control [12], fuzzy logic control (FLC) [13], linear mode control [14] has been suggested, and research is still going on to enhance the HEVs so that it can serve the need of people more appropriate way. So, to make it convenient for the researchers to get into the research of the enhancement of HEVs this paper presents a review of different HESS used in HEVs and also makes a comparison between them on the basis of battery life, robustness, efficiency etc. This paper also makes a cross comparison between different HESS and provides with the advantages and disadvantages of different HESS in HEVs. This paper makes a detailed review of different control strategies used in battery–UC HESS model for HEV and a comparative analysis is presented which can help the researchers of this field. Apart from the introduction the paper is divided into five more sections. Section II gives a brief information about hybrid storage system (HESS) that can be used as power source in HEVs. In this section different HESS configurations have been compared and presented in terms of its pros and cons. Section III deals with the controls strategies used in Battery – UC type HESS to optimize its output and a comparison is made between them. At last section IV and V gives the review outcome results and conclusion respectively.

2. HYBRID ENERGY STORAGE SYSTEM (HESS)

The hybrid energy storage system means combination of two or more than two energy storage systems, and the

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vehicles which use this hybrid energy storage system are called HEV's. The configuration of HEV can be further divided in four types on the basis of energy storage systems used by them.

2.1 Battery - Ultra Capacitor

This combination reduces loss of energy and also increases battery life spam. The ultra-capacitor in this model aids the battery by decreasing its stress during peak hours. This combination gives adequate energy system that have the ability to minimize cost, increases systems dependability and it also provides dispense load-leveling function. This combination is further divided into three divisions; active, passive and semi active. The semi active type is again divided in two divisions; battery semi active and ultra-capacitor semi active. Active type is divided as parallel active and cascade active. These classifications have been shown in Fig. 1.

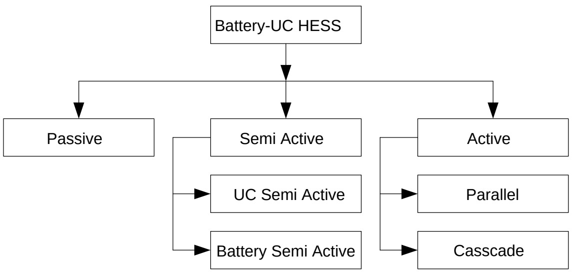

Fig. 1. Classification of battery-UC HESS [18].

2.2 Fuel Cell-Ultra Capacitor

In this combination the energy sources are ultra-capacitor and fuel cell. In fuel cell when flow of current is zero than the voltage is at maximum value. The value of voltage decreases with the increase of current because of overvoltage activation and losses in the membrane due to ohmic resistance. There is a sudden drop in voltage at high value of current because transport of gases in the reaction is not able to follow reaction's amount. Hence, fuel cell is bound for limited supply of current. Thus, the power response of fuel cell is slow which is compensated by ultra-capacitor which has a fast power response. Thus, the performance which is specified for EV is maintained.

2.3 Fuel Cell –Battery

Here the fuel cell is used as primary source of power whereas battery is used as secondary source of power. The fuel cell is capable of fulfilling large load demand because of increased energy density properties to charge up the battery module. When the fuel amount drops below the allowed limit the battery helps the system to continue its sustainable performance.

2.4 Battery - Ultra Capacitor- Fuel Cell

The motto for such configuration is maintaining distribution of energy amongst the sources so that they can fulfill the demand of power at different objectives when required. This combination provides excellent performance during continuous operations and it also provide long range of driving because of its many sources of the energy. The major issue with such type of combination is current fluctuations in battery, storage capacity, and state of charge level of battery. Different combinations of HESS for HEV are shown in Figure 2. The different parameters of HESS are compared in table 1 [15].

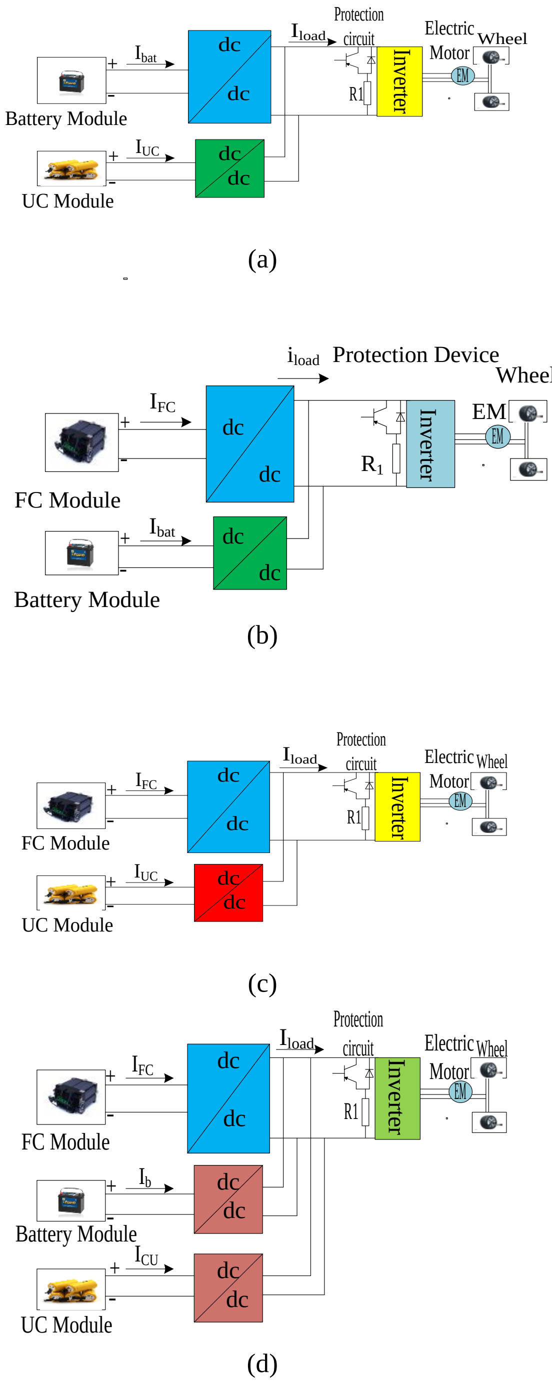

Fig. 2. Diagram of HEV having (a) Battery – UC configuration (b) FC – battery configuration (c) FC – UC configuration (d) Battery – UC – FC configuration.

3. CONTROL TECHNIQUES FOR BATTERY – UC HESS CONFIGURATION

Among the entire above mentioned configuration battery – UC has been the most important configuration for researchers because of its advantages of sizing, cost efficiency, low maintenance etc. In this section we will look for the different control strategies which have been used for this configuration.

After making comparison between different HESS configurations based on different parameters, a cross comparison is made between these configurations in Table 2, which focus on presenting the information related to these HESS configurations.

Table 1. Comparison of different parameters of Battery-FC, UC-FC, UC-Battery, UC-FC-Battery [15].

Comparison parameters	FC – Battery	FC - UC	Battery - UC	Battery – UC – FC
Configuration	Main source- FC Secondary source- Battery	Main source- FC Secondary source- UC	Main source- Battery Secondary source- UC	Main source- FC Secondary source- UC and Battery
Starting load demand managed by	Battery	FC	Battery	Battery and FC
Transient load demand managed by	FC	UC	UC	UC
Implementation	Easy	Easy	Easy	May be complex
Energy conversion efficiency	High	High	Higher	Highest
Estimation of SOC	Under low level of SOC battery is charged by FC.	Under low level of SOC UC is charged by FC.	Under low level of SOC UC is charged by battery, otherwise battery will be charged by UC	Battery and UC are charged by FC when their SOC's are under low level
Robustness	Good	Good	Good	Good
Battery life	Extraneous	Long	Long	Longest
Battery stress	Brought down by FC	Brought down by UC	Brought down by UC	Brought down by FC and UC
Emission	Less	Less	Nil	Less
Reliability	Good	Good	Good	Excellent
Frequency management	High frequency elements are controlled by FC, low frequency elements are controlled by battery	High frequency elements are controlled by UC, low frequency elements are controlled by FC	High frequency elements are controlled by UC, low frequency elements are controlled by battery	High frequency elements are controlled by UC, low frequency elements are controlled by battery and FC
Dynamic performance	Good	Good	Good	Better
Driving cycle performance	Good	Good	Good	Good
Conversion efficiency	High	High	High	Highest

Table 2. Cross comparison between different HESS configurations for EV.

Compared by	Battery-UC	FC – Battery	FC – UC	Battery – UC – FC
Battery-UC	NA	• Battery ageing is slowed down. • Faster response and good dynamic performance. • Larger cost reduction and faster computational speed	• Improved durability by minimizing power demand of FC • Prolonged battery life • Hydrogen consumption is minimized	• Give rapid dynamic response • Prolonged battery life • Give high efficiency and reliability on the basis of consumption of hydrogen and UC/battery SOC
FC – UC	• Service continuity and safe functioning is guarantee • UC current is maintained at its reference value • Computational speed is fast	• Robust and stable performance is provided • Optimal sizing of component is ensured • Optimal power distribution is maintained	NA	• FC power demand is minimized, hence durability is improved • Optimal energy distribution is insured • Robust and stable performance is provided

FC-Battery	• FCs fuel consumption is reduced and efficiency of operation is increased • Battery life increased • FC warm-up time is reduced	NA	• Battery ageing is slowed down, and fuel consumption is reduced • Operational efficiency is increased • DC bus voltage regulation is insured	• Overall power capability is increased • Regeneration of power is insured during deceleration • Optimal component sizing is provided • Efficiency is optimized
Battery-UC-FC	• performance of system such as dynamic response, power density is improved	• Downside effect of dynamic response is reduced	• Service continuity and dependable functioning is guarantee • Reliability and efficiency is improved	NA

3.1 MPC Technique

This technique has been proposed in [16]. It consists of back propagation neural network (BPNN) along with pontryagin's minimum principle (PMP). The BPNN algorithm foretell about the speed of vehicle and its running nature for different modes of driving, whereas PMP reduces the estimated load. This technique is verified in MATLAB. In this technique the balance between economy and performance is taken care of through equation given below

$$P_b + \eta P_{uc} = P_d \quad (1)$$

Where, P_b is battery power, P_{uc} is ultra-capacitor power, η denotes coefficient of converter and P_d denotes power demand. The diagram of this technique is given in Figure 3.

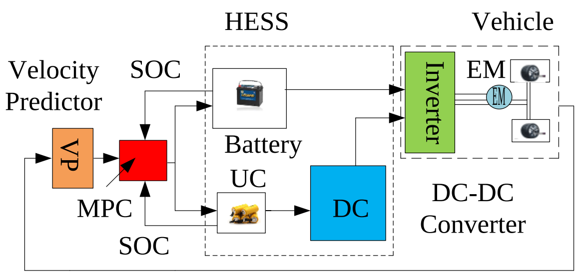

Fig. 3. MPC technique proposed [16].

Another MPC is proposed in [17]. In this technique response time of battery and UC is taken in account to improve the lifetime of battery. The SOC and voltage of battery as well as UC in this technique are maintained at a constant level. Input current required is given by eqn. (2)

$$i_t = \frac{p_t}{v_{bus}} \quad (2)$$

Where, p_t is sum of power stored by sources and v_{bus} is DC bus voltage (constant).

3.2 Semi-Active Battery-Uc Topology Control Technique

This technique is given in [18]. This technique uses peak current control; this gives stable DC voltage and also reduces current fluctuations. For control purpose bidirectional DC to DC converter is used in three different modes, buck mode, standalone mode and boost mode. Focus of this technique is to regulate DC voltage properly and also reducing the size so that total cost can be brought down. This technique is authenticated by dSPACE- 1103 controller board through MATLAB.

3.3 Real Time Energy Management Strategy (EMS)

The strategy proposed [19] here obtains real time result of different drive cycle. In this three drive cycles are taken in consideration: New European Driving Cycle (NEDC), WLTC class2 and ARTEMIS. Adaptation problems are taken care of by using PMP. Reduced–scale power hardware in loop (HIL) simulation platform is used to validate the technique.

Other strategy given in [20] is a small experimental platform with an objective of improving power management with help of performances of various sources and used components. Three–wheelers considering the Indian traffic and road condition is used to demonstrate this strategy. The operation modes under consideration are; deceleration mode, constant speed mode and acceleration mode. In this strategy RMS current is reduced which increases battery performance and its lifetime is also increased. Reference current of UC and battery are calculated by following equations.

$$I_{ref} = \frac{P_{UC}}{V_{UC}} \quad (3)$$

$$I_{batt\_ref} = \frac{P_{demand}}{V_{batt}} - I_{ref} \quad (4)$$

Here, I_{ref}, P_{UC} and V_{UC} are reference current, UC power and UC voltage respectively. P_{demand} and V_{batt} are power demand and terminal voltage of battery respectively.

3.4 Rule based EMS

It is given in [21]. In this technique firstly current controller is used that stabilizes the flow of current among the sources, after this a voltage controller is used to maintain the SOC of UC at a reference value. The total required power of vehicle is given by following equation.

$$P_{veh} = P_{aer} + P_{acc} + P_{roll} + P_{slop} \quad (5)$$

Here, P_{veh}, P_{aer}, P_{acc}, P_{roll} and P_{slop} are vehicle power required, aerodynamic drag power, accelerating power, rolling power and slope resistance power respectively, whose values can be calculated by following equations.

$$P_{aer} = \frac{1}{\eta}\frac{C_{aer}A_{aer}}{76140}\mu_{eh}^{3} \quad (6)$$

$$P_{roll} = \frac{\mu_{veh}}{\eta}\frac{MgfCos(\alpha)}{3600} \quad (7)$$

$$P_{slop} = \frac{\mu_{veh}}{\eta}\frac{MgfSin(\alpha)}{3600} \quad (8)$$

$$P_{acc} = \frac{\mu_{veh}}{\eta}\frac{\delta M}{3600}\frac{d\mu_{veh}}{dt} \quad (9)$$

Here, M is vehicle mass, g constant of gravity, η is drive efficiency, α is slope angle of road and $\mu_{veh}$is velocity of vehicle. The current required is expressed by following equation.

$$I_{load} = \frac{P_{veh}}{V_{bus}} \quad (10)$$

Here, $P_{veh}$and V_{bus} are power required by vehicle bus voltage respectively. Driving cycle which are tested by this USA urban dynamometer schedule (UDS), and new European driving cycle (NEDC). The diagram of given technique is given in Figure 4.

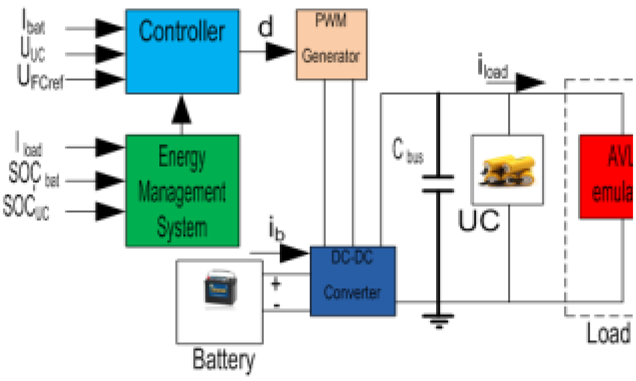

Fig. 4. Diagram of proposed rule based EMS [21].

3.5 Fuzzy Logic Based Control Technique

This is presented in [22]. It contains FLC and filter that aim to keep the peak current of battery at a reference value and also maintain stable UC voltage. After testing it on different driving cycle the outcome of the experiment gave a controlled SOC of UC with a stable operating DC voltage.

Other EMS based on FLC in given in [23]. Its aim is to keep an eye on the fluctuations in power arising due to variation in load. In this technique the SOC of battery is taken in consideration instead of UC-SOC, and appropriate measures are taken to monitor the change of SOC. This system has been simulated on MATLAB and its characteristics are shown according to the changes. Diagram of the above mentioned technique is shown in Figure 5.

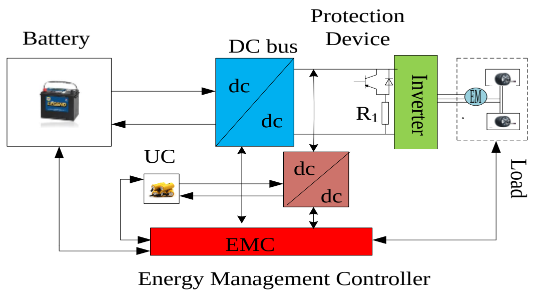

Fig. 5. Diagram of FLC based control technique for battery – UC HEV [23].

Another method is proposed in [24]. In this strategy appropriate amount of power is delivered to the vehicle on the basis of different driving modes. This strategy gave excellent torque and speed control of the vehicle, the performance of the vehicle was improved by fuzzy power management technique.

The advantages and drawbacks of the above mentioned techniques has been given in tabular form in Table 2 [15].

4. REVIEW OUTCOME RESULTS

This paper gave brief knowledge about different HESS combinations that can be used in a HEV and also made comparison between them so that they can be easily understood. This paper also discussed about different control strategies that can be used in battery – UC combination, most of them very tasted and verified using MATLAB. The overall results and outcome of this review for battery-UC configuration are as follows:

The MPC and rule based techniques uses UC for power response during transient, due to which energy losses are minimized. At the same time this technique also limits flexibility of system, maintenance cost is increased, and harmonics in current is created and also raises the run time of system.

The real time EMS gives stability to DC – link and dynamic response of the system is also increased, but this has complex and complicated calculations.

The FLC based EMS is much efficient, most reliable and also flexible, but it has a drawback of limiting the input variables and causes increment in run time.

Table 3. Comparison between control techniques for battery–UC configuration [15].

Ref. No.	Control techniques	Advantages	Drawbacks
S. Yu. et. al. [16]	Efficient MPC	• UC is charged by battery when the SOC level of UC is low • During high power requirement UC responses efficiently	• Accuracy of prediction is low • Computational complexity
B. Hredzak et. al. [17]	MPC	• It compensates the power component • Optimal working is maintained by following specified limitations	• Battery response only when slow current change occurs' • Current harmonics are generated when inductor fails to work
P. Bhattacharyya et. al. [18]	Semi-active battery-UC topology	• Inductor current is compensated by DC – link stability • Cost is minimum and efficiency is maximum • High current fluctuation is taken care of	• Backflow of power can occur due to fault in diode • Instability occurs in converter
S. D. Vidhya [20]	Improved real time power split strategy	• RMS current of battery is reduced • Increased battery life • UC is used efficiently	• Lead acid battery is not feasible • Motor cruising power is increased
Q. Zhang et. al. [21]	Rule – Based EMS	• Increased battery life • Potential balancing problem of battery is solved • Storage capacity is increased	• Limited battery range • Applicable for limited EV range • Depth of discharge for battery is low
X. Wang et. al. [23]	FLC	• DC bus voltage is stable at the time of change in load • Battery current variation is limited • Large efficiency, excellent dynamics, good reliability • Charging and discharging is simple as well as effective • Increased battery life	• Speed is lower • System run time is increased • Number of input variables are limited

5. CONCLUSIONS

The performance analysis of different HESS has been done and it is found that all hybrid energy storage systems can be used for HEV but battery-ultra capacitor hybrid storage system is the best suited for HEV, and amongst all the control techniques discussed in this paper FLC based EMS is most suited for battery –UC HESS configuration. This work suggests that research should be focused on developing batteries which have higher power density and UC should be designed to make the system more efficient. More efficient algorithms can be developed so that power sharing between the sources can be carried out in most optimal way. Emphasis should be made to enhance the driving cycle in HEV so that optimal function is maintained.

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