# Dynamic Modeling and Analysis of Power Sharing Control Strategy Based Fuel Cell/Battery Assisted Hybrid Electric Vehicle System

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**Abstract-** A dynamic modeling of Fuel cell/Battery assisted hybrid electric vehicle system is presented in this article and two suitable power sharing control strategies are integrated into the system with the objective of minimizing the fuel consumption and maximizing the battery life through its safe operating limit. This prominent goal is accomplished into the developed hybrid vehicle system by incorporating suitable control strategies without compromising the drivability of the vehicle. The proposed hybrid electric vehicle is capable of sustaining the peak power demand and utilizes the regenerative power in an effective manner for charging the energy storage system which could be possible with the relative power control strategy. In this paper, the proposed vehicle is modeled for its different hybridized configurations utilizing the model components such as dynamic PEM-Fuel Cell (PEMFC) system modeled by NARX network, Ni-MH battery system, DC/AC converters, PMAC traction motor and a power sharing controller. The proposed hybrid electric vehicle with two control strategies are modeled and evaluated in a MATLAB/Simulink environment. Simulations and comparison results shows that the PEMFC system assisted by battery during peak power demand accomplishes an improved fuel economy of hydrogen consumption and maximizes the battery SoC at the end of the driving schedule in a safe operating limit, which has a greater influence on the battery life cycle. Also, a comparative analysis is performed for the suitable selection of PMAC motor power rating to be adopted into the proposed vehicle model based on the fuel economy and efficient utilization of the battery.

**Keywords**—PEM fuel cell, Ni-MH Battery, NARX Recurrent Neural Network, Power sharing control strategy, Hybrid Electric vehicle, Fuel economy.

## 1. Introduction

Due to the continuous increase in demand of energy for the development of a nation, the apprehension about the reduction of the fossil fuel stock is growing. The Statistical analysis with the current rate of discovery of new oil reserves and the current consumption rate reports that the world oil reserve will be depleted by 2049 [1]. Among several sectors, the vehicle sector is the most promising and emerging one which utilizes the fossil fuel to a large extent which leads to air pollution and global warming. The massive utilization of Internal Combustion Engine (ICE) vehicles is dramatically contributing for the cause of depletion of fossil fuels and they create vigorous environmental pollution. Advanced pollution free energy source like Fuel cell plays a major role in the recent years towards the development of automotive applications to reduce the depletion rate of fossil fuels, air pollution and global warming.

Fuel cell is preferred for the propulsion because it provides high efficiency and lower emission when compared with the internal combustion engine (ICE). The fuel cell offers higher efficiency than the internal combustion engine (ICE) as it is not subjected to the “Carnot cycle” efficiency limit and it directly converts the free energy from the hydrogen fuel into electrical energy without any moving parts. Moreover, as there is no $CO_2$ and other harmful emissions, fuel cell is considered as a clean energy source and it's only by product is the water. Consequently, many researches and development works for fuel cell vehicle are currently emerging in the recent years [2].

Several works have been cited in the literature towards the development of fuel cell hybrid vehicle and some control strategies for energy management in the vehicle are discussed for the effective fuel utilization. Jenn Hwa Wong et al. [3] proposed a parallel energy-sharing control strategy for the application of fuel cell hybrid vehicles in which the fuel cell generator and the energy storage units (both battery and ultra-capacitor modules) are interfaced using direct current (DC) bus. The existence of two auxiliary energy sources for supporting single energy source increases the system complexity and eventually reduces the efficiency. In [4], some of the trade-off between the various parameters in the modeling of energy storage units is discussed. A flexible and novel strategy for multi-objective control of the converter in the hybrid power supply to regulate the output current of the fuel cell energy source and the battery charging voltage or current while regulating the battery discharging current is discussed in [5]. In [6-8], an artificial neural network model is proposed for replacing the complex mathematical model of the proton exchange membrane fuel cell systems which provide appropriate mapping between input and output parameter without requiring any empirical equation and relationship among process parameters. An artificial recurrent layered neural network model is proposed in [9] for replacing the nonlinear state space model of the PEM fuel cell which eventually reduces the modeling complexity in a wide range. In [10-11], ANN models of PEM fuel cell for electrical vehicle application are developed using a simple static feed forward network which predicts the fuel cell output response.

In this paper, the prominent energy source (Fuel Cell) and energy storage module (Battery) are combined for the development of hybrid electric vehicle with the inclusion of two energy management strategies to effectively share the power between the two sources. Also, to get rid of the mathematical modeling complexity of fuel cell, an intelligent parametric modeling of PEM fuel cell using recurrent neural network approach is established in the proposed work that replaces the conventional mathematical modeling of PEM fuel cell. Besides the selection of efficient control strategy, the model accounts for the selection of optimal PMAC motor power rating to be adopted to achieve for the effective operation of the hybrid vehicle. Moreover, the optimal proposed energy management strategy facilitates in providing significant power flow between the two energy sources that massively improves the fuel economy and maximizes the drivability of the battery assisted vehicle.

## 2. Dynamic Hybrid Electric Vehicle Model

The crucial components involved in the development of the electric vehicles are the energy sources, power split controller, power electronic circuitry and the transmission systems.

The main contribution of the energy sources in the traction system is to deliver the power for the load demand and additionally, the storage devices are having the ability of storing the regenerative power from the electric vehicle. To stabilize the output response of the energy sources, power electronic converter circuitry are used and fed its constant output to the traction motor that drives the vehicle. The development of the vehicle transmission system incorporates both AC motor modeling and vehicle dynamics modeling. Thus all the components intricate in the proposed model are developed individually and integrated to form a Fuel Cell Hybrid Electric Vehicle. The complete model of the proposed hybrid electric vehicle architecture with the integration of the key components is shown in Fig. 1.

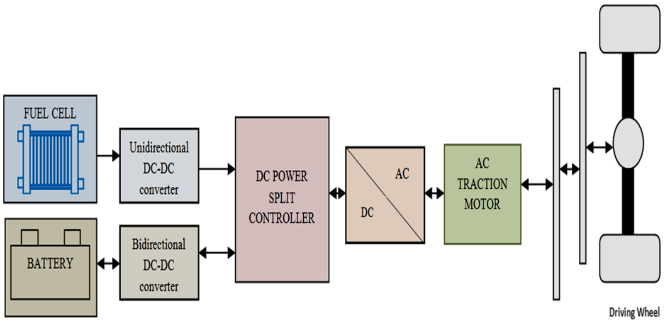


**Fig. 1.** Framework of the Fuel Cell Hybrid Electric Vehicle Model

## 3. Modeling of Energy Sources

The energy sources recommended for the electrical vehicle can be the battery, ultra capacitor and renewable energies like solar, wind etc. Though battery is suggested for operating the electric vehicle, it sustains only for a short duration thereby the vehicle can be operated only for a short run. Also, the battery can be used only for the low power vehicle driven application that limits the usage of a standalone battery driven electric vehicle. But in order to meet the high power demand, a battery alone is not sufficient to drive the vehicle because of its charge storage limitation. On the other side, some of the limitations encountered in the renewable energy sources are the uneven nature variations, discontinuous operation, etc., which makes the energy sources unfavorable for various situations. These factors emphasize the need for developing a prominent energy source for powering the electric vehicle. One such promising source of electric power which is not only characterized by its higher efficiency but also provides a clean energy with low emission is the fuel cell in which the electrochemical energy process occurs between the fuel (usually hydrogen gas) and oxidant (usually oxygen) produces the dc electricity in a controlled manner [12,13]. Among several types of fuel cell, PEM (Proton-Exchange Membrane) fuel cell is more preferable for the vehicle propulsion than the other cell types as it holds the features of fast start-up, low operating temperature (50°C–100°C), solid electrolyte, high power density, favorable power-to-weight ratio, low corrosion, long cell/stack life, and low sensitivity to orientation [14,15].

### *3.1 Hybrid Energy Sources Modeling*

The major issue that emerges with the standalone fuel cell model is the deficiency of delivering startup power due to its cold start problem. At start up, the fuel cell system consume certain period of time for initiating the chemical reaction involved in the fuel cell to generate electric energy. Instantaneous propulsion of electric vehicle powered with the standalone fuel cell energy source is practically not possible. It takes a definite period of time called 'cold start period' for the propulsion of electric vehicle that affects the comfort level in driving the electric vehicle at start. These problems can be eradicated with the invention of proposed fuel cell hybrid electric vehicle system in which the fuel cell system is assisted with some auxiliary energy source such as battery or ultra-capacitor. The startup power required by the fuel cell hybrid vehicle will be suitably provided by these auxiliary energy sources. The power delivered from the auxiliary energy source is used for propelling the vehicle initially during cold start period where the fuel cell system lacks in generating the power. Hence this paper is also focused on the development of a suitable control strategy with the consideration of all the constraints for the power sharing between the energy sources. With the invention of hybrid energy source powered electric vehicle system, the wastage of braking regenerative power from the vehicle can be effectively utilized by the auxiliary energy storage device for its charging purposes. Further the fuel consumption by the fuel cell can also be optimized and thereby the overall efficiency of the hybrid fuel vehicle system can be improved.

In this work, the fuel cell model uses the Artificial Neural Network (ANN) technique which appropriately relates the output and the input of the PEMFC system without acquiring any empirical equation and process parameters. ANN is a very effective data model framing tool that has the ability of capturing and representing the intricate output and input relationships. The benefit of ANN lies in its capability of representing both linear and nonlinear relationship and it is capable of learning these relations directly from the modelled data. ANN approach can acquire the knowledge from the trained data sets and it need not require any prior knowledge of strong relationship between the output-input parameters of a PEMFC system. Among several neural network structures, the NARX Recurrent Network is preferred as an optimal one because it holds the feature of recurrent feed loop. The output response from the network relies on both input parameters and past output response which improves the convergence rate while minimizing the network response error. Hence the NARX network can be substituted as a PEM fuel cell model in hybrid vehicle system. Similarly, the Ni-MH (Nickel Metal Hydride) battery is preferred among various types of battery because of its long run and high energy density. A mathematical model of the battery is adopted in this study implemented based on the mathematical equations that are obtained using curve fitting techniques relating the various factors that governs the battery performance.

### *3.2 Neural Network Based Fuel Cell Modeling*

The mathematical modeling of fuel cell for developing an electric vehicle model is highly tedious, because the relationship between the PEMFC's output voltage, partial pressure of oxygen and hydrogen inside the fuel cell and stack operating temperature are highly nonlinear and involves different kind of physical phenomena such as electrochemical and thermodynamic processes in the model development [16]. Developing a precise Fuel cell model using the mathematical approach requires proper and accurate knowledge of processing parameter, which is difficult to estimate [17]. In order to eradicate the mathematical modeling complexity, an intelligent parametric modeling of PEMFC system using artificial neural network (ANN) methodology is established that replaces the conventional mathematical modeling of PEM fuel cell.

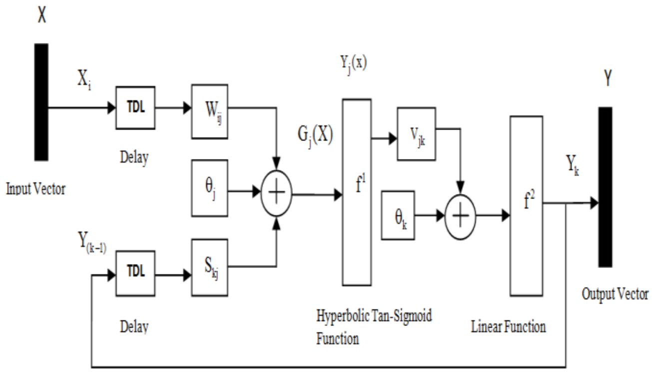


**Fig. 2.** NARX Recurrent Network Architecture

In this paper, the modeling of PEM fuel cell using the NARX Recurrent Neural (NRN) Network is accomplished for a 5kW Ballard MARK V Fuel cell system consisting of 35 cells connected in series. The NARX Recurrent Network is a dynamic recurrent non-linear autoregressive network with exogenous inputs (NARX). It has feedback connection from the output of the network to the input layers and also the present output signal from the network is regressed on past values of the output signal and present values of an independent (exogenous) input signal. The developed recurrent network model is being used as a substitute for the PEM fuel cell system. The NARX Recurrent Network modeling parameters and specifications are shown in Table 1. The proposed recurrent architecture of the ANN model is shown in Fig. 2.

**Table 1.** Network Modeling Parameters

| | | |
|---|---|---|
| Network type | | Dynamic Recurrent |
| Training algorithm | | Levenberg–Marquardt |
| Maximum Epochs | | 1000 |
| Activation function | Input-Hidden | Tangential sigmoid |
| | Hidden-Output | linear |
| Error Goal | | 1E-06 |
| Number of Hidden layer/Neurons | | 1/20 |

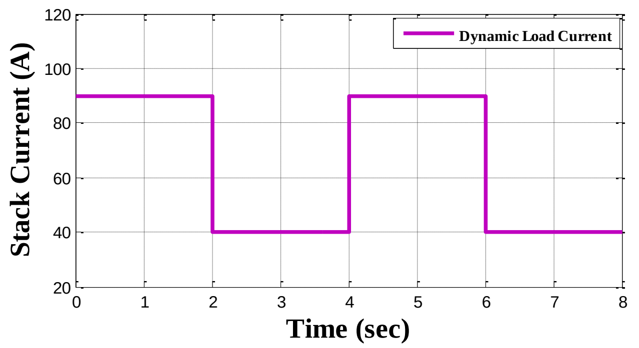


**Fig. 3.** Dynamic High Current Variation Profile

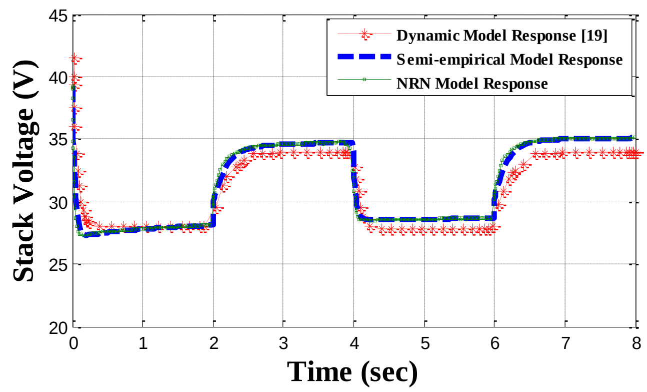


**Fig. 4.** Dynamic voltage response of the PEMFC model

The data required to generate the network are simulated and derived from the experimentally validated semi-empirical model [18]. The input-output data sets measured for developing the proposed NARX network are current density, partial pressure variations of the Hydrogen & Oxygen reactant while the output data sets are cell voltage, stack power and hydrogen consumption. The Number of data set taken for the proposed network model is 3500 and they are normalized between the ranges of -1 to 1 using Min-Max algorithm. The performance goal was achieved for a better prediction performance with the minimum error value of 1.4224E-08 in 5 epochs. To validate the developed NARX model, a high current variation profile that changes over a short period of time from 0 to 8 seconds between 90A and 40A as shown in Fig. 3 is used. The dynamic response of stack voltage from the NARX network model is validated with the result obtained from the model proposed in [19]. As seen in Fig. 4, the dynamic response of the NRN model developed in this section based on the semi-empirical model discussed in [18, 20] shows a good agreement with the Ballard MARK V model presented in [19].

### *3.3 Battery Modeling*

In this paper, the energy storage device to assist the fuel cell during peak power demand is the battery which utilizes the regenerative power in an effective manner. The battery modeling plays a vital role in order to estimate the overall performance, Life cycle and the operating characteristics as it is still the critical component [21] to model the electric vehicle. Among several types, Ni-MH battery is taken as an optimum one for the modeling. This is due to the fact that the Ni-MH battery performs better than Ni-Cd battery as it has twice the amount of energy density [22]. The Ni-MH battery model is developed which incorporates the modeling of charge and discharge model of the battery as it has the ability of charging and discharging at a charge rate of 6 and 10 coulomb respectively. These two models are established purely based on the experimental data acquired from the data sheet specifications given by the manufacturer [23]. Mathematical form of Multi- regression equations that relate the various factors inside the battery are obtained using the curve fitting techniques. The curve fitting techniques are used to fit the actual data and the MATLAB/Simulink™ environment is used in developing the model.

The charging and discharging model based on the curve fitting techniques is given as follows [24]:

Charging voltage $V_c$ in terms of charge input, $CI$ :

$$V_c = 0.1562\,CI^8 + 0.316\,CI^7 - 4.301\,CI^6 + 10.78\,CI^5 - 12.02\,CI^4 + 6.515\,CI^3 - 1.734\,CI^2 + 0.381\,CI + 1.581 \quad (1)$$

Discharging voltage $V_d$ in terms of depth of discharge, $dod$ :

$$V_d = -3.128e^{-5}\,dod^8 + 0.0005658\,dod^7 - 0.003473\,dod^6 + 0.0045\,dod^5 + 0.04172\,dod^4 - 0.212\,dod^3 + 0.4105\,dod^2 - 0.3667\,dod + 1.166 \quad (2)$$

The state of charge ( $SoC$ ) can be computed based on the product of charge efficiency of the battery model and the charge input. The battery specification used for the model developed is stated and enlisted in Table 2.

**Table 2.** Battery Specifications [23, 24]

| Parameter | Specifications |
|---|---|
| Battery Used | NiMH (Panasonic) |
| Battery Model/Type | HHR650D |
| Nominal Voltage | 1.2V |
| Rated Capacity | 6.5Ah |

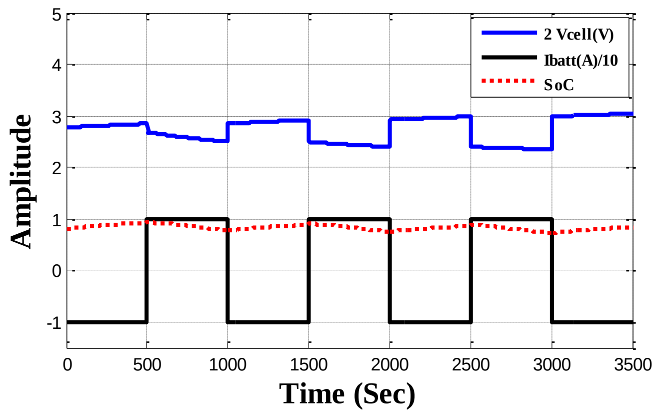


**Fig. 5**. Dynamic response of the Ni-MH battery model

The simulated dynamic response of the Ni-MH battery state of charge (SoC) and the corresponding terminal voltage for its load variation profile is obtained from the developed model and it is shown in Fig. 5. It is seen that the proposed Muti-regression battery model shows its robustness towards the prediction of SoC, charging and discharging voltage for a charging and discharging current profile.

In this section, the modeling of PEM fuel cell and Ni-MH battery is discussed along with its dynamic response for the load changing context. The proposed energy source models can have the ability of providing appropriate power demand by the vehicle for its propulsion towards a specified driving pattern. Further, it can be seen from Fig. 4 and 5, the output response from them is highly nonlinear and found to be unregulated. Hence, the next section deals with the suitable converter modeling that provide a stabilized output to meet the vehicle requirement.

## 4. Converter Modeling

The power electronic converters are used in the vehicle traction system for stabilizing the energy source output due to the fact that the output of the source is dynamically varying because of chemical reactions inside both the fuel cell and battery. The power electronic converters of two approaches are used in the proposed modeling for operating the hybrid electric vehicle, namely the unidirectional/bidirectional DC-DC converter and DC-AC bidirectional converter. The bidirectional converter also has the ability of accepting the regenerative power developed during braking/deceleration and hence the battery can be charged and discharged accordingly.

### *4.1. DC-DC Converter Modeling*

The occurrence of the electrochemical reaction inside the energy sources develops a non-linear output response. Hence it is necessary to stabilize the source output such that it could meet the supply requirement of the motor. In this hybrid system, the converter employed along with the fuel cell is unidirectional DC-DC converter in which the power flows from fuel cell towards the traction motor as it does not have the ability to utilize the power developed from the wheels of the vehicle during regenerative braking. The modeling of converter accompanied with the battery should be in a way which could utilize regenerative power and also need to deliver whenever power is required by the vehicle. Thus a bidirectional DC-DC converter is preferred to establish a power flow to and from between the battery and the traction motor. The converter developed for the fuel cell is quite similar to the one used for the battery with the exception that there will be a limit fixation in case of converter used in fuel cell to avoid the negative current input to the fuel cell.

The proposed DC/DC converter model along with a suitable controller is implemented using the output voltage and current equations as the reference. The output voltage of the converter in terms of input and duty ratio is given as,

$$V_{out} = \frac{V_{in}}{1-D} \tag{3}$$

The output current of the converter mainly depends on the converter efficiency and the duty ratio as given by,

$$I_{out} = \frac{I_{in}}{\eta(1-D)} \tag{4}$$

where,

D – Duty cycle

$\eta$ – Efficiency of the DC-DC converter

### *4.2. DC-AC Bidirectional Converter Modeling*

A suitable power electronics converter circuit is mandatory to convert the voltage from the DC bus to AC voltage for providing appropriate AC power to the AC traction motor. It can be accomplished by a DC-AC Bidirectional Converter model. The two modes of operation performed by this converter module are DC to AC conversion mode (during motoring mode), when the power flows from source to the load (positive power) and AC to DC conversion mode (during generating mode) when the power flows from load to the source (negative power). The relationship between the DC power and the AC power can be obtained using the converter efficiency.

The peak current value can be determined using the predetermined information of torque command and the torque constant as given by,

$$I_{pk} = \frac{T_{command}}{K_e} \tag{5}$$

where,

$T_{command}$ – Torque Command (in Nm)

$K_e$ – Torque Constant

The three phase current for energizing the AC traction motor can be computed from the peak value of the current and the phase angle (rotor angle) as given by,

$$I_{abc} = I_{pk}\left[\sin\theta + \sin\left(\theta - \frac{2\pi}{3}\right) + \sin\left(\theta - \frac{4\pi}{3}\right)\right] \tag{6}$$

where,

$I_{pk}$ – Peak current (in Amps)

$\theta$ – Rotor angle (in rad)

## 5. Vehicle Transmission System Modeling

The development of the vehicle transmission system incorporates both traction motor and vehicle dynamics modeling. In this paper, the vehicle model is developed for the high power vehicle driven applications and hence PMAC is preferred as the traction Motor. The behavior of the motor is modeled by look-up table method based on the experimental tests available in the form of efficiency maps acquired from the ADVISOR tool. By using the three phase input current from the DC–AC bidirectional converter and the speed of the vehicle, the torque developed by the motor can be estimated by determining the rotor angle from the speed.

The torque developed by the motor is given as,

$$T = K_e \left[ i_a \sin\theta + i_b \sin\left(\theta - \frac{2\pi}{3}\right) + i_c \sin\left(\theta - \frac{4\pi}{3}\right)\right] \quad (7)$$

where,

$\theta$ – Rotor angle (in rad)

$K_e$ –Torque constant

$i_a, i_b, i_c$ – Phase currents in Amps.

Here, the rotor speed in rad/ sec acquired from the radius of the wheel (0.282 m) and linear motion of the vehicle (m/s) is used to evaluate the rotor angle, $\theta$ in radians. The motor power output can be obtained using efficiency map whose inputs are motor torque and the speed of the motor. In this paper, the performance analysis of four different ratings of the AC traction motor acquired from ADVISOR tool, namely unique mobility 100kW, continuous 58kW, Honda 49kW and Siemens 33kW is done to identify the optimal motor to be integrated onto the vehicle.

**Table 3.** Vehicle Specification adopted in the study

| S.No | Vehicle Specifications | Values |
|---|---|---|
| 1. | Curb weight (kg) | 918 |
| 2. | Rolling resistance coefficient | 0.009 |
| 3. | Aerodynamics drag coefficient | 0.335 |
| 4. | Density of Air (kg/m$^2$) | 1.2 |
| 5. | Acceleration due to gravity (m/s$^2$) | 9.81 |
| 6. | Surface Area (m$^2$) | 2 |
| 7. | Motor Rated Voltage (V) | 415 |

The next stage in the development of the fuel cell hybrid vehicle is the vehicle dynamics modeling and it is designed in concern with the total resistive force acting on the vehicle and power required to propel the vehicle. The total resistive force acting on the wheel is the combination of forces such as grade force, rolling resistance force, aerodynamics drag force and inertial force [25]. The vehicle dynamics modeling is developed with the concern of all these forces in action to drive the vehicle. The vehicle specification used for the model developed is stated and enlisted in Table 3. The output power ($P_m$) from the motor (mechanical/propulsive power) with the inputs of driving cycle pattern in the form of travelling velocity (instantaneous velocity of the moving vehicle, $V_a$) is governed by the total resistive forces ($F_t$) that the vehicle has to overcome and it is given by [26],

$$P_m = F_t \times V_a \quad (8)$$

$$F_t = \left(F_{ad} + F_{rr} + F_{if} + F_{grade}\right) \quad (9)$$

where,

$F_{ad}$ - Drag force

$F_{rr}$ - Rolling resistance force

$F_{if}$ - Aerodynamics inertial force

$F_{grade}$ - Grade force

The electrical power ($P_e$) required by the motor is given by,

$$P_e = P_m / \eta \quad (10)$$

where,

$\eta$ - Drive train efficiency

These discrete components are then integrated to form a complete hybrid electric vehicle model. The developed hybrid vehicle's performance can be analyzed by using the popular driving cycles namely New European Drive Cycle (NEDC) and Urban Dynamometer Drive Schedule (UDDS) drive cycle pattern as the system primary input. In the next section, two energy management strategies adopted in the proposed hybrid vehicle model to effectively share the power between the two energy sources are discussed.

## 6. Energy Management Strategy

The main objective of the Energy Management Strategy (EMS) is to prioritize the requesting power from the traction motor and assign the available power resources from the PEM Fuel cell generation device and Ni-MH battery storage device in an augmented way for minimizing the fuel consumption and operating the battery within the safe operating limit that improves the battery life. To claim this objective, two rule based power sharing control strategy is proposed in this fuel cell hybrid electric vehicle model. The two strategies EMS-A and EMS-B is proposed in this paper in view of reducing the fuel consumption while maximizing the drivability of the battery by taking the advantage of the multiple vehicle modes. This can be achieved by the potential energy recovery during braking and as well as the availability of the additional degrees of freedom in the vehicle operating modes with respect to the power split for satisfying the power demand.

The flowchart representation of the proposed energy management strategy EMS-A & EMS-B for sharing the power between the energy sources is shown in Fig. 6. The flowchart representation shown is used to completely visualize the mode on which the fuel cell hybrid vehicle is operated. With the consideration of Irequest (current request) and the State of charge as the inputs, the vehicle mode such as electric mode or hybrid mode is eventually determined.

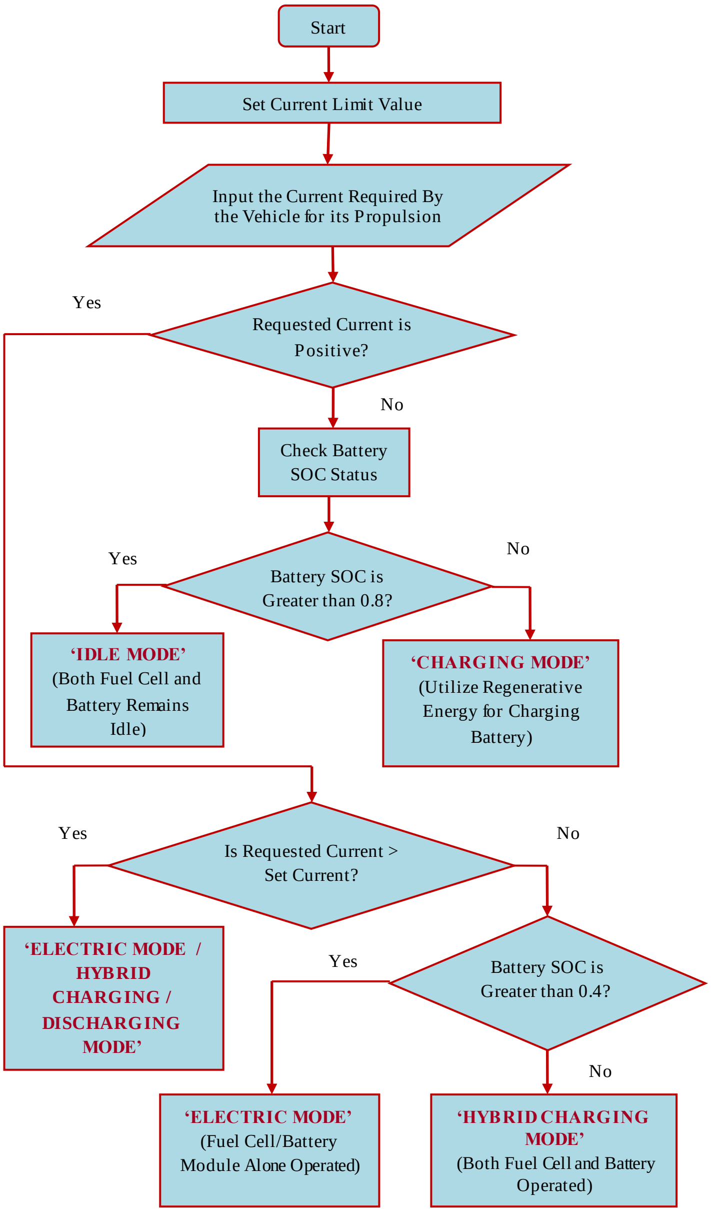


**Fig. 6.** Flowchart of Energy Management Strategy EMS-A & EMS-B

### *6.1. Energy Management Strategy-A*

In the rule based strategy EMS-A, the maximum power limited by the set current is drawn from the battery via bidirectional DC-DC converter to drive the traction motor and the rest of the peak power is assisted by the Fuel cell system.

The Battery and the Fuel cell system ON/OFF condition is controlled by the set of following rules that governs the energy management strategy EMS-A.

For the positive power requirement of the vehicle (motoring operation), the following rules are adopted:

1. If the SoC of the battery is above the SoC lower limit of 0.4 and the power request by the traction motor is less than the power limited by the set current, then the requested power can be distributed by the Battery alone and the Fuel cell must be turned OFF.

2. If the SoC of the battery is above the SoC lower limit of 0.4 and the power request by the traction motor is more than the power limited by the set current, then the requested power can be distributed by the Battery and the Fuel cell must be turned ON.

3. If the SoC of the battery is below the SoC lower limit of 0.4 and the power request by the traction motor is less than the power limited by the set current, then the requested power can be distributed by the Fuel cell alone and the Battery must be turned ON for charging.

4. If the SoC of the battery is below the SoC lower limit of 0.4 and the power request by the traction motor is more than the power limited by the set current, then the requested power can be distributed by the Fuel cell alone and the Battery must be turned OFF.

For the negative power requirement of the vehicle (regenerative operation), the following rules are adopted:

5. If the SoC of the battery is above the SoC upper limit of 0.8, then the power request (regenerative power) by the traction motor is not utilized and they are dissipated as heat due to friction in the inherent brake pad/shoe system, a heat resistant material. Both Battery and the Fuel cell must be turned OFF.

6. If the SoC of the battery is below the SoC upper limit of 0.8, then the power request (regenerative power) by the traction motor is utilized for charging the battery and the Fuel cell must be turned OFF.

### *6.2. Energy Management Strategy-B*

In the rule based strategy EMS-B, the maximum power limited by the set current is drawn from the Fuel cell system via unidirectional DC-DC converter to drive the traction motor and the rest of the peak power is assisted by the battery.

The Battery and the Fuel cell system ON/OFF condition is controlled by the set of following rules that governs the energy management strategy EMS-B.

For the positive power requirement of the vehicle (motoring operation), the following rules are adopted:

1. If the SoC of the battery is above the SoC lower limit of 0.4 and the power request by the traction motor is less than the power limited by the set current, then the requested power can be distributed

by the Fuel cell alone and the Battery must be turned OFF.

2. If the SoC of the battery is above the SoC lower limit of 0.4 and the power request by the traction motor is more than the power limited by the set current, then the requested power can be distributed by the Fuel cell and the Battery must be turned ON.

3. If the SoC of the battery is below the SoC lower limit of 0.4 and the power request by the traction motor is less/more than the power limited by the set current, then the requested power can be distributed by the Fuel cell and the Battery must be turned ON for charging.

For the negative power requirement of the vehicle (regenerative operation), the following rules are adopted:

4. If the SoC of the battery is above the SoC upper limit of 0.8, then the power request (regenerative power) by the traction motor is not utilized and they are dissipated as heat due to friction as explained earlier. Both Battery and the Fuel cell must be turned OFF.

5. If the SoC of the battery is below the SoC upper limit of 0.8, then the power request (regenerative power) by the traction motor is utilized for charging the battery and the Fuel cell must be turned OFF.

The above set of rules can be used to state the different operating modes of the hybrid electric vehicle. The different operating modes based on the charge sustaining & depletion rate are pure electric mode, hybrid charging mode, hybrid discharging mode, idle mode and battery charging mode. These vehicle operating modes are based not only on the SoC availability and also due to the power limited by the set current. In the next section, the performance analysis of four different ratings of the AC traction motor is done to identify the optimal motor to be integrated onto the vehicle. Also, the power flow and the power sharing between the energy sources using the Energy Management Strategies EMS-A and EMS-B are analyzed and discussed to adopt a suitable control strategy in the proposed hybrid electric vehicle model.

## 7. Results & Discussion

In this section, the simulation results of the fuel cell hybrid electric vehicle are discussed and analyzed to identify the optimal motor rating and a suitable energy management control strategy to be integrated onto the vehicle. The simulink model of the Fuel cell Hybrid Electric Vehicle contains NARX network based fuel cell pack and the battery pack as an energy sources. They are suitably integrated with the Converters, PMAC motor and the vehicle dynamics model driven and monitored by the energy management strategy controller. The complete specifications and parameters of the components adopted in the proposed hybrid electric vehicle are shown in Table 4.

**Table 4.** Vehicle Components & its Specifications

| S.No | Vehicle Components/ Specifications | Values |
|---|---|---|
| 1. | Fuel Cell Array (5 stacks in series) | 25kW |
| | Fuel cell- Nominal Voltage | 129.5V |
| 2. | Battery Pack system | 104Ah |
| | Battery- Nominal Voltage | 180V |
| 3. | Initial SoC | 0.8 |
| 4. | SoC Higher limit | 0.8 |
| 5. | SoC Lower limit | 0.4 |
| 6. | Fuel Cell/Battery Set current (Power) | 20A (8kW) |
| 7. | PMAC Motor Rating (optimal) | 49kW |
| 8. | PMAC Motor - Nominal Voltage | 415V |

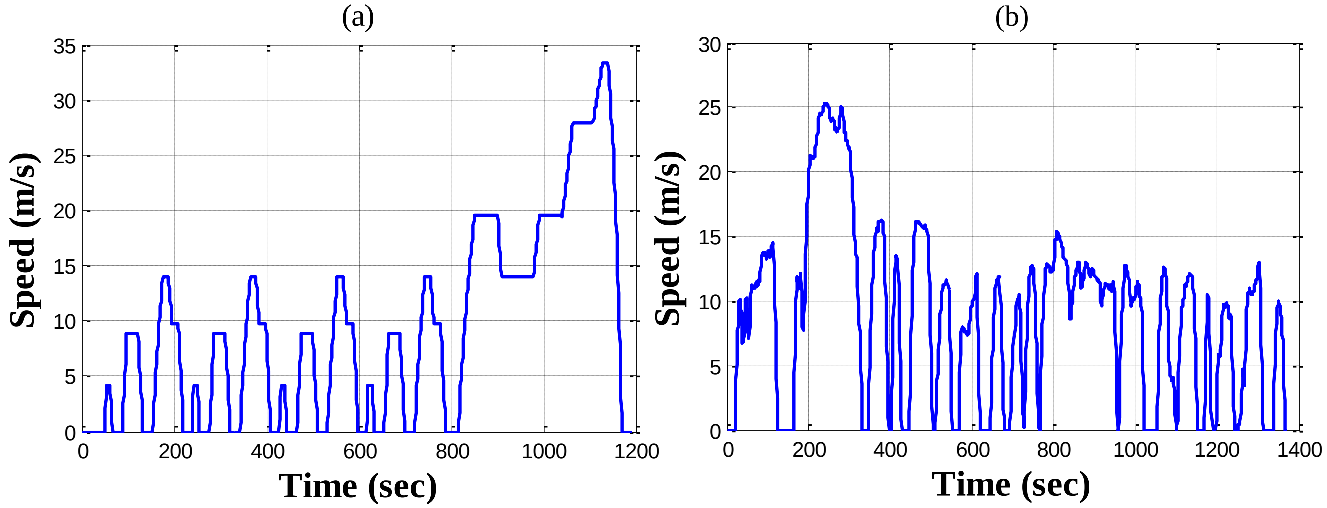


**Fig. 7.** (a) NEDC and (b) UDDS drive cycle Pattern

**Table 5.** Performance Estimation and comparison of the proposed control strategies for different motor ratings

| Control Strategy | Drive Cycle | NEDC | | | | UDDS | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Motor Rating** | **33kW** | **49kW** | **58kW** | **100kW** | **33kW** | **49kW** | **58kW** | **100kW** |
| EMS-A | Final SoC | 0.377 | 0.387 | 0.382 | 0.387 | 0.399 | 0.400 | 0.400 | 0.400 |
| | Fuel Economy (g) | 39.43 | 28.52 | 34.55 | 31.47 | 51.65 | 29.86 | 34.19 | 30.60 |
| | *Pfc_avg (kW) | 13.54 | 13.95 | 14.97 | 15.30 | 7.848 | 6.438 | 6.595 | 6.453 |
| | **Pbat_avg (kW) | 2.216 | 2.130 | 2.139 | 2.135 | 3.994 | 2.663 | 2.833 | 2.681 |
| EMS-B | Final SoC | 0.436 | **0.519** | 0.395 | 0.500 | 0.396 | **0.439** | 0.394 | 0.423 |
| | Fuel Economy (g) | 27.14 | **23.33** | 25.60 | 24.61 | 33.49 | **22.50** | 25.33 | 22.34 |
| | *Pfc_avg (kW) | 3.359 | 2.859 | 3.019 | 3.019 | 3.610 | 2.477 | 2.810 | 2.463 |
| | **Pbat_avg (kW) | 6.000 | 5.999 | 6.000 | 6.000 | 6.106 | 6.101 | 6.105 | 6.101 |

* Pfc_avg -Average Power Delivered by Fuel Cell System (kW)
**Pbat_avg -Average Power Delivered by Battery Pack System (kW)

The performance of the developed vehicle model is analyzed based on the popular drive cycles pattern namely New European Drive Cycle (NEDC) and Urban Dynamometer Driving Schedule (UDDS) as the system primary input. It is a rather simple pattern consisting of periods of continuous/constant acceleration, deceleration and constant speed. This cycle, however, is not a true resemblance of actual driving conditions in an urban scenario. It is presented here, as these are standards with which European car builders have to discuss when declaring their vehicle's performance in terms of emissions and achievable range. The NEDC (ECE_EUDC) and UDDS drive cycle pattern for the analysis of the developed vehicle model is shown in Fig. 7.

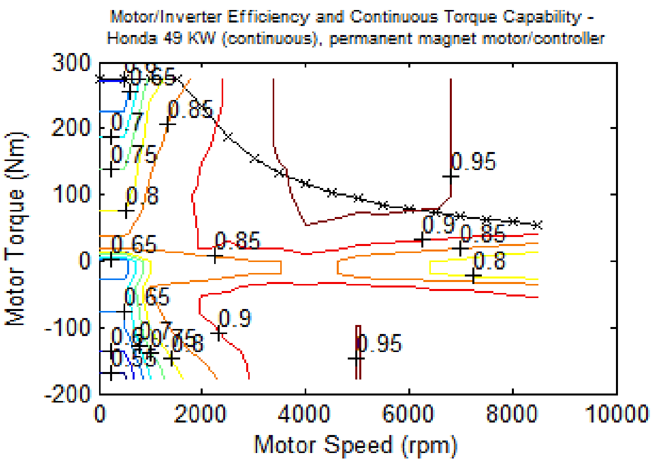


**Fig. 8.** Contour map of the 49kW Honda PMAC motor Efficiency for the motor torque and speed

In the proposed EMS-A strategy, the battery pack is used as the main sources and the neural network based fuel cell is used as the peak power source. The fuel cell system is operated only during the peak power demand arises and hence it is called peak power sources (PPS). In EMS-A, the battery pack operation is limited to 8kW (20 Amps) and the additional power demand greater than 8kW (20 Amps) is sustained by the fuel cell system. Similarly, for the proposed EMS-B strategy, the neural network based fuel cell is used as the main sources and the battery pack is used as the peak power source. The battery pack is operated only during the peak power demand arises and hence it is called peak power sources (PPS). In EMS-B, the fuel cell system is limited to 8kW (20 Amps) and the additional power demand greater than 8kW (20 Amps) is sustained by the battery system.

The behavioral analysis and optimality analysis on different motor ratings against the vehicle parameter is carried out using both EMS-A and EMS-B control strategy for the NEDC and UDDS drive cycle. Table 5 summarizes the performance estimation and comparison of the proposed control strategies over different PMAC motor ratings. It can be seen from Table 5 that the 49kW PMAC motor offers optimum result among all the available motor ratings in terms of vehicle performances such as maintaining the SoC of the battery at the end of the each drive cycle and amount of hydrogen fuel consumption for a complete driving schedule. It is observed that the SoC at the end of the NEDC and UDDS drive cycle is 0.519 and 0.439 for the EMS-B which is quite appreciable than the final SoC obtained for the EMS-A control strategy. Further, the hydrogen fuel consumption of the NEDC and UDDS drive cycle is 23.33g and 22.5g obtained for the EMS-B control strategy is also relatively less than the fuel consumption for the EMS-A when it is adopted for driving the vehicle. Fig. 8 shows the contour map of the 49kW Honda PMAC motor efficiency for the motor torque and speed adopted in the proposed vehicle model that illustrates the boundary of motor operating region.

Fig. 9 shows the simulation results of the power shared between the two energy sources for the power requirement of the vehicle and Battery SoC throughout the driving schedule when it is subjected to NEDC drive cycle for the integration of EMS-B power split controller. It can be seen that the SoC at the end of the driving schedule is 0.519. Similarly, the simulation results for the hybrid electric vehicle when it is subjected to UDDS drive cycle for the integration of EMS-B power split controller can be seen in Fig. 10. The results presented in Fig. 10 shows that the SoC at the end of the driving schedule is 0.439. Thus, the analysis of power sharing control strategy over the hybrid electric vehicle demonstrates that the control strategy EMS-B dominates the

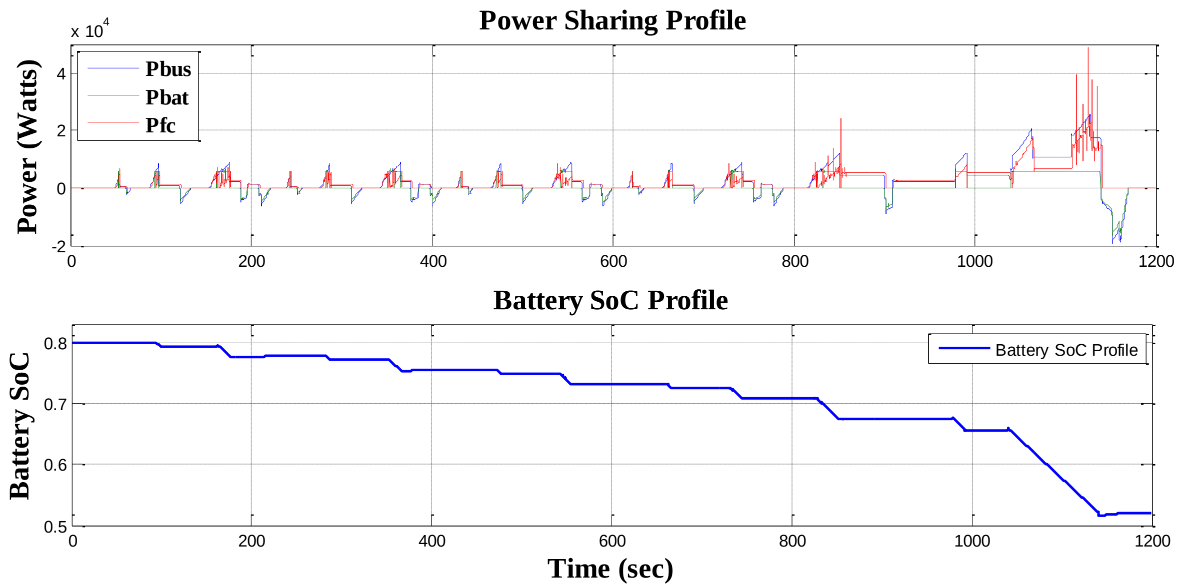


**Figure 9.** Optimal Power sharing (EMS-B) and Battery SoC profile on NEDC

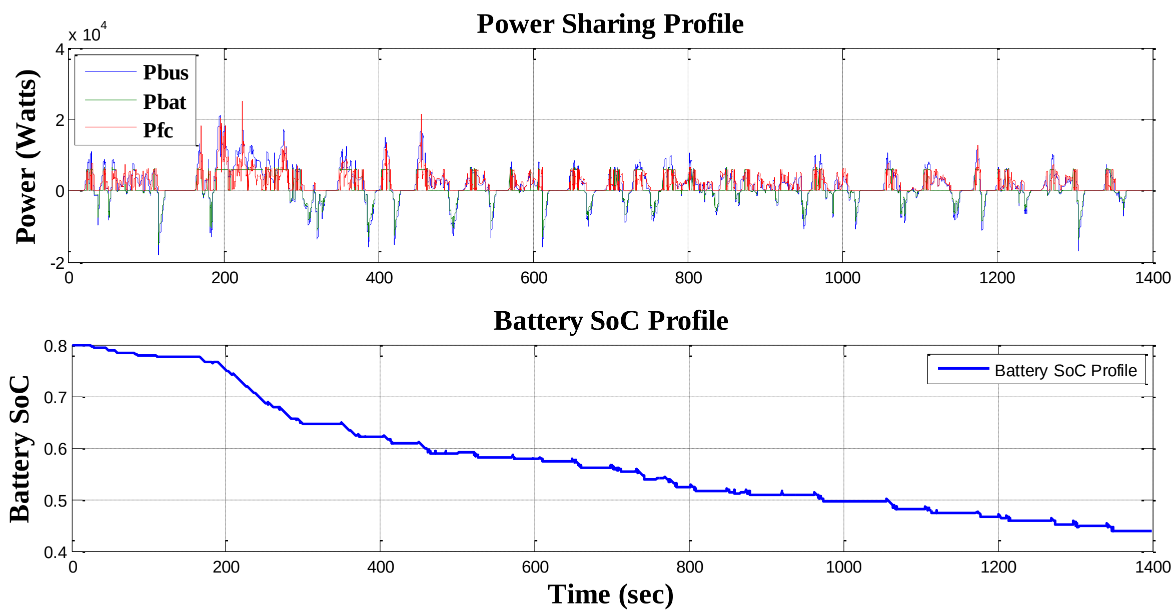


**Figure 10.** Optimal Power sharing (EMS-B) and Battery SoC profile on UDDS

EMS-A as it has the advantages of optimizing the SoC of the battery within the safe operating limit along with the reduction of hydrogen fuel consumption.

**Table 6.** Estimation of Improvement in Fuel economy for EMS-B

| Drive Cycle | Control Strategy | Motor Rating | Final SoC | Fuel Economy (g) | IFE* (%) |
|---|---|---|---|---|---|
| NEDC | EMS-A | 49kW | 0.387 | 28.52 | - |
| | EMS-B | | **0.519** | **23.33** | **18.19** |
| UDDS | EMS-A | | 0.400 | 29.86 | - |
| | EMS-B | | **0.439** | **22.50** | **24.64** |

*IFE - Improvement in Fuel Economy (%)

Having obtained an optimal power sharing control strategy (EMS-B) with the consideration of maintaining the SoC of the battery within the safe operating limit greater than 0.4, it is essential to compare the fuel economy status and its improvement. Keeping in mind, the optimal results of the EMS-B power sharing control strategy over the hybrid electric vehicle and its improvement in fuel economy relative to EMS-A is summarized in Table 6.

As can be seen in Table 6, the fuel economy of the proposed EMS-B control strategy for the fuel cell hybrid electric vehicle is found to have an 18.9% and 24.64% improvement relative to the baseline control strategy EMS-A across both the NEDC and UDDS driving cycles. Hence, the obtained results confirm the optimality of the control strategy EMS-B in both the aspects of fuel economy improvement and end SoC maintenance after any complete driving schedule. Further, the optimal control strategy EMS-B will be more appropriate for a plug in hybrid electric vehicle as it improves the life of the battery in a more appropriate manner and it guarantees in reducing the emissions.

## 8. Conclusion

This work presents a dynamic modeling of Fuel cell/Battery assisted hybrid electric vehicle system and the analysis was done based on the two power sharing control strategies namely EMS-A and EMS-B. The individual subsystems of the vehicle model were modeled first by investigating them with the suitable input and output data from sensibly designed tests. To start with, the modeling of PEM fuel cell was accomplished for a 5kW Ballard fuel cell system based on NARX Recurrent Neural (NRN) network and its dynamic response was validated appropriately with the benchmark data. Next, a multi-regression Ni-MH battery model is developed based on curve fitting techniques to suitably hybridize with the fuel cell system. Two power sharing control strategy EMS-A and EMS-B has been investigated in the proposed hybrid electric vehicle model with the key objective of improving the hydrogen fuel economy while preserving the battery SoC within the safe operating limit. From the simulated results of the power sharing strategies integrated with the vehicle model, performance comparison were done among four different PMAC motor ratings and the Honda 49kW PMAC motor is found to yield an optimal performance as it assures a less hydrogen fuel consumption for all the driving schedules. Compared to EMS-A, the hybrid electric vehicle integrated with the EMS-B power sharing control strategy can achieve a fuel economy improvement of upto 18.9% on the NEDC cycle and upto 24.64% on the UDDS cycle. Further, the control strategy EMS-B functions well with the consideration of end SoC that was maintained within the safe operating limit greater than 0.4 irrespective of the driving cycles adopted for the investigation. Thus the power sharing control strategy EMS-B is well suited for the fuel cell hybrid electric vehicle system in terms of both end SoC maintenance and fuel economy improvement for different driving cycles. Moreover, the proposed control strategy EMS-B assures and expected to work well on all driving cycles and real-life driving conditions for the hybrid vehicle systems.

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