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Performance of DC Motor Drive Application for Parallel Current Sharing Boost Converters by Using Fuel and Battery Energy Sources

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ABSTRACT:

The hybrid source consists of fuel cells (FCs) stack, battery packs and Ultracapacitor (UC) modules. In the proposed parallel energy sharing control, each source is connected to a DC bus via power electronics converters. The proposed optimization is based on the knowledge of individual boost parameters. Every loss through the structure are modeled by equivalent resistors. Using an accurate online estimation of those resistors, the losses through each individual converter can be determined. Then, a new current sharing scheme is defined aiming to maximize the global efficiency of the overall structure. A basic analysis of each component of the investigated system is presented. The main objective of this paper is to manage the energy transfer from the PEMFC stack to the DC bus based on wide high efficiency range. A battery pack is used for reducing the size of the stack and thus the cost, with by which regenerative braking is also achieved. In order to testify the nonlinear V-I characteristic curve of the PEMFC system experiments have been carried out. The performance of the overall system in steady state is studied via simulation in MATLAB/SIMULINK software.

Keywords: ***- Fuel cell, battery, Ultracapacitor, Hybrid source, Fuel cell hybrid vehicle, Energy management control and Parallel energy-sharing control.***

I.INTRODUCTION

The rapid depletion of fossil fuels and the increasing environmental concerns has led the researchers to the developments in the field of clean and energy efficient transportation. The recent developments in all electric vehicles seem to have a promising outcome of the green transportation research. The conventional battery based vehicle (BEV) and hybrid electric vehicle (HEV) are the two major variants of electric vehicle, and are already available in the commercial market. The HEV with a combination of conventional ICE engine and battery as an auxiliary power source is already well accepted globally, but the battery based electric vehicle (BEV) has not seen a very good commercial success even after government subsidies in most of the countries. It has been identified that the limitation of driving range and driving parameters like peak velocity, maximum acceleration and limited number of charge/discharge cycle of battery are the major concerns for its successful commercialization. Therefore, the increase in driving range along with driveline efficiency has become the main research areas in electric vehicle development. However, it is well accepted fact that recovering the kinetic energy for certain instances out of the total drive cycle (e.g. during braking) can increase its driving range effectively. In [1], an investigation is carried out on this energy recovery using two HEVs, ―Honda Insight‖ and ―Toyota Prius‖ and it has been proven that there is a significant increase in driving range (almost 30% and 20% respectively) by employing this regenerative braking mechanism. To efficiently capture and store the energy during regenerative braking, the energy storing element must possess high charge acceptance capability as peak power is received

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for very short duration of time. Since, battery is the only power source in most of the plug-in-EVs, the energy storage system (ESS) cannot supply or receive peak and sharp power variations. This results several limitations such as – inefficiency in satisfying peak demand period on a single charge, inability to perform under transient load variations etc. However, oversizing the battery module could be one of the solutions to address these issues, but this in turn increase the weight, volume and cost of the overall system. Therefore a single energy source (such as battery) seems to be inefficient in increasing the driving range while capturing regenerative energy. A super capacitor, on the other hand, has high power density, relatively light weight and increased life cycle capacity. Therefore, a combination of these two energy sources can satisfy most of the desired criteria due to their complimentary nature. In this paper, some of the reported configurations for hybrid energy storage systems (HESS) are discussed and their pros and cons are mentioned. Next one of the popular configuration i.e. multiple parallel connected converter configuration is presented in detail. Modeling of each of the elements, used in this configuration is carried out in MATLAB/ Simulink interface and the simulation results are produced. Finally the results are compared with the conventional battery based energy storage system.

This paper proposed a parallel energy sharing control for the FCEV combining of FC generator, battery and UC modules. The aim of this paper is to discuss on the control structures and the design of the proposed parallel energy-sharing algorithm. With parallel energy-sharing control, the load demand can be simultaneously provided by all energy sources, however, with different contribution depending on the characteristics of energy sources and the control strategy. In other words, parallel energy control can provide higher degree of energy sharing and greater output power during steady state. ESUs can be used to compensate power requirement once the load demand is larger than the maximum power available from the FC generator. Consequently, the overall volume of the hybrid sources can be downsized and optimized. The battery, on the other hand, can be operated in a narrow charge-discharge cycle and work in idle condition during steady state provided that the based power demand can be fulfilled by the FC.

II. DIFFERENT HESS CONFIGURATIONS

This section reviews the available topologies for hybrid energy storage systems joining battery and super capacitor. In a hybridized energy storage system, maximum possible driveline efficiency can be achieved by maintaining the amount of load current supplied by battery at a nearly constant (average) value, whereas the super capacitor will respond to the dynamic load current demands. The power sharing between two heterogeneous energy sources can be controlled by either adding a dc/dc converter in the system or simply by the internal impedances of the energy storing elements. A number of different configurations is available in literature [2-11] mostly for hybrid electric vehicle drive train, but can be applied to the pure electric vehicle drive train also. Some of the basic configurations are presented in Fig. 1 through Fig. 5. Directly combining two different energy sources in parallel is the simplest method for hybridization. In the passive parallel configuration [2, 3], shown in Fig. 1, increased peak power and extended battery discharge life can be achieved as compared to the battery alone system. As the two sources are connected directly in parallel to the dc bus, the power sharing between the two sources will be controlled by their internal series resistance only and cannot be controlled based on load power demand. Also during regenerative braking, high current peaks may cause internal temperature rise in the battery.

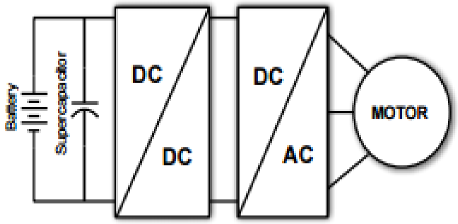

Fig. 1. Passive parallel configuration

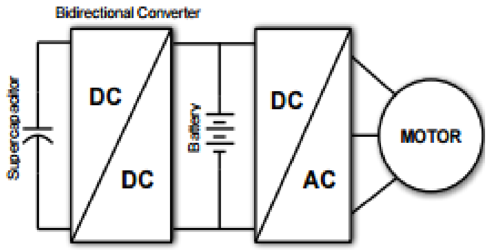

Fig. 2. Supercapacitor/ battery active configuration

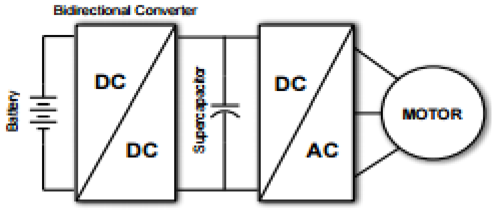

Fig. 3. Battery/ supercapacitor active configuration

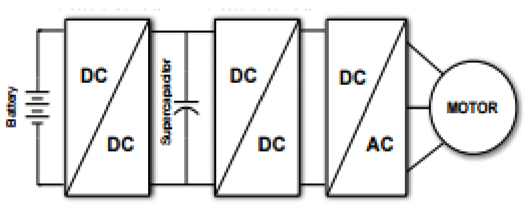

Fig. 4. Cascaded converter configuration

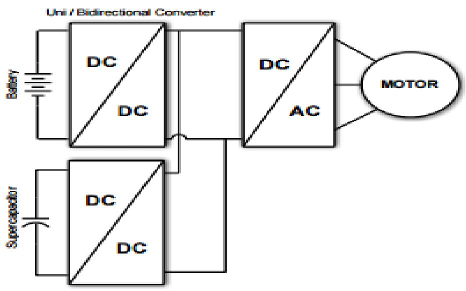

Fig. 5. Multiple parallel connected converter configuration

To capture and reuse the regenerative energy in both directions a dc/dc converter can be used in between these two energy sources. Fig. 2 shows a Super capacitor/Battery active configuration [4, 5] where the battery is directly linked to the DC bus and SC is connected through a converter. In this type of configuration power flow in/out of one source is controlled through a bidirectional dc/dc converter, thus controlling total power sharing between two energy sources, but no control over the battery current during different driving conditions like peak acceleration or regenerative braking.

Another disadvantage of this configuration is the limitation on battery bank sizing as it must be sized to match the dc bus voltage. If the position of battery and SC is interchanged, the battery/supercapacitor active configuration (Fig. 3) can be achieved [6, 7]. In this configuration the supercapacitor is directly connected to the dc link to acts as a low pass filter The main disadvantage of this configuration is the instability of the dc bus voltage due to the higher self discharge rate of the supercapacitor. In cascaded configuration (Fig. 4), bidirectional dc/dc converters are connected in parallel to each of the energy sources [8]. The major drawback of this configuration is the introduction of additional converters which must be sized in order to handle the total power, thereby increasing the implementation complexity and cost of the overall system. In [9-11] multiple parallel connected converter configuration (Fig. 5) is presented where power contribution of battery and SC to the dc link can be controlled efficiently by using dedicated dc/dc converters for each energy source connected in parallel. With a proper power flow management algorithm this configuration can provide better flexibility of choosing both the energy sources with different ratings other than dc bus voltage. The dc/dc converter associated with SC is generally bidirectional and operates in constant voltage mode to maintain a steady dc link voltage. On the other hand, the converter connecting the battery to the dc link can be unidirectional operating in constant current mode to minimize battery stress thereby increasing battery life.

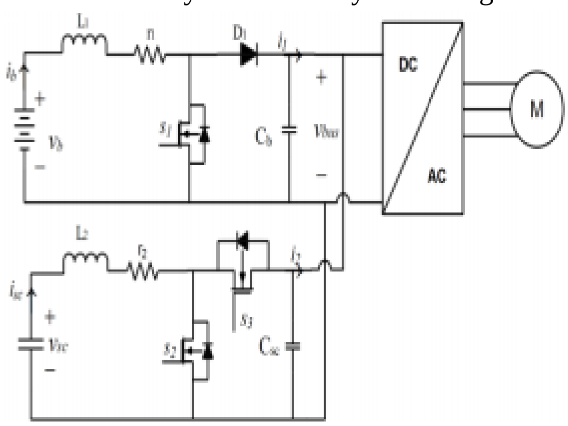

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Fig. 6. Circuit level diagram of multiple parallel connected converter configuration

III. MULTIPLE PARALLEL CONNECTED CONVERTER SYSTEM MODELING

Among the different HESS configurations multiple parallel connected converter configuration is chosen for investigation in this work for its control flexibility. The block level configuration is shown in Fig. 5 and the circuit level diagram is shown in Fig. 6. For modeling and simulation purpose, a lithium ion battery is used as primary energy source and a supercapacitor (used as auxiliary source) is connected in parallel to the battery. As both of the energy sources are connected to the dc link through dedicated dc/dc converter, battery and SC sizing are free to the dc link voltage rating. A. Drive Cycle and Load The load is modeled as the Urban Dynamometer Driving Schedule (UDDS) [12] using ADvanced VehIcle SimulatOR (ADVISOR) software. The UDDS represents a standard city driving conditions for light duty vehicle testing. It simulates a city route of 7.45 miles with frequent stops in 1369 seconds with average speed of 19.59 mph. For simulation, A duration of 90s [Fig 7] with average speed, acceleration and braking is used. The power required to fulfil the load demand as per the drive cycle is obtained from the ADVISOR software. B. Battery Model For simulation, Toyota prius plug-in electric vehicle's battery specifications [13, 14] are considered here. The battery is modeled (Fig. 8) as a simple dc voltage source (Voc) representing its open circuit voltage with a series resistance representing its internal ohmic resistance (Rb).

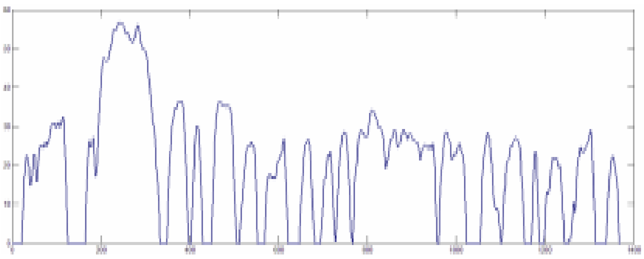

Fig. 7. Urban Dynamometer Driving Schedule (UDDS)

The battery load voltage can be expressed as,

$$V_l = V_{oc} - R_b * I_b \quad (1)$$

The battery instantaneous power is shown as,

$$P_b = V_l * I_b \quad (2)$$

From the above expressions, the battery current can derived as

$$I_b = \frac{-V_{oc} \pm \sqrt{V_{oc}^2 - 4P_b * R_b}}{2R_b} \quad (3)$$

The state of charge (SoC) of the battery can be expressed as,

$$SoC_b = \frac{q_0 - \int i_b dt}{q_n} * 100\% \quad (4)$$

Where, q0 is the initial charge, qn is the rated ampere-hour (Ah) value and ib is the current of the battery supplied to the super capacitor.

C. Super capacitor Model:

Following classical model, super capacitor is modeled as a capacitor with a series resistance, shown in Fig. 9. The super capacitor capacitance (Csc) and the series resistance (Rsc) are the function of temperature and SC current. The super capacitor terminal voltage can be expressed as,

$$V_{sc} = V_c - I_{sc} * R_{sc} \quad (5)$$

The super capacitor power will be,

$$P_{sc} = V_{sc} * I_{sc} \quad (6)$$

The super capacitor state of charge (SoC) can be expressed as

$$SoC_{sc} = \frac{V_{sc}}{V_{nom}} * 100\% \quad (7)$$

Where, Vnom represents the rated maximum voltage of super capacitor. Using above equations the SC current can be derived as

$$I_{sc} = \frac{-SoC_{sc} * V_{nom} \pm \sqrt{(SoC_{sc} * V_{nom})^2 - 4P_{sc} * R_{sc}}}{2R_{sc}} \quad (8)$$

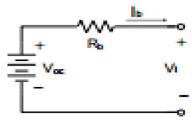

Fig. 8. The battery model

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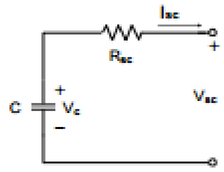


Fig. 9. The super capacitor model

In this model a self discharge resistance, which act normally parallel to the capacitance, is ignored for simplicity. This self discharge resistance generally considered for long term energy storage.

D. Boost Controller for Battery Current Control

In this configuration, battery is connected to the dc bus through a boost converter as shown in Fig. 6. The boost converter operates in averaged current mode control to maintain the battery output current at a nearly average value.

The inductor is considered as an inductance (L1) with its series resistance (r1). The switching pulse width modulated signal is expressed as sj (j = 1, 2, 3) in a set {0, 1}. Using the average state space model the battery current can be expressed as,

$$\frac{di_b}{dt} = (s_j - 1) * \frac{v_{dc}}{L_1} - \frac{r_1 * i_b}{L_1} + \frac{v_b}{L_1}$$

(9)

and the converter output voltage can be expressed as,

$$\frac{dv_{bus}}{dt} = -(s_j - 1) * \frac{i_b}{C_b} - \frac{i_1}{C_b}$$

(10)

Where, i1 is fraction of the load current that is to be supplied by the battery and ib is the output current of the boost converter, vb is the battery terminal voltage and vbus is the dc bus voltage. E. Bidirectional Controller for Super capacitor interfacing the bidirectional dc/dc converter operates in either boost mode or buck mode depending on the load current requirement. The super capacitor discharges through the boost converter for (isc > 0) and the converter operates as a buck converter in charging mode (isc < 0). The goal of the bidirectional dc/dc converter is to maintain the voltage reference for super capacitor and switch the converter direction of operation depending upon the load current change. The reference for SC current is denoted as iscref and a binary variable α controls the converter operation such as,

α =

1,if iscref > 0 (Boost mode)

0,if iscref < 0 (Buck mode).

Hence, the supercapacitor current can be expressed as,

$$\frac{di_{sc}}{dt} = -(\alpha * (1 - s_j) + (1 - \alpha) * s_{j+1}) * \frac{v_{dc}}{L_2} - \frac{r_2 * i_{sc}}{L_2} + \frac{v_{sc}}{L_2} \quad (11)$$

The amount of load current supplied by super capacitor is obtained as,

$$i_2 = (\alpha(1 - s_j) + (1 - \alpha) * s_{j+1}) * i_{sc} \quad (12)$$

IV. SIMULATION RESULTS

In this paper the performance of multiple parallel connected converter topology is compared with a conventional battery based energy storage system. For simulation Toyota Prius electric vehicle's battery specification is considered as standard (shown in TABLE I). Toyota Prius electric vehicle (TPEV) drive train is simulated in ADVISOR software for UDDS standard drive cycle for a duration of 90s (t = 10 – 100). The battery current profile is obtained for the ADVISOR software as shown in figure 10. In multiple parallel connected converter configuration as the battery is connected through a boost converter, a downsized battery module can be applied. Again for supercapacitor module, a 48 V standard pack is chosen with a nominal capacitance of 165F. 7 modules are connected in series to achieve 340.2V terminal voltage. Component specification used for simulation is shown in TABLE II.

TABLE 1
TOYOTA PRIUS BATTERY PARAMETERS

Parameter	Value
Battery Type	Lithium ion
Rated Voltage	345.6 V
Rated capacity	15.04 Ah
Internal resistance	0.56104 Ω

TABLE 2
TOYOTA PRIUS BATTERY PARAMETERS

Parameter	value
Battery speciation	

Battery Type	Lithium ion
Rated Voltage	226 V
Rated capacity	13.9 Ah
Internal resistance	0.207 Ω
Super capacitor specification	
Capacitance	165F
Rated voltage	48.6
ESR	0.0063 Ω
Peak current	1970A

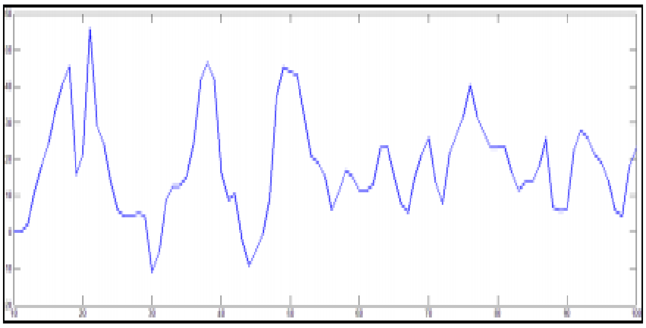
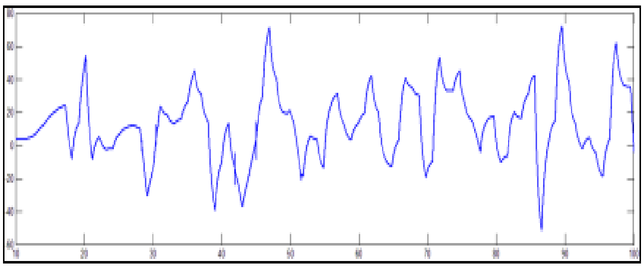
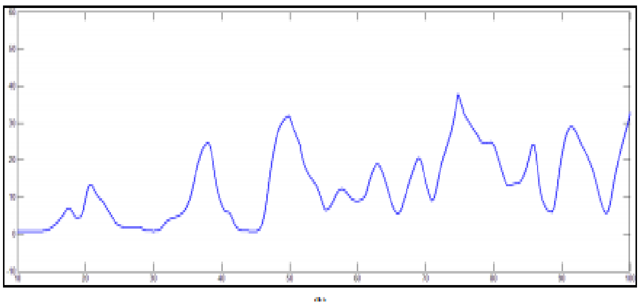


Fig. 10. Battery current profile in conventional battery based system



(a)



(b)

Fig. 11. Current profile of HESS (a)Supercapacitor current, (b) Battery current

Fig. 10 illustrates the load current profile of a conventional battery based and the profile of the battery current and supercapacitor current are shown in Fig. 11. These current profile variations are simulated for a reference load waveform (Fig 7) which has several transients as it is reflecting a number of accelerations and braking instances. From Fig. 10 it is clear that the energy source (i.e. battery) of a conventional battery based system has to absorb several transients consisting peaks and sometimes negative pulses. These transients put electrical stresses on the battery and shorten its lifecycle. Moreover, the driving range cannot be improved by this conventional battery based system as the battery has comparatively lower charge acceptance capacity. On the contrary in HESS configuration almost all the peaks during acceleration and braking are supplied (and absorbed) by the supercapacitor alone (Fig 11(a)) while the battery maintains almost flat load profile (Fig. 11(b)) bypassing the transients. This combination increases the lifecycle of the battery along with increasing the driving range.

V. CONCLUSION

The depleting fuel reserves and growing environmental concerns has led to sudden increase in demands for vehicles utilizing clean energy. Electric vehicles are an appropriate solution. Commercially available EVs use battery based energy storage systems which cannot fulfil the requirements of most of the EVs to compete with the conventional fuel vehicle. So, the concepts of hybrid energy storage systems arise. In this paper one of the available configurations of HESS has been studied. The TOYOTA Prius plug-in EV drive train is simulated using ADVISOR software and load profile is obtained for the vehicle. The multiple parallel connected converter configuration is simulated in MATLAB/Simulink platform. In this configuration battery is connected to the dc link using a boost converter whereas the SC is connected in parallel through a bidirectional dc/dc converter. Battery, supercapacitor and converters are modeled in Simulink. The current profile of the energy source of a conventional battery based system (i.e. battery) is compared to the energy storage current profile of HESS (i.e. battery and super capacitor) using multiple

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parallel connected converter configuration. The simulation results indicate that in multiple parallel connected converter configuration the battery provides the average load demand and the super capacitor is responsible for delivering all transient load demand such as power requirement during high acceleration and barking, thereby, increasing the driving range.

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