AMAE Int. J. on Production and Industrial Engineering, Vol. 02, No. 01, June 2011

Integration and Performance Analysis of Flywheel Energy Storage System in an ELPH Vehicle

Abhinav Pandey[1], Abhishek Jain[1], Vipul Arora[1] & Satish C. Sharma[2]
[1]Department of Mechanical & Industrial Engineering, IIT Roorkee, Roorkee, India
Email: {abhi5ume, ajainume, vipulume}@iitr.ernet.in
[2]Department of Mechanical & Industrial Engineering, IIT Roorkee, Roorkee, India
Email: sshfme@iitr.ernet.in

***Abstract*—The paper deals with the study related to integration of Flywheel Energy storage system (FESS) to an already available model of parallel hybrid vehicle with pre-transmission torque coupling, i.e., replacing the conventional chemical battery with an equivalent mechanical battery. Advantages like high reliability, long cycle life, high energy storage capacity and deep discharge of an FESS can potentially enhance the performance of the hybrid vehicles. FESS employed for the analysis comprises an integrated flywheel homopolar inductor machine with High-frequency drive. The simulation results of an Electrically Peaking Hybrid (ELPH) are used as a base work in the present analysis. The ELPH model uses a control strategy to optimize the vehicle performance with a major concern for battery performance. The paper analyzes the performance of considered FESS model under the same control strategy and driving conditions. A MATLAB/SIMULINK model is used for the analysis of the vehicle for both urban and highway drives. Finally a comparison is drawn between the performance of the chemical battery, working in its best efficiency range, as a result of the applied control strategy, to that of the considered FESS. It is inferred from the simulated results that the performance of employed FESS is satisfactory in comparison to chemical batteries. It is therefore expected that FESS can be effectively employed in hybrid vehicles**.

***Index Terms*—Hybrid Vehicle, FESS, ELPH Vehicle**

I. INTRODUCTION

Conventional Internal Combustion Engine (ICE) vehicles bear the disadvantages of poor fuel economy and environmental pollution. Basis of poor fuel economy are (i) Operation of engine in lower efficiency region during most of the time in a drive cycle and (ii) Dissipation of vehicle kinetic energy during braking [1]. Electric battery operated vehicles have some advantages over the ICE driven vehicles, but their short range is a major lacuna in their performance. The shortcomings of both of these can be overcome by using a Hybrid Electric Vehicle (HEV). An HEV comprises conventional propulsion system with an on-board Rechargeable Energy Storage System (RESS) to achieve better fuel economy than a conventional vehicle as well as higher range as compared to an Electric Vehicle. HEVs prolong the charge on RESS by capturing kinetic energy via regenerative braking, and some HEVs also use the engine to generate electricity through an electrical generator (M/G) to recharge the RESS. An HEV's engine is smaller and may run at various speeds, providing higher efficiency. Reference [2] suggests that HEVs allow fuel economy and reduced emissions compared to conventional ICE vehicles by:

1. Allowing the engine to stop under vehicle stop condition,
2. Downsizing the engine for same peak load requirements, as the motor will assist the engine for such higher loads, and
3. Allowing regenerative braking, not possible in conventional vehicle. In urban drive conditions, about 30% of the fuel can be saved through regenerative braking because of the frequent stop and go conditions [1].

Series and Parallel hybrids are the two major configurations of the HEVs. Even in Parallel Configuration of Hybrid Vehicles, there are several possibilities in which an arrangement between the engine, motor and transmission can be made to achieve the desired performance from the vehicle. In general there are two methods to couple the energy of the engine and motor namely, (i) Speed Coupling, and (ii) Torque Coupling. In Speed Coupling the speeds of engine and motor are added in appropriate fractions to achieve the final speed of the drive, whereas in Torque Coupling the torque from the engine and motor are summed up in Torque Coupler, which can be either an epicyclic gear train or simply the rotor of the electric machine (motor). In latter case the rotor of the electric machine is integrated with the shaft from the engine through a clutch. The parallel hybrid is considered for the present analysis because of its significant advantages over the series hybrid, such as lower emissions, improved efficiency, simpler configuration and better performance. The configuration considered for the analysis is 'Pre-transmission torque coupled parallel hybrid drive train' [1]. There are various candidates for onboard RESS. So far lead acid batteries have dominated the industry because of their compactness, easy availability and low cost. However, batteries have a number of disadvantages, such as limited cycle life, maintenance and conditioning requirements, and modest power densities [3]. To overcome these shortcomings, research activities have focused upon other alternatives of Energy Storage System (ESS). FESS is a prominent candidate for ESS applications in HEVs. Flywheels in particular offer very high reliability and cycle life without degradation, reduced ambient temperature concerns, and is free of environmentally harmful materials [4]. Flywheels offer many times higher energy storage per kilogram than conventional batteries, and can meet very high peak power demands. Power density, which is a crucial

---

The paper was presented at *International Joint Journal Conference in Engineering*, *IJJCE* 2009.

Vipul Arora, B.Tech MIED, IIT Roorkee. aroravipul89@gmail.com

DOI: 01.IJPIE.02.01.132

parameter for ESS in HEVs, of an FESS is much higher as compared to a chemical battery. Deeper depth of discharge, broader operating temperature range adds to the advantages of using an FESS over batteries. The FESS employed for the present analysis is an 'Integrated Flywheel Energy Storage System with Homopolar Inductor Motor/Generator and High-Frequency Drive' [5]. The use of integrated design has various benefits over other contemporary FESS designs. Some of these advantages are reduced system weight, lower component count, reduced material costs, lower mechanical complexity, and reduced manufacturing cost.

II. SYSTEM DESCRIPTION

The arrangement used for analysis consists of an 'Electrically Peaking Hybrid Electric propulsion system' that has a parallel configuration [6]. Through the use of a parallel configuration the engine has been downsized as compared to the engine required for a similar conventional ICE vehicle. A small engine of power approximately equal to the average load power is used in the model. An AC induction motor is used to supply the excess power required by the peaking load. The electric machine can also absorb the excess power of the engine while the load power is less than the peak value. This power, along with the regenerative braking power, is used to charge the FESS to maintain its State-Of-Charge (SOC) at a reasonable level. Fig. 1 shows a schematic diagram of the complete vehicle configuration illustrating the pre-transmission torque coupling, and the other major components of the drive.

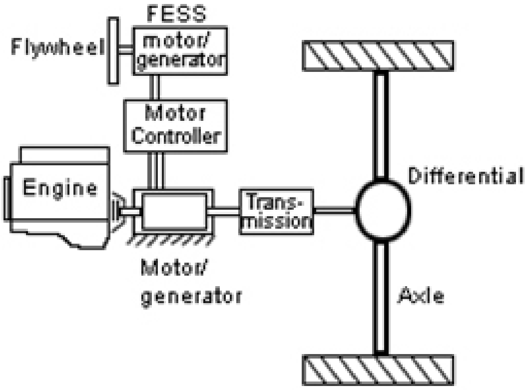

Fig. 1. Pre-transmission torque coupled ELPH

The operation of the vehicle is managed by a vehicle controller. It sends control signals to the motor controller, engine controller (throttle) and FESS controller depending upon the control strategy and the input signals. Basically the input signals are from the acceleration pedal and brake pedal. With the electrically peaking principle, two control strategies for the drive have been used [6]. The first one is called 'MAXIMUM BATTERY SOC' control strategy, which in particular aims at maintaining a particular range of SOC in the battery at any instant.

In this SOC range, the battery is having maximum efficiency and thus, the best performance of the vehicle which is employing a chemical battery, can be achieved through this strategy. Under this strategy the engine and electric motor are controlled so that the battery SOC is maintained at its appropriate level for as much duration as possible. This control strategy may be used in urban driving, in which repeated acceleration and deceleration is common and high battery SOC is absolutely important for normal driving. This control strategy, which basically aims at the best performance of the chemical battery, is employed in the analyzed model comprising FESS, so that a direct comparison can be drawn over the performance level of an FESS as compared to a chemical battery, working in its best efficiency range. The other control strategy developed is called 'ENGINE TURN-ON AND TURN-OFF' control strategy. Under this, the engine is turned on and off depending upon the instantaneous SOC of the RESS. This strategy can be used during highway driving. An integrated flywheel system is one in which the energy storage accumulator and the electromagnetic rotor are combined in a single-piece solid steel rotor. This allows the housing of the motor to comprise a large part of the vacuum and burst containment of the flywheel, enabling significant savings in total system weight and volume. By using an integrated design, the energy storage density of a high power steel rotor FESS can approach that of a composite rotor system, but the cost and technical difficulties associated with a composite rotor are avoided. High efficiency, a robust rotor structure, low zero torque spinning losses, and low rotor losses are the key requirements for an FESS electrical machine. PM motors are currently the most commonly used motors for flywheel systems [1]. However PM rotors tend to be more temperature sensitive, mechanically complex, and costly. Homopolar inductor motors present an attractive alternative with a low-cost rotor, machined from a single piece of steel, which is more robust and less temperature sensitive than PM rotors. 'In addition, a homopolar inductor motor with a slotless stator and six-step drive eliminates the stator slot harmonics and maintains low rotor losses while also allowing operation at unity (or any desired) power factor' [5]. As discussed in previous sections, it is quite clear that employment of FESS in place of chemical battery will lead to a better performance of hybrid vehicles. A scan of the available literature, to the best of authors' knowledge, indicates that very few efforts have been aimed at replacing the chemical batteries with FESS altogether. Thus, to bridge the gap in this field, this work has been carried out.

DOI: 01.IJPIE.02.01.132

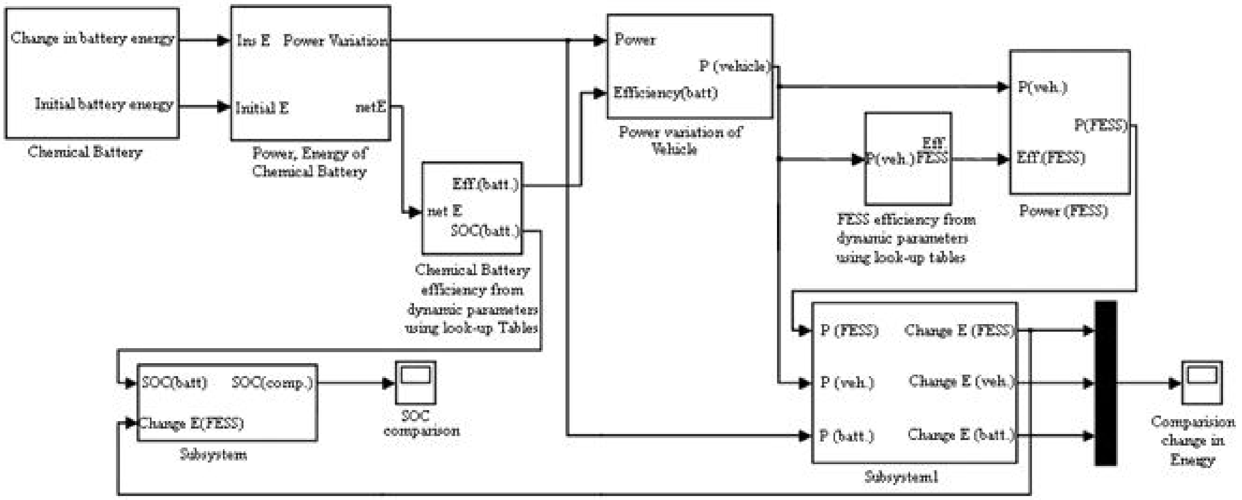

Fig. 2. MATLAB/SIMULINK model used for the analysis

III. MATLAB/SIMULINK MODEL

The work presented in this paper uses the simulation results of the discussed ELPH propulsion system based vehicle, as obtained in [3] using V-ELPH computer simulation package, developed at Texas A&M University. The paper provides various plots depicting the performance of various components of the vehicle. The simulation results are mathematically treated and are combined with the results of the practical testing as well as the simulated results of the FESS considered [5]. A SIMULINK model (Fig. 2) is used to perform these mathematical operations for two particular drive cycles namely (i) FTP-75 Urban Drive, and (ii) FTP-75 Highway Drive. The figure illustrates the various components of the SIMULINK model, which are used to perform various operations, mentioned in the following text. The variations of change in energy level of the chemical battery with respect to time, over the complete drive cycle, are presented in [6]. The plots provided in [1] depict the variation of change in energy of the battery vs. time for the two above mentioned drive. These variations are used to produce the look-up tables, which are used in the analysis. The initial SOC of the battery is assumed to be at a level of 50%. Thus the instantaneous energy of the battery E_{batt}, will become

$$E_{batt} = E_{0(batt)} + \Delta E_{batt} \tag{1}$$

where $E_{0(batt)}$ is the assumed initial energy level of the battery and ΔE_{batt} is the change in the energy of the battery at any instant with respect to the initial energy of the battery.

Then the instantaneous power level of the battery P_{batt}, can be determined by simply differentiating the instantaneous energy of the battery with respect to time.

$$P_{batt} = \frac{dE_{batt}}{dt} \tag{2}$$

The plot between the efficiency of the battery η_{batt}, and its SOC [6] i.e. the efficiency of the chemical battery at any instant as a function of its instantaneous SOC has been determined by drawing look-up tables in SIMULINK model. The instantaneous power of the vehicle interacting with the RESS i.e. basically the instantaneous electrical machine power of the vehicle, can be determined as follows

$$P_{veh} = P_{batt} . \eta_{batt}, \qquad \text{if} \quad P_{batt} < 0$$

$$(3)$$

$$P_{veh} = \frac{P_{batt}}{\eta_{batt}}, \qquad \text{if} \quad P_{batt} \geq 0$$

where positive and negative values of P_{batt} corresponds to the charging state and discharging state of the battery respectively, and

$$\eta_{batt} = f(SOC) \tag{4}$$

Now if the chemical battery of the system is replaced by a mechanical battery i.e. an FESS, then this interacting instantaneous power at the vehicle end will now interact with the FESS.

Reference [5] presents the plot of efficiency of the FESS vs. Power. The values from the plot are used to generate the look-up table, used in the SIMULINK model, which provides the instantaneous efficiency of the overall FESS η_{FESS}, as a function of its instantaneous power i.e. $\eta_{FESS} = f(P_{FESS})$, averaged over the speed range of the flywheel.

Now the instantaneous power of the FESS, P_{FESS} can be determined as follows

$$P_{FESS} = P_{veh} . \eta_{FESS}, \qquad \text{if } P_{veh} > 0$$

$$(5)$$

$$P_{FESS} = \frac{P_{veh}}{\eta_{FESS}}, \qquad \text{if } P_{veh} \leq 0$$

where positive and negative value of P_{veh} corresponds to the energy flow from vehicle to the FESS and from FESS

DOI: 01.IJPIE.02.01.132

to vehicle respectively. Now the change in FESS energy level ΔE_{FESS}, with respect to its initial energy level at any instant *t*, can be determined as follows

$$\Delta E_{FESS} = \int_0^t P_{FESS}.dt \qquad (6)$$

$E_{0(FESS)}$, the initial energy of the FESS i.e. at the start of the drive cycle is added to this change in energy to get the instantaneous energy level of the FESS. Then the quantity is divided by the total energy capacity of the FESS ($E_{\max(FESS)}$), to get the instantaneous State Of Charge of the FESS, SOC_{FESS}.

$$SOC_{FESS} = \frac{(E_{0(FESS)} + \Delta E_{FESS})}{E_{\max(FESS)}} \qquad (7)$$

In a similar manner the instantaneous SOC of the battery, SOC_{batt} can be determined, and finally a comparison between the two is drawn to establish the satisfactory performance of an FESS in a parallel hybrid drive train.

$$SOC_{batt} = \frac{(E_{0(batt)} + \Delta E_{batt})}{E_{\max(batt)}} \qquad (8)$$

IV. Results and Discussion

The numerically simulated results comparing the performances of the chemical battery and the FESS are generated for the complete drive cycles viz. (i) FTP-75 Urban (ii) FTP-75 Highway, through the explained SIMULINK model. Fig. 3 shows the results comparing the State Of Charge of the flywheel i.e. SOC_{FESS} to that of the battery, i.e. SOC_{Batt} over the FTP-75 urban drive cycle. The results are obtained for a cycle of 1400 seconds. The control strategy used for the urban drive cycle is 'MAXIMUM BATTERY SOC'. It is observed from the plot that even in deep discharge states such as at around 200 seconds, the performance of the FESS is satisfactory and over the complete drive cycle, its performance is as good as the chemical battery.

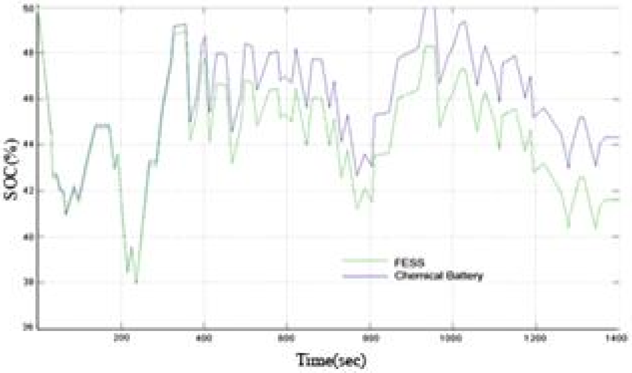

Fig. 3. Plot between SOC of the FESS and the Time for FTP-75 Urban Drive Cycle

Fig. 4 depicts the plot between SOC_{FESS}, SOC_{Batt} vs. Time over the complete FTP-75 Highway drive cycle. The control strategy used for this drive cycle is 'ENGINE TURN-ON AND TURN-OFF'. Examining the plot it can be clearly inferred that during the very deep discharge zone, i.e. around 350 and 650 seconds the FESS is able to provide the necessary power as per the vehicle traction requirements. And during the deceleration of the vehicle i.e. during the regenerative braking mode, the FESS is able to capture significantly high amount of energy, as provided by the motor/generator set. The latter is evident from the plot, as during the time zone of around 550 seconds, when a high charging of the FESS takes place. These investigations depict that the performance of the FESS over the highway drive is completely comparable to that of the best performance of the battery.

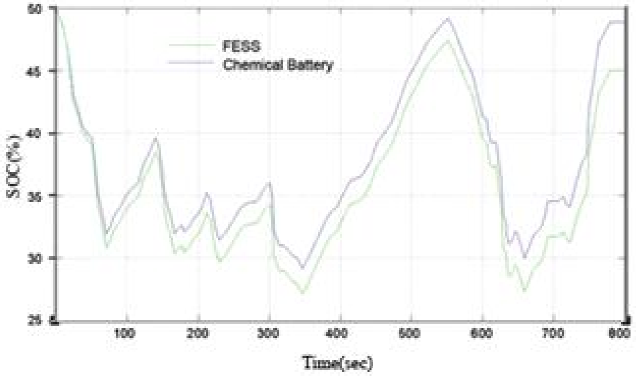

Fig.4. Plot between SOC of the FESS and the Time for FTP-75 Highway Drive Cycle

It is observed that for both the drive cycles, the final SOC level of the FESS at the end of the drive cycle is about 2. 5% lower than that of the chemical battery. But this is for the case of the best performance of a chemical battery, where as there is still a scope of significant improvement in the FESS performance.

V. Conclusions

From the numerically simulated results and the discussion in the preceding sections, it may be inferred that the Flywheel Energy Storage System (FESS) can be effectively employed in hybrid vehicles. The FESS performs satisfactorily if compared to a chemical battery, working in its best efficiency range. The results indicate that FESS performance is not just comparable to the chemical batteries, but also its employment will enhance the overall performance of the hybrids.

DOI: 01.IJPIE.02.01.132

REFERENCES

[1]Mehrdad Ehsani, Yimin Gao, Sebastien E. Gay, Ali Emadi, "Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design," CRC Press, 2004.

[2]Katras¡nik Tomaz¡, " Hybridization of powertrain and downsizing of IC engine – A way to reduce fuel consumption and pollutant emissions – Part 1, *Energy Conversion and Management*," Vol. 48, 2007, pp. 1411-1423.

[3] Ali Emadi, "Handbook of Automotive Power Electronics and Motor Drives," CRC Press, 2005.

[4] Haichang Liu, Jihai Jiang, "Flywheel energy storage—An upswing technology for energy sustainability," Energy and Buildings, Vol. 39, May 2007, pp. 599-604.

[5] P. Tsao, M. Senesky, and Seth R. Sanders," An Integrated Flywheel Energy Storage System With Homopolar Inductor Motor/ Generator and High-Frequency Drive," IEEE Trans. On Industry Applications, Vol. 39, Nov/Dec. 2003,pp. 1710-1725.

[6] M. Ehsani, Yimin Gao, and Karen L. Butler, "Application of Electrically Peaking Hybrid (ELPH) Propulsion System to a Full-Size Passenger Car with Simulated Design Verification," IEEE Trans. On Vehicular Technology, Vol. 48, Nov. 1999,pp. 1779-1787.

[7] Niels J. Schouten, Mutasim A. Salman, Naim A. Kheir, "Energy management strategies for parallel hybrid vehicles using fuzzy logic," Control Engineering Practice, Volume 11, February 2003, pp. 171-177.

[8] Joeri Van Mierlo, Peter Van den Bossche, Gaston Maggetto, "Models of energy sources for EV and HEV: fuel cells, batteries, ultracapacitors, flywheels and engine-generators," Journal of Power Sources, Vol. 128, 29 March 2004, Pages 76-89.

[9] Zhou, Yuliang Leon, "Modeling and Simulation of Hybrid Electric Vehicles," *M.A.Sc. Thesis*, University of Victoria, December 2007. Available from: http://www.iesvic.uvic.ca/publications/theses.htm.

DOI: 01.IJPIE.02.01.132