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Simulation and Comparison of HEV Battery Control for Best Fuel Economy and Longer Battery Life

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Abstract

Almost all HEV battery control strategies keep the battery state of charge (SOC) within a lower limit (SOCmin) (these strategies also called charge sustaining strategies). The goal from sustaining the SOC in this way is to prolong the battery life. But the question is; what is the optimal value of (SOCmin) for a battery, to achieve best fuel economy and longer battery life at the same time?; knowing that when (SOCmin) is too low (around SOCmin=0.2) we get good fuel economy per one speed cycle but the battery dies soon and cannot perform a lot of cycles, but when (SOCmin) is high (around SOCmin=0.8) the battery can survive for a larger number of speed cycle but with poor fuel economy per cycle. The objective of this paper is to propose a method to investigate and solve this problem by simulation using Simulink environment; we used the manufacture's data of a Ni-MH battery, empiric equations, and appropriate control strategy to find the optimal value of (SOCmin). The study shows that, for best fuel economy per one cycle; the (SOCmin) value must be as small as possible, for longer battery life; the (SOCmin) value is about (SOCmin=0.85) and for the optimal case (which is the total improvement brought by the battery from first time use until its end of life); the optimal (SOCmin) value is about (SOCmin=0.7).

Keywords— Battery ageing, HEV Battery Control, Ni-MH Battery, HEV Simulation

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1 Introduction

HEV battery does not remain forever but it has a lifetime expressed by the number of cycle the battery can be discharged and charged before its death or by the total Amper-hour the battery can supply before its death. During a battery's lifetime, its performance slowly deteriorates because of the degradation of its electrochemical constituents. Battery manufacturers usually provide aging data that will show this degradation. However the data they provide result from standard aging tests, in which the battery is discharged and charged thousands of times with identical current profiles. Using these data many aging models have been developed ([1], [2]) that relate the maximum number of battery cycles to the Depth of Discharge (DOD) of the current profile used.

Battery manufacturers define a battery's end of its life when it reaches 80% of its rated capacity. After this moment, it can still be used for a long time at reduced capacity. Research shows that the life of a battery is influenced by many factors. The most important factors are extreme temperatures, overcharging, over discharging, rate of charge or discharge, and the DOD of battery cycles [3]. Most of the previous work in this topic compared the effect of the aging factors to a battery's cycle life. The cycle life of a battery is defined as the number of discharge cycles a battery is capable of delivering before its nominal capacity falls below 80% of its initial rated capacity. These cycles are identical, which is not the case for HEV applications.

In this paper we focus on HEV battery which the current history cycles differ according to the driving cycles the vehicle experiences so we will use the total Amp-hour to describe battery life, the objective is to find the optimal SOCmin for a 6.5 Ah Ni-MH battery to obtain good fuel economy and longer battery life at the same time, for that we need to use a simulation for an HEV powertrain to obtain the variation of fuel economy with different SOCmin values, and then we use an appropriate life prediction method to find the variation of battery life with the same SOCmin values as used in the fuel economy, finally we make a balance between fuel economy and battery life then we find the optimal solution, by choosing the SOCmin value that gives the

best total fuel economy, that means the sum of fuel economy for repeated drive-cycle, from the first use of the battery until its end of life.

2　Modeling and Simulation

Nomenclature
SOC: Battery state of charge
SOH: State Of Health of the battery
SOCmin: Lower battery state of charge limit
SOCmax: Upper battery state of charge limit
(SOCmax =1) in this research
E0: Battery open circuit voltage
Vbatt: battery voltage
R0, R1, C1: Battery interne resistors and capacitor
DOD: Depth of Discharge of the battery
L_{Ah} : Battery life expressed in Amper-hour
L_{AhR} : Rated battery life expressed in Amper-hour
L_{cyc} : Battery life expressed as number of cycles at the of discharge DOD
L_{cycR} : Rated battery life expressed as number of cycles at the depth of discharge DOD and battery actual capacity C_A

2.1　System Simulation

A simulation for a parallel HEV powertrain Fig 1 has been made to find the fuel consumption for different (SOCmin) values over the FTP72 speed cycle; the different component models for this simulation are described below. The simulation results have been validated by the 'Advanced vehicle simulator' (ADVISOR) developed by the National Renewable Energy Laboratory
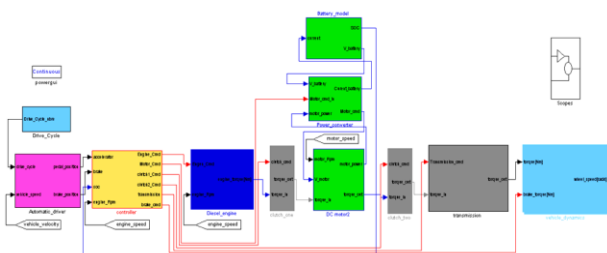

Figure 1: Top level simulation model for the hybrid vehicle implemented in Simulink

2.2　The Motor/ Generator Model

The electric motor utilized in this research is PMSM. The motor/generator is modeled using static lookup tables, where the maximum torque of the motor/generator is indexed by the motor speed. And its efficiency is indexed by the operating torque and speed Fig 2.
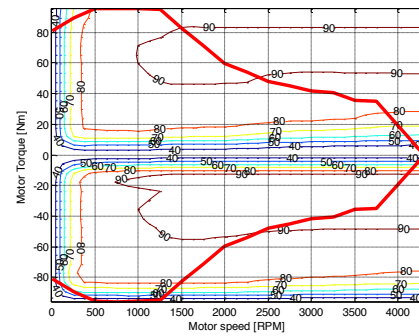

Figure 2: Motor/Generator efficiency and maximum torque

2.3　The Engine Model

The engine is modeled statically using the fuel consumption map Fig 3. A set of data in terms of torque and speed of the engine and the corresponded fuel consumption in each operating point obtained from the diesel engine in the Low Emission Vehicle Research Laboratory test bench Fig 4. Using interpolation extrapolation the fuel consumption in other operating points is found and using appropriate MATLAB program the specific fuel consumption is then deduced Fig 5.
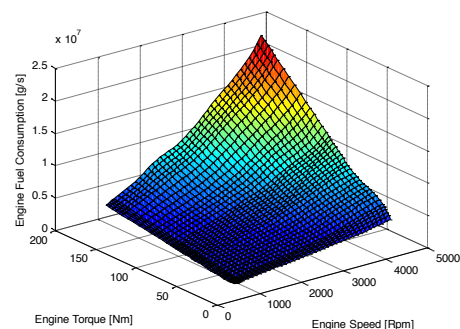

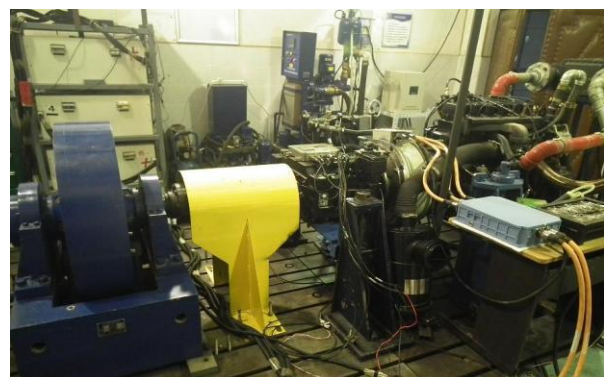Figure 3: Engine fuel consumption rate [g/s] as function of engine speed and its torque from test bench

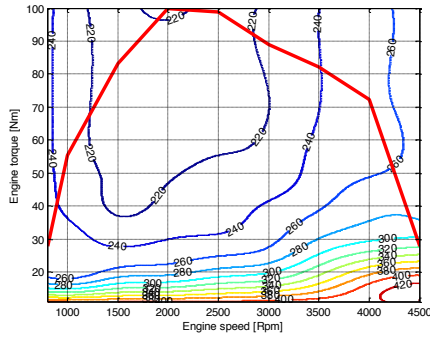Figure 4: Low Emission Vehicle Research Laboratory test bench

Figure 5: Engine maximum torque and specific fuel consumption [g/KWh]

2.4 The Battery Model

Once all the parameters including charging and discharging resistances (R0), open circuit voltage (E0) of the battery versus state of charge (SOC) were measured by experiments, those values are used as look up tables Fig 6. The model consists of two parts: SOC calculation block and voltage calculation block

In each time step the parameters are updated according to the battery state of charge. The maximum charging and discharging power, terminal voltage and current is limited in the model.

To obtain an electrical model that accurately reproduces the battery's voltage response over time; a dynamic model is used (Randle First order where (R1) and (C1) are assumed to be constant) Fig 7.
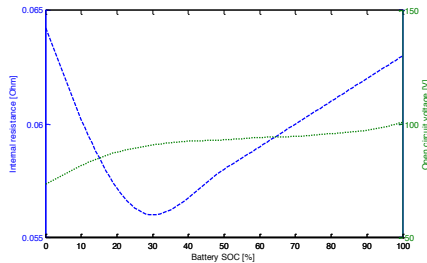

Figure 6: Battery resistance (R0) and open circuit voltage versus SOC
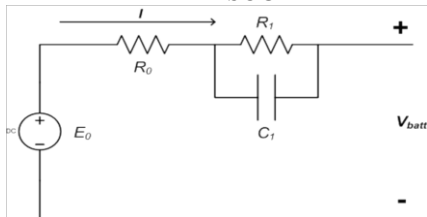

Figure 7: Randle first order battery electrical model.

$$\frac{dVc}{dt} = \frac{1}{R1 \cdot C1} \cdot Vc + \frac{1}{C1} \cdot I$$

$$Vbatt = E0 - Vc - R0 \cdot I$$

2.5 The Hybrid Controller

The goal of the hybrid controller is to split the power between the engine and the motor. In this research this hybrid controller is based on logic rules see [4] for more information. The SOCmin is a parameter which we can change then we run the simulation for different

values and finally we get the corresponding fuel consumption versus SOCmin Fig 8.

3 Simulation results for the fuel consumption

We change the SOCmin in the controller and for each time we take the corresponding fuel economy over the FTP-72 drive-cycle, we find the curve below. SOC correction means that the electric energy has been transformed into equivalent fuel consumption, and has been taken in consideration.
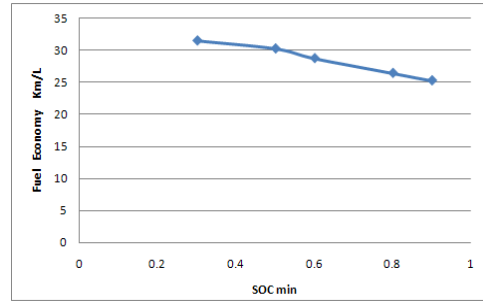

Figure 8: Fuel Economy with SOC correction (Km/L), vs SOCmin.

4 Battery Life Prediction

4.1 Aging of Ni-MH

Battery aging generally means both or one of the following performance levels to depreciate: Power or Capacity. Aging occurs through regular cycling of the battery, calendar time, and abusive operation [5]. Any combination of the failure modes listed below causes the degradation of the battery. Much research has been done to relate battery aging characteristics to DOD and operating temperature.

The main modes of failure for Ni-MH batteries are the following:

- Surface corrosion of negative electrode
- Decrepitation of alloy particles
- Loss of water in the electrolyte (separator dry-out)
- Crystalline formation
- Cell reversal
- High self discharge
- shorted cells

The common definition of battery life is its cycle life. This definition has a meaning when the load history of the battery is regular, so that the cycle is always the same. However, the problem in HEVs, the battery is not cycled on a regular basis, because the current history depends on the driving path and on power management strategy used by the controller. Thus, the definition of life as number of cycles will not be clear since in one cycle we can have a small charging signals see Fig 12 and Fig 13. For this reason, in this work the battery life L_{tot} is expressed as a total amount of discharge Amp-hour that can be drawn from the battery, i.e., time

integral of the current, as proposed by [1]. According to this definition, the battery end of life is reached as soon as the sum of charge drawn from the battery also known as the total ampere-hour or charge life arrives at a certain level. The two definitions of life are equivalent, and they can be derived from each other, considering that the amount of charge drawn from the battery during each cycle is the product of nominal capacity and DOD.

4.2 Total Amount of Discharge Amp-hour Calculation

The method used here for predicting battery life which depends on DOD and discharge rate as first approximation, is similar to the method proposed by [1].

4.2.1 Influence of Depth of Discharge (DOD)

Figure 9 shows how different DOD values on the battery will affect its cycle life. If the battery undergoes full discharges of 100% DOD, the battery will only be able to provide a few hundred of these cycles.

$$\text{deff} = \left(\frac{D_A}{D_R}\right)^{u0} \cdot e^{u1 \cdot \left(\frac{D_A}{D_R}-1\right)} \cdot d_{actual} \qquad (3)$$
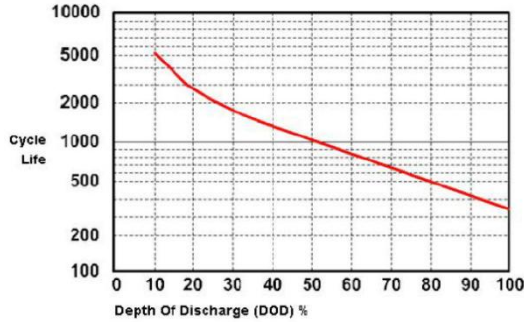

Figure 9: Depth of Discharge (DOD) Effect on Rated Cycle Life of Ni-MH Batteries [3]

4.2.2 Influence of Discharge Rate

It is expected that the rate of discharging the battery will also have affects on a battery's cycle life. The battery stresses more when higher currents are demanded from it. The higher the discharge rate, the greater the loss in conductivity between adjacent particles in the active material matrix, drawing the same amount of charge through a plate structure that is generally less conductive will lead to uneven current distributions and higher stress on the cell. This increased stress will likely lead to shorter the battery life, in a manner analogous to mechanical fatigue.

$$\text{deff} = \frac{C_R}{C_A} \cdot d_{actual} \qquad (4)$$
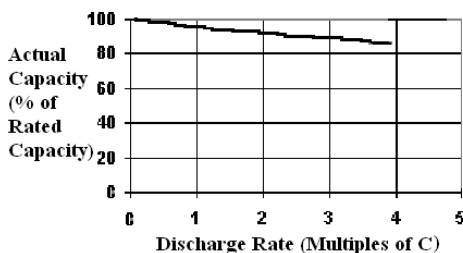

Figure 10: Effect of Discharge Rate on Capacity

4.3 Computing the Effective Discharge

The effects of DOD and discharge rate are combined simply by multiplying the factors expressed in Equations 3 and 4:

$$d_{eff} = \left(\frac{D_A}{D_R}\right)^{u0} \cdot e^{u1 \cdot \left(\frac{D_A}{D_R}-1\right)} \cdot \frac{C_R}{C_A} \cdot d_{actual} \qquad (5)$$

For our battery we have:
C_R=6.5Ah
D_R=0.3
u0=0.8038
u1=0.4091

Using equation 5, for each SOCmin (D_A) and every discharge current (the medium value of the discharging as first approximation) we first find the actual capacity from Fig 10, and then we use (equation 5) to find the effective discharge d_{eff}

The number of cycle L_{cyc} is the number N such as:

$\sum_0^N d_{eff} = L_{AhR}$
$L_{AhR} = L_{cycR} \cdot DOD \cdot Ah0$

In the other hand the charge life of a battery can be derived from the new cycle life using the following equation:

$L_{Ah} = L_{cyc} \cdot DOD \cdot Ah0 \qquad (6)$

For example if SOCmin=0.8 that means DOD=20%

$L_{Ah} = 2700 cycles \cdot \frac{20}{100} \cdot (6.5Ah) = 3510Ah$

This last value means that the battery will supply until 3510 Ampere hour of electric energy at 20% DOD, before its end of life.

Now after we know the life of the battery expressed on Ampere-hour, we introduce the effect of both DOD and current rate, expressed in (equation 5), we made a repeated drive-cycle (FTP 72) simulation with the same battery, until the sum of the effective discharge (d_{eff}) become equal to this ampere-hour life (equation 6), at that time we say that the battery has reached its end of life and we take the number of repeated drive-cycle and make it in function with SOCmin see Figure 15.

4.4 Influence of Temperature

The operating temperature can have a double effect on a battery's performance. Temperature can both increase the efficiency of the battery and can significantly shorten its life. As temperature increases, the effective internal resistance of the battery decreases. This will improve the battery efficiency, however higher temperature causes faster chemical reactions, and in particular it will increase the rate of unwanted chemical reactions that causes permanent damage to the components of a battery. Previous work has shown that exposure of a nickel-metal hydride (Ni-MH) battery to a temperature of 45°C will decrease its cycle life by almost 60% [3]. Fig 11 shows the relationship between the percentage of cycle life available and the change in temperature. Note that in this research, the temperature is assumed to be constant T=20°C.
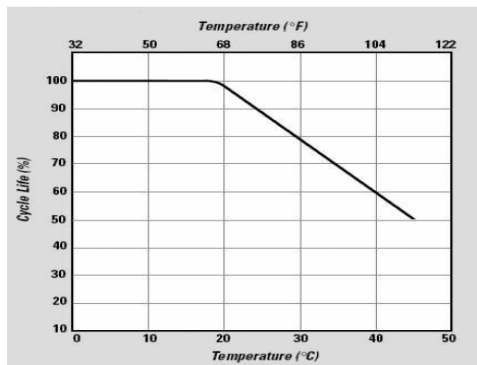
Figure 11: Influence of the temperature on cycle life [3]
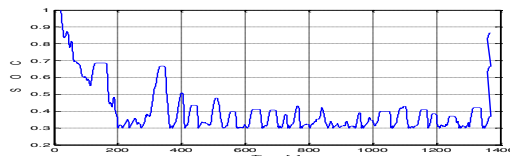
5   Results and Discussion

Figure 12: Battery SOC versus time for SOCmin=0.3 and SOCmax=1, over FTP 72 cycle.
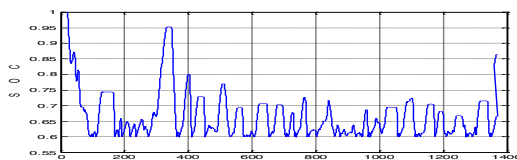

Figure 13: Battery SOC versus time for SOCmin=0.6 and SOCmax=1, over FTP 72 cycle.
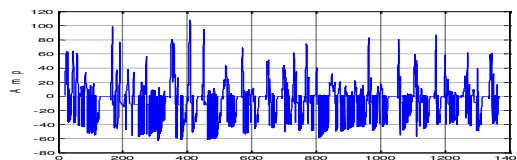

Figure 14: Battery current versus time for SOCmin=0.6 and SOCmax=1, over FTP 72 cycle.
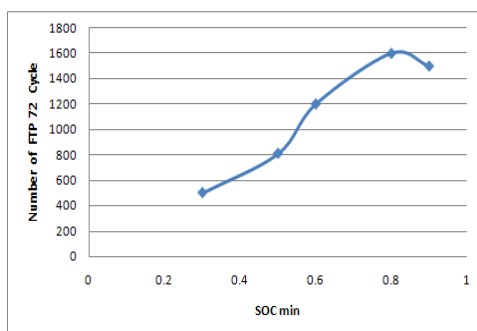

Figure 15: Number of FTP-72 cycle the battery can perform before its end of life, vs SOCmin.

Table 1: Fuel economy improvement compared to conventional vehicle with the same characteristics.

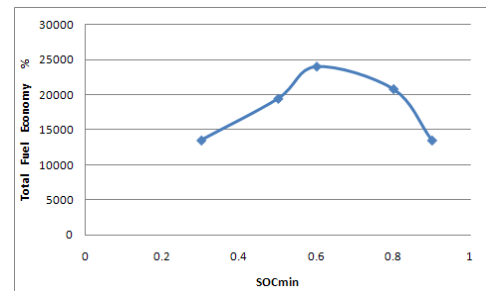| SOCmin	0.3	0.5	0.6	0.8	0.9
Improvement	27%	24%	20%	13%	9%

Figure 16: The total improvement brought by the battery until its end of life, vs SOCmin (the unit is percent compared with the conventional vehicle).

In Fig 8 we notice that the fuel economy (Km/L) is better when SOCmin is small. In the same time the Figure 15 shows the number of time of FTP-72 drive-cycle the battery can supply before its end of life, for example if SOCmin=0.3 the fuel economy over FTP-72 drive-cycle is 31.47 Km/L (27% improvement compared with a conventional vehicle), but the battery will deteriorate after making only 500 time the same repeated drive-cycle (FTP-72). The curve has a maximum between 0.8 and 0.9.

In Fig 16 we have the improvement brought by the battery over repeated FTP-72 cycle until its end of life, for each SOCmin value. It is obvious that the optimal SOCmin value in this case is between 0.6 and 0.8. In other description Fig 16 means for each SOCmin value we multiply the improvement (Table 1) with the number of time of repeated FTP-72 cycle the battery can supply Fig 15, it means the total improvement brought by the battery until its end of life, this improvement is measured by a percentage of the fuel consumption for a conventional vehicle with the same characteristics of the hybrid found in another simulation. So if the value of SOCmin =0.6, the total improvement is the number of time of repeated drive-cycle equal to 1200 multiplied by the improvement= 20% Thus: 1200*20%=24000%.

Conclusion

A parallel HEV simulation for tracking the fuel economy for different SOCmin values and a life prediction model that can give the life of a Ni-MH battery for different SOCmin values and for variable discharging current has been performed in this paper, finally, a balance between fuel economy and battery life has been described to find the optimal SOCmin value that gives the best total fuel economy, from the first day until the battery end of life

References

[1] S Drouilhet and B Johnson "A battery life prediction method for hybrid power applications" Proceedings of the 35th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, 1997

[2] Meisam Amiri, Mohsen Esfahanian Mohammad Reza Hairi-Yazdi, Vahid Esfahanian "Minimization of power losses in hybrid electric vehicles in view of the prolonging of battery life" Journal of Power Sources 190 (2009) 372–379

[3] R. Somogye "An Aging Model of Ni-MH Batteries for Use in Hybrid-Electric Vehicles", Master Thesis, The Ohio State University, Columbus, 2004

[4] Boukehili Adel, Zhang Youtong and Sun shuai 'Parallel HEV Controller Modeling for Power Management' Proceedings of the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition, Shenzhen, China. 2010

[5] J. Kopera, 'Considerations for the Utilization of NiMH Battery Technology in Stationary Applications'. Cobasys. Orion, MI. 1999.

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