Designing Energy Storage Systems for Hybrid Electric Vehicles

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Abstract

Every design problem faces the need to satisfy multiple objectives; in the case of designing energy storage systems for hybrid electric vehicles, the problem is no different. This paper presents a method to design an energy storage system by combining different battery and ultra-capacitor technologies. The choice of energy storage elements depends on the desired performance of the vehicle, and the efficiency, mass and cost of the energy storage system. From knowledge of the characteristics of battery and ultra-capacitor options, a Pareto set of optimal solutions is generated to help select the best energy storage system.

1. Nomenclature

$a(t)$	Vehicle linear acceleration (m/s ²).
a_0	Constant coefficient of rolling resistance.
a_1	First coefficient of rolling resistance.
A_f	Frontal area (m ²).
Ah_{max}	Battery capacity (Ah).
$Ah_{used}(t)$	Battery capacity used (Ah).
Bat	Batteries.
B_{cost}	Battery cost (\$).
B_{losses}	Battery losses (W).
B_m	Battery mass (kg).
c_D	Coefficient of drag.
C	Ultra-capacitor capacitance (F).
$f_i(x)$	i^{th} objective function.
$F_D(t)$	Force required to overcome drag (N).
$F_{MO}(x)$	Multi-objective function.
$F_R(t)$	Force required to overcome resistance (N).
$F_{Veh}(t)$	Force required to drive vehicle (N).
$F_\gamma(t)$	Force required to overcome road slope (N).
$I_{Bat}(t)$	Battery cell current (A).
$I_{Uc}(t)$	Ultra-capacitor cell current (A).
$loss_{Bat}$	Losses per battery unit (W).
$loss_{Uc}$	Losses per ultra-capacitor unit (W).
m_{Bat}	Battery unit mass (kg).
m_{Uc}	Ultra-capacitor unit mass (kg).
m_v	Vehicle mass (kg).
n_c	Number of ultra-capacitors.
n_p	Number of parallel strings of batteries.

n_s	Number of batteries in series per string.
$P_{EM}(t)$	Electric motor instantaneous power (W).
$P_{ESU}(t)$	Energy storage unit instantaneous power (W).
$P_{ESU}^{req}(t)$	Power requested of energy storage unit (W).
$P_{ICE}(t)$	Engine instantaneous power (W).
$P_{Veh}(t)$	Vehicle instantaneous power at wheels (W).
$P_{Bat}(t)$	Battery cell instantaneous power (W).
$P_{BatP}(t)$	Battery pack instantaneous power (W).
$P_{Uc}(t)$	Ultra-capacitor cell instantaneous power (W).
$P_{UcP}(t)$	Ultra-capacitor pack instantaneous power (W).
r_{wh}	Radius of wheels (m).
R_{int}	Battery or ultra-capacitor internal resistance (Ω).
SoC_0	Initial cell state of charge (%).
$SoC_{Bat}(t)$	Battery cell state of charge (%).
$SoC_{Uc}(t)$	Ultra-capacitor cell state of charge (%).
t	Time (s).
$T_{wh}(t)$	Torque at wheels (Nm).
Uc	Ultra-capacitors.
U_m	Ultra-capacitor mass (kg).
U_{cost}	Ultra-capacitor cost (\$).
U_{losses}	Ultra-capacitor losses (W).
v_{ICE*}	Vehicle linear speed corresponding to engine threshold (m/s).
$v(t)$	Vehicle linear speed (m/s).
$V_{Bat}(t)$	Battery cell voltage (V).
V_{max}	Voltage at maximum state of charge (V).
V_{min}	Voltage at minimum state of charge (V).
V_{oc}	Battery ideal open circuit voltage (V).
$V_{oc}(t)$	Ultra-capacitor open circuit voltage (V).
w_i	Weight of i^{th} objective.
ΔP_{BatP}^{max}	Maximum change in battery pack power per time step (W).
Δt	Time step (s).
$\omega_{wh}(t)$	Angular speed at wheels (rad/s).
Θ_{Veh}	Vehicle coefficient of inertia (kg/m ²).
$\gamma(t)$	Road slope ($^\circ$).
ρ_a	Air density (kg/m ³).
ρ_{Bat}	Gravimetric power density of batteries (W/kg).
ρ_{Uc}	Gravimetric power density of ultra-capacitors (W/kg).
σ_{Bat}	Power value per dollar of batteries (W/\$).
σ_{Uc}	Power value per dollar of ultra-capacitors (W/\$).
ε_{Bat}	Power-to-losses ratio of batteries.
ε_{Uc}	Power-to-losses ratio of ultra-capacitors.

μ_{Bat}	Gravimetric energy density of batteries (Wh/kg).
μ_{Uc}	Gravimetric energy density of ultra-capacitors (Wh/kg).
λ_{Bat}	Energy value per dollar of batteries (Wh/\$).
λ_{Uc}	Energy value per dollar of ultra-capacitors (Wh/\$).
α_{Bat}	Energy-to-losses ratio of batteries (h).
α_{Uc}	Energy-to-losses ratio of ultra-capacitors (h).

2. Introduction

Hybrid electric vehicles are a viable alternative to conventional vehicles, offering lower emissions and improved gas consumption by supplementing the main energy source with an electric motor, powered by an energy storage unit. The electric motor can also act as a generator to store regenerative braking energy in the vehicle's energy storage unit. Generally, the vehicle's energy management analysis consists of a hybrid control strategy which determines the load division during vehicle operation. However, because the energy storage unit dictates the energy and power capabilities of the electrical drive, the vehicle's energy management must begin at the design stage of sizing the vehicle components. These decisions affect the vehicle's performance, initial and operating costs.

Although there are a number of energy storage components to choose from, this paper focuses on batteries and ultra-capacitors. Batteries are high energy density devices; while, ultra-capacitors are high power density devices. A combined system capitalizes on the advantages offered by both technologies [1]. This paper designs an optimal energy storage system from batteries and ultra-capacitors.

Previous work in this area proposed a design methodology of an energy storage unit for vehicles by comparing the energy and power capacities of the available technology and sizing them to meet the load requirements of the vehicle described by the expected drive cycle. The objective in [2] was to minimize the weight of the energy storage unit while operating within normal operating conditions. Another method in [3] was to design an ultra-capacitor pack which supplemented the existing battery pack, minimized the internal losses, increased the peak power and extended the runtime of the energy storage unit.

In this paper, a more comprehensive design will be offered which reduces the size of the original battery pack because the energy storage unit is now a combination of both batteries and ultra-capacitors. The constraints of downsizing of the battery pack will be governed by the load requirements of the vehicle. The optimization parameters include the weight, cost and system losses of the battery and ultra-capacitor packs as well as the configuration number which is the number of parallel strings to series strings. As the purpose of energy management is to balance economically attractive options with technically feasible solutions, the final design will offer a lighter and

smaller energy storage system to meet load requirements and with improved performance.

3. Hybrid Electric Vehicle Model

With multiple energy sources, hybrid power trains can be either a series or parallel configuration. In a series configuration, the wheels are only powered by the electric motor; in a parallel configuration, the wheels can be powered by the electric motor, the internal combustion engine or both. The majority of hybrid vehicles emerging on the market now prefer to use the parallel configuration over the series configuration. In the series configuration, the electric motor is responsible for all power requests; therefore it must be sized for the vehicle's peak power. In the parallel configuration, the electric motor is only responsible for part of the vehicle's power request; therefore a smaller motor can be used. Although the series configuration allows the engine to always operate at its optimal point, there is an unnecessary energy conversion process: mechanical energy from the engine to electrical energy for storage and back to mechanical energy to the wheels by the motor. This lengthened process, which results in undesirable losses, along with the extra generator between the engine and energy storage system, is eliminated in the parallel power train configuration shown in Fig. 1. The direct connection of the electric motor and the engine to the wheels is represented in (1).

Figure 1. Parallel power train configuration [4]

$$P_{Veh}(t) = P_{ICE}(t) + P_{EM}(t) \quad (1)$$

The power requested at the wheels is determined from the vehicle characteristics and the target drive cycle. As presented in [5], this method is backward-facing since the information flows from the drive cycle and back through the drive train in (2).

$$P_{Veh}(t) = T_{wh}(t)\omega_{wh}(t) \quad (2)$$

$$\omega_{wh}(t) = \frac{v(t)}{r_{wh}} \quad (3)$$

The angular speed request is the vehicle linear speed divided by the wheel radius. The torque request in (4) is the torque necessary for the vehicle to accelerate and to

overcome drag, road slope, and rolling resistance forces in (5) – (8).

$$T_{wh}(t) = r_{wh} F_{veh}(t) + \frac{\Theta_{veh} a(t)}{r_{wh}} \quad (4)$$

$$\text{where } F_{veh}(t) = F_D(t) + F_\gamma(t) + F_R(t) \quad (5)$$

$$F_D(t) = \frac{\rho_a v(t)^2 c_D A_f}{2} \quad (6)$$

$$F_\gamma(t) = gm_v \sin \gamma(t) \quad (7)$$

$$F_R(t) = gm_v \{a_0 + a_1 v(t)\} \cos \gamma(t) \quad (8)$$

The internal combustion engine is assumed to be able to achieve any power request instantaneously. Since engines are inefficient during low speeds and most efficient at higher speeds, the hybrid control strategy will only request engine operation when the speed is greater than a predefined threshold which reflects the engine's optimal range. When this threshold is exceeded, the engine will be responsible for providing all of the requested vehicle power. The engine control can be modeled as in (9).

$$P_{ICE}(t) = \begin{cases} 0 & v_{wh}(t) < v_{ICE*} \\ T_{wh}(t) \omega_{wh}(t) & v_{wh}(t) > v_{ICE*} \end{cases} \quad (9)$$

The electric drivetrain consists of the electric motor, inverter, and energy storage unit. There is no DC/DC converter between the energy storage unit and the inverter because as demonstrated in [6], a DC/DC converter causes large energy losses and can be eliminated by operating the energy storage unit at a higher voltage. The undesirable effects of the DC/DC converter are then avoided. In this paper, the electric motor and inverter inefficiencies will be assumed negligible. All the power delivered by the motor to the wheels will be the power delivered by the energy storage unit to the inverter giving (10). In addition, the recovery of regenerative braking energy is 100% efficient.

$$P_{EM}(t) = P_{ESU}(t) \quad (10)$$

The energy storage unit consists of an ultra-capacitor pack and battery pack to take advantage of the different characteristics of the each technology.

$$P_{ESU}(t) = P_{BatP}(t) + P_{UcP}(t) \quad (11)$$

Ultra-capacitors are modeled as an ideal capacitor with a series internal resistance as shown in Fig. 2. This model is based on the models used in [7]. The initial ultra-capacitor state of charge is assumed to be known in (12). The open-circuit voltage is determined from the device state of charge in (13). Since the voltage across the capacitor is merely the open-circuit voltage less internal resistance losses, the ultra-capacitor current can be determined from (14) as a function of the power request, internal resistance, and open-circuit voltage. With knowledge of the capacitor current, the capacitor state of charge in (12) can be updated.

Figure 2. Ultra-capacitor model

$$SoC_{Uc}(t) = \begin{cases} SoC_0 & t = 1 \\ \frac{V_{oc}(t-1) - \frac{I_{Uc}(t-1)\Delta t}{C} - V_{min}}{V_{max} - V_{min}} & t > 1 \end{cases} \quad (12)$$

$$V_{oc}(t) = SoC_{Uc}(t)(V_{max} - V_{min}) + V_{min} \quad (13)$$

$$I_{Uc}(t) = \frac{V_{oc}(t) - \sqrt{V_{oc}(t)^2 - 4R_{int}P_{Uc}(t)}}{2R_{int}} \quad (14)$$

Based on the model in [7], the battery is modeled as an ideal open circuit voltage supply with a series internal resistance as shown in Fig. 3. Similar to (14) for the ultra-capacitor, the battery current is a quadratic function of the internal resistance, open-circuit voltage and power request. The battery terminal voltage given in (15) is the ideal open circuit voltage less internal losses in the battery. By using (16) to keep track of the battery capacity used thus far, the state of charge can be found from (17).

Figure 3. Battery model

$$V_{Bat}(t) = V_{oc} - I_{Bat}(t)R_{int} \quad (15)$$

$$Ah_{used}(t) = \begin{cases} Ah_{max}(1 - SoC_0) + I_{Bat}(t)\Delta t & t = 1 \\ Ah_{used}(t-1) + I_{Bat}(t)\Delta t & t > 1 \end{cases} \quad (16)$$

$$SoC_{Bat}(t) = \begin{cases} SoC_0 & t = 1 \\ \frac{Ah_{max} - Ah_{used}(t)}{Ah_{max}} & t > 1 \end{cases} \quad (17)$$

4. Pareto Optimality

In multi-objective (MO) optimization problems, the objectives are usually competitive with one another, every

solution is a trade-off between objectives and there is not necessarily a unique optimal solution for all objectives. A Pareto optimal solution optimizes the multiple objectives however, this does not necessarily correspond to the optimal solution of each of the individual objectives. To move from the Pareto optimal solution to the optimal solution of an individual objective, some other objective of the MO problem will be reduced.

In this design example, the weighted sums approach will be used to solve for Pareto optimal solutions because of its simplicity and linear characteristic. Each objective is normalized and modeled as a constraint in the MO problem as done in [8]. The objective function of the MO problem is a weighted sum of the individual objective values as given in (18).

$$F_{MO}(x) = \sum_{i=1}^n w_i f_i(x) \quad (18)$$

A problem with the weighted sums approach is the difficulty in selecting the appropriate value for each of the weights. Varying the weights will lead to different Pareto solutions and the collection of these solutions form a Pareto set [9].

5. Problem Formulation

The challenge faced in designing an energy storage unit for hybrid electric vehicles is finding a balance between technically feasible and financially attractive solutions. The formulation given in (19)-(38) determines the best distribution of power between the ultra-capacitors and the batteries. In this problem, the objectives include lightness in weight (20), cost-effectiveness (21), and efficiency (22). The constraint in the problem is that the energy storage unit must be able to satisfy the anticipated power requests of the vehicle (23) while operating the devices within capacity.

$$\min \sum_i w_i f_i(B_m, U_m) \quad i = mass, cost, losses \quad (19)$$

$$s.t. \quad f_{mass}(B_m, U_m) = B_m + U_m \quad (20)$$

$$f_{cost}(B_{cost}, U_{cost}) = B_{cost} + U_{cost} \quad (21)$$

$$f_{losses}(B_{losses}, U_{losses}) = B_{losses} + U_{losses} \quad (22)$$

$$P_{ESU}^{req}(t) \leq P_{BatP}(t) + P_{UCP}(t) \quad \forall t \quad (23)$$

$$|P_{BatP}(t) - P_{BatP}(t-1)| \leq \Delta P_{BatP}^{max} \quad t \geq 2 \quad (24)$$

$$|P_{BatP}(t)| \leq \rho_{Bat} B_m \quad \forall t \quad (25)$$

$$|P_{UCP}(t)| \leq \rho_{Uc} U_m \quad \forall t \quad (26)$$

$$|P_{BatP}(t)| \leq \sigma_{Bat} B_{cost} \quad \forall t \quad (27)$$

$$|P_{UCP}(t)| \leq \sigma_{Uc} U_{cost} \quad \forall t \quad (28)$$

$$|P_{BatP}(t)| \leq \varepsilon_{Bat} B_{losses} \quad \forall t \quad (29)$$

$$|P_{UCP}(t)| \leq \varepsilon_{Uc} U_{losses} \quad \forall t \quad (30)$$

$$E_{Bat}(t) \leq \mu_{Bat} B_m \quad \forall t \quad (31)$$

$$E_{Uc}(t) \leq \mu_{Uc} U_m \quad \forall t \quad (32)$$

$$E_{Bat}(t) \leq \lambda_{Bat} B_{cost} \quad \forall t \quad (33)$$

$$E_{Uc}(t) \leq \lambda_{Uc} U_{cost} \quad \forall t \quad (34)$$

$$E_{Bat}(t) \leq \alpha_{Bat} B_{losses} \quad \forall t \quad (35)$$

$$E_{Uc}(t) \leq \alpha_{Uc} U_{losses} \quad \forall t \quad (36)$$

$$P_{BatP}(t) \begin{cases} \geq 0 & \text{if } P_{ESU}(t) \geq 0 \\ = 0 & \text{if } P_{ESU}(t) = 0 \\ \leq 0 & \text{if } P_{ESU}(t) \leq 0 \end{cases} \quad (37)$$

$$P_{UCP}(t) \begin{cases} \geq 0 & \text{if } P_{ESU}(t) \geq 0 \\ = 0 & \text{if } P_{ESU}(t) = 0 \\ \leq 0 & \text{if } P_{ESU}(t) \leq 0 \end{cases} \quad (38)$$

The advantage of ultra-capacitors is its ability to handle high current spikes and high power requests, meanwhile batteries have limited current and power capabilities. Equation (24) constrains the change in battery power to ensure smooth battery operation which leaves ultra-capacitors with the responsibility of handling transients and power spikes. Equations (25)-(36) ensure that the power and energy demands are within the capacity of the technology. Gravimetric power and energy densities ρ and μ are commonly used parameters to quantitatively describe the available power with respect to weight. The power value per dollar terms σ and λ are defined in this paper describe the marginal power derived from each additional unit and the cost for each additional unit. The power-to-loss ratios ε and α describe the efficiency of each unit due to Ohmic losses. Equations (37) and (38) ensure that there is no charging and discharging between the battery and ultra-capacitor packs. After this optimization procedure determines the power distribution between packs, a second optimization problem finds the minimum number of cells per pack for batteries and ultra-capacitors.

$$\min \sum_j n_j \quad j = Bat, Uc \quad (39)$$

$$s.t. \quad P_{jP}(t) \leq n_j m_j \rho_j \quad (40)$$

$$P_{jP}(t) \leq n_j cost_j \sigma_j \quad (41)$$

$$P_{jP}(t) \leq n_j loss_j \varepsilon_j \quad (42)$$

$$P_j(t) = \frac{P_{jP}(t)}{n_j} \quad (43)$$

$$n_j \geq 1 \quad (44)$$

The second optimization procedure is embedded in a reiterative loop to ensure that the energy storage system operates within state of charge constraints, power limits, and system constraints such as the minimum and maximum motor controller voltages.

These optimization problems are programmed using the General Algebraic Modeling System (GAMS) interface [10] using the DICOPT solver for mixed-integer linear

problems (MINLP), the OSL solver for mixed-integer problems (MIP) and the CONOPT solver for non-linear problems (NLP).

6. Case Study

This multi-objective problem formulation is used to design an energy storage system for a midsize SUV, the *Chrysler Pacifica* whose details from [11] and [12] are listed in Table 1. The first 505s of the *EPA UDDS* drive cycle [13] is known as Phase 1 and used as the typical vehicle drive cycle for this study. It is sampled at a rate of 3 second. Two systems are considered, *Maxwell BCAP0008* ultra-capacitors [14] with *Thundersky TS-LP6163A* lithium ion batteries [15] and *Maxwell BCAP0008* ultra-capacitors with *Panasonic HHR650D* nickel metal hydride batteries [16].

Table 1. Vehicle data

Vehicle mass	2121 kg
Wheel diameter	0.739 m
Drag coefficient	0.352
Frontal area	2.85 m ²
Coefficient of friction	0.012

Table 2. Ultra-capacitor data

Manufacturer	Maxwell
Technology	Ultra-capacitors
Ultra-capacitor	BCAP0008
Mass of cell	0.4 kg
Rated voltage	2.5 V
Rated current	450 A
Internal resistance	0.0009 Ω
Capacitance	1800 F
Cost per cell	\$50

Table 3. Battery data

Manufacturer	Thundersky	Panasonic
Technology	Lithium ion	Nickel metal hydride
Battery	TS-LP6163A	HHR650D
Mass of cell	1.4 kg	0.17 kg
Rated voltage	3.6 V	1.2 V
Minimum voltage	2.8 V	1.0 V*
Maximum voltage	4.25 V	1.4 V*
Rated current	40 A	6.5 A
Maximum current	150 A	32.5 A
Capacity	40 Ah	6.8 Ah
Cost per cell	\$80**	\$15***

*Interpolated from typical discharge characteristics graph.

**Based on price listed in [17].

***Based on price listed in [18].

After populating the Pareto set from the MO problem, the system constraints and system control data listed in Tables 4 and 5 are applied to the designer's choice of solution to ensure that the batteries and ultra-capacitors are not discharged beyond the recommended range.

Table 4. System constraints

Motor controller minimum voltage	260 V
Motor controller maximum voltage	385 V

Table 5. System control data

Vehicle threshold speed for engine on	64.8 km/h
Maximum change in battery pack power per time step	1000 W
Initial battery state of charge	80 %
Battery state of charge range	65 – 95 %
Initial ultra-capacitor state of charge	90 %
Ultra-capacitor state of charge range	50 – 100 %

7. Analysis and Discussion

A Pareto set of solutions from the higher level MO problem is shown in Fig. 5 for lithium ion batteries. From this plot, the designer has a set of points which clearly identify the tradeoffs of valuing mass versus cost versus losses. If the objective is to minimize the losses of the system, the designer could spend \$11315.90 for an energy storage unit that weighs 141.1 kg and have the least amount of losses. This solution however, is far from other points, indicating that a large tradeoff was made to achieve such low losses. If the designer relaxes their tolerance for losses, they can move to another point which significantly improves one of the other objectives, mass or cost. The Pareto solution set enables the designer to see how the value of their design criteria affects their design solution and the options that would otherwise be available.

Fig. 6 shows the distribution of power during 20 – 200s of the UDDS drive cycle with a 100 kg energy storage system composed of 130 ultra-capacitors and 38 lithium ion batteries. From this plot, it is easy to see how the batteries supply a steady power request serving as the base supply while the ultra-capacitors deal with all the transients and supply the varying power requests.

Fig. 7 shows the state of charge of individual battery and ultra-capacitor cells during 20 - 505 s for the same, 100 kg energy storage system. Since this is such a short time period relative to the battery's typical discharge period, not much change in the battery's state of charge is observed as it hovers about the 80%, the initial state of charge. The ultra-capacitors however are heavily used. They obtain their minimum state of charge of 50% at 140 s. The second optimization problem, which determines the minimum number of cells, is embedded within a reiterative process to increase the number of cells until the system operates

Figure 4. Energy storage options with *Maxwell* ultra-capacitors and *Thundersky* lithium ion batteries

Figure 5. Energy storage options with *Maxwell* ultra-capacitors and *Panasonic* nickel metal hydride batteries

within the acceptable range. The state of charge stays within the desired range as shown in Fig. 7 when the ultra-capacitor count is increased to 215 units. This is a significant increase and is a result of assuming a very low-level energy management scheme which only turned on the engine at a speed of 64.8 km/h. In actual implementation a more sophisticated hybrid control strategy should be utilized. However, this simple control demonstrated that the original sizing of 130 units is able to operate within acceptable limits for 2 minutes.

Figure 6. Load distribution over three minutes

Figure 7. Cell state of charge

The Pareto set for an energy storage system composed of ultra-capacitors and nickel metal hydride batteries is shown in Fig. 6. The only solution which is comparable to the lithium ion batteries in terms of cost and weight is a pack weighing 99 kg for \$12363 however, it experiences relatively significant losses. All other options are incomparably expensive. Based on these values, lithium ion batteries should be used instead of nickel metal hydride batteries.

8. Conclusion

This paper presents a solution to designing an energy storage system which must satisfy multiple objectives. The Pareto optimal solutions are presented to the designer who can then evaluate which tradeoffs are acceptable. The use of a combined energy storage system consisting of ultra-capacitors and batteries has a number of benefits. First, the batteries are discharged less rapidly because with the presence of the ultra-capacitors, the batteries can be used to provide a steady base power while the ultra-capacitors can be used to provide high peaking currents when necessary. During implementation, a more sophisticated energy management control scheme is necessary. In addition, since each technology has its limitation, batteries have low power densities and high energy densities while ultra-capacitors have high power density but low energy density, the combined system reduces the weight and cost in comparison to only using one technology. Furthermore, it was shown that the lithium ion batteries are a better candidate for a hybrid electric vehicle energy storage system.

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