Optimization of Energy Storage System for Hybrid Electric Vehicle

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Abstract

BAE Systems, L&A as an industry leader of Ground Vehicle for military, has long history to develop Hybrid Electric Vehicle (HEV) [1]. The Propulsion Integrated Product Team (IPT) has been developing and improving the design tool for HEV Propulsion System. This paper presents a study [2, 3] to develop a methodology to determine optimal Energy Storage System (ESS) size for a Hybrid Electric Vehicle (HEV).

In this paper, the criterion of the study to drive vehicle utility is presented including measures and its importance, and establishing relationship between Energy Storage System Size and Vehicle Utility. The study results a tool to determine the optimal size of ESS as well as to evaluate and compare various ESS designs for any HEV.

1. Introductions and Objective

The Propulsion IPT of BAE Systems is responsible for development of an Energy Storage System (ESS) of Hybrid Electric Vehicle (HEV) for military. This includes physical architecture, battery chemistry type selection and associated battery management, energy/power management, thermal management, component design and implementation that best meets the Military HEV requirements.

What is the optimal size of ESS for a HEV?

The size study was initiated to answer the above question. The principal technology focus is the ESS capability to deliver power and energy to maximize vehicle utility including performance and fuel efficiency at given mass and space constraints. Previous investigations had focused on gravimetric power and energy, or the volumetric power and energy of battery cell. These are the perfect measures to compare various energy storage devices, but these fail to address the significant ancillary and supporting components necessary to implement an energy storage system. Furthermore, it is very difficult to match these measures with vehicle utilities. Therefore, the power and energy of various ESS sizes were used in this study instead.

To provide a realistic evaluation of system, the entire ESS was analyzed, including DC/DC Converter, battery cells, the thermal management system, battery monitoring system, and module design.

A key objective of the size study is to develop a methodology to determine the optimal ESS size to maximize a vehicle utility. This study includes the followings:

- Determine measures to evaluated Vehicle Utility
- Determine importance of each measure
- Determine utility curves to normalize measures

2. Scope

2.1 Description of ESS

An ESS design consists of the following major components:

- Battery Cells
- Battery monitoring electronics and management system
- DC/DC Converter
- Thermal management system
- Physical Architecture

2.1.1 Battery Cells

The Battery Cells, when connected together to form a single battery, act as the platform power/energy source for mobility load leveling capability and silent operations, delivering power in support of the vehicle demands. Within this document the term ‘battery’ refers to a collection of battery cells either connected in series or series-parallel, depending on the architectural design considered.

2.1.2 Battery Management System (BMS)

The roles of BMS are

- Protect the cells or the battery from damage
- Prolong the life of the battery
- Maintain the battery in a state in which it can fulfill the functional requirements of the application for which it was specified.

2.1.3 DC/DC Converter

The role of the DC/DC Converter in the ESS is to serve as the high voltage converter between the battery and the high voltage bus. A DC/DC Converter is necessary if the high voltage bus is to be maintained at a fixed voltage. In systems with no DC/DC Converter, the battery sets the voltage of the high voltage bus, which results in the bus voltage fluctuating as the battery SOC fluctuates, and the battery is charged and discharged. The benefits of having a DC/DC converter in the system include a stiffer high voltage bus that can improve motor performance, better battery utilization, faster response to quickly varying loads, and more flexibility in power management schemes that can improve generator operation and overall efficiency. The no DC/DC converter options were ultimately determined to not be viable options because it was shown that the elimination of the DC/DC converter would increase the mass and volume of components outside the ESS, resulting in a net decrease in the system's power and energy density.

2.1.4 Thermal Management System

The role of the Thermal Management system is to cool the ESS components, namely the battery cells, during operation. In the ESS with the integrated DC/DC converter, the Thermal Management system is also responsible for cooling the DC/DC converter.

2.1.5 Physical Architecture

The ESS Physical Architecture refers to the supporting structure required to mount the ESS in the vehicle, as well as how these components are arranged in the ESS. It includes electronic packaging, cabling, connectors, coolant connections and any other mechanical parts. Size and Mass allocations for the major components are used to determine positioning.

2.2 Ground Rules and Assumptions

- Automotive performance will be evaluated in an aggregate form over a specified driving duty cycle.
- To evaluate vehicle performance and fuel efficiency, Vehicle simulation model which is based on Hybrid Electric Drive System (HEDS) was used. The vehicle model which has following key features:
  - Series Electric Drive
  - Drivetrain electrical and mechanical dynamics
  - Vehicle mechanical dynamics, e.g. terrain interaction, driver response
- Unique Power/Energy Management Control Scheme was developed and implemented to improve vehicle performance and fuel efficiency.
- Logical Decision for Windows (LDW) software was used as the tool for combining the measures into vehicle utility.
- DC/DC Converter is bi-directional, with identical power ratings for charge and discharge

2.3 Evaluation Criteria for Vehicle Utility

The following criterion was determined to provide objective and clear distinguishing characteristics allowing the optimal ESS size to be chosen. The criterion has 3 high level measures, which are ESS Mass, ESS Cost, and Vehicle Performance. Vehicle Performance was divided into 5 sub-measures, which are Elapsed Time, Fuel Consumption, Dash Time, Peak Power of ESS, and Usable Energy of ESS. Each of the measures was considered independently and the method for establishing a metric for that parameter was determined by consensus.

Measures and its Weights are the followings:

- ESS Mass: 25%
- ESS Production Cost: 25%
- Vehicle Performance:
  - Elapsed Time: 15%
  - Fuel Consumption: 15%
  - Dash Time: 5%
  - Peak Power: 5%
  - Usable Energy: 10%

3. Description of Measures

3.1 ESS Production Cost

Energy Storage System production cost includes DC/DC converter, and Battery production cost measures.

The DC/DC Converter Production Cost is a quantitative measure of the cost to produce the DC/DC Converter system for each ESS architectural option. Rough Order of Magnitude (ROM) cost quotes received from suppliers for a converter sized between 90kW and 180kW were used for reference.

The battery production cost includes the battery cell, module materials and interconnections, battery monitoring system (BMS), and thermal management system. ROM cell production cost quotes, were obtained from the suppliers at large volumes with a projected cost for the year 2008.

3.2 ESS Mass

The ESS mass is a sum of 5 major ESS components that described in Section 2.1. Each component mass was generated by sizing equations for each of the components. The sizing equations were derived from data for prototype systems, CAD Models, manufacturer's data, and design calculations.

3.3 Vehicle Performance

3.3.1 Elapsed Time

This measure is the time required for a vehicle to complete the driving duty cycle defined by the Propulsion IPT. Elapsed Time was evaluated by engineering simulation to determine the time required to complete the mission.

3.3.2 Fuel Consumption

This measure is the consumed fuel to complete the driving duty cycle defined by the Propulsion IPT. Fuel consumption was evaluated by engineering simulation to determine the amount of fuel required to complete the mission.

3.3.3 Dash Time

Dash Time is defined as time from the point where the crew initiates action to a representative distance at which the vehicle has physically moved out of the danger zone. Dash Time was evaluated by engineering simulation to determine the time required to move the vehicle out of the danger zone.

3.3.4 Peak Power

The Peak Power measure is a quantitative measure of the ESS ability to provide power to TDS (Traction Drive System) and auxiliary systems. Auxiliary power would objectively be supplied to the weapons systems to increase lethality by mounting larger or larger numbers of more power demanding weapons.

3.3.5 Usable Energy

The Usable Energy metric is a quantitative measure of the silent watch capability without using engine power. The Usable Energy was calculated for each ESS size at End of Life (EOL) condition.

4. Utility Curves

The utility curves for each measure individually were constructed. In each case, the maximum and minimum values for the measure, the utility value represented by these measures, and the appropriate shapes for the utility curves were considered (see Figure 1).

In order to create the maximum discrimination between ESS, the following rules were applied:

- For Peak Power and Usable Energy
  - Lowest score received zero utility
  - Highest score received one utility
- For ESS Mass, ESS Cost, Dash Time, Fuel consumption, and Elapse Time
  - Lowest score received one utility
  - Highest score received zero utility

Later, some of these utility curves were revised to more balance the spread of the data versus the weighting of the measures.

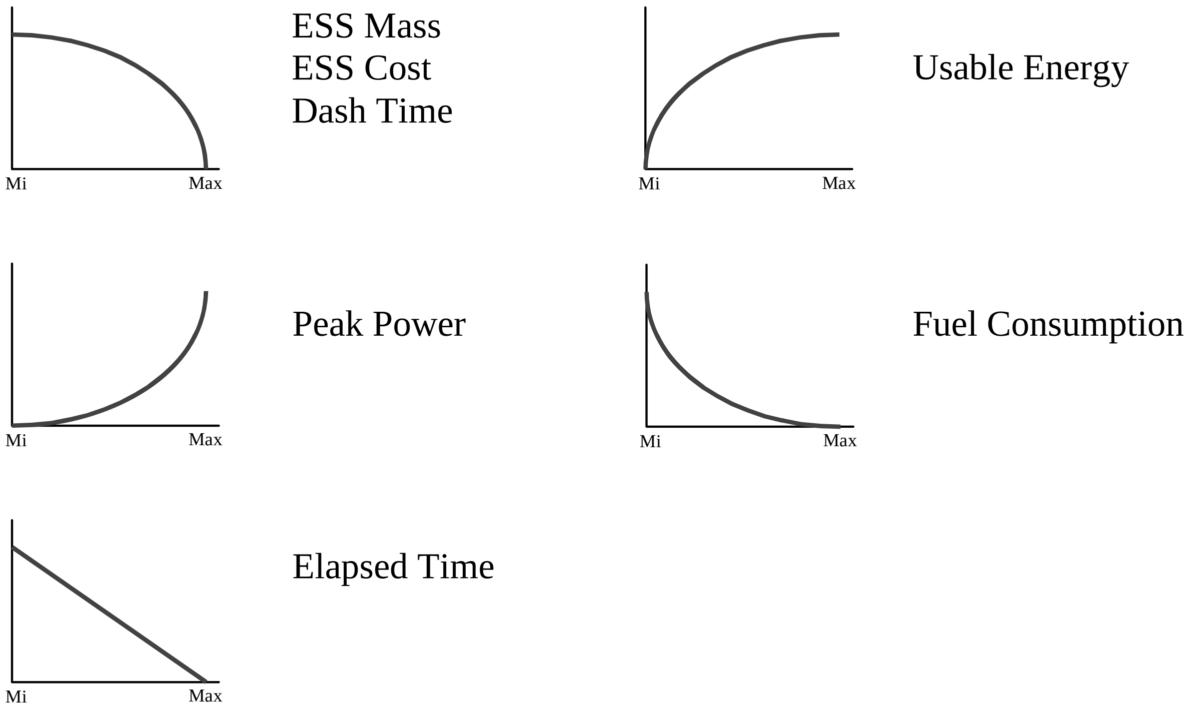


Figure 1: Utility Curves for Measures

5. Results

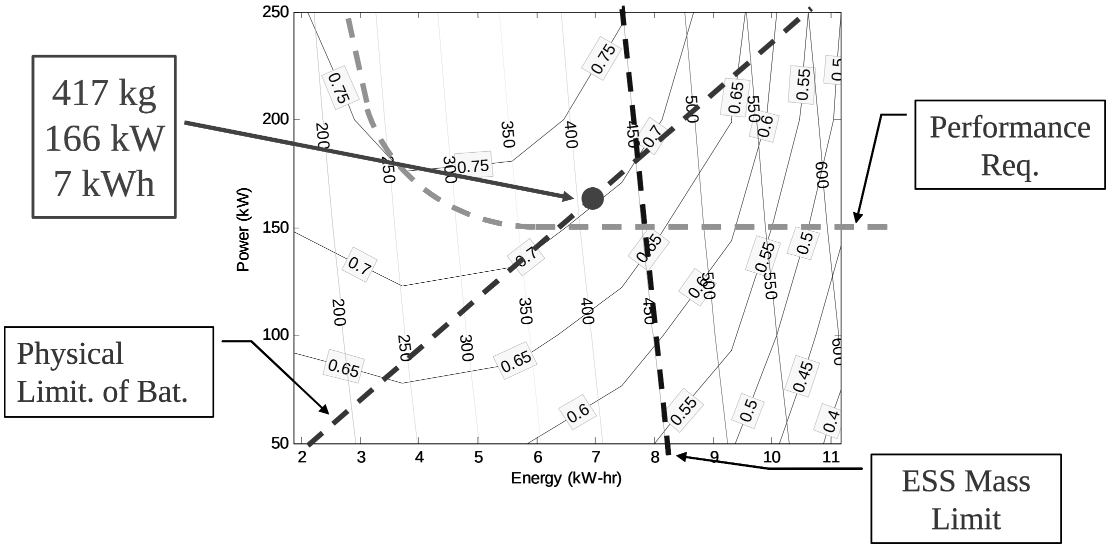
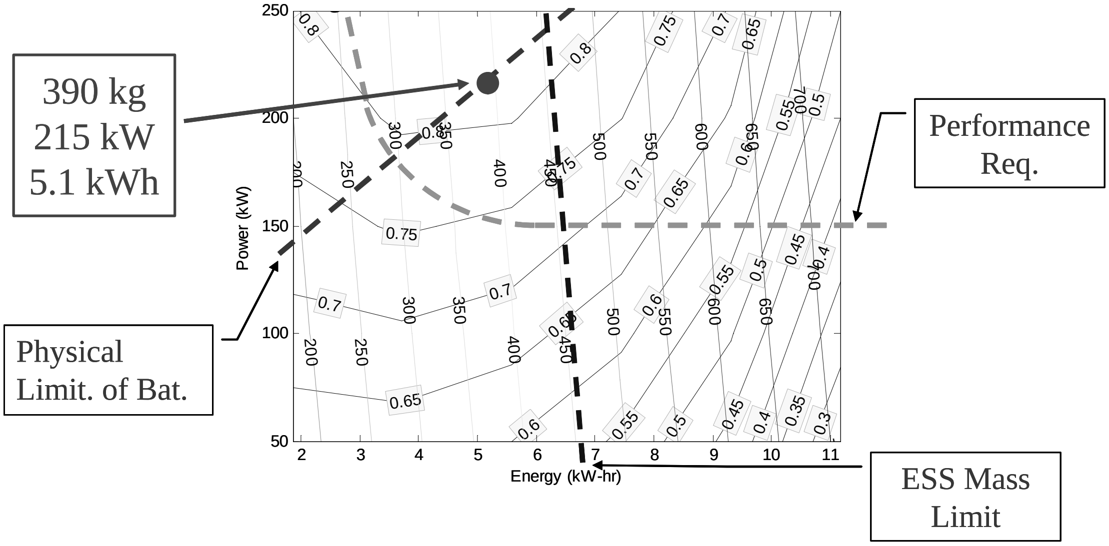


Figure 2: Vehicle Utility Plot for Cell Type A’s ESS

After all of the measures were evaluated, LDW was used to combine measures and generate vehicle utility. The results from LDW were converted to ESS power and energy chart and it combined with all constraints including physical limit of battery, vehicle performance requirements and maximum allowable ESS mass (450 kg). Figure 2, 3, and 4 are three samples of our test cases for evaluation of the Optimization Tool.



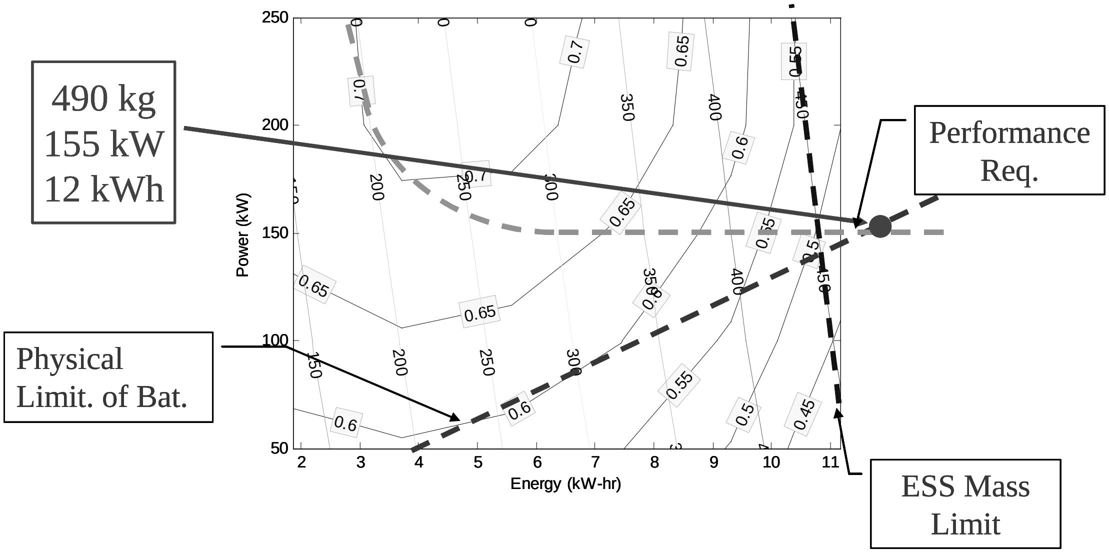
390 kg
215 kW
5.1 kWh

Performance Req.

Physical Limit. of Bat.

ESS Mass Limit

Figure 3: Vehicle Utility Plot for Cell Type B's ESS



490 kg
155 kW
12 kWh

Performance Req.

Physical Limit. of Bat.

ESS Mass Limit

Figure 4: Vehicle Utility Plot for Cell Type C's ESS

Figure 2 shows the result of ESS design based on Cell Type A (ESS A). All constraints formed triangular shape area, which provide viable solution for Military HEV. Therefore, optimal ESS size using Cell Type A is 166 kW of power and 7 kWh of energy.

Figure 3 shows the result of ESS design based on Cell Type B (ESS B). All constraints formed circular sector area, which provide viable solution for Military HEV. Therefore, optimal ESS size using Cell Type B is 215 kW of power and 5.1 kWh of energy.

Figure 4 shows the result of ESS design based on Cell Type C (ESS C). All constraints couldn't form any area. Thus, this ESS using Cell Type C is not viable solution for Military HEV. If maximum allowable ESS mass is relaxed to 500 kg, optimal ESS size using Cell Type C will be 155 kW of power and 12 kWh of energy.

6. Conclusions

The best ESS option for the specific military HEV was from Cell Type B, which results highest vehicle utility (0.82) among ESS designs. The optimal size of this system was 215 kW in power and 5.1 kWh in energy. The utility isobar shows that power is more important than energy for military HEV. Therefore, ESS design with high power cell has highest utility.

A methodology to determine optimal Energy Storage System size for a Hybrid Electric Vehicle was developed and implemented. This tool is able to determine the optimal size of given ESS design to maximize vehicle utility. Also, this tool provides capability to make realistic comparison of various technologies. Furthermore, this tool has flexibility to apply to other type of HEV, e.g. mild hybrid, full hybrid, etc.

7. References

1. *Conference Articles:* Gordon Shafer. Electric Drive for the Future Scout and Cavalry System (FSCS), Vehicle Technologies Conference Proceedings, 1997.

2. *Reports:* Dongwoo Song, Perry Tsao. Energy Storage System (ESS) Trade Study. 2005.

3. *Reports:* Dongwoo Song. Energy Storage System Sizing Study Report. 2005.