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Energy Storage Sizing of Hybrid Electric Vehicles with Power Efficiency Considerations

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Abstract

Proper storage sizing of hybrid electric vehicles is essential for the optimal utilization of on-board energy sources. Unlike previously developed sizing methods, where component size is bounded by power, energy, weight, volume, cost constraints, this work introduces an efficiency-based method by which supercapacitors are sized in a battery electric vehicle. An extensive efficiency model is developed, which take into account of various power-sharing methods and supercapacitor state-of-charge deviation. The proposed method is applied to the EPA UDDS, ARTEMIS, and WLTC drive cycle tests. Results of this study suggests that the percentage mass of the supercapacitor should be 7-13% of the total mass of the hybrid energy storage system.

Keywords: efficiency, energy storage, ESR, HEV, modeling

Nomenclature

$BESS$	Battery energy storage system
ESR	Equivalent series resistance
h	Degree of hybridization
$HESS$	Hybrid energy storage system
k	Battery-to-supercapacitor voltage ratio
r	Power ratio (fractional power of supercapacitor)
SoC	State-of-charge

1 Introduction

Electric vehicles (EVs) are essential for reducing global energy consumption where 27% of the energy is occupied by the transportation sector[1]. Currently, the most common energy storage media in pure EVs is the lithium-ion battery due to its high energy density and cost per unit weight in comparison to other battery chemistries. However, a conventional battery electric vehicle is driven by a single energy source. Since the performance of the vehicle is affected by both the energy and power output capability of the energy storage system, this leads to sub-optimal sizing of the battery pack in order to meet multiple design requirements.

To optimize the design of the battery pack without significant effect on drive range, many concept vehicles integrating a high-power secondary energy source, typically the supercapacitor, have been developed at the research stage. In [2], power-sharing between a lithium-ion cell and supercapacitor reduced the rate of capacity and impedance degradation, which alludes to battery life extension. A test vehicle developed at the University of Toronto with supercapacitor power-assist has demonstrated a 36% increase in maximum power capability[3]. Despite the benefits of hybridization, co-integration has been a slow process at the commercial level. Supercapacitors are commonly employed for short term power-assist in public transportation systems and ICE vehicles with regenerative braking capability[4]-[6]. This is due to strict limitations in the mass and size of most passenger vehicles in favor of mobility.

Therefore, appropriate sizing of the hybrid energy storage system (HESS) is critical to ensure its feasibility in modern EVs. Among existing sizing methods, the relative size of the battery and supercapacitor is usually determined using real-world drive cycles. In one case, a limit is set on the maximum power output of the battery using rule-based power-split control, and size the supercapacitor to meet power and energy requirements[7]. Drive cycle assessment is often refined by introducing other factors into sizing optimization, most commonly weight, volume, energy savings, and initial/replacement cost[8], [9]. However, a key issue in such sizing methods is that a comprehensive model for efficiency assessment has not been well-established. Efficiencies of respective energy sources are typically found by directly measuring the loss under different SoC and loading conditions[9].

This paper introduces a comprehensive model to quantify power loss, mainly associated with the ESR of each energy storage technology. The proposed model takes into account the key factors such as variation in SoC and power distribution. To find an approximation for the ideal degree of hybridization, the model will be applied to commonly used battery and supercapacitor energy storage technologies, along with selected drive cycle tests (EPA, ARTEMIS, WLTC, etc.).

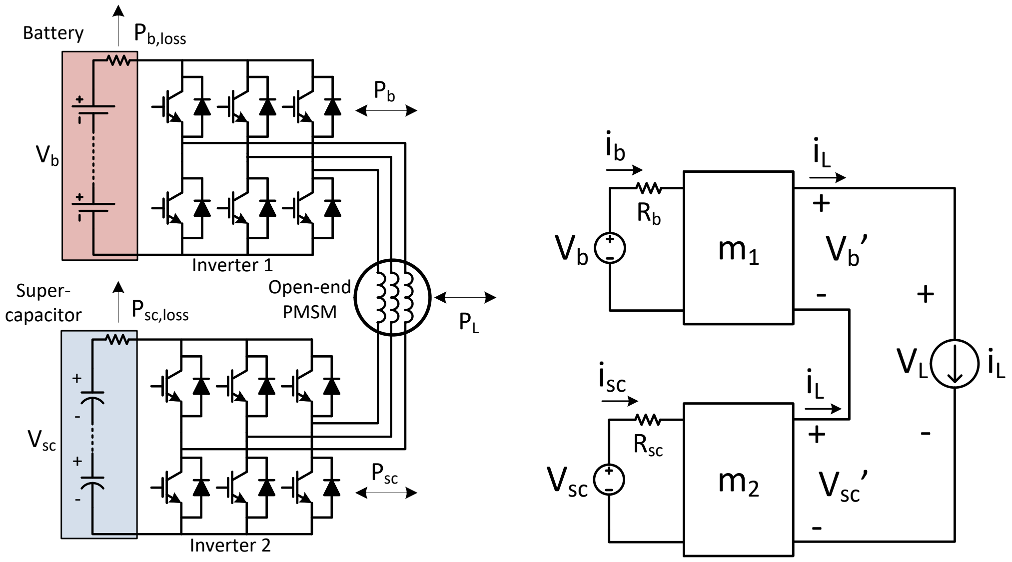
2 System overview

The sizing method developed in this work aims to identify the practical size of the supercapacitor relative to that of the battery in a hybrid electric vehicle. While conventional methods size the supercapacitor based on the energy required during sudden acceleration and/or braking, the proposed method also examines the efficiency in the hybridized system, which is directly related to the power dissipated in its effective resistance. This is essential for determining the size of each energy source because the effective resistance is, in principle, the *weighted sum* of the battery ESR and supercapacitor ESR. Therefore, if the HESS is sized appropriately, it can be used to optimize the efficiency of the energy storage system and reduce peak loading in the battery as intended.

The proposed sizing method applies the following assumptions:

- **Mass:** To ensure that the addition of supercapacitors does not infringe on the mass limitation of the vehicle, the total mass of the energy source shall remain constant, as suggested in [10]. This is achieved by shifting the weight of the battery module to the supercapacitor bank as the degree of hybridization increases. In this analysis, the mass of the combined battery and supercapacitor energy storage system shall be 25% of the vehicle's curb weight.
- **Scope of efficiency:** Power efficiency is evaluated based on the ESR loss of the energy storage devices. As such, the output power is measured prior to mechanical losses associated with the drivetrain and vehicle dynamics.
- **Battery c-rate:** The battery shall be charged or discharged within the recommended c-rate specified by the manufacturer. This is to ensure that battery loading does not significantly affect ESR, as it has been demonstrated that high discharge rate (3C) can lead to 28% increase in the dc internal resistance[11].
- **ESR:** The dc internal resistances of the battery and supercapacitor are constant.
- **Supercapacitor SoC:** Usable energy in the supercapacitor shall be limited to 75%, from 25% to 100% SoC, to minimize significant voltage loss.

The powertrain under study is a state-of-the-art high voltage drive, using a dual-end connection of the electric motor and two traction inverters[12]. The dual inverter traction system provides increased speed range and supercapacitor integration without use of dc/dc power converters or additional magnetic materials, thus offering an efficient and light-weight solution attractive for HEVs. This is preferred over conventional hybridization methods discussed in [13] because high voltage drives are gaining widespread attention in future EV traction systems[14].



(a) Direct supercapacitor integration method[12]

(b) Model for proposed sizing method

Figure 1: Hybrid powertrain for this study

2.1 Degree of hybridization

The first step in the proposed sizing method is to define the characteristics of each energy source at different hybridization levels. In this study, the degree of hybridization is defined as the fractional mass of the supercapacitor over the total mass of the HESS. Thus, the mass of each energy source is

$$M_b = (1-h)M_{total} \tag{1}$$

$$M_{sc} = hM_{total} \tag{2}$$

where parameters denoted by subscript “b” and “sc” refers to the battery and supercapacitor, respectively. In the hybridized system shown in Fig. 1(a), the battery and supercapacitor ESRs are

$$R_b = R_{b,module}\left(\frac{s_b}{p_b}\right) \tag{3}$$

$$R_{sc} = R_{sc,module}\left(\frac{s_{sc}}{p_{sc}}\right) \tag{4}$$

where s and p denote the number of series and parallel-connected battery or supercapacitor modules, and the ESR per module is taken from the datasheet. The series-parallel arrangement of the battery and supercapacitor modules are

$$s_b = \frac{V_b}{V_{b,module}} \tag{5}$$

$$s_{sc} = \frac{V_{sc}}{V_{sc,module}} \tag{6}$$

$$p_b = \frac{M_b}{s_b M_{b,module}} \tag{7}$$

$$p_{sc} = \frac{M_{sc}}{s_{sc} M_{sc,cell}} \tag{8}$$

2.2 Modeling the effective resistance

To study how the effective resistance of the HESS varies with hybridization, an average model of the powertrain system with energy storage is derived (Fig. 1(b)). The input and output voltages of the inverters are related via the converter modulation index, m_1 and m_2

$$m_1 = \frac{V_b'}{\frac{1}{2}V_b} \tag{9}$$

$$m_2 = \frac{V_{sc}'}{\frac{1}{2}V_{sc}} \tag{10}$$

By power balance, the battery/supercapacitor current and load current also have the same relation

$$i_b = \frac{1}{2}i_L m_1 \tag{11}$$

$$i_{sc} = \frac{1}{2}i_L m_2 \tag{12}$$

The load current in subsequent sections shall be expressed in terms of the single phase stator winding current, assuming unity power factor

$$P_L = \frac{3}{2}V_L i_s \tag{13}$$

$$i_L = \frac{3}{2}i_s \tag{14}$$

Sinusoidal pulse width modulation is selected as the switching method for this system, hence the maximum achievable output voltage in the converters is assumed to be one-half of the supply voltage. In this analysis, the voltage drop across the ESRs are omitted due to their minimal impact on the available supply voltage.
The total power loss through the ESR of the hybrid energy storage system is

$$P_{loss} = R_b {i_b}^2 + R_{sc} {i_{sc}}^2 \tag{15}$$

By substituting i_b and i_{sc} with (11) and (12)

$$P_{loss} = \underbrace{\left(\frac{3}{2}\right)^2 \left[R_b \left(\frac{1}{2}m_1\right)^2 + R_{sc}\left(\frac{1}{2}m_2\right)^2\right]}_{R_{eff}} {i_s}^2 \tag{16}$$

Aside from the respective ESR of the energy storage system, the total power loss is also related to the utilization of the battery and supercapacitor converter. Thus, more power should be demanded from the energy storage unit with lower ESR to improve efficiency. In the dual inverter drive, the power in each energy source can be independently controlled by regulating the inverter voltage to be a fraction of the load voltage. Thus, to have an intuitive sense of how any arbitrary power-sharing method affects efficiency, the fractional power (r) supplied by the supercapacitor is introduced into (16) via the voltage relations

$$V_b' = (1-r)V_L \tag{17}$$

$$V_{sc}' = rV_L \tag{18}$$

where the load voltage is the sum of the inverter output voltages

$$V_L = V_b' + V_{sc}' \tag{19}$$

Combining (9)-(19)

$$P_{loss} = \underbrace{\left(\frac{3}{2}\right)^2 \left(\frac{V_L}{V_b}\right)^2 \left[R_b(1-r)^2 + R_{sc}r^2k^2\right]}_{R_{eff}} {i_s}^2 \tag{20}$$

where k represents the voltage ratio between the battery and supercapacitor. This expression shows that the key parameters affecting the ESR loss of the system includes the power-split method, nominal voltage of each energy source, and the degree of hybridization. A global minimum in the effective resistance may be identified from (20), and this corresponds to the optimal degree of hybridization. In practice, the supercapacitor voltage varies (reduced to half of its nominal voltage when energy depletes by 75%). Also, the power distribution between the battery and supercapacitor may change significantly under dynamic driving conditions. In this case, the point of optimal efficiency can shift dynamically as well.

An alternative solution is to compare the effective resistance of the HESS to that of a battery energy storage system (BESS). This provides an approximation to the optimization problem. To find the effective resistance of a BESS, (20) can be used by setting the power ratio to zero

$$R_{BESS} = R_{eff}|_{r=0} = \left(\frac{3}{2}\right)^2 \left(\frac{V_L}{V_b}\right)^2 R_b \tag{21}$$

As for a hybrid energy storage system, rearranging (20) yields

$$R_{HESS} = R_{BESS} \underbrace{\left[(1-r)^2 + \frac{R_{sc}}{R_b} r^2 k^2\right]}_{preferrably<1} \tag{22}$$

This expression suggests that if the second term is less than 1, then the efficiency of the hybrid energy storage system *during supercapacitor power-assist* will be higher than that of a battery-only energy storage system for the same drive range. However, power and energy trade-off must be considered. The energy efficiency of the vehicle in a full drive cycle may not necessarily improve due to the reduction in battery size. Overall, implications of hybridization on drive range remain to be inconclusive [15]. Instead of assessing potential energy savings, this work attempts to optimize efficiency during short-term peak loading in order to minimize the effects of temperature on battery health.

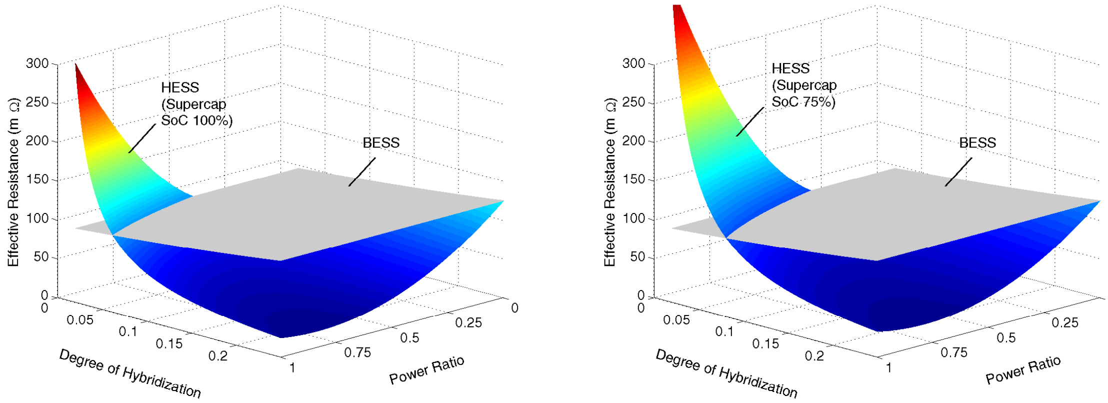
The battery and supercapacitor used in this study are Valence U1-12XP and Maxwell BMOD0083 modules, and their system parameters are listed in Table 2. Figure 2 compares the HESS and BESS using (21) and (22), which gives a spatial visualization of the effective resistance as a function of h, r, and supercapacitor SoC. A list of selected operating points are shown in Table 1. Note that from an efficiency perspective, the hybridized system has poor efficiency at very low degree of hybridization, and decreases further as the supercapacitor discharges. However, the sizing method should also consider loss of drive range as hybridization level increases. Therefore, the recommended degree of hybridization should remain close to the region where the two planes intersect. To narrow the range of valid operating points within this space, the supercapacitor SoC boundary and power-sharing method should be defined as well. Among existing hybridized systems, there are many distinct power-split control strategies, and most of which use predefined drive cycles as the basis for their hybrid energy storage management scheme[13]. Therefore, the next section will leverage common standardized driving schedules to identify the practical range of r and supercapacitor energy usage.

3 Relation to real-world driving patterns

The proposed sizing method can be refined by applying it to real-world driving conditions. To account for the variability in driving behavior, three types of standard drive cycles are examined. The first is the EPA Urban Dynamometer Driving Schedule (UDDS), which is used for light-duty vehicles in North American city driving conditions. Then the European ARTEMIS drive cycle is tested to simulate relatively more aggressive urban drive behavior, especially during regenerative braking. Finally, the global test procedure known as the Worldwide Harmonized Light Vehicle Test Cycle (WLTC) simulates driving schedules in a wide range of speed conditions, up to 135km/h.

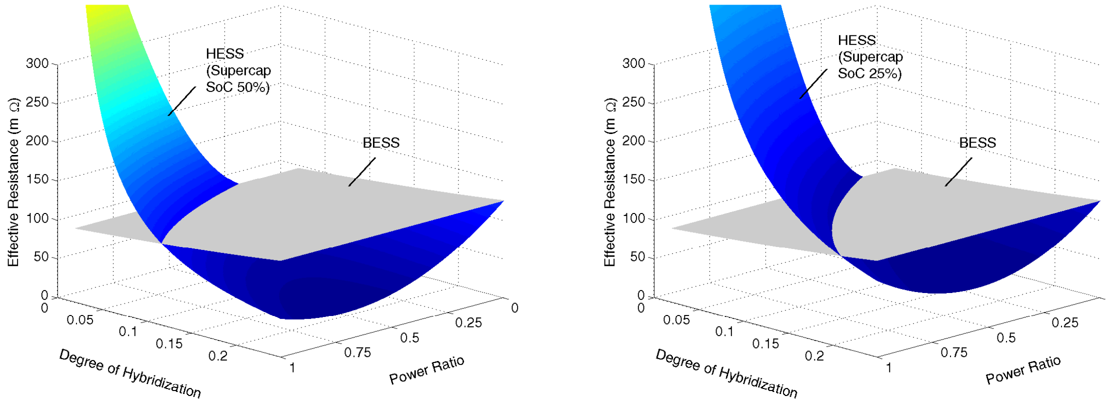
Table 1: Minimum Degree of Hybridization Extrapolated from Fig. 2

r_{max}	Supercap SoC	h_{min}
1	100%	6.2%
	75%	8.1%
	50%	11.7%
	25%	20.9%
0.5	100%	2.2%
	75%	2.9%
	50%	4.2%
	25%	8.1%



(a) Supercapacitor SoC at 100%

(b) Supercapacitor SoC at 75%



(c) Supercapacitor SoC at 50%

(d) Supercapacitor SoC at 25%

Figure 2: Comparing effective resistance of a HESS and BESS. This shows that a hybridized system in any region below R_{BESS} achieves higher efficiency.

3.1 Vehicle dynamics

The energy storage system should supply sufficient power to account for the mechanical loss of the vehicle and electrical loss of the motor drive. This study considers losses due to air drag and rolling resistance[7], which are expressed as

$$F_d = \frac{1}{2}\rho C_d A_f {v_{car}}^2 \tag{23}$$

$$F_r = C_r M_{car} g \tag{24}$$

Here, ρ is the air density, C_d is the coefficient of air drag, C_r is the coefficient of rolling resistance, A_f is the frontal area, and M_{car} is the mass of the vehicle. From [21], a typical 500-2000kg passenger car has a frontal area expressed by

$$A_f = 1.6 + 0.00056(M_{car} - 765) \tag{25}$$

The power supplied by the energy storage system, including the efficiency of the motor (η_{motor}), is

$$P_{HESS} = \frac{1}{\eta_{motor}} v_{car}\left(M_{car}\frac{dv_{car}}{dt} + F_d + F_r\right) \tag{26}$$

where the total power is split between the battery and supercapacitor

$$P_{HESS} = P_b + P_{sc} \tag{27}$$

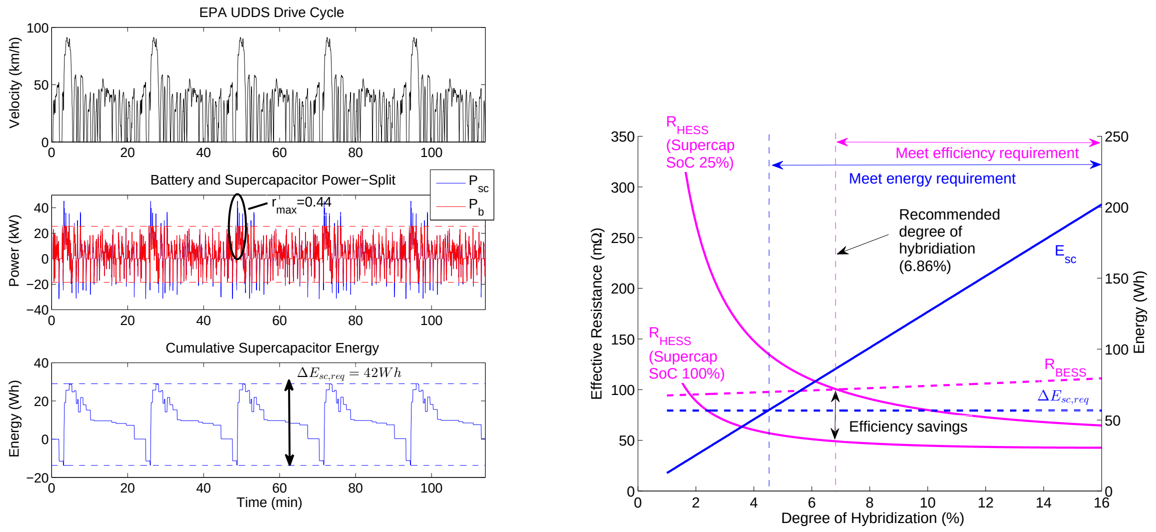
A list of parameters describing vehicle dynamics is summarized in Table 2.

Table 2: System Parameters

HESS[16],[17]	Voltage	Capacity	ESR	Mass		
Valence U1-12XP	12V	40Ah	$15m\Omega$	6.5kg		
Maxwell BMOD0083	48V	26Wh	$10m\Omega$	10.3kg		
Vehicle parameters	Mass	Inverter voltage[18]	η_{motor}[19]	C_d[20]	C_r[20]	A_f[21]
	2000kg	350V	93%	0.32	0.015	$2.3m^2$
Drive cycle	v_{max}	P_{max}	P_{min}	ΔE_{sc}	r_{max}	h
EPA UDDS	91km/h	43.2kW	-33kW	42Wh	44%	6.86%
ARTEMIS	58km/h	36.2kW	-62.8kW	39Wh	70%	12.5%
WLTC	135km/h	43.6kW	-39.4kW	95Wh	50%	10%

3.2 Power-Split Method

To extrapolate the range of power ratios and supercapacitor energy consumption from drive cycle data, a power-sharing method must be defined. From the list of existing control methods for the battery-supercapacitor HEV, a rule-based power-split algorithm is selected due to its robustness[13]. A c-rate limit is set for the battery (usually defined by the manufacturer), and the supercapacitor supplies the remaining peak load. In this case study, the recommended charging c-rate of the Valence battery modules is 0.5C. Since there is a wide range of discharging c-rates, this analysis defines a maximum c-rate that results in no net change in supercapacitor energy from start-to-end of the drive cycle. The maximum discharge c-rate of the battery in the UDDS, ARTEMIS, and WLTC were found to be 0.7C, 0.5C, 1.1C, respectively. This is to ensure optimal utilization of the supercapacitor for long-term driving schedules.

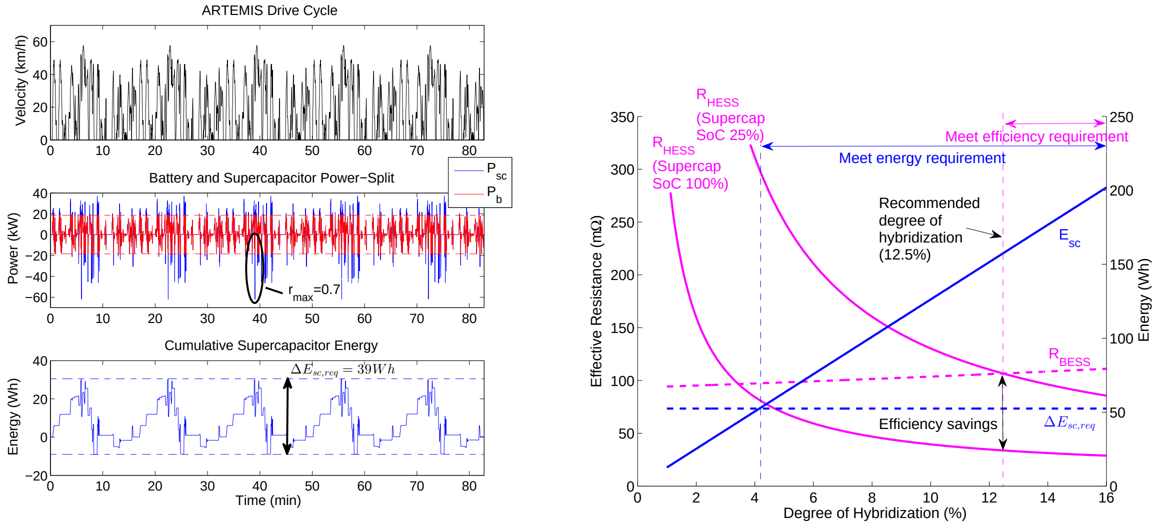


(a) (b)

Figure 3: Analysis of the EPA UDDS drive cycle. This shows that the supercapacitor in some instances must supply up to 44% of the total power, and 42Wh in a full discharge. The ideal degree of hybridization is 6.86%.

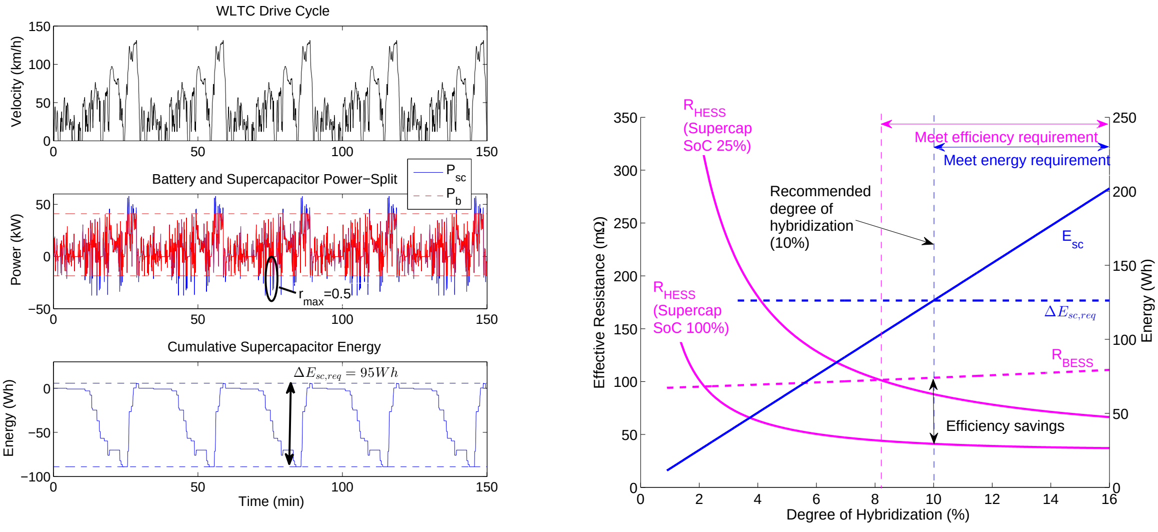
3.3 Results and discussion

Figure 3(a) shows the EPA UDDS driving schedule cycled 5 times over 120 minutes. The battery supplies the maximum charging and discharge rate specified in the previous section. From this driving pattern, the supercapacitor provides up tp 44% of the total output power, and requires at least 42Wh of usable energy. Based on these requirements, the effective resistance of the HESS at $r = 0.44$, and the supercapacitor energy with respect to the degree of hybridization are plotted in Fig. 3(b). The supercapacitor energy (with 25% overhead) shows that the system needs at least 4.5% supercapacitor in order to supply the required energy for this drive cycle. However, in the worst case scenario where the supercapacitor



(a) (b)

Figure 4: Analysis of the ARTEMIS drive cycle. This shows that the supercapacitor in some instances must supply up to 70% of the total power, and 39Wh in a full discharge. The ideal degree of hybridization is 12.5%.



(a) (b)

Figure 5: Analysis of the WLTC drive cycle. This shows that the supercapacitor in some instances must supply up to 50% of the total power, and 42Wh in a full discharge. The ideal degree of hybridization is 10%.

is near depletion, the hybridized system must have at least 6.86% supercapacitor in order to achieve higher efficiency than the BESS. Therefore, considering both energy and efficiency requirements, the recommended degree of hybridization for the EPA UDDS drive cycle is 6.86%. Using this proposed sizing method, the ARTEMIS drive cycle (Fig. 4) requires at least 4.16% hybridization to meet energy usage, but 12.5% hybridization to meet efficiency requirements. Thus, similar to the EPA drive cycle, efficiency analysis sets the recommended h value to 12.5%. Figure 5 shows the WLTC drive cycle covering a wide range of vehicle speeds. As a result, this leads to an increase in supercapacitor energy usage, which sets the recommended degree of hybridization to 10%.

A general conclusion from applying the proposed sizing method to real-world drive cycles is that based on commonly adopted power-split methods, the acceptable degree of hybridization ranges from 7-13%. This is equivalent to the percentage of the total range loss in a hybridized system. However, utilizing a high-power density secondary energy source can improve the lifespan of the battery, and provide an optimally sized energy storage system to minimize range loss.

4 Conclusion

This work develops a novel energy storage sizing method for hybrid electric vehicles. The concept is to quantify the power loss in the energy storage system by evaluating the effective resistance in the battery and supercapacitor. An efficiency model is proposed, and considers key factors such as state-of-charge and power-sharing method in the efficiency analysis. By applying the proposed method to common drive cycles, the recommended size of the supercapacitor is 7-13% of the total mass of the HESS.

Acknowledgments

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References

[1] R. Schmidt, "Information technology energy usage and our planet," in *11th Intersociety Conf. on Thermal and Thermomechanical Phenomena in Electronic Systems*, vol., no., pp.1255-1275, 28-31 May 2008.

[2] Clark G. Hochgraf, John K. Basco, Theodore P. Bohn, Ira Bloom, "Effect of ultracapacitor-modified PHEV protocol on performance degradation in lithium-ion cells," *Journal of Power Sources*, Volume 246, 15 January 2014, Pages 965-969.

[3] L. Shao et al., "Ultracapacitor/battery hybrid energy storage system with real-time power-mix control validated experimentally in a custom electric vehicle," *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Charlotte, NC, 2015, pp. 1331-1336.

[4] P. Weissler. (2013, February 20). *Mazda introduces supercapcitor-type regenerative braking*. Automotive Engineering Magazine.[Online]. Available: http://articles.sae.org/11845/.

[5] *Innovative technologies for light rail and tram: a European reference resource*, Sintropher, London, UK, 2015.

[6] *ZeEUS eBus Report: An overview of electric buses in Europe*, ZeEUS, Belgium, 2016.

[7] R. Sadoun, N. Rizoug, P. Bartholomes, B. Barbedette and P. Le Moigne, "Influence of the drive cycles on the sizing of hybrid storage system battery-supercapacitor supplying an electric vehicle," *IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society*, Melbourne, VIC, 2011, pp. 4106-4112.

[8] Masoud Masih-Tehrani, Mohammad-Reza Ha'iri-Yazdi, Vahid Esfahanian, Ali Safaei, "Optimum sizing and optimum energy management of a hybrid energy storage system for lithium battery life improvement," *Journal of Power Sources*, Volume 244, 15 December 2013, Pages 2-10.

[9] Yi-Hsuan Hung, Chien-Hsun Wu, "An integrated optimization approach for a hybrid energy system in electric vehicles," *Applied Energy*, Volume 98, October 2012, Pages 479-490.

[10] E. Ozatay, B. Zile, J. Anstrom and S. Brennan, "Power distribution control coordinating ultracapacitors and batteries for electric vehicles," *Proceedings of the 2004 American Control Conference*, Boston, MA, USA, 2004, pp. 4716-4721 vol.5.

[11] Gang Ning, Bala Haran, Branko N. Popov, "Capacity fade study of lithium-ion batteries cycled at high discharge rates," *Journal of Power Sources*, Volume 117, Issues 12, 15 May 2003, Pages 160-169.

[12] S. Lu, K. A. Corzine and M. Ferdowsi, "A Unique Ultracapacitor Direct Integration Scheme in Multilevel Motor Drives for Large Vehicle Propulsion," in *IEEE Transactions on Vehicular Technology*, vol. 56, no. 4, pp. 1506-1515, July 2007.

[13] Siang Fui Tie, Chee Wei Tan, "A review of energy sources and energy management system in electric vehicles," *Renewable and Sustainable Energy Reviews*, Volume 20, April 2013, Pages 82-102.

[14] C. Jung, "Power Up with 800-V Systems: The benefits of upgrading voltage power for battery-electric passenger vehicles," in *IEEE Electrification Magazine*, vol. 5, no. 1, pp. 53-58, March 2017.

[15] R. Carter, A. Cruden and P. J. Hall, "Optimizing for Efficiency or Battery Life in a Battery/Supercapacitor Electric Vehicle," in *IEEE Transactions on Vehicular Technology*, vol. 61, no. 4, pp. 1526-1533, May 2012.

[16] Valence, "Valence Module Range," UEV-18XP datasheet, Sept. 2015.

[17] Maxwell, "48V Modules," BMOD0083 P048 B01 datasheet, 2013.

[18] M. H. Westbrook, "Vehicle design and safety," in *The Electric Car: Development and future of battery, hybrid and fuel-cell cars*, Warrendale, PA, and London, UK: SAE Inc., and IEE, 2005, ch. 8, sec. 3, pp. 124.

[19] *Improving Motor and Drive System Performance: A Sourcebook for Industry*, Washington State University Energy Program and the National Renewable Energy Laboratory, pp. 33.

[20] T. D. Gillespie, "Road Loads," in *Fundamentals of Vehicle Dynamics*, Salem, MA: SAE Inc., 1992, ch. 4, pp. 98-117.

[21] J. Y. Wong, "Aerodynamic Forces and Moments," in *Theory of Ground Vehicles*, 3rd ed. Danvers, MA: JW.A, 2001, ch. 3, sec. 2, pp. 211.

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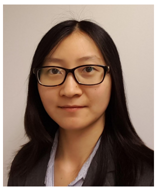

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