Case Study of Dual ESS for a Full-electric Bus Combining a Li-Ion Battery with an Environmentally-friendly DLCAP™

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Abstract

Green Houses Gas (GHG) emission reduction and fossil fuel economy are becoming important global issues. In Chinese cities, new commercial vehicles using diesel engines are not allow--new buses must be zero-emission electric vehicles (E-bus). A fully-loaded E-bus with a mass of 15 to 19 tons requires batteries offering both high energy for long driving range and high-power for acceptable vehicle acceleration. Advantages may be gained by using a dual energy storage system, part comprised of batteries with high energy to provide long range and part comprised of electrochemical capacitors with high power to provide acceleration and efficient regenerative energy capture. This paper examines performance advantages possible with such dual energy storage systems in pure electric E-bus vehicles. Two different control strategies were investigated. Results show that a 44% range increase is possible over an all-battery system.

Keywords: GHG, Li-Ion Battery, E-Bus, E-Vehicle, ECAP, EDLC, Dual ESS, Energy Storage

1 Introduction

Batteries are energy storage devices and electrochemical capacitors (ECAPs) are power delivery devices. The intent of this study was to optimally use each technology by combining them into a dual energy storage system (ESS). Today's battery technology has been dramatically improved to store higher energy and deliver more power, but a major disadvantage remains—low efficiency during short-duration charging, which is important for regenerative energy capture during a vehicle stopping event. In this study the battery is used primarily during constant-speed "cruising" while the ECAP is used primarily for acceleration and for energy capture during deceleration. Two different cases are examined in this study. For the first dual ESS case, acceleration power is provided solely by the ECAP until it reaches its minimum voltage, then the battery is used. For the second case, acceleration power is provided by the battery up to a specified level, then ECAP power is used to achieve higher power levels. ECAP minimum voltage is limited by the maximum current of a DC/DC converter between the battery and the ECAP. This paper discusses power management of the dual ESS, ECAP design parameters, and predicted performance of a system after eight years of operation at temperatures characteristic of Beijing, China.

2 Basic System diagram

Figure-2 shows a block diagram of a dual ESS powering an electric bus (E-bus). Included are an ECAP, a battery, and a bi-directional DC/DC converter (CON). This architecture has been previous discussed.[(1,2)]

Key points:

- The battery is used mainly for constant speed operation (cruising). The ECAP is used to provide acceleration power and to capture regenerative energy during deceleration.

- ❖ Power management is performed by the DC/DC CON System. Its specifications are listed in Table-1.
- ❖ The ECAP is modelled for DLCAP™ cells that are manufactured by Nippon Chemi-Con, which use a safe PC-based electrolyte that is most suitable for public transportation vehicles.
- ❖ The battery module contains Li-ion batteries with the parameters listed in Table-2.

Table-1 Bi-directional DC/DC Converter. Basic specification

Input voltage range	Power	Function
300 V to 900 V	150 kW	CAN Communication system Power management Diagnostic for failure mode System protection

Table-2 Li-Battery module parameters

Rated voltage	650 V
Capacity	240 Ah

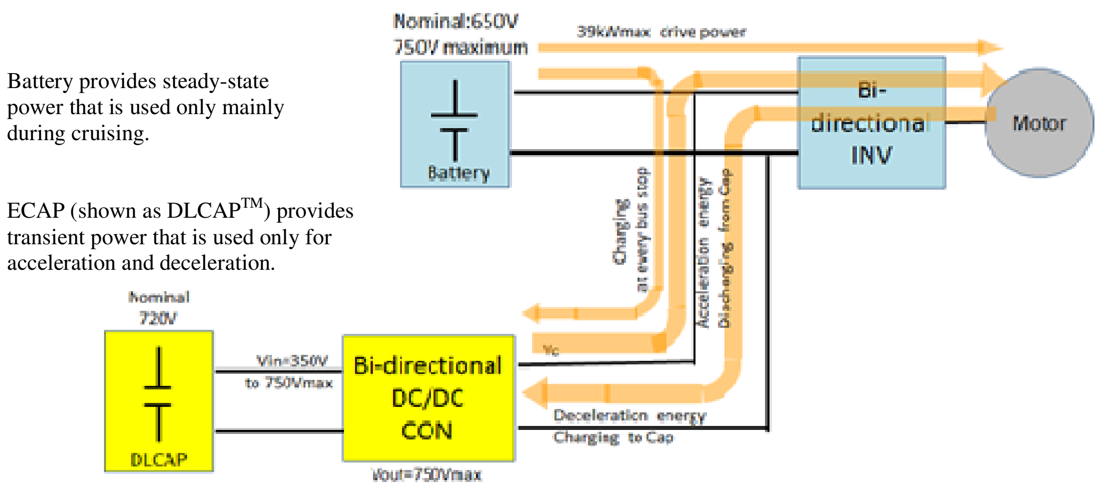


Figure-2. Block diagram of the dual ESS used to power the E-bus. Battery power is limited to 39 kW.

The two ESS cases examined in this study include:

Case-1: Acceleration power is provided by the ECAP until its voltage reaches 350 V. Additional power is only then provided by the battery.

Case-2: Acceleration power is always provided by the battery until it reaches the 39 kW level. Power above this level is provided by the ECAP.

Figure-1 shows the energy capture efficiency of a lithium-ion battery and an ECAP.[3] For vehicle deceleration times (charging times) of 20 s, ECAP regenerative energy capture efficiency is above 95% while that of the battery is less than 60%. The 40% difference represents heat in the battery--its life may be reduced without a thermal manage-ment system to limit the temperature rise.

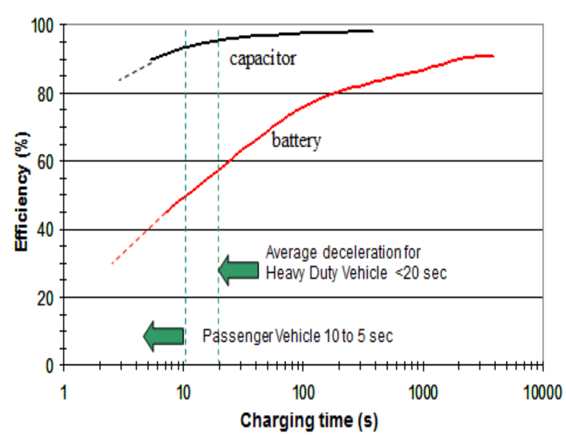


Figure-1 Energy capture efficiency of a Li-ion battery compared with an ECAP[3].

3. Initial design parameters for ECAP (shown as DLCAP™)

Key points:

- ❖ The nominal system voltage is 720 V.
- ❖ Selected ECAP cells are 2400 F, 2.5 V rated DLCAP™ having an ESR of 0.8 mΩ. A module will have 300 cells in series, giving a capacitance value of 8 F and an ESR of 0.24 Ω.
- ❖ Operating voltage window is 750 V to 350 V.
- ❖ DC/DC CON maximum current Imax is 250 A.
- ❖ Bi-directional DC/DC CON system will control charge/discharge of the ESS DLCAP™ module.
- ❖ The E-bus is a class 8 heavy duty vehicle with a fully loaded weight of 18,000 kg.

The energy that can be captured by the ECAP module during E-bus deceleration is calculated using the maximum and minimum voltage limits: $E=C\bullet[\ Vmax^2 - Vmin^2\ ]/2$. While 350 V is the minimum allowed by the DC/DC CON, the effective voltage window for the ECAP module is less because of the IR jump in the ECAP voltage at the start of energy capture due to its series resistance. For Imax=250 A at Vmin=350V, the IR jump is V = 250 A x 0.8 mΩ = 75V and Vmin = 350 V + 75 V = 425 V. Thus the maximum energy that can be recaptured is $E = C\bullet[\ Vmax^2 - Vmin^2\ ]/2 = 4\bullet[\ 720^2 - 425^2] = 1.35$ MJ.

Using 1.1 MJ, to allow for design margin, there is sufficient energy to accelerate the fully-loaded bus to 40 km/h, as shown in Figure-3, with all acceleration energy coming from the ECAP.

Peak power for acceleration, calculated using the 250 A maximum current at 350 V, is 88 kW (250 A x 350 V). This peak power level will accelerate the bus to 40 km/h in 27 seconds, as shown in Figure-4.

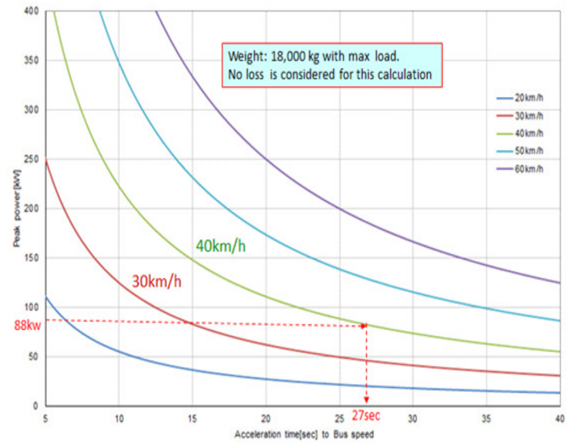


Figure-4. Calculated times to reach different bus speeds versus acceleration peak power levels.

Figure-4 shows the final velocity of the fully loaded bus as a function of acceleration time and peak power. Thus the bus can reach 40 km/h in 15 seconds with a peak power of 150 kW. The case study in this paper uses 40 km/h at 27 seconds and a peak power of 88 kW as a baseline. Figure-5 shows the voltage discharge profile and peak current for a DLCAP™ module designed to deliver the required peak power to accelerate the E-bus to 40 km/h in 27 seconds.

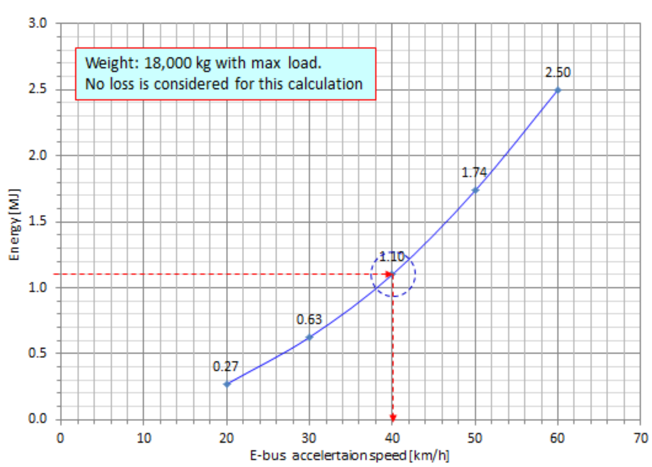


Figure-3. Fully loaded E-bus velocity versus its kinetic energy.

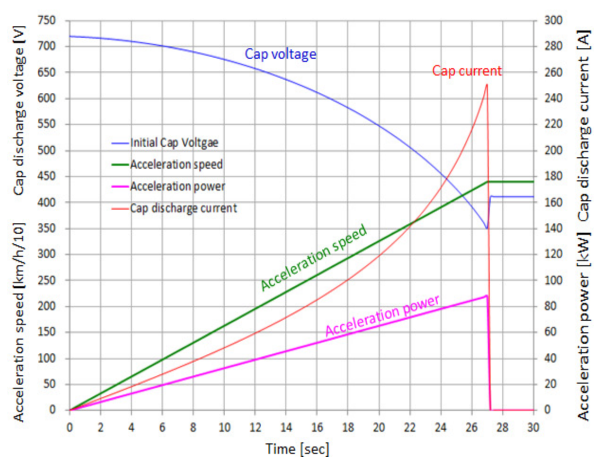
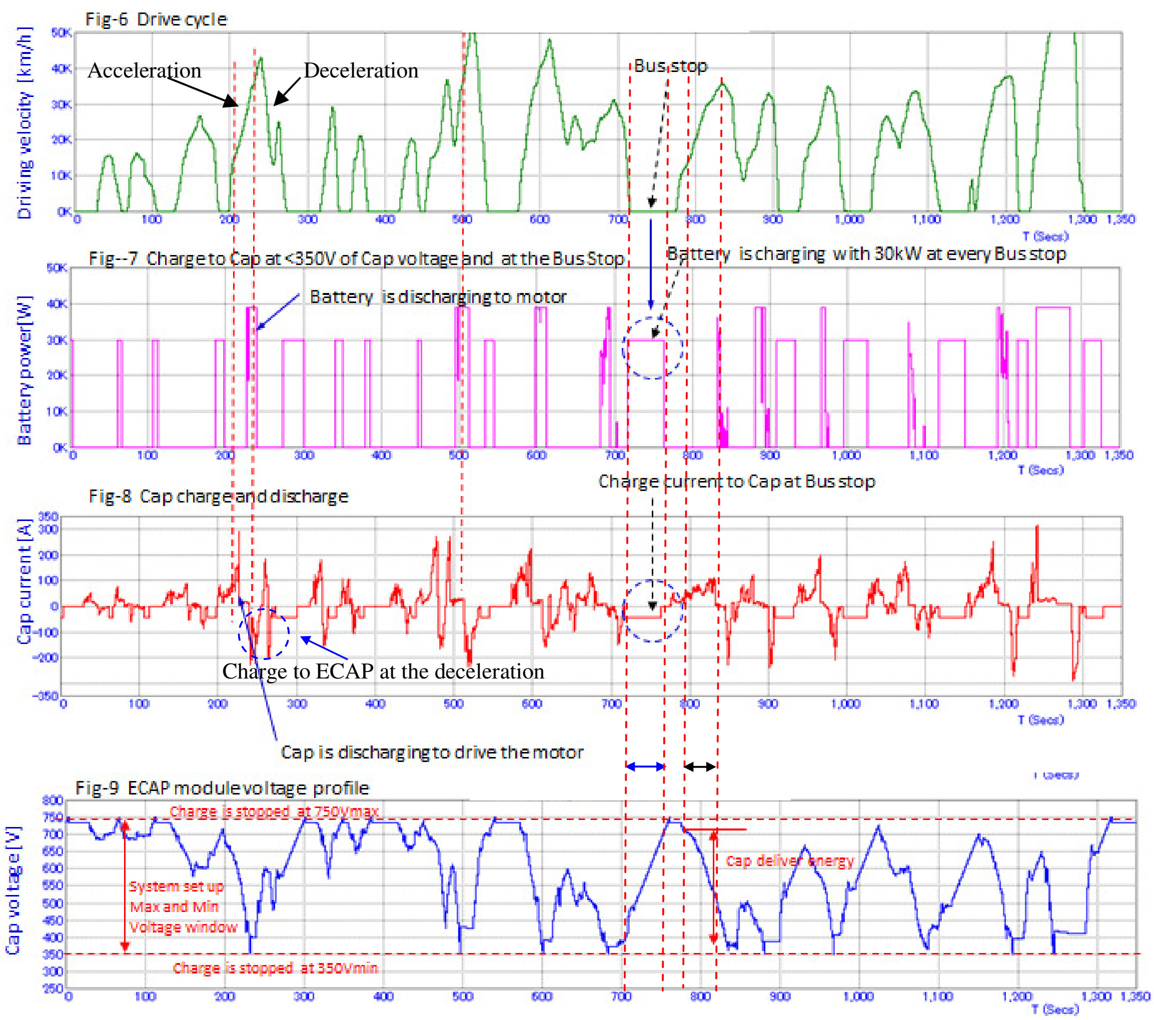


Figure-5. DLCAP™ module discharge profile for acceleration power.

4. Analysis of Power sharing between Battery and ECAP.

Figure-6 shows the hypothetical E-bus drive cycle. Acceleration power, for Case-1, is always provided by the ECAP. Figure-8 is the companion ECAP module current profile and Figure-9 is the companion ECAP module voltage profile. Note the ECAP module discharge during acceleration switches to battery power when its voltage reaches 350 V. The maximum input current of the DC/DC CON input is limited to 250 A in this case. Figure-7 shows battery power to the drive motor and to the ECAP to charge it during deceleration and at bus stops. Battery power is limited to 39 kW to drive the motor. Battery power to the ECAP at a bus stop is set to a value of 30 kW.

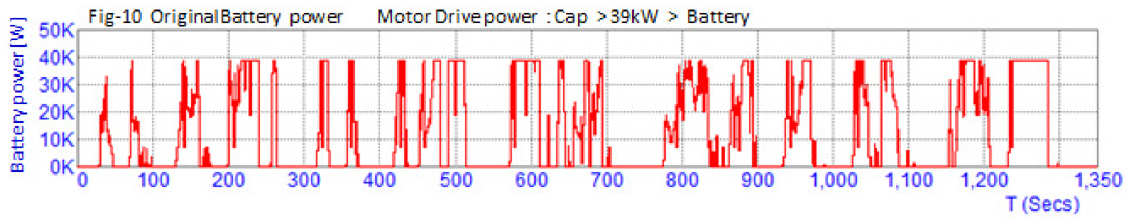


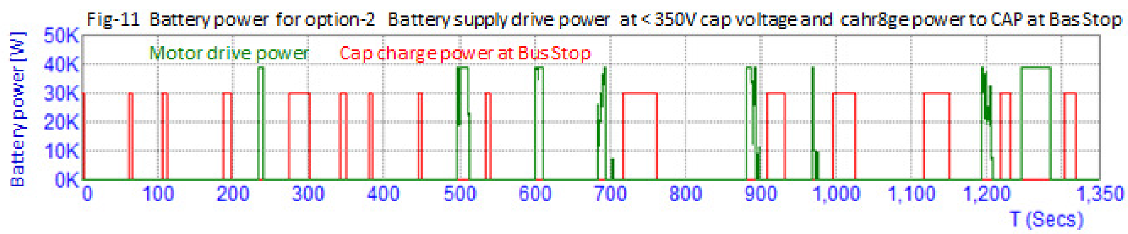
The ECAP module is assumed to be fully charged (720 V) at the start of a drive cycle. Acceleration is from the ECAP or battery. As described in Case-1, the discharge mode will be from the ECAP module, ending the discharge at 350 V, then switched to the battery. The battery will discharge up to 36 kW maximum. Once the bus has been accelerated to 40 km/h, much less power is needed to maintain it at this same speed (cruising).

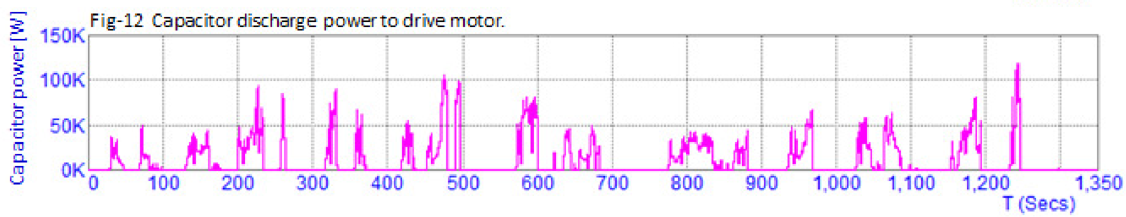
The kinetic energy of the 18-ton E-bus at a speed of 40 km/h is $M \bullet Vo^2/2 = 1.1$ MJ. The energy required from the battery to maintain the cruising speed at 40 km/h depends upon energy losses due to tire friction, drive train inefficiencies, wind resistance, and so on. This energy is supplied by the battery.

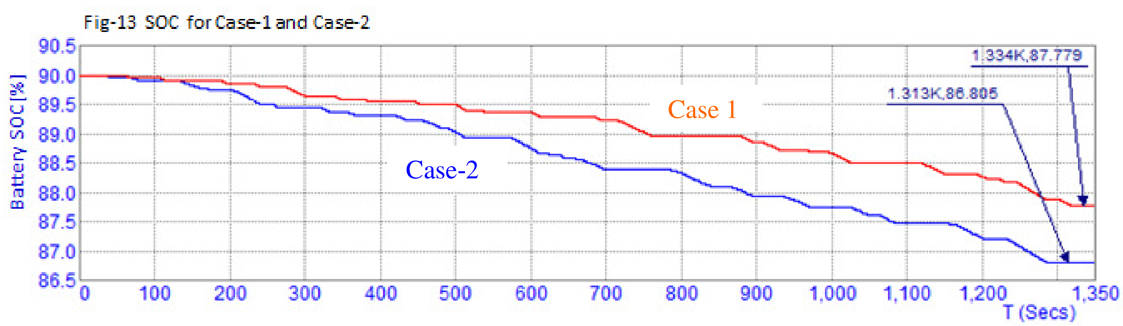
5. Analysis of Battery power and the SOC during one driving cycle.

For the same Figure-6 drive cycle, Case-2 acceleration power is completely provided initially by the battery. When its power reaches 39 kW, acceleration power is switched to the ECAP. Figure-10 shows the battery discharge power for Case-2. Figure-11 shows battery and capacitor power for Case-1, where the ECAP module supplies acceleration power until its voltage reaches 350 V, at which time power switches to the battery. Figure-12 shows ECAP discharge current to drive the motor in Case-1. Figure-13 compares the state of charge (SOC) of the battery for Case-1 with Case-2 over one cycle. A 2.2% SOC change is found for Case-1 and a 3.2% SOC change is found for Case-2.









Key points of this analysis are:

- ❖ Battery capacity: Usage 90% to 20% [70% of the SOC window]
- ❖ One cycle battery energy = 6.52 MJ (5 kW constant for sub power) T=1,304 sec.
- ❖ Battery capacity : 650 V, 240 Ah battery at 90% SOC stores 505 MJ.
- ❖ Driving distance for one cycle: 5834 m=5.8 km

Using the battery SOC change during one cycle, we can determine the driving range of the E-bus:

For Case-1: 90% - 87.779% = 2.221%
70% / 2.221% = 31.5 cycles.
Driving range = 5.8 km • 31.5 = 183 km

For Case-2: 90% - 86.805% = 3.159%
70% / 3.159% = 21.9 cycles.
Driving range =5.8 km • 21.9 = 127 km.

Thus, Case-1 shows a 44% increase in the driving range over Case-2. Although the calculations do not consider utility energy (non-motive) during driving, the resulting drive distance improvement ratio should be the same to first order.

6. Life Analysis

Table-3 Monthly average temperature at Beijing city

Month	1	2	3	4	5	6	7	8	9	10	11	12
Temperature(°C)	-4.6	-2.2	4.5	13.1	19.8	24.0	25.8	24.4	19.4	12.4	4.1	-2.7

Running distance per day: 120km Running days per year: 300 days Life expectancy: 8 years

Table 3 lists by month Beijing, China's average temperature. This data allows ECAP performance change to be estimated over its life. For example, after eight years of operation, approximately 10 kW less acceleration power and 10% lower speed will be available than initially provided due to capacitor degradation. The SOC does not have significant impact, owing to there being less charging power to the ECAP module from the battery and more drive power from the battery due to the lower capacitance value. Figure-14 shows the predicted ECAP capacitance decrease over time at the Table-3 temperatures. After eight years of operation at the Table-3 temperatures, capacitance loss is predicted to be ~28%. Figure-15 shows the impact of capacitance loss on acceleration performance (initially then again and after 8 years of operation).

Fig-14 Capacitance life degradation curve

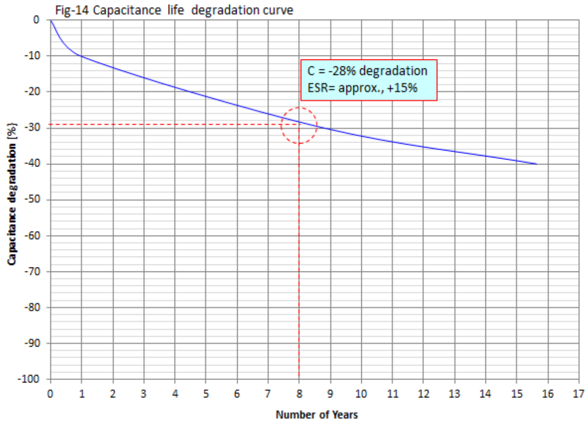


Fig-15 8th years profile simulation

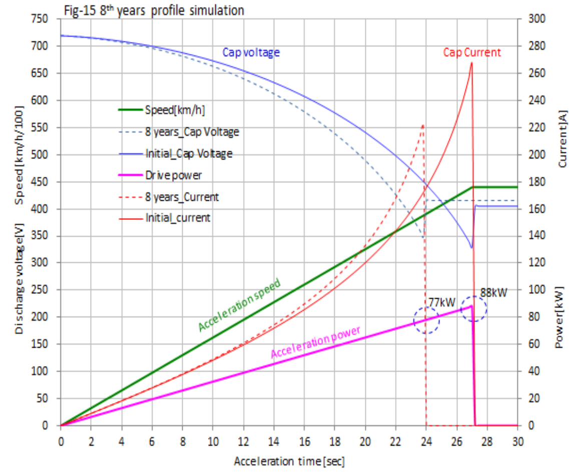


Figure-16 shows initial battery power for driving the motor and charging the ECAP at every bus stop for the designated drive cycle. Figure-17 shows battery power for year eight. The SOC in Figure-18 does not show significant change compared to the initial SOC, shown in Figure-13.

Fig-16 Initial Battery power

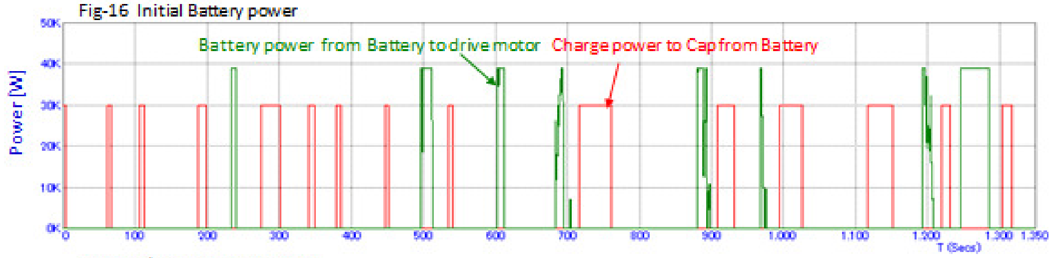


Fig-17 8th year Battery power

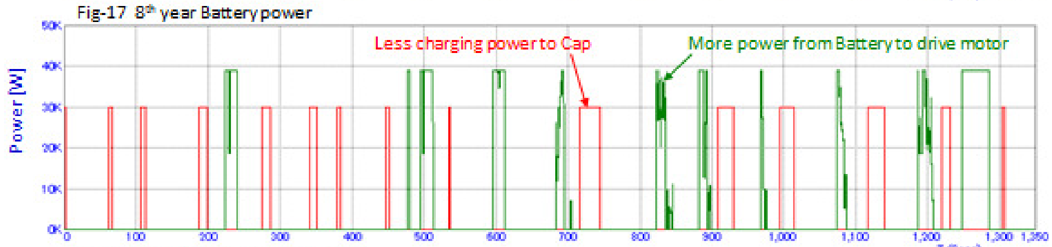
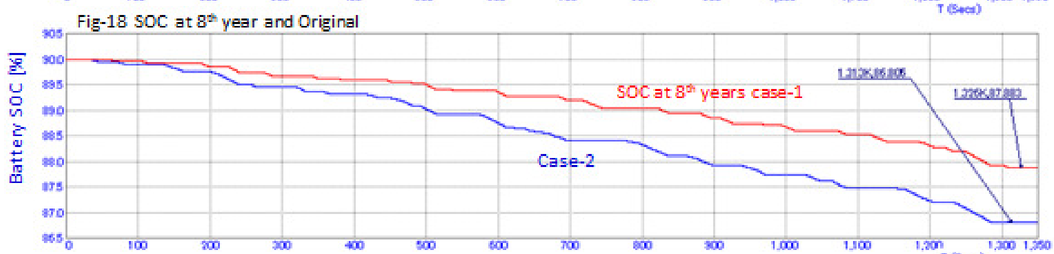


Fig-18 SOC at 8th year and Original



7. Summary

This study demonstrated that a dual ESS offers advantages. Case-1, where the ECAP is used solely to accelerate the vehicle until the lower voltage limit is reached, offered the greatest advantage, increasing drive distance by ~44%.

These results are based on performance and life simulations. Validation will require development and testing of an actual system.

Economic issues, which were not addressed in this study, are important and should be included in further investigations.

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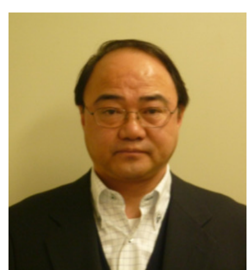

Kazuhiro Sakuma, has headed business development of the DLCAP™ product line since 2004 for Nippon Chemi-Con Group. His current focus relates to expanding the DLCAP™ business in China.