Automobile Efficiency Improvements using Electrochemical Capacitor Energy Storage

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Abstract

MAZDA Motor Corporation has developed an advanced energy recovery system to boost the efficiency in its passenger vehicles. A key feature of this i-ELOOP™ energy recovery system is its use of electrochemical capacitors (EECAP/DLCAP™) that were developed by Nippon Chemi-Con especially for advanced automotive applications. Using this system, fuel consumption typically is reduced 10%. Energy storage technologies other than capacitors were considered for the i-ELOOP™, including lithium-ion batteries, but rejected primarily because they could not provide fast, efficient, and safe charging. This paper describes the storage system architecture then discusses the special capacitors used in this advanced storage system to implement into a conventional passenger vehicle without major design change and the cost impact.

Keywords:Energy Recovery,i-ELOOP™, Electrochemical capacitor (EECAP/DLCAP ™),Energy storage technology, EDLC

1. Introduction

Improving the efficiency of energy use can save money as well as reduce carbon dioxide emissions, as shown in Figure 1. Internal-combustion-engine automobiles are major contributors to fossil fuel consumption and carbon dioxide generation and efforts to improve their energy efficiency include development of gas-electric hybrid vehicles.

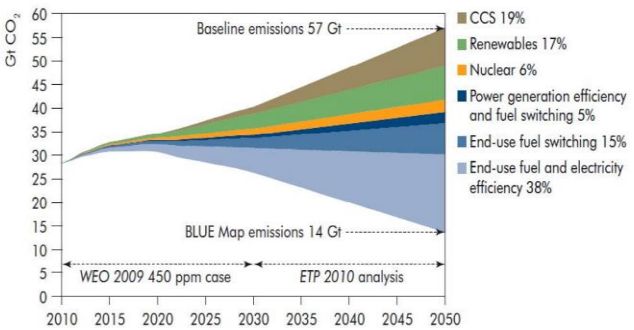

Fig-1. CO2 emissions by technology for Blue Map scenario. Source: Energy Technology Perspectives 2010 Cork, 15 November 2010

The improved energy efficiency of these hybrid vehicles depends on vehicle design and the addition of energy storage to recapture kinetic energy during vehicle deceleration events. Later this stored energy is used for vehicle drive or to provide utility power (vehicle electrical load). Key features of the regenerative energy capture storage system are that it must be safe, have high cycle life and long calendar life, and operationally be highly efficient so as to allow recovery and use of a significant fraction of the energy that normally would be wasted.

2. Vehicle Drive Cycle and Power Profile

The quantity of energy available to capture during vehicle deceleration depends on vehicle characteristics like mass and drive cycle. Various standard drive cycles have been proposed and our analysis uses Japan Drive cycle_JC08, which is shown in Figure 2.[1] During one 20 minute cycle the vehicle goes a distance of approximately 30 km with speeds ranging from ~25 to ~80 km/hr. Driving one of these cycles every day in a year results in total distance travelled of 10,000 km/year.

Power requirements for the drive cycle depend on vehicle mass. This is shown in Figure 2 for the JC08 cycle [1] assuming a gross vehicle mass of 1.53 tons, which includes the mass of the driver and one passenger. Note the positive power peaks are associated with vehicle acceleration and the negative power peaks are associated with vehicle stopping. The duration of these negative features, each of which represents a charging event, are less than 25 seconds in all cases and are sometimes as short as only a few seconds. The time integral of the negative features in Figure 3 represents the theoretical maximum energy available for recapture, which is 610 Wh for one cycle. This amount of energy, however, is never actually available for captured because of power limitations of the alternator and mechanical losses such as rolling friction, direction change, and aerodynamic drag. In a conventional passenger vehicle, typically no more than ~25% of this 610 Wh amount is available for capture, i.e. only 150 Wh, which is about equal to 1 hr of vehicle utility power in a typical small automobile. Inefficiencies of the energy storage system used to recapture this energy will reduce the energy even more. Thus, efficiency of a storage system added to a vehicle is important and it determines the amount of fuel consumption reduction.

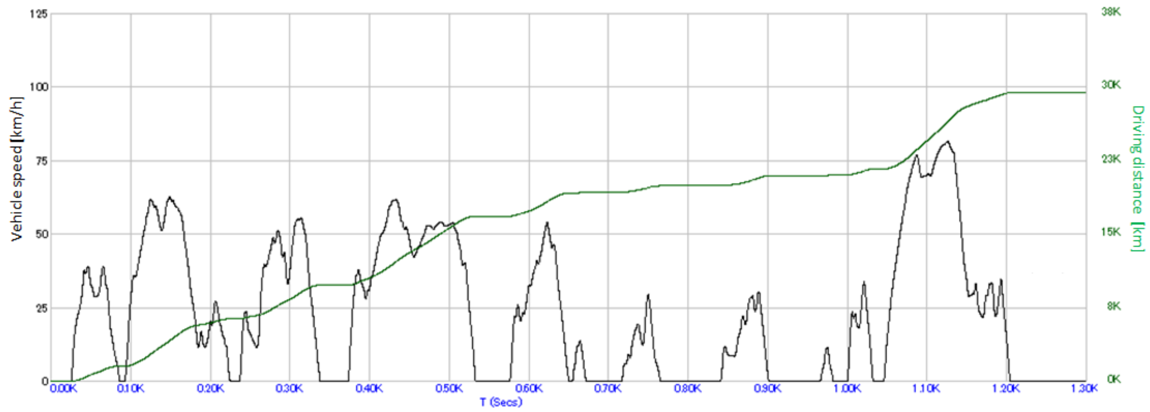

Figure 2: Japanese Drive cycle JC08 showing driving speed and distance travelled versus time. Each cycle lasts 20 minutes and covers approximately 30 km of distance.

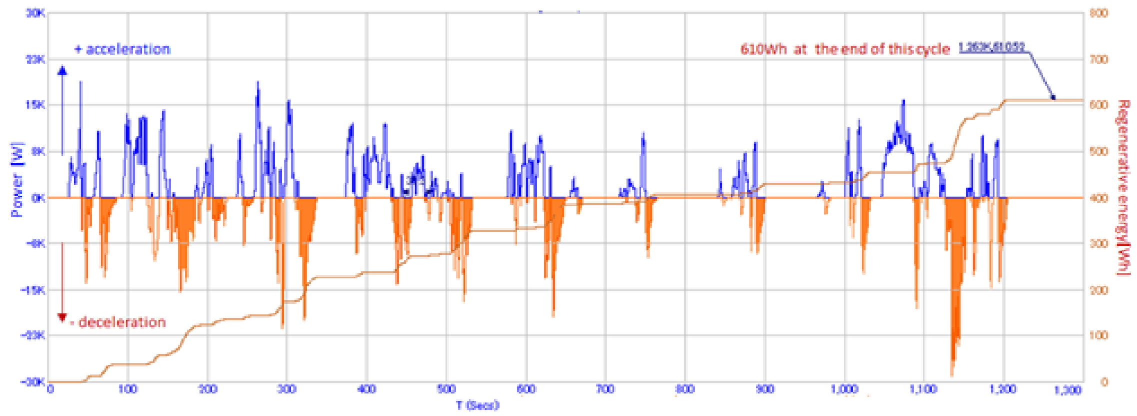

Figure3: Power profile for a 1.53 metric ton vehicle following the Japanese JC08 Drive cycle. Theoretical maximum recapture energy is 610 Wh. Only approximately 25% of this amount (150 Wh) is actually available to be recycled.

3. Energy Storage Technology

Two technologies are commonly used for reversible energy storage in vehicle systems--batteries and capacitors. Batteries have much higher energy density and thus offer the significant advantage of longer driving range when used in all-electric vehicles. Capacitors, on the other hand, have much higher power performance, higher efficiency, and operate for millions of full depth-of-discharge cycles. [2] Figure 4 compares room temperature charging efficiency of a high-rate lithium ion battery with a that of a symmetric electrochemical capacitor. [3] Here each storage device is charged at a constant-current value from minimum to maximum voltage and the charge time and efficiency are reported. Charging is used because this is the process that occurs during vehicle deceleration when waste energy is being captured and stored. Referring to Figure 4,

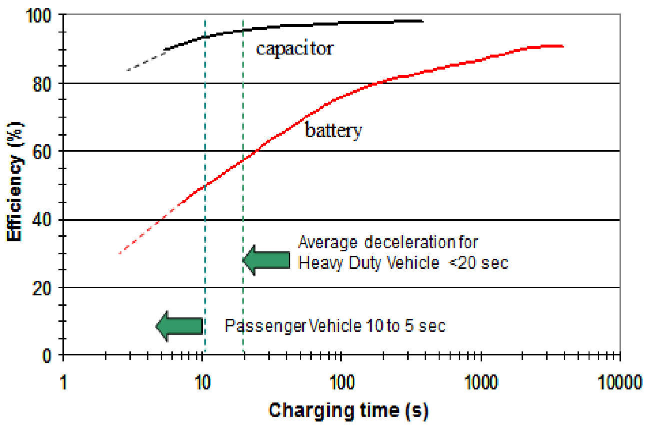

Figure4: Energy efficiency comparison during charging of an electrochemical capacitor to a high-rate lithium ion battery (initially at 10% SOC)

capacitor charging efficiency is greater than 95% during a 25-second-charge, the duration of the longest charging feature in the Figure 3 power profile. In comparison, battery efficiency for this same charge time is only 60%. The difference increases at shorter charge times. Another comparison reported a three-fold difference in energy storage efficiency between a lithium ion battery and a capacitor during a 6 second charge. [1]

Because a smaller amount of the available energy is captured by the battery, more energy is dissipated as heat, which must be removed to prevent an unacceptable temperature rise that may create safety issues. Management of such large heat loads adds complexity to the storage system as well as mass and cost.

A common approach for improving charging efficiency and life of a battery system is to oversize it, which also increases the size and cost of the storage system. A capacitor system need not be oversized and can use a simpler heat management system.

4. i-ELOOP^{TM} Energy Recovery System

Figure 5 shows the configuration of the i-ELOOP^{TM} system developed by MAZDA.[4][5] The i-ELOOP^{TM} system captures, stores, and then uses energy that normally is wasted. In addition, it minimizes or eliminates engine idling while the vehicle is stopped. When the vehicle is stopped, energy stored in the i-ELOOP^{TM} system is used to provide power for the air conditioner, headlights, radio, etc. The heart of the system is the DLCAP^{TM} module, comprised of 10 series-connected DXE1200F electrochemical capacitor cells that were developed by Nippon Chemi-Con especially for this application. Each 2.5 V cell is rated at 1200 F and has an ESR value that is less than 0.8 mΩ. The low ESR is key to the high power capability and efficiency of the PC-electrolyte electrochemical capacitors (DLCAP ^{TM}) specification.

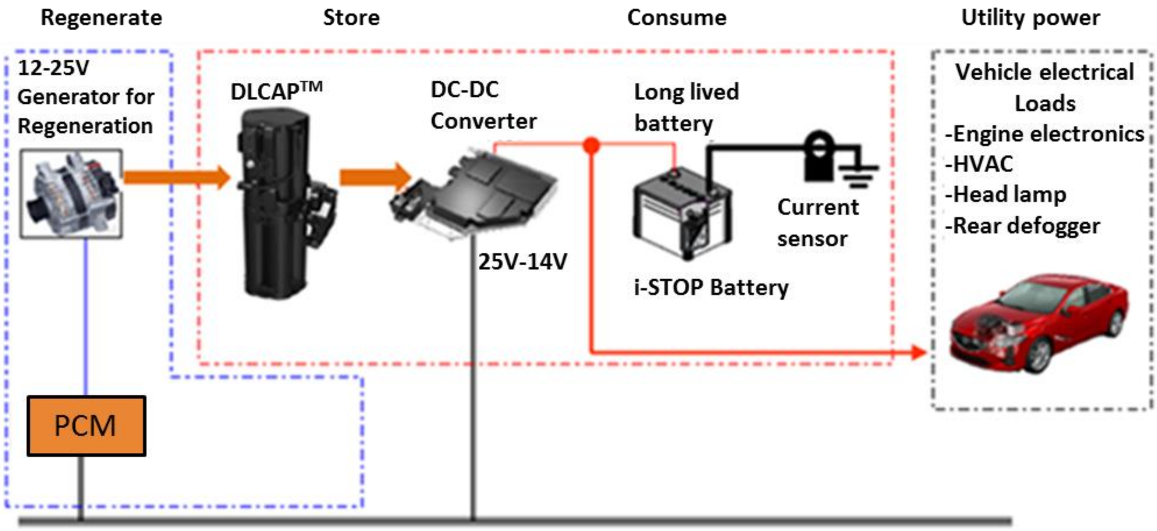

Figure 5: i-ELOOP^{TM} system developed by MAZDA to improve vehicle fuel economy and degrease emission. Energy is stored in the DLCAP^{TM} during regenerative braking that is used for utility power(the vehicle electrical load).

5. The case study for the estimated deliverable energy from DLCAP^{TM} at JC08

Figure 6 and 7 show the simulation results of the charge/discharge voltage of DLCAP^{TM} module during the drive cycle power profile shown Figure 3.

In this simulation, the vehicle electric load was 480W, a typical load current for a passenger vehicle, with an alternator voltage window of 25V to 12V. Total current is 178A with an average current of 40A over a one hour driving period. See Table 1 for typical vehicle electric loads.

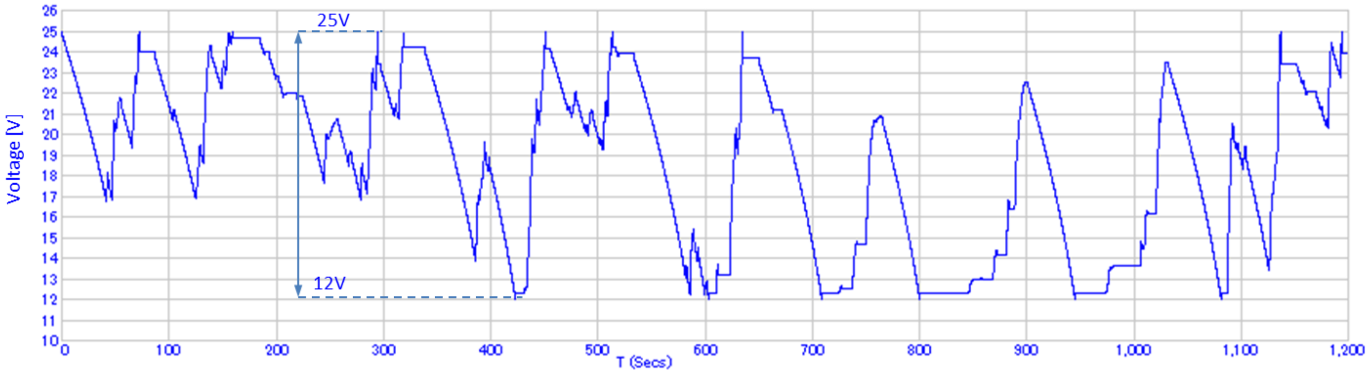

Figure 6: DLCAP™ module voltage profile for drive cycle JC08 shown in Figure 2.

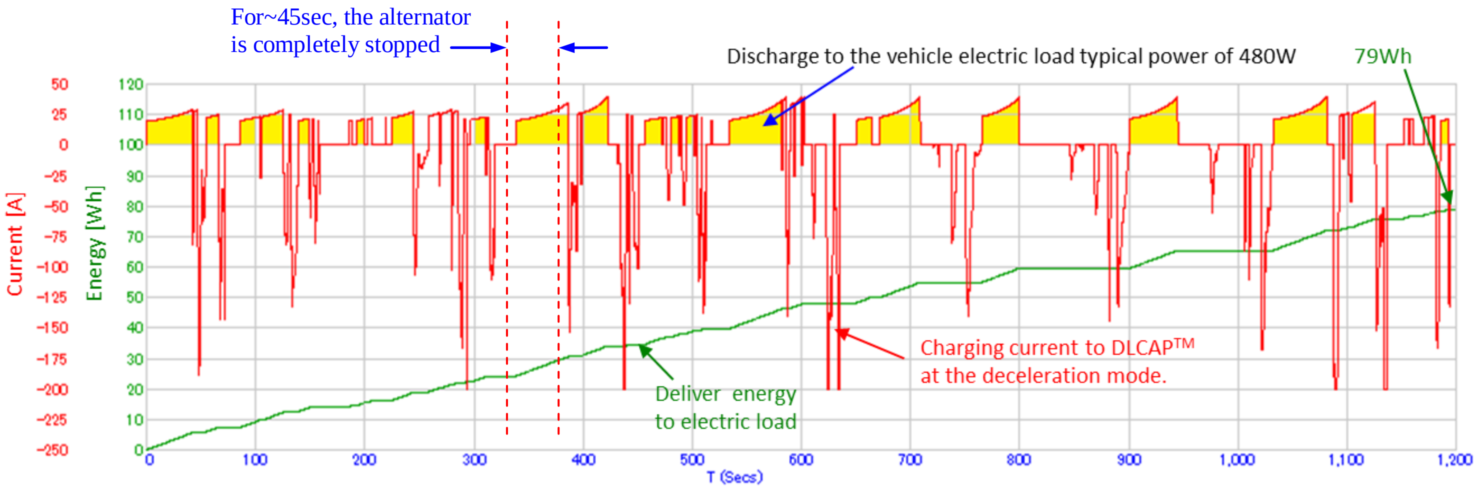

Figure 7: DLCAP™ discharge current and delivered energy to the vehicle electric load. Note a positive current peak is associated with discharge to the vehicle electric load and a negative current peak is associated with charge current to DLCAP™ module at deceleration mode. The capacitor charging current is limited to 200A due to the alternator requirement.

Table 1: Typical vehicle electric load (Utility load)

Typical load	Current[A]
EPS	100
Air conditioner	30
Radiator fan motor	30
Fuel pump	8
ECU	10
Others (Audio, wipwer, lump, so on)	

Source: Jtec-R/Japan electronics Technology Research

The calculated typical vehicle electric power is 12Vx40A=480W and the total energy to the electric load from the alternator without i-ELOOP™ system during 1200 sec of the JC08 drive cycle with continuous engine running for one cycle is 480W x 1200sec/3600sec = 160 Wh. The DLCAP™ module in the i-ELOOP™ will provide 79 Wh in that one cycle. See Figure 7. Thus 49% of the total energy is saved with DLCAP™ i-ELOOP™ system. The calculated annual energy savings based on driving 20 days a month x 12 months a year x 160 Wh x 49% is approximately 18.8 kWh.

A picture of the DXE1200F electrochemical capacitor and the 10-capacitor modules used in the i-ELOOP™ system is shown in Figure 8 and DLCAP™ module key parameters are listed in Table 2. A new alternator was developed for this application. A picture is shown in Figure 9 and parameters for this alternator are listed in Table 3.

DXE1200F
ϕ40x150mm

DLCAP™ module
(10 cells of DXE1200F)

Figure 8. Nippon Chemi-Con DXE series 1200F /2.5V and DLCAP™ Module.

Table-2: Key parameters of the DLCAP ™ module

rated voltage	25V
Capactance	120F
Typical ESR	9mΩ
Store Enegy	37.5KJ
Operating temperature	-30℃ to 70℃

Figure 9. 12V to 25V valuable output Generator - Alternator used with the i-ELOOP™ system, [4][5]

Table-3: Parameters of newly developed alternator for the Mazda i-ELOOP™ system

Valuable output voltage	12V to 25V
Maximu current	200A
Maximu output power	5KW

6. Field test data

Figure 10 [4] shows field test data for an approximately 5 minute driving profile on Hwy 405 in California, USA. The vehicle speed is ~120 km/h to 80 km/h with frequent deceleration. In this driving mode, the vehicle electric load will be provided from the regeneration energy most of the time. The capacitor voltage profile is showing the discharging current to the vehicle electric load. 30A to 40A of the electric load will be the most common number for practical driving.

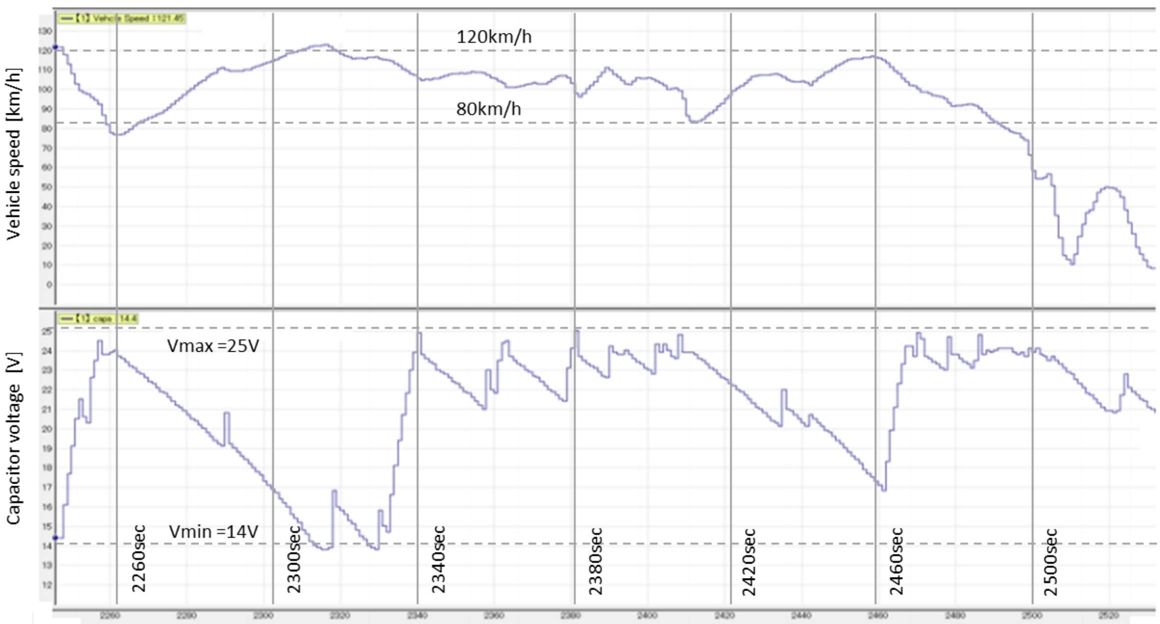

Figure 10: Field test data for driving on Hwy 405 California USA. [4]

Figure 11 [4] shows the fuel economy improvement as a function of load current. The i-ELOOP™ concept is that regenerative energy store into the DLCAP™ is used for the electric load, which is an energy recycling loop. The fuel economy improvement depends on driving mode and load current. The fuel economy improvement for the driving mode shown as Figure 10 is ~10%. [4]

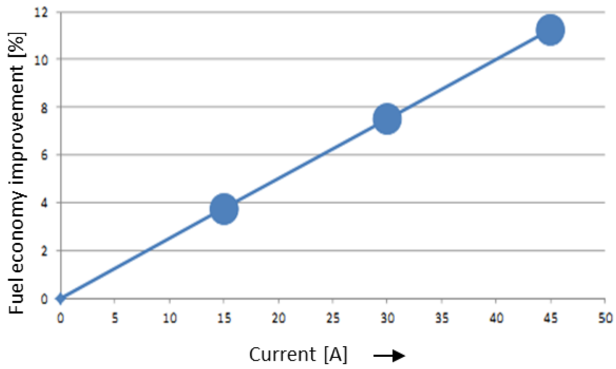

Figure 11: Fuel economy improvement ratio vs load current.

7. Summary

- The MAZDA passenger vehicle i-ELOOP energy conservation system using special Nippon Chemi-Con DLCAP™ electrochemical capacitors has demonstrated a 10% reduction in fuel consumption.
- Electrochemical capacitors clearly are the superior storage system technology for this automotive application.

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