EVS26
Los Angeles, California, May 6-9, 2012

Ultracapacitor Test System

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Abstract

Electric Double Layered Capacitors (EDLC), commercially known as ultracapacitors or supercapacitors, have many advantages over batteries including high power density, ability to charge and discharge significantly faster, longer life cycle, and lower cost. Effective implementation of an ultracapacitor bank requires the ability to sense and understand causes of failure in the forms of overvoltage, overcurrent, and temperature. The purpose of developing a test system for ultracapacitors is to define optimal and safe operating conditions of the cell bank. The EDLC test system includes a SPICE model to predict the behaviour of the cells to be evaluated as well as a physical system that provides the source and load for charging and discharge as well as a data acquisition system. The configuration allows the charging source, discharging load, and the measurement sensors for the EDLCs to be changed independent of each other. This allows the system to be easily scaled for varying capacity EDLCs or multiple cells. It also supports varying charge methods by incorporating an independent charge source. Preliminary testing using a constant voltage charging method has displayed the proper operation of the measurement system and verified the predictions of the simulation model. This proves the system can provide the comprehensive EDLC characteristic set required to effectively design and implement a full scale system to supplement the battery power in our electric mass transit vehicle.

Keywords: EDLC (electric double-layer capacitor or supercapacitor), bus, energy storage, data acquisition

1 Introduction

There have been numerous applications in electric vehicles that have shown energy storage and efficiency improvements with the addition of Electric Double Layered Capacitors (EDLC) [1-6]. EDLCs are also commercially known as ultracapacitors and supercapacitors. EDLCs have some advantages over batteries including high power density, ability to charge and discharge significantly faster, longer life cycles, and lower cost per amount of energy versus high performance batteries [2,3,6]. These properties make EDLCs an excellent supplemental source of energy to batteries, which are known for having higher energy density and lower current leakage.

Electric vehicles are an ideal media for the use of EDLCs because of the large current draws required to initially move the vehicle and the significant amount of energy that can be recovered from regenerative breaking. The ability to rapidly charge from the generated energy allows the EDLC to capture more energy, which can then be used as a power supplement to the motor or used to safely charge the battery system [5-6]. EDLCs also make an excellent power buffer between the power system and the battery system by assisting in sourcing the initial current spike that is characteristic of electric motors [7]. This not only provides more power at startup, but also reduces the stress to the batteries which have a life on the order of 1/1000 of the duty cycles compared to an EDLC bank. This saves in the overall cost and maintenance time for the vehicle [8]. To effectively implement EDLCs it is important to monitor various conditions to prevent damage to the cells. This system is designed to test the characteristics of an EDLC cell to aid in finding the optimal implementation strategy, while ensuring that the cell is not damaged due to improper use.

This test system will provide the proper information to develop a full scale EDLC bank to be implemented in a mass transportation electric vehicle. The targeted electric vehicle is shown in Fig. 1 below.

Figure 1: Electric Mass Transit Vehicle – Design Target

The full scale system will benefit from the knowledge of the protection circuitry and charge and discharge strategies this system will provide. Using this data the EDLC bank can be designed to utilize a balance between performance and safe operation, which are typically contradicting design goals [4]. The test system will also be able to verify manufacturing specifications to ensure that the cells, once purchased, are within tolerance of the advertised performance.

2 EDLC Properties

EDLCs are similar to batteries in that misuse can cause the cell to degrade at an accelerated rate. To prevent this degradation the cell voltage, current, and temperature need to be monitored [4,9,10,11]. Exceeding the recommended specifications in any of these parameters can cause permanent damage and even destroy the cell in extreme cases.

2.1 EDLC Voltage

Voltage is a critical characteristic of EDLCs. The voltage level has a squared relationship to the overall energy stored in the cell making it appealing to charge the cell to the maximum rated voltage to use the optimal amount of storage capacity available. Charging beyond this level however causes the cell to degrade at an increased rate [1].

In addition to simply limiting the cell voltage below the rated value, balancing the voltage between cells in a bank is also important. Unbalanced cells can cause inconsistent current draws between cells, and the condition can worsen over time [4].

For these reasons, the voltage of each cell in a bank provides valuable information to not only ensure that the cells are operating within their ratings, but to monitor the degradation over time.

2.2 EDLC Current

A major advantage of EDLCs over batteries is the amount of current they are capable or sourcing or sinking. Large cells (typically 1000s of Farads) are capable of charging or discharging at hundreds of amps continuously and thousands of amps for short periods. This property makes EDLCs excellent at absorbing power spikes and smoothing power as well as sourcing the power spikes to protect batteries from this harmful behaviour.

Though it is possible to apply too much current to an EDLC this is the least likely fault condition due to their high tolerance. It is still beneficial to monitor the current in the cell for feedback to charging circuitry. Constant current charging helps overcome the exponential charging time behaviour exhibited from constant voltage charging.

2.3 EDLC Temperature

EDLCs have a temperature range of approximately -40°C to 65°C depending on the cell. Throughout this range the capacity of many EDLCs remains relatively constant giving them an advantage over batteries operating in cold environments. The upper range can present some problems especially in operating in warmer climates [10].

The cells naturally heat during use depending on the amount of current passing through the cell and the number and rate of charge and discharge cycling. Therefore, it is necessary to monitor the temperature of the cell. Typically this measurement is taken on a lead of the cell very near the cell [11]. This provides an acceptable approximation of the internal temperature of the cell.

Exceeding the maximum operating temperature of the cell by small portions will reduce the life of the cell. As the cell temperature continues to increase it can reach a point where it will vent in an attempt to relieve pressure built up in the cell. If the cell temperature increases beyond this the cell can be in danger of melting or under rare and extreme cases explode. These conditions are easily avoided by maintaining the cells internal temperature below the maximum operating temperature.

3 Simulation

A valuable tool for evaluating EDLCs is an accurate simulation. This allows the user to test new methods of charging discharging as well as predicting characteristics such as run time for a specific system and degradation over time. The simulations that accompany the EDLC test system have been completed using the free Simulation Program with Integrated Circuit Emphasis (SPICE) program developed by Linear Technologies (LTSPICE IV).

3.1 Constant Voltage Model

The constant voltage (CV) model was constructed first for a single cell. There were several aims for the CV model including: verifying EDLC model, predict behaviour with a CV source, and verifying its accuracy against the measured data from the physical system.

LTSPICE contains a built in extensive capacitor model. A specific SPICE model of the test EDLCs was not available; however, so these were constructed within the program using the standard polarized capacitor model and data from the specific datasheets of cells intended to be tested. The first cell used had a capacity of 0.47 F and rated for 2.7 V. This was modelled after the UM series EDLC from EVerCAP. The model used a constant 5 V source and a voltage divider to charge the cell to 2.5 V with a limited current. By configuring the circuit in this manner, proper operation of the system can be verified with a physical setup without protection circuitry because the cell will not exceed the 2.7 V rating, the current limiting resistors will prevent excessive current conditions, and the combination of relatively low current, single cycle, and slow cycle rate will not overheat the cell causing a thermal failure. The schematic of the model is shown below in Fig. 2.

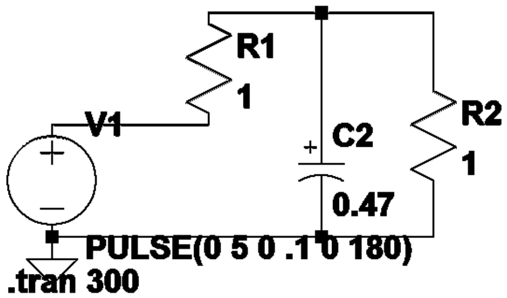

Figure 2: Constant Voltage Model

The model was then simulated by turning on the source for 5 s, then shutting off the source and allowing the EDLC to discharge through the power circuit. The model shows the characteristic RC behaviour that was expected. It also predicts an approximate charge time of 100 mS to reach 90% of its final voltage, but taking the full 5 seconds to reach 98.9% of the final voltage. The output of the simulation is shown in Fig. 3.

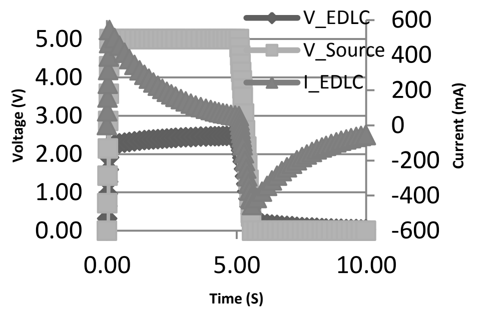

Figure 3: Constant Voltage Output

This setup will be used to compare against the physical setup to evaluate the accuracy of the capacitor model and overall accuracy of the simulated circuit.

Next, the same circuit was simulated replacing the EDLC with a 100 F 2.7V cell from IOXUS. This not only provides predictions for a higher capacity cell, but also evaluates the generality of the capacitor model. By using cells of varying capacities and different companies, adjustments can be made if necessary to the model to support these differences. The same voltage and current limitations were present when the new cell was placed in the model as shown in Fig. 4.

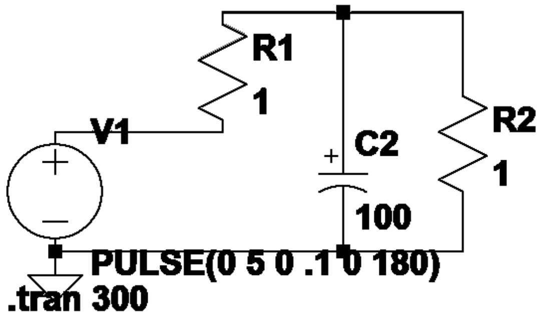

Figure 4: Constant Voltage 100F Cell

The results of the simulation are shown below in Fig. 5. As expected, the 100 F requires a considerable increase in time to charge. The model predicts it will take 180 seconds to finally reach 2.5 V.

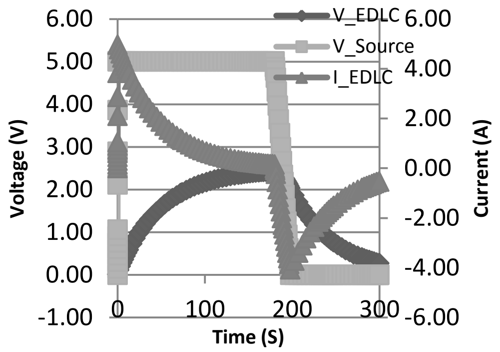

Figure 5: CV 100F Cell Output

The results predicted by the CV models are the simplest to verify with a physical model, but to implement a high performance bank of cells a faster means of charging the cells would be preferred.

3.2 Constant Current Model

The next model constructed was a constant current (CC) model. CC sources provide many advantages in terms of decreasing the amount of time required to charge the cell. The CC model allows the source voltage to exceed the suggested rating of the cell to keep the current constant. A hazard of this approach is the possibility of overcharging the cell and exceeding the rated voltage. Fortunately, the physical test system is designed to monitor this behaviour and prevent these conditions, but the model software makes capturing this behaviour with built in functionality significantly more complex. Therefore, to simplify the simulation circuit the amount of time the source is on was found through trial and error to not exceed the rated cell voltage. The schematic of the circuit incorporating the 0.47 F cell is shown in Fig. 6.

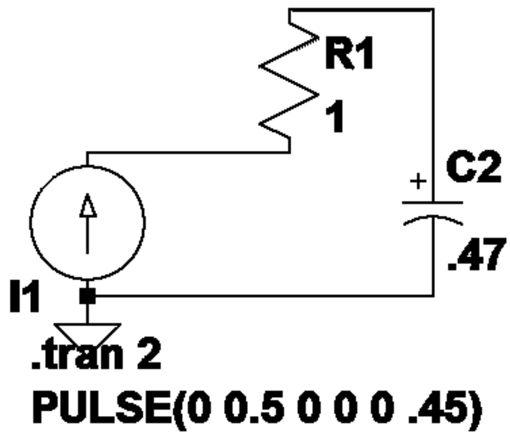

Figure 6: Constant Current Model

The simulation output shown in Fig. 7 demonstrates the significant decrease in charge time by using the constant current source. The EDLC is now predicted to reach its maximum voltage is approximately 0.5 seconds versus 5 seconds for CV.

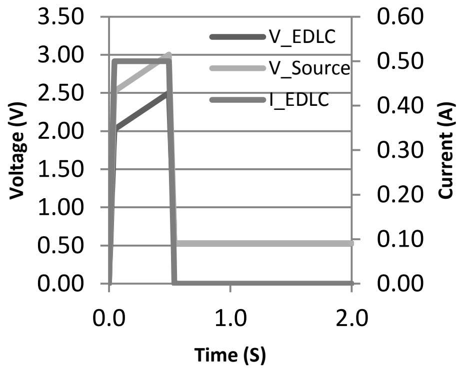

Figure 7: Constant Current Output

Next, the capacitor was replaced with the 100 F cell and the simulation was rerun. The output is shown in Fig. 8 below.

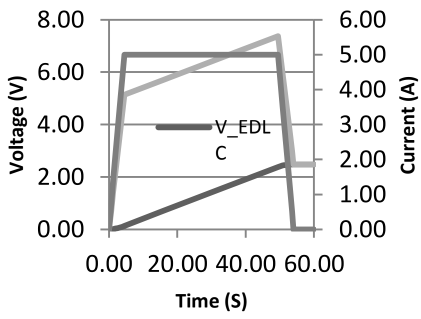

Figure 8: Constant Current 100F Output

These schematics are not excellent examples of the discharge characteristics of the EDLC as it simply backflows the power supply, but they are intended to predict the advantage of using a constant current source to charge the EDLC. This simulation shows a decrease in charge time of the 100 F cell from 180 seconds for the CV source to 49.5 seconds for the CC source.

These simulations, in addition to predicting the behaviour of the cells, give an approximate measurement range for the various sensors to be used in the test system.

4 Physical Test System

Thus far the simulation models have been a tool to estimate the behaviour of the EDLCs, but to verify the accuracy of the models and evaluate the real EDLCs a test system has been constructed. It is constructed in a modular fashion with one part handling the data acquisition portion that will monitor the characteristics of interest, while the other portion will serve the purpose of driving the source for the EDLC.

This configuration allows the user to either change a measurement sensor or the EDLC circuit independent of each other. The advantage is allowing fast dynamic changes to the EDLC circuit to run varying tests to evaluate specific properties as well as changing source and load characteristics without making adjustments to the measurement system. On the measurement side, a small change in a sensor to change the operating range can quickly and easily scale this system from small cells to cells over 1000 F.

4.1 Hardware Configuration

The hardware makeup of the system is based around the Parallax Propeller microcontroller. It handles communication with the analog to digital converter as well as the USB to serial interface to stream the data to the computer.

A MAX1270 A/D chip handles the measurement conversions. This chip has 12 bit resolution, 110 ksps sampling rate, and 8 bipolar input channels. The bipolar inputs are ideal to handle the positive current into the cell and negative out without require external components to offset and scale the voltage. It is also operates on a single +5 V input.

A 0.025 Ohm shunt resistor was selected to provide the current measurement. A finned heatsink was also used to provide greater heat dissipation to extend the range of the shunt. The differential measurements of the shunt are then passed through an instrumentation amplifier built from generic low noise opamps and tuned to a gain of 10. This sets the range of the shunt to $\pm$ 20A for an input range of $\pm$ 5V. The current range also falls in the recommendation power rating for the shunt with the added heatsink.

The thermocouple circuit was built around the LT1025 cold joint compensator and a low noise opamp. This circuit converts the typical output of a variety of types of thermocouples to 10 mV/°C and provides a cold joint measurement. This configuration allows the user to select a thermocouple that best suits their needs by simply connecting the leads to the correct pins for the thermocouple type without requiring a change in the rest of the circuitry.

4.2 Software Configuration

The software is implemented in two pieces: microcontroller code and computer code. The microcontroller code handles reading the sensor information, filling a byte buffer, and sending the buffer through a USB port. Assembly was used to implement the SPI communication to the A/D converter, and the proprietary SPIN language implemented the rest of the logic.

After receiving the measurements, they are encoded in the form "%xxxx*yy". Where the percent sign denotes the start of a measurement, xxxx is the A/D value, * denotes the start of the identifier, and yy is a two character code to identify the measurement. This form is generated for each measurement and concatenated together to form the transmit buffer.

The computer side that receives this buffer is implemented in LabVIEW. It receives the buffer at 250 KBaud, decodes the buffer, and places the information into corresponding variables. Finally, the information is displayed on a front panel for a real time look at the test and the data is stored to a file for offline analysis.

4.3 Measurements

There are four measurements taken by the test system including: source voltage, EDLC voltage, EDLC current, and EDLC temperature. The voltage of the source measurement will allow us to track the type of charging algorithm being used. This measurement is also useful in aligning the characteristics of the EDLC with the state of the source and loads. The source voltage is read through a simple divider circuit, using high valued resistors to minimize the effects to the rest of the system, which can be easily adjusted to appropriately scale the signal amplitude to safe ranges for the A/D converter regardless of the actual source voltage.

The EDLC voltage is taken to prevent an overvoltage condition and provide feedback information to the charging algorithm. The EDLC voltage is also used to calculate the State of Charge (SOC) of the cell. This value is useful for providing a "fuel" gauge for the EDLC.

The EDLC current measurement is taken to ensure that overcurrent conditions are not occurring. In addition to protection, it is foreseeable to use a computer controlled charging system and the current measurement provides more flexibility in the feedback for the controller rather than using an opamp feedback circuit.

Finally, a type K thermocouple is joined to one of the EDLC leads with thermal compound to maximize the heat transfer from the lead to the thermocouple joint to more accurately represent the internal temperature of the EDLC. The type K thermocouple provides a more than adequate measuring range compared to the operating range of the EDLC and is a relatively inexpensive and accurate temperature sensor.

5 Results

The model used to simulate the physical system had the addition of another resistor in series with the EDLC to more accurately capture the effect of the shunt resistor used to measure current. The true values of the current limiting resistors were also measured and adjusted in the model. The model continued to assume that the power supply was ideal with a 5 V output. The final model configuration is shown in Fig. 9 below.

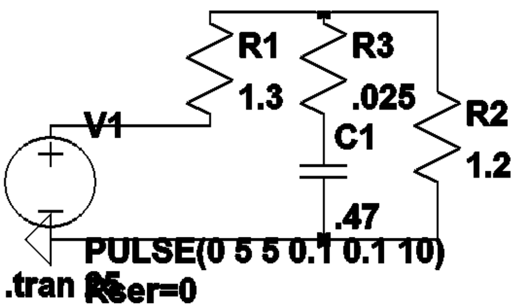

Figure 9: Test System CV Model

The model was then simulated using the 0.47 F EDLC with a 5 second delay, 10 seconds of power on, and finally off for 10 seconds. Fig. 10 below shows the predicted results of the system.

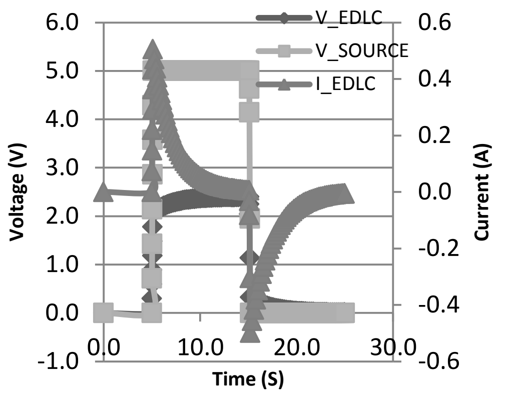

Figure 10: Simulation Results for Test System Model

The physical system was then configured and run with the same power conditions as the simulation. The measurements were taken at 1 KHz throughput rate. Fig. 11 below shows the voltage measurement of the source.

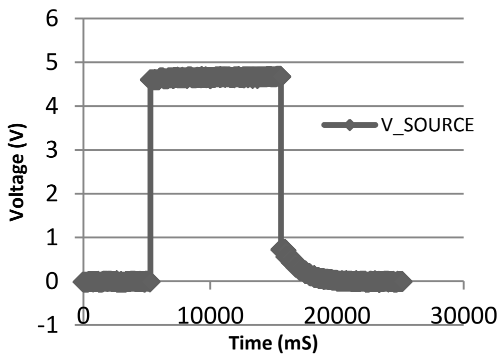

Figure 11: Source Voltage for CV test

Next, Fig. 12 shows the voltage reading of the EDLC.

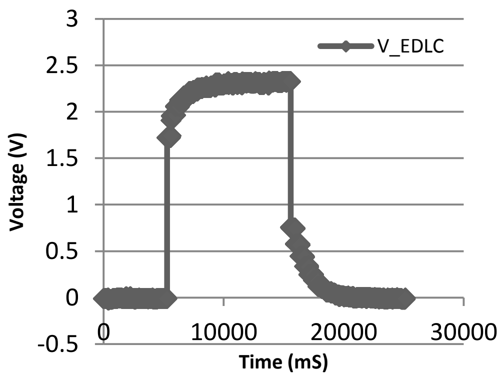

Figure 12: EDLC Voltage Measurement

Fig. 13 below shows the current measurement from the shunt resistor providing the current through the EDLC.

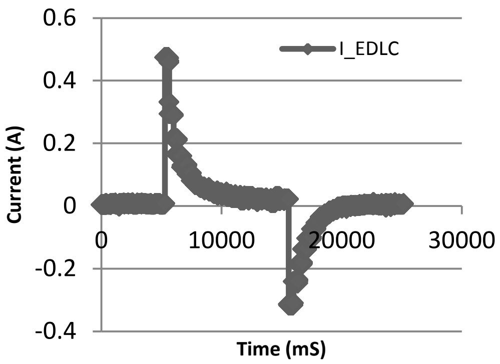

Figure 13: EDLC Current Measurement

Finally, the EDLC temperature measurement using the thermocouple reading is shown below in Fig. 14.

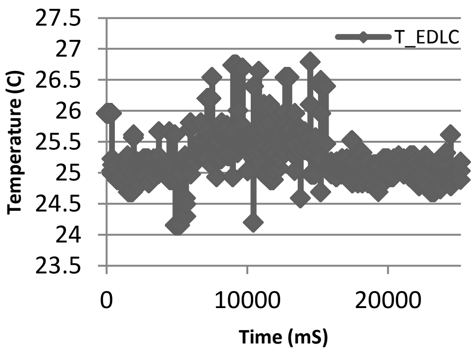

Figure 14: EDLC Temperature Measurement

All data shown in the figures are raw measurements without any filtering. This was done to identify noise in the measurement system in addition to verifying the operation of the system.

6 Conclusions/Future Work

It can be seen that the physical system is properly measuring the values of interest and the expected EDLC behaviour was observed. It was also seen that the model closely predicted the true behaviour of the system. The EDLC voltage after 10 seconds was measured as 2.412 V. The model predicted it would be 2.398 V resulting in an error of only 0.58%. Despite the acceptable accuracy, the model assumed a power supply voltage slightly higher than the actual output, but it predicted a lower ending voltage. A future revision of the model will include a more realistic power supply model to correct this behaviour.

The EDLC current was measured to peak at 473 mA, while the model predicted a maximum current of 505 mA. This resulted in 6.3% error between the system and the model. It is again expected that this is a by-product of an idealistic power supply model. The model does; however, provide valuable information as to the approximate maximum current expected. This information will help properly size components and measurement ranges to ensure safe operation for larger capacity cells and multiple cell banks.

The final measurement of interest of the EDLC was the temperature. It is seen that the average temperature only increased around 1 °C. The operation of the thermocouple was checked against an infrared temperature sensor and a separate thermocouple measurement system using a hot plate and the system was verified to be reading properly. This means that the level of current being sourced to the EDLC and the single charge and discharge cycle was not high enough to significantly increase the internal temperature. Future tests will include more aggressive current supplies to find the temperature limits of the EDLC.

Overall, the system is operating properly and provides the much needed information to continue EDLC testing and design larger EDLC banks that operate safely and optimally.

Acknowledgments

I would like to thank the University of Kansas Mechanical Engineering Department, as well as, the University of Kansas Transportation Research Institute for funding this research.

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Dr. Bryce Baker earned his Ph.D. from the University of Kansas in 2010. He is currently working in a Post-Doc position in the Intelligent Systems and Automation Laboratory at KU. Dr. Baker's primary research interest is developing control systems for machines, and has a wide range of research experience working with ethanol vehicles, expert systems for manufacturing and biped robotics. He is currently working on designing an electric mass transit bus capable of driving the hilly bus routes, in Lawrence Kansas.

Dr. Terry Faddis received a D.E. degree from the University of Kansas in Mechanical Engineering. He is currently the director of the Intelligent Systems and Automation Lab, and has extensive experience in the application of microprocessors and sensors to advanced electromechanical systems. His current research focus is more efficient alternative energy systems including dewatering algae for biodiesel generation and a pure electric mass transit bus.