Potential of Energy Storage and Rapid Charge System Using Electric Double Layer Capacitors for the Solar Right Rail

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Abstract

Air pollution caused by exhaust gas, increasing carbon dioxide by burning fossil fuels, and the risk of drain on fossil fuels are the major problems of fossil fuels. In addition, low self-sufficiency rate of fossil fuels is also a large problem in Japan. 84.6% of electricity is generated by fossil fuels in Japan, so electrification such as electric vehicle does not mean breakaway from fossil fuels. Electricity should be generated by clean energy such as renewable energy in order to settle the problems of fossil fuels. A light rail system which runs on 100% renewable energy named the “Solar Light Rail” is proposed by authors. Experiments using a prototype model are carried out to demonstrate availability of the rechargeable power supply method using electric double layer capacitors. Two types of experiments are reported in this paper. From the experiment combination of PV and biomass, it was confirmed that clean stable energy is effective for this system under the bad condition for PV. In the experiments using PV, experimental condition is changed from passed experiments and energy consumption per run is decreased. Low energy consumption brings about running for longer time after sunset. The handmade equipment can be more efficient, and better result is expected by improvement.

Keywords: transportation, renewable energy, biomass, electric double layer capacitor

1. Introduction

In Japan, hybrid vehicles (HV) and electric vehicles (EV) are spreading. Fig. 1 shows the number and the rate of HV and EV, reported by the statistics of Automobile Inspection & Registration Information Association in Japan. The rate of HV and EV is only 7% for all automobiles in March 2016. However, the number and the rate of those vehicles are increasing every year.

The consumption of fossil fuels is one of the biggest causes of the environmental problem such as increasing in carbon dioxide and air pollution by the exhaust gas. The drain on fossil fuel is also a major issue. Furthermore, the self-sufficiency ratio of fossil fuels in Japan is extremely low. The self-sufficiency rate in 2015 of oil was 0.3%, that of natural gas was 2.5%, and that of coal was less than 0.1%. The excessive dependence on fossil fuels is undesirable for stable energy supply.

If all automobiles are replaced to EV, will the environmental problem by fossil fuels in the field of transportation be settled? Fig. 2 shows the power energy source of Japan in 2015. 84.6% of electricity is made from fossil fuels. It is reported that using electricity means consuming fossil fuels. The problem of fossil fuels will not be solved by only electrification. In order to settle the problem, all electricity must be made without fossil fuels, and should be generated by renewable energy.

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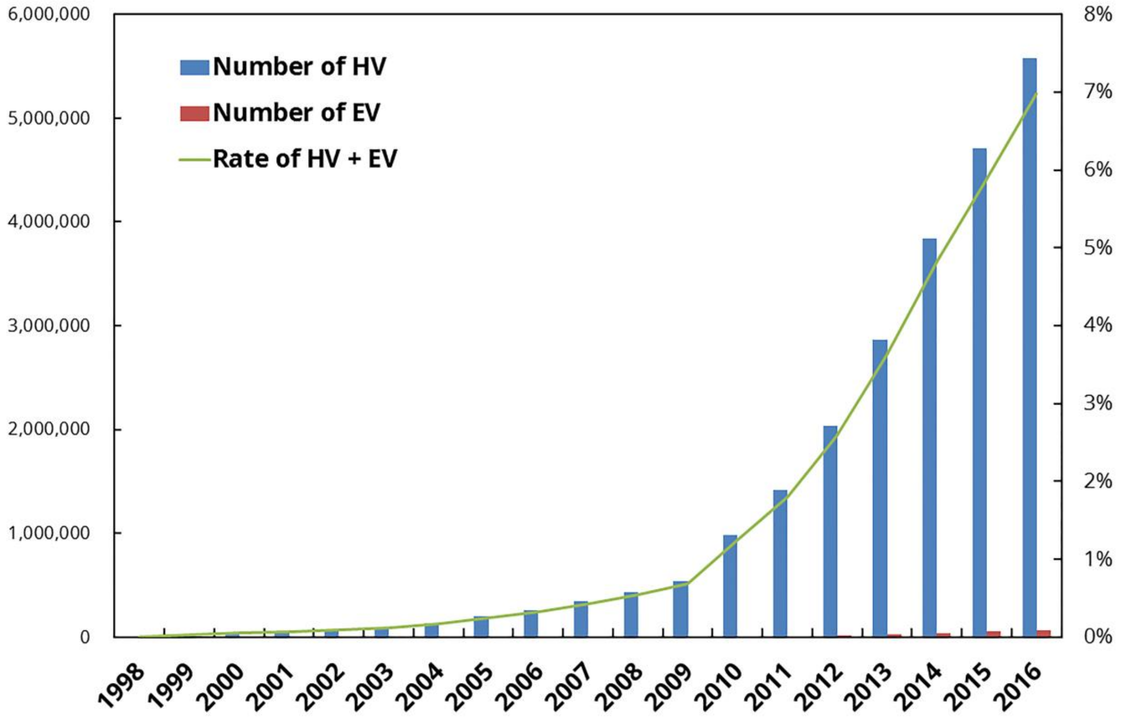

Fig. 1: The number and the rate of hybrid vehicle (HV) and electric vehicle (EV) in Japan

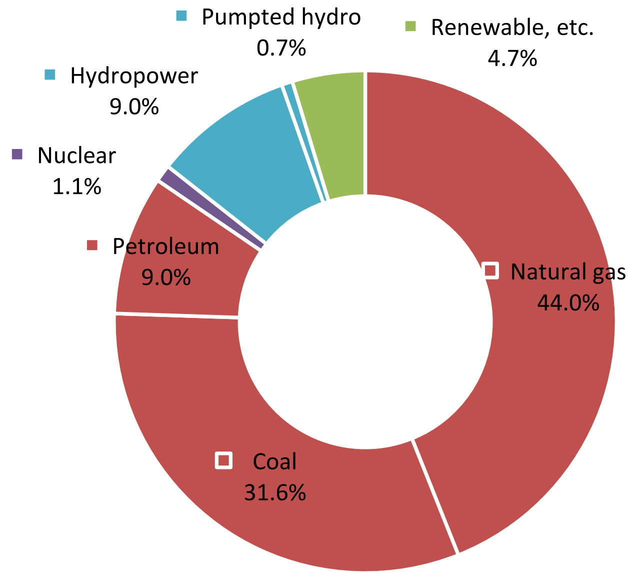

Fig. 2: Power energy source of Japan in 2015

1.1 The Solar Light Rail

A light rail is also known as a tram and a streetcar. A light rail which runs on 100% renewable energy such as solar, wind and micro hydro power generation is proposed by authors, and this light rail system is named the "Solar Light Rail".

The HIT solar panel produced by Panasonic is known as high efficiency silicon PV module. The energy conversion efficiency of this module is 19.7%, and the efficiency of thermal power generation with natural gas is 40%. Since the rolling resistance of iron wheels is lower than that of rubber tires, rail transport system is suitable for renewable energy.

A light rail is suitable transport system for the movement in the town. It is easy to ride without stairs like subways and easy to across the rail without railroad crossing. Moreover, it is easy to know the name of street since rail trucks are installed on the road. For shifts from car-based town planning to people-based town planning, a light rail is reviewed in Europe and the United States.

It is easy to think of spreading solar panels all over the roof of the railcar to supply electricity like a solar car. However, the railcar cannot run in rainy days and during the night. In addition, it is hard to use wind turbines and water wheels in this method.

In conventional light rail system, most of electricity is supplied from thermal power plants to the railcar through the electric wire. Replacing thermal power plants to renewable energy power plants is also dreamed up. Even in this method, the railcar cannot run when the renewable energy power plants do not work such as a night without wind. Moreover, the power transmission loss cannot be neglected. The rate of transmission loss in Japan is 5.6%. Assuming 5.6% of loss is not a wise policy for renewable energy.

The first tram in Japan opened in 1895 in Kyoto. The railcars ran on electricity by hydro power generation at Lake Biwa. A light rail in Calgary, Canada runs on wind power generation. Several light rail systems already run on renewable energy. However, location requirements are limited to come true.

The power supply method, which is feasible in almost any location, to have a light rail run on renewable energy is shown in Fig. 3.

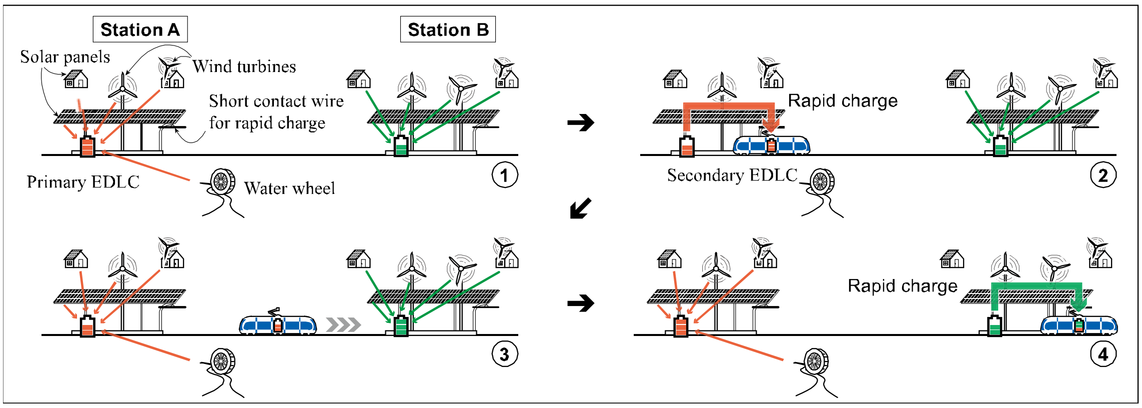

Fig. 3: Power supply method of the Solar Light Rail

1) Solar panels are mounted on the roof of the platform and around the station. Wind turbines are built around the station. Straight blade vertical axis wind turbines are suitable for this system, since their wind turbine noise is less than that of horizontal axis wind turbines. If there is a river or a water channel, micro hydro, not requiring a dam, should be used. An energy storage device is installed at the station, and this device is always charged from solar panels, wind turbines and water wheels. There is a short contact wire for rapid charge at the station.

2) Another energy storage device is also mounted on the railcar. When the railcar stops at the station, the energy storage device mounted on the railcar is charged rapidly from the energy storage device installed at the station through the short contact wire and a pantograph on the railcar.

3) The railcar runs to the next station by charged electricity.

4) There are same power generation system and an energy storage device at the next station, and rapid charge is carried out when the railcar stops at the next station. The railcar is operated by continuing this cycle.

Electric double layer capacitors (EDLCs) are suitable for the energy storage device of this system. In this system, energy storage devices repeat charge and discharge. The lifetime of EDLC is longer than that of batteries. High electric current is able to be put into and out from EDLC, and it makes rapid charge during railcar stopping. It becomes an advantage for this system that heavy metals are not included in EDLC. The capacitance of EDLC is lower than that of batteries. However, usually distance between stations of a light rail is shorter than that of railways, and charged electricity for an energy storage device mounted on the railcar should have quantity necessary to arrive at the next station. Therefore, low capacitance will not be a disadvantage in this system. In this system, an EDLC unit installed at the station is called the “primary EDLC”, and an EDLC unit mounted on the railcar is called the “secondary EDLC”.

According to the test outcome by the Railway Technical Research Institute of Japan, their hybrid light rail vehicle named “Hi-tram” consumes 8.9 MJ of electricity per kilometers at the maximum air conditioning load. If the interval between stations is 500 m for the assuming Solar Light Rail line, 4.5 MJ of electricity is required to reach the next station. When the voltage of secondary EDLC is 1500 V, the required capacitance of 4 F is calculated with eq. 1. The required time for rapid charge is calculated with eq. 2. It takes 6 seconds when this EDLC unit is charged at 1000 A.

$$W = \frac{1}{2}CV^2 \quad [\mathrm{J}] \qquad \text{(eq. 1)}$$

$$Q = CV = It \quad [\mathrm{C}] \qquad \text{(eq. 2)}$$

If railcars arrive and depart every 10 minutes in this assumed line, 15 kWh of electricity is required for every hour at a station. If this line works from 6:00 to 24:00 every day, the required electric power at a station is 270 kWh for one day, and 98,550 kWh for one year. If 98,550 kWh of electricity is supplied by renewable energy, the Solar Light Rail is feasible in the calculation.

1.2 Experiments using a prototype model

Demonstration experiments using solar panels and a handmade small scale prototype model were already carried out. From conventional experiments carried out under disadvantage condition for photovoltaic such as in winter or in cloudy day, it was confirmed that the proposed power supply system functions effectively in the daytime. The maximum voltage of the conventional primary EDLC was lower than the open circuit voltage of solar panel. Electricity had to be consumed to keep lower voltage, and electricity was not stored for after sunset. So the railcar could continue running for only one hour after sunset in passed experiments.

The experimental equipment was renewed this time. The gauge of rail is widened to 15 inches (381 mm) from 5 inches (127 mm). The voltage of the solar panel and the breakdown voltage of EDLCs rose.

Biomass is also a clean energy. Electricity is generated without an influence of climatic condition by biomass. In this paper, two types of experiments are reported. One is an experiment with combination of PV and biomass, and the other is an experiment with new equipment and new experimental condition.

2. Experimental equipment

Fig. 4 shows the schematic diagram of the experimental equipment.

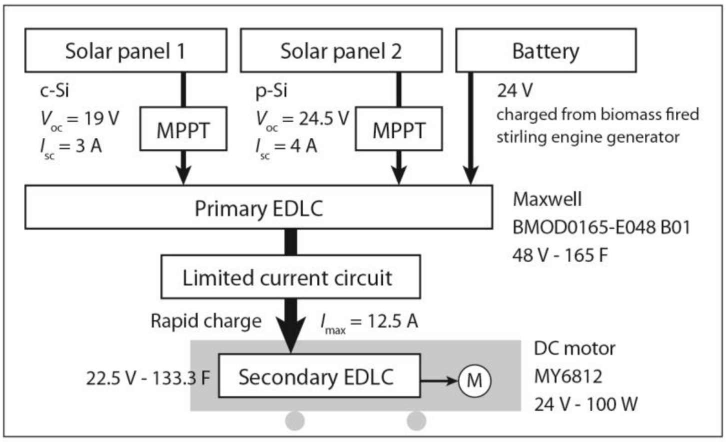

Fig. 4: The schematic diagram of experimental equipment

2.1 Solar panels

Two solar panels are used in the experiments. One is a mono-crystalline silicon panel made by ARCO Solar, Inc. 11 circular cells are wired in series, and three sets of wired cells are connected in parallel. Although this solar panel has been used more than 20 years, open circuit voltage of 19 V and short circuit current of 3A are still measured in preliminary experiments. This solar panel is called as “solar panel 1” in this paper.

The other is a handmade solar panel using 56 poly-crystalline silicon solar cells made by Suntech Power Co. Measured open circuit voltage for one cell is 1.75 V, and short circuit current is 1 A. 14 rectangular cells are wired in series, and four sets of wired cells are connected in parallel. Open circuit voltage of 24.5 V and short circuit current of 4 A is expected this panel. This solar panel is called as “Solar Panel 2” in this paper.

These two solar panels are connected to the primary EDLC through the maximum power point trackers.

2.2 EDLC units

An EDLC unit model BMOD0165-E048 manufactured by Maxwell Technologies, Inc. is used for the primary EDLC. The capacitance is 165 F and maximum voltage is 48 V.

The secondary EDLC is fabricated with cylindrical EDLC cells. The capacitance for one cell is 600 F and maximum voltage is 2.5 V. 9 cells are wired in series, and two sets of wired cells are connected in parallel. The secondary EDLC becomes the capacitance of 133.3 F and the maximum voltage of 22.5 V. A resistor of 3.3 kΩ is wired in parallel for each EDLC cell as a voltage balancing resistor.

2.3 A limited current circuit

An excessive electric current flows when the primary EDLC is connected to the secondary EDLC directly. A limited current circuit is installed between the primary EDLC and the secondary EDLC during the rapid charge for safety. A small limited current circuit of 1.25 A is made with a three terminal regulator of LM317T, and the 12.5 A of limited current circuit for this system is made with connecting 10 small circuits in parallel.

2.4 A railcar and rail trucks

A 15 inches (381 mm) gauge four-wheel car is fabricated with four independent wheels. Driving force from the 100 W DC motor is decelerated at 22.25:1 and is transferred to the left rear wheel through the chain. The structure of a power controller is simple enough. The base current of the transistor is controlled by the variable resistor. The speed of the railcar depends on voltage of the secondary EDLC and the base current of the transistor.

Rail trucks are not made with rails for railways. A 1.8 m of iron angle bar is used for rail trucks. Total extension of the straight rail truck becomes 14.4 m.

2.5 Stirling engine generation system

Fig. 5 shows the schematic diagram of a biomass fired Stirling engine generation system. Biomass pellets are stored in the pellet hopper, and fed into the furnace automatically by pellet feeder. The Stirling engine works with combustion heat of biomass pellet and cold water. 1 kW of AC generator is connected to the Stirling engine, and electric power is supplied to load. Rated voltage of this system is DC 60 V, and five car batteries are installed for load balancing. Two of these batteries are used for charging to the primary EDLC.

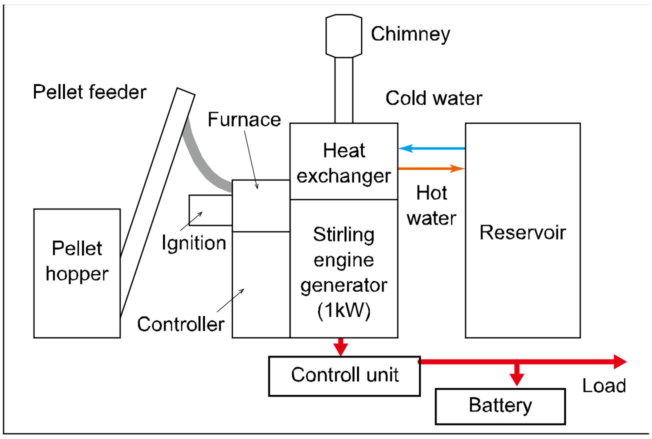

Fig. 5: The schematic diagram of biomass fired Stirling engine generation system

3. Experiment 1: Combination of PV and biomass

The experiment using a biomass Stirling engine generator was carried out during the science workshop for children held on 10th October 2016 at Tokyo Tower (Tokyo, Japan). The event started at 10:00 and closed at 18:00. Many children visited our booth and enjoyed to riding the railcar one round trip on the 14.4 m of straight rail truck.

Fig. 6 shows the voltage transition of the solar panel 2, the primary EDLC and the secondary EDLC recorded with a data acquisition system IOtech Personnel Daq/55. The voltage of the solar panel 2 and the primary EDLC was recorded continuously since the solar panel 2 and the primary EDLC was always connected to the data acquisition system. However, the voltage of the secondary EDLC was recorded with break since the secondary EDLC was connected to the data acquisition system only during the rapid charges.

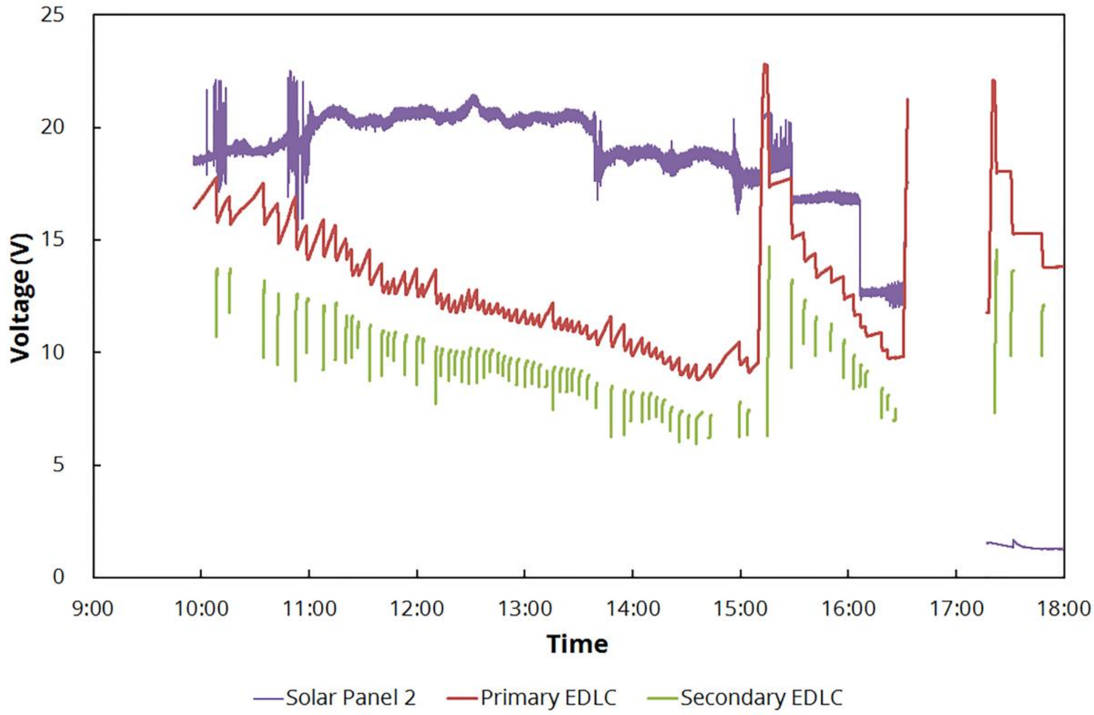

Fig. 6: Voltage transition of solar panel 2, primary EDLC and secondary EDLC under the experiment held on 10th October 2016

It was overcast from early morning. The voltage of the primary EDLC barely reached to 17 V at the beginning of the event. The railcar continued running without rest and the voltage of the primary EDLC dropped every time rapid charge was carried out. The railcar hardly moved around 15:00 since the voltage of the secondary EDLC also dropped, so a charging from the battery which was charged by the biomass fired Stirling engine generation system was carried out at 15:10. The voltage of primary EDLC rose to 22.8 V from 9.6 V. After that charging from battery was carried out at 16:30 and 17:18, and the railcar could continue running until the end of the event. The voltage was not recorded from 16:33 to 17:17 because of trouble of the laptop for data recording.

In this experiment, the railcar ran without the rest during overcast day. Even in harsh condition for photovoltaic, the railcar could continue running by charging from battery which is charged by the biomass fired Stirling engine generation system. It was confirmed that combination of clean energy such as biomass is effective to supply electricity stably for the Solar Light Rail. For practical use, the clean and stable generation system should be installed at main stations and stations which are located at a disadvantage to photovoltaic.

4. Experiment 2: Change of experimental condition

The experiment using new equipment without biomass stirling engine generation system was carried out on 1st November 2016 at Hachioji Campus of Tama Art University (Tokyo, Japan). The voltage of the solar panel 2 rose to 24.5 V from 17.5 V. The maximum voltage of the primary EDLC rose to 48 V from 17.5 V, and that of the secondary EDLC rose to 22.5 V from 15.0 V. Since the voltage of the primary EDLC became higher than the voltage of solar panels, it was not necessary to worry about overcharge of the primary EDLC.

The experimental condition is also changed. In conventional experiment, the railcar went forward and back 3 to 5 times on the 9 m of straight rail after rapid charge. In this experiment, the railcar went forward and back 1 time on the 14.4 m of straight rail. Running distance was decreased from 90 m to 28.8 m for each run. The time for rapid charge was fixed to 2 minutes.

The rail truck was laid on the corridor of the building and solar panels were put on the balcony facing south west. The sunrise was 6:03 and sunset was 16:46. It was rainy in the morning and became overcast in the afternoon. Fig. 7 shows the voltage transition of the solar panel 2, the primary EDLC and the secondary EDLC under the experiment. The voltage of the primary EDLC reached to 16 V at 10:55, and the first rapid charge was carried out at 11:00. The second rapid charge was carried out at 11:30, and interval of rapid charge was fixed to 15 minutes from the third rapid charge. The voltage of the solar panel 2 became lower than that of the primary EDLC at 15:38 since the sun disappeared behind a building.

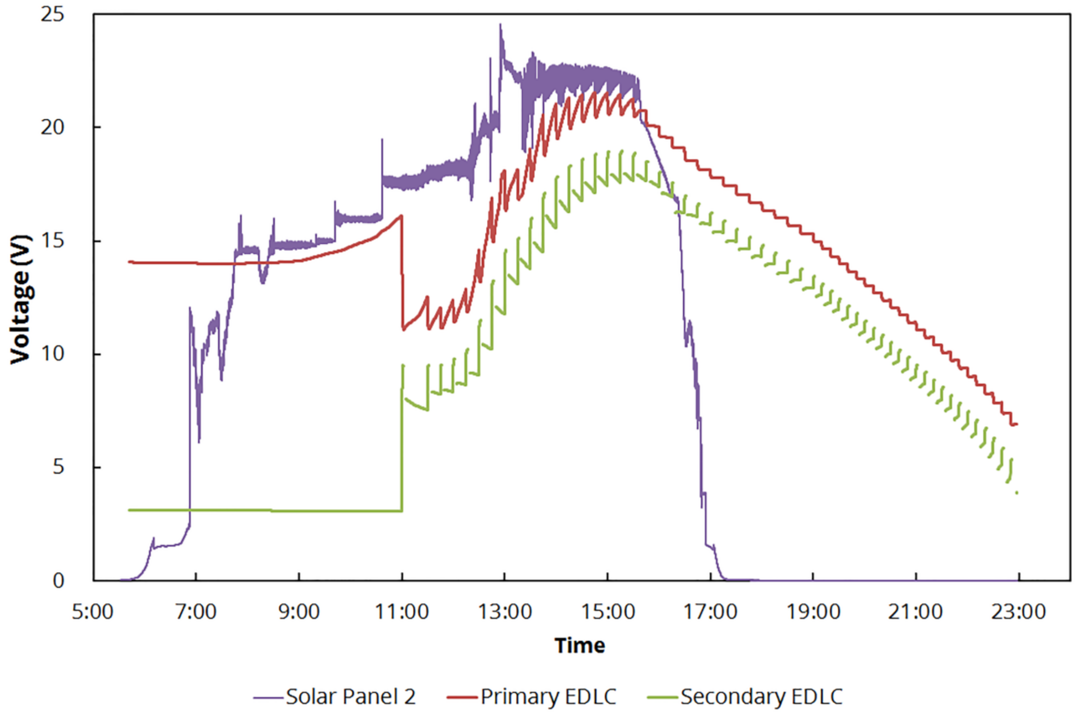

Fig. 7: Voltage transition of solar panel 2, primary EDLC and secondary EDLC under the experiment held on 1st November 2016

Finally, the railcar stopped at 22:56 and the final rapid charge was carried out at 22:50. The railcar continued running for 6 hours after sunset. Interval of rapid charge was shortened from 15 minutes to 10 minutes after 19:00. The final rapid charge would be carried out at 24:45 if the interval was not changed.

In the conventional experiments, the voltage of the secondary EDLC fell about 2.8 V in average after run. The capacitance of the secondary EDLC was 100 F, so the railcar consumed 280 C of electric charge per run. In this experiment, the voltage of the secondary EDLC fell about 1.0 V in average. The capacitance of the secondary EDLC was 133.3 F, so the railcar consumed 133.3 C of electric charge per run. 68% of shortening of distance per run caused 47.6% of decrease in energy consumption. Lower energy consumption brought about running longer time after sunset. This handmade equipment, such as rail trucks, a power controller, a power transmission system and electric circuits, can be more efficient. Better result is expected from improvement of equipment.

5. Conclusion

In this paper, a power supply method for a light rail which runs on 100% renewable energy is proposed. Two types of experiments using a prototype model were reported. In the experiment combination of PV and biomass, the railcar continued running by electricity which was brought from biomass under poor surroundings for PV. It was cleared that combination of clean stable energy is effective for the proposed system. The clean energy generation system should be installed at main stations to support power generation by unstable renewable energy.

In the experiment using only PV, railcar could continue running for 6 hours after sunset by 47.6% of reducing energy consumption per run. It was confirmed that low energy consumption brings about running for long time after sunset. The handmade equipment could be more efficient, so better result is expected by improvement of equipment.

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