Basic research on an electric fixed-route bus system with green fast charging at every bus stop using a simulator

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Received: 28 July 2016; Revised: 16 November 2016; Accepted: 26 January 2017

Abstract
In a sustainable city, public transportation is prohibited from emitting greenhouse gases. A vehicle running on electric power generated from a green energy source does not emit carbon dioxide (a major greenhouse gas) and is thus optimal for reducing greenhouse gas emissions. To pursue this goal, we propose a public transport system consisting of electric buses that are quickly charged at every bus stop, using electric power generated from green energy sources. Such a system resolves the problem of low mileage per charge for heavy batteries. This system would also be able to effectively use low density and widely available solar energy to generate power at bus stops, which are widely distributed throughout a city. In this paper, an electric bus system that is rapidly charged at every bus stop, using electric power generated from green energy sources is introduced first. Next, the simple full-size electric bus simulator is constructed by extrapolating the parameters obtained from the single-passenger electric vehicle. Then, the simulations in some characteristic cases are performed, and the results are examined, especially the change of the state of charge (SOC) of the battery mounted on the bus, the energy charging to the bus at the bus stop and the travel time including the stoppages of 20 s at each bus stop. Last, the storage equipment capacity of the full-scale electric bus and the specifications of the bus stop, in particular the capacity of the solar modules, are estimated using the constructed simulator.

Key words : Environmental engineering, Public transportation, Automobile, Electric bus, Solar energy, Greenhouse gas, Boosting charge, Simulator

1. Introduction

As a result of the severe accident in the Fukushima Daiichi nuclear power station after the Great East Japan earthquake and tsunami on March 11, 2011, many people have begun to consider the best way to provide a safe and secure electrical power supply to Japan. Many have suggested that further promotion of renewable energy is required. The feed-in tariff system for renewable energy was started in 2012, marking the beginning of practical and widespread deployment of renewable energy. However, the electrical power supply from thermal power plants, which burn petroleum or coal, has increased, while that from nuclear power plants has stagnated. The emission of greenhouse gases such as carbon dioxide has therefore increased, and it decreased in 2014 with effort of energy conservation, greater adoption of renewable energy and fuel conversion (Ministry of the Environment, Government of Japan, 2015).

Slowing down global warming is an urgent issue, and public bus transportations should be taken the lead in reducing carbon dioxide emissions. This work focusses on a bus system where buses are rapidly charged at every bus stop. Because of the lower mileage requirement, this allows a reduced weight of the storage device mounted on the bus. Furthermore, a zero-emission public transport system could be realized by powering the bus by electricity generated from renewable energy sources near each bus stop. Particular attention has been paid to the distribution of bus stops to effectively utilize widely distributed and low density renewable energy sources such as solar energy.

In this system, the duration of a short stop at a bus stop, during which passengers get on and off, was assumed to be 20 s. One of the most important tasks for successful implementation of the proposed system was therefore the
management of the fast charging that charges the bus with sufficient electricity for it to arrive at the next bus stop. Additionally, reducing the weight of the storage device mounted on the bus was a key issue.

In this paper, an electric bus system that is rapidly charged at every bus stop, using electric power generated from renewable energy sources is described, and in order to compensate for the assumption of 20-second short stop at a bus stop, a wireless voltage control system supplying maximum power within the normal voltage range of the lithium-ion battery is introduced for the management of the fast charging. Then, the electric bus simulator is constructed by extrapolating the parameters obtained from the single-passenger electric vehicle, and its validity is confirmed. The simulations in some characteristic cases are performed, and the results are examined, especially the change of the state of charge (SOC) of the battery mounted on the bus, the energy charging to the bus at the bus stop and the travel time including the stoppages of 20 s at each bus stop. Finally, the capacity of the storage equipment for the full-scale electric bus and the specifications of the bus stop are estimated using the constructed simulator, in particular the capacity of the solar modules.

This article is based on the paper presented at the International Workshop on Environmental & Engineering hosted by Japan Society of Mechanical Engineers (Kawashima, 2014).

2. Proposed electric bus system

Figure 1 illustrates an electric bus system that is rapidly charged at every bus stop, using electricity generated from a solar energy source. Carbon dioxide emissions can be reduced by about 50% by changing conventional vehicles with internal combustion engines to electric vehicles. However, the mileage of a single charge of these electric vehicles is only about 150 km owing to the constraint of battery weight, even with a lithium-ion battery. Electric vehicles, in particular large ones, are less attractive than conventional vehicles, because the energy density of lithium-ion batteries is approximately 1% that of gasoline. As a result, the use of electric buses has been limited to public corporations.

![Fig. 1 Illustration of the electric bus system rapidly charged at every bus stop, using electricity generated from a solar energy source.](image)

Additionally, environmental considerations have led to a re-examination of railway transportation, reflecting a “modal shift”. This has been applied to buses, more specifically to trolley buses. However, most trolley bus routes have been discontinued because [1] the cost of laying overhead contact wires is high, [2] tall vehicles cannot go through areas where overhead contact wires pass, and [3] the adverse impact on the landscape. In Japan, trolley buses are currently operated on only two lines in the long tunnels of the Kurobe-Tateyama Alpine route, where other vehicles are not permitted and where environmental damage is considered to be the greatest problem for maintaining the landscape. Based
on these considerations, the intermittent charging of buses at every bus stop has been proposed (Fujioka, 2006).

The electric bus in the proposed system combines the merits of an electric vehicle with those of a trolley bus. The electric bus would carry a motor and a small storage device, for example, lithium-ion batteries or capacitors. The storage device only needs to store sufficient energy for the bus to travel to the next bus stop. The small capacity of the storage device is one of the primary features of this system. Current collectors are also installed, as in a trolley bus. When the bus stops at a bus stop, the storage device is rapidly charged by the electricity supplied from the overhead contact wires installed at each bus stop. Charging continues for approximately 20 s, during which passengers get on and off the bus, and then several further seconds during which the bus accelerates away from the bus stop. The charged electric bus then travels to the next bus stop as an independent electric vehicle.

To achieve zero carbon dioxide emissions, this bus must run on electricity generated from renewable energy sources. Renewable energy sources are of low density and widely distributed. Therefore a high number of and widely distributed power plants are required for effective power generation; a citywide network of bus stops fits this description. In other words, the bus stop is a suitable location to generate renewable electricity.

Therefore, an electric bus system was proposed that was rapidly charged at every bus stop, using electricity generated from a solar energy source. The electric power that charges the bus is generated by photovoltaic modules installed near each bus stop. The effectiveness of this system was confirmed by demonstration experiments that used a golf cart with current collectors powered by capacitors as a model bus. The voltage of the capacitor was stabilized by a DC-DC converter. The golf cart was able to repeat the cyclic operation of running as an independent electric vehicle for approximately 100 s, stopping to charge for 20 s, and then accelerating with the electricity supplied by the contact wires for approximately 2 s. The area of the photovoltaic modules required at every bus stop was estimated for the actual operation of a fixed-route bus (Kawashima and Fujioka, 2008).

Next, the lithium-ion battery and capacitor were compared as potential storage devices for this system, which required a boosting charge. Both were found to have advantages and disadvantages, and could be used for the proposed system. Additionally, methods were proposed to calculate the capacity of these storage devices. The validity of the bus system was confirmed by a demonstration experiment, using a more-full-scale-car-like single-passenger electric vehicle that was driven by two in-wheel motors and powered by a lithium-ion battery or capacitor (Haseo and Kawashima, 2010). A photograph of the model bus and the model bus stop is shown in Fig. 2. The overhead contact wires were 6 m long in order to supply electricity to the model bus while the bus started and accelerated.

![Fig. 2 Model bus based on single-passenger electric vehicle and model bus stop with boosting charge system. The lithium-ion battery and capacitor were compared as potential storage devices for this system. Both were found to have advantages and disadvantages, and could be used for the proposed system. Then, the validity of the bus system was confirmed by a demonstration experiment, using this electric vehicle (Haseo and Kawashima, 2010).](image)

Then, a minivan, which allows changing the number of passengers, was selected as the experimental vehicle running in our campus, and it was converted to an electric vehicle. And the reliability of the proposed electric bus system, in which the bus is charged rapidly at every bus stop using solar energy, was confirmed by the demonstration experiment, that is to say, the proposed bus was able to continue operations. Additionally, in order to determine the capacity of the storage device to minimize this weight, a simulator calculating the energy consumption between bus stops including the
effect of number of passengers was developed by extrapolating the parameters obtained from the converted electric minivan, and the minimum capacity of the storage device mounted on the bus and the required capacity of the photovoltaic modules to be installed near each bus stop were calculated (Kawashima, 2015a).

A similar transit system, known as a “contact-wireless trolley bus” or a “hybrid trolley bus”, has been introduced. This system, in which capacitors and pantographs are mounted on the bus, is currently operated in Shanghai, China. The pantographs are expanded to charge capacitors when the bus stops at the bus stop. After charging, the pantographs are compressed and the bus departs. The bus travels to the next bus stop as an independent electric vehicle. The main difference between the Shanghai system and the proposed system is that in the latter, to reduce stoppage time, electricity is supplied to the bus not only while it is stationary at the bus stop but also while it accelerates departing from the bus stop. Furthermore, in the proposed system electrical power was generated from renewable energy sources through distributed power plants located near bus stops. In Japan, a hybrid electric bus that was equipped with both an internal combustion engine and an electric motor was tested between the international and domestic terminals of Haneda International Airport in 2008. The bus was charged by a non-contact feeding system. However, it was charged in the garage, not on the road while passengers were getting on and off. A wireless charging bus is also tested in Mannheim, Germany from 2013. The bus was charged using the coil installed in each bus stop by the electromagnetic induction type wireless system during which passengers get on and off. In Sapporo, Japan, two types of hybrid battery trams were tested during the winter of 2007–2008. The trams were equipped with lithium-ion batteries (Ogasa, 2010) or nickel-hydrogen batteries (Akiyama, 2008) and ran on electrical power supplied by an overhead contact wire. The batteries were charged when the tram was in contact with the overhead contact wire, and the trams ran on power stored in the batteries when they were not in contact with the overhead contact wire. The purpose of the Sapporo system, which was different from that of our proposed system, was to reduce the cost of facilities such as overhead contact wires, in case the tracks had to be extended. A Battery-Driven Train (ACCUM) was be put to practical use in Karasuyama Line, East Japan Railway Company from March, 2014. The train runs by collecting electricity by the pantograph and charges the mounted storage battery in the electrified section, then it runs by battery in the non-electrified section.

But few efforts have investigated the system using electric power generated from green energy sources.

The management of boost charging is one of the key technologies for the proposed public transportation system. For charging the maximum power under the assumption of 20-second short stop at a bus stop, the constant current charging within the normal voltage range of the battery is required, because the difference between the maximum charging voltage of the lithium-ion battery and the rating voltage is not large, and the charging voltage thereby easily reaches the maximum charging voltage. Additionally, the internal resistance differed for every battery by the degradation. Therefore, the voltage control of the battery terminal is important. In addition, if the battery terminal condition is transmitted to the DC-DC converter through the current collectors, many contact wires are required. The facility thereby becomes complex. Therefore, a wireless charging voltage control system is developed for the proposed electric bus model, that is to say, a system to control the terminal voltage of the battery by changing the output voltage of the DC-DC converter.

Figure 3 shows the block diagram of the electric bus system with rapid charging at every bus stop, using solar energy and the wireless charging voltage control system (as shown by the dotted line). The system composed of a battery management board, a microcomputer board with a wireless transmitter, and a microcomputer board with a wireless receiver. The battery cell voltages were measured by the battery management board (Demo board for LTC6802-2 manufactured by Linear Technology Co.). The measured data were sent to the microcomputer board (AKI-H8/3052F produced by AKIZUKI DENSHI TSUSHO Co., Ltd.), and the total voltage of the battery was calculated. The result was transmitted to another microcomputer board to control the output voltage of the DC-DC converter through the small wireless transmit and receive units (WCU-241D manufactured by Keitsu Electric Co., Ltd.).

Then, the effectiveness of the proposed system was demonstrated experimentally. The system was mounted on the single-passenger electric vehicle as shown in Fig. 2. It was driven by two in-wheel motors of 500 W rated power and a maximum velocity of about 30 km/h. Two current collectors were installed on the roof. Two batteries were mounted on the rear and connected in series. Each battery had seven cells and the total rated voltage was 53.2 V.

In the model bus stop, the power was generated by solar cell modules that were rated at 10.7 kW and were installed on the roof of our school building. The generated power was stored in a lithium-ion battery with a rated voltage of 181 V and capacity of 40 Ah. The electricity was supplied to the model bus through the DC-DC converter (JSLGM200-96-
204 manufactured by Nippon Stabilizer Industry Co., Ltd.; The maximum output voltage and current are 96 V and 204 A, respectively), the overhead contact wires, and the current collectors. The feeding time was extended by using long contact wires, because it allowed the model bus to feed during the departure acceleration. A pick-up guide was installed at the approach end of each contact wire to ensure easy contact with the current collector (Fig. 2). For safety, the control system was also installed on the overhead contact wires. The electricity supply turned on automatically when contact between the contact wires and collectors was confirmed, and turned off automatically when the collectors reached the other edge and when no contact between the wires and the collectors was detected.

In the experiment, the model bus drove twice around our school building for 70 s (about 420 m), stopped at the model bus stop for 20 s to charge, and then started and accelerated with electricity supplied by the contact wires. At the bus stop, the model bus stopped near the approach end of the contact wires and accelerated to the other edge similar to a trolley bus. This running pattern was repeated five times. The voltage of the mounted battery, output current from the battery, input current from the collector, pedal position, and revolution speed of the in-wheel motor were measured at 10-ms intervals by a portable data logger (NR-2000 manufactured by KEYENCE Co.).

Figure 4 shows the experimental result with the charging voltage control, and represents the voltage changes of the battery (bold lines) and the charging current changes (solid lines) of the middle three of the five repeats. The maximum charging voltage of the mounted lithium-ion battery is 58.8 V (broken line), and the maximum charging current is 90 A. Although the charging current decreases gradually in the middle of charging, the terminal voltage is held under the maximum charging voltage. It is found that this system is almost able to perform the boosting charge at the maximum charging voltage under the conditions. And, the battery degradation can be reduced and the risk of the battery damage decreases. Therefore, it is verified that the proposed wireless charging voltage control system is effective and the assumption of 20-second short stop at a bus stop is acceptable.
3. Electric bus simulator

The main feature of the proposed electric bus system is the reduction in the required capacity of the mounted storage device, as it only needed to store the electricity needed to reach the next bus stop. This can lead to a reduction in the weight of the electric bus, which is currently the main obstacle to the practical deployment of electric buses. To fully exploit this feature, it is necessary to estimate the energy consumed between bus stops and to ascertain the minimum capacity of the mounted storage device with which the bus is able to continually operate. To determine this, a simulator is developed to calculate the energy consumption of the electric bus. The simulation parameters for the full-size electric route bus are extrapolated from those of the single-passenger electric vehicle shown in Fig. 2.

3.1 Single-passenger electric vehicle

The inputs for the simulator are distance, slope pitch, maximum and minimum velocities, and the maximum torque rate (i.e., the position of the accelerator pedal) for each running pattern. The running pattern consists of acceleration, running at a constant speed, and deceleration, and is divided across the bus route by signals and bus stops. The outputs are the running distance, the energy supplied by the battery, and the energy charged to the battery, including the regenerative energy. Therefore, the motor controller characteristics follows those of the in-wheel motor installed on the single-passenger electric vehicle.

Although an accurate simulation model can be developed with the inclusion of the dynamic characteristics of electrical systems, such as the motor and the battery, the number of parameters increases together with the time and effort required. Therefore, the electric bus model is represented as a single mass particle shown in Fig. 5.

The equation of motion for the model is as follows:

\[ \frac{m}{dt^2} = F - R - (C + K) \frac{dx}{dt} - mg \sin \theta \]

where \( m \) is the mass of the bus; \( F \) the driving force calculated from the motor torque with considering the tire radius; \( R \) the running resistance; \( C \) the damping coefficient; \( K \) the back electromotive force constant; and \( \theta \) the inclined angle of the slope.
The power consumption $P$, the driving force $F$, the running resistance $R$, the damping coefficient $C$, the back electromotive force constant $K$ and the regenerative power $P_r$ are identified based on the acceleration, coasting, and deceleration running test results changing the throttle position. An example of experimental test results is shown in Fig. 6. The solution of the dynamic equation (1) is obtained as follows:

$$v = v_\infty + (v_\infty - v_0) \exp \left( -\frac{t}{\tau} \right)$$

where, $v_0$ is the initial velocity, $v_\infty = (F - R - mg \sin \theta)/(C + K)$ is the terminal velocity, $\tau = m/(C + K)$ is the time constant. The terminal velocity and the time constant are decided through trial and error, and the parameters are identified. The approximated lines of the acceleration running (red line) and the deceleration running with regenerative braking (blue line) are also shown in Fig. 6. The identified relationship between the throttle position and the electric power consumption is shown in Fig. 7 with the experimental results. And the identified relationship between the vehicle velocity and the regenerative power (red line) is shown in Fig. 8 with the experimental results.

Additionally, the torque is limited by the maximum power. In the single-passenger electric vehicle, the regenerative brake is also manipulated by the brake pedal. It is therefore assumed that the regenerative brake is manipulated in an ON-OFF like manner. Furthermore, it is assumed that the electric vehicle continues to decelerate because of the constant force by the combined use of the regenerative brake and the foot brake at velocities below 7.31 km/h, because the regenerative brake torque gradually weakens according to the velocity.
The validity of the single mass model and the identified parameters was confirmed by the model experiment. The velocity and the power consumption estimated by using the identified bus model are shown in Figs. 9 and 10, with the experimental results under the conditions of the model bus accelerating on the flat road, decelerating using the regenerative brake and stopping to turn right, climbing the slope of 0.0436 rad and accelerating on the flat road, decelerating using the regenerative brake to turn left, accelerating on the flat road and decelerating using the regenerative brake to turn left, accelerating on the flat road, decelerating using the regenerative brake and stopping to turn left, then accelerating on the flat road and descending the slope of 0.0698 rad by adjusting the velocity and accelerating on the flat road, and decelerating using the regenerative brake and stopping.

From these figures, the simulation results of the vehicle’s velocity and the power consumption agree with the experimental results. This confirms the validity of the single mass model and the identified parameters.
3.2 Full-size electric bus simulator

The simulation parameters for the full-size electric bus are derived by extrapolating from those of the single-passenger electric vehicle data. The mass of the full-size bus is assumed to be 15,300.0 kg and the mass of the single-passenger electric vehicle is 207.4 kg. The mass of the full-size bus is therefore about 73.8 times that of the single-passenger electric vehicle. The tire diameter of the full-size bus is 0.99 m and that of the single-passenger electric vehicle is 0.38 m. The tire diameter of the full-size bus is therefore about 2.6 times that of the single-passenger electric vehicle. The power consumption $P$ of the full-size electric bus model, the driving force $F$, the running resistance $R$, the damping coefficient $C$, the back electromotive force constant $K$ and the regenerative power $P_r$ are therefore obtained by multiplying the parameters of the single-passenger electric vehicle model by 73.8, and the coefficients concerning the velocity of the damping coefficient $C$, the back electromotive force constant $K$ and the regenerative power $P_r$ are obtained by divided them by 2.6 or $2.6^2$ according to the power of the velocity. These parameters are expressed as a function of the vehicle mass $m$ and the tire diameter $d$ as follows:

1. Acceleration running
(1) Relationship between the throttle position $T_p$ [%] and the electric power consumption $P$ [kW]:

\[ P = m(13.1 \cdot T_p - 0.410) \] (3)

(2) Relationship between the throttle position $T_p$ [%] and the driving force $F - R$ [N]:

\[ F - R = m(-1.21 \times 10^{-4} \cdot T_p^2 + 0.0403 \cdot T_p - 0.141) \] (4)

(3) Relationship between the throttle position $T_p$ [%] and the coefficient $C + K$ [kg/s]:

\[ C + K = m(3.02 \times 10^{-4} \cdot T_p + 0.0646)/d \] (5)

2. Coasting
(4) Running resistance $R$ [N]:

\[ R = 0.504 \cdot m \] (6)

(5) Coefficient $C + K$ [kg/s]:

\[ C + K = 0 \] (7)

3. Deceleration running with regenerative braking
(6) Relationship between the vehicle velocity $dx/dt$ [m/s] and the regenerative power $P_r$ [kW] after the dead time of 1.3 s:

\[ P_r = 0 \quad \text{in the dead time}, \] (8a)

or

\[ P_r = m \left(0.0174 \left(\frac{dx}{dt}\right)^2 - \frac{0.629}{d} \cdot \frac{dx}{dt} + 2.89\right) \quad \text{in the velocity over 19.0 km/h}, \] (8b)

or

\[ P_r = 0 \quad \text{in the velocity under 19.0 km/h}. \] (8c)

(7) Running resistance $R$ [N]:

\[ R = 1.73 \cdot m \quad \text{in the dead time}, \] (9a)

or

\[ R = 0 \quad \text{in the velocity over 19.0 km/h}, \] (9b)

or

\[ R = 1.01 \cdot m \quad \text{in the velocity under 19.0 km/h}. \] (9c)
(8) Coefficient $C + K$ [kg/s]:

\[ C + K = 0 \text{ in the dead time,} \quad (10a) \]

or

\[ C + K = 0.102 \cdot \frac{m}{d} \text{ in the velocity over } 19.0 \text{ km/h,} \quad (10b) \]

or

\[ C + K = 0 \text{ in the velocity under } 19.0 \text{ km/h.} \quad (10c) \]

For simplicity, it is assumed that the accelerator pedal in the acceleration is manipulated discretely at three set torque rates of 100%, 50%, and 0%. The torque rate is set to 100% when driving uphill to keep the acceleration and the other rate is set to 50%. It is assumed that the storage device consisted of lithium-ion batteries and that the bus is operated using the energy between 40–70% of the battery capacity, i.e., the SOC of 40–70% for the boosting charge. In the simulation results, the capacity of the storage device is set to 60 MJ, and the initial SOC is set to 60% for the fast charging.

4. Simulation results and considerations

4.1 Fixed-route bus simulation

The bus route from the Atsugi Bus Center to the Tobio Housing Complex via the Kanagawa Institute of Technology is selected. This route included four steep slopes. They are 410, 335, 85, and 170 m in length, have average gradients of 2.68, 2.98, 5.88, and 4.10%, and are 3.76, 6.94, 7.38, and 7.78 km, respectively, from the departure bus depot. Both ways of the route are divided into 85 running patterns, and the distance, the pitch of the slope, and the maximum and minimum velocities of each running pattern are used as input for the simulator.

The representative simulation result are shown in Fig. 11 and 12. Figure 11 shows the time histories of the vehicle velocity (a bold line) and the power including the regenerative power (a solid line). This figure includes the result of the bus climbing in a time between about 550 s and 650 s. Each running pattern is confirmed.

![Fig. 11](image)

**Fig. 11** Changes of the vehicle velocity and the power including regenerative power. This figure includes the result of the bus climbing in a time between about 550 s and 650 s. Each running pattern is confirmed.

![Fig. 12](image)

**Fig. 12** Change of the SOC of the battery mounted on the bus. Although the SOC was less than 50% halfway to the bus terminal because of the uphill, it had been recharged to 60% at the last bus stop as a result of the power regeneration on the return route because of the downhill. This demonstrates that continuous operation is possible.
The input travel distance is 16.61 km and the distance calculated by the simulator is 16.44 km. The relative error is therefore 1.02%. The validity of the simulator can be confirmed.

From Fig. 12, although the SOC decreases for running uphill on the outward journey, the SOC is returned at the terminal for running downhill on the return journey. This therefore demonstrates that continuous operation is possible using the estimated battery capacity.

The travel time set by the bus operator is 22 min (1320 s) for the outward journey and 23 min (1380 s) for the return journey, and the calculated travel time is 3164 s. The relative error is 17.2%, because the calculated travel time includes the stoppages of 20 s at each bus stop.

For comparison, the simulation in the case of no passenger is conducted. As the results, the energy charged at every bus stop is 2.22 MJ for the continuous operation, the travel distance is 16.43 km, and the travel time is 2943 s. The travel time is shortened because the weight of the bus is reduced by 28.7% and the maximum torque rate as the simulation input makes large acceleration. Next, the maximum torque rate is reduced by 42% in order to equalize the travel time. As the results, the energy charged at every bus stop is 2.09 MJ, the travel distance is 16.44 km, and the travel time is 3164 s. The consumption energy is reduced by 13.6%.

Then, the maximum torque rate for running uphill is reduced by half and equalized to the other rate for the lightweight and the energy conservation. The simulation result are shown in Fig. 13 and 14. Figure 13 includes the result of the bus climbing in a time between about 550 s and 650 s. Figure 14 shows the SOC of the battery mounted on the bus in the case that the bus is charged the energy of 2.36 MJ at every bus stop for the bus is able to operate continuously. And the travel distance is 16.44 km, and the travel time is 3205 s. The consumption energy is reduced, although the travel time is increased because of lower acceleration. In this case, the rated power of the motor can be reduced by half, then the weight of the bus can be saved.

From these results, it is clarified that the energy consumption is affected by not only the bus route but also the maximum torque rate. The other simulation results in the case of running on flat road only, the case of constant decelerating using the mechanical brake for comfortable riding, the case of improving the performance of regenerative brake and the case of increasing the maximum velocity by a speed-up gear were reported (Kawashima, 2015b).
4.2 Specification of the lithium-ion battery mounted on the bus and the bus stop

The capacity of lithium-ion battery mounted on the bus is estimated based on the simulation results of the fixed route bus, that is, the bus is charged the energy of 2.42 MJ at every bus stop. When it is assumed that the charging voltage at the bus stop is 600 V and the charging time including the time during which the bus accelerated while being fed from the contact wires is 23 s, a charging current of 176 A is required. The lithium-ion battery cells mounted on the bus can be charged to 6C, which means that a charging current of 180 A is possible if the capacity of each battery cell is 30 Ah. The maximum charging voltage of each cell is 4.1 V, and the rated voltage is 3.8 V. Under these conditions, the bus-mounted storage device can be designed as 147 battery cells connected in series, resulting in a total capacity of 60 MJ and corresponding to energy required for about 60% of the energy of a round trip. This confirmed that the capacity and weight of the mounted storage device in the proposed electric bus can be greatly reduced compared with a generic electric fixed-route bus.

Furthermore, the discharged or charged energy in one round trip is 104 MJ. The bus is therefore able to operate for at least 1700 roundtrips, under the assumption that the life of the lithium-ion battery is 3000 cycles of full charging and discharging. It will be expected that the bus is able to operate for more than 1700 roundtrips because the mounted lithium-ion batteries are charged and discharged in an SOC of 50–70%.

4.3 Estimation of the bus stop specification

Next, the bus stop is considered. The maximum voltage of the contact wire is 600 V and the maximum current is 180 A. The DC-DC converter is therefore set to limit the voltage to 600 V and the current to 180 A, and to automatically change between constant-current and constant-voltage functions.

The storage device is connected to the photovoltaic modules that are installed near the bus stop and to the commercial power source through the power conditioner (Fig. 3). Therefore, power shortages from the photovoltaic modules in bad weather or at night are compensated for by a commercial power source; surplus power generated by the photovoltaic modules is fed into this commercial power source. The storage device installed on the bus stop is required for the boosting charge. The capacity must be several times the boosting charge energy to the bus in order to prevent large currents being supplied by the commercial power source. The device can be expected to function as a power supply in an emergency.

The rated generating power of the photovoltaic modules is estimated by assuming that the energy of the discrete boosting charge to the bus is smoothed by the batteries and the commercial power source. Additionally, it is assumed that the photovoltaic module with a nominal maximum output of 1 kW generated 1,200 kWh in a year and that the bus is operated at 15 min intervals from 06:00 to 23:00, i.e., the bus stop supplied electrical power to the bus 69 times. Under these assumptions, the bus stop supplies a power of 167 MJ per day. Therefore, each bus stop requires photovoltaic modules rated at 14.1 kW. It needs the installation area of 70.5 m² under the assumption that the conversion efficiency is 20%. This area is too large to install it on the roof of the bus stop, then the photovoltaic modules must be installed around the bus stop at this time.

5. Conclusions

First, the electric bus system is described, in which the bus is rapidly charged at every bus stop using solar energy. This system is able to reduce carbon dioxide emission.

One of the main characteristics of the proposed electric bus system is the low weight of the storage device on the electric bus. To determine the capacity of the storage device and minimize this weight, a simulator is constructed that calculates the energy consumption between bus stops by extrapolating the parameters obtained from the single-passenger electric vehicle. The results confirm that the proposed bus is capable of continuous operations, and the influence of some parameters is examined.

Then, the minimum capacity of the storage device mounted on the fixed-route bus is designed. It is confirmed that the capacity of the storage device can be decreased.

Finally, the required capacity of the photovoltaic modules to be installed near each bus stop is estimated.
Acknowledgement

This work was supported by the “High-Tech Research Center” Project for Private Universities through a matching fund subsidy from MEXT (Ministry of Education, Culture, Sports, Science and Technology, Japan), 2007-2011.

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