Development and Application of a Bilateral DC-DC Converter for an Energy-saving Type Battery Charger and Discharger

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Abstract

It is proposed and examined how to develop an energy-saving type battery charger and discharger system. This system mainly consists of two sets of batteries and a microcomputer controlled bilateral up/down dc-dc converter. At first, three types of bilateral dc-dc converters were constructed with various switching elements and their efficiency characteristics were investigated, then the most suitable model was selected and recommended for realizing an energy-saving type battery charger & discharger.
Next, various charging and discharging experiments for lead-acid batteries were tried, a mathematical model of the battery was proposed and a decision method for the battery model parameters was also described. These model parameters are useful in the diagnosis of batteries to estimate their remaining life. The battery charger & discharger proposed in this research can be applied for reuse techniques of deteriorated lead-acid batteries.

Keywords

bilateral dc-dc converter, microcomputer controlled, energy-saving, battery charger & discharger

1. INTRODUCTION

For developing an EV (Electric Vehicle), bilateral dc-dc converters are useful because of the necessity for drive and regenerative brakes for the driving motors [Hattori et al., 2001]. Moreover, it is important to estimate the mileage for the running pattern of the EV.
We have proposed and developed various types of dc-dc converters. For example, a bilateral up/down dc-dc converter with a forward function only and another one with forward-backward bi-directional movement.
In order to estimate the mileage, we have made an electrical equivalent circuit of a racing EV driven by a dc motor and have simulated numerically the drive performance of the EV considering its battery characteristics [Hattori et al., 2002, Hattori et al., 2003]. Many times charging and discharging measurements for the battery were needed to get the battery characteristics. Therefore, electrical energy for the discharging state was wasted as thermal energy in a resistor element.
In this research, we propose an energy-saving type battery charger & discharger, which consists of two sets of batteries with electric double layer capacitors, an ac-line rectifier and a micro-computer controlled bilateral up/down dc-dc converter, for the purpose of improving on the above mentioned energy waste.
Such an energy-saving battery charger & discharger is necessary for determining the parameters of the equivalent circuit of a given battery, and also useful in the diagnosis and reuse technique of deteriorated lead-acid batteries.

2. BIRATERAL DC-DC CONVERTERS AND SWITHING ELEMENTS

We have proposed various types of bilateral dc-dc converters according to their application. The effi-ciency of the dc-dc converter depends on its structure and switching elements. In order to select a suitable circuit model for an energy-saving type battery charger and discharger system, three types of dc-dc converters have been constructed and investigated as described in the following section.

2.1 Step-down converter constructed by IGBT and it's characteristics

A bilateral step-down dc-dc converter with reversible polarity is shown in Figure 1. This dc-dc converter has been developed for driving an inverted-pendulum type EV in our laboratory. This circuit mainly consists

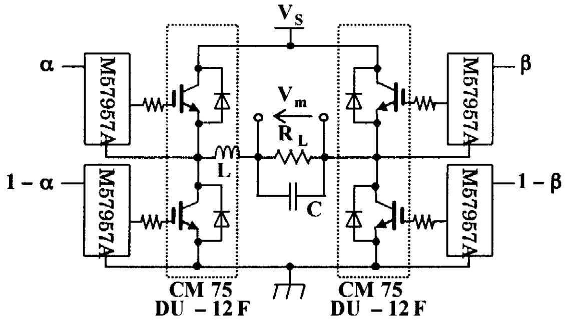


Fig. 1 Step-down dc-dc converter constructed with IGBT

of IGBT (Insulated Gate Bipolar Transistor): CM75DU-12F (600V, 75A) and gate driving hybrid IC: M5795A (± 15V). Each hybrid IC is supplied by its own isolated power source. In Figure 1, α is duty factor (α =ton/T, ton : turn-on interval, T: switching period) and (1- α) works in complement with α . In this case, α can take a value between ($0 \leqq \alpha \leqq 1.0$) because of the independent power source for each gate driving IC. β and (1- β) have the same relationship as between α and (1- α). Gate driving signals α , (1- α), β and (1- β) are generated and a controlled by microcomputer (H8/3048F: 16bit, 16MHz, 128kB Flash ROM, A/D, D/A, PWM, etc.).

The relationship between the source voltage Vs and the output voltage Vm is as follows.

$$Vm = (\alpha - \beta) \cdot Vs \qquad (1)$$

The load resistor RL in Figure 1 is used to measure the efficiency characteristics of the dc-dc converter. The efficiency η vs. output power Pout is shown in Figure 2 with the parameters of the load resistors.

Figure 2 shows that the efficiency for Pout =70W is about 83% and the one for 150W is about 92%. The reason why the efficiency is not so high for this circuit originates from the loss of the gate driving IC (about 7.5W altogether).

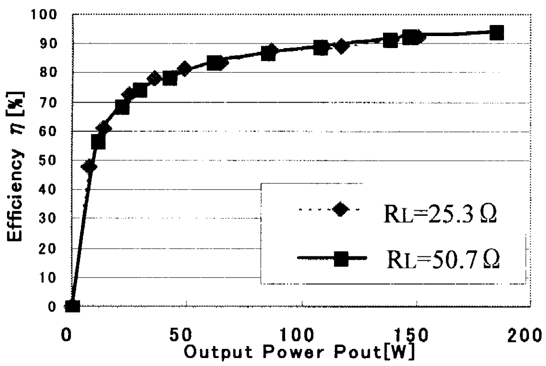


Fig. 2 Efficiency characteristic of step-down converter

2.2 Up/down converter with reversible polarity constructed with IPM and FET and their characteristics

A bilateral up/down dc-dc converter with reversible polarity is shown in Figure 3. This dc-dc converter has been developed in our laboratory for driving a small, low-speed, one-person EV sometimes called the "Senior Car". The relationship between Vs and Vm is as follows.

$$Vm = (\beta - \gamma)/ \alpha \cdot Vs \qquad (2)$$

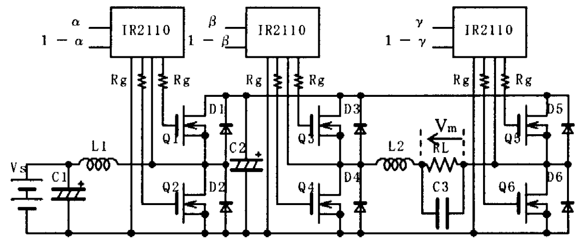


Fig. 3 Up/down dc-dc converter with reversible polarity

This circuit was tested with several combinations of main switching and gate driving elements as follows:

(a) Circuit A : FET(IRF3710, 100V, 57A, 23m Ω) + Driver IC(IR2110) [$0 \leqq \alpha , \beta , \gamma \leqq 0.95$]
(b) Circuit B : FET(IRF3710) + Photo Coupler + Transistor [$0 \leqq \alpha , \beta , \gamma \leqq 1.0$]
(c) Circuit C : IPM(PM30CSJ060,600V,30A) + Photo Coupler [$0 \leqq \alpha , \beta , \gamma \leqq 1.0$]
(Where, IPM means Intelligent Power Module.)

Figure 3 shows the case of "Circuit A" which needs only one power source for the driver IC because of the adoption of a boot-strap circuit for high-side gate turn-on. Therefore, the high-side FETs can not continuously be kept in a turn-on state. "Circuit B" and "Circuit C",

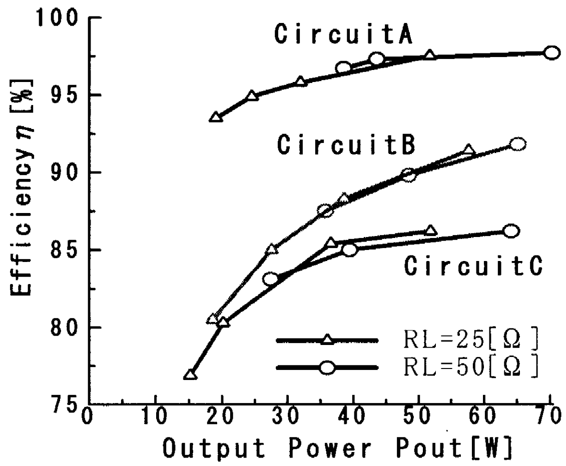


Fig. 4 Efficiency of up/down converter

on the other hand, use isolated power sources for each gate drive circuit. α, β, γ, therefore, can take the value 1.0, which means a continuous turn-on state.
The efficiency characteristics for these circuits are shown in Figure 4.
Figure 4 shows that the efficiency for Pout = 70W, "Circuit A" is about 97%, "Circuit B" is about 92% and "Circuit C" is about 85%. These results suggest that "Circuit A" is the most suitable for developing an energy-saving type battery charger & discharger.

2.3 Up/down converter with fixed polarity constructed with FET and its characteristics

From the results of 2.1 and 2.2, it is clear that the dc-dc converter constructed by the combination of FET and Driver IC has good efficiency. As battery charging and discharging use does not need a polarity reversible function, we have constructed a microcomputer con-trolled bilateral dc-dc converter with fixed polarity by using FET and Driver IC as shown in Figure 5.

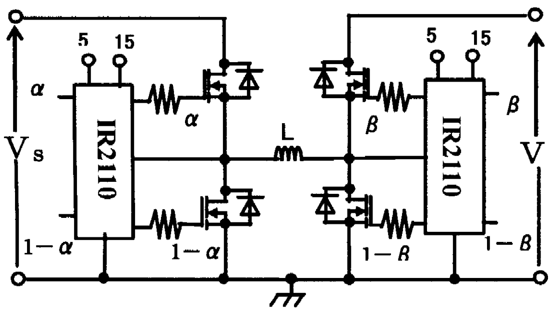


Fig. 5 Up/down converter with fixed polarity

This converter is also useful for driving a racing EV that requires only a forward movement function. The relationship between Vs and Vm is as follows.

$$Vm = \alpha / \beta \cdot Vs \quad [0 \leqq \alpha, \beta \leqq 0.95] \qquad (3)$$

The efficiency vs. output power of this converter with the load resistor (RL=25 Ω) was measured as shown in Figure 6. And, Figure 6 shows that the efficiency for Pout=70W is about 94% and for 150W it is about 98%. The power loss of the microcomputer and Driver ICs together is less than 1W.

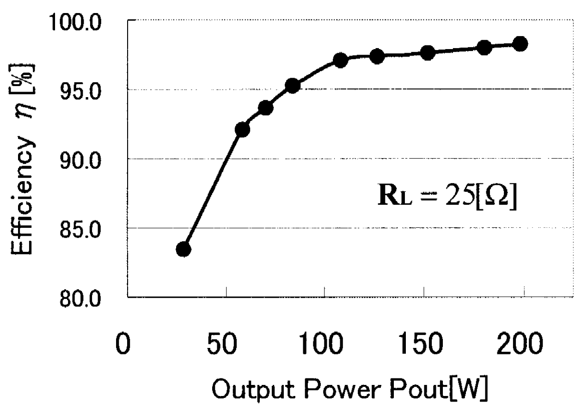


Fig. 6 Efficiency of the converter of Fig. 5

3. DEVELOPMENT OF AN ENRERGY SAVING TYPE BATTERY CHARGER AND DIS-CHARGER (C&D) SYSTEM

3.1 Necessity of energy-saving type battery C & D system

It is important to know quantitatively a battery's behavior in charging and discharging states for develop-ing an EV.
Therefore, it is required that a mathematical model for a given battery should be derived from its charging and discharging characteristics.
Examples of measured data for a new battery [12V, 7.5Ah] are shown in Figure 7 and Figure 8.
Figure 7 shows a decreasing curve of no-load voltage of the battery after it is fully charged. This decreasing phenomenon almost ceases after 20-30 minutes.

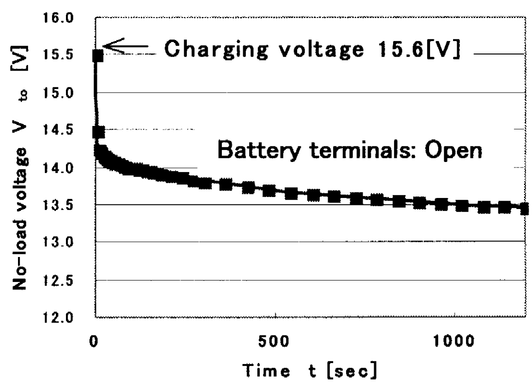


Fig. 7 No-load voltage after charging

Figure 8 shows the curves of (4A discharging + Open + 4A discharging) and (7A discharging + Open + 1A charging + Open + 4A discharging). In Fig.8, restoration phenomena are observed for no-load terminal voltage after discharging, but the same no-load steady state voltage gives a unique discharging curve.

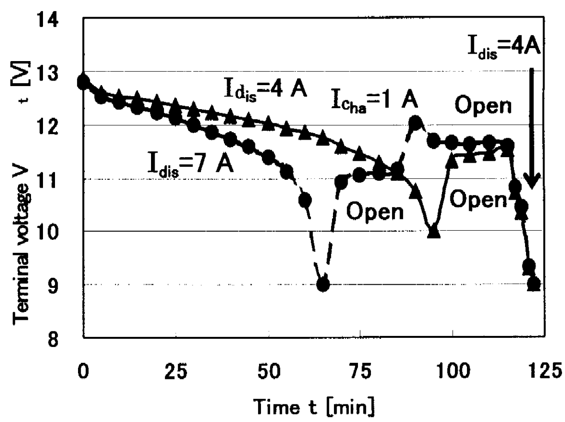
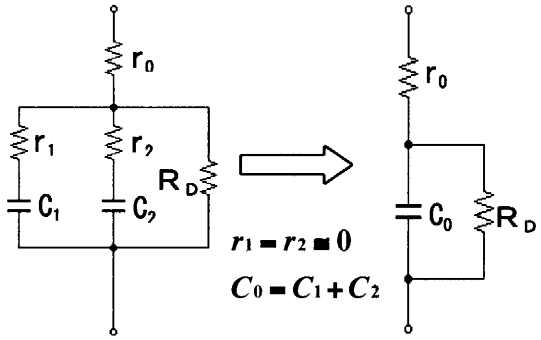


Fig. 8 Behavioral examples of the battery

As shown in Figure 7 and Figure 8, battery behaviors are very complicated. Therefore, a mathematical model for a battery should be like Figure 9-(a), at least, to express the restoration phenomenon, however, Figure 9-(b) is convenient for practical discharging use.
In a practical discharging state, as $R_D \fallingdotseq \infty$ [Ω], then C_0 and r_0 are derived from the following equations referring to Figure 10.



(a) General model (b) Practical model

Fig. 9 Simplified model for a battery

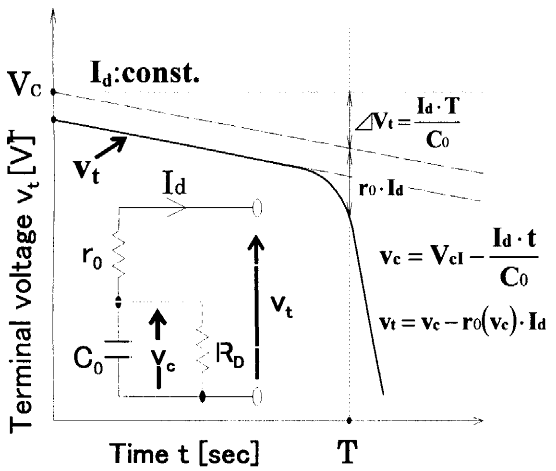


Fig. 10 Decision method for model parameters

$$C_0 = I_d \cdot T / \Delta v_t \quad (4)$$
$$r_0 = (V_{cI} - v_t) / I_d \quad (5)$$

In order to decide the model parameters, many charging and discharging processes are inevitable. Therefore, an energy-saving type battery charger & dis-charger is necessary.

3.2 Structure of the C & D system

In this section, we propose an energy-saving type battery charger & discharger as shown in Figure 11, for the purpose of improving energy waste that occurs in the charging and discharging process.
In Figure 11, battery 2 is the object battery for charging. First of all, battery 2 is charged from an ac power source

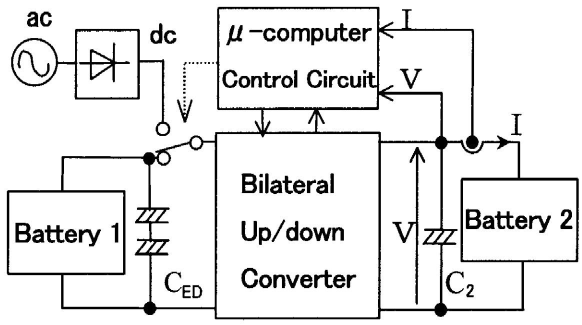


Fig. 11 Energy-saving battery charger & discharger

through a rectified circuit and a bilateral up/down dc-dc converter under a specified condition of microcomputer control. Next, battery 2 can discharge through the bilateral circuit toward battery 1, which is in parallel with electrical double layer capacitors under a specified condition. At this time, if battery 2 is required to be charged again, battery 1 can charge battery 2.
Therefore, a discharging and charging process with less loss can be realized by using this proposed equipment. In the bilateral up/down dc-dc converter in Figure 11, we have adopted the polarity fixed type converter shown in Figure 5.

4. APPLICATION OF THE ENERGY-SAVING TYPE C & D SYSTEM

4.1 Application for diagnosis of batteries

In order to decide the mathematical model parameters for a given battery, we measured discharging characteristics of a new battery [12V, 7.5Ah] under various constant-discharging currents as shown in Figure 12.

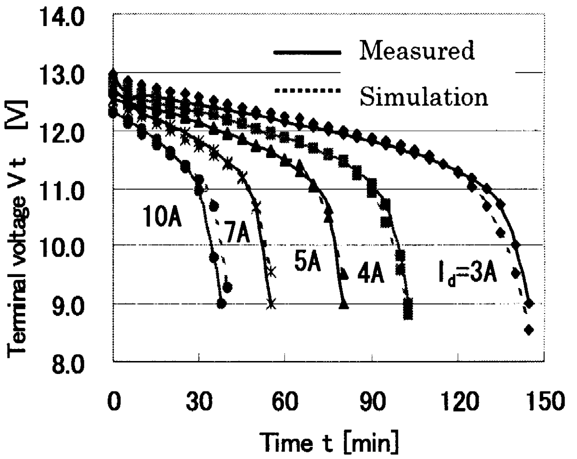


Fig. 12 Discharging characteristics (new battery)

The no-load terminal voltage just before discharging V_{cI} (= open voltage) is about 13.25V for each curve. The initial value of R_D (that is R_{DI}: the value of just finished charging) was estimated as 73.5 Ω .
Figure 13 shows the relation between the decrement ratio of terminal voltage ΔV_T for interval T (=50min)

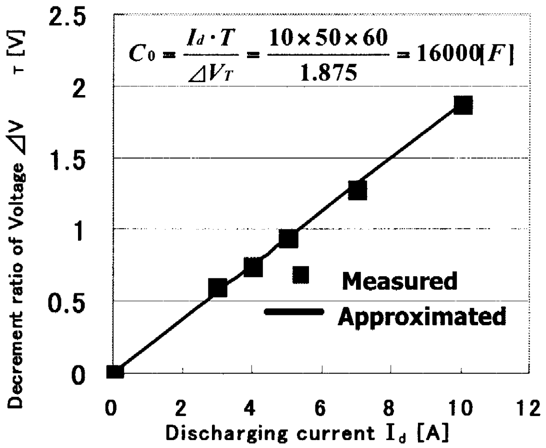


Fig. 13 Decision method of equivalent capacitance

and the discharging current I_d ,which is obtained from Figure 12. It is observed from this graph that ΔV_T is approximately proportional to I_d. Therefore, we can obtain an equivalent capacitance C0 from equation (4).

In this case C_0 equals about 16000[F]. Next, we treat the equivalent internal resistor r_0 as the function of the battery internal voltage v_c, and the initial value of $r_0(v_c)$ is defined as r_{0I}. We can obtain $r_0(v_c)$ from Figure 12 by using the equation (5).

The experimental results are described approximately as the following single equation with two parameters.

$$r_0(v_c) = r_{0I}\left\{1 + \left(\frac{13.5 - v_c}{13.5 - V_{d0}}\right)^n\right\} \quad (6)$$

Where, $r_{0I} = 0.1[\Omega]$, $V_{d0} = 11.85[V]$, $n = 14$

The simulation results are also shown in Figure 12 with dotted lines, and it can be seen that both measured and simulated results have good similarity each other.

Figure 14 shows the discharging curves of an old (deteriorated) battery [12V, 38Ah], where each solid and dotted line corresponds to the measured and simulation results, respectively.

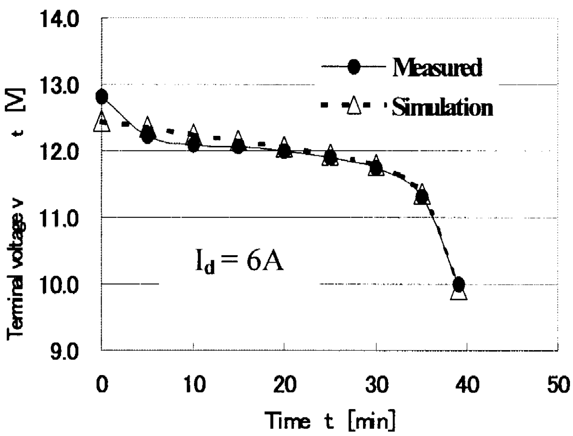


Fig. 14 Discharging characteristics (old battery)

This battery was charged at 16.25V and the final stable charging current was 0.37A, then the R_{DI} (Initial value of the equivalent parallel resistor R_D) was estimated as about 44 Ω . The remaining model parameters and the discharging parameters for this battery were obtained as follows.

$$\left.\begin{array}{l} C_0 = 18000F,\ r_{0I} = 0.14\ \Omega,\ V_{d0} = 12.55V, \\ n = 14,\ \ I_d = 6A,\ V_{cI} = 13.3V \end{array}\right\} \quad (7)$$

From these results, an old or deteriorated battery has a tendency to decrease in C_0 and R_{DI}, and to increase in r_{0I} and V_{d0}, compared with a new battery. For example, this deteriorated battery [12V, 38Ah] would be expected to have C_0 = 80000F if it were new, but it has only 22.5% of this expected value.

These changes in batteries' model parameters can be applied to diagnose and estimate the remaining life of a given battery.

4.2 Application for reuse technique of deteriorated batteries

It has been reported recently that a deteriorated battery can be made active again through repeated slow charging and discharging with a few organic polymer additives in the battery [Kozawa et al., 2002]. Many deteriorated lead-acid batteries have an accumulation of PbSO4 on the negative electrode of each battery. An additive, such as PVA polymer, is used to remove the PbSO4 from the negative electrode. As one of the C & D system applications, we tried to measure the restoration characteristics of a deteriorated battery by adding PVA polymer in the battery.

We used the same battery [12V, 38Ah] experimented with and examined in the former section as a deteriorated battery. We charged it at 2A to the fully charged state for about two days and discharged it at 30-35A several times, then measured its discharging characteristics at 6A. The results of the experiments are shown in

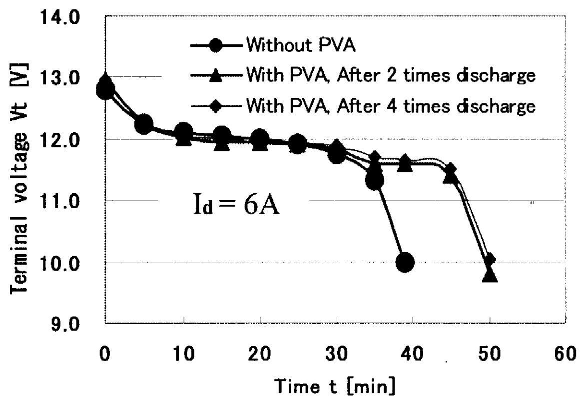


Fig. 15 Improved characteristics for a deteriorated battery

Figure 15.

Figure 5 shows that adding PVA polymer in the deteriorated battery is effective to some extent, however, more experiments are required to establish the magnitude of improvement. Therefore, we are going to continue the experiments.

5. CONCLUSION

An energy-saving type battery charger & discharger system was proposed and its development was examined. In the three types of bilateral dc-dc converters constructed with various switching elements, a FET type bilateral up/down dc-dc converter with fixed polarity was selected and recommended for its high-efficiency to realize the C & D system.

Various charging and discharging experiments for lead-acid batteries were tried, and a mathematical model of the battery was proposed. In addition, a decision method for the battery model parameters was also described. It was confirmed that these model parameters are useful in the diagnosis of batteries to estimate their remaining life. Moreover, it was clarified that "the battery charger & discharger" proposed in this research is also useful in the application of reuse techniques of deteriorated lead-acid batteries by adding a few organic polymer additives.

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References

Hattori, M., J. Ohuchi, T. Oizumi, H. Goto, Y. Egashira, and Y. Abe, Proposal and Development of High-performance Commuter E.V. with Low-voltage Type Battery, *FIRST CIRCULAR OF CHINA-JAPAN ELECTRIC VEHICLE JOINT CONFERENCE* (in Beijing), 187-193, 2001.

Hattori, M., Y. Egashira, Y. Ohmori, and T. Oizumi, Development and Evaluation of a Racing EV for Energy-saving Contest (EV Ecorun in SUGO), *Journal of Asian Electric Vehicles*, Vol. 1, No. 1, 63-68, 2003.

Hattori, M., Y. Egashira, Y. Ohmori, and T. Oizumi, Development and Evaluation of Driving System for EV using a Brush-less DC Motor, *Research Reports of Sendai National College of Technology*, No. 32, 85-92, 2002.

Hattori, M., Y. Egashira, Y. Ohmori, and T. Oizumi, Development of an Energy-saving Racing EV using Brush-less Dc motor, *Journal of Asian Electric Vehicles*, Vol. 1, No. 1, 121-124, 2003.

Kozawa, A., M. Yamashita, S. Ikeda, Y. Tagawa, J.C. Nardi, and S. Minami, Reuse of Deteriorated Lead-acid Batteries by A New Reactivation Treatment in For Cities of China : Beijing, Shanghai, Shenzhen,and Shengdu, *Asian Electric Vehicle Conference-2 Abstracts* (Held in Osaka, Japan), 42, 2002.

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