High Efficiency Series Chopper Power Train for Electric Vehicles Using a Motor Test Bench

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Many researchers have studied electric vehicles (EVs) for improving their efficiency to increase the driving range. The system design of an electrical power train has significant influence on the total driving range per charge and has been widely researched. A series chopper power train using a buck-boost chopper has been proposed as an electrical power train system. This electrical power train achieves high efficiency due to low and high inverter input voltage in the low and high speed regions, respectively. In previous studies, a high efficiency control optimizing the chopper output voltage was proposed, and a motor test bench with characteristics similar to actual EVs was constructed by using a battery emulation system with voltage variation characteristics, which occur due to the state of charge (SOC) and internal resistance. This paper shows the effects of optimizing the chopper output voltage on the driving range per charge in both efficiency estimation and the motor test bench experiment. This allows the verification of the usefulness of optimizing the chopper output voltage for increasing the efficiency. The results indicate an improvement of 0.9\% and 2.7\% in the driving range per charge during efficiency estimation and the motor test bench experiment, respectively.

Keywords: electric vehicle, buck-boost chopper, motor test bench, power electronics

1. Introduction

Electric vehicle (EV) is expected to save the total energy consumption of the world\textsuperscript{(1)}. One of problems of the EV is that the driving range per charge is shorter. Considering the capability of the present battery storage and cost, the EV is suitable for the urban driving which is for short distance commuters\textsuperscript{(2),(3)}. From the view point of practical use of commuter EV’s in a city area, a prediction of the actual driving range is given by the urban driving patterns such as JC08 mode in Japan or LA-4 mode in USA. These measurement regulations are strictly controlled by laws\textsuperscript{(4)}. Under such a driving mode, the total driving distance of the EV can be treated as a function of multiple factors, such as efficiencies of each electrical instrument, battery characteristics, and structure of electrical power train.

The structure of electrical power train has a large influence to the total driving range per charge. Therefore, many researchers developed and proposed systems, that have advantages over the conventional electrical power train as shown in Fig. 1\textsuperscript{(5)}. Fratta \textit{et al}. proposed the system, which has a boost converter inserted between the battery and the inverter. In this system, the EV can run at high speed regions when the battery has low SOC (State of Charge). Estima \textit{et al}. showed the improvement of the efficiency by using a converter\textsuperscript{(6)}. However, the minimum voltage of the inverter input voltage is fixed to the battery voltage.

In order to solve this problem, the series chopper power train using the buck-boost chopper as shown in Fig. 2 was proposed\textsuperscript{(7)}. This system is capable of having the equivalent characteristics to the boost chopper, and the efficiency of the inverter can be increased by step-down conversion of the chopper at the low speed regions.

In the previous research\textsuperscript{(7)}, the actual EV called “KANA” was used as shown in Fig. 3. The electrical power train can be changed to the non-chopper power train and the series chopper power train. The driving range per charge with and without the chopper was compared by using the actual EV. As the result, the usefulness of the series chopper power train using a buck-boost chopper was shown. However, these experiments had two problems. One was that the experiments could not be performed many times because of the long time and high cost. The other was that the results were not theoretically supported.

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In order to solve the first problem, the motor test bench was constructed in the previous research (8). By using the motor test bench, many studies about the series chopper power train have been published (8)–(10). These previous studies showed the following achievements;

- Efficiency optimization of the chopper output voltage in the series chopper power train (8).
- Construction of the battery emulation system and application of flux weakening control to the inverter (9).
- Evaluation of the effects of the chopper output voltage and the weight of the chopper (10).

From the above, a motor test bench with the same environment as the actual EV was constructed. The experiments of the driving range per charge could be performed by using the motor test bench. The usefulness of the series chopper power train using a buck-boost chopper was shown by using the result from the experiments of the motor test bench.

However, the efficiency estimation was not performed yet. Therefore, the effect of the chopper output voltage, the weight of the chopper, and so on could not be estimated.

In this paper, the effect of the chopper output voltage using the driving range per charge can be evaluated by using the efficiency estimation based on motor test bench experiments. This makes it possible to verify the usefulness of the series chopper power train with a buck-boost chopper by using the result from the efficiency estimation. This paper provides the optimization for the series chopper power train and the results of the efficiency estimation, the motor test bench experiments, and the actual EV experiments. The outline of this paper is shown in Fig. 4.

This paper is organized as follows. In Sect. 2, the electrical power trains of the EV are described. Section 3 shows the equipment of the motor test bench. Section 4 shows the compatibility between the motor test bench and the actual EV. Section 5 shows the effect of the optimization of the chopper output voltage by using the efficiency estimation and the motor test bench. Finally, Sect. 6 concludes this paper.

### 2. Electrical Power Train for EV

The typical EV electrical power train has battery-inverter-motor combination as shown in Fig. 1. The DC voltage is converted into three phases by the inverter to drive a motor. This kind of electrical power train is called a “non-chopper power train” in this paper. Non-chopper power train has advantages because of the simplicity and well-established technology. However, from the viewpoint of energy saving, non-chopper power train has disadvantages. At the high speed regions, a high voltage is required for the motor. However the inverter input voltage is fixed to the battery voltage. The minimum voltage of the battery is designed based on the voltage required for driving at high speed regions. On the other hand, at low speed regions, high voltage is not required. Therefore, the inverter is applied with extra voltage, which leads to a decrease of efficiency in the inverter and the motor. At a low SOC and high speed regions, the lack of voltage is compensated by the flux weakening control (11). However, as the battery voltage drops, this compensation is not achieved. Therefore, the maximum speed is dropped (see Fig. 5).

If the DC link voltage is variable, the motor and inverter efficiency of various speed regions can be optimized. From these considerations, the series chopper power train was proposed as shown in Fig. 2. This kind of electrical power train is called “series chopper power train” in this paper.

In the series chopper power train, the DC-DC chopper is required to have functions of the buck-boost mode, high efficiency, compactness, light weight, and high reliability. SAZZ (Snubber Assisted Zero voltage Zero current Switching)
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chopper is one of the candidates \cite{12}. The circuit of the SAZZ chopper is shown in Fig. 6. The SAZZ chopper is composed of “capacitors $C_{chop \_in}$ and $C_{chop \_out}$”, “main switches $S_1$, $S_2$, $S_3$, and $S_4$”, “reactors $L_1$, $L_2$, and $L_3$”, “auxiliary switches $S_{1a}$, $S_{2a}$, $S_{3a}$, and $S_{4a}$”, “snubber capacitors $C_1$, $C_2$, $C_3$, and $C_4$”, “snubber diodes $D_1$, $D_2$, $D_3$, and $D_4$”, and “regeneration diodes $DRB_1$, $DRB_2$, $DRB_3$, and $DRB_4$”. The SAZZ chopper is a bidirectional buck-boost chopper which can conduct the zero voltage and zero current switching by using the snubber capacitors and the auxiliary switches. In the literature, 98% efficiency was reported at four quadrant operation with 25 kW output power.

3. System of Motor Test Bench

3.1 Basic Configuration of Motor Test Bench The motor test bench consists of chopper, inverter, motor, and DC power supply. The experimental equipment and the diagrams of electrical power trains are shown in Figs. 7–9. The motor test bench is based on the actual EV \cite{7}. The motors and the SAZZ choppers of the same specifications are used in the motor test bench and the actual EV. The specifications of each equipment are shown in Tables 1 \cite{11,13}. The specifications of the motor, the inverter, and the chopper are same between the motor test bench and the actual EV. Although, the manufacturer of the inverter is different.

The EV is composed of the battery, the chopper, the inverter, and the motor. There is a difference of the DC power supply and the actual battery between the motor test bench and the EV. In order to perform the experiments on the same condition of the actual EV, the DC power supply needs to emulate the Li-ion battery.

3.2 Battery Emulation System The system of the DC power supply needs to have two characteristics in order to emulate the Li-ion battery. The first one is the battery voltage variation corresponding to the SOC (i.e. capacity consumption). The second one is the battery voltage variation corresponding to the current and internal resistance.

Table 2 and Fig. 10 show the battery characteristics of a single cell Li-ion battery. This is a representation method for adjusting the characteristic condition of each battery. However, the actual battery is composed of 80 cells. In order to achieve the battery voltage variation corresponding to the SOC, the discharge characteristics were measured. The experimental result on the condition is shown in Fig. 11, when the discharge current is fixed to 25 A. The discharge current (25 A) is decided by considering the load torque of the JC08 mode and the battery characteristics. In many regions of the JC08 mode, battery output current is less than 25 A. The capacity ratio is 100% at 25 A. As experimental result, the battery capacity is 20736 mAh. The battery voltage is 334 V at the SOC = 100% and 208 V at the SOC = 0%.
4. Compatibility Between Actual EV and Motor Test Bench

4.1 Comparison This part shows the comparison between the motor test bench and the actual EV by running the JC08 mode. JC08 mode is the driving pattern that is regulated by Ministry of Land, Infrastructure, Transport and Tourism in Japan. The speed command of the driving pattern is shown in Fig. 13.

In JC08 mode, the driving resistance such as the acceleration and deceleration force, the friction force and the aerodynamic force are determined by the characteristics of each vehicle. The total driving resistance torque is calculated from the function of the acceleration and deceleration force $F_{acc}$ [N], the friction force $F_{rol}$ [N], and the aerodynamic force $F_{air}$ [N] from (3) to (5). The load torque is calculated by (6) and Table 3.

$$F_{acc} = M \frac{d(\omega_m)}{dt},$$

$$F_{rol} = \mu M g,$$

$$F_{air} = \frac{1}{2} \rho A C_d (\omega_m)^2,$$

$$T_{load} = r F_{all} = r (F_{acc} + F_{rol} + F_{air}),$$

where $\omega_m$ [rad/s] is the angular velocity of the motor, $T_{load}$ [Nm] is the load torque, $F_{all}$ [N] is the total driving resistance force, $M$ [kg] is $M_{car}$ or $M_{car} + M_{chop}$, and other variables are shown in Table 3.

The load torque is achieved by the load motor in the motor test bench. In the experiment using the actual EV, the EV runs using the JC08 mode on the chassis dynamometer. The chassis dynamometer is an instrument used to measure power...
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Table 4. Comparison methods of drive system

| Power train     | Measurement range | Total weight [kg] | Profile                  |
|-----------------|-------------------|-------------------|--------------------------|
| Case 1          | Non-chopper       | 334 - 250 V       | $M_{car}$                |
| Case 2          | Series chopper    | 334 - 208 V       | $M_{car} + M_{chop}$ (i) in Fig. 14 |
| Case 3          | Series chopper    | 334 - 208 V       | $M_{car} + M_{chop}$ (ii) in Fig. 14 |

Table 5. Results of comparison between motor test bench and actual EV

| Results from motor test bench | Results from actual EV | Error    |
|-------------------------------|------------------------|----------|
| Distance                      | Ratio in Case 1        | Distance | Ratio in Case 1 | Distance | Ratio |
| Case 1                        | 86.3 km                | 100.0%   | 85.6 km         | 100.0%   | 0.8%  | 0.0%  |
| Case 2                        | 86.8 km                | 100.5%   | 85.8 km         | 100.2%   | 1.2%  | 0.3%  |

by running on the roller, which achieves the load torque.

The comparison in this paper is divided into three cases as shown in Table 4 and as follows;

**Case 1: Non-chopper power train**

The non-chopper power train is used. The total weight is $M_{car}$. In comparison, the maximum speed of the EV specifications can not be achieved if the battery voltage becomes below 250 V as shown in Fig. 5. Therefore, the motor test bench repeated the JC08 mode until the battery voltage is reduced from 334 V to 250 V.

**Case 2: Series chopper power train and profile (i)**

The series chopper power train is used. The total weight is $M_{car} + M_{chop}$. The chopper output profile is shown in Fig. 14 (i) and following equation.

$$V_{chop\_out} = \begin{cases} 
3.5\omega_m, & (3.5\omega_m \geq 150) \\
150, & (3.5\omega_m < 150)
\end{cases} \cdots \cdots (7)$$

The DC voltage can be boosted by the chopper in the series chopper power train. Therefore, the motor test bench repeated the JC08 mode until the SOC of the battery is reduced from 100% to 0% (from 334 V to 208 V).

**Case 3: Series chopper power train and profile (ii)**

The series chopper power train is used. The total weight is $M_{car} + M_{chop}$. The chopper output voltage profile is the optimizing voltage profile as shown in Fig. 14 (ii) and next section. The motor test bench repeated the same condition as Case 2.

In this section, Case 1 and Case 2 are discussed, and the driving ranges per charge are compared between the results of the motor test bench and those of the actual EV.

**4.2 Comparison Results Between Motor Test Bench and Actual EV**

Table 5 and Figs. 15–20 show the experimental results when the EV and the motor test bench ran the JC08 mode repeatedly under the condition described in Sect. 3.1. The changes of the battery voltage in the actual EV without and with chopper are shown in Figs. 15–16, respectively. In these figures, horizontal axis means time [s], and the maximum time of one cycle of the JC08 mode is 1204 s. “1st”–“11th” means the cycle number of the JC08 mode. Adjacent lines in one figure are connected. For example, the last
point of the 1st line and the beginning point of the 2nd line are connected. The changes of the battery voltage in the motor test bench without and with chopper are shown in Figs. 17–18, respectively.

From Figs. 15–18, it turns out that the DC power supply voltage shows relative characteristics to the battery successfully. There is a difference between the time when the voltage drops to 250 V and 208 V in the non-chopper power train and the series chopper power train compared with the each power train data. This is because the energy consumption per one JCO8 mode cycle is different as shown later. However, as shown in Fig. 18, when the change of the battery voltage stops, the battery voltage do not reach to the 208 V. This is because the measurement sampling period of power analyzer is lower than the one of the SAZZ chopper (power analyzer: 20 Hz, SAZZ chopper: 25 kHz). The SAZZ chopper judges whether to continue the experiment. Therefore, the instantaneous voltage drop of the chopper input voltage could not be measured in this experiment.

Next, the distance is discussed. Table 5 shows the results of the distance from the motor test bench and the actual EV. In Case 1, the difference of the driving range per charge between the motor test bench and the actual EV is about 0.8%. In Case 2, the difference of the driving range per charge between the motor test bench and the actual EV is about 1.2%. From these results, the ratios of distance in Case 2 to the one in Case 1 are about 100.5% in the motor test bench and about 100.2% in the actual EV. Thus, the difference of these ratios is about 0.3%. From the above, it is proved that each error of the driving range per charge and the distance ratio in Case 2 to the one in Case 1 between the motor test bench and the actual EV is small. Therefore, similar characteristics are also confirmed from the point of view of the distance.

Next, the energy consumption per one JCO8 mode cycle is discussed. Comparison results of the energy consumption are shown in Figs. 19–20. From these results, the difference becomes large. From the result in the non-chopper power train as shown in Fig. 19, there is a difference of about 2.5 Wh (about 1%) between the actual EV and the motor test bench. On the other hand, from the result in the series chopper power train as shown in Fig. 20, there is a difference of about 10 Wh (about 4%). These errors are caused by the following reasons:

- Chopper efficiency due to the variation of the output power between the right wheel and the left wheel.
- Individual difference of each equipment.

Except for the error by the difference of these devices, the shapes of each energy consumption show the same characteristic. Therefore, the motor test bench has the compatibility to the actual EV.

5. Optimization of Chopper Output Voltage

This section shows the method optimizing the chopper output voltage profile using the buck-boost chopper on the series chopper power train (a).

In the high speed regions, when the chopper output voltage is lower than the minimum voltage of the demanded running the speed, the inverter output voltage needs to be compensated by the flux weakening control. Thus, the copper loss increases, and the efficiency of the motor decreases. As the chopper characteristics, the larger the ratio of buck-boost becomes, the worse the chopper efficiency becomes. In order to optimize the chopper output voltage, the following two experiments need to be performed.

(a) The efficiencies of the inverter and motor are measured.
(b) The chopper efficiency in low speed regions is measured.

In the previous research (8), by the experiment (a), the speed reference was changed from 10 km/h to 70 km/h, the torque was changed from 10 Nm to 70 Nm. And the inverter input voltage was changed from 10 V to 330 V. As a result, it turned out the inverter input voltage of the highest efficiency was the minimum voltage to achieve running the speed without the flux weakening control. Thus, in this paper, by using this optimization characteristic, the chopper output voltage is set to the minimum voltage to achieve running the speed in the high speed regions.

In the experiment (b), if the stepping down ratio is too large, the efficiency of the chopper drops significantly. Therefore, only in the low speed regions, the chopper efficiency is measured by changing the value of chopper input voltage and that of chopper output voltage. The chopper input voltage is changed from 210 V to 330 V by 10 V steps. And the chopper output voltage is also changed in the range to achieve running the speed.

The experimental results of the total efficiency of the chopper, the inverter, and the motor are shown in Figs. 21–22 at 10 km/h and 20 km/h. From these figures, the total efficiency becomes maximum value at 10 km/h when the chopper output voltage is about 90 V. And in the same way, the total efficiency becomes maximum value at 20 km/h at about 110 V.

Therefore, the optimized chopper output voltage profile is obtained by connecting these points in the low speed region.

In the high speed regions, the previous paper (8) showed the
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5.1 Efficiency Estimation of Profile Optimization

The overview and calculation flow of the efficiency estimation are shown in Fig. 23. The flow is as follows:

(1) The chopper output voltage was decided by the speed based on the JC08 mode (see Fig. 14).
(2) The total efficiency was decided by the chopper output voltage and the speed (see Fig. 24). The total efficiency was based on the experimental data as shown in Figs. 21–22, and the efficiency table shown later.

(3) The capacity consumption was calculated by the output power and the total efficiency. The battery voltage was decided by the capacity consumption.

(4) The efficiency estimation was determined whether to continue or stop.

(5) The driving range could be calculated by the speed and the sampling time.

From the above, by repeating the efficiency estimation, the driving range per charge can be speculated.

In the comparison, the efficiency table obtained by the experiments in the motor test bench is used. The condition of the efficiency table is follows;

- Constant torque : 50 Nm
- Constant speed : 10, 20, ··· ···, 80 km/h
- Chopper input voltage : 290 V

In this experiment, the data of 20 sec by intervals of 0.05 sec was measured by a power analyzer, and the efficiency table was made by averaging these data. The total efficiencies at using regions of two profiles are shown in Fig. 24.

In the driving range per charge, the total energy consumption is calculated as the following equation;

\[
E = \sum\left(\frac{\omega_{m}T_{load}}{\eta_{tab}}\right)dt
\]

where \(E\) [Wh] is the total energy of the electrical power train, \(T_{load}\) [Nm] is the load torque, \(\eta_{tab}\) is the total efficiency of the electrical power train, and \(dt\) denotes the sampling time of the power analyzer.

By calculating the estimation of the driving range per charge, the effect of the chopper output voltage profile optimization is speculated. In this efficiency estimation, the voltage variation characteristic is used in Fig. 11.

The estimation results are shown in Table 6. From the results, the distance of profile (ii) runs about 1% longer than the one of profile (i). It is expected that the improvement of the driving range per charge can be further increased. However, the distance is about 13% difference between the motor test bench and the efficiency estimation. This efficiency estimation could not consider the transition of the torque, because the efficiency table was measured on the condition of constant torque. In the high torque regions, the flux weakening current is increased. And the increase of the energy consumption of profile (i) is speculated.

5.2 Experiment Using Motor Test Bench

In the motor test bench, the experiments were performed in the same
condition of the efficiency estimation.

The comparison of the energy consumption per one JC08 cycle is shown in Fig. 25. The results of the driving range per charge is shown in Table 7. From Table 7 and Fig. 25, about 2.7% improvement of the energy consumption and the driving range are confirmed. Then, the effect of optimizing the chopper output voltage profile can be confirmed in the motor test bench. The difference of the distance between the efficiency estimation and the motor test bench experiment is caused in the transient property.

Therefore, by optimizing the chopper output voltage, it is also expected about 2.7% further improvement of the driving range per charge in the actual EV.

6. Conclusions

This paper showed the utility of a series chopper power train using a buck-boost chopper by the comparison of the driving range per charge through three approaches: the efficiency estimation, the experiments using the motor test bench, and the experiments using the actual EV. From the results of the driving range per charge in the actual EV and the motor test bench, there were errors of about 1% and 4% of the energy consumption in the non-chopper power train and the series chopper power train, respectively. The compatibility between the motor test bench and the actual EV was shown by the experiment of the driving range per charge. As one method for high efficiency of the series chopper power train, the chopper output voltage was optimized. In the efficiency estimation of the optimization, about 0.9% of the driving range per charge was improved, and in the experiment of the motor test bench, about 2.7% of the driving range per charge was also optimized. From the above, by optimizing the chopper output voltage, the improvement is also speculated in the actual EV using a buck-boost chopper. These results show the utility of the series chopper power train using a buck-boost chopper.

As for future works, improvement of the efficiency estimation will be needed for further high accuracy comparison.

Errors between the actual EV and the motor test bench will need to be reduced for further high accuracy compatibility. In addition, it could be compared in further detail by consideration of the temperature information and discharge current characteristics in the battery system.

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