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High Power Density Battery Charger for Plug-In Micro EV

Shinichiro Hattori*,**, Haruhi Eto*, Fujio Kurokawa***

* Nagasaki University, Japan

** Isahaya Electronics Corporation, Japan

*** Nagasaki Institute of Applied Science, Japan

(sin_hattori@idc-com.co.jp, haruhi-eto@nagasaki-u.ac.jp, kurokawa_fujio@nias.ac.jp)

6-41 Tsukuba, Isahaya, Nagasaki, 854-0065, Japan, Tel: + 81 957 26 3592,

Fax: + 81 957 26 5257.

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Abstract- Household distributed power systems that the renewable energy such as the PV and the wind power are introduced as energy sources are expected to spread in the future as efforts for global decarbonization. EV has already been recognized the role as a battery for the energy management of the household distributed power system. The Micro EV which is a kind of EV requires frequent charging from a household AC outlet due to its small capacity, so it is necessary to suppress the harmonics of the AC power source and charge the battery at an appropriate power factor. For this reason, the charger of micro EV generally has two stages of a converter which performs input control with a PFC (power factor correction) function and a converter which performs charge control. However, the reduction in size and the weight is an important factor for the traveling performance of EVs, and the miniaturization and the weight reduction are also required for the onboard charger. Therefore, in this paper, a method to control the input current and charge control to the battery with a single converter is proposed. By using the proposed single-stage converter, it is possible to dramatically improve the energy density and the power conversion efficiency. Moreover, it is confirmed that the proposed circuit can cope with dc input from the dc bus, and is also an effective application in the dc bus based household distributed power system which is expected to spread in the future.

Keywords dc-dc converter, distributed power system, PFC, single-stage converter, battery charger.

1. Introduction

Household distributed power systems that the renewable energy such as the PV and the wind power are introduced as energy sources are expected to spread in the future as efforts for global decarbonisation[1]. However, the power generation by renewable energy is unstable in the meteorological environment in Japan where there are four seasons and the weather changes frequently[2], the stabilization by the charging and the discharging of batteries which are installed on the ac bus is quite necessary[3-6]. In view of this, the role of EV batteries have been recognized as supporting the household batteries to enhance the power stabilization as well. Also, in Japan where natural disasters occur frequently, EV batteries become an important power source in addition to the renewable energy in the event of a disaster. In that case, the EV is connected to the household distributed power system via the distribution panel as shown in Fig. 1[7-12].

An EV is generally more expensive than a gasoline-powered vehicle, and it takes a long time to charge from a household AC outlet, so it is difficult to be disseminated in areas without quick charging facilities. Therefore, the micro EV that can be charged in a relatively short time even when charging from a household AC outlet is attracting attention as personal mobility for short distance travel such as shopping and delivering luggage, and it is expected to used widely in the future.

In general, the micro EV has a battery charger mounted on the vehicle so as not to require a special charging spot. It is necessary to lighten the weight of the vehicle in order to increase the cruising distance. It is also required for the on-board charger that the charging time is short and being

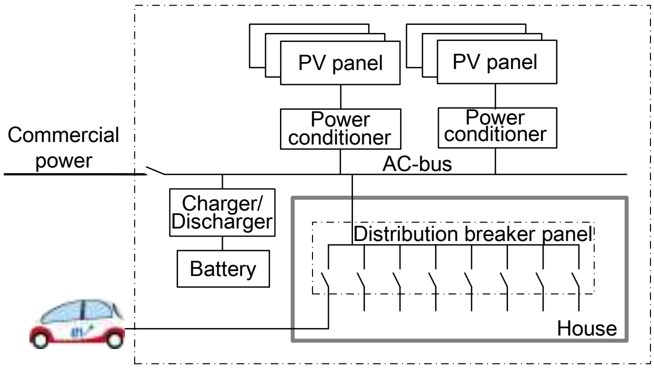


Fig. 1. Configuration of a household distributed power system.

compact and lightweight as well as being able to charge from a household AC outlet. Therefore, in order to reduce the weight of the micro EV, a battery with a small capacity of about 1/10th of the standard EV is mounted. Therefore, charging from a household AC outlet is absolutely necessary so that a battery with small capacity can be charged frequently while parking at home. Generally, a distribution breaker of about 15 A is installed to the household AC power supply, and there is a limitation that the AC current when charging is less than the capacity of the distribution breaker. Therefore, the efficiency of the charger is an important factor in order to obtain the maximum charging output from the limited input capacity.

The conventional charger is a two-stage converter system combining a power factor correction circuit (PFC)[13, 14] and a dc-dc converter[15, 16], which has problem that makes the size of the charger larger and the efficiency lower.

On the other hand, a single-stage converter is a very effective system from the viewpoint of the miniaturization and the efficiency[17-21]. However, there has not been a detailed report on a single-stage converter whose input is the household ac power and whose output capacity exceeds 1 kW so far.

Therefore, in this paper, a method to control the input current and charging power to the battery with a single dc-dc converter for use as a charger of micro EV battery is proposed. This method makes it possible to dramatically improve the power density and improve the power conversion efficiency which are important for miniaturization of the micro EV.

And then, the operation mechanism of the battery charger of the single-stage converter at battery charging is presented, and the improvement of power density and the efficiency is demonstrated by the analysis and the experiment.

2. Circuit Configuration and Operation

Figure 2 shows a block diagram of the proposed single-stage converter type charger. It consists of a rectifier diode for full-wave rectification of the AC input, a low pass filter to eliminate the switching ripple of the main switch, a bridge circuit which is the main switch, an isolation transformer, and a secondary side rectifier diode.

In the control circuit of the proposed single-stage converter, the AC input voltage after rectification is not smoothed but is input to the bridge circuit to perform the power conversion with the pulsating voltage after rectification which has a frequency twice the input frequency. Control of input current and control of average output voltage or average output current are simultaneously performed by one converter to realize PFC function.

As shown in Fig. 3, the conventional charger is a two-stage converter system combining a power factor correction circuit (PFC) and a dc-dc converter. In the case of charging from a household AC outlet, it is necessary to control the input current to a sine waveform by the PFC control circuit of first converter from the viewpoint of suppressing input current harmonics. The PFC circuit which is the first converter performs boost operation and controls the input current in a sine waveform. The dc-dc converter as the second converter stabilizes the output and charges the battery. For this reason, in the case of the conventional two-stage converter method, it is necessary to perform the two-stage power conversion that are from ac to high voltage dc and from high voltage dc to battery voltage dc in order to charge the battery from the household commercial AC power. There is a problem that makes the size of the charger larger and the efficiency lower.

The circuit of the two-stage converter is shown in Fig. 4, and the circuit of the proposed single-stage converter is shown in Fig. 5.

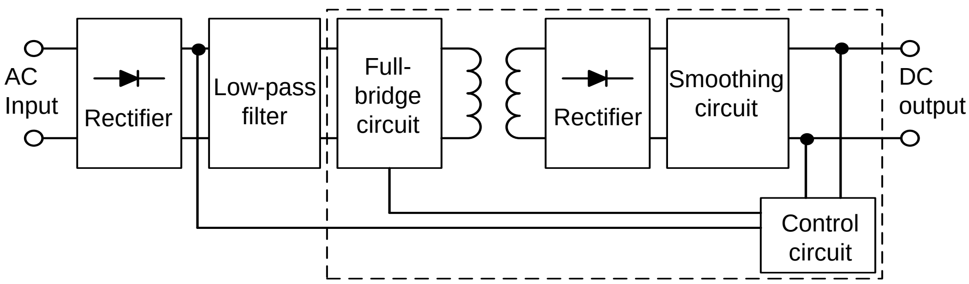


Fig. 2. Block diagram of single-stage converter.

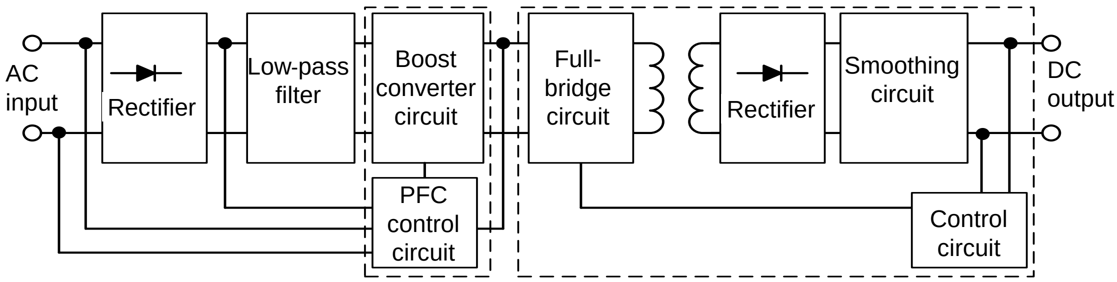


Fig. 3. Block diagram of two-stage converter.

In the two-stage converter, the first converter operates as a Boost Converter. The input current is controlled to a sine waveform, and the boosted power is stored in the capacitor C1 as a high voltage DC. Therefore, a capacitor with high withstand voltage and large capacity are required for the capacitor C1. Since such a capacitor is large in the size and high in the cost, the two-stage converter becomes large in circuit and expensive.

On the other hand, as shown in Fig. 5, in the single-stage converter, there is no boost converter corresponding to the first converter of the two-stage converter. The AC voltage is rectified by the rectifier to be fed directly to the bridge circuit and the input current and the average voltage or current of output are controlled. Therefore, a capacitor with high withstand voltage and high capacity corresponding to C1 in Fig. 4 required for the two-stage converter is not required as well. In addition, a smoothing capacitor with high withstanding voltage and high capacity corresponding to C2 in Fig. 4 is not required.

Therefore, the proposed method of single-stage converter is very effective for miniaturizing the circuit and reducing the cost.

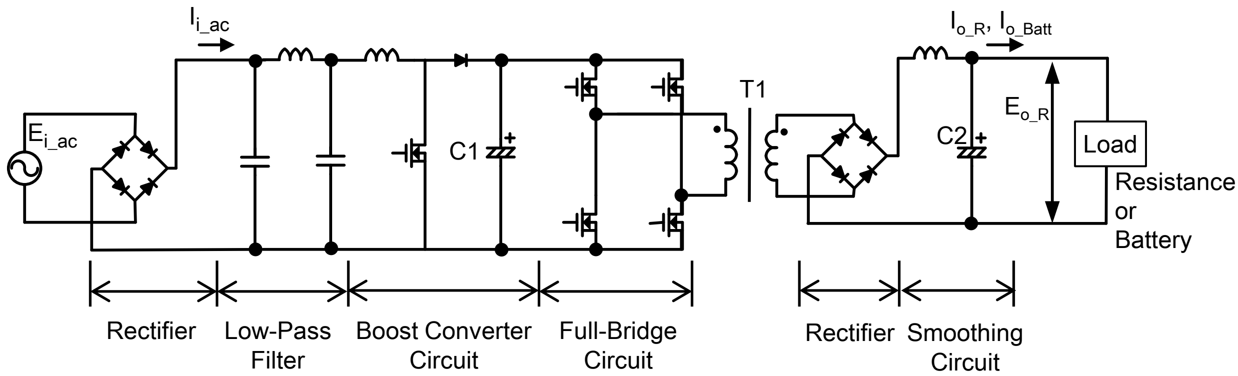


Fig. 4. Conventional configuration of two-stage ac-dc converter for battery charger.

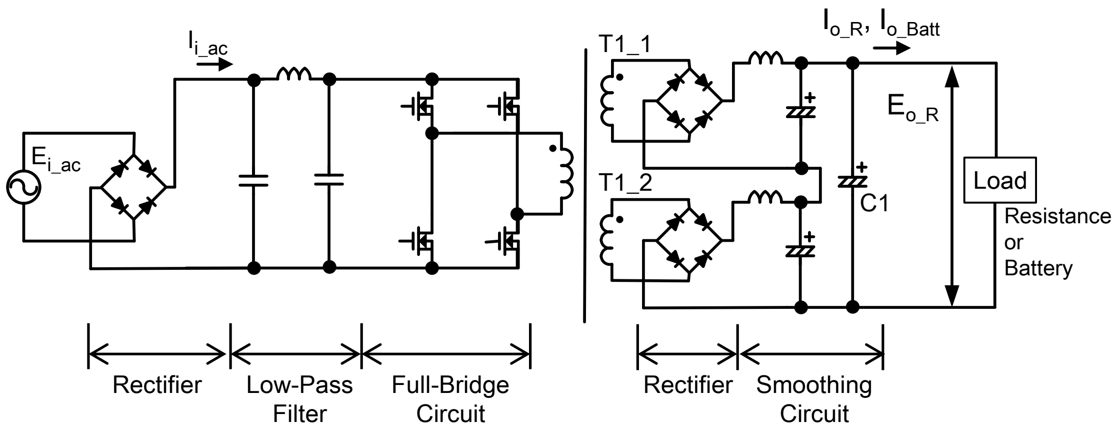


Fig. 5. Proposed configuration of single-stage ac-dc converter for battery charger.

3. Control Method of the Single-Stage Converter

Figure 6 shows the control block diagram of the proposed single-stage converter type battery charger. The converter is controlled so that the average value of the output voltage E_{O_Batt} and the output current I_{O_Batt} are the target value determined according to the specifications of the battery. At the same time, control is performed so that the input current becomes a sine wave.

Specific operation is described below.

Detect output current I_{O_Batt} with A-D converter # 1 and calculate moving average value Ni_{o_avg} with output current average calculator. Ni_{o_avg} is sent to the output current PI controller to perform the control calculation shown in equation (1) and determine the compensation value N_{PI_io} according to the output current.

$$N_{PI_{i_o}} = I_{N_B} + I_{K_P\left(I_{N_R} - Ni_{o_{avg}}\right)} + I\_K_I \sum\left(I\_N_R - Ni_{0\_avg,n}\right) \qquad (1)$$

In the same way, the output voltage E_{O_Batt} detected with A-D converter #2 is also averaged into Ne_{o_avg}. Ne_{o_avg} is sent to the output voltage PI controller to perform the control calculation shown in equation (2) and determine the compensation value N_{PI_eo} according to the output voltage.

$$N_{PI_{e_o}} = V_{N_B} + V_{K_P\left(V_{N_R} - Ne_{o_{avg}}\right)} + V\_K_I \sum\left(V\_N_R - Ne_{0\_avg,n}\right) \qquad (2)$$

The output current compensation value N_{PI_io} and the output voltage compensation value N_{PI_eo} are compared in a comparing calculator, and the smaller value is sent as the output compensation value N_{PI_o} to the input current reference current generator.

In the input current reference generator, obtain the reference value I_{ref} of the input current control by calculating the equation (3) using the sinusoidal wave SWe_{i_ac} synchronized with the phase of the input voltage and the output correction value N_{PI_eo}, and the obtained I_{ref} is sent to the input current PI controller.

$$I_{ref} = \mathrm{SW}e_{i\_ac} \times N_{PI\_o} \qquad (3)$$

In the input current PI controller, the control calculation shown in equation (4) is performed using the input current Ni_{i_ac} detected by the A-D converter # 3 and the reference value I_{ref} of the input current control to determine the control value N_{PI}. The control value N_{PI} is sent to the PWM generator and drives the main switch via the gate drive circuit.

$$N_{PI} = I_{ac_{N_B}} + I_{ac_{K_P\left(I_{ref} - Ni_{i\_ac}\right)}} + I_{ac}\_K_I \sum\left(I_{ref} - Ni_{i\_ac}\right) \qquad (4)$$

In addition, when supplying power from a household outlet, charging is performed changing the reference value of the output current so that the effective current of the input does not exceed 10 A in order to avoid an operation of the distribution breaker.

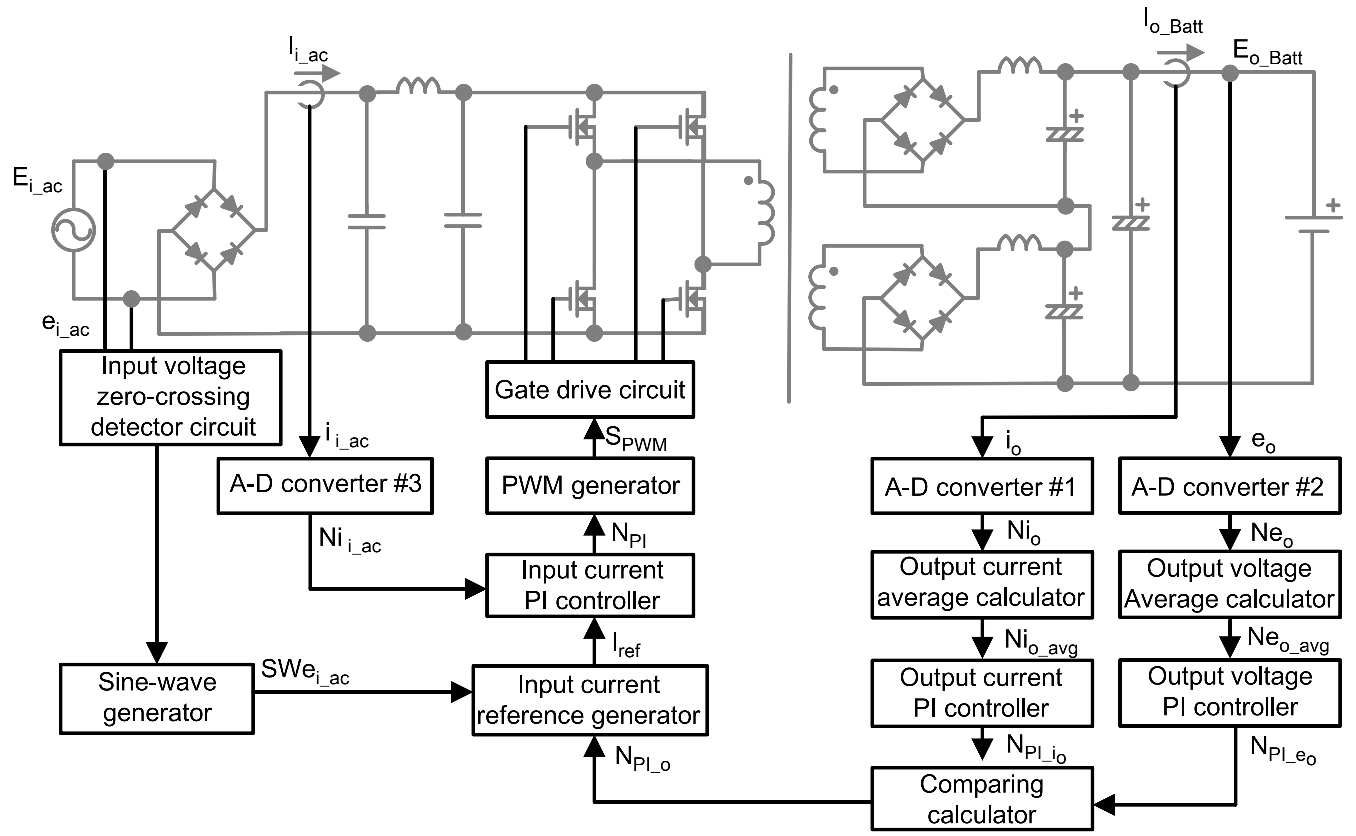


Fig. 6. Configuration of digital control single-stage converter.

4. Design of Converter Circuit

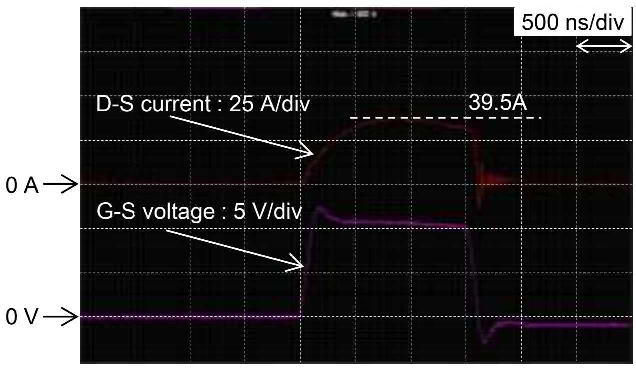
Figure 5 shows a block diagram of the single-stage converter used in this experiment. The bridge circuit is a full-bridge type which a high output voltage can be obtained easily against the input voltage. For a transformer, as described in Section 2, higher turn ratio is necessary in order to obtain higher secondary output voltage. However, when the higher turn ratio is adopted to one transformer, the rectifier diode on the secondary side needs higher withstanding voltage. A rectifier diode with higher withstand voltage generally has higher forward voltage and larger loss. Since the cost of the diode also increases, the rectifier diodes on the secondary side of the transformer are connected in series after rectification so that rectifier diodes with low withstand voltage can be used.

In battery charging, the output voltage of the converter needs to be higher than the battery voltage. Since the single-stage converter performs power conversion from pulsating current voltage obtained by full-wave rectification of AC input by bridge circuit, in the vicinity of the zero cross of the input voltage, the pulsating voltage input to the bridge circuit is low, and as a result the output voltage also becomes low. Therefore, in the vicinity of the input voltage zero crossing point, the electric power necessary for charging is not obtained, and distortion of the input current occurs.

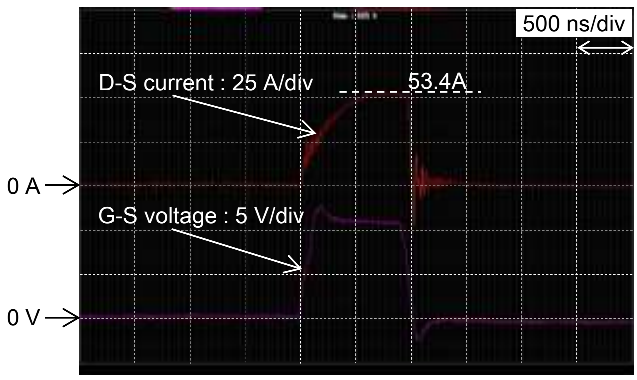
For instance, when the turn ratio of the transformer is doubled from 1: 1 to 1: 2, the on-time of the main switch becomes 1/2 near the peak voltage of the input, and the current flowing through the main switch becomes double. Therefore, the average loss of the switch is doubled and the instantaneous loss is quadrupled, which is a factor of deteriorating the efficiency. Therefore, it is important to decide an appropriate turn ratio in order to obtain characteristics that are comprehensively optimum in operation. In this paper, the optimum turn ratio was determined experimentally by comparing the characteristics at the turn ratios 4:3, 1:1 and 3:4. Since two transformers are used in series in this proposed circuit, the composite turn ratios are 2:3, 1:2, 3:8, respectively.

The switching waveforms at the peak voltage of input when using each transformer are shown in Figs. 7 (a) - (c).

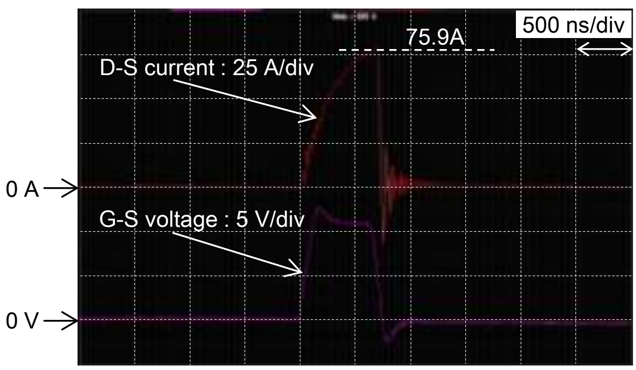
In each transformer, the maximum current, the instantaneous loss flowing through the main switch M1 at the peak voltage of input, the efficiency of converters at 800 W of the output power and the power factor of the input are shown in Table 1.



(a) Turn ratio = 4:3.



(b) Turn ratio = 1:1.



(c) Turn ratio = 3:4.

Fig. 7. Waveform for voltage and current at M1 drain-source.

Table 1. Specifications Corresponding to Turn Ratio

	Case 1	Case 2	Case 3
Turn ratio	4:3	1:1	3:4
Maximum current (A)	39.5	53.4	75.9
Main switch M1 power loss (W)	18.0	21.5	37.1
Efficiency (%)	88.2	84.8	79.1
Power factor (%)	95.0	97.4	98.1

The efficiency of converter and the power factor of converter input of each converter is shown graphically in Fig. 8 and Fig. 9.

This result indicates that the increasing the loss of the main switch by the higher turn ratio is a factor in the efficiency reduction and that a high output can be maintained even in the vicinity of the zero cross point of input voltage by increasing the turn ratio of the transformer.

The efficiency is highest when the turn ratio is 4: 3. As for the power factor, when the turn ratio is 4: 3, it is lower than the others, but the input current harmonic is below the limit value of IEC 61000-3-2 Class A as shown in Fig. 10, and this satisfies the standard. Therefore, priority was given to efficiency that is more important in power conversion, and the turn ratio is determined to be 4: 3.

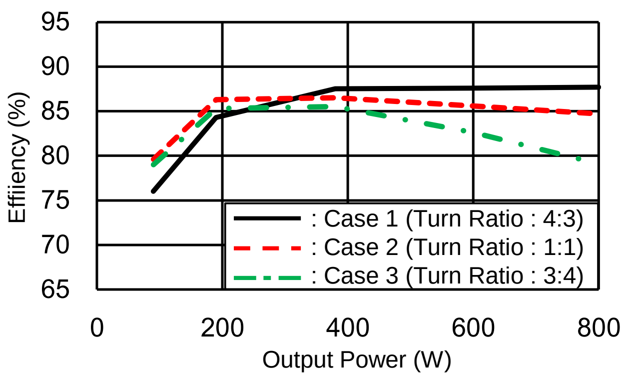


Fig. 8. Efficiency characteristics.

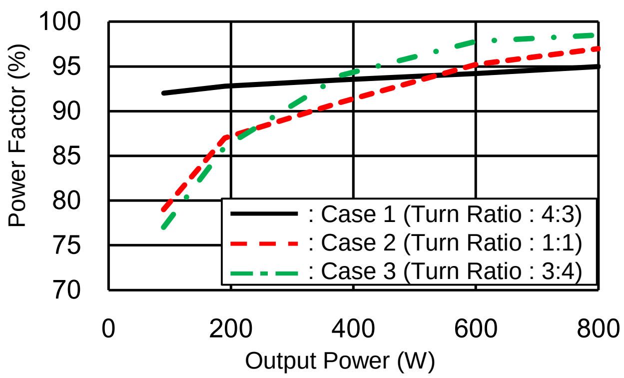


Fig. 9. Power factor characteristics.

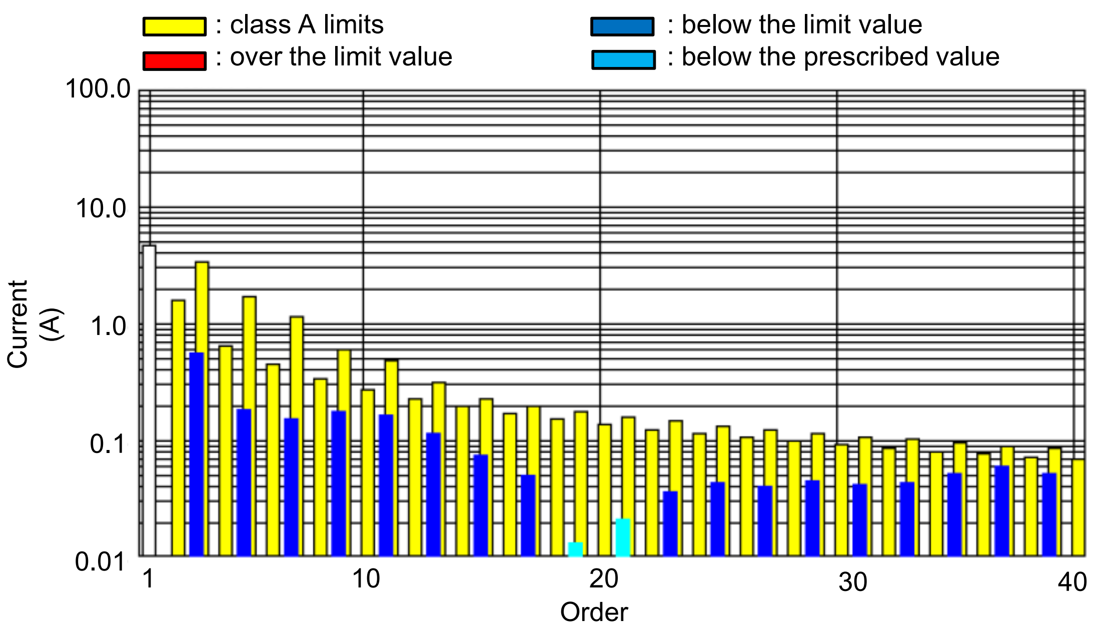


Fig. 10. Power line harmonics in the case of E_{i_ac} = 200 Vrms at the full load condition.

5. Output Characteristics of Elementary Substance of Converter

Figure 11 shows the output characteristics of the converter at a transformer turn ratio of 4: 3. According to the input voltage, the converter performs constant current operation of 12 A at the input voltage of 100 Vrms and 24 A at the input voltage of 200 Vrms.

However, in the proposed charger, since it is assumed that the power is taken from a household outlet, the output current is controlled so as not to operate the distribution breaker. When the input voltage is 100 Vrms, the output current is 12 A at the load resistance of 5.8 Ω or less, but at the lager load resistance than 5.8 Ω, the output current gradually decreases. At input voltage of 200 Vrms, the output current decreases at larger load resistance than 3 Ω. As shown in Fig.12, the output voltage includes ripple of about 4 V synchronized with the frequency of the input voltage. However, there is no fluctuation in the average output voltage and a stable voltage is obtained according to each output current and load resistance.

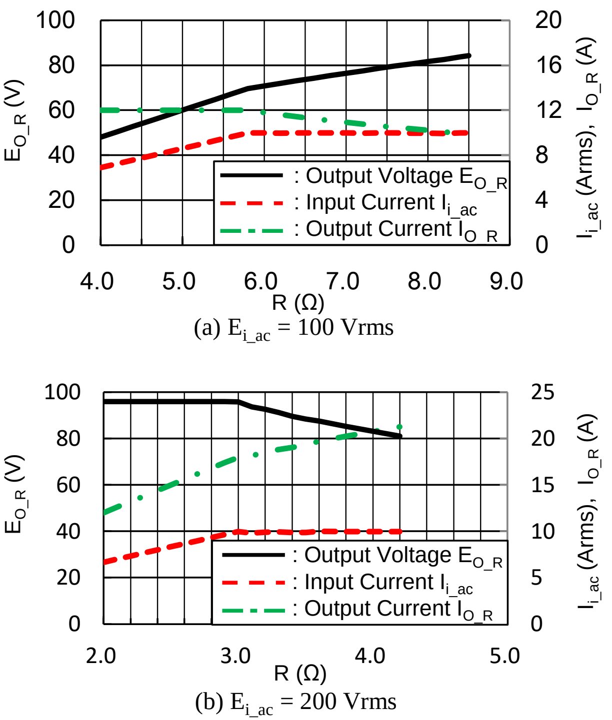


Fig. 11. Output characteristics.

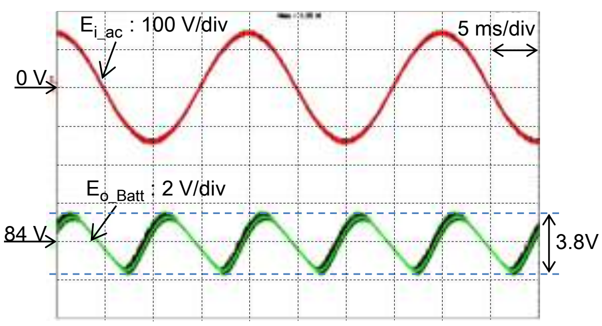


Fig. 12. Waveform for input and output voltage.

6. Charging Characteristics of Single-Stage Converter

The following batteries are used for the experiment. 6 pieces of valve-regulated lead-acid batteries (VRLA) which are commonly installed for small mobility are connected in series to form a battery of 72V-60Ah and 4.2kWh. The specifications are shown in Table 2.

Figure 13 shows the output current waveform when charging the battery with a single-stage converter, and Figure 14 shows charging characteristics. As shown in Fig. 13, ripple current of around 1 A which is synchronized with the commercial power frequency exists in the charging current, this is within ±10% of charging current, which satisfies the required specifications of the battery. Also, as shown in Figure 14, the average charging current is stable without a fluctuation.

Table 2. Specification of Battery

Nominal voltage		12	V
Nominal capacity		60	Ah
Weight		21	kg
Internal resistance at 25℃	At full charge	3.5	mΩ
Temperature dependence on capacity(1/3C)	45℃	111	%
	25℃	100	%
	0℃	84	%
Self-discharge at 25℃	Remain capacity after 3month storage	91	%

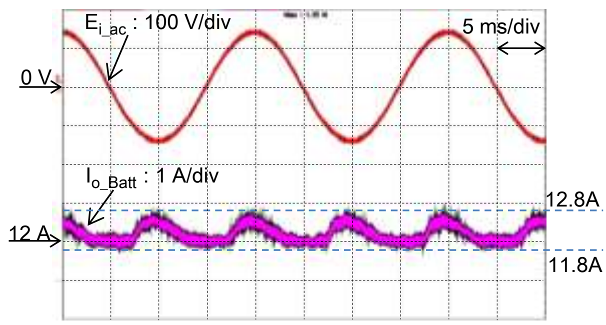


Fig. 13. Waveform for input voltage and output current.

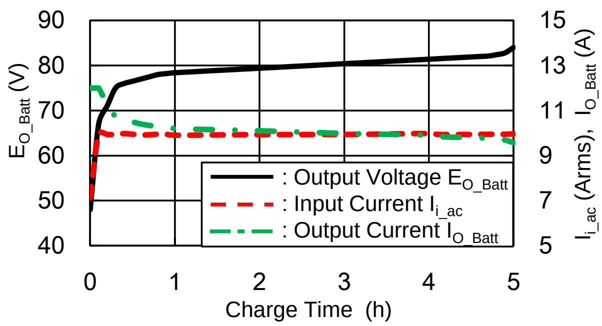


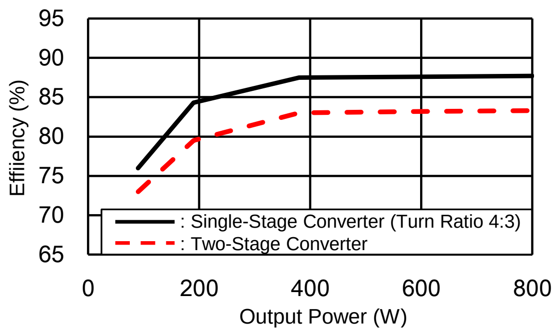
Fig. 14. Charging characteristics of battery at E_{i_ac} = 100 Vrms.

Figure 15 shows the efficiency and the power factor of the single-stage converter and the two-stage converter in the case when the input voltage is 100 Vrms.

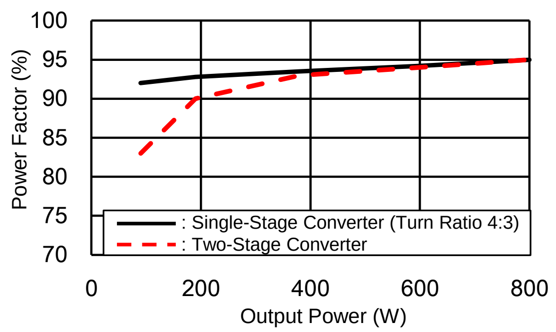
The efficiency at output power of 800 W mainly used during charging is 88.4% in single-stage converter. It is higher by 4.7% than the efficiency 83.7% of two-stage converter. The power factor is 95% in both the single-stage converter and the two-stage converter, and it is almost the same. However, in the two-stage converter, the power factor conspicuously decreases as the load decreases, and the power factor at 100 W is about 83%. This is considered to be due to intermittent operation occurring at light load in the two-stage converter. On the other hand, the proposed single-stage converter has no intermittent operation even at light load and maintains high power factor.

Figure 16 shows the efficiency and the power factor of the single-stage converter and the two-stage converter in the case when the input voltage is 200 Vrms.

The efficiency at the output power of 1600 W mainly used during charging is 88.9% in the single-stage converter. It is higher by 3.4% than the efficiency 85.5% of the two-stage converter. The power factor is 94.5% in both the single-stage converter and the two-stage converter, and it is almost the same. However, in the two-stage converter, the power factor conspicuously decreases as the load decreases, and the power factor at 200 W is about 82.5%. This is considered to be due to intermittent operation occurring at light load in the two-stage converter as in the case of the input voltage of 100 V. On the other hand, the proposed single-stage converter has no intermittent operation even at light load and maintains high power factor even in the case of the input voltage of 200 V.

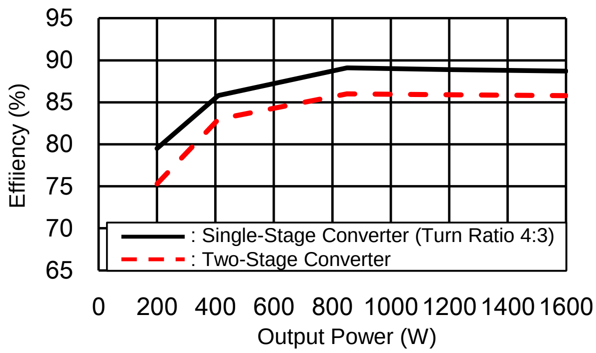


(a) Efficiency.

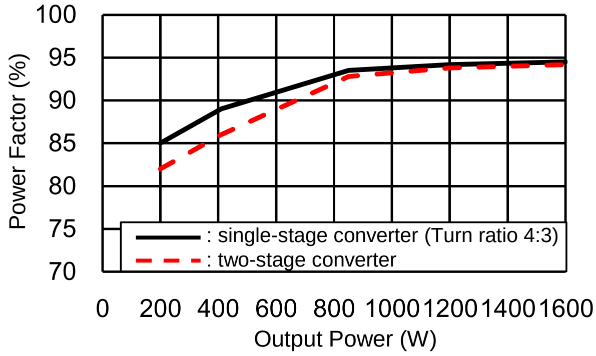


(b) Power factor

Fig. 15. Efficiency and power factor characteristics at E_{i_ac} = 100 Vrms.



(a) Efficiency.



(b) Power factor

Fig. 16. Efficiency and power factor characteristics at E_{i_ac} = 200 Vrms.

The ac bus is regarded in the power distribution system of the household distributed power system in this paper, but the dc bus system is also expected to be widely used in the future[22]. Therefore, the characteristics when dc input is applied to the proposed single-stage converter obtained by the experiment is shown in Figure 17. This result shows that there is no reduction in efficiency at dc input and that the proposed single-stage converter can be used on a dc bus.

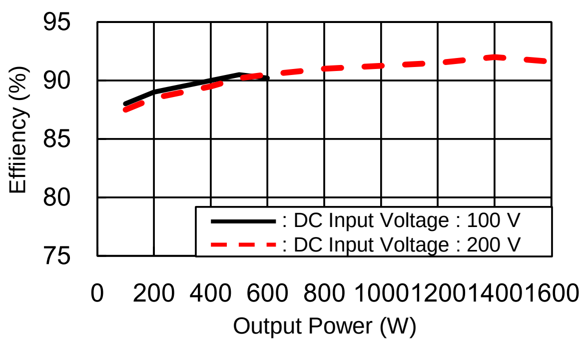


Fig. 17. Efficiency characteristics at dc input.

Figure 18 shows a photograph of the charger proposed in this paper. The volume of the conventional two-stage converter[23] is 7736 cm^3, the volume per unit electric power is 4.9 cm^3 / W, and the weight is 4.2 kg. The volume of proposed single-stage converter is 3844 cm^3, the volume per unit electric power is 2.4 cm^3 / W, and the weight is 3.1 kg. The power density per volume is increased by 50.2% and the weight was reduced by 26.2% compared to the conventional two-stage converter. This result shows that the proposed single-stage converter is extremely effective for miniaturization and weight reduction for battery charger.

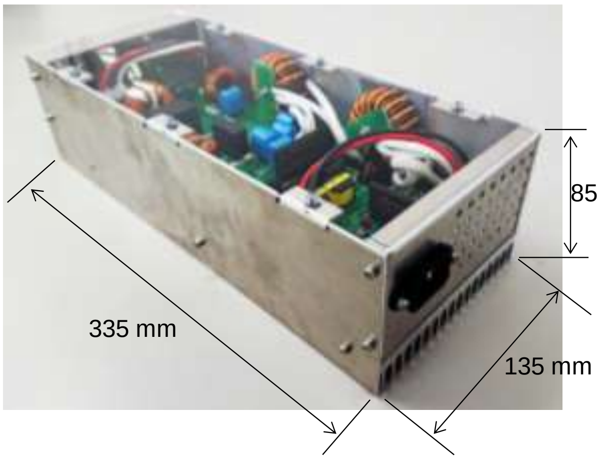


Fig. 18. Proposed battery charger.

7. Conclusion

It is clarified by analysis and experiment that the proposed method of single-stage converter is effective for miniaturization and weight reduction required for a charger of micro EV charging from a household AC outlet.

As a result, compared with the two-stage converter, the efficiency is higher by 4.7% at the input voltage 100 Vrms and higher by 3.4% at the input voltage 200 Vrms. The proposed single stage converter achieves high power factor as same as the two-stage converter. The volume of charger is reduced by 50.2% and the weight by 26.2% to realize the miniaturization and the reduction of weight of the charger.

In addition, although ripples of 100 Hz and 120 Hz caused by the commercial power frequency occur, that is acceptable in battery charging applications.

Currently, the ac bus is the mainstream for household distributed power systems because almost household electrical products are ac equipments. However, the effectiveness of the dc bus has been proposed from the viewpoint of improving the total efficiency of the distributed power system and the growth of the introduction of renewable energy, and the dc bus is also expected to be widely used in the future. The single-stage converter proposed in this paper can be applied to dc input with the same circuit configuration, and from this point of view, it can be said that the single-stage converter is an effective solution of the charger of micro EV which is charged from the household distributed power system.

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