Two-Battery HEECS Inverter with over 99.7% Efficiency at 2.2 kW Output and Measurement Accuracy Based on Loss Breakdown

Atsuo Kawamura∗a) Fellow, Satoshi Nakazaki∗ Student Member
Shogo Ito∗ Student Member, Sakahisa Nagai∗∗ Member
Hidemine Obara∗ Member

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A DC-AC conversion efficiency of over 99.7% is experimentally measured using a two battery high efficiency energy conversion system (HEECS) inverter. The accuracy of the efficiency measurement is evaluated by two methods: the direct measurement method and the loss breakdown method. After several measurements, calculations and analyses it is concluded that the measurement error based on the loss breakdown method is 0.04%.

Keywords: inverter, high efficiency, multi-level, HEECS

1. Introduction

1.1 Research Motivation and Background The pursuit of the highest energy conversion efficiency from the scientific viewpoint can contribute to the field development in power electronics using the advantage of wide band gap devices. Even though the power density may not be increased, the possible highest energy conversion efficiency is important issue in the future direction of this field.

Authors have been investigating the higher efficiency of DC-DC power conversion. In (1) the efficiency over 99.5% DC-DC conversion is experimentally demonstrated. In (2) the efficiency can be close to 100% under the assumption that the voltage output variation is restricted using the partial voltage boost circuit. On the other hand, if the pure sinusoidal output waveform is required in DC-AC energy conversion, the minimization of switching loss and the filter loss becomes mandatory. In (3)–(5) the high efficiency 99.4% inverter operation was reported, however the theory that indicates an approach to efficiency 100% DC-AC conversion is not shown yet. From the scientific view point the method to approach the efficiency 100% is very important. Authors have developed the concept of the partial voltage boost into partial power conversion principle and theoretically shown the realization of the high efficiency power conversion in (6).

In a few kW power range authors have investigating the high efficiency and in (7) the efficiency 99.65% was reported with 2.2 kW output. When the efficiency approaches to 100%, the measurement becomes very difficult, because the measurement accuracy of the instruments for the loss estimation is not negligibly small.

1.2 Literature on High Efficiency Inverter Loss Measurements There are several papers concerning the high efficiency inverters. However, elaborate loss estimation is not their main concern. In (4) 99.2% efficiency was measured by a power meter, and in (3) no description can be found on the measurement. In (5) 99% efficiency is measured by a power meter and loss breakdown analysis was done, in which the switching loss was measured by the double pulse test (8) (9), and was converted to the equivalent AC loss. Accuracy of each loss measurement is not mentioned and the accuracy of the measured efficiency is not found. The actual switching condition is different from that of the double pulse test, thus it is difficult to estimate the measurement error of the actual circuit. In (10) the switching loss is measured and compared with and without SBD (Schottky barrier diode) using double pulse test. This double pulse test is standardized and is very useful to compare the power device switching characteristics. However, it may not be useful to estimate the switching loss of the operating condition of the individual circuit.

On the contrary DC-DC energy efficiency can be measured at the very high accuracy by the back to back circuit topology, in which the output terminal of the DC-DC converter is connected to another same topology DC-DC converter and it works as a regenerative converter(10). However, if the operation is DC-AC, then a transformer is needed for this topology, in which the non-linear magnetizing current flows. And it is very difficult to precisely measure the conversion loss including the transformer loss.

1.3 Outline of the Proposed Total Loss Estimation Method In this paper we propose a new method (loss breakdown method) to evaluate the total loss of the inverter with the higher accuracy. In section 3.3 a possibility is shown that the measurement accuracy of the total loss becomes higher in adding all component losses than in estimating the total loss by the subtraction of input and output power when the measurement error is estimated based on the accuracy...
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The equation of a power meter, current probe and measurement instruments. Next in section 4.1 the loss of each component is measured. The switching loss is measured under the DC-DC operation of the actual circuit topology. And in section 4.2 the loss of the ideal DC-AC operation is calculated, and component loss of DC-AC operation is added. The accuracy of the loss breakdown method is discussed in section 4.3. As a result, the value of energy conversion efficiency is obtained with high accuracy.

The structure of the paper is as follows. In the chapter 2 characteristics of the proposed HEECS inverter is summarized, and in the chapter 3 the total loss is measured by the conventional method. In the chapter 4 all losses are measured based on the proposed loss breakdown method and discussion is made on the accuracy, and the chapter 5 concludes this paper.

2. Two Battery HEECS Inverter

2.1 Basic Operation and Reason of High Efficiency

Figure 1 depicts the proposed topology, which is based on the principle of “Partial Power Conversion”, and named as two battery HEECS inverter. The first power stage of this converter is similar to the two battery HEECS chopper in (2), which has two batteries and each battery has special connection to buck converters. When the output voltage command is lower than the battery #1 voltage $E_1$, only switches S1 and S2 operates and lower buck converter generates PWM output voltage, while the switch S3 is always in “on state”. When the output voltage command is between $E_1$ and $(E_1 + E_2)$, where $E_2$ is the battery #2 voltage, then the switch S2 is always in “on state” and the upper buck converter generates PWM waveform. As a result, a typical waveform of the output voltage $v_{sw}$ in Fig. 1 is illustrated in Fig. 2(a), where the output voltage command is a full rectified waveform. Through the LC filter shown in Fig. 1, the filtered output voltage $v_{dc}$ is controlled so that a full rectified waveform is synthesized as shown in Fig. 2(b).

In the second power stage, an unfolding inverter unfolds the full rectified waveform into the complete sinusoidal waveform. The final voltage $v_{ac}$ is illustrated in Fig. 2(c). The unfolding inverter changes the switching mode once in a half cycle, thus the switching loss is negligible. The total efficiency can be optimized by the proper selection of $E_1$ and $E_2$.

Typical waveforms are shown in Fig. 3, in which an inductor current, DC output voltage and AC output voltage waveforms are measured at 2.2 kW output.

The main reason of the high efficiency conversion may be the following two:

1. This type of DC-DC conversion can be said to be a multi-level conversion, thus the switching loss can be reduced. Due to the partial power conversion principle only the small power is processed by the chopper with proper $E_1$ and $E_2$ voltage ratio and the loss is reduced. The selection of $E_1$ and $E_2$ can be found in reference (6). And the inductor current of this topology stays almost in the positive half B-H curve, the hysteresis loss is smaller than that of full sinusoidal wave.

2. At the DC-AC side power stage, the switching occurs once in a half cycle and it is under the zero-voltage switching, thus the switching loss is very small. Also, the different power factor operation is confirmed by experiments, but this issue will be reported in other opportunity.

2.2 Specification of 5kW Two Battery HEECS Inverter

The specifications of the prototype of 5kW HEECS inverter is summarized in Table 1, where the highest possible efficiency is the target of this research, thus the power density is not considered this time. The target output rating is selected to be single phase 400 V peak, 25 A peak and 5 kW at the 20 kHz switching frequency. The output is supposed to be connected to the utility grid, and a pure AC output voltage is assumed. The inductor material is amorphous, and
the physical size is large ($165 \times 90.5 \times 230 \text{mm}$) to increase the inductance and reduce the resistance. The diameter of the core is 50 mm and the turn number is 61 each in parallel connection. The copper thickness of the PCB board is 175 $\mu\text{m}$ and in (7) it was 35 $\mu\text{m}$. Those parameters are summarized in Table 1.

### 3. Measurement of Efficiency

#### 3.1 Conventional Loss Measurement Method (Direct method)

The measurement methodology may be called “direct loss subtraction calculation method (for abbreviation direct method)”, in which the total input power and the total output power are measured, and the subtraction is assumed to be a loss. The procedure will be discussed here, and the instruments are summarized in Table 2.

The powers are measured just in front of the PCB (Printed Circuit Board), and the power from battery $E_1$ is defined as $P_1$, and the power from the battery $E_2$ is defined as $P_2$. The power measured in front of the unfolding inverter is defined as $P_3$, the load power at the resistance is defined as $P_4$. The loss of the HEECS chopper is calculated by $P_1 + P_2 - P_3$, and the total inverter loss is calculated by $P_1 + P_2 - P_4$. Thus, the efficiency of DC-DC ($\eta_{dc-ac}$) and the DC-AC ($\eta_{ac-dc}$) are defined as follows.

$$\eta_{dc-ac} = 1 - \frac{P_1 + P_2 - P_4}{P_1 + P_2} \quad (1)$$

$$\eta_{ac-dc} = 1 - \frac{P_1 + P_2 - P_3}{P_1 + P_2} \quad (2)$$

In this method, if the measured power (from $P_1$ to $P_4$) has error, then that error remains as the error in the loss. Thus, a new approach will be proposed in the next 3.3.

In order to suppress the ripple component of the input currents from $E_1$ and $E_2$ and increase the accuracy of the measurement, a filter is inserted between the batteries and HEECS chopper. This filter is shown in Appendix 1. The DC power is measured after this filter, thus the filter loss is not included in the efficiency measurement in the following procedure. Also all measurement instruments and the HEECS inverter under the test are installed in a constant temperature chamber when the measurements are carried out under the direct method.

#### 3.2 Measurement Results

For eleven resistive load conditions the DC-AC operation is made, and the loss was measured, and the efficiency and the loss are shown in Fig. 4. From this figure it is observed that at 2.2 kW output the loss of 5.8 W was calculated by the direct method and based on equation (2) the efficiency 99.72% was obtained. From now on this accuracy of efficiency will be discussed at this operation point.

#### 3.3 Measurement Error of the Direct Method and Reason for the More Accurate Measurement

The accuracy of the power meter is estimated based on the combination of reading error and full-scale error(12). The procedure is summarized in Appendix 2. The result is summarized that the measurement of 2230 W output includes the possible error of 8.46 W, which is the 0.38% of the output power. Since the loss is estimated by the difference of input and output power, the measurement error should be in the same order of 0.38%.

To measure very high efficiency such as 99.7%, we should carefully calculate the error of the loss measurement. Thus,
a new method is proposed based on the measurement of each element loss. This method is called “total loss calculation based on loss breakdown (for abbreviation loss breakdown method)” in this paper. Under DC-AC operation the voltage and current of the each component is changed as AC waveform, thus the loss is calculated first under DC-DC operation loss measurement and second under DC-AC operation loss measurement.

These loss components can be listed as follows. For DC-DC operation, switching loss of the power device (turn-on and turn-off loss), conduction loss of the power device, line resistance loss of PCB, conduction loss of the inductor, ripple current loss in inductor and ESR loss of the capacitor should be added.

For the DC-AC operation, in addition to the above elements, fundamental frequency iron loss of the inductor, fundamental frequency ESR loss of the capacitor, and conduction loss of the unfolding inverter should be added.

The loss of all components can be categorized into (1) conduction loss, (2) switching loss and (3) loss of the inductor. The measurement accuracy of the conduction loss is high because the power meter is not used for measurement. And a large part of the total loss may be composed of conduction loss. The detailed investigation on the loss accuracy will be mentioned in section 4.3.1.

The efficiency based on the loss breakdown can be calculated in the following two equations. Defining the efficiency of DC-DC and DC-AC as $\eta_{dc-dc-bd}$ and $\eta_{ac-dc-bd}$ respectively, and also defining the DC-DC conversion all loss and DC-AC conversion all loss as $P_{loss_{dc-dc}}$ and $P_{loss_{dc-ac}}$, the efficiency can be calculated in the next equation without the input power.

$$\eta_{dc-dc-bd} = 1 - \frac{P_{loss_{dc-dc}}}{(P_1 + P_{loss_{dc-dc}})} \quad \cdots \quad (3)$$

$$\eta_{ac-dc-bd} = 1 - \frac{P_{loss_{dc-ac}}}{(P_1 + P_{loss_{dc-ac}})} \quad \cdots \quad (4)$$

The measurement of the input power is not required, thus the input power measurement error due to the harmonics can be erased. The output power $P_1$ and $P_2$ is DC and AC respectively with less harmonics than in the input power $P_1$ and $P_2$, thus this is one of the reasons of high accuracy. However many measurements and calculation are required in this loss breakdown method.

4. Loss Breakdown Method and Discussion on the Measurement Error

First, loss of all possible components will be measured or calculated. Then the total loss measurement accuracy is theoretically evaluated by summation of the measurement error of each component.

4.1 Loss Breakdown at DC-DC Operation

First, the efficiency, which is calculated by the loss as difference of the input and output power, is measured by “direct method”. Figure 5(a) depicts the efficiency of the DC-DC operation and Fig. 5(b) depicts the total loss.

Next, each loss is measured as accurate as possible, however, in this paper data of five operation points are listed among 19 operating points in Table 3. All measured data in this paper are statistically processed as mentioned later in Discussion.

(4.1-1) Switching Loss Measurement on the Actual Circuit

DC-DC Operation (Appendix 3)

Switching characteristics obtained by the double pulse test (not precisely reflected in the switching loss, thus the actual switching was measured and losses were calculated. The measured loss in Appendix 3 is the function of the DC load current, because loss at the actual DC-DC operation is measured.

(4.1-2) PCB Distribution Line Resistance (Appendix 4)

By the support of IPEC Co., the DC resistance of the inductor is measured and 6.24 mΩ was obtained, which is summarized in Table 3(b).

(4.1-3) Winding Resistance of the Inductor

By the support of IPEC Co., the DC resistance of the inductor is measured and 6.24 mΩ was obtained, which is summarized in Table 3(b).

(4.1-4) Ripple Current Loss in the Inductor (Appendix 5)

As shown in Appendix 5 the ripple loss is estimated by the subtraction of the DC current Joule loss from the total inductor loss power measurement. The accuracy of this method will be discussed later in section 4.3.

(4.1-5) Ripple Current ESR Loss of the Capacitor (Appendix 6)

As shown in Appendix 6, the ripple current through the capacitor is measured and the ESR loss is calculated, however it is negligible.

All of these losses are summarized in Table 3. It is observed that the losses measured by the direct methods are very similar to those measured by the loss breakdown method. The right-hand side column of Table 3(b) shows the difference between two methods. In this paper the total error estimation is set to be the first priority, and the maximum
Table 3. Efficiency investigation of DC-DC stage

(a) DC-DC conversion efficiency (direct method)

| Operating condition (duty ratio) | Source voltage $V_s$ [V] | Output voltage $V_{dc}$ [V] | Output current $I_{dc}$ [A] | Output power $P_{dc}$ [W] | Total loss [W] | Efficiency [%] |
|---------------------------------|--------------------------|----------------------------|---------------------------|-----------------|---------------|---------------|
| 1                               | 277.5                    | 123.5                      | 374.3                     | 10.75           | 4023.6        | 5.89          | 99.85          |
| 2                               | 277.6                    | 123.9                      | 374.3                     | 10.75           | 4023.6        | 5.89          | 99.85          |
| 3                               | 278.8                    | 123.8                      | 358.8                     | 9.66            | 3244.1        | 5.58          | 99.83          |
| 4                               | 278.9                    | 124.8                      | 197.2                     | 5.70            | 1124.5        | 5.25          | 99.53          |
| 5                               | 279.4                    | 124.8                      | 138.4                     | 4.00            | 554.3         | 4.19          | 99.24          |

(b) DC-DC conversion efficiency. (loss breakdown method)

Table 4. DC-AC inverter efficiency investigation at 2.2 kW output

(a) DC-AC conversion efficiency (direct method)

| Power device | Inductor | PCB | Total loss [W] | Efficiency [%] | Loss difference [W] | Efficiency difference [point] |
|--------------|----------|-----|----------------|----------------|---------------------|-------------------------------|
| $P_{in}$+$P_{out}$ | Conduction loss [W] | Conduction loss [W] | Fund-freq-comp iron loss [W] | Rippur-comp iron loss [W] | Line resistance conduction loss [W] | Eff [W] | Diff [point] |
| 1.60         | 2.27     | 0.79 | 0.00           | 0.32           | 0.24                | 5.21                         | 99.88 | 0.57 0.01 |
| 1.56         | 2.38     | 0.72 | 0.00           | 0.34           | 0.24                | 5.25                         | 99.87 | 0.64 0.02 |
| 1.45         | 2.43     | 0.58 | 0.00           | 0.35           | 0.23                | 5.63                         | 99.84 | 0.55 0.03 |
| 2.63         | 1.10     | 0.20 | 0.00           | 0.49           | 0.09                | 4.52                         | 99.60 | 0.73 0.06 |
| 2.30         | 0.54     | 0.10 | 0.00           | 0.63           | 0.04                | 3.61                         | 99.35 | 0.58 0.10 |

(b) DC-AC conversion efficiency. (loss breakdown method)

4.2 Loss Measurement at DC-AC Operation

Figure 4 is the result of the efficiency measurement by the “direct method”. In the “loss breakdown method” individual loss is calculated by 2 steps. Step 1: the ideal DC-AC conversion loss is estimated without fundamental frequency iron loss (which is the loss at the full-wave rectified waveform at 50 Hz) using the results in the section 4.1, Step 2: then that iron loss is added to the ideal DC-AC conversion loss as well as the conduction losses of the unfolding inverter circuit.

(4.2-1) Ideal DC-AC Conversion Efficiency and the Loss

As shown in Appendix 7, using the efficiency map, the efficiency and the loss are calculated as follows. By dividing the 90 degrees electrical angle into 19 sections, the efficiency and loss in each segment are calculated. Integrating this quarter cycle, the ideal DC-AC conversion efficiency becomes 99.80%. The fundamental frequency inductor iron loss is excluded. The ideal DC-AC loss can be calculated, and it is shown in Table 4.

(4.2-2) Iron Loss under Full-rectified Sinusoidal Current Waveforms (Appendix 5)

As shown in Appendix 5, two kind of loss evaluation methods are compared, one of which is orthodox B-H curve measurement (#2 in Appendix 5) and the other is direct measurement of the inductor loss measurement (#1 in Appendix 5). The value of #1 has a little smaller than that of #2. This may be because the B-H curve loss section area of DC operation in HEECS inverter is smaller than half of B-H curve loss section area of AC operation at the same output voltage and current operating condition.

(4.2-3) Loss at the Capacitor under the Full-rectified 50 Hz Sinusoidal Waveform (Appendix 6)

As shown in Appendix 6 the capacitor current is measured and the ESR loss is estimated based on the current RMS. It is concluded that the loss is negligibly small.

(4.2-4) Conduction Loss of the Unfolding Inverter

In Table 4 the conduction losses are calculated using the switching devise conduction resistance and the rms current.

(4.2-5) Switching Loss of the Unfolding Inverter

The switching occurs once at every half cycle and it is the zero voltage switching. Thus, the switching loss is negligible.

The Table 4 is the summary of this section, in which the efficiency of the inverter operation is 99.72% by the direct method and 99.71% by the loss breakdown methods at 2.2 kW output.

4.3 Discussion on Accuracy

4.3.1 Comparison of the Measurement Error Between Direct and Loss Breakdown Methods

The measurement errors of DC-DC and DC-AC are summarized in Tables 5 and 6 respectively.

(1) As for DC-DC operation, the resolution of measurement are listed in Table 5, in which only 5 cases of the 19 operating points are shown as calculated in the manner mentioned in Appendix 2. 3, 4 and 5. Under the direct method, the maximum measurement error among $P_1$, $P_2$, and $P_3$ is listed in the third column, and it is assumed that the maximum loss calculation error after the subtraction $P_1 + P_2 - P_3$
Table 5. Resolution investigation on DC-DC conversion

| Operating point (duty ratio) | Instrument resolution (max error ratio) | Difference of input and output power | Power device inductor | PCB | Total loss error [W] |
|-----------------------------|----------------------------------------|-------------------------------------|----------------------|-----|---------------------|
| [1] d\textsubscript{in}=0.95 | Max measurement error                   | 26.223                              | 0.13                 | 0.017+rdg.+f.s. | 0.007+rdg.+f.s. | 0.320 | 0.034 | 0.667 | Total |
| [2] d\textsubscript{in}=0.79 | Max measurement error                   | 24.878                              | 0.203                | 0.103+rdg.+f.s. | 0.007+rdg.+f.s. | 0.345 | 0.034 | 0.692 | Total |
| [3] d\textsubscript{in}=0.47 | Max measurement error                   | 22.381                              | 0.188                | 0.106+rdg.+f.s. | 0.006+rdg.+f.s. | 0.345 | 0.035 | 0.678 | Total |
| [4] d\textsubscript{in}=0.70 | Max measurement error                   | 7.798                               | 0.342                | 0.057+rdg.+f.s. | 0.004+rdg.+f.s. | 0.494 | 0.014 | 0.910 | Total |
| [5] d\textsubscript{in}=0.50 | Max measurement error                   | 3.574                               | 0.298                | 0.039+rdg.+f.s. | 0.001+rdg.+f.s. | 0.627 | 0.007 | 0.964 | Total |

Table 6. Resolution of inverter efficiency measurement at 2.2 kW output

| Method | Direct method | Loss breakdown method |
|--------|---------------|-----------------------|
| Measurement part | Power measurement | DC-DC operation at 33.3 \(\Omega\) | Iron loss error [W] | Inverter loss error [W] | Total loss error [W] |
| Resolution | Largest power meter resolution among \(P_1\), \(P_2\), and \(P_3\) | Resolution based on difference between input and output power | Equivalent accuracy error | Resolution of fundamental frequency iron loss (from Appendix F) 0.45 | Current probe Resolution (rdg.+f.s.) | 14.121 |
| Accuracy rate [%] | 8.456 | 0.747 | 0.171 | 0.012 | 0.930 |

is the maximum measurement error among \(P_1\), \(P_2\), and \(P_3\) and it is listed in the fourth column.

Under the loss breakdown method the accuracy of loss measurement is investigated by splitting the loss into the following three categories.

(a) conduction loss error: The conduction loss of devices, inductor and the PCB is made of a product of resistance and square of current. As shown in Appendix 2, the accuracy is proportional to accuracy of resistance \(\times \) current sensor accuracy. In Table 5, the resistance of SCT3017AL device and inductor is assumed to be 100% correct and PCB has 6.7% error as shown in Appendix 4. The 4 kinds of case temperature of SCT3017AL device are measured by Infrared Camera (thermo sensor) and they are between 37 and 45 degrees. The temperature difference between the case and junction is estimated to be below 1 degree based on the thermal resistance and consumed loss at device. The on resistance variation from the room temperature to this range is estimated to be 1.7% increase based on the data sheet. Thus this ratio is added as the resistance error of these devices. The current sensor accuracy is estimated by combination of reading and full scale as shown in Appendix 2. This conduction loss error is smaller than others in Table 5.

(b) switching loss error: The switching loss of the actual circuit is measured in the manner mentioned in Appendix 3, and mainly due to the Rogowski coil sensor, the estimated loss error is 13%. The time lag difference between the isolation voltage and Rogowski current probe is adjusted to be within one ns by the de-skew tool using device (DCS015). The temperature rise is small as mentioned in the previous paragraph, thus the switching characteristics do not change so much.

(c) 20 kHz ripple loss error of the inductor: It is very difficult to measure the ripple loss, thus it is estimated by the subtraction of conduction loss from the measured inductance power, as mentioned in Appendix 5. However, the power measurement of the inductor has a large error and it is a little smaller than the measured value, thus it is assumed to be 100% error.

The total maximum loss error of the direct method is distributed from 2.3 W to 26 W, which are calculated by the estimation method as shown in Appendix 2. The \(P_1\), \(P_2\) and \(P_3\) have the power measurement error and the largest one among them is selected to be the maximum loss error. The total loss error of the breakdown method is obtained by adding all possible loss errors and it is distributed from 0.67 W to 0.96 W as observed in Table 5. The tendency of loss error is different between two. In the direct method the power meter measurement error is dominant, and in the loss breakdown method the error of the inductor loss is large.

These errors can be converted to equivalent sinusoidal error as follows. Defining the total error of all components at the measuring point \(k\) in Table 5 as \(e_k\), the equivalent sinusoidal error \(E_{\text{total}}\) is obtained by weight averaging through a quarter cycle of the sinusoidal waveform in equation (5).

\[
E_{\text{total}} = \left( \sum_{k=1}^{19} \alpha_k e_k \frac{P_k}{P_{\text{out}}} \right) P_{\text{out}} \quad (k = 1 \ldots 19) \ldots (5)
\]

Variables and weighting coefficient \(\alpha_k\) are defined in Appendix 7. And \(P_{\text{out}}\) is the output AC power at 33.3 \(\Omega\) resistive load. After calculation these equivalent sinusoidal errors become 14.121 W and 0.747 W for direct and loss breakdown methods respectively as shown in the bottom in Table 5.

(2) As for the DC-AC conversion, the measurement errors of two methods are summarized in Table 6. Under the direct method, the subtraction of the input and output power includes 8.46 W measurement loss error and it is smaller than 14.12 W equivalent DC-AC loss error in Table 5. Thus the smaller value is used as measurement error.

Under the loss breakdown method the loss can be separated
into following three categories.

(d) ideal DC-AC loss error: This is estimated from equation (5) and it is used in Table 6. This value includes the copper loss of the inductor.

(e) fundamental frequency iron loss of inductor: The inductor loss under a full rectified current waveform is measured by the power meter and the 50Hz conduction loss is subtracted as mentioned in Appendix 5 in detail. This resulted in 0.38 W. The fundamental frequency hysteresis loss is also measured under pure sinusoidal current of 8.01 A and it resulted in 0.55 W. The maximum measurement error is assumed to be 0.55 – 0.38 = 0.17 W, which is 45% of the estimated loss.

(f) conduction loss of the unfolding inverter: The conduction loss error of the unfolding inverter can be calculated as similar as DC-DC. The on resistance is assumed to be 100% correct as that of data sheet and the current sensor error is reflected. The loss in this module (BSM180D12P2C) is about 1.5 W, thus the temperature rise is very small and the resistance change is neglected.

As the final result, the measurement error of the loss breakdown becomes 0.930 W as shown in Table 6.

### 4.3.2 Accuracy Comparison of Direct and Loss Breakdown Methods

From Table 6 the measurement error (resolution) at the direct method is 8.46 W and that of the loss breakdown methods is 0.930 W. It is shown that the proposed loss breakdown method has better accuracy than the direct method after many measurements and calculations. It is observed in Tables 5 and 6 that the accuracy is highly affected by the inductor and a little by switching loss measurement error, and almost not by the conduction loss measurement.

From the calculation of 0.930 ÷ (2229.9 + 6.47) = 0.00042, it is concluded that the proposed loss breakdown method has 0.04% accuracy in the efficiency measurement, and on the contrary the direct method has 0.38% accuracy.

Table 7 is a summary of the above discussion. Based on the discussion on the section 4.2, the efficiency of the direct methods and the breakdown method are 99.72% and 99.71% respectively as shown in Table 4. Thus, in this paper the efficiency of HEECS inverter at 2230 W output is concluded to be 99.72±0.38% under direct method and 99.71±0.04% under loss breakdown method.

### 4.4 Further Discussion

#### 4.4.1 Loss Breakdown Ratio at 2.2 kW

From the above mentioned analysis, it is clarified that the measurement error of the efficiency at 2230 W is ±0.04%. However, in this paper further investigation of the error is no longer discussed. Instead, the efficiency obtained by two difference methods (direct and loss breakdown) show almost same value, thus the loss breakdown is summarized in Fig. 6, the main data of which are from Table 3 and Table 4. It is observed from this figure that if the higher efficiency is targeted, the conduction loss becomes the main obstacle of this goal. Also it is observed from Fig. 4 that the higher efficiency of the two battery HEECS inverter shows 99.78% at 1210 W and the measurement error seems to be near 0.04%. And the main loss may remain in the conduction loss. The new approach how to reduce the loss at this higher efficiency operation point will be discussed in another paper soon.

#### 4.4.2 Data Processing

All measured data used in this paper are statistically processed as is analyzed in Appendix 8. The largest variance was for the data of direct measurement of DC-DC conversion. After the analysis of the possible accuracy, it is concluded that the statistical variance in the measured data is smaller than that of the instrument accuracy.

### 5. Conclusions

The high efficiency over 99.7% at 2.2 kW was achieved using two battery HEECS inverter after one hardware change and several measurement improvements from the previous publications. This power circuit is made of DC-DC and DC-AC power stages. In the DC-DC power stage the switching occurs only at the place where power conversion is required based on the partial power conversion principle, and as a result the total efficiency becomes very high. Also the loss in the inductor is reduced due to the full sinusoidal rectified waveform operation. In the DC-AC power stage, the switching is ZVS (zero voltage switching) and the switching loss is very small. The high efficiency is experimentally proved in the proposed HEECS topology.

To evaluate the high efficiency, two kinds of loss measure-
ment method are compared, which are direct and loss breakdown methods. After measurement of all possible losses, the measurement accuracy of both approaches is investigated, and it is concluded that the efficiency and accuracy of the proposed loss breakdown measurement in this paper is 99.71 ± 0.04%.

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Appendix

1. Filter in the DC Voltage Side
The harmonics suppressing filter is inserted between the DC power supplies as shown in app. Fig. 1 and the circuit under test and the power measuring accuracy is improved. The parameters are selected by trial and error approach.

2. Accuracy Estimation of Power and Current Measurement Instruments and Conduction Loss
The accuracy of the power measurement of 2.2 kW is estimated as follows (12).

The specifications of the current probe, voltage sensor, and power meter are listed in Table 2. The error ratio becomes (0.3 + 0.02)% at rdg. and (0.01 × (current probe rating/measurement range) + 0.03)% at f.s. Considering the current range 8 A, voltage range 300 V and power range 2.4 kW, the power measurement error can be calculated.

\[
P_{\text{error}} = \frac{2230 \times 0.32}{100} + \frac{2400 \times 0.01}{100} + 0.02 = 7.14 + 1.32 = 8.46 \quad \text{(A1)}
\]

This result is shown in app. Table 1 and the ratio to the measured power (2230 W) becomes 0.38%. For the other 19 DC-DC operating points the similar procedure is adapted.

The accuracy of the current measurement is as follows. As one example, the current 11.27 A is investigated at the operation point [1] in Table 3. The error ratio becomes (0.3 + 0.02)% at rdg. and (0.05×(current probe rating/measurement range) + 0.02)% at f.s. Considering the current range 20 A, the current measurement error can be calculated.

\[
I_{\text{error}} = \frac{11.27 \times 0.32}{100} + \frac{20 \times 0.07}{100} = 0.036 + 0.014 = 0.050 \quad \text{(A2)}
\]

If this is converted to the ratio, it is 0.050/1.127 = 0.044.

The accuracy of conduction loss calculation is as follows. The conduction loss accuracy is resistance accuracy x 2 x current sensor accuracy. Because if it is assumed that the resistance of component 100% correct, and the error rate of the current sensor is α, the conduction error becomes 1 - (1 - α)^2 = 2α. Thus if the above value is used, the conduction loss estimation error becomes 0.0088. However the error rate is related to the total reading value, thus evaluation of the total error requires many computations.
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app. Table 1. Estimation of DC-AC measurement instrument accuracy

| Read error [W] | reld. error [W] | Power range [W] | Cs. error [W] | Total error [W] | Efficiency rate [%] |
|----------------|----------------|-----------------|---------------|-----------------|-------------------|
| 2350           | 7.13           | 6600            | 0.96          | 8.09            | 0.36              |

app. Table 2. Switching loss breakdown at 5 different DC-DC operating points

| Operating point | $I_{sw} [A_{dc}]$ | $S_1 [W]$ | $S_2 [W]$ | $S_3 [W]$ | $S_4 [W]$ | $S_5 [W]$ | Total [W] |
|-----------------|------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1.              | 1.95             | 0.080     | 0.080     | 0.060     | -0.080    | 0.5250    | 0.365     | 0.480     | 1.540     |
| 2.              | 1.79             | 0.080     | 0.080     | 0.058     | -0.085    | 0.5250    | 0.345     | 0.470     | 1.503     |
| 3.              | 1.70             | 0.060     | 0.080     | 0.052     | -0.090    | 0.5300    | 0.320     | 0.410     | 1.404     |
| 4.              | 0.67             | 0.300     | 0.500     | 1.470     | 0.540     | 0         | -1.200    | 1.600     | 2.635     |
| 5.              | 0.50             | 0.300     | 0.500     | 1.300     | 0.500     | 0.020     | -1.200    | 1.510     | 2.300     |

app. Fig. 2. Calculated switching loss at nine dc operation points

3. Switching Loss Measurement at the Constant Resistive Load with Different Output Voltage

The switching loss of four power devices were measured with constant resistive load 33.3 $\Omega$. The operation condition is DC-DC operation with difference duty ratio. The current is measured by Rogowski coil type sensor and the voltage is measured by an isolation type probe. The switching loss is calculated by integration of the product of the instantaneous voltage and current through the switching period. The summation of all switching loss is shown in app. Fig. 2 as function of load current including 9 operating points. Five among them are listed in app. Table 2 in detail, where a negative value means a kind of discharging mode of $C_{oss}$. The accuracy of the current probe is 2% and 3% error due to the geometric location of wire and sensor at measurement, and also 2% error due to the adjacent wired current. Thus, the total accuracy of the current measurement is 7%. The voltage probe accuracy is 1%, and the calculation error of the switching power is assumed 5%, and as a result total 13% error of the switching measurement is assumed. This number is used in Table 5 when the total accuracy is calculated.

4. PCB Distribution Line Resistance Measurement

Under the technical support of RITA Electronics Ltd., several kinds of the distribution line resistance of the PCB were measured with constant resistive load 33.3 $\Omega$. The operation condition is DC-DC operation with difference duty ratio. The current is measured by Rogowski coil type sensor and the voltage is measured by an isolation type probe. The switching loss is calculated by integration of the product of the instantaneous voltage and current through the switching period. The summation of all switching loss is shown in app. Fig. 2 as function of load current including 9 operating points. Five among them are listed in app. Table 2 in detail, where a negative value means a kind of discharging mode of $C_{oss}$. The accuracy of the current probe is 2% and 3% error due to the geometric location of wire and sensor at measurement, and also 2% error due to the adjacent wired current. Thus, the total accuracy of the current measurement is 7%. The voltage probe accuracy is 1%, and the calculation error of the switching power is assumed 5%, and as a result total 13% error of the switching measurement is assumed. This number is used in Table 5 when the total accuracy is calculated.

5. ESR Loss of the Capacitor at 50 Hz and 20 kHz

When the load resistance is 33.3 $\Omega$ in DC-AC operation, the capacitor current is measured as shown in app. Fig. 3. The rms current times the ESR (3.5 m$\Omega$) becomes 2 mW, which is negligible. And also in DC-DC operation, the ESR loss due to the ripple current is very small.

6. The Ideal DC-AC Conversion Efficiency Neglecting the Fundamental Frequency Loss at the Inductor

Using the efficiency data at the DC-DC operation, the ideal DC-AC conversion efficiency is calculated, which ignores the fundamental frequency inductor loss. The concrete calculation is as follows. Dividing the duration of the electrical angle 0 to 90 degree into $N$ (= 19) segments, the efficiency of each segment is measured. Integrating the efficiency times the instantaneous energy at each segment through the whole
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app. Table 4. Inductor loss at 50 Hz full bridge rectified sinusoidal waveform

| $P_L$ [W] | $I_L$ [A rms] | $L_L$ [mH] | $R_L$ [mΩ] | $P_R$ [W] | $P_{loss}$ [W] | $P_{total}$ [W] |
|----------|---------------|------------|------------|-----------|---------------|----------------|
| 0.92     | 9.00          | 8.48       | 0.54       | 0.38      | 0.38          | 0.55           |

app. Table 5. Ripple component iron loss

| Typical operation points | $P_{AC}$ [W] | $I_{AC}$ [A] | Measured Ripple component iron loss of 20 kHz | DC conduction loss at 6.24 mΩ | #3 Iron loss (subtraction of DC copper loss from measurement (inductor loss) [W] |
|-------------------------|---------------|-------------|---------------------------------------------|------------------|--------------------------------------------------|
| 1                       | $d_w=0.95$    | 393.60      | 11.27                                      | 2.71             | 0.74                                              |
| 2                       | $d_w=0.79$    | 374.38      | 10.75                                      | 1.13             | 0.32                                              |
| 3                       | $d_w=0.47$    | 295.80      | 9.66                                       | 0.66             | 0.58                                              |
| 4                       | $d_w=0.70$    | 197.20      | 5.70                                       | 0.70             | 0.20                                              |
| 5                       | $d_w=0.50$    | 138.40      | 4.00                                       | 0.73             | 0.10                                              |

app. Fig. 3. Capacitor current at HEECS AC operation. ($E_1 = 280$ V, $E_2 = 125$ V, 400 Vpeak AC output voltage)

quarter cycle, the total efficiency is calculated.

When we write procedure in equation, that is as follows.

Dividing the quarter cycle of a sinusoidal voltage into $N$ for the resistive load, the electrical angle is defined as $\theta_k$ [rad], and the output power is defined $P_k$ [W] at the $\theta_k$. The energy from the voltage source to the load during the center of $(\theta_k - \theta_{k-1})$ and $(\theta_{k+1} - \theta_k)$ is calculated in the next equation,

$$E_k = \frac{P_k\beta(\theta_{k+1} - \theta_{k-1})}{2}$$  \hspace{1cm} (A3)

$\beta$ is the conversion coefficient from electric angle to time and $\theta_0 = 0$, $\theta_{N+1} = \pi/2$.

Since the efficiency $\eta_k$ at electric angle $\theta_k$ is measured, the average DC-AC conversion efficiency $\eta_{av}$ through a quarter cycle becomes,

$$\eta_{av} = \frac{\sum E_k \eta_k}{\sum E_k} = \sum \alpha_k \eta_k$$ \hspace{1cm} (A4)

The weighting coefficient $\alpha_k$ is defined as follows.

$$\alpha_k = \frac{E_k}{\sum E_k} \hspace{1cm} (k = 1 \ldots N)$$ \hspace{1cm} (A5)

Following this procedure 99.80% efficiency of ideal DC-AC is obtained and also the total loss is calculated. The fundamental iron loss is not included in the measure efficiency $\eta_k$ because these are measured at DC-DC operations. These results are shown in Table 4.

8. Statistics of Data Processing

There are many kinds of data in this paper, and the statistics processing is summarized in this appendix.

The kinds of data can be categorized as follows; In the direct method, they are voltage, current, power and loss obtained by the difference between input and output power, and in the loss breakdown method they are switching loss, copper and iron losses of the inductor.

Among those the largest variance is observed at the loss calculation of DC-DC conversion under direct method. The next largest is DC-AC loss calculations of DC-AC conversion under direct method. Other measurement data show the almost same data at difference measurement date.

Thus, assuming a Gauss distribution of measurement error, the standard deviation is calculated for these two kinds of data.

As for the DC-DC conversion, the 19 operation points are selected and 3 times measurements of these points through 4 different days were executed and the standard deviations is calculated as shown in app. Table 6. After converting these DC-DC deviations into DC-AC conversion under the similar manner in Section 4.3.1, the value of 0.18 W is obtained. If 95% probability is guaranteed, 2 time of this deviation ($\sigma$) is required and it becomes 0.36 W. In Table 5, the equivalent total error at sinusoidal output is shown as 0.747 W and it is larger than 2$\sigma$. This means that the instrument accuracy error is larger than this 2$\sigma$. Thus, it is concluded that the statistics deviation can be ignored in this measurement.

As for the DC-AC conversion, the 12 measurements were done through 4 different days and the normalized deviation becomes 0.045 W. From the Table 6 the estimated equivalent error of the loss breakdown method at sinusoidal output is 0.930 W, thus, this statistics variance can be also ignored.

Atsuo Kawamura (Fellow) received the Ph.D. degree from the University of Tokyo in 1981. After his five-year-stay at the University of Missouri-Columbia, he joined Yokohama National University in 1986. After he became a professor emeritus in 2019, he is a professor of power electronics endowed chair. His main interests are in power electronics and robotics. He is Fellow of IEE of Japan and IEEE.
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Satoshi Nakazaki (Student Member) received the B.E. and M.E. degrees in electrical and computer engineering from Yokohama National University, Kanagawa, Japan, in 2018 and 2020. Since April in 2020 he has joined Honda Motor Co. Ltd. His research interests are in power electronics.

Sakahisa Nagai (Member) received the B.E., M.E., and Ph.D. degrees in electrical and computer engineering from Yokohama National University, Kanagawa, Japan, in 2014, 2016, and 2019, respectively. In 2019, he joined the University of Tokyo, Chiba, Japan, as a project assistant professor. His research interests include sensorless actuation, motion control, wireless power transfer, and power electronics.

Shogo Ito (Student Member) received the B.S. degree in Electrical and Electronics Engineering from Yokohama National University, Japan, in 2019. Now he is a candidate of the M.S. degree in Electrical and Electronics Engineering from Yokohama National University, Japan. His research interests include power electronics. He is a student member of the Institute of Electrical Engineers of Japan (IEIJ).

Hidemine Obara (Member) received the Ph.D. degree in electrical and electronics engineering from Chiba University, Japan in 2015. From Oct. 2015 to Mar. 2016, he was a postdoctoral researcher in Tokyo Metropolitan University. Since Apr. 2016, he has been with Yokohama National University as an assistant professor. His research interests include circuit topology, system integration, and implementation for multi-level power converters. Dr. Obara is a member of IEEE and IEE of Japan.