Proposal of Virtual Transformer-based Back-to-Back Asynchronous Loss Measurement using a Single Set of Measurement Instruments for One Inverter and Experimental Verification

Atsuo Kawamura* a) Fellow, Yoshiki Nasu* Student Member, Yasuhiko Miguchi* Member, Hadi Setiadi* Member, Hidemine Obara* Member

(Manuscript received Jan. 00, 20XX, revised May 00, 20XX)

In this study, a virtual transformer-based loss measurement method is proposed for inverter power conversion efficiency measurements, and the accuracy of this method is theoretically analyzed. This concept is further extended to a practical measurement procedure, wherein asynchronous loss measurements are conducted for powering and regenerating operations using a single set of measurement instruments. The average efficiency can be obtained with a very high accuracy after calibration of the measurement instruments. A high-efficiency system inverter was selected as the converter under test, and its efficiency and accuracy were experimentally measured and validated. An efficiency of 99.75% ± 0.006% was obtained at an output of 1600 W.

Keywords: High efficiency, loss measurement, virtual transformer, measurement accuracy, inverter

1. Introduction

Widespread use of wide-band-gap power devices enables the realization of very high-efficiency power conversions, and several high-efficiency studies over 99.5% can be found in the field of DC–DC conversions (4) and DC–AC conversion (6–11). When a very high efficiency is reported, high accuracy of the measurement is required to guarantee a higher efficiency measurement. It has been reported (6,8) that the loss measurement by the direct subtraction of input and output powers results in an accuracy of 0.38%.

For very accurate total loss measurements, calorimetric methods are widely used (6,12,13), wherein the entire converter under test is installed in a thermally insulated chamber, and the total loss is measured as heat dissipated in this chamber. Such methods are relatively time consuming because the steady state of heat balance is mandatory in the chamber, but an accuracy of 0.0025% can be calculated in a DC–DC conversion (12). In DC–AC conversion, a very high accuracy of 0.003% (10) but a very low accuracy of 0.1% has been reported (9), which can be achieved through a combination of calorimetric and electric measurements. Other approaches for realization of high accuracy are very few. In the case of DC–DC conversion, the total loss can be measured via a back-to-back (BTB) connection of powering and regenerating operation converters (5,14), and an efficiency accuracy of 0.02% has been reported (14). However, this approach cannot be used for DC–AC conversion. The authors reported (9) that by a loss breakdown approach in all electric measurements, an accuracy of 0.04% was realized for DC–AC conversion. However, it requires numerous data measurements, and the data-handling process is extremely complicated.

The authors reported (15) that by introducing a virtual ideal transformer-based BTB measurement, the average efficiency of the powering and regenerating operations of inverters can be theoretically measured at an accuracy of 0.002%. This idea is extended to a more practical measurement, and a new approach called virtual transformer-based BTB asynchronous loss measurement is proposed using a single set of measurement instruments (VTASLM). The measuring procedure is that we first prepare one set of measuring instruments and one power converter under test, calibrate the power measuring instruments, and measure the losses of powering and regenerating operations. The average efficiency and accuracy were calculated using the proposed equations. The originality of this study is as follows. (1) VTASLM is proposed based on all electric measurement instruments, and the average efficiency and accuracy are theoretically derived, and a concrete measurement procedure is proposed. (2) Using a HEECS inverter (15) as a converter under test, the efficiency and the accuracy were measured, and the proposed (VTASLM) method was verified to measure the loss with a high accuracy.

The remainder of this paper is as follows. In Section 2, a basic theory of a new loss measurement method is proposed, followed by the introduction of the loss measurement principle of VTASLM and an analysis of the accuracy. In Section 3, a measurement experiment was conducted, and the accuracy was calculated. Section 4 discusses further improvement of the accuracy, and Section 5 concludes this paper. The appendices include an (1) analysis of the measurement instrument accuracy, (2) investigation of the calibration method, and (3) investigation of approximation error.

2. Analysis on Loss Measurement Method using Virtual Ideal Transformer and Practical Solution

2.1 BTB Loss Measurement of Inverter using a Virtual Ideal Transformer

As shown in Fig. 1, the power converters under test are connected in a BTB manner under powering and regenerating operations through an ideal transformer. An ideal
Fig. 1. A back-to-back (BTB) loss measurement system based on a virtual ideal transformer.

transformer is called so because of the fact that the output of the powering inverter #1 is connected to the electronic load, and the power amplifier is connected to the AC terminal of regeneration inverter #2, and the power flow is controlled such that the powering AC output (P2) and the regenerating AC input power (P3) are identical with the same frequency and amplitude. This function is identical to that of an ideal transformer. The terminals of the DC input (P1) to the powering inverter and the DC output (P2) of the regenerating inverter are electrically connected. In Fig. 1, the difference (P3) between P1 and P2 is the total loss of the two inverters if the ideal transformer works perfectly.

The input DC power P1 is defined as the DC power of powering inverter #1, and P2 is defined as the output AC power. The efficiency from P1 to P2 is defined as the powering inverter efficiency \( \eta_p \), which is as follows:

\[ \eta_p P_1 = P_2 \]  

In contrast, the input AC power to the regenerating inverter #2 is defined as P3, and the difference between P2 and P3 is defined as P0, as follows:

\[ P_3 = P_2 - P_0 \]  

P3 is converted to P2 with the regenerating efficiency \( \eta_r \) as follows:

\[ \eta_r P_3 = P_2 \]  

The efficiency of the virtual transformer is identical to the theoretical efficiency from P1 to P2, as follows:

\[ \eta = \eta_p \eta_r \]  

The terminals of the DC input of inverter #1 and DC output of inverter #2 are connected, and the power difference is defined as P0, as follows:

\[ P_0 = P_1 - P_2 \]  

Eliminating P1, P3, and P0, and solving only for P0, P2, and P3 yields

\[ \frac{I}{\eta_p} - \frac{P}{\eta_r} = \frac{P_0}{P_2} \]  

The efficiency is very close to unity and Taylor expansion

\[ \frac{1}{x} \approx 2 - x \]

yields

\[ \frac{\eta_p + \eta_r}{2} \approx \eta_{ave} = 1 - \frac{P_0 + P_2}{2 P_2} \]  

where the average efficiency is defined by (6). The assumption of \( \eta_i \approx \eta_{ave} \) and \( P_0/P_2 \ll 1 \) results in the following:

\[ \eta_{ave} \approx 1 - \frac{P_0 + P_2}{2 P_2} \]  

The modeling error in (7) is discussed in Section 4.1. The following new symbols were defined to derive the theoretical accuracy:

\[ P_{pm} = P_2 \pm \Delta P_2 \]  

\[ P_{pm} = P_2 \pm \Delta P_2 \]  

\[ P_{pm} = P_2 \pm \Delta P_2 \]  

\[ \eta_{ave} = \eta_{ave} \pm \Delta \eta_{ave} \]  

where the symbol with suffix m is the measured value, and the one without the suffix is the true value. Furthermore, \( \Delta \) is the measurement error.

Substituting these in (7), we have

\[ \Delta \eta_{ave} \approx \left( \frac{\eta_{pm} - \eta_{ref}}{2 P_2} \right) \left( \frac{\frac{2 \Delta P_2}{P_{pm}} \Delta \eta_r + \frac{2 \Delta \eta_r}{P_{pm}}}{\frac{2 \Delta P_2}{P_{pm}} + \frac{2 \Delta \eta_r}{P_{pm}}} \right) \]  

The accuracy of the average efficiency in (7) can be evaluated using (12), and the modeling error in (12) is discussed in Section 4.1.

In the literature, an accuracy of 0.002% is theoretically possible with zero adjustment of P1 and/or P0 in (7).

However, the adjustment of zero P1 and/or P0 is very difficult in the actual hardware; thus, a non-zero-adjustment approach is proposed in the following section.

2.2 Virtual Transformer-based BTB Asynchronous Loss Measurement using a Single Set of Measurement Instruments (VTASLM)

If P3 or P0 cannot be set to zero in Fig. 1, wherein two inverters are synchronously operated, then the loss measurement is equal to the case when inverters #1 and #2 are asynchronously operated at different times. If two inverters are independently operated, the phenomena are independent in terms of the loss measurement.

If the powering and regenerating operations can be operated at different times, then it is equivalent to the two independent loss measurements, as shown in Fig. 2-a and 2-b.

Furthermore, instead of two sets of inverters and the measurement system, one set of one inverter and measurement instruments is prepared, and the inverter is operated in the powering and regenerating modes. If the losses are measured in the powering and regenerating modes independently in Fig. 2-a and 2-b, this is identical to the measurement method mentioned in the previous paragraph. We refer to this as the VTASLM method.

To guarantee a high accuracy of this loss measurement, the following two points are important. (i) The measurement error caused by the powering and regenerating power measurements, wherein the current-flowing direction is opposite in Fig. 2-a and 2-b, should be calibrated, and the error should be used as a calibration value. (ii) There is freedom in selecting the operation points P1, P3, and/or P2: and P0 if they stay within a certain boundary; thus, the accuracy due to this freedom should be investigated. For (i), a calibration method is proposed in Section 2.3, and the theoretical efficiency and accuracy are derived in Section 2.4. For (ii), it is
discussed in Sections 2.4, 3.2, and 4.2. The measured efficiency is the average value; thus, this freedom has a very small influence on the deterioration of accuracy.

There is an important principle that the power difference on the same instrument has very high accuracy, and this is derived and mathematically proved in Appendix 1. This result was used in this study.

2.3 Relation between Two Types of Measured Powers of Different Current Directions Using the Same Instruments

As a preparation of the accuracy derivations in Section 2.4, an analysis where the measured power in Fig. 2-b can be converted to that in Fig. 2-a is described in Appendix 2. \( P_1 \) and \( P_3 \) or \( P_2 \) and \( P_4 \), are measured under the condition that the direction of the current probe is positive in Fig. 2-a and negative in Fig. 2-b; thus, the polarity of the two types of measured power is positive and negative, and the absolute values are slightly different if the current measurement technique is not symmetrical in the positive and negative ranges. A practical technique to measure this difference is presented in Appendix 2. The power differences of DC and AC power measurements are defined as calibration values, and they are denoted as \( \varepsilon_{\text{IDC}} \) and \( \varepsilon_{\text{IAC}} \), respectively. Two types of DC powers measured under the same instruments but only the directions of the DC current probe are positive and negative are defined as \( P_{\text{trd}}(p, A) \) and \( P_{\text{trd}}(n, A) \). A detailed definition of the symbols is provided in Appendix 1. For example, \( P_{\text{trd}}(p, A) \) indicates that this is the measured DC power (m) in Fig. 2-a and the current direction is positive (p) and measured at operating point A. Similarly, the AC power measured is defined as \( P_{\text{non}}(p, A) \) and \( P_{\text{non}}(n, A) \) at different current directions.

The two types of powers measured using the same instrument with different current directions can be converted by adding the calibration values \( \varepsilon_{\text{IDC}} \) and \( \varepsilon_{\text{IAC}} \). The derived results are presented in Appendix 2.

\[
P_{\text{trd}}(p, A) = P_{\text{trd}}(n, A) + \varepsilon_{\text{IDC}} \quad \text{(A10)}
\]

\[
P_{\text{non}}(p, A) = P_{\text{non}}(n, A) + \varepsilon_{\text{IAC}} \quad \text{(A11)}
\]

2.4 Derivation of Average Efficiency and Accuracy of VTAASLM Method

The numerator \( P_1 + P_0 \) in the second term on the right-hand side of (7) represents the total loss measured in Fig. 1 at the same instant. This measured value is equal to the summation of loss in Fig. 2-a and 2-b measured at the same instant (synchronously), and it can be equal to the following:

“Synchronous measurement of \( P_1 \) and \( P_0 \) in Fig. 2-a and Fig. 2-b”

\[
P_{\text{av}} = P_{\text{im}}(p, A_1) - P_{\text{im}}(p, A_1) + P_{\text{m}}(p, A_1) - P_{\text{m}}(p, A_1) \quad \text{...(13)}
\]

The right-hand side of this equation is the summation of the loss in the powering mode (1st and 2nd terms) and loss in the regenerating mode (3rd and 4th terms); thus, the operation point is only \( A_1 \).

Next, we measure the power loss at operation point \( A_2 \) in Fig. 2-a, and the regenerating loss at operation point \( B_1 \) in Fig. 2-b at different times (asynchronously) using only one set of instruments and a converter under test, the total loss becomes

“Asynchronously measured loss \( P_1 + P_0 \) using one set of measuring instruments and a converter under test”

\[
P_{\text{av}} = P_{\text{im}}(p, A_1) - P_{\text{im}}(p, A_1) + P_{\text{m}}(p, B_1) - P_{\text{m}}(p, B_1) \quad \text{...(14)}
\]

Owing to the definition \( P_{\text{m}}(p, B_1) \) in Fig. 2-b is identical to \( P_{\text{m}}(n, B_1) \) in Fig. 2-a because only the current direction is reversed. Similarly, \( P_{\text{m}}(p, B_1) \) in Fig. 2-b is the same as that of \( P_{\text{m}}(n, B_1) \) in Fig. 2-a.

“Replacement of asynchronously measured loss \( P_1 + P_0 \) in Fig. 2-b with Fig. 2-a”

\[
= P_{\text{im}}(p, A_1) - P_{\text{m}}(p, A_1) - P_{\text{m}}(n, B_1) + P_{\text{im}}(n, B_1) \quad \text{...(15)}
\]

Furthermore, using (A10) and (A11) in Section 2.3, the power \( P_{\text{m}}(n, B_1) \) and \( P_{\text{trd}}(n, A_1) \) measured in the negative current direction can be replaced with \( P_{\text{trd}}(p, B_1) \) and \( P_{\text{trd}}(p, A_1) \), which are measured in the positive current direction.

“Replacement of asynchronously measured loss \( P_1 + P_0 \) in Fig. 2-a with only positive current power measuring in Fig. 2-a”

\[
= (P_{\text{im}}(p, A_1) - P_{\text{im}}(p, A_1)) + (P_{\text{im}}(p, A_1) - P_{\text{im}}(p, B_1)) - \varepsilon_{\text{IAC}} + \varepsilon_{\text{IDC}} \quad \text{...(16)}
\]

As the operating points \( A_1 \) and \( B_1 \) denote the powering and regenerating points, the first and second parentheses represent the total losses \( P_1 \) and \( P_0 \), respectively, measured in the positive current direction in Fig. 2-a. The third and fourth terms are the calibration values when the power measurement is calibrated in different current directions. Thus, the sum of the first and second parentheses is equal to the total loss \( P_1 + P_0 \) when all the current probes are in the positive direction, and the powers are measured as shown in Fig. 2-a. This term is defined as \( (P_1 + P_0)_{\text{av}} \) in Fig. 2-a, then by substituting equations (14) to (16), the following is derived:

\[
(P_1 + P_0)_{\text{av}} = \frac{P_{\text{trd}}(p, A_1) + P_{\text{trd}}(n, A_1) - \varepsilon_{\text{IAC}} + \varepsilon_{\text{IDC}}}{2} \quad \text{...(17)}
\]

where

\[
P_{\text{trd}}(p, A_1) + P_{\text{trd}}(n, A_1) - \varepsilon_{\text{IAC}} + \varepsilon_{\text{IDC}} \quad \text{...(18)}
\]

\[
P_{\text{trd}}(p, A_1) + P_{\text{trd}}(p, A_1) - P_{\text{trd}}(n, A_1) \quad \text{...(19)}
\]

\[
P_{\text{trd}}(p, A_1) + P_{\text{trd}}(p, B_1) - P_{\text{trd}}(p, B_1) \quad \text{...(20)}
\]

Operating points \( A_1 \) and \( B_1 \) indicate the different operating points of the powering and regenerating operations. Equations (19) and (20) represent the asynchronously measured losses under the powering and regeneration conditions. The difference between the absolute values of \( P_{\text{trd}}(p, A_1) \) and \( P_{\text{trd}}(p, B_1) \) is intended to be controlled within 1 W in the following experiments. This influence will be discussed in the second paragraph of Section 3.2 and in Section 4.1.

The final target is the averaged loss in the steady state; thus, the average action of (17) yields the following equation:

\[
\text{ave}(P_1 + P_0)_{\text{av}} = \text{ave}(P_{\text{trd}}(p, A_1)) + \text{ave}(P_{\text{trd}}(p, B_1)) - \text{ave}(\varepsilon_{\text{IDC}}) \quad \text{...(21)}
\]

where “ave” denotes averaging. From (18), the following equation is derived.

\[
\text{ave}(P_{\text{trd}}) = \text{ave}(P_{\text{trd}}(p, A_1)) + \text{ave}(P_{\text{trd}}(p, B_1)) - \text{ave}(\varepsilon_{\text{IDC}}) \quad \text{...(22)}
\]

The actual measurement is performed by obtaining the average of (19) and (20). Substituting these results into (7) yields the following averaged efficiency:

\[
\eta_{\text{ave}} = 1 - \frac{\text{ave}(P_1 + P_0)_{\text{av}} - \text{ave}(P_1 + P_0)_{\text{av}})}{2P_1} \quad \text{...(23)}
\]

2.5 Practical Analysis of Measurement Accuracy

The accuracy can be calculated using (12). The first parentheses of the right-hand side of (12) are calculated from (23); thus, the second parentheses of the right-hand side of (12) are analyzed.

(2.5-1) The numerator \( (\varepsilon_{1m} + \varepsilon_{2m}) \) of the first term of the second parentheses on the right-hand side of (12):

\( P_1 \) and \( P_0 \) denote the power differences of the AC and DC power in (2) and (4), respectively. From the analysis in Section 2.4, these two kinds of power differences are equal to the first and second parentheses of (14), respectively. The reading (rdg) error of these power differences can be estimated by multiplying rdg. error coefficient \( \alpha_{\text{rdg}} \) for the rdg power difference, as shown in Appendix 1. The rdg error coefficient of AC and DC power are the same, and the average of \( P_1 + P_0 \) measured at the current positive instruments in Fig. 2-a is calculated in (21); thus, this term becomes \( \alpha_{\text{rdg}} \times \text{ave} \)
The average losses of the powering and regenerating operations obtained from (22) are based on independent phenomena of operation; thus, the variance in the measurements can be independently calculated. Measurements were performed several times, by changing the dates and durations. The standard deviation of (22) is defined as $\sigma_{\text{loss}}$ as a function of the output power $P_1$. The maximum was defined as $\sigma_{\text{loss max}}$ and under the assumption of a 95% probability of standard deviation, twice of $\sigma_{\text{loss max}}$ was selected as the variance of measurement (22).

The average values of $\varepsilon_{\text{1DC}}$ and $\varepsilon_{\text{1AC}}$ were calculated following the measuring procedure described in Appendix 2 and measured several times. The variances are defined as $\sigma_{\text{1DC}}$ and $\sigma_{\text{1AC}}$, respectively, and were obtained from independent phenomena; thus, the total variance $\sigma_{\text{1AC-DC}}$ was calculated as

$$\sigma_{\text{1AC-DC}} = \sqrt{\sigma_{\text{1DC}}^2 + \sigma_{\text{1AC}}^2}; \quad (24)$$

Under the assumption of a 95% probability of standard deviation, this value was selected as the variance of the second parentheses of right-hand side of (12).

This term is the measuring error of $P_1$; thus, it was calculated by combining the reading accuracy coefficient ($\varepsilon_{\text{rdg}}$) and full-scale error ($\varepsilon_{\text{rs}}$), as shown in Appendix 1.

The Power Analyzer PW 6001 outputs data every 2 s, and 100 data points were calculated following the procedure presented in Appendix 2 in the power range of 500–2200 W. The Power Analyzer PW 6001 outputs the data every 10 ms, 100 data points can be averaged over 1 s. The average of these 20 data points, which are output every 2 s, can be considered a one-time measurement, and four measurements were performed by changing the measurement date and time. The DC power measurement calibration value $\varepsilon_{\text{1DC}}$ was larger than that of AC. Selecting the horizontal axis as the output power $P_1$, $\varepsilon_{\text{1DC}}$ is plotted, as shown in Fig. 3, where there is little output dependence between 500 W and 2200 W. Thus, the variances were calculated as an average, as presented in Table 1. As for the $\varepsilon_{\text{1AC}}$, the same tendency was observed. The total variance $\sigma_{\text{1AC-DC}}$ was calculated using Equation (24). The reason that $\varepsilon_{\text{1DC}}$ was larger than that of $\varepsilon_{\text{1AC}}$ is that the zero-adjustment operation when the current probes are used for the first time has a slightly larger variance in DC power measurement than in AC power measurement because the HEECS inverter has two DC voltage sources. The obtained values are used in Section 3.2.

Second, thrice the single inverter average loss, which is half of (21), and the average efficiency in (23) are shown in Figs. 4 and 5, respectively. $P_1$ was controlled to be within 1.4 W in the experiments. The Power Analyzer PW 6001 outputs data every 10 ms, and 100 data points can be averaged over 1 s. The average of 20 data that are output every 2 s can be considered a one-time measurement, and three measurements were performed by

| Calibration value | Variance |
|-------------------|----------|
| Average (W)       |          |
| DC Power          | $\varepsilon_{\text{1DC}}=0.0118$ Eq.(A12) | $\sigma_{\text{1DC}}=0.0420$ |
| AC Power          | $\varepsilon_{\text{1AC}}=0.0065$ Eq.(A13) | $\sigma_{\text{1AC}}=0.0231$ |
| Average           | $\varepsilon_{\text{1AC-DC}}=0.0116$ Eq.(24) | $\sigma_{\text{1AC-DC}}=0.0479$ |

3. Measurement Results

3.1 Loss Measurement and the Efficiency Calculation

The HEECS inverter was selected as a converter under test, and the measurement was performed following the procedure described in Section 2.6. The measurement instruments listed in Appendix 1 were preheated before the measurements, and all the equipment were installed in a constant temperature chamber for measurement. The HEECS inverter has two DC voltage sources, and the DC power was obtained by summing the outputs of the two DC power measurement instruments, which have the same rdg. coefficients. Thus, it is considered that the two voltage sources effectively work as one voltage source. The direction of the two DC current probes was changed simultaneously for calibration.

The calibration data are presented in Table 1; the calibration was performed following the procedure presented in Appendix 2 in the power range of 500–2200 W. The Power Analyzer PW 6001 outputs the data every 10 ms, 100 data points can be averaged over 1 s. The average of these 20 data points, which are output every 2 s, can be considered a one-time measurement, and four measurements were performed by changing the measurement date and time. The DC power measurement calibration value $\varepsilon_{\text{1DC}}$ was larger than that of AC. Selecting the horizontal axis as the output power $P_1$, $\varepsilon_{\text{1DC}}$ is plotted, as shown in Fig. 3, where there is little output dependence between 500 W and 2200 W. Thus, the variances were calculated as an average, as presented in Table 1. As for the $\varepsilon_{\text{1AC}}$, the same tendency was observed. The total variance $\sigma_{\text{1AC-DC}}$ was calculated using Equation (24). The reason that $\varepsilon_{\text{1DC}}$ was larger than that of $\varepsilon_{\text{1AC}}$ is that the zero-adjustment operation when the current probes are used for the first time has a slightly larger variance in DC power measurement than in AC power measurement because the HEECS inverter has two DC voltage sources. The obtained values are used in Section 3.2.

Second, thrice the single inverter average loss, which is half of (21), and the average efficiency in (23) are shown in Figs. 4 and 5, respectively. $P_1$ was controlled to be within 1.4 W in the experiments. The Power Analyzer PW 6001 outputs data every 10 ms, and 100 data points can be averaged over 1 s. The average of 20 data that are output every 2 s can be considered a one-time measurement, and three measurements were performed by

| Calibration value | Variance |
|-------------------|----------|
| Average (W)       |          |
| DC Power          | $\varepsilon_{\text{1DC}}=0.0118$ Eq.(A12) | $\sigma_{\text{1DC}}=0.0420$ |
| AC Power          | $\varepsilon_{\text{1AC}}=0.0065$ Eq.(A13) | $\sigma_{\text{1AC}}=0.0231$ |
| Average           | $\varepsilon_{\text{1AC-DC}}=0.0116$ Eq.(24) | $\sigma_{\text{1AC-DC}}=0.0479$ |

3.2 Concrete Procedure of the VITASLM Method

The procedure can be summarized as follows:

1. Prepare one set of measuring instruments and one inverter under test.
2. Calibrate the AC and DC power measurement instruments by changing the flow direction of the current probe and obtaining calibration values ($\varepsilon_{\text{1AC}}$ and $\varepsilon_{\text{1DC}}$) and the variances.
3. Measure the powering loss (19) and regenerating loss (20) separately and calculate the average efficiency in (23) using the calibrated loss (21).
4. The accuracy can be calculated using (12), (23), and (25).

Fig. 3. Calibrated $\varepsilon_{\text{1DC}}$ under four times DC power measurements as a function of $P_1$ when the current-flowing direction was changed.
changing the measurement date and time. At an output of approximately 1600 W, the loss was approximately 4 W in Fig. 4, and the efficiency was approximately 99.75%, as shown in Fig. 5.

### 3.2 Accuracy Calculation of the Measured Data

The accuracy is calculated using (25). The first term of this equation was obtained from the rms error. The second term can be explained as follows. Fig. 6 depicts an illustrative example of the 10-ms output waveform of \( P_{AC}(p,A_t) \) from the PW6001 power analyzer. This waveform exhibits stochastic properties with a ±1 W variation. However, powering and regenerating operations are independently controlled using a deadbeat control\(^{19,20} \). As described in Section 2.4, the average value of the loss must be obtained. Thus, using the averaging process mentioned in Section 3.1, the average losses were calculated. The variance of the measured losses (\( \sigma_{Loss} \)) was plotted, as shown in Fig. 7, as a function of the output power \( P_2 \) between 800 W and 2200 W. The maximum variance \( \sigma_{Loss_{\text{max}}} \) was found to be 0.021 W at an output of 1600 W, which is equivalent to an accuracy of 0.002%. The results are summarized in Table 2. The third term in (25) was calculated using \( \sigma_{L_{\text{AC-DC}}} \) in Table 1.

As already mentioned in the paragraph explaining (19) and (20) in Section 2.4, the operation points are intended such that the power difference \( P_3 \) between \( P_2 \) and \( P_4 \) is within 1 W, but it was within 1.4 W in the experiments. The variance of loss due to this operation mismatch can be calculated as follows. As an example, when the output power \( P_2 \) is 2000 W, the loss is approximately 5 W, as shown in Fig. 4. If the output power is 2001.4 W, then the loss increase may be \( 5 \times 1.4/2000 = 0.0035 \) W. This can be negligible because it is smaller than \( 2 \times \sigma_{Loss_{\text{max}}} \) and \( 2 \times \sigma_{\text{L_{AC-DC}}} \) for the measured data. However, if \( 2 \times \sigma_{\text{L_{AC-DC}}} \) decreases, this effect cannot be ignored.

Using the abovementioned results, the accuracy can be calculated based on (12) using (23) and (25), as shown in Fig. 8. The accuracy was found to be approximately 0.006% at an output of approximately 1600 W. This value is larger than 0.002%, which is equivalent to the accuracy of \( \sigma_{Loss_{\text{max}}} \) as mentioned in the first paragraph of this section; the measured data are stable with 0.002% variance but have a 0.006% measuring error at 95% probability.

It was reported\(^9 \) that the HEECS inverter has an efficiency of 99.71% ± 0.04%. The HEECS inverter under test in this paper was revised from this literature (8) and the on-resistance of the unfolding inverter became one-fourth; thus, the obtained efficiency of 99.75% was within the tolerance of the estimated efficiency.

### 4. Discussions

#### 4.1 Methods for Improvement of Measurement Accuracy

Several candidates for improving the measurement accuracy are...
available, and these are as follows: (i) increasing the robustness of control stability in powering and regenerating modes\(^{(19,20)}\), (ii) improving the reading error coefficients \(\sigma_{\text{rdg}}\)\(^{(16,17)}\), (iii) precise calibration of the power measurement instruments, (iv) increasing the precision of the harmonic power measurement\(^{(21)}\), and (v) decreasing the mathematical approximation error presented in Section 2.1.

The direct influence of the robustness of control stability is related to variance \(\sigma_{\text{rmsmax}}\), because this variance is reflected in the fluctuations of the measured real-time data. A stable and robust deadbeat control may reduce this fluctuation; however, this fluctuation is also influenced by other factors such as noise in the measurement instrument and freedom of operating points discussed in the second paragraph of Section 3.2. As presented in app. Table 1, the bit number of this power analyzer is 18; thus, the minimum resolution of 1000 W becomes 0.01 W, including polarity. Fig. 3 shows that \(\eta_{\text{DC}}\) was measured at a resolution of 0.01 W. As the rdg error is estimated by the product of the measured (or reading) power of \(\sigma_{\text{rdg}}\), which is directly related to the increase in accuracy. However, for instance, the accuracy of 0.006% at 1600-W output obtained in Section 3.2 can be broken down as follows: (i) approximately 60% from \(\sigma_{\text{DC}}\), (ii) approximately 20% from the reading error of \(P_2+P_4\), (iii) approximately 15% from \(\sigma_{\text{rmsmax}}\), and (iv) approximately 5% from \(\Delta P_2/\Delta \text{P}_{\text{rms}}\), which are obtained from (25). This implies that the calibration of the instruments proposed in Section 2.3 is the most dominant.

The influence of harmonic power is discussed here. According to a previous study\(^{(21)}\), the output harmonic power is estimated to be approximately 3% of the full output when the switching frequency is 20 kHz, which is the HEECS inverter switching frequency under test\(^{(8)}\). The current probe measurement error\(^{(17)}\) was 1% from the app. Table 1 and the power measurement rdg. accuracy\(^{(19)}\) became 1.02%. Furthermore, from Fig. 4, it is assumed that when the output power is 2000 W, the total average loss is approximately 5 W. In the proposed VTASLM method, losses are measured in powering and regenerating operations and added together. Thus, even though harmonic power is not very precisely measured, if the harmonic power provided from the DC voltage source to the inverter in powering and the harmonics power coming back from the inverter to the DC voltage source in regenerating operation are the same, they get canceled out in the proposed measuring method. If we can assume that the harmonic power is almost the same in powering and regeneration, the measuring error must be miniscule. If these assumptions are accepted, then the measurement loss error of the harmonic power is estimated as 5 W × 3% × 1.02% = 0.0015 W. This error is one order smaller than \(\sigma_{\text{DC}}\); thus, this error can be negligible as for the data measured in Section 3.

Two types of mathematical approximation are discussed in Section 2.1. Equation (6) can be rewritten as

\[
\eta_{\text{ave}} = 1 - \frac{P_2+P_4}{2P_2} (1 - \eta_{\text{DC}})P_2
\]

This equation indicates the mathematical approximation error from (6) to (7). The first two terms on the right-hand side are identical to the average efficiency (7); thus, the third term on the right-hand side is the mathematical approximation error. For example, using the measured value at a 1600-W output, this error becomes \((1 - 0.9975) \times 1.4/(2 \times 1600) \approx 1.2 \times 10^{-6}\), where the efficiency can be obtained from Fig. 5 under the assumption \(\eta_1 \approx \eta_{\text{ave}}\), and \(P_2\) was controlled to be within 1.4 W in the experiments, as mentioned in the last paragraph of Section 3.1. The accuracy in (12) is approximately \(6 \times 10^{-5}\) at an output of 1600 W, as shown in Fig. 8. This indicates that the approximation mathematical error from (6) to (7) is negligibly small compared to the accuracy (12). However, it is important to note that if \(P_1\) becomes larger, the approximation error increases. In addition, the derivation of the accuracy (12) is shown in Appendix 3, and the mathematical approximation error is estimated as the order of the multiplication of the first-order approximation, which is negligibly small.

4.2 Relation between Average Efficiency and Operating Points

In Fig. 1, we have the freedom of selecting the operating values of \(P_2\) and \(P_4\). The difference between \(P_2\) and \(P_4\) is tried to be controlled to be within 1 W, as mentioned in the paragraph explaining (19) and (20) in Section 2.4. This is illustrated in Fig. 9. If we select \(P_2\) and \(P_4\) to be close to each other, the difference in the efficiency of the powering and regenerating operations becomes less. However, the average efficiency was obtained using the proposed VTASLM method. For example, if the operation point is 2000 W, which is shifted to 2010 W, the loss change due to this 10 W drift is approximately \(5 \times 10^{-5}\) W. This is smaller than that of \(2 \times \eta_{\text{DC}}\). The average efficiency does not change much beyond the measurement accuracy in the measurement range of this experiment. However, the mathematical modeling error of efficiency (7) is a function of \(P_1\), as discussed on (26) in the last paragraph of Section 4.1.

Fig. 9. Freedom of operation point selection and average efficiency (illustrative explanation)
5. Conclusions

A new VTASLM method was proposed for the accurate loss measurement of inverters in all the electrical instruments, and its validity was confirmed by experimental measurements.

One set of measurement instruments and one converter under test are required, and the powering and regenerating modes should be prepared for measurement. After the calibration of the power measurement instruments by changing only the current direction, the loss measurement is asynchronously conducted in powering and regenerating operations. The average efficiency and accuracy can be calculated using the equations derived herein. A HEECS inverter was selected as the converter under test, and the loss was measured in the output power range between 800 W and 2,200 W. At 1,600 W, an average efficiency of 99.75% was observed with an accuracy of approximately 0.006%. Several aspects are discussed from the viewpoint of achieving higher accuracy in Section 4.

The proposed VTASLM methods can be used to measure the average efficiency at a very high accuracy using only electrical measurement instruments; thus, it will be useful for the development of high-efficiency inverters.

Acknowledgement

This project was supported by JSPS KAKENHI Grant Number 17H06147.

References

(1) O. Kreutzer, M. Billmann, and M. Maerz: “A passively cooled 15 kW, 800 V DCDC converter with a peak efficiency of 99.7 ¼”, IEEE Aicon 2017 Proceedings, pp. 1390-1396 (2017)
(2) Y. Gao, V. Sankaranarayanan, E. M. Dedey, G. D. Moksmimov, and R. W. Erickson: “Drive-Cycle Optimized 99% Efficient SiC Boost Converter Using Planar Inductor with Enhanced Thermal Management”, IEEE Workshop on Control and Modeling for Power Electronics (COMPEL) (2019)
(3) F. Xue, R. Yu, and A. Huang: “Fractional Converter for High Efficiency High Power Battery Energy Storage System”, IEEE ECCE2017 (2017)
(4) Y. Tsuruta, H. Obara, and A. Kawamura: “Development of 3.3 kV-100 kW Extremely High Efficiency SiC Chopper”, The 44th Annual Conference of the IEEE Industrial Electronics Society, (IECON) 2018, pp. 1164-1169 (2018)
(5) Y. Tsuruta and A. Kawamura: “Realization and Highly Precise Measurement of 50 kW HEECS Chopper with 99.5% Efficiency”, IEEE Journal of Industry Applications, Vol. 8 No. 5 pp. 843-848 (2019)
(6) J. A. Anderson, E.J. Hanak, L. Schrittwieser, M. Guacci, J.W. Kolar, and G. Deboy: “All-Silicon 99.35% Efficiency Three Phase Seven 3-Level Hybrid Neutral Point Clamped Flying Capacitor Inverter”, CESS Trans. On Power Electronics and Applications, Vol. 4, No. 1, pp. 50-61 (2019)
(7) Y. Shi, H.Li, L. Wang, Y. Zhang: “Intercell Transformer (ICT) Design Optimization and Interphase Crosstalk Mitigation of a 100-kW SiC Filter-Less Grid-Connected PV String Inverter”, IEEE Open Journal of Power Electronics, Vol. 1, pp. 51-63 (2020)
(8) A. Kawamura, S. Nakazaki, S. Ito, and S. Nagai: “Over 99.7% Efficiency Two Battery HEECS Inverter at 2.2 kW Output and Measurement Accuracy Based on Loss Breakdown”, IEEE Journal of Industry Applications, Vol. 9, No. 6, pp. 663-673 (2020)
(9) J. Zhu, K.H. Chen, R. Erickson, D. Moksmimov: “High efficiency SiC Traction Inverter for Electric Vehicle Applications”, pp. 1428-1433, APEC2018 (2018)
(10) J. Rabkowski, D. Persifitis, H. Nee: “Design Steps Towards a 40-kVA SiC Inverter with an Efficiency Exceeding 99.5%”, APEC2012 (2012)
(11) N. Kim, M. Biglarbegian, B. Parkhileh: “Flexible High Efficiency Battery-Ready PV Inverter for Rooftop System”, APEC2018, pp. 3244-3249 (2018)
(12) D. Christen, U. Badstueuber, J. Bieha, J.W. Kolar: “Calorimetric Power Loss Measurement for Highly Efficient Converter”, IEEE ECCE-Asia2010, pp. 1438-1445 (2010)
(13) L. Aarniovaara, A. Kosonen, P. Sillanpaa, M. Niemelä: “High-Power Solar Inverter Efficiency Measurements by Calorimetric and Electric Method”, IEEE Trans. PELS, Vol. 28, No. 6, pp. 2798-2805 (2013)
(14) T. Yamagushi, H. Akagi, S. Kinouchi, Y. Miyazaki and M. Koyama: “A 750-V, 100-kW, 20-kHz Bidirectional Isolated DC/DC Converter Using SiC-MOSFET/SBD Modules”, IEEE Transactions on Industry Applications, Vol. 134-D, No. 5, pp. 544-553 (2014) (in Japanese).
(15) A. Kawamura, Y. Nasu, Y. Miguchi, H. Setiadi, H. Obara: “Discussion on a new high accuracy loss measurement method of high efficient HEECS inverter”, IEJE, Tech. Comm. Meet. On Semiconductor Power Conversion, SPC-21-089 (2021)
(16) HIOKI PW6001 Manual, June2017 revised edition
(17) HIOKI CT6862 Manual, Oct.2018 revised edition 8
(18) A. Kawamura, S. Nagai, S. Nakazaki, S. Ito, and H. Obara: “A very high efficiency circuit topology for a few kW inverter based on partial power conversion principle”, in Proc. of IEEE Energy Conversion Congress and Expo, Sept. (2018)
(19) Y. Miguchi, Y. Nasu, H. Obara, A. Kawamura: “Current control of very high efficiency single-phase grid-connected inverter (HEECS)”, IEJE, Tech. Comm. Meet. On Semiconductor Power Conversion, SPC-20-128 (2020)
(20) Y. Nasu, Y. Miguchi, H. Setiadi, H. Obara, A. Kawamura: “Regenerative operation with two battery HEECS inverter”, IEJE, Tech. Comm. Meet. On Static Power Conversion, SPC-21-082 (2021)
(21) K. Hayashi: “High resolution measurement of power measurement”, HIOKI technical article (2016)

Appendix

1. Measurement Accuracy of Absolute Measurement and the Power Difference Measured at the Same Instruments

To undertake a clear analysis of the power measurement, a symbol of power P_{2m}(p,A_1) is introduced, and it is defined as follows: p in the parentheses indicates the positive direction of the current probe. If it is n, it is the negative direction of the current or reverse of the positive direction. A_1 in the second term in the parentheses indicates the operating point. If the power is measured at another operation point A_2, it is shown. The suffix m of P_2 indicates that it is a measured or reading value of P_2, and the value without this suffix is the true value. P_2, P_3, and other symbols correspond to those in Figs. 1 and 2. An illustration of the relation between the true value and the reading value is shown in the app. Fig. 1. If it is assumed that the power reading P_{2m}(p,A_1) is 2230 W with the positive (p) current-flowing direction at operating point A_1, using the current probe CT6862(17) and the power analyzer 6001(16), the measuring error ΔP_{2m}(p,A_1) is calculated as follows: The major specifications of the instruments are shown in the app. Table 1. Measurement error of P_{2m}(p,A_1)=(ΔP_{2m}(p,A_1)) = 2230 W (reading) × (0.03% [reading (rdg. coefficient of the current probe) + 0.02% (rdg. coefficient of the power analyzer)] + 3000 W (power analyzer range 300V × 10A) × (0.01%[full scale (fs.) coefficient of current] × current rating/current measurement range + 0.03%[fs. coefficient of power analyzer])=2230 × (0.05 + 0.02)/100 + 3000 × (0.01 × (50/10) + 0.03)/100
=1.561 + 2.4 = 3.961 W. .................................................. (A1)

where the rdg. coefficients and f.s. errors of the current probe and power analyzer are combined and defined as \(\alpha_{rdg}\) and \(C(p,P_2)\), respectively. Using these notations, (A1) becomes

\[\Delta P_{2m}(p,A_1) = \alpha_{rdg} \times 2240 + C(p,P_2).\]  ................................................................. (A2)

It is assumed that if the measurement range is the same, the f.s. error \(C(p,P_2)\) remains constant. If measurement error (A1) is converted to accuracy, it becomes 3.961/2230 = 0.18\%, which means that the absolute value accuracy of (A1) is 0.18\%.

In contrast, in app. Fig. 1, it is assumed that another measurement \(P_{2m}(p,A_2)\) is obtained at another operating point \(A_2\), and the accuracy of the power difference \(P_1 = P_{2m}(p,A_2) - P_{2m}(p,A_1)\) is estimated. We also assume that \(P_{2m}(p,A_2)\) is measured in the same range of \(P_{2m}(p,A_1)\), and the following measuring error of \(\Delta P_{2m}(p,A_2)\) is derived.

\[\Delta P_{2m}(p,A_2) = \alpha_{rdg} \times 2240 + C(p,P_2)\]  ................................................................. (A3)

The difference \(\Delta P_1 = \Delta P_{2m}(p,A_2) - \Delta P_{2m}(p,A_1)\) (A3) – (A1) = 0.007W  ........................................... (A4)

This means that the accuracy of the power difference depends only on rdg. coefficient, \(\alpha_{rdg}\) (0.07\%). However, if the measurement instruments used in (A1) and (A3) are different, rdg. coefficient and/or f.s. error may be different. If so, (A4) cannot be true. If the same instruments are used but only the direction of the current is different, the error can be calibrated using the method introduced in Appendix 2. The accuracy of (A4) is guaranteed only if this calibration is properly completed.

2. Practical Calibration Method of the Power Measurement Instruments when the Current Directions are Positive and Negative, and How to Use the Calibration Value

An illustration of the loss measuring in Fig. 2-a at two operating points \(A_1\) and \(B_1\) is shown in the app. Fig. 2, where the current direction of the instruments for measuring \(P_1\) is positive (p) at operating point \(A_1\) and negative (n) at operating point \(B_1\). The current direction of the instrument for measuring \(P_2\) is positive (p) at both \(A_1\) and \(B_1\).

The loss \((P_1 - P_2)\) measured at the current direction positive of \(P_1\) at operating point \(A_1\) and that with current direction negative of \(P_1\) at operating point \(B_1\) are compared, and the difference \(\varepsilon_1\) is given in the following equation.

\[\varepsilon_1 = (P_{1m}(p,A_1) - P_{2m}(p,A_1)) - (P_{1m}(n,B_1) - P_{2m}(p,B_1))\]  ................................................................. (A5)

Using notation, in Appendix 1., this becomes,

\[\varepsilon_1 = [P_{1m}(p,A_1) - P_{2m}(p,A_1)] - (P_{1m}(n,B_1) - P_{2m}(p,B_1)) + \alpha_{rdg}[P_{1m}(p,A_1) - P_{2m}(p,A_1)]\]  ................................................................. (A6)

The first term in parentheses is the true loss difference between \(A_1\) and \(B_1\). For example, if there is a 1-W difference between the outputs of 2000 W at \(A_1\) and \(B_1\), the loss difference due to this difference is estimated to be \(5 \times 1/2000 = 0.0025\) W. (5 W is assumed to be an approximate loss at 2000 W output from Fig. 4.) This error is defined as \(\varepsilon_11\). The second term in the parentheses is rdg. error of this loss power difference; thus, it is estimated to be 0.0025 \(\times \alpha_{rdg}\), which is very insignificant and can be defined as \(\varepsilon_12\). Subsequently, (A6) becomes

\[\varepsilon_1 = \varepsilon_11 + \varepsilon_12 + C(p,P_1) - C(n,P_1)\]  ................................................................. (A7)

\(\varepsilon_11\) and \(\varepsilon_12\) are very small compared with \(\varepsilon_1\), and they are negligible; thus, (A7) becomes

\[\varepsilon_1 = C(p,P_1) - C(n,P_1)\]  ................................................................. (A8)

This \(\varepsilon_1\) may be constant around these operating points. Next, as a
thought experiment, operation points $A_1$ and $B_1$ are set to be the same at (A5), the following is obtained:
\[
\epsilon_1 = (P_{\text{in}}(p, A_1) - P_{\text{in}}(n, A_1)) - (P_{\text{in}}(n, A_1) - P_{\text{in}}(p, A_1))
\]
\[
\epsilon_1 = \left(1 - \frac{P_{\text{in}}(n, A_1)}{P_{\text{in}}(p, A_1)}\right) \frac{P_{\text{in}}(n, A_1) - P_{\text{in}}(p, A_1)}{P_{\text{in}}(n, A_1)} - \epsilon_{\text{in}}(1 - \epsilon_{\text{in}})
\]

The second and fourth terms were canceled. If the calibration value of the DC power measurement $P_1$ is defined as $\epsilon_{\text{DC}}$, the following equation is derived:
\[
P_{\text{in}}(p, A_1) = P_{\text{in}}(n, A_1) + \epsilon_{\text{DC}}
\]

Similarly, for the AC power calibration value $\epsilon_{\text{AC}}$, the following equation is derived:
\[
P_{\text{in}}(p, A_1) = P_{\text{in}}(n, A_1) + \epsilon_{\text{AC}}
\]

Referring to (A5), the calibration values can be measured using the following two equations:
\[
\epsilon_{\text{DC}} = (P_{\text{in}}(p, A_1) - P_{\text{in}}(n, A_1)) - (P_{\text{in}}(n, B_1) - P_{\text{in}}(p, B_1))
\]
\[
\epsilon_{\text{AC}} = (P_{\text{in}}(p, C_1) - P_{\text{in}}(n, C_1)) - (P_{\text{in}}(n, D_1) - P_{\text{in}}(p, D_1))
\]

The losses in the powering and regenerating modes are independently and separately (asynchronously) measured as average values.

These (A10) and (A11) are used in Section 2.4 when the power measured in the reverse current direction is converted to the value measured in the current positive direction. An accurate power difference estimation by this conversion supports the high measurement accuracy of the proposed VTASLM method.

3. Derivation of the Accuracy (12) and Mathematical Approximation Error

Putting (8)–(11) into (7) yields
\[
\eta_{\text{ave}} = 1 - \frac{P_{\text{in}}(n, A_1) - P_{\text{in}}(p, A_1)}{P_{\text{in}}(p, A_1)}
\]

Applying Taylor expansion under the assumption that $(\bar{\tau} \Delta P_1 + \bar{\tau} \Delta P_0)/(P_{\text{in}} + P_{\text{em}}) \ll 1$ and $\Delta P_1/P_{\text{in}} \ll 1$ yields the following,
\[
\eta_{\text{ave}} = 1 - \frac{P_{\text{in}}(n, A_1) - P_{\text{in}}(p, A_1)}{P_{\text{in}}(p, A_1)} + \frac{\bar{\tau} \Delta P_1}{P_{\text{in}}(p, A_1)} + \frac{\bar{\tau} \Delta P_0}{P_{\text{in}}(p, A_1)}
\]

The left-hand side of (A15) denotes the true average efficiency, and the first two terms on the right-hand side are the proposed average efficiencies (7). The third term on the right-hand side is the proposed accuracy (12), and the fourth is the higher order term. Thus, the mathematical approximation error of accuracy (12) can be evaluated using the fourth term. At the 1600-W output, the value of the third term of (12) is 0.006%, as can be seen from Fig. 5; thus, this higher-order fourth term is negligibly small.