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CALIBRATION PROCESS QUANTITY REDUCTION OF THE THERMAL VOLTAGE CONVERTER STANDARD USING A THREE-STAGE BUILD-UP AND BUILD-DOWN METHOD

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ABSTRACT

Currently, three single junction–type Thermal Voltage Converter (TVC) standard units represent the highest standard of AC (Alternating Current) voltages owned by the Electrical Metrology Laboratory, Research Centre for Metrology—Indonesian Institute of Sciences. The accuracy of the single junction–type TVC is maintained regularly via intercomparison processes using a one-step build-up and build-down method. To reduce the calibration process quantity, three steps of build-up and build-down measurements that refer to the 4 V measurement point of a HOLT production single junction–type TVC were carried out. The dissemination processes with the best measurement accuracy up to 20 ppm were successfully obtained from measurement points between 1 V and 20 V via 4–1V, 4–2V, 4–3V, 4–6V, 4–10V, and 4–20V formations.

Keywords: AC voltage quantity; Accuracy; Maintenance; Single junction–type Thermal Voltage Converter (single junction–type TVC)

1. INTRODUCTION

The Electrical Metrology Laboratory (EML) maintains its AC (Alternating Current) voltage standards at 1–1000 V using three single junction–type Thermal Voltage Converter (TVC) standard units (Hermach, 1976; Syahadi et al., 2015). The accuracy levels of these standards are maintained via measurement processes based on the intercomparison method. Basically, the ability of the measurement points between 1 V and 1000 V in the 10 Hz to 1 MHz range (Oldham et al., 1997) can be determined by varying operational couples between three single junction–type TVCs and six voltage divider resistances. The single junction–type TVCs have the technical identifications of T2.5-1V (Ballantine), T5-2V (Ballantine), and TE (Holt), while the technical identifications of the six voltage divider resistances are $Z_{VD}1$, $Z_{VD}2$, $Z_{VD}3$, $Z_{VD}4$, $Z_{VD}5$, and $Z_{VD}6$ (Halawa & Al-Rashid, 2010).

Pair combinations of the above single junction–type TVCs and voltage divider resistances can produce 15 measurement point capabilities, namely 1 V, 2 V, 3 V, 4 V, 6 V, 10 V, 20 V, 30 V, 60 V, 100 V, 200 V, 300 V, 500 V, 600 V, and 1000 V. Each measuring point must be calibrated to an international standard, such as the Korea Research Institute of Standards and Science (KRISS) standard using the one-step build-up and build-down (OSBUBD) method. OSBUBD has ever been used by Klonz et al. (1995) and Kinard et al. (1997).

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The objective of this research is to develop a new method that can reduce the calibration process quantity, but is still acceptable from a metrological point of view. This new method is called the Three-Step Build-Up and Build-Down (TSBUBD) method. In this approach, three measuring points, namely 4 V, 100 V, and 600 V, are used as the reference points. The 4 V measurement point is built up to 4–6V, 4–10V, and 4–20 V formations and built down to 4–1V, 4–2V, and 4–3V formations. The 100-V measurement point should be disseminated downward to 100–30 V and 100–60 V, and upward to 100–200 V and 100–300 V. The 600 V measurement point should be built up and built down to 600–1000 V and 600–500 V, respectively.

Currently, this research is limited to the 4-V measurement point. This means that the total calibration cost can be reduced by 47%. If the TSBUBD method works well, it will be applied or extended to the 100-V and 600-V measurement points, and the calibration cost will be reduced by up to 80%.

2. METHODOLOGY

AC voltage standards are derived from the DC (Direct Current) voltage standard using a high-precision D/A converter or power-to-force or heat converter (Sasaki & Takahashi, 1999). In this study, power-to-heat conversion is used.

The authors developed a new method, TSBUBD, which was validated utilizing the older OSBUBD method. The measurement setup and uncertainty calculation methods of OSBUBD and TSBUBD are the same. Their differences emerge in their comparison steps (Table 1) and the quantity of intercomparison. The intercomparison process for TSBUBD only occurs at 4 V, while for OSBUBD, it is carried out at 2, 3, 4, 6, and 10 V.

Table 1 Comparison between the OSBUBD and TSBUBD methods

OSBUBD (standard pair)	TSBUBD (standard pair)
10–20 V	4–20 V
6–10 V	4–10 V
4–6 V	4–6 V
4–3 V	4–3 V
3–2 V	4–2 V
2–1 V	4–1 V

2.1. Measurement Setup

In this study, the single junction–type TVCs were mounted in a special arrangement (Figure 1). The mounting was technically designed to minimize electric static noises caused by bad contacts on the T-connector for both single junction–type TVCs and the reverse-forward switch. A good leveling performance was created by centralizing the position of both single junction–type TVCs in a straight-line alignment. This mounting was adopted for optimizing the connection between the two connector surfaces of the instruments.

Figure 1 Holt and Ballentine TVC mounting

AC–DC voltage difference instruments were set up using Budovsky and Ingils' (1999) method, as shown in Figure 2. The AC or DC signal was applied sequentially via a switch to an instrument called a *Unit Under Calibration* (UUC) and a standard (reference, REF). The Electromagnetic Frequency (EMF) outputs of the instruments were monitored using two Digital Nanovoltmeters (DVM1 and DVM2). After the stabilization process was complete, the computer initiated the DVM1 and DVM2 readings simultaneously.

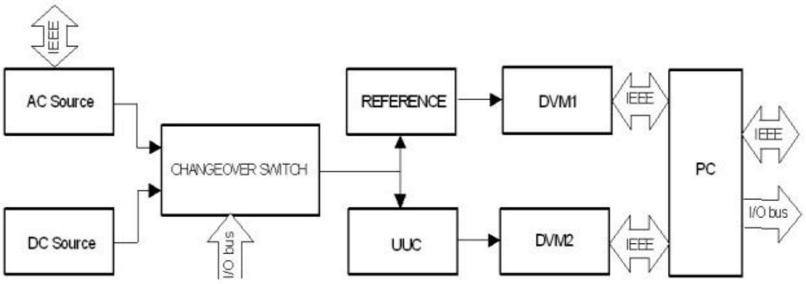

Figure 2 Basic measurement setup of the AC–DC voltage difference

2.2. AC–DC Difference Standard Configuration

EML has three single junction–type TVCs, namely T2.5, T5, and TE. If these TVCs are combined with six voltage divider resistances—ZVD1, ZVD2, ZVD3, ZVD4, ZVD5, and ZVD6—then the measurement capabilities can be increased to 15 measurement points, namely 1V, 2V, 3V, 4V, 6V, 10V, 20V, 30V, 60V, 100V, 200V, 300V, 500V, 600V, and 1000V.

The accuracy of the 15 standard unit measurement points was maintained via comparisons. Two common comparison methods for single junction–type TVC unit accuracy maintenances are called *upward dissemination* (build up) and *downward dissemination* (build down). Thus, the integrated upward and downward dissemination process can be termed the *Build Up and Build Down* (BUBD) method.

2.3. Mathematical Model and Uncertainty of the AC–DC Difference Measurement System

The difference between the AC and DC voltages can be presented in the form of a mathematical model (Sasaki & Takahashi, 1999), as follows:

$$\delta_{AC-DC} = \frac{V_{AC} - V_{DC}}{V_{DC}} \,|E_{AC} = E_{DC}, \tag{1}$$

where $d_{AC\text{-}DC}$ is the AC-DC difference (ppm) V_{AC} is the AC voltage, and V_{DC} is the average DC voltage in the forward (DC+) and reverse (DC-)directions. The quantities of E_{DC} and E_{AC} represent the output EMFs of the thermocouple when the DC voltage (V_{DC}) and AC voltage (V_{AC}) are applied to the thermal converter. In this case, V_{AC} is required to produce an output EMF that is equal or nearly equal to the V_{DC} (Hermach, 1976). In the above condition, the *n* variable needs to be included as the exponent of the thermal converter

$$E = KV^n, \tag{2}$$

where *E* is the EMF output of the thermal element for the single junction–type TVC, *V* is the applied voltage, K is a constant that depends on the heater current, and *n* is a number between 1.6 and 1.9.

The relationship between a small change of the thermal element heater voltage (ΔV) and the corresponding change of output (ΔE) is expressed as follows:

$$E_{Out} = k.V_{In}^{n}, \tag{3}$$

where

$$n = \frac{\Delta E_{Out}}{E_{Out}} . \frac{V_{In}}{\Delta V_{In}}.$$

From the comparison between single junction–type TVC$_{REF}$ and single junction–type TVC$_{UUC}$, a substitution variable is obtained in the equation form $V_{In}^{AC1} = V_{In}^{AC2}$ .The number 1 is the initial $A = \pi r^2$value for the reference, while 2 is the initial for the UUC, so that Equation 3 can be expanded into a new equation, as follows:

$$\Delta\delta = \delta_2 - \delta_1 = \frac{E_{Out}^{AC1} - E_{Out}^{DC1}}{n_1 . E_{Out}^{DC1}} - \frac{E_{Out}^{AC2} - E_{Out}^{DC2}}{n_2 . E_{Out}^{DC2}}, \tag{4}$$

where $\Delta\delta$ is a correction value of the AC–DC difference between REF and UUC, δ_1 is the AC–DC difference in the REF single junction–type TVC unit, and δ_2 is the AC–DC difference in the UUC single junction–type TVC unit.

Based on Equation 4, the mathematical model for evaluating the AC–DC difference measurement of UUC becomes

$$\delta_{UUC} = f(x)$$

$$\delta_{UUC} = \left(\delta_{REF-TVC} + \Delta_{Drift}\right) + \left(\delta_{Repeat} + \Delta_{connector} + \Delta_{Temp} + \Delta_{Sens} + \Delta_{Freq}\right) + \delta_{UUC-stability} \tag{5}$$

where δ_{UUC} is the AC–DC difference of the UUC TVC, $\delta_{REF\ TVC}$ is the AC–DC difference of the REF TVC, Δ_{Drift} is the correction drift of the REF TVC, $\delta_{repeatability}$ is the repeatability of the AC–DC difference, $\Delta_{connector}$ is the correction of the connector, $\Delta_{temperature}$ is the correction of the temperature, $\Delta_{sensitivity}$ is the correction of the TVC's sensitivity, $\Delta_{frequency}$ is the correction of frequency, and $\delta_{UUC\ stability}$ is the correction of the UUC TVC's stability. It should be noted that permanent changes or drifts that occurred after calibration were omitted.

For each type B component of uncertainty (Joint Committee for Guides in Metrology, JCGM, 2012), estimations were made as the best possible estimation of the standard deviation of the uncertainty component and an estimation of the likely uncertainty of the value of the standard deviation. In this research, there were some uncertainty sources. The individual components of uncertainty are as follows:

1) Repeatability/ESDM (Experimental Standard Deviation of the Mean): This is the standard deviation of the mean of the five or more measurements that were made during calibration. The number of degrees of freedom is one fewer than the number of measurements made. The sensitivity coefficient of repeatability is defined as

$$C_1 = \frac{\partial(f(x))}{\partial(\partial_{Repeat})} = 1;$$

2) The uncertainty of the single junction–type TVC as the EML standard: This is obtained from a calibration process. The EML standard (TVC Fluke REF-2V and TVC Fluke REF-4V) were calibrated by UUC-CSIRO (Commonwealth Scientific and Industrial Research

Organisation) in March 2001 and UUC-KRISS in 2008. The sensitivity coefficient of the REF TVC is

$$C_2 = \frac{\partial(f(x))}{\partial(\partial_{REF-TVC})} = 1;$$

3) Connector uncertainty: Connector uncertainty due to the skin effect, transmission line, and other effects in the connectors and tee-pieces was determined in the measurement process. The sensitivity coefficient of the connector is

$$C_3 = \frac{\partial(f(x))}{\partial(\partial_{Connector})} = 1;$$

4) Drift of the single junction–type TVC standard: This is an additional uncertainty due to the possibility of changes since the last calibration. The estimated standard deviation of this component is derived from the available history of the standard. The sensitivity coefficient of the DC source is

$$C_4 = \frac{\partial(f(x))}{\partial(\partial_{Drift})} = 1;$$

5) Temperature change: The temperature change during the measurement was relatively small. The sensitivity coefficient of temperature is

$$C_5 = \frac{\partial(f(x))}{\partial(\partial_{Temp})} = 1;$$

6) The uncertainty of index "n": This must be treated as one of the systematic error sources. The uncertainty in the index "n" contributes to the total uncertainty; the main source of error in the index measurement is the output EMF voltage (ΔE_{UUC}, ΔE_{REF}). The sensitivity of index "n" (C_6) can be evaluated using

$$\delta_{UUC} = f(\delta) = \frac{E_{REF\,AC} - E_{REF\,DC}}{n_{REF}\ E_{REF\,DC}} - \frac{E_{UUC\,AC} - E_{UUC\,DC}}{n_{UUC}\ E_{UUC\,DC}} + \delta_{REF} \quad ,$$

$$C_{n-UUC} = \frac{\partial(f(\delta))}{n_{UUC}} = -\frac{E_{UUC\,AC} - E_{UUC\,DC}}{n_{UUC}^2\ E_{UUC\,DC}} = -\frac{1}{2^{1.9}} x200ppm = -50\ ppm = -57x10^{-5} \quad ,$$

$$C_{nREF} = \frac{\partial(f(\delta))}{n_{REF}} = -\frac{E_{REF\,AC} - E_{REF\,DC}}{n_{REF}^2 . E_{REF\,DC}} = -\frac{1}{2^{1.9}}\ x\ 200\ ppm = -50\ ppm$$
$$= -57x10^{-5};$$

7) Traceable frequency meter: This monitors the accuracy to which the oscillator can be set in the frequency; however, no frequency adjustment was performed in the present study. The frequency uncertainty was ascertained (standard deviation) from the known changes in the REF and UUC with frequency, and a combined component of uncertainty was calculated. The sensitivity coefficient of frequency is

$$C_7 = \frac{\partial(f(x))}{\partial(\partial_{Freq})} = 1; \text{ and}$$

8) UUC stability: This is an estimate of the UUC's instability during the period of calibration (up to 1 month), and not a prediction of the stability between calibrations. The sensitivity coefficient of UUC stability is

$$C_8 = \frac{\partial(f(x))}{\partial(\partial_{UUC-Stability})} = 1.$$

All components of uncertainty were analyzed based on the square root of the sum of the squares (RSS) of their individual values. This RSS value was then stated as the combined standard uncertainty. The effective number of degrees of freedom of the combined standard uncertainty can be calculated using the following formula:

$$v_{eff} = \frac{\sqrt{\sum u_C^2}}{\sum \frac{u^4}{v_C}},$$

where u_c is the component of uncertainty and v_c represents the degrees of freedom of u_c.

Expanded uncertainty was obtained by multiplying the combined uncertainty with the coverage factor *k*. This factor is derived from the student *t* factor at a 95% confidence level. In mathematical form, the expanded uncertainty is

$$U_{Expanded} = k.U_C. \tag{6}$$

3. RESULTS AND DISCUSSION

The starting point of this research was the aim of establishing the accuracy level of the single junction–type TVC standard units. This was obtained from calibration processes for a Multi-Junction Thermal Voltage Converter (MJTVC) standard unit that is eligible as an international standard.

Through this study, the accuracy characteristics of six single junction–type TVC measurement points were analyzed. The traceability process of these six measurement points, namely 1 V, 2 V, 3 V, 6 V, 10 V, and 20 V, could in fact be represented by only one measurement point. This process was not only economically beneficial, but also metrologically acceptable, as it was conducted using the TSBUBD method at the 4 V measurement point (as the REF), as shown at Figure 3. Each step was traceable, as it referred to a 4 V standard measurement unit that was calibrated to KRISS.

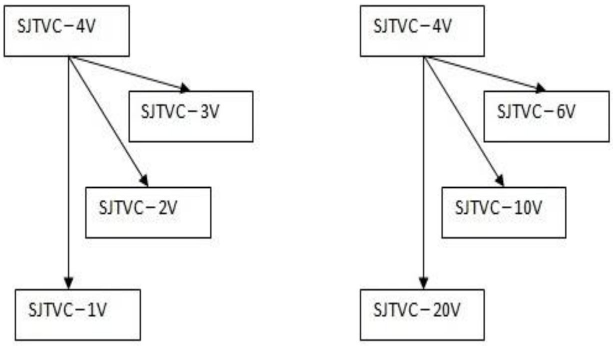

Figure 3 TSBUBD method

The advantage of applying the measurement method proposed in this study is that it saves costs and calibration time. Application of this measurement method based on the validation process will enable a decrease in the competence value if there is an increase in the measurement uncertainty value. Therefore, in future, technical development of the measurement method should be carried out to obtain the value of the source of the minimum uncertainty.

There were at least two errors that influenced the AC–DC difference measurements, namely a thermal conversion error and a loading effect error. The sources of the thermal conversion error were serial inductance from the measurement cable (L_{Line}, reach ≤ 1 ppm); shunt admittance from the parasitic capacitance between the TE input terminals (C_{input}, several ppm at 1 MHz); total skin effect from the heater resistance (R_{H1} and R_{H2} leads, R_{TC1} and R_{TC2} bead resistance, $R_{tee\text{-}connector}$, and $R_{housing}$, tens of ppm at 1 MHz); distributed capacitance at the bead (extremely small); and bead admittance where, at frequencies up to 1 MHz, the capacitance was at the pF or nF level and resistance was greater than 100 MΩ where in this case was ≅0.5 GΩ. The thermal conversion error could also be influenced by thermoelectric characteristics (Huang et al., 1995). The thermal conversion error was extremely small (Halawa & Al-Rashid, 2010) and could be omitted using a fast-reversal DC (FRDC) technique.

As shown in Figure 4, there were two types of information that we wanted to obtain. These were the AC–DC difference and the measurement uncertainty. These matters are investigated separately below.

Based on Equation 5, δ_{UUC} can be obtained from δ_{REF} (standard variable value) and n (thermal sensitivity response element). From the first measurement of the input single junction–type TVC, U_{In-1}^{DC} = 1.00000V and nanovoltmeter $E_{Out\text{-}1}$ = 6.09653 mV, and from the second measurement of the input single junction–type TVC, U_{In-2}^{DC}= 0.99000V and nanovoltmeter $E_{Out\text{-}2}$ = 5.99098 mV. Therefore,

$$\Delta E_{Out} = (6.09653 - 5.99098)\text{ mV}$$
$$= 0.10555\text{ mV},$$

and

$$\Delta U_{In}^{DC} \quad = (1.00000 - 0.99000)\text{ V} = 0.01\text{ V}.$$

Then, n can be obtained as

$$n = \frac{0.000106}{0.00609} \cdot \frac{1.00000}{0.01} = 1.81 \; .$$

This fulfils the criteria 1.6 $\leq$ n $\leq$ 1.9.

Based on Equation 4, $\Delta\delta_{UUC}$ for the TSBUBD method is presented in Table 2. The results depend on the AC voltage frequencies.

Following Budovsky's (2002) method, the measurements were conducted sequentially five times (n = 5), where each sequence consisted of three measurement variables, namely AC, DC+, and DC–. A type A measurement uncertainty due to random error emerged (Table 5). The measurement system was technically validated through an APMP (Asia Pacific Metrology Programme) International Comparison of AC–DC Transfer Standards participation coordinated by the National Measurement Institute, Australia, and a technical review from 2002 by KRISS.

Based on Equation 4, the AC–DC differences for the six formations at certain operating frequencies are presented in Table 3.

Table 2 $\Delta\delta_{\mathrm{TSBUBD}}$ measurement result

	$\Delta\delta_{\mathrm{TSBUBD}}$ (ppm)					
Freq. (kHz)	Formation 4–3	Formation 4–2	Formation 4–1	Formation 4–6	Formation 4–10	Formation 4–20
0.02	–9	–4	0.3	–3	–11	–9
0.04	–8	–5	0	–3	–11	–8
0.5	–8	–5	–2	–3	–12	–8
1	–7	–6	3	–3	–11	–8
10	11	–3	3	–2	3	–10
20	16	–3	3	–2	7	–10
50	20	–1	5	–2	6	–11
100	23	1	6	–2	4	–15
200	27	3	6	0.1	–1	–19
300	30	4	8	2	–2	–23
500	36	5	7	4	–4	–34
700	42	6	9	6	–1	–47
1000	54	6	12	9	0.4	–95

Table 3 δ_{TSBUBD} for the six formations at some operating frequencies in ppm

	δ_{TSBUBD} (ppm)						
Freq. (kHz)	Certificate 4 V	Formation 4–3	Formation 4–2	Formation 4–1	Formation 4–6	Formation 4–10	Formation 4–20
0.02	–1	–9	–4	0.3	–3	–11	–9
0.04	–2	–8	–5	0	–3	–11	–8
0.5	–2	–8	–5	–2	–3	–12	–8
1	–2	–7	–6	3	–3	–11	–8
10	–1	11	–3	3	–2	3	–10
20	–1	16	–3	3	–2	7	–10
50	4	20	–1	5	–2	6	–11
100	9	23	1	6	–2	4	–15
200	18	27	3	6	0.1	–1	–19
300	25	30	4	8	2	–2	–23
500	35	36	5	7	4	–4	–34
700	41	42	6	9	6	–1	–47
1000	47	54	6	12	9	0.4	–95

Referring to Equation 5, the measurement accuracy can be obtained by integrating several sources of measurement uncertainties in Table 3. The AC–DC difference measurement accuracies at the operating frequencies for the standard single junction–type TVC (REF) in TSBUBD and calibrated single junction–type TVC (UUC) in OSBUBD can be seen in Tables 4 and 5, excluding the formation of 4–3V and 3–4V, which have the same value for both TSBUBD or OSBUBD.

In this research, the validation of the TSBUBD was assessed mathematically using a ratio error number (E_n):

$$E_n = \frac{x_{TSBUBD} - x_{OSBUBD}}{\sqrt{U^2_{TSBUBD} + U^2_{OSBUBD}}}, \tag{7}$$

Table 4 AC–DC difference values of the OSBUBD and TSBUBD methods in uV

Freq (kHz)	SJTVC Standard	3–2V (OSBUBD)	4–2V (TSBUBD)	2–1V (OSBUBD)	4–1V (TSBUBD)	6–10V (OSBUBD)	4–10V (TSBUBD)	10–20V (OSBUBD)	4–20V (TSBUBD)
0.02	–4	–7	–10	–3	–1	–7	–49	–4	–38
0.04	–8	–10	–13	–4	–2	–10	–52	–31	–41
0.5	–8	–13	–15	–5	–4	–13	–56	–31	–40
1	–8	–14	–15	–5	1	–7	–52	–44	–40
10	–4	–10	–9	–3	2	50	9	–121	–44
20	–4	–4	–8	–1	2	65	22	–162	–44
50	16	8	6	5	9	97	40	–138	–28
100	36	19	19	10	15	112	53	–100	–24
200	72	39	43	18	24	132	68	–24	–4
300	100	51	58	23	33	153	92	43	9
500	140	71	80	33	42	199	124	110	4
700	164	77	95	37	50	253	159	165	–25
1000	188	81	107	41	59	341	190	248	–193

Table 5 Measurement uncertainties of the OSBUBD and TSBUBD methods in uV

Freq (kHz)	SJTVC Standard	3–2V (OSBUBD)	4–2V (TSBUBD)	2–1V (OSBUBD)	4–1V (TSBUBD)	6–10V (OSBUBD)	4–10V (TSBUBD)	10–20V (OSBUBD)	4–20V (TSBUBD)
0.02	28	28	28	28	28	28	28	28	28
0.04	20	20	20	20	20	20	20	20	20
0.5	20	20	20	20	20	20	20	20	20
1	20	20	20	20	20	20	20	20	20
10	20	20	20	20	20	20	20	20	20
20	20	20	20	20	20	20	20	20	20
50	24	24	24	24	24	24	24	24	24
100	2	2	2	2	2	2	2	2	2
200	48	48	48	48	48	48	48	48	48
300	48	48	48	48	48	48	48	48	48
500	68	68	68	68	68	68	68	68	68
700	84	84	84	84	84	84	84	84	84
1000	104	104	104	104	104	104	104	104	104

where X_{TSBUBD} is the AC–DC difference value of UUC, X_{OSBUBD} is the AC–DC difference value of REF, U_{TSBUBD} is the uncertainty value of UUC, and U_{OSBUBD} is the uncertainty value of STD. The validation value is confirmed if the value of E_n is between –1 and 1. Based on those two measurement results of TSBUBD and OSBUBD, the E_n value was obtained as shown in Table 6.

Table 6 E_n value of TSBUBD to OSBUBD

Freq. (kHz)	$TSBUBD_{4–2V}$ to $OSBUBD_{3–2V}$	$TSBUBD_{4–1V}$ to $OSBUBD_{2–1V}$	$TSBUBD_{4–10V}$ to $OSBUBD_{6–10V}$	$TSBUBD_{4–20V}$ to $OSBUBD_{10–20V}$
0.02	–0.1	0.1	–1.0	–0.8
0.04	–0.1	0.1	–1.5	–0.3
0.5	0.0	0.1	–1.5	–0.3
1	–0.1	0.2	–1.6	0.1
10	0.0	0.2	–1.4	2.5
20	0.2	0.1	–1.5	3.9
50	0.0	0.1	–1.7	3.1
100	0.0	0.1	–1.7	2.1
200	–0.1	0.1	–0.9	0.3
300	–0.1	0.1	–0.9	–0.5
500	–0.1	0.1	–0.8	–1.1
700	–0.1	0.1	–0.8	–1.6
1000	0.2	0.1	–1.0	–3.0

TSBUBD could reduce the calibration process from 15 to 3 times; in other words, it eliminated 80% of the required cost and time. However, as Table 6 shows, there were some frequencies in the build-up that could not fill the validation. Hence, it is suggested that TSBUBD should be expanded to a four- or five-step build-down technique.

4. CONCLUSION

This research produced a new intercomparison format called the TSBUBD method for single junction–type TVC dissemination processes. The experiment, using a three-step build-up and build-down method at a 4-V reference measurement point, produced measurement accuracies from 20 μV to 104 μV for six measurement formations, namely 4–1 V, 4–2 V, 4–3 V, 4–6 V, 4–10 V, and 4–20 V at working frequencies of 20 Hz to 1 MHz. This finding means that calibration processes for these six measurement points (1 V, 2 V, 3 V, 6 V, 10 V [10 Hz and 200 kHz], and 20 V [20 Hz–1 kHz, 200–300 kHz, and 1000 kHz]) can be represented by only one calibration process at 4 V. This method should be developed for the next 60 V and 500 V reference measurement points. If this development process is completed, all AC standard calibration processes will be reduced from 15 units (1V, 2V, 3V, 4V, 6V, 10V, 20V, 30V, 60V, 100V, 200V, 300V, 500V, 600V, and 1000V) to 3 units (4 V, 60 V, and 500 V). Based on Table 6, the three-step method has been validated can reduce the required cost and time by 80%.

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