§2 Development of Thermal Voltage Converters

2. 1 Introduction

A set of new thermal voltage converters (TVCs) has been developed for the purpose of improving the precision in the ac-dc transfer standard at ETL. The performances of the new TVCs were carefully evaluated to serve as the group of reference in the ac-dc transfer standard of Japan. The important characteristics of the TVCs include the thermoelectric transfer difference, dependence of the ac-dc difference on the voltage/current level or temperature, low-frequency characteristics, and high-frequency characteristics. The structure and the performance of the new TVCs are described in detail in the sections 2.2 and 2.3.

In addition to the new TVCs, a TVC with improved high-frequency performance (HF-TVC) has been constructed. The HF-TVC has special structures such that the frequency characteristic of the TVC can be calculated by the geometry and dimensions of the TVC-input circuits. The construction of the HF-TVC and the method to calculate the frequency characteristics are described in the section 2.4.

2. 2 Structure

The new TVCs of ETL uses commercially available 10 mA SJTC elements type-SS283 from Best Technology. The SJTC element has the following features;

(a) 'Evanohm' heater with small Thomson coefficient.

(b) 'Cold-ceramic' bead to avoid flaming of the heater.

(c) Pt-Ir support-leads with small Peltier coefficient against Evanohm.

(d) 'Peltier pads' at heater/support-lead junctions to reduce Peltier effects.

Those features, especially the use of the low-temperature-hardening ceramic was found out to be quite effective to reduce the thermoelectric effects. All the SS283 SJTC measured at ETL showed the thermoelectric transfer difference smaller than 1 ppm.

To cover the whole range of the testing voltage (2 V to 20 V) at ETL, three types of TVCs were manufactured. The 5V-range TVCs cover the voltage range from 2 V to 5 V, the 10V-range TVCs cover from 4V to 10V, and the 20V-range TVCs cover from 8V to 20 V, respectively. Since the nominal input current of the SS283 SJTC element is 10 mA, total input resistance of 500 Ω, 1 kΩ, 2 kΩ are required for the 5V-range, 10V-range, and 20V-range TVCs, respectively.

Traditionally, the SJTC elements and the current limiting resistors ('range resistors') have been housed in separate chassis, and they are combined in use for the appropriate voltage range. Alternatively, it is also possible to put the current-lim iting resistors in the same chassis. The advantages of the se parate-chassis method are:

(a) Reduction of number of SJTC element to construct a group.

(b) Thermal separation between the SJTC element and the range-resistor.

While the advantages of the same-chassis method are:

(a) Better frequency performance.

(b) Reduced skin-effect of connector between the two chassis.

(c) No wearing-off of connectors between the two chassis.

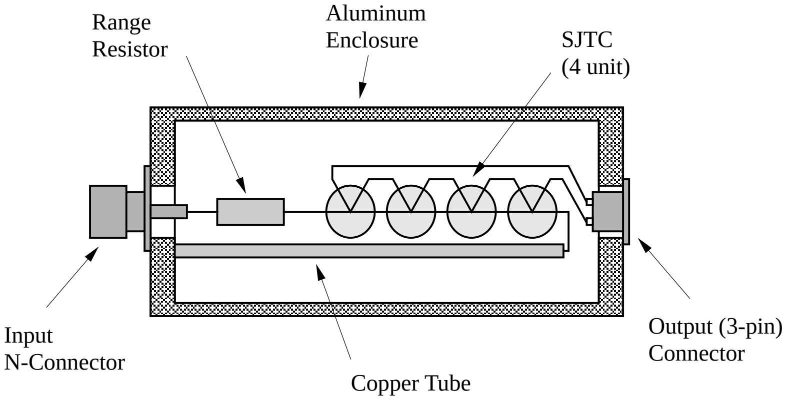

Figure 2.1 *The construction of the new TVCs developed at ETL. The four 10-mA SJTC elements are mounted inside an aluminum cylinder. A type-N receptacle and a low-thermal 3-pin connector are used as the input and the output connectors.*

(d) No return current through chassis.

In the development of the new TVCs, both configurations have been manufactured and evaluated. Since the traditional types of the TVCs are described in detail in the literature [6-8], the new TVCs with the same-chassis construction will be described in this paper.

The geometry of the new TVCs is shown in **figure 2.1**. Four SS283 SJTC elements were connected in series to increase the output EMF voltage. Since the total heater resistance of the four SS283 SJTC elements is 100 Ω, the values of the current-limiting resistors are chosen as 400 Ω, 900 Ω, 1900 Ω for the 5V-, 10V-, and 20V-range TVCs. The SJTC elements and the range resistor are mounted inside aluminum cylinder of 65 mm in diameter and 170 mm in length. The chassis is connected to the ground potential of the input circuit, providing the electrical shield for the SJTC elements and the range resistor. The chassis also acts as a thermal guard for the variation of the ambient temperature. The type-N receptacle (N-R), which matches to the standard type-N male Tee-connector, is used as the input connector. Thin copper tube is used in the wiring of the input circuit to reduce frequency dependence due to the skin-effect. A low-thermal 3-pin connector (Lemo/EGG2B303CLM) is used in the EMF output circuit from SJTC elements.

2. 3 Performance

In this section, the performance of the newly developed standard TVCs are evaluated. The subjects of the evaluation are as follows;

(a) Thermoelectric transfer difference of the reference TVC due to Thomson and Peltier effects and its dependence on ambient temperature or voltage level,

(b) Low-frequency characteristic due to thermal ripple which is dominant below 100 Hz, and

(c) High-frequency characteristic due to skin-effect and stray capacitance and inductance which is dominant above 10 kHz.

The results of the evaluation are described in detail in the following sub-sections.

2. 3. 1 Thermoelectric difference

The thermoelectric transfer difference due to Thomson and Peltier effects is the main source of ac-dc difference in the frequency range between 100 Hz and 10 kHz. In the case of type-SS283 SJTC elements, the thermoelectric transfer differences are expected to be smaller than 1 ppm. The thermoelectric transfer difference of the new TVCs were evaluated by combining the following two methods;

(a) Comparison to the MJTC from PTB.

(b) FRDC-DC difference measurement.

The evaluation of thermoelectric transfer difference is the main theme of this paper, and the procedure of such evaluations will be summarized in chapter 9. In this section, dependence of the thermoelectric transfer difference on current/voltage-level and on ambient temperature is described.

(1) Voltage/Current level dependence

Each of the 5V-, 10V-, and 20V-range TVCs covers 40% to 100% of the rated voltage. Due to the variation of the voltage, the power dissipated on the heater of the SJTC-element varies from 16% to 100% of the rated power. The change in the thermoelectric effects in the SJTC element causes the voltage/current level dependence of a TVC.

An example of current-level dependence of an SJTC element is shown in **figure 2.2**. The SJTC specified as 91-T07 in the figure is the type-SS283 SJTC element used in the new TVCs. The other SJTC specified as ETL105921 is one of the original ETL-design SJTC used in the former standard [36]. The measurement was performed at 1 kHz changing the value of range resistors. The solid curves represent curve-fitting of the data by 2nd and 4th order terms. In this measurement, the effect of thermoelectric EMF due to the Seebeck effect in the SJTC elements are neglected. In the case of SS283 SJTC element, the ac-dc difference varies about 0.5 ppm between the 40% and 100% of the rated current.

(2) Temperature Dependence

The change in the ambient temperature can affect the EMF output of the SJTC-element which has a temperature coefficient of the order of 0.1 %/K. However, when the ambient temperature of the TVC changes slowly with time, temperature at both hot-junction (bead) and cold-junction (grass bulb) keeps the same temperature difference. In this condition, the temperature distribution, and hence ac-dc difference due to the thermoelectric effects, should not be affected by the change in the ambient temperature.

In order to confirm this assumption, the ac-dc difference of a reference TVC (T07R02) and a Fluke 792A was compared with large variation in the ambient temperature. The TVC (T07R02) was placed inside a 10 mm thick aluminum box as in the case of usual measurement condition. The re-

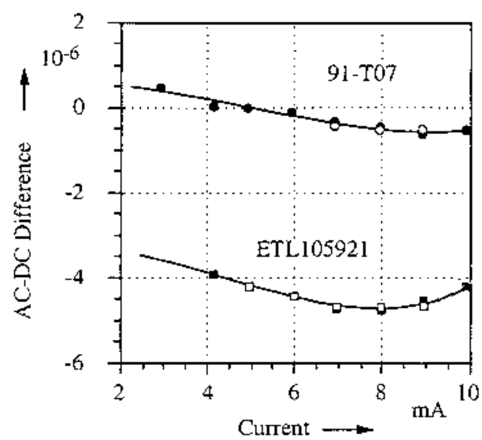

Figure 2.2 *Level dependence of SJTC elements. The SJTC element specified as 91-T07 in the figure is a SS283 SJTC element used in the new standard TVC. The SJTC element specified as ETL105921 is from the former ETL-standard. Solid curves represent curve-fitting of the data by 2nd and 4th order terms.*

sult of the evaluation is shown in **figure 2.3**. As shown in the figure, no correlation was observed between the ac-dc difference and the ambient temperature.

2. 3. 2 Low-frequency characteristics

When sinusoidal voltage of frequency f is applied to a TVC, joule heating varies with double-frequency $2f$. If the frequency is fast enough, i.e., if the thermal time constant τ is much longer than the period of the double-frequency heating ($\tau >> 1/f$), the variation of temperature becomes negligible due to the thermal inertia of the heater. At frequency below 100 Hz, thermal inertia of the heater becomes insufficient to suppress the double-frequency thermal ripple. The thermal ripple causes the ac-dc difference of a TVC due to the imperfections in the SJTC elements;

(a) Non-linearity of input-output characteristic of TVC [9],
(b) Frequency dependence of the heater-resistance[13,14],
(c) Imperfect averaging of the voltage ripple in EMF output.

In the case (c), the effect to the ac-dc difference may be reduced by use of a low-pass filter or by setting the integration time of a DVM to the multiple of the input frequency. While in the case (a) and (b), the effects are based on the thermal properties of the SJTC elements, and the contribution to the ac-dc difference has to be evaluated.

The circuit diagram for the evaluation of the LF-characteristic of a TVC carried out at ETL is shown in **figure 2.4** [50]. The circuit is basically the same as the ac-dc difference comparator circuit which is described in the next chapter, except that a shunt resistance R_p will be connected in parallel with the heater resistance of reference TVC (TVC#2). The resistance R_r represents the range-resistor described in section 2.1. In the circuit, the power at the heater is kept con-

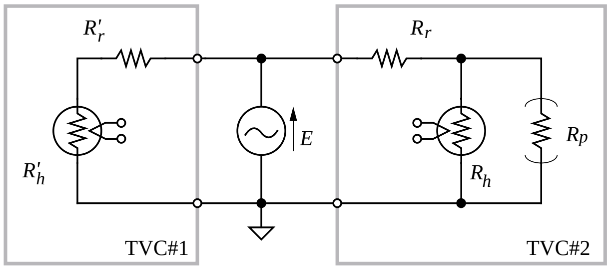

Figure 2.4 *The circuit diagram for the evaluation of the low-frequency characteristic of a TVC. The value of the shunt resistance* R_p *is chosen such that the power at the heater is kept constant against the variation of heater resistance.*

stant against the variation of heater resistance R_h, on condition that the resistance R_r and R_p satisfy the following equation:

$$\frac{1}{R_h} = \frac{1}{R_r} + \frac{1}{R_p}. \qquad (2.1)$$

In the evaluation of LF-characteristic of the 5V-range standard TVC, which has range-resistance of $R_r = 400\ \Omega$ and heater resistance of $R_h = 100\ \Omega$, the parallel resistance is calculated to be $R_p = 133\ \Omega$. In this case, the amount of joule heating on TVC#2 is reduced to be 39% of the rated power. Reduction of the joule heating also improves the linearity of the input-output characteristic of TVC#2. Hence the LF-characteristics of the TVC#1 can be evaluated by comparing with the TVC#2 shunted by R_p, on condition that the LF-characteristic of the TVC#2 is equal to or smaller than TVC#1.

A result of the LF-characteristics of a 10-V range TVC (T04R11) is shown in **figure 2.5**. The evaluation was performed at the voltage of 5 V and 10 V. The MJTC (PTB#73)

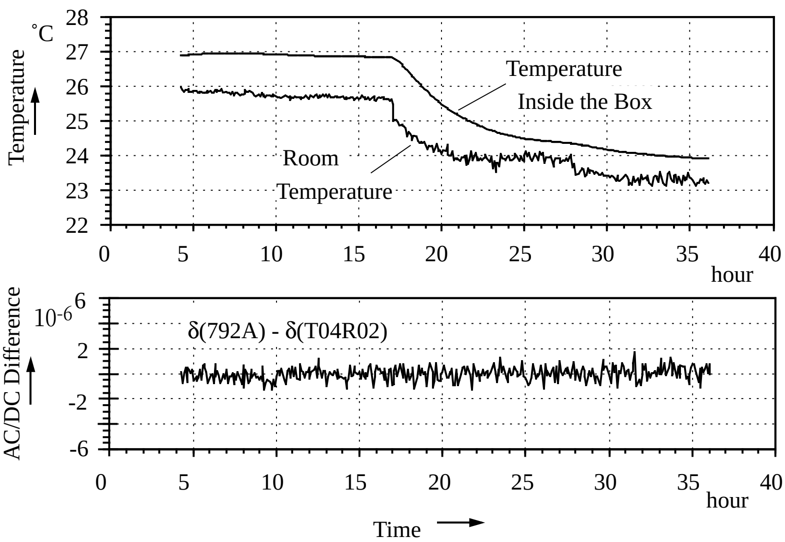

Figure 2.3 *The effect of change in the ambient temperature on the ac-dc difference measurement. The ac-dc difference of a reference TVC (T07R02) and a Fluke 792A was compared with large variation in the ambient temperature.*

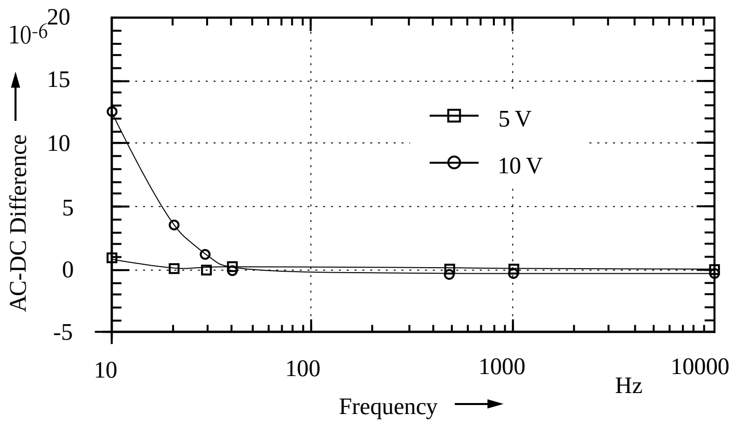

Figure 2.5 *Low-frequency characteristics of a 10-V range TVC (T04R11). The evaluation was performed at the voltage of 5 V and 10 V using a MJTC (PTB#73) as a reference standard.*

which has smaller LF-characteristics was combined with a shunt resistor to further reduce the LF-characteristics. As shown in the figure, the test TVC (T04R11) has the LF-characteristic of more than 10 ppm for 10 V, 10 Hz. The effect decreases rapidly with the increase of frequency, and reduces to below 1 ppm for f >40 Hz. In the case of 5V measurement, the T04R11 is operated at 25% of the rated power. The output characteristics of the TCs are very close to the square low in this region (n≈2). Due to reduced non-linearity, the LF-characteristic in the frequency range 10 Hz to 100 Hz is reduced to be smaller than 1 ppm. The method described above gives sufficient accuracy for the frequency range >40 Hz to be covered by ETL. The measurement of LF-characteristic at lower frequency range (<40 Hz) is in progress at JEMIC using either a thermal method [46] or a waveform-synthesis method[45].

2. 3. 3 High-frequency characteristics

In the frequency range higher than 10 kHz, frequency characteristic of the TVC-input circuit due to the skin-effect, dielectric loss, and the stray inductance and capacitance becomes non-negligible compared with thermoelectric effect. For the frequency higher than 100 kHz, the frequency characteristic contributes more than 1 ppm and becomes the dominant term in the ac-dc transfer difference.

The frequency characteristic of the standard TVC(10V01) was evaluated using the following two independent references;

(a) A standard TVC (T04R11) calibrated at PTB.

(b) A special TVC (HF-TVC#393) developed at ETL.

The TVC (HF-TVC#393) has a special construction so that its high-frequency characteristic is calculable from its structure and dimensions. The design and the performance of the HF-TVC will be described in detail in the following section 2.4. The ac-dc differences of the new TVCs were defined at the branch of the tee connector.

The result of the evaluations is shown in **figure 2.6**. The method agreed within the 95% confidence level given by PTB (3 ppm at 100 kHz and 30 ppm at 1 MHz), and both methods confirmed the noticeably small frequency depen-

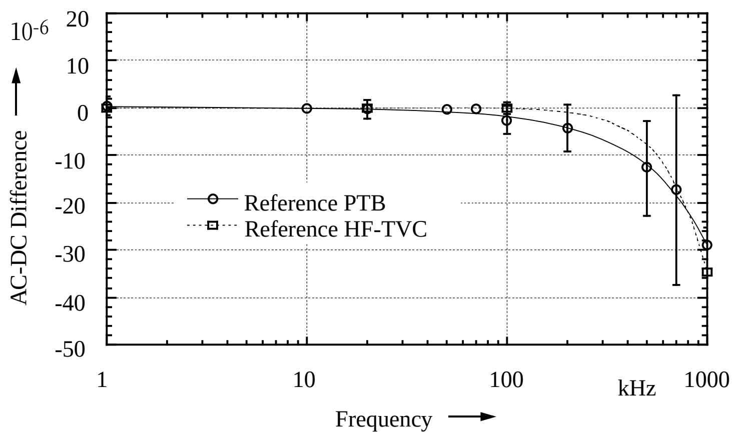

Figure 2.6 *High-frequency characteristic of a 10-V range TVC (T04R11). The evaluation was performed using two independent references, i.e., (a) a TVC (T04R11) calibrated at PTB, and (b) a HF-TVC(#393) developed at ETL.*

dence of the new standard TVC up to 1 MHz.

2. 4 High-frequency standard

High-frequency characteristic of a TVC-input circuit becomes the dominant term in the ac-dc transfer difference for the frequency higher than 100 kHz. In order to evaluate the high-frequency characteristics of the new TVCs up to 1 MHz, a High-Frequency-standard TVC (HF-TVC) has been constructed at ETL[30]. The HF-TVC is specially designed so that the frequency characteristic is calculable from the shape and dimension of the input circuit.

2. 4. 1 Construction

The construction of a HF-TVC constructed at ETL is shown in **figure 2.7**. The range-resistor is made of Ni-Cr-Al-Mn alloy wire-resister (Nuema). 'U-shape' configuration is used for the wire resistor so that the inductance of the input circuit can be evaluated precisely. Only one SJTC element is used in the case of HF-TVCs in order to realize simpler circuit-configuration.

In the frequency range higher than 10 kHz, the frequency characteristic of the input connector becomes significant. A tee connector (N-TA-RRR) is widely used in the comparison of two TVCs, and the center of the tee connector is defined as the 'reference-plane' from which the frequency characteristic is evaluated. In the case of the HF-TVC, the connecting point between the inner conductor of the N-R plug and the input coaxial cable (RG174) is taken as the reference point. Since the effect from the connector is avoided, it is possible to perform a precise evaluation on the frequency characteristic of the HF-TVC. On the other hand, since the N-P plug imitates the half part of the N-TA-RRR tee connector, the difference in the shape and dimension of the two connectors contributes a major source of uncertainty.

2. 4. 2 Mathematical model

The frequency characteristic of the HF-TVC was evaluated using a mathematical model shown in **figure 2.8**. In this model, the wire resistor is represented by the four-terminal distributed-parameter circuit, and a SJTC element is connected at its output terminal. The input-output characteristic of four-terminal network circuit is represented by a conductance matrix ***G***:

$$\begin{pmatrix} I_{in} \\ I_{out} \end{pmatrix} = \begin{pmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{pmatrix} \cdot \begin{pmatrix} E_{in} \\ E_{out} \end{pmatrix}. \tag{2.2}$$

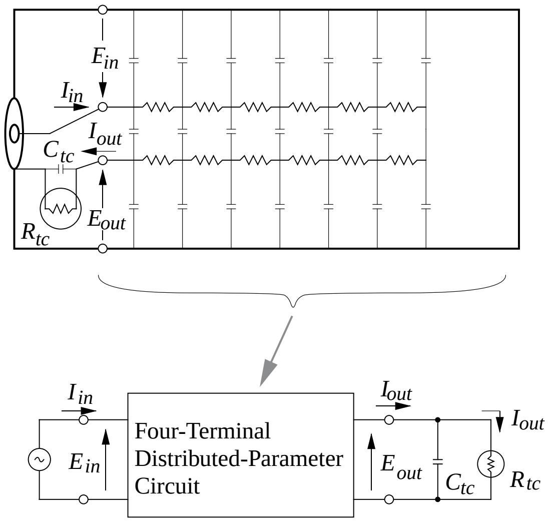

Figure 2.8 *A mathematical model for the evaluation of the frequency characteristic of the HF-TVC. The wire resistor is represented by the four-terminal distributed-parameter circuit, and a SJTC is connected at its output terminal.*

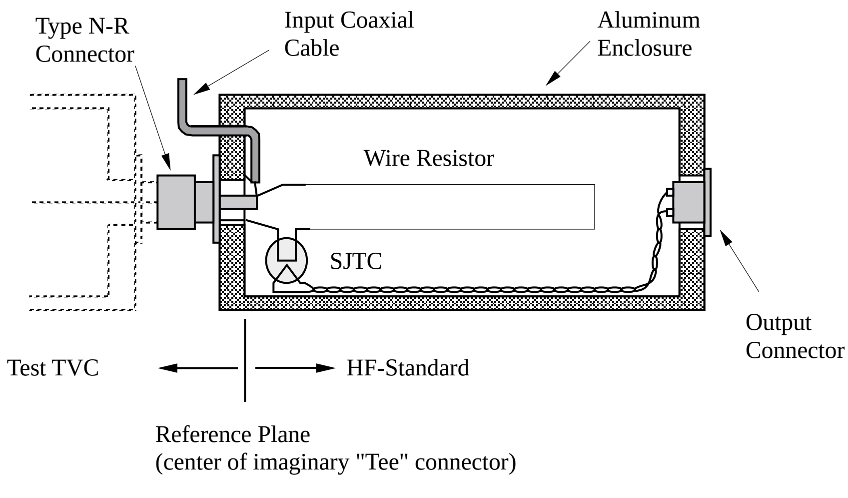

Figure 2.7 *The construction of a HF-TVC developed at ETL. A U-shape wire-resistor is used so that the circuit parameter of the input circuit can be evaluated precisely. The connecting point between the inner conductor of the N-R plug and the input coaxial cable is taken as the reference point.*

When the SJTC element of conductance G_{tc} is connected to the output, the boundary condition for the output is given by

$$I_{out} = G_{tc} \cdot E_{out}. \tag{2.3}$$

The conductance G_{tc} is calculated using the heater resistance R_{tc} and capacitance C_{tc} between the two input leads of the SJTC as

$$G_{tc} = j\omega C_{tc} + 1/R_{tc}. \tag{2.4}$$

Substituting (2.3) and (2.4) to (2.2), the ratio of output power to the input power is described as

$$\left|\frac{E_{out}}{E_{in}}\right| = \frac{|G_{21}|}{|G_{tc} - G_{22}|}. \tag{2.5}$$

The elements in the conductance matrix ***G*** is calculated by applying Kirchoff's theorem to the distributed network circuit. [Refer to Appendix A for the derivation.]

$$\begin{pmatrix} I_{in} \\ I_{out} \end{pmatrix} = \begin{pmatrix} A+B & A-B \\ -A+B & -A-B \end{pmatrix} \cdot \begin{pmatrix} E_{in} \\ E_{out} \end{pmatrix}$$

$$\text{here, } \begin{cases} A = \dfrac{\alpha l_0}{j\omega L_w + R_w} \tanh(\alpha l_0) \\ B = \dfrac{\beta l_0}{j\omega L_w + R_w} \coth(\beta l_0) \end{cases}. \tag{2.6}$$

The symbols L_w and R_w represent the inductance and the resistance of the wire-resistor. The parameters αl_0, βl_0 are non-dimensional constants defined by

$$\begin{cases} \alpha l_0 \equiv \sqrt{j\omega C_s (j\omega L_w + R_w)/2} \\ \beta l_0 \equiv \sqrt{j\omega (2C_w + C_s)(j\omega L_w + R_w)/2} \end{cases}. \tag{2.7}$$

The symbols C_w and C_s represent the capacitance between the wires and the capacitance between the wire to the shield, respectively. Substituting the elements of matrix (2.6) to (2.5), the ratio of output power to the input power is calculated as

$$\left|\frac{E_{out}}{E_{in}}\right| = \frac{\left|-\alpha l_0 \tanh(\alpha l_0) + \beta l_0 \coth(\beta l_0)\right|}{\left|G_{tc}(j\omega L_w + R_w) + \alpha l_0 \tanh(\alpha l_0) + \beta l_0 \coth(\beta l_0)\right|}. \tag{2.8}$$

Since $|\alpha l_0| \ll 1$ and $|\beta l_0| \ll 1$, the hyperbolic functions in (2.8) can be expanded as

$$\begin{cases} \tanh z = z\left[1 - \left(z^2/3\right) + \ldots\right] \\ \coth z = (1/z)\left[1 + \left(z^2/3\right) + \ldots\right] \end{cases}. \tag{2.9}$$

Substituting G_{tc}, $|\alpha l_0|$, and $|\beta l_0|$ to (2.4) and (2.7), and neglecting the terms higher than ω^3, the ratio E_{out}/E_{in} is evaluated as

$$\left|\frac{E_{out}}{E_{in}}\right| = \frac{R_{tc}}{R_w + R_{tc}} \cdot \left[1 - \frac{\omega^2}{3} L_w (C_s - C_w) + \omega^2 \frac{R_{tc}}{R_w + R_{tc}} \cdot L_w C_{tot} + \frac{\omega^2}{18}(C_s - C_w)^2 \cdot R_w^2 - \frac{\omega^2}{2}\left(\frac{L_w + C_{tot} R_w R_{tc}}{R_w + R_{tc}}\right)^2\right]$$

$$\text{here, } C_{tot} = C_{tc} + \frac{C_w + 2C_s}{3}. \tag{2.10}$$

2. 4. 3 Evaluation of frequency characteristics

In this section, the frequency characteristic of the HF-TVC constructed at ETL is evaluated using the formula (2.10) which is derived in the previous section.

The circuit parameters C_w, C_s, and L_w in (2.10) can be calculated from the shape and the dimension of the HF-TVC. The circuit parameters for the wire-resistor are calculated using the following formula.

$$L_w = \left[4l_0 \times \left(\log_e\left(\frac{d}{a_w}\right) + \frac{1}{4}\right) - 4d\right] \times 10^{-7} \ \text{H}$$

$$C_w = \frac{2\pi\varepsilon_0 l_0}{\log_e(d/a_w)} \times 10^{-10} \ \text{F}$$

$$C_s = \frac{2\pi\varepsilon_0 l_0}{\cosh\left(\left(a_w^2 + a_s^2 - (d/2)^2\right)/2a_w a_s\right)} \times 10^{-10} \ \text{F} \tag{2.11}$$

Using the length $l_0 = 88 \times 10^{-3}$ m, separation $d = 8 \times 10^{-3}$ m, and diameter of the wire resistor $a_w = 0.015 \times 10^{-3}$ m, and also using the inner diameter of the shield $a_s = 31 \times 10^{-3}$ m, we obtain $C_w = 0.39 \times 10^{-12}$ F, $C_s = 0.89 \times 10^{-12}$ F, $L_w = 227 \times 10^{-9}$ nH.

The shunt capacitance between the lead of SJTC element is calculated using the following formula.

$$C_{tc} = \left[\frac{2\pi(\varepsilon_0 l_{lead} + \varepsilon_{tc} l_{tc})}{\log_e(d_{lead}/a_{lead})}\right] \times 10^{-10} \ \text{F} \tag{2.12}$$

Using the length $l_{lead} = 11 \times 10^{-3}$ m, separation $d_{lead} = 4 \times 10^{-3}$ m, and diameter of the lead of SJTC $a_{lead} = 0.125 \times 10^{-3}$ m, and using the length of the lead in the glass $l_{tc} = 4 \times 10^{-3}$ m, we obtain $C_{tc} = 0.26 \times 10^{-12}$ F. Here, the dielectric factor was assumed to be $\varepsilon_{tc} \cong 5\varepsilon_0$. The resistance R_w, R_{tc} were directly measured to be $R_w = 368$ Ω, $R_{tc} = 25$ Ω

The frequency characteristic of the HF-TVC evaluated using the circuit parameters are summarized in **table 2.1**. The most significant contribution comes from the inductance-resistance ratio of the wire-resistor [$(\omega L/R)^2$ term], which gives frequency characteristic of 7 ppm at 1 MHz. The total contribution of the terms to the frequency characteristic of the HF-TVC was evaluated to be

$$\Delta\delta_{LCR} \cong 4.9 \pm 7.7\times10^{-18} f^2. \qquad (2.13)$$

Considering the inaccuracy of the mathematical modeling of the HF-TVC, the 1σ-equivalent uncertainty for each term was estimated to be 100% of the evaluated value. The total uncertainty was calculated by taking the RSS of the uncertainties for each term.

In addition to the effect from the impedance-parameter (*L*, *C*, *R*) of the TVC input circuit, the skin-effect of the PtIr lead of the SJTC element can also contribute to the frequency characteristic of the HF-TVC. For the PtIr wire with resistivity of $\rho = 2.7\times10^{-7}\ \Omega\cdot\mathrm{m}$ and with dimensions 0.25±0.05 mm in diameter and 75 mm in length, change of resistance $\Delta R_{skin\text{-}effect}$ due to the skin-effect is estimated to be

$$\Delta R_{skin-effect}/(R_w + R_{tc}) \cong 2.8 \pm 0.6\times10^{-18} f^2. \qquad (2.14)$$

The skin-depth of the PtIr wire was evaluated to be ≈4 mm at 1 MHz. Since it is much larger than the diameter of the lead, the skin-depth increases as the square of the input frequency.

Adding the contribution from the skin-effect, the frequency dependence of the ac-dc difference of the HF-TVC is evaluated to be

$$\delta_{HF-effect} \cong 7.7 \pm 7.7\times10^{-18} f^2. \qquad (2.15)$$

Another source of uncertainty arises from the use of N-P plug, to which a test-TVC is connected. As described in section 2.4.1, the N-P plug imitates the half part of the N-TA-RRR tee connector with which the reference plane is defined. Hence the difference in the shape and dimension of the two connectors have to be taken as a source of uncertainty in the calibration of the test TVC.

In the case of 10V-range TVC which has the input resistance of 1 kΩ, the contribution from the skin-effect in the N-P connector to the ac-dc difference is estimated to be -2.8 ppm at 1 MHz. Similarly, the contribution from the effect of stray capacitance and inductance in the N-P connector is estimated to be -1.6 ppm at 1 MHz. Since the difference in the dimension of the two connectors is smaller than 10%, the uncertainty arising from the use of the N-P connector is estimated to be smaller than 10 % of the total contribution from the N-P connector. Hence the uncertainty due to the use of N-P connector is evaluated to be smaller than 0.1 ppm at 100 kHz and smaller than 1 ppm at 1 MHz.

Table 2.1 *List of error-terms in the frequency characteristic of the HF-TVC, and their contribution to the corrections in the ac-dc transfer difference.*

Error Term		Correction (at 1 MHz)
(1)	$\frac{1}{3}L_w C_w \omega^2$	-2.6×10^{-6}
(2)	$-\frac{1}{3}L_w C_s \omega^2$	$+1.1\times10^{-6}$
(3)	$\frac{1}{18}(C_s - C_w)^2 R_w^2 \omega^2$	-0.6×10^{-6}
(4)	$\frac{R_{tc}}{R_w + R_{tc}} L_w C_{tot} \omega^2$	-0.1×10^{-6}
(5)	$-\frac{1}{2}\left(\frac{L_w + C_{tot} R_w R_{tc}}{R_w + R_{tc}}\right)^2 \omega^2$	$+7.1\times10^{-6}$
Total Correction (Uncertainty)		$+4.9\times10^{-6}$ (7.7×10^{-6})

2. 5 Summary

A group of new thermal voltage converters (TVCs) has been developed at ETL. One of the new TVCs was calibrated by PTB with uncertainty of 1 to 1.5 ppm (1σ-equivalent) in the frequency range 10 to 100 kHz using the standard MJTCs of PTB. The dependence of the ac-dc difference on the voltage/current level was measured to be smaller than 1 ppm for 40% to 100% of the rated voltage. The high-frequency characteristics of the TVC were measured to be smaller than 10 ppm up to 100 kHz. Those performances of the new TVCs are sufficient as the new reference standards of ETL.

In addition to the standard TVCs, a TVC with improved high-frequency performance (HF-TVC) has been developed. The frequency characteristic of the HF-TVC was calculated by the geometry and dimensions of the TVC input circuits, and were evaluated to be smaller than 10 ppm up to 1 MHz. By the use of the HF-TVC, frequency characteristics of the new standard TVC have been determined with a precision better than 1 ppm up to 100 kHz.