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Uncertainty Evaluation of Josephson Voltage Standard in the level of 10^{-10}

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10의 -10승 수준에서 조셉슨 전압표준기 불확도평가

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Abstract

The most recent improvement in the 10 V array system was carried out with focusing on noise reduction. We have evaluated the uncertainty of the 10 V Josephson array system after the improvement. The uncertainty evaluation of 10 V standard included a comparison with a programmable Josephson array system at 1 V. Every contribution to the measurement uncertainty was evaluated in the level of 10^{-10}. The estimated combined uncertainty was found to be approximately 10^{-9} at 10 V, which was limited only by the indirect verifying method. In the near future, a direct comparison with another 10 V Josephson voltage standard is expected to be carried out to provide more accurate uncertainty evaluation for the KRISS Josephson voltage standard.

Keywords : Josephson voltage standard, Uncertainty, Comparison, Josephson junction array, SI

I. Introduction

The most fundamental role of national measurement institute (NMI) is to realize SI units according to "Mise en Pratique" recommended by CIPM (Comité International des Poids et Mesures) and to maintain the units as national measurement standards. For more than two decades, Josephson voltage standards have been used for the practical realization of SI electrical units and have been serving as the national voltage standard in many countries. Technology in Josephson voltage standard (JVS) has been under rapid development beginning from a single junction type mV level JVS to modern 10 V JVS based on around 20 thousand SIS (Superconductor – Insulator – Superconductor) Josephson junctions, and recently a Programmable Josephson Voltage Standard (PJVS) which is capable of low frequency (LF) voltage standard as well as DC voltage standard has been established in several metrology laboratories. However, so far the PJVS technology can provide up to 1 V level only. Thus the conventional 10 V JVS of SIS junctions are still widely used for national

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voltage standards in many countries, because the best uncertainty is attainable at 10 V, at which the best demonstrated uncertainty is about 10^{-10} [1]. As is well known the principle of JVS is based on the frequency-voltage relation of Josephson junction,

$$V_J = n(h/2e)f \qquad (1)$$

where V_J is DC voltage across the junction, n is step number (integer), $h/2e$ is flux quantum whose inverse $2e/h$ is called Josephson constant, and f is external microwave frequency. This equation states that the DC voltage can be very precisely represented by precisely known frequency. Since the principle is simple and perfect, the practical realization requires handling of few electronic devices. However, when we take out the generated voltage from the Josephson array to compare an unknown voltage under measurement, we need to average out a thermal EMF offset of a few hundred nanovolt in cryoprobe wires lying across a huge temperature difference. The bias-reverse process for reversing the Josephson array polarity is necessary for precisely removing the thermal offset. Other devices for the handling and operation such as low-pass (LP) filters in cryoprobe and measurement circuit, bias-reverse controller with oscilloscope for I-V monitoring, and nanovolt detector should be also considered. Typical uncertainty components are microwave frequency, leakage through wires and filters, drift of thermal EMF (electromotive force) during the bias reverse time, and the nanovolt detector. The formula for representing the output voltage of the JVS (see Fig. 1) can be written as (2)

$$V_S = V_J(1 - r/R) + \varepsilon \qquad (2)$$

where R is parallel leakage resistance, r is total series resistance of a pair of wire from the Josephson array to the point of the leakage resistance, and ε is residual thermal EMF offset. Therefore, the measurement capability of the JVS is mainly dependent on these uncertainty sources. In KRISS, the first 1 V JVS was established in 1990 [2] and successfully maintained with 1 V KRISS array chips. In 2002, the 10 V JVS system was established using 10 V Josephson array to provide calibration of secondary DC voltage standards, Zener voltage standards which typically has 10^{-7} stability level. Verification of the 10 V JVS had been carried on the basis of internal comparison with the previously developed 10:1 resistive ratio system with uncertainty level of 10^{-8} [3]. However, as the need of international comparison was recently raised for the global MRA (Mutual Recognition of Arrangement) between NMI's, further improvement of uncertainty level became urgent. The improvement of the KRISS 10 V JVS was done especially in increase of noise filtering and decrease of LF EMI noise, which enabled the longer data collection and faster polarity reverse process. This paper reports the recent uncertainty evaluation of the KRISS JVS according to the popular international guide called GUM [4].

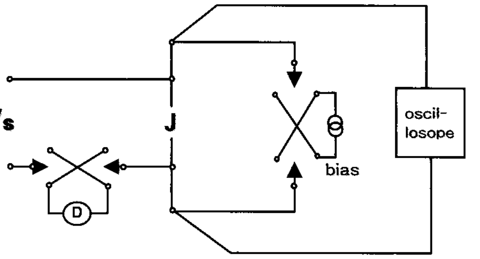

Fig. 1. Schematic diagram of the improved JVS system.

II. Improvement

The noise reduction power of simple RC (or LC) filter increases as the parallel capacitance increases and series resistance (or inductance), however this also means increased leakage effect (see Fig. 2). Previously used LP filter has the leakage resistance of a few GΩ only. However, when 10^{-10} uncertainty level is concerned, the insulation of 800 GΩ or higher is required for total series resistance of 80 Ω. The 80 Ω series resistance which is a few tens of times higher than previous system is now used in the new LP filter. An enhanced leakage effect can occur

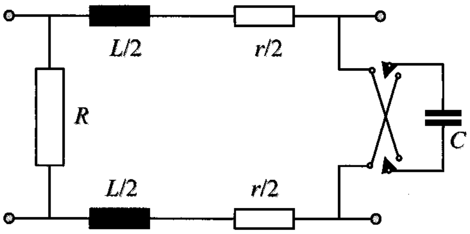

Fig. 2. Improved LP filter with effectively high insulation.

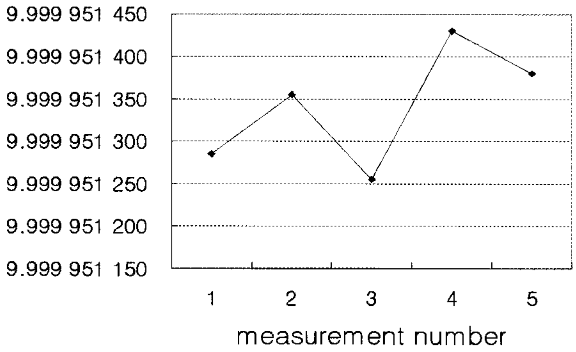

Fig. 3. Calibration data of a Zener at 10 V by the JVS.

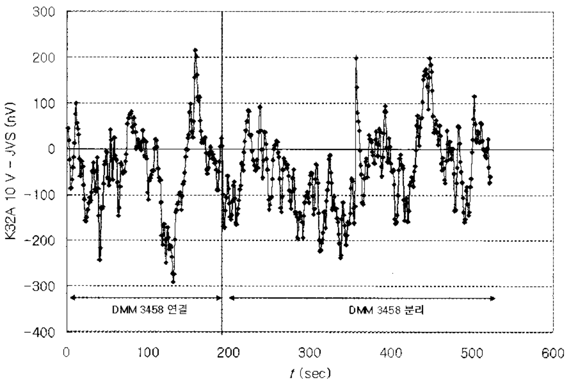

Fig. 4. Noise of Zener recorded with respect to 10 V JVS.

especially during the polarity reversing process because of the so called ‘polarization current’ [5]. A special method was invented to keep the polarity of the capacitor to the same direction during every polarity reverse process, for which a reverse switch was employed and operated synchronously to the bias reverse process. The improved LP filter is inserted between the Josephson array and comparison measurement circuit shown in Fig. 2. In order to minimize EMI effect and leakage effect to the nanovolt detector, it was re-located to lower potential part in the comparison measurement circuit. An optical isolation of GPIB data acquisition was tested and found to be useful to remove the loops between instruments tied to PC. Fig. 3 is a measurement result of a Zener voltage standard with the improved 10 V JVS system. Because of the more effective noise filtering, the step number control becomes much easier, and polarity reverse typically can be done much faster. It takes only 1 minute (about 5 to 10 times shorter than before). This improved feature is important because we can now finish the measurement before the thermal EMF drift significantly affects the measurement. Fig. 4 shows that the 10 V array is kept at the same step number without step jumps even with external disturbance from digital multimeter (DMM) for monitoring the array voltage and the Zener under measurement for about 10 minutes during the comparison measurement of the Zener voltage standard. The 10 minutes is more than sufficient because the typically required time to keep the step is about 1 minute for measurement of Zener.

III. Uncertainty Evaluation

3.1. Leakage effect

As mentioned earlier, the leakage effect in the LP filter can be time-dependent if capacitor is falsely reversed. Even with the false reverse, the leakage resistance was higher than 500 GΩ for the typical time interval of measurement process. In a normal case, the polarity of the capacitor is always constant, and the leakage effect to the series resistance can be safely put as 10^{-10}. The leakage effect is now bigger in the cryoprobe than the LP filter. It was necessary to disconnect all wires to the Josephson array chip to evaluate the cryoprobe leakage. Fig. 5 shows the transient leakage resistance between + and − wire measured at the cryoprobe output terminal from 1 minute after reversing the polarity of 5 V test voltage. This leakage effect is supposed to come from the feed-through capacitors at cryoprobe top and insulating coatings of the wires as well. Assuming the fastest reverse operation, we take the smallest resistance 36 GΩ of Fig. 5 as the R for eq. (2). The series resistance of the pair of wires in the cryoprobe was measured to be 4 Ω, therefore the leakage error is estimated to be about 1.1×10^{-10}. For other possible leakage paths in the measurement circuit, the leakage effect was also checked, but found to be negligible. Combining those two leakage effect, the total leakage error can be put as 2.1×10^{-10}. Taking this as a half width of rectangular probability distribution for the leakage effect correction, the standard uncertainty (1 σ) of leakage effect can be put as $2.1\times10^{-10}/\sqrt{3} = 1.2\times10^{-10}$, that is 1.2 nV for 10 V JVS and the corresponding degree of freedom can be put as infinitely large [6] because the assumed half width is more than safe in this case.

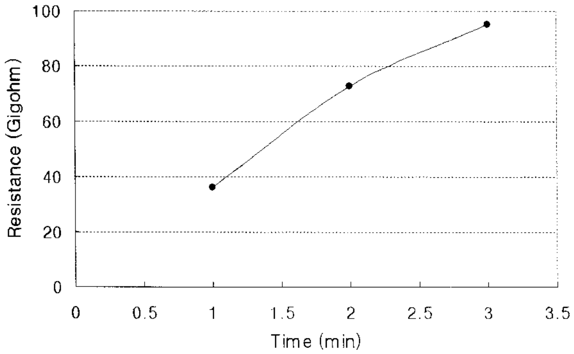

Fig. 5. Transient leakage resistance of between two wires in cryoprobe.

3.2. Residual thermal EMF

The thermal EMF in the cryoprobe is the most significant one, but there also exist smaller thermals in the measurement circuits containing reverse switches. All these thermal offsets are effectively subtracted by the polarity reverse process. The polarity reverse process is designed to subtract thermals even though they are drifting at constant rate. However, there is always a possibility that the drift carries slight non-linear components, which can give the residual thermal EMF. In addition, if the contacts of the reverse switches have un-equal thermals between + and – position, the small imbalance can also give the residuals. The non-linear drift effect in the cryoprobe wires are irregular and can be treated as it is already included in type A uncertainty. The reverse switch residuals are too small to be measured directly. Instead we carried the reverse process to subtract thermals with zero voltage of perfect shorts as an unknown voltage under measurement. We have measured the zero voltage over several years which showed typical standard deviation is less than 1 nV. We can put 1×10^{-10} as the standard uncertainty for the residual thermal EMF with infinite degrees of freedom.

3.3. Nanovolt detector

The nanovolt detector is a special type with a superior offset stability. For the special type of detector 1 nV (10^{-10}) is regarded as a safe margin [7]. We take this as a standard uncertainty with infinite degrees of freedom.

3.4. Microwave frequency

Microwave source, Gunn diode is controlled by a special source-lock counter, whose time base is phase-locked to the KRISS standard frequency better than 10^{-13}. The typical Gunn-diode frequency is about 75 GHz, whose stability achieved by the source-lock counter is about ±3 Hz at worst. We can take a triangular probability distribution for the frequency uncertainty to obtain the standard uncertainty to be 3 Hz/$\sqrt{6}$ = 1.2 Hz, which corresponds to 0.16×10^{-10} (infinite degrees of freedom).

3.5. Type A

We considered all the type B uncertainties in the above. All the random fluctuations now fall into type An uncertainty, which is calculated from the repeated measurement data. Problem is that the only suitable voltage source for this evaluation of such an extremely accurate measurement system is an extra JVS, which requires rather expensive Josephson array and precision instruments and also full evaluation of all detailed parts as well. So far available are only the measurement result of Zener voltage standard which must be severely contaminated by instability of the Zener. The best experimental result obtained with our best Zener shows standard deviation of 44 nV (N=6), which leads to a type A uncertainty of 18 nV (1.8×10^{-9}). As an indirect evaluation way, margins of all the possible random changes of previously mentioned uncertainty sources will be indirectly inferred on the basis of comparison with 1 V PJVS. This will be discussed in the next section. Table 1 is the uncertainty budget for the 10 V JVS output, V_s.

Table 1. Uncertainty budget for the 10 V JVS output.
(The 18 nV in parenthesis is temporarily given from experimental data with a Zener, not from JVS itself)

Uncertainty sources	Uncertainty contribution (nV)	Probability distribution	Degree of freedom	Type
1. Microwave frequency	1.6	Triangular	∞	B
2. Leakage	1.2	Rectangular	∞	B
3. Residual thermals	1	t	∞	A
4. Nanovolt detector	1	N/A	∞	B
5. Random fluctuation	(18)	t	5	A
Combined standard uncertainty	(19)		(6)	

IV. Comparison with 1 V programmable JVS

The 1 V programmable JVS (PJVS) has been in operation for several years with the array chip fabricated at NIST. For comparison with 10 V JVS, we adjusted its output at 1 V level. After microwave frequency, power, and bias current were optimized to the PJVS, all other instruments except microwave source and bias supply were disconnected to minimize EMI effect. Special care for single ground point was taken in connecting two arrays. Microwave frequency for PJVS was varied from 18.3 GHz, 18.4 GHz to 18.5 GHz, and accordingly the microwave frequency for JVS was adjusted from 74.745 GHz, 74.756 GHz to 74.74 GHz. The calculated PJVS voltage was 1.108 940 919 7 V, 1.115 000 706 2 V and 1.121 060 492 6 V, respectively. Fig. 6 shows the comparison result. Taking average for all data (N=24) and making correction of leakage effect of -2.1×10^{-10}, the result can be put as follows.

$$U_{\mathrm{PJVS}} - U_{\mathrm{JVS}} = 0.74\ \mathrm{nV} \pm 0.17\ \mathrm{nV}\ (u_{\mathrm{A}}) \qquad (3)$$

The combined standard uncertainty for origin of the difference 0.74 nV was not clearly identified yet. However, we suppose that it can be attributed the residual thermal EMF, which was not corrected this time. In addition, the type B uncertainty according to the same approach is estimated to be $\sqrt{\{(0.16\ \mathrm{nV})^2 + (0.12\ \mathrm{nV})^2 + (1\ \mathrm{nV})^2 + (1\ \mathrm{nV})^2\}} = 1.43$ nV. Therefore the combined standard uncertainty will be $\sqrt{\{(0.17\ \mathrm{nV})^2 + (1.43\ \mathrm{nV})^2\}} = 1.5$ nV with effective degree of freedom of 25.[4] Therefore, even though we failed to make proper corrections, the measurement result agrees well within the standard uncertainty. As for the type A uncertainty, which we would expect for 10 V JVS comparison, the maximum possible fluctuation depends on EMI level during comparison. However, we can assume that it will not exceed 10 times of that of the 1 V PJVS comparison, i.e. less than 1.7 nV, with which we will be able to attain the combined standard uncertainty of 10^{-10} order. To confirm this assumption, we are planning to carry a JVS-JVS comparison at 10 V in the near future.

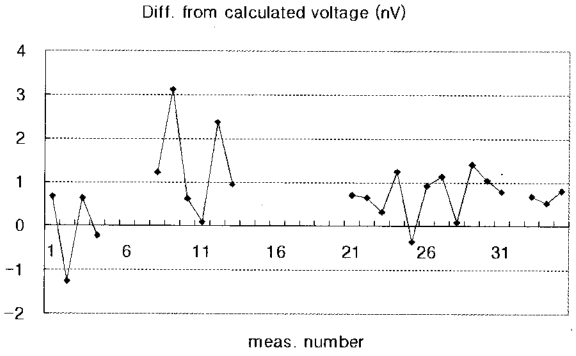

Fig. 6. Comparison result of PJVS - 10 V JVS at 1 V.

V. Conclusion

The noise of 10 V JVS system was significantly reduced by the recently fabricated LP filter. The polarity reverse of the Josephson array can be done about ten times faster than before which reduces all the residual drift effects and contributes to smaller deviation of result. Compared to previous system, the type A uncertainty for Zener voltage standard was improved by more than 2 times. The uncertainty of JVS itself excluding the effect of device under test is expected to be order of 10^{-10}, which is much less than the present evaluation result $\sim 2\times10^{-9}$ (1σ), which is based on the experiment with Zener. For more precise evaluation, comparison of JVS-JVS at 10 V is under preparation.

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