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STEP UP METHODS FOR ENSURING STANDARD TRACEABILITY OF EXTENDED RANGE IN ELECTRICAL MEASUREMENTS

Kyu-Tae Kim, *Sung-Won Kwon, Jae Kap Jung, Sang-Hwa Lee, Hwa Gean Lee*

Center for Electricity and Magnetism, KRISS, Daejeon, Rep. Of Korea, ktkim@kriss.re.kr

Abstract: The Josephson voltage standard and the quantum Hall resistance standard is a clear and solid basis to realize SI traceable calibrations for all electrical measurements of varieties of applications. However, the traceability link is necessarily required between the well-established SI ampere and the wide measurement range at application sites for routine calibration works. The step-up technology is a simple and useful method which can be applied in various electrical measurement fields.

Keywords: Step up, traceability, standard, high voltage, high current

1. INTRODUCTION

The SI definition of ampere, a clear and solid basis to realize traceable calibrations for all electrical measurements is now most accurately represented by the Josephson voltage standard and the quantum Hall resistance standard at many national metrology institutes. However, the highest accuracy representation should focus a fixed or a very narrow range of measurement for example, 1 V or 10 V in voltage and 1 mA or 1 A for resistance while practical application requires high voltage up to several hundred kV or several tens of kA. Therefore the traceability link between the wide measurement range at application ground and the well-established SI ampere is necessarily required for routine calibration works to support industry. Traditionally typical example of step up method in electrical metrology can be found in the so-called “Bootstrap” method in AC-DC thermal voltage transfer, where standard thermal voltage transfer at low voltage is used as a reference to determine another thermal transfer of higher voltage range. Another example can be found in high voltage or high current field. The key devices for the measurement of voltage and current are voltage divider and current shunt. By using voltage divider, unknown high voltage is converted to low voltage which can easily be measured by many measurement instruments, and by using current shunt unknown high current is converted to a voltage of easily measurable range. But a technical difficulty in terms of metrology of high voltage and high current arises from the fact that the converting coefficient is not constant regardless of its operating voltage of current level, and in order to establish the traceability link, the converting coefficient should be determined with a tolerable uncertainty, which should be sufficiently small to ensure the high accuracy at the desired measurement range at work. The 2:1 step up technology for high voltage has been suggested in 2003[1], where the converting coefficient is divider ratio and it has been demonstrated that the voltage coefficient of the divider ratio. The same principle can be applied for high current shunt. In this paper, the basic principle of 1:2 step-up methods will be described with typical application examples for DC high voltage calibration, DC high current calibration.

2. BOOTSTRAP METHOD FOR AC-DC THERMAL VOLTAGE TRANSFER

It would be more helpful to quote the expert explanation about the “bootstrap” method, “The bootstrap method is a descriptive term for the process of comparing thermal voltage comparator (TVC) of adjacent voltage ranges. Suppose you have a TVC with voltage range of 0.3 V ~ 1 V with known AC-DC difference δ_1. Now compare this TVC at a level of 1 V to a second TVC having voltage range of 1 V ~ 3 V to measure (δ_2- δ_1). δ_2 is the AC-DC difference of the second TVC. If you assume δ_2 is independent of voltage level, you now have the 1 V ~ 3 V TVC calibrated. Since there is no check to make that δ_2 is the same for the voltage range 1 V ~ 3 V, this process is analogous to lifting yourself free of ground by pulling upward on your own bootstrap.” [2]. An example of the method can be found in Fig. 1, where 1 V to 1 kV step up process at KRISS is shown.

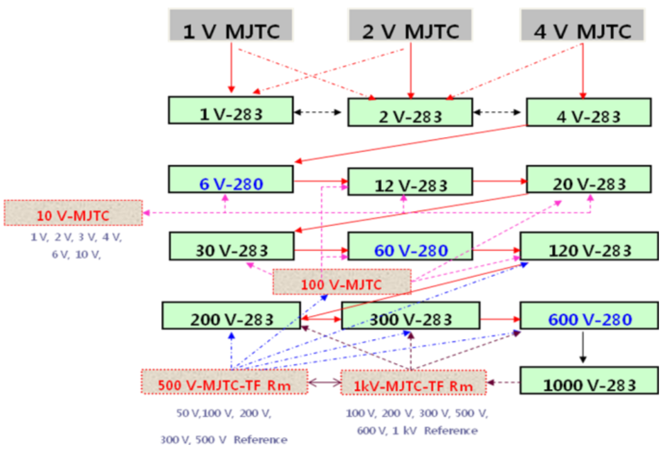

Fig.1 The AC voltage step up process at KRISS. MJTC: Multi-Junction Thermal Converter, TF: Thin Film.

Although the bootstrap method is simple and useful, it does not fully guarantee the traceability, unless the assumption that AC-DC difference is the same for any voltage within each finite voltage range is verified by some other independent evaluation or reasonable uncertainty related to the assumption should be given.

3. PRINCIPLE OF STEP UP TECHNOLOGY

The idea of bootstrap in AC-DC thermal voltage transfer can be applied for DC high voltage and DC high current. However, an unbroken chain of several hundred kV or several tens of kA to standard voltage or current is a technically challenging issue because of their extremely high level of voltage or current. So, instead of taking the presumption that voltage or current coefficient is constant in any voltage or current within a given range, a direct evaluation of the coefficients of the two devices is included in the 1:2 step up technology. The step up principle will be separately described for DC high voltage and DC high current for clarity.

1. Step up for DC high voltage

High voltage (HV) divider is a key device for going up to the high voltage. To evaluate the voltage coefficient of the divider ratio at the same time of calibration of a high voltage source, we employ twin dividers of the same model for a binary (1:2) step up procedure. Let the two HV resistors be R_A and R_B of the two dividers, both are of the same nominal resistance and one low voltage (LV) resistor, *r*. The LV resistor is used commonly as the LV section for the two dividers, as shown in Fig. 2. The ratios of the two dividers are defined as Γ_A = 1+ R_A /r and Γ_B = 1+ R_B /r, respectively. Assuming that the ratio, an arbitrary reference voltage V_1 is known, we are going to determine the ratios $\Gamma_A(V_1)$, $\Gamma_B(V_1)$ and double voltage V_2, which is approximately $2V_1$. Firstly we can determine $\Gamma_A(V_1)$, $\Gamma_B(V_1)$ by measuring the divided voltages of low level with calibrated voltmeter as described in Fig. 2(a). In the next step, HV source output is set to the double voltage, V_2 and applied to the double-stacked divider where the two HV resistors are in series and the common LV section of resistance *r* is attached to the stacked HV section. By measuring the divided output voltage m_s, the unknown doubled voltage is determined using the following equation.

$$\begin{aligned} V_2 &= m_s \left(R_A\left(V_1\right) + R_B\left(V_1\right) + r \right) / r \\ &= m_s \left(\Gamma_A\left(V_1\right) + \Gamma_B\left(V_1\right) - 1 \right) \end{aligned} \qquad (1)$$

This V_2, once determined, is used as a new reference voltage for the next step up procedure.

The whole step can be repeated *n*-times taking the calculated double voltage V_2 as a new reference voltage to determine a high voltage of approximate $2^n V_1$. The Fig 2(c) shows the first step of the 2nd step up procedure to determine the ratios at double voltage V_2. The corresponding equations for the ratio values are as follows;

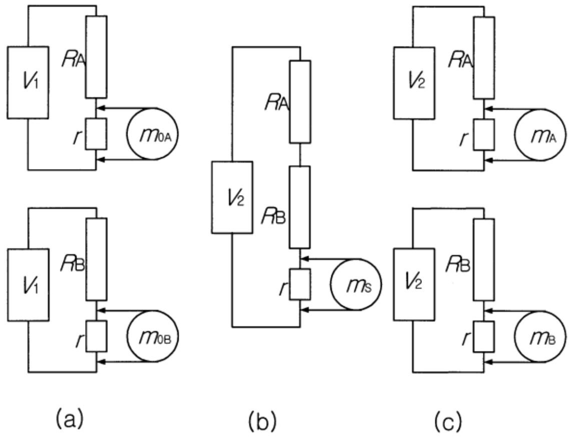

Fig. 2. Binary step up procedure for double voltage V_2~$2V_1$.

$$\Gamma_A\left(V_2\right) = V_2 / m_A \qquad (2)$$

$$\Gamma_B\left(V_2\right) = V_2 / m_B \qquad (3)$$

In Fig. 3, a photo of stacked divider for the step up measurement is shown.

Fig. 3. Stacked HV dividers for the binary step up procedure.

2. Step up for DC high current

The same principle can be applied for DC high current. The key device, current shunt should be prepared also in pairs for the binary step up of DC current. Assuming that a reference current I_0 is already known, we are going to determine double current *I*, which is approximately set to be $2I_0$. Firstly the shunt resistance values at I_0, $R_a(0)$ and $R_b(0)$ are determined by the usual 4-terminal measurement, where output voltage is measured at the separate voltage output terminal using a high resolution voltmeter. In the next step, the current is set to double value of ~$2I_0$ and the two shunts are connected in parallel so that each shunt carries a current level of ~I_0, for which the shunt resistance is known.

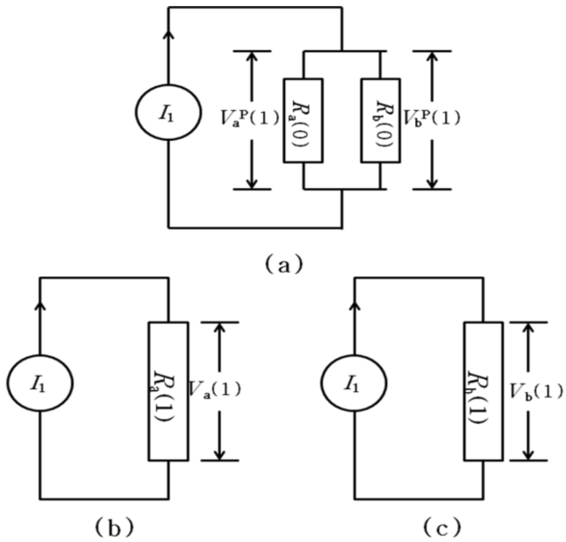

Fig. 4. Binary step up procedure for double current I_1.

With using the shunt resistance and shunt voltage determined by the 4-termianl measurement for each shunt, we calculate the current value at each shunt, and sum the two current values to determine the value of the double current I_1. Fig. 4 (a) shows the parallel configuration for determination of the double current I_1. As the above I_1 belongs to the first step up procedure, we used subscript, "1", then the mathematical expression for this is given by the following equation, where the superscript "p" means "parallel configuration".

$$I_1 = V_a^{p}(0)/R_a(0) + V_b^{p}(0)/R_b(0) \qquad (4)$$

This I_1, once determined, is used as a new reference current for the next step up procedure.

The whole step up procedure can be repeated n-times to obtain higher current of $I_n \sim 2^n I_0$. Fig. 4 (b) and (c) show the first step of the 2^{nd} step up procedure to determine shunt resistance at double current I_1. The corresponding equations for the shunt resistances are as follow;

$$R_a(1) = V_a(1)/I_1 \qquad (5)$$

$$R_b(1) = V_b(1)/I_1 \qquad (6)$$

In Fig. 5, a photo of stacked divider for the step up measurement is shown.

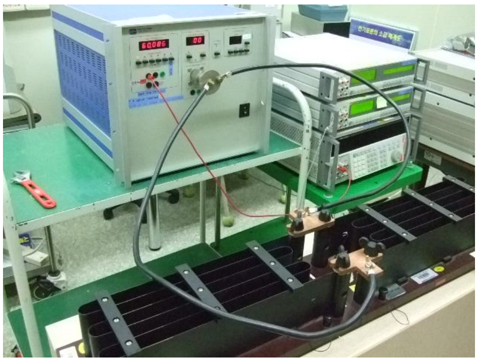

Fig. 5. Measurement system for the binary step up of DC high current.

4. DISCUSSION AND CONCLUSION

The basic idea of "bootstrap" step up which has long been used in AC-DC thermal voltage transfer can be also used for high voltage and high current. But the main conceptual difference of the binary step up method is the rigorous determination of voltage or current coefficient of the transfer device (voltage divider, current shunt). That is, the determined coefficient is consecutively reused for the next determination of the unknown double voltage or current. The method and its principle can be useful in many metrology fields for which traceability should be inherited up to higher range of measurement. Another advantage is its simplicity and transparency with convenience. Concerning uncertainty propagation of accumulative effect in the binary step up procedure with high number of steps, n, the expected estimate is that the final relative uncertainty is approximately proportional to $\sqrt{n}$. Therefore accurate voltage measurement is a key to obtain small uncertainty. Since voltage measurement is the most accurate in the electrical metrology, a reasonably small uncertainty is possible with optimum design of experiment, such as initial voltage or current, number of steps, voltmeter range selection for each step etc. Once comparable uncertainty established, it would be important to make comparison with other methods, for example, direct current comparator (DCC) method, which has been used as a standard method for resistance measuring bridge. The binary step up method can be also useful for verification of ratio of DCC method.

References:

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