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The Establishment of High DC Shunt Calibration System at KRISS and Comparison With NRC

Kyu-Tae Kim, Jae Kap Jung, Young Seob Lee, Eddy So, *Fellow, IEEE*, and David Bennett

***Abstract*— The application of a binary step-up method has been investigated at the Korea Research Institute of Standards and Science (KRISS) for establishment of high dc standards based on the calibration system of high dc shunts up to a few thousand amperes in which the current dependence of the shunt resistance can be measured. A successive step-up method with a pair of high dc shunts was suggested to link the unknown high current to the values of low current level which are already known. The step-up approach was further modified with employing a current monitor to extract the information on the current dependence of the shunt and the source current changes during the step-up measurement. To validate the modified step-up technology, a comparison of high dc shunt resistance was carried out with National Research Council (NRC) in which both the KRISS and the NRC results agreed well within the standard deviation of the measurement on the order of about 0.01%.**

***Index Terms*— Calibration, current measurement, current supplies, current transformers, electrical resistance measurement, shunts.**

I. Introduction

THE measurement of the high dc is expected to play a significant role in the future electric energy industry. High dc shunts are frequently used for measuring these currents and calibration of these shunts is required to link them to the normal resistance standard at low current. However, it should be noted that the shunt resistance at high currents can sensitively depend on the test current. Thus, one of the important technical requirements for the high dc shunt calibration is how to measure the high current effect on the shunt resistance. High dc comparator (DCC) technology has been used [1]–[3] to provide high-precision shunt resistance calibrations for the nominal test current over a few thousand amperes. However, a simple potentiometric method can be an alternative approach to calibrate the high dc shunts when using high-resolution digital voltmeters which are usually available in many laboratories. In this paper, we will describe a binary step-up method developed at Korea Research Institute of Standards and Science (KRISS) to obtain the information on the current dependence of the shunt resistor; the principle, the development status, and finally the comparison result with the National Research Council (NRC), Canada.

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II. Modified Step-Up Method

The purpose of the binary step-up method is to calibrate the unknown double current using a pair of shunts with the same nominal value in parallel. The resistance values given at the initial test current are used as a reference to calibrate the double current. By measuring the output voltages of the two shunts in parallel, the approximately equally divided currents through the two shunts are calculated and summed to obtain the value of the double current. In the next step, the calibrated double current is, in turn, used as a reference current to calibrate the unknown shunt resistances at the double current. By applying the double current to each shunt to measure the output voltage of the shunt, the shunt resistance is calibrated for the two shunts. Then, the calibrated shunt resistances at the double current can be used as a new reference for further calibration of the quadruple current. By repeating the step-up procedure in this way by n times, one can extend the current calibration range up to 2^n of the initial test current. This method can provide a way to calibrate the shunt resistance as a function of binary current points. However, during the investigation for the application of the step-up method, it was found that the source current changed depending on ON–OFF–ON history and load resistance change. Our first measurement result on our standard 1000-A shunt is shown in Fig. 1 [4] where the first part is the sum of voltages of the two shunts in parallel with a double current, 1000 A applied to the two shunts to calibrate the double current, and the second part is the voltage of the shunt1 with the double current of the same setting current value applied to the shunt1 to calibrate the resistance of the shunt1 at the double current. Since the resistances of the two shunts were approximately equal within 70×10^{-6} Ω/Ω at the initial current 500 A and the resistance of the shunts tended to increase at higher current by thermal effect, we expected the voltage of the shunt1 at the double current 1000 A would be higher than the previous sum of the two voltages. However, the result in Fig. 1, the ∼0.01% decrease in voltage is opposite to the expected direction of change. This can be attributed to the source current change during the measurement. To overcome the problem, the step-up method was modified so that a dc current transformer (dc CT)

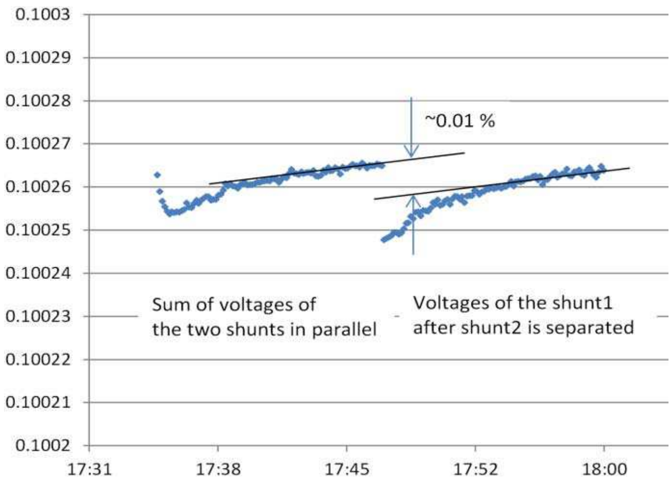

Fig. 1. Voltage readings in volts for the evaluation of the current dependence of the 1000-A shunt during the 500–1000 A step-up procedure [4].

was used as the current monitor. The current monitor was connected to the source output during all measurements to monitor and compensate the source current change during the step-up measurement. The modified step-up procedure is as follows.

1) Double current is applied to the pair of shunts in parallel to measure both shunt voltages. Since the resistances of the two shunts are already known at the initial current, i.e., the half of the double current, we can calculate the value of the double current and also the calibration factor of the current monitor at the double current. The calibration factor can be defined by the ratio of the output signal level with respect to input current.
2) Source current is set to zero and one shunt is disconnected from the other shunt, the device under test (DUT) shunt, so only the DUT shunt and the current monitor are connected to the current source. Then, the source current is turned back to the previous value to measure the DUT shunt output at the double current. With the simultaneously recorded output signal of the current monitor and the already determined calibration factor, we can trace the calibration value of the double current whenever it changed during the DUT shunt measurement, thus so does the calibration value of the DUT shunt resistance as a function of time. In the following section, our experimental details for setup from 500 to 1000 A carried out by the modified step-up technology at KRISS will be described.

III. Experimental Setup

To test the dc shunt calibration by the modified step-up method, a single step-up procedure from 500 to 1000 A was implemented.

A. Equipment

A 4000-A range multistage current extender for the DCC bridge provided by a commercial supplier was used as the high current source. Two 1000-A shunts were used as the pair of shunts for the step up. The nominal resistance was 0.1 mΩ. One of them chosen as the DUT was identified by a serial number (S/N) 70 506, and the other by a S/N 68 342. For the source current monitor, a dc CT system consisting of a 3000-A dc CT, a controller and a 0.1-Ω high power standard resistor as the dc CT output current sensor was used. The dc CT was set with ratio selection of 1000:1 so that the 1-A output current is obtained as a secondary current for the 1000-A source current. The secondary current results in a voltage drop of 0.1 V across the 0.1-Ω high power resistance standard in the CT burden. The calibration certificate for the 0.1-Ω high power standard resistor says that overall uncertainty is 50×10^{-6} Ω/Ω under temperature condition 23 °C±2 °C from which we can assume that temperature coefficient would be approximately within $\pm 25 \times 10^{-6}$ Ω/Ω/°C. Since the normal room temperature variation during the measurement is much smaller than the maximum deviation ±1 °C, the temperature effect of the high power standard resistor would be much smaller than our level of precision, 50×10^{-6} Ω/Ω to 100×10^{-6} Ω/Ω. The dc CT was installed in series at the output of the source all the time so that any change of the source current can be traced during the whole step-up measurement. Three digital multimeters (DMMs) of 8(1/2) digit were used to simultaneously record all necessary voltage signals; two of them were for the shunts, and the third one was for the dc CT system.

B. Experimental Condition

Since the shunt resistance is sensitive to the temperature, the laboratory temperature was controlled at 23 °C with maximum deviation of ±1 °C. Humidity was controlled at 50% with maximum deviation of ±10%. Normally, an appropriate cooling fan was used for each shunt. The room temperature and the other thermal conditions such as the use of the cooling fan, current activating time to the shunt and number of cables at connections were carefully controlled to the same. Considering that manufacture's specification for the temperature coefficient of the shunt is 20×10^{-6} Ω/Ω/°C and the normal room temperature variation is much smaller than the maximum deviation ±1 °C, the temperature effect would be much smaller than our level of precision, 50×10^{-6} Ω/Ω to 100×10^{-6} Ω/Ω. All the equipment was warmed up for more than 2 h before measurement. In consideration of that the voltages to be measured are in low level, zero offset measurements were made for the three DMMs before and after the measurements, and linear drifts of the zero offset were corrected. Since good connections are very important for the high current measurements, all the high current cables were checked against any bad conduction, and all the connections to the high current terminals were made very tight by a tool. For a better reproducibility of the cable contacts regardless of connecting angle, a circular shape copper washer was used in every connection between the terminal and the cable lug.

IV. Measurement Result

For the step-up experiment from 500 to 1000 A, we need the precalibrated values of resistances of the two shunts at 500 A. For these values, we used the resistance measurement data

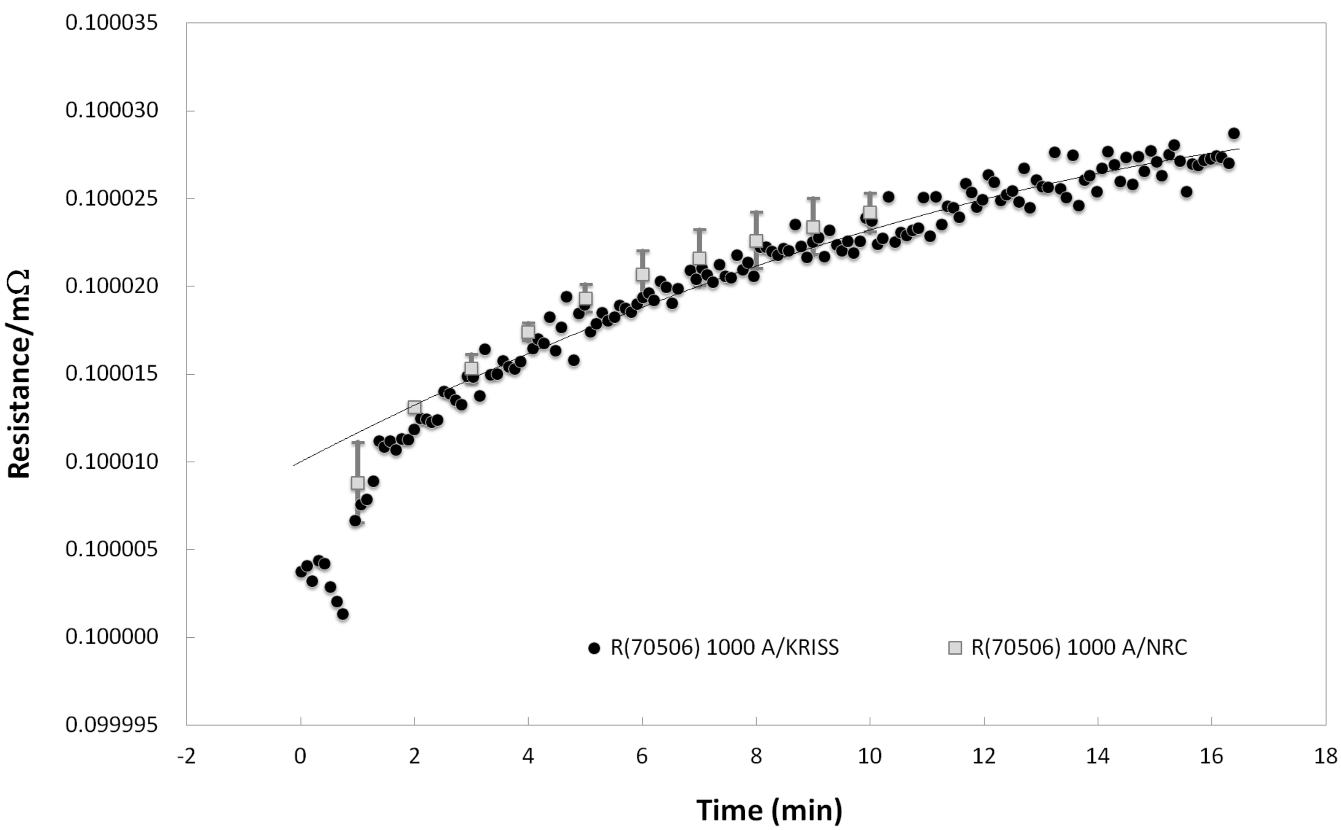

Fig. 2. Shunt-resistance measurement result as a function of time after 1000-A test current applied. The solid circles: the KRISS measurement by the modified step-up procedure. The gray squares: the NRC measurement. The vertical lines on the NRC data represent the two standard deviation margins.

for multiple test current points provided from the NRC in the process of comparison-related cooperation between the KRISS and the NRC. For the calculation of the source current, the calibration factor of the dc CT system was measured with the measurement step of the two shunts in parallel. The calibration factor came close to $1.000\,00 \times (0.1\ \mathrm{V}/1000\ \mathrm{A})$ within a few part per million deviations as the source became stabilized in 10 or 15 min after the source begins to generate the double current 1000 A. Finally, the measurement results for the DUT shunt resistance at the double current 1000 A are shown as in Fig. 2. The solid circles show KRISS measurements. If we take the 10 minute data, the relative increase of the DUT resistance by the increase of the test current from 500 to 1000 A was approximately $+189 \times 10^{-6}$ in relative to the nominal.

V. Comparison With NRC

To validate the step-up measurement result, it was compared with the shunt measurement by the NRC which was carried out with transporting the two shunts S/N 68 342 and S/N 70 506 owned by the KRISS as the traveling standards.

The NRC measurement results are shown as gray squares in Fig. 2. The vertical lines on the NRC data represent the two standard deviation margins. Both the KRISS and NRC results show that the fast initial variation decays to a smooth stabilization in about 10 min, but still slowly increasing even after about 20 min. The solid curve is a best fitting of the last group of KRISS data to a second-order polynomial equation.

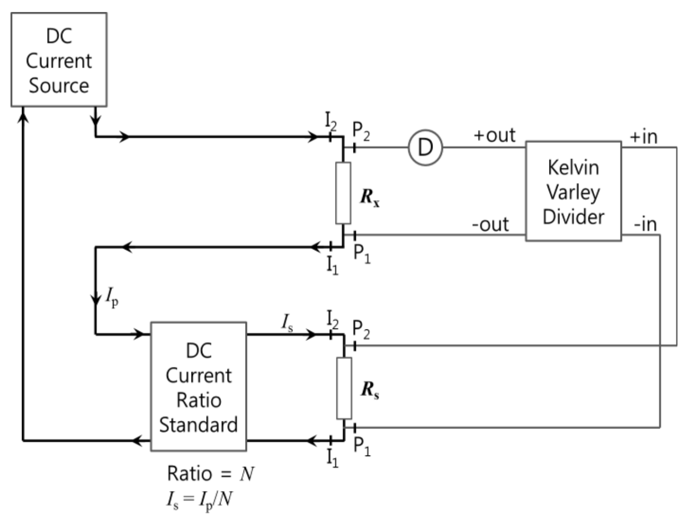

Fig. 3. Calibration of a dc shunt.

If we take the fitted curve as representing the KRISS measurement result, the difference between KRISS and NRC at the time of 10 min is $-9.9 \times 10^{-10}\ \Omega$, approximately -10×10^{-6} in relative to the nominal. This seems to be an excellent agreement in considering that the overall uncertainty of the KRISS measurements is estimated to be on the order of 0.01%.

Fig. 3 shows the NRC basic circuit used to calibrate a dc shunt R_X at test current I_P of the order of 1000 A, using

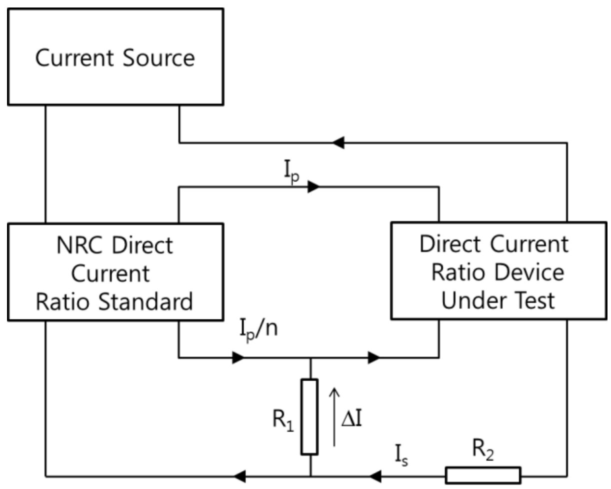

Fig. 4. Calibration of dc ratio device.

a calibrated 0.2-Ω current shunt R_S designed for relatively much smaller currents. The dc ratio standard in series with R_X produces a secondary current I_S which is applied to a calibrated current shunt R_S that is designed for current of a few amperes. The voltage across R_S is compared to that across R_X, using a Kelvin–Varley divider and a voltage detector D, as shown in Fig. 3. Neglecting the error of the dc ratio standard and the loading effect of the Kelvin–Varley voltage divider, the resistance of R_X is given by

$$R_X = R_S/(N_{\text{Direct\_Current\_Ratio\_Standard}} \cdot \text{Ratio}_{\text{Kelvin–Varley}}) \quad (1)$$

where $N_{\text{Direct\_Current\_Ratio\_Standard}}$ is the ratio of the dc ratio standard, and $\text{Ratio}_{\text{Kelvin\_Varley}}$ is the ratio indication shown by the Kelvin–Varley Divider.

A series of two sets of measurements were performed to determine the resistance of the KRISS 0.1-mΩ shunts at 1000 A overtime at intervals of 1 min, using the NRC dc ratio standard as the dc ratio standard over a period of 10 min. After a period of time to allow the shunt to return to normal ambient temperature, the primary current I_P was reversed and the second set of measurements was performed. An average resistance was determined for R_X at each 1 min interval. A second series of measurements were performed, replacing the NRC dc Ratio Standard with the KRISS dc CT. Corrections were made to the measured values of R_X, to account for the measured error of the KRISS dc CT and the loading effect of the Kelvin–Varley divider upon the voltage across R_S. The KRISS dc CT was calibrated at 1000 A dc with respect to the NRC dc Ratio Standard using the differential calibration circuit shown in Fig. 4.

The error ϵ of the KRISS dc CT, is given approximately by $\epsilon = \Delta I \,/\, I_S$. Therefore

$$\epsilon = (\Delta V_1/V_2) \cdot (R_2/R_1) \quad (2)$$

where R_2 and R_1 are the shunt resistors used to measure I_S and ΔI, respectively. ΔV_1 and V_2 are the voltages measured across the corresponding shunt resistors. The KRISS dc CT, being based on DCC technology, has ratio errors of the order of 10^{-6} A/A. At this level of error, the impact of any departure from nominal values of R_1 and R_2 has no significant effect on the measurement of ϵ (second-order effect).

The ratio error of the KRISS dc CT was found to be $(-4 \pm 4) \cdot 10^{-6}$ A/A.

The measured values of the KRISS DUT, S/N 70 506 measured at 1000 A after 10 min, based on the average value of resistance for normal and reversed current measured with both systems, as described above, are shown in Table I. The agreement between both systems indicates good performance on the part of both systems. When additional measurements were performed, additional measurement variances could be observed, which in some cases yielded measurement uncertainties of as much as 20×10^{-6} Ω/Ω. This measurement uncertainty was attributed to the stability of the shunt, which in turn may have been attributed to temperature changes in the laboratory or thermal voltages. This was consistent with the manufacturer's specifications for this shunt of having a temperature coefficient of 20×10^{-6} Ω/Ω/°C and a 12-month stability of 25×10^{-6} Ω/Ω.

TABLE I
MEASURED RESISTANCE OF KRISS DUT, S/N 70 506 AT 1000 A AFTER 10 MIN, USING KRISS AND NRC DC RATIO STANDARDS

Direct Current Ratio Standard	Measured Shunt Resistance (mΩ)
KRISS DC CT	0.1000238 ± 0.0000006
NRC DC Ratio Standard	0.1000241 ± 0.0000006

VI. DISCUSSION AND CONCLUSION

The quality of the step-up measurement can be affected by many parameters as mentioned in the previous report [4]. The most significant in the simple version of the step-up method was the ability of the high-current source to keep the output current the same not only during the source current ON–OFF–ON but also during the load change from parallel to series connection which seems very difficult to achieve with the high current range. However, by employing a high dc CT as a current monitor in the modified step up procedure, the source current change at the double current could be traced during the whole step up and effectively corrected. To validate the modified step-up measurement technology, the shunt calibration at 1000 A was compared with the NRC by transporting the 1000 A shunt of nominal resistance of 0.1 mΩ owned by the KRISS. The difference between KRISS and NRC measurement at the time of 10 minute was approximately -10×10^{-6} Ω/Ω in relative to the NRC result. This seems to be an excellent agreement in considering that the overall uncertainty of the KRISS measurement is estimated to be on 0.01% order. Thus, the comparison result with the NRC supports validity of the modified step-up procedure developed at KRISS. A further research work to apply the step-up method to higher current range will be also useful.

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