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The High Resistance Measurement up to 100 PΩ using a Low Resistance, a Low Voltage Source and a Commercial Digital Multimeter

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Abstract – The potentiometric measurement result for a high resistance up to 100 PΩ using a low resistance, a low voltage source and a commercial digital multimeter(DMM) is presented. With the method, a resistance can be easily, fast and economically measured. Using the method, resistance ranges over the 10 GΩ range which is difficult to measure using a commercial DMM and resistance ranges between 100 TΩ and 100 PΩ which cannot measure using an insulation tester were measured within accuracy of a few percent. It is expected that it can be useful to determine the temperature and voltage effect of a high resistance and an insulation material because it uses a reference resistance with a low resistance, very low temperature and voltage effect. Besides, it is expected that it can be useful to calibrate a dc high voltage divider with a large resistance ratio and a very low resistance because arbitrary resistance ratio measurements are possible with it.

Keywords: Ultra-High resistance measurement, Potentiometric method, Voltage source-voltmeter method

1. Introduction

Insulation resistance is very important in electric motors, transformers, telecommunication, heavy industry, high voltage industry, electromagnetic materials measurements, marine and aviation industry, etc. A variety of insulation resistance measurement equipment and testers are widely used. For accurately measuring them, international standards such as IEC, etc. describe measurement procedures and methods for an insulation resistance between 1 MΩ and hundreds of TΩ. In telecommunication field, resistances which are less than GΩ are used and it can be known by applying voltage and measuring current through an insulation resistance or directly measuring with a commercial insulation tester or a DMM. Also, it can be accurately and precisely measured using several comparison methods [1-17]. However, insulation resistances which are used at industry are mostly over a few TΩ and it is difficult to measure them using an insulation tester. That is because measuring current is very low in the high resistance region and so, it is directly influenced by surrounding electromagnetic interference. Though the effect can be reduced by shielding entire measurement system and using special cables such as triaxial cables and double shielded coaxial cables, it is difficult to reduce leakage resistance effect which is produced by system insulation resistance and measuring instruments because system insulation resistance over a few hundreds of TΩ is needed to cover the effect and very difficult to keep the resistance. Two bridge methods are widely used to eliminate the effect at present. One is a guarded active-arm bridge method which applies to a guard circuit the same voltage with applying to a main circuit to eliminate the leakage effect [14]. The other is a modified Wheatstone bridge method which compares two resistances using two voltage sources instead of two ratio-arm resistances of a traditional Wheatstone bridge to minimize the leakage effect [1]. The former needs a complex circuit which uses an auxiliary circuit for guarding and it is not easy to measure an ultra-high resistance range accurately. The latter is typically used to make 10 to 1 ratio measurements and so should use several steps to obtain a high resistance from a low resistance. This paper presents a simple, fast and economic method to directly measure a high resistance up to 100 PΩ without leakage effect and several steps using a low resistance, commercial low voltage source and DMM.

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2. Bridge Method

2.1 Guarded active-arm bridge

The guarded active-arm bridge as shown in Fig. 1 consists of two stable voltage sources, V_1 and V_2, that drive the main resistors, Rx and Rs, and the guard resistors, r_x and r_s. The detector D measures the current difference flowing through Rx and Rs. When a resistance over 10 TΩ is measured, an accurate balance of the bridge cannot be obtained because the voltage differences between the main and guard circuits produce leakage currents in the case of the high resistor Rx having a large nominal deviation.

This unbalance causes errors in measuring the difference

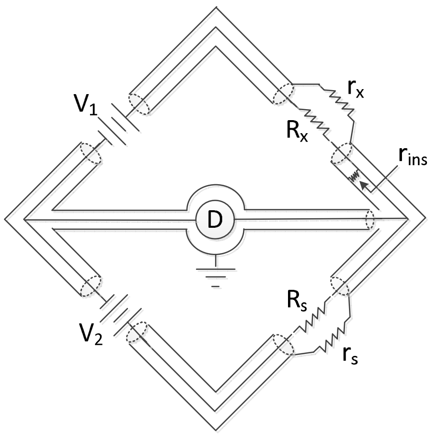


Fig. 1. Guarded active-arm bridge. r_{ins} means the insulation resistance between the main and guard circuits

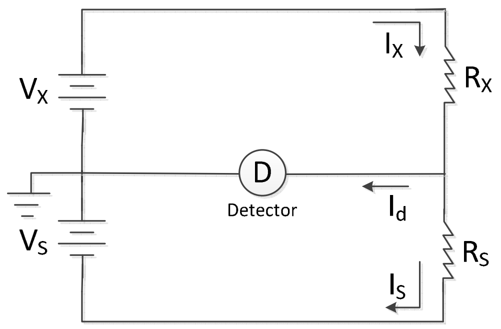


Fig. 2. Modified Wheatstone bridge

current in detector D of the main circuit. Two techniques are used to solve the problem of unbalanced main and guard resistor ratios. The first one is to select the proper guard resistor, r_x, related to the unknown resistor, Rx. The second one is to adjust the input voltage of the unknown guard resistor, r_x until the guard circuit midpoint which is the junction of r_x and r_s is at the same potential as the main circuit midpoint which is the junction of R_x and R_s. After balancing the guard circuit, then the main circuit can be balanced in order to eliminate leakage currents flowing through the insulation, R_{ins}, of the midpoint junctions. While this method can be used to accurately measure a high resistance without any leakage resistance effect, it needs a sensitive dual balance simultaneously. Also, it uses a 10 to 1 ratio normally and is not proper for a large resistance ratio measurement. Besides, it is difficult to use it for on-site measurements.

2.2 Modified Wheatstone bridge

As shown in Fig. 2, the bridge uses two voltage sources with very small source resistances in place of two ratio arms of a traditional Wheatstone bridge which the arm resistances are typically between a few kΩ and a few 100 kΩ. When voltage V_x and V_s are applied to the bridge circuit, the current seen by the detector (a feedback type electrometer) is given by

$$I_d = I_x + I_s = V_x / R_x - V_s / I_s \quad (1)$$

At a bridge balance, I_d=0 and Eq. (1) is simply given by

$$R_x=(V_x/V_s)R_s \quad (2)$$

This method has an advantage to measure a high resistance without leakage resistance effect because any leakage resistance of R_x and R_s can only affect measurement sensitivity of the detector. However, several steps are needed to measure an ultra-high resistance because a 10 to 1 ratio is normally used to accurately compare an unknown high resistance with a reference resistance using the method. Also, it is difficult to use it for on-site measurements with the same as the guarded active-arm bridge.

3. Voltage Source-DMM Method

Fig. 3(a) shows to connect a unknown high resistance R_X, reference resistance R_{S1} and a voltage source V in series and to measure voltage V_{S1} across R_{S1} using a DMM [11]. Fig. 3(b) shows leakage resistances, a DMM input resistance and lead wire resistance effects when

$$V=I\bullet(R_X+R_{S1}\bullet R_P/(R_{S1}+R_P),\ R_P=R_L\bullet R_{DMM}/(R_L+R_{DMM}),$$
$$V_{S1}=i_L\bullet R_L=i_{S1}\bullet R_{S1}=i_{DMM}\bullet R_{DMM}\ ,\ I=i_L+i_{S1}+i_{DMM} \quad (5)$$

connect like Fig. 3(a). From Fig. 3(a) with neglecting those effects,

$$V=I\bullet (R_X+R_{S1}),\ V_{S1}=I\bullet R_{S1} \quad (3)$$

Eq. (3) can be rewritten by

$$R_X=R_{S1}\bullet (V/V_{S1}-1) \quad (4)$$

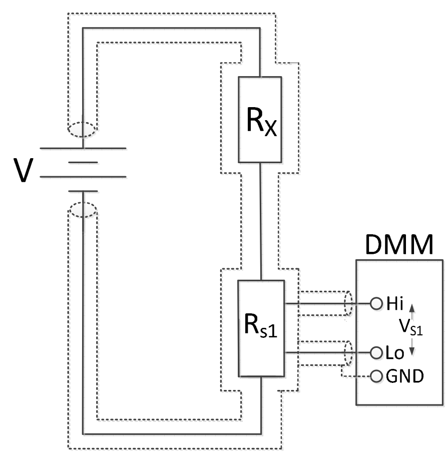


Fig. 3 (a) Voltage source-voltmeter method Dotted lines mean electric shielding

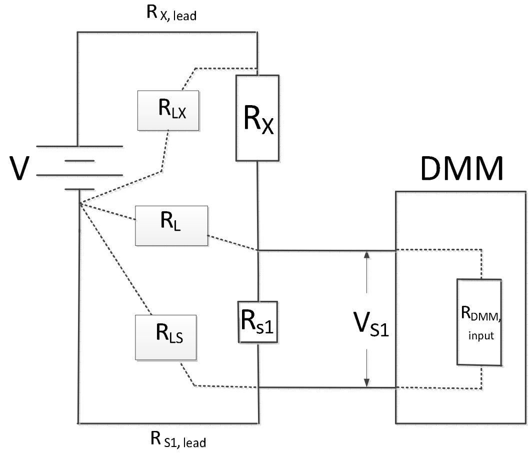


Fig. 3. (b) Effect of leakage resistances, a DMM input resistance and lead wire resistances

With including those effects as shown in Fig. 3(b), Eq. (3) is modified by

In Eq. (5), the lead wire resistance effect is excluded because it is generally less than a few Ω and the leakage resistance R_{LX} and R_{LS} do not influence on DMM voltage measurements.

Eq. (5) can be summarized by

$$V/V_{S1} - 1 = R_X/R_{S1} \bullet (1 + R_{S1}/R_L + R_{S1}/R_{DMM}) \quad (6)$$

Practically, R_{S1} is much smaller than R_L and R_{DMM} and thus the last two terms of Eq. (6) are negligible. As a result, it can be known that Eq. (4) can be normally used for high resistance measurements instead of Eq. (6). From Eq. (4) and the measurement principle, even a very high resistance can be accurately determined because the high resistance is compared with a low reference resistance by the method. That means a high resistance can be determined with only one step from a low resistance. That is different from the previous methods which need several steps to measure the high resistance. Also, on-site measurements such as high voltage measurements at industry field are possible with using the method if a high voltage divider is connected in place of Rx in Fig. 3(a).

4. Setup

To measure a high resistance R_X in the insulation resistance region as shown in Fig. 3(a), a dc voltage calibrator with 0.001 % stability is used to apply up to 1 kV, one 1 GΩ standard resistor was used as R_{S1} except one 10 GΩ standard resistor which is used for 100 PΩ measurements. To measure a voltage across R_{S1}, a commercial DMM which has 0.1 μV resolution and 100 GΩ DMM input resistance was used and also the resistances between 10 GΩ and 100 PΩ are used for R_X measurements. Generally, the resistance up to 100 TΩ is made of high resistance materials. However, the typical

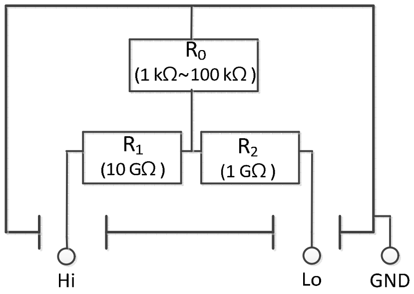


Fig. 4. The wye network of a resistance over 1 PΩ

structure over a 1 PΩ resistance consists of three component resistors as shown in Fig. 4. The resistance between 1 PΩ and 100 PΩ, Rx, can be given from a well-known wye-delta transformation [18]

$$R_X = R_1 + R_2 + (R_1 x R_2)/R_0 \quad (7)$$

The measurement temperature and humidity were (23±1) ℃ and (45±5) % R.H., and also applying voltage was up to dc 1 kV without self-heating effect.

The resistance between 1 PΩ and 100 PΩ, Rx, can be given from a well-known wye-delta transformation by

$$R_X = R_1 + R_2 + (R_1 x R_2)/R_0 \quad (8)$$

A commercial DMM which has an input resistance R_{DMM} over 100 GΩ was used and the system leakage resistance RL is generally higher than 1 TΩ. So, the error for 1 GΩ reference, R_{S1}, from the last two terms of Eq. (6) is negligible within 1 %. In the case, Eq. (4) can be used instead of Eq. (6) and the resistance ratio R_X/R_{S1} is given by the ratio of an applying voltage to a measured voltage. For R_X between 10 GΩ to 100 PΩ which cannot measure using a commercial DMM, some combinations of measuring voltage V_{S1}, resistance ratio R_X/R_{S1} and test voltage V for obtaining R_X within a few percent of accuracy are shown in Table 1.

Table 1. Combinations of measuring voltages, resistance ratios and test voltages for obtaining R_X

Test Voltage (V)	Measuring Voltage (V_{S1})	Resistance Ratio (R_X/R_{S1})	R_X (Nominal Value)
1000 V	0.1 mV	10^7:1	100 PΩ (10^{17} Ω)
100 V	0.01 mV	10^7:1	10 PΩ (10^{16} Ω)
100 V	0.1 mV	10^6:1	1 PΩ (10^{15} Ω)
100 V	1 mV	10^5:1	100 TΩ (10^{14} Ω)
100 V	10 mV	10^4:1	10 TΩ (10^{13} Ω)
100 V	100 mV	10^3:1	1 TΩ (10^{12} Ω)
100 V	100 mV	10^2:1	100 GΩ (10^{11} Ω)
100 V	1 V	10:1	10 GΩ (10^{10} Ω)

Table 2. Measurement results for R_X between 10 GΩ and 100 PΩ with R_S of 1 GΩ

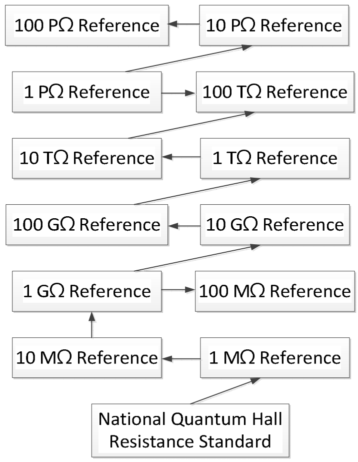
R_X (nominal value)	Test voltage (V)	R_X		Relative difference between A and B (%)
		Measured value(A)	Calibrated value(B)	
100 PΩ (10^{17} Ω)	1000	107 (20)	100 (10)	7
10 PΩ (10^{16} Ω)	100	9.9 (5)	10.0 (3)	1
1 PΩ (10^{15} Ω)	100	0.98 (3)	1.00 (1)	2
100 TΩ (10^{14} Ω)	100	100.3 (1.0)	100.1 (0.1)	0.2
10 TΩ (10^{13} Ω)	100	10.02 (0.5)	10.00 (0.02)	0.2
1 TΩ (10^{12} Ω)	100	1.0006 (0.05)	1.0001 (0.01)	0.05
100 GΩ (10^{11} Ω)	100	100.00 (0.05)	100.04 (0.01)	0.04
10GΩ (10^{10} Ω)	100	10.004 (0.05)	10.002 (0.01)	0.02

5. Measurement results and Discussion

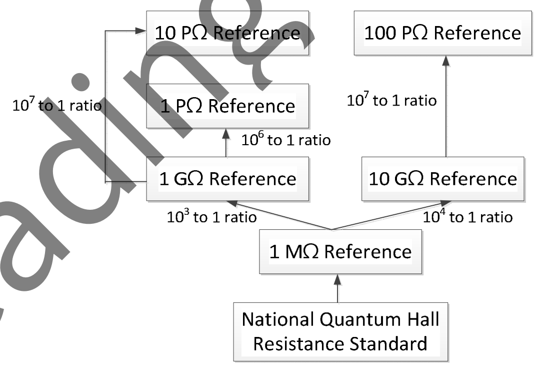
In Table 2, B means the calibrated values using the national high resistance standard system and the number in parentheses shows relative expanded uncertainties with coverage factor of 2 which are estimated according to the ISO/IEC Guide [19] and are expressed as %. The uncertainty factors associated with DMM measurements are estimated referring to the literature [20, 21].

From this result, it is shown that the difference between the measurement results and the calibrated values over 10 GΩ to 100 PΩ are agreed within 0.1 % ~ a few percent. Also, PΩ or higher ranges which cannot measure with commercial insulation testers and high resistance meters can be measured using a commercial DMM and even at a low voltage like 100 V. Though the DMM of $6^{1/2}$ digit resolution was used, measurement accuracy and uncertainty can be better if a DMM of higher resolution is used. Furthermore, the method can be used to investigate the temperature and voltage effect of high resistances because reference resistances with low temperature and voltage effect are used. Besides, the method can be used to accurately measure the high voltage arm resistance of dc high voltage divider which is used to measure hundreds of kV. Also, it is expected that the method can be used to measure low resistance which has less than 1 kΩ if the compliance current of a voltage source and the lead resistance effect of a measuring circuit are estimated.

Additionally, as well as the resistance ratio shown in Table 1, it is also possible to make an arbitrary resistance ratio measurement within the resolution limit of a DMM voltage range, with the method. Therefore, the method has an advantage of reducing measurement steps greatly by comparing with the previous bridge methods as shown in Fig. 5.



(a) Bridge methods. the 10 to 1 ratio measurements are made for all the comparison.



(b) Voltage source-DMM method

Fig. 5. Comparison of measurement steps for bridge methods and voltage source-DMM method for PΩ range measurements

6. Conclusion

The method presented has an advantage that can measure ultra-high resistances up to 100 PΩ using a low resistance, a commercial voltage source and a DMM by comparing with previous methods. That means that an ultra-high resistance which cannot measure with an insulation tester and a high resistance meter can be directly measured using a low resistance by only one step. Also, insulation testers and high resistance meters are accurately calibrated with the high resistances which are calibrated using the method. Furthermore, it can be used to measure the temperature and voltage effect of a high resistance or an insulation material. A dc high voltage divider and a low resistance can also be calibrated using it because an arbitrary resistance ratio measurement can be made with it. Additionally, it is expected that it can be used for establishing a national high resistance standard system in the near future.

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