Development of an AC Standard Shunt With Small Phase Angle and High Stability

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Abstract

The authors developed an ac standard shunt, rated 10 A, 0.1 Ω, for the frequency from dc to 10 kHz that has highly stable resistance value and small phase angle error. Using this ac standard shunt, ac power and current may be measured with high accuracy. The change in the resistance value of the ac shunt is within ±1 μΩ/Ω when the ambient temperature is (23±3)C. The change in the resistance value is 2.5 μΩ/Ω per year. The phase angle of the ac shunt is 6 μrad at 1 kHz. Stability of the shunt, which is calibrated once a year, corresponds to 3 μW/W of uncertainty with regard to ac power measurement at 1 kHz.

1. Introduction

In order to measure current with high accuracy, a shunt is commonly used. However, when ac current is converted into ac voltage with generally used dc shunts, due to the influence of the proportion of the quadrature component to the resistance value (hereafter referred to as "phase angle"), a phase shift occurs between the original current and the converted voltage. The quadrature component of the shunt is caused by the inductance and distributed capacitance of the shunt, and the interaction of the current circuit and voltage circuit. Moreover, the resistance value of the shunt changes with aging, change in the ambient temperature, etc. This change in the resistance value is the cause of error in the magnitude of the current. The change in the resistance value, and the phase difference between the original current and converted voltage are causes of error in ac power measurement.

In JEMIC, *standard shunt for phase angle determination*[1] has been used for these measurements. This shunt has very small phase angle. However, the resistance value is easy to change by aging and change in the ambient temperature mainly. Therefore improvement of the stability has been required. Expansion of the rated current has been desired because it is insufficient as a practical standard shunt. In addition, since the shunt is large and has a lot of hand-wired parts, its handling is inconvenient. Accordingly, miniaturization of the shunt has been also desired.

For these reasons, the authors have developed an ac standard shunt (hereafter referred to as "ac shunt"), shown in figure1, that has high accuracy for ac power measurement.

Figure 1. Developed AC shunt.

2. Design of the AC Shunt

It is ideal for the ac shunt that the resistance value is independent of ambient temperature, aging, magnitude of input current, frequency, etc. It is also desirable that the ac shunt has no phase angle. However, actual shunts have quadrature component, temperature coefficient of the resistance value, etc. Thus, the ac shunt is designed under the following conditions in order to minimize the change in the resistance value and phase angle[2].

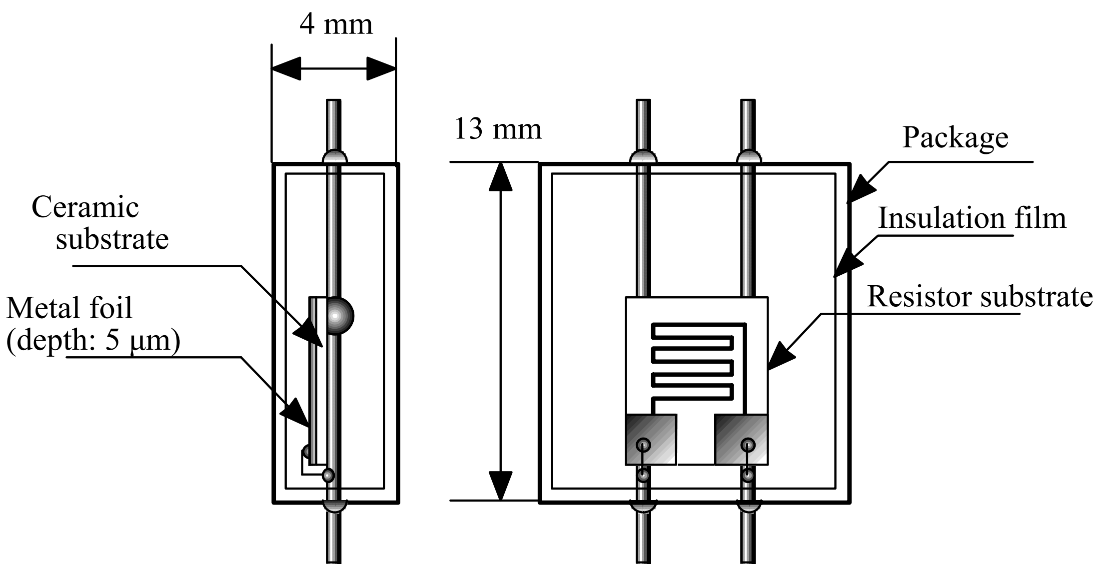
1) The resistors used in the ac shunt are newly designed as shown in Figure 2. The resistor, rated 10 Ω, 0.3 W, is four-terminal type and is comprised of a metal foil resistive element that has superior characteristics with respect to long-term stability and temperature coefficient. The

resistor is designed to minimize inductance, skin effect and eddy current.

2) The ac shunt is comprised of 100 resistors as shown in Figure 3. These resistors are connected in parallel to obtain desirable resistance value, 0.1 Ω, and rated current, 10 A, as a practical standard shunt. This may enable expansion of the rated current without loss of the characteristics of the resistors.

3) The resistors are arranged on circuit boards designed to reduce mutual inductance between the current circuit and voltage circuit of the ac shunt. These circuit boards dispose the resistors on a circumference in order to distribute input current uniformly. The ac shunt is comprised of four-terminal-type resistors and two circuit boards. One of the boards is connected to current leads of the resistors and another is connected to voltage leads. Hence, the current circuit and voltage circuit may be separated.

4) The ac shunt consists of circuit boards instead of hand-wired parts. Since wiring parts become more stable physically, long-term stability may be improved.

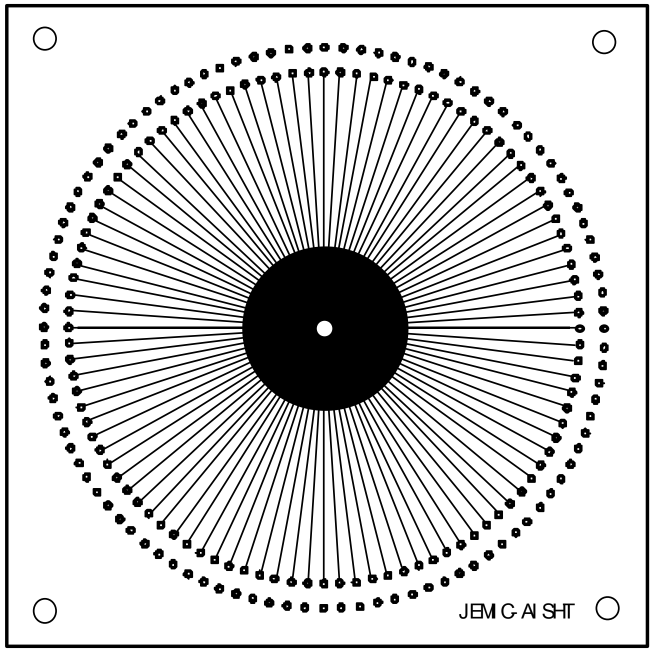


Note:

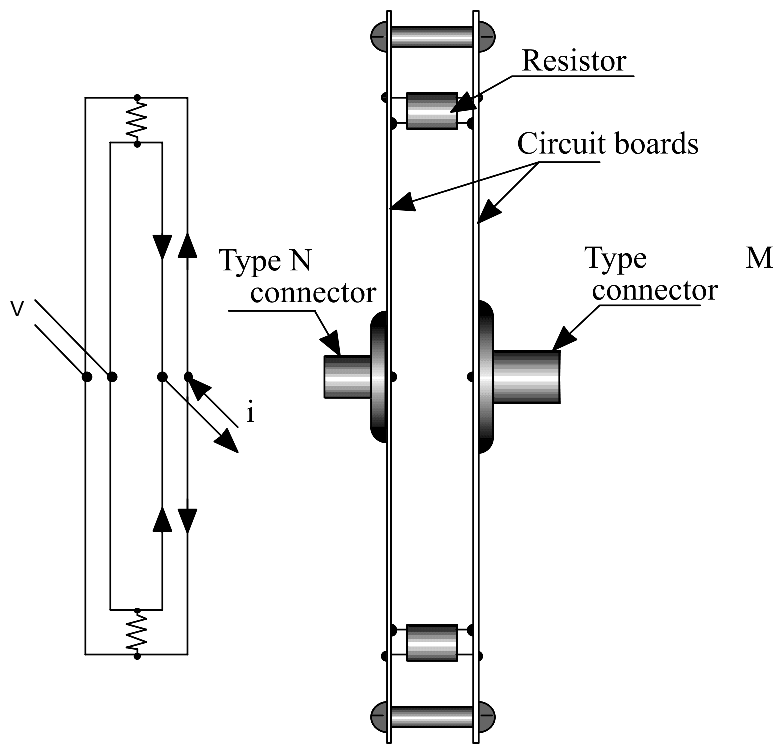
Resistance: 10 Ω± 100 μΩ/Ω TCR: within 10 μΩ/Ω per ℃

Rated power: 0.3 W Long-term stability: 10 μΩ/Ω per year

Figure 2. Metal foil resistor.



a) Circuit board



b) Side view

Figure 3. Configuration of the AC shunt.

3. Characteristics of the AC Shunt

The various characteristics of the ac shunt are as follows:

1) Self-heating characteristic

The change in the resistance value for self-heating time is shown in figure 4. The resistance value becomes within 1 μΩ/Ω from a stable point in 5 minutes. It approaches within 0.1 μΩ/Ω by more 10 minutes self-heating.

2) Temperature characteristic

Figure 5 shows the change in the resistance value for change of the ambient temperature. Temperature coefficient is within 0.3 μΩ/Ω per C at (23±3) C.

3) Current characteristic

The change in the resistance value against change of the test current is shown in figure 6. Self-heating was done for 30 minutes at each test point. The change in the resistance value is 2 μΩ/Ω for the change from 0.3 A to 5 A and 8 μΩ/Ω for the change from 5 A to 10 A. As a result, the change in the resistance value doesn't exceed ±0.5 μΩ/Ω even if magnitude of the test current changes by ±2 % of the current.

4) Long-term stability

The changes in the resistance values are approximately 2.5 μΩ/Ω per year for the test current from 1 A to 10 A as shown in figure 7.

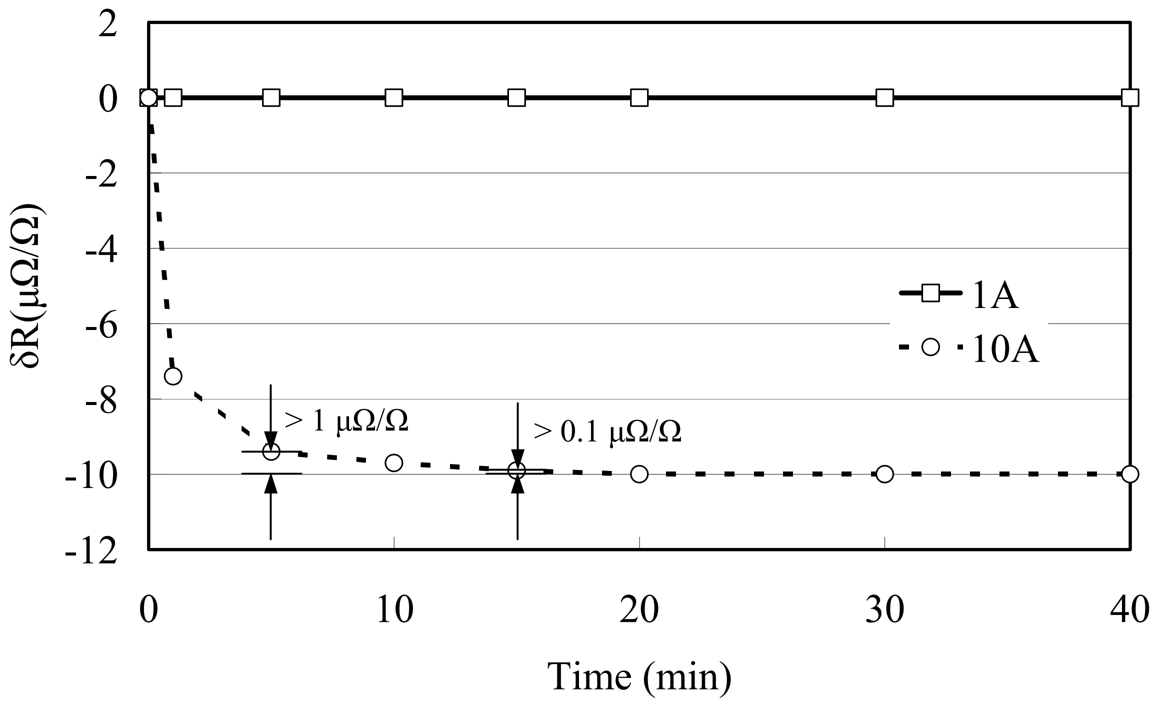


Figure 4. Self-heating characteristic.

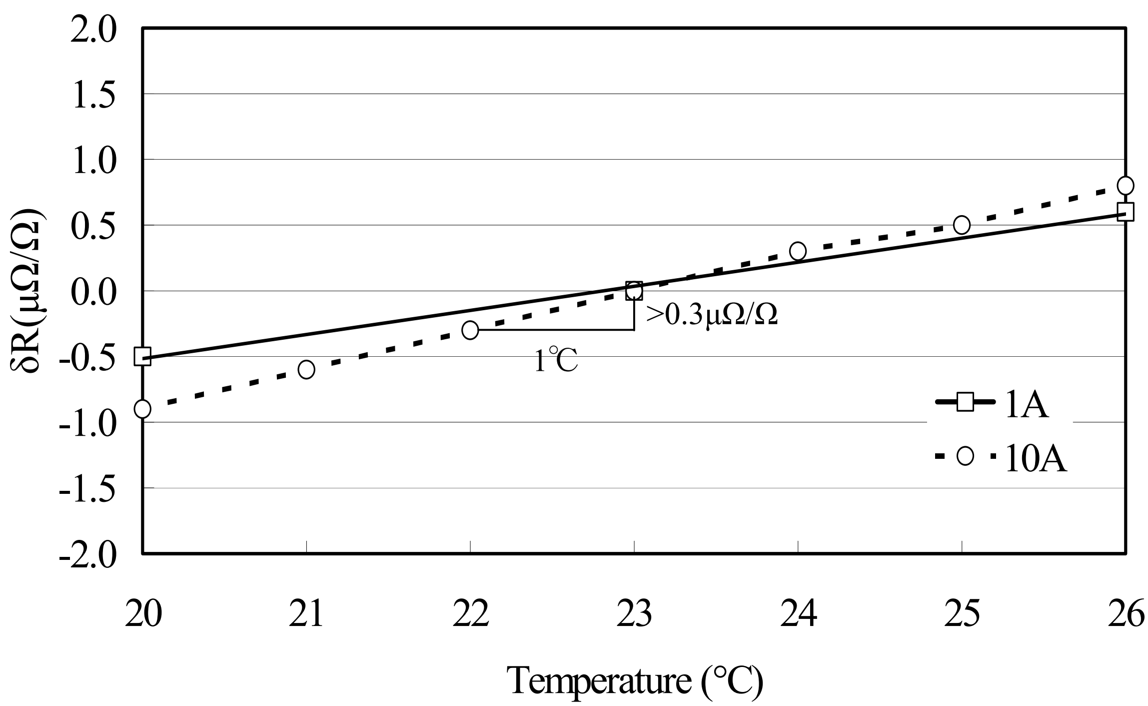


Figure 5. Temperature characteristic.

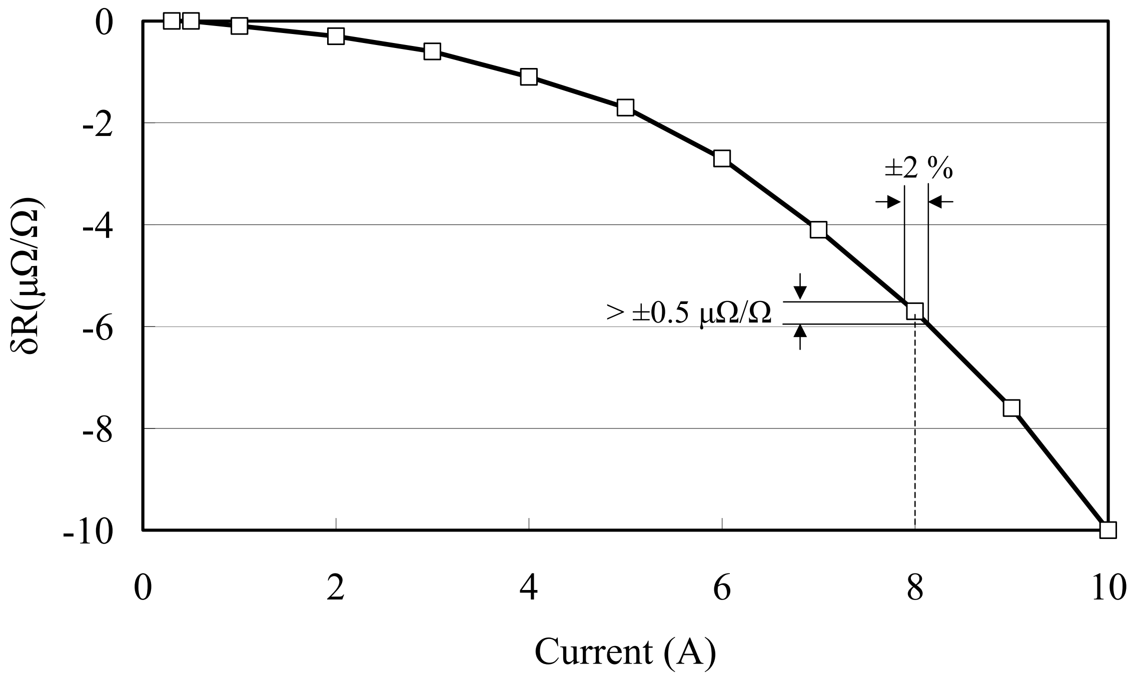


Figure 6. Current characteristic.

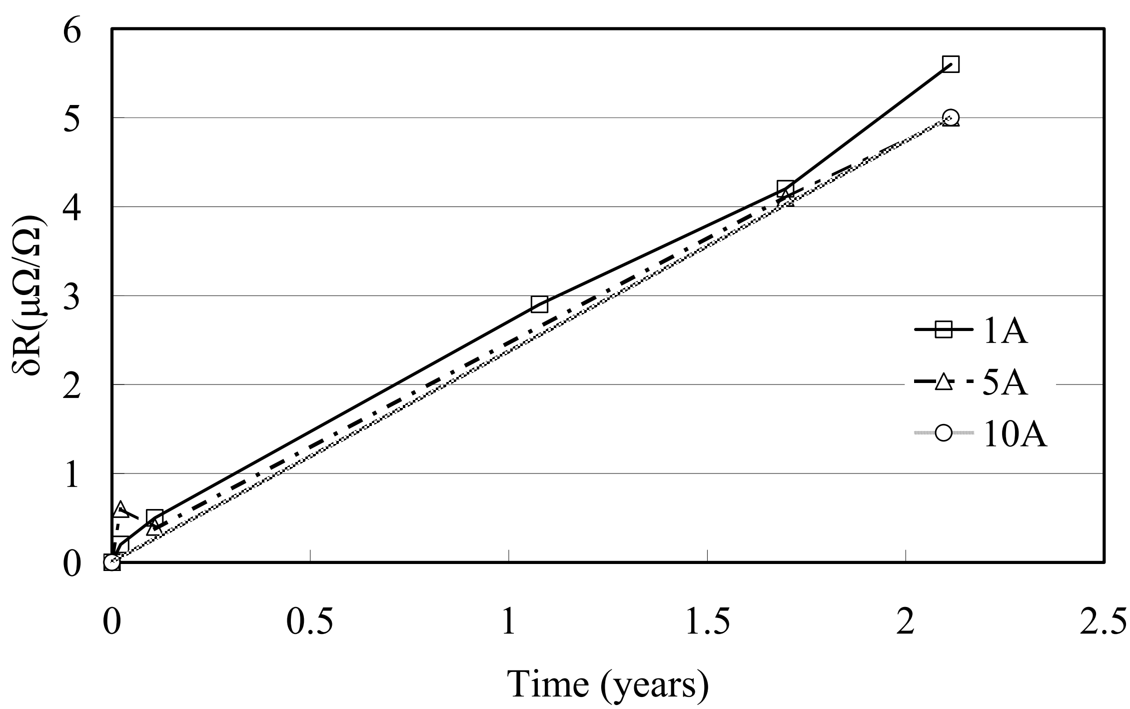


Figure 7. Long-term stability.

Table 1. AC resistance value and phase angle of the AC shunt.

Values in parentheses are estimated uncertainties.

	DC	60 Hz		1 kHz		10 kHz	
current	resistance	resistance	phase angle	resistance	phase angle	resistance	phase angle
A	mΩ	mΩ	μrad	mΩ	μrad	mΩ	μrad
1	100.0051(±0.0002)	100.0051(±0.0002)	0(±0)	100.0051(±0.0002)	6(±1)	100.0051(±0.0002)	56(±7)
2	100.0051(±0.0002)	100.0051(±0.0002)	0(±0)	100.0051(±0.0002)	6(±1)	100.0051(±0.0002)	56(±7)
3	100.0050(±0.0002)	100.0050(±0.0002)	0(±0)	100.0050(±0.0002)	6(±1)	100.0051(±0.0002)	56(±7)
4	100.0050(±0.0002)	100.0050(±0.0002)	0(±0)	100.0050(±0.0002)	6(±1)	100.0050(±0.0002)	56(±7)
5	100.0049(±0.0002)	100.0049(±0.0002)	0(±0)	100.0049(±0.0002)	6(±1)	100.0050(±0.0002)	56(±7)
6	100.0048(±0.0002)	100.0048(±0.0002)	0(±0)	100.0048(±0.0002)	6(±1)	100.0049(±0.0002)	56(±7)
7	100.0047(±0.0002)	100.0047(±0.0002)	0(±0)	100.0047(±0.0002)	6(±1)	100.0047(±0.0002)	56(±7)
8	100.0045(±0.0002)	100.0045(±0.0002)	0(±0)	100.0045(±0.0002)	6(±1)	100.0046(±0.0002)	56(±7)
9	100.0043(±0.0002)	100.0043(±0.0002)	0(±0)	100.0043(±0.0002)	6(±1)	100.0044(±0.0002)	56(±7)
10	100.0041(±0.0002)	100.0041(±0.0002)	0(±0)	100.0041(±0.0002)	6(±1)	100.0041(±0.0002)	56(±7)

4. Calculation of AC Resistance Value and Phase Angle

An equivalent circuit of the ac shunt is fundamentally expressed in R, L and C as shown in figure 8. Where R is calibrated dc resistance value of the ac shunt. L is inductance of 100 resistors connected in parallel. The inductance of each resistor is estimated to be 10 nH by comparison between the resistor and resistance wire. Hence L corresponds to 0.1 nH. C is distributed capacitance and is estimated to be 1120 pF.

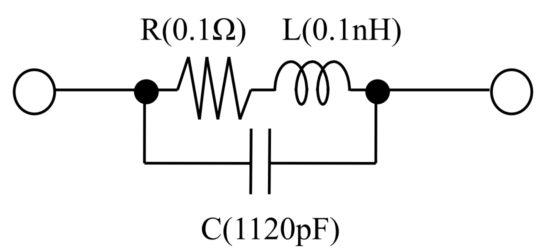


Figure 8. Equivalent circuit.

The other elements that affect the resistance value and phase angle of the ac shunt are the mutual inductance among resistors, and the mutual inductance between the current circuit and the voltage circuit. It is confirmed by experiments that these influence is sufficiently small. Moreover, the influence of skin effect and eddy current may be negligible since it is very small within 10 kHz.

Based on the equivalent circuit, the ac resistance value and phase angle are calculated. Table 1 shows examples of calculations.

5. Conclusion

Developed ac shunt satisfies expected characteristics. Table 2 shows a main specification of the ac shunt. Its stability corresponds to 3 μW/W of uncertainty with regard to ac power measurement at 1 kHz, if the ac shunt is calibrated once a year. Therefore, the ac shunt will enable more accurate measurements concerning ac power and current. Moreover, practicality is advanced because of miniaturization and improvement of the handling.

Table 2. Specification of the AC shunt.

nominal resistance value	0.1 Ω	
rated current	10 A	
maximum input power	30 W	
long-term stability	2.5 μΩ/Ω per year	
temperature coefficient	0.3 μΩ/Ω per ℃	at (23± 3)℃
phase angle	(0± 0) μrad	at 60 Hz
	(6± 1) μrad	at 1 kHz
	(56± 7) μrad	at 10 kHz

References

1. A. Igarashi, "Time Constant Measurement of Shunt", *JEMIC Technical Report*, Vol.14, No.1, pp.1-7, April 1979

2. D.L.H. Gibbings, "A design for resistors of calculable a.c./d.c. resistance ratio", *Proc.IEE*, Vol.110, No.2, pp.335-347, February 1963