A SIMPLE METHOD FOR THE ACCURATE MEASUREMENT OF SMALL ATTENUATIONS*

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(Received June 14, 1973)

I. Introduction

The fast development of telecommunication creates the necessity of the more and more precise measurements of four-pole parameters. In the National Office of Measures of Hungary (OMH) the attenuation measurement was previously restricted to d.c. measurements. At present, the Soviet made measuring sets type Dl-1 and Dl-2 permit precise measurements of attenuation from 100 kHz to 16 GHz. The operation of these sets in based on the parallel intermediate frequency substitution method [1]. The dynamic range of the instruments is approximately 70 dB.

The main defect of this method derives from the fact that essentially a single channel system being, it is very sensitive to amplitude and frequency instabilities of the signal generator and the local oscillator. Taking all sources of error into consideration, the estimated total error of these attenuation measuring sets is 0,02 to 0,03 dB/10 dB.

In case of larger attenuations this accuracy is acceptable but below 10 or 20 dB it is by far not satisfactory. The very high requirements of accuracy in measurements of small attenuations imposed to the OMH to elaborate a new attenuation measuring set.

II. Principle of operation and design outlines

Thus the purpose was to select a method to measure attenuation below 10 to 20 dB with an accuracy better than 0.01 dB.

In view of our financial and technical possibilities, an improved version of the audio modulation substitution method was chosen. The simplified flow chart of the system is shown in Fig. 1. The modulated R. F. power of the signal generator is divided into test and reference channels. The test channel includes

* Abridged text of the Doctor Techn. thesis of the author, agreed of the Faculty of Electrical Engineering Technical University, Budapest in May 1973.

a variable attenuator, the unknown attenuator between isolating and matching elements and the barretter demodulator. In the reference channel the barretter demodulator is in the first place. The A.M. modulated R.F. power develops an A.F. voltage across the barretter. This voltage passes through the audio standard attenuator and the audio phase shifter. The signals of the two channels are combined on a transformer and their difference is amplified and observed on a zero indicator.

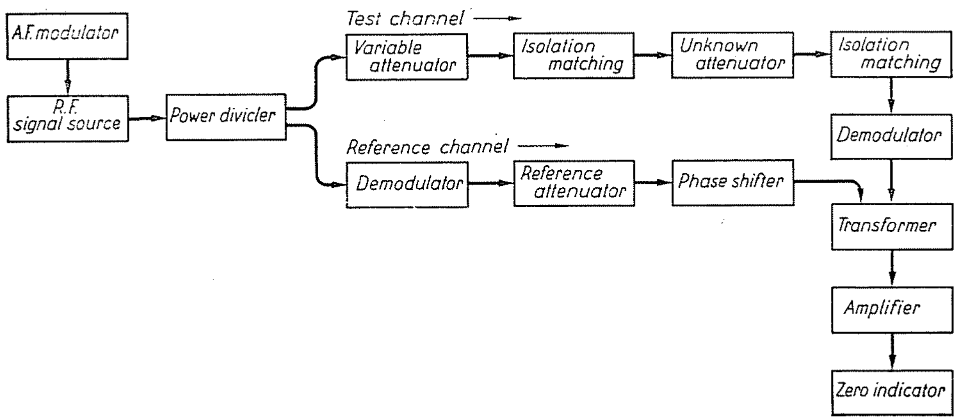

Fig. 1. Double channel audio modulation substitution system for attenuation measurement

The output balance can be achieved by equalising the test and reference signals for magnitude and phase. After the insertion of the unknown attenuator into the test channel the restitution of balance requires the insertion of attenuation at the audio standard into the reference channel in dB twice the unknown because of the square law characteristics of the barretter. The method is practically independent of frequency. It can be applied from some hundred kHz up to the microwave range.

Modulator, generator

One of the main advantages of the version shown in Fig. 1 of this method is the dual channel system moderating the requirements for signal generator and modulator. As the frequency of modulation, 1000 Hz was conveniently selected because of the relative sensitivity versus frequency plot of the barretter demodulator and the frequency response of the audio standard attenuator. At radio frequency and in the microwave range the sinusoidal and the square wave modulation was used, respectively.

Isolation and matching

Their role is to improve the matching conditions and to eliminate the interaction between the elements of the circuitry. To a mismatch error smaller than ± 0.001 dB a fairly good detector and generator matching VSWR < 1.02 are needed at the insertion point depending on the input and output VSWR of the attenuator to be measured.

Variable attenuator

It controls the R.F. power on the barretter in the test channel.

Demodulator

Both the test and the reference channel have a detector, required to recover modulation from the carrier. Because of its larger dynamic range and more stable characteristic, barretter demodulator is used instead of a crystal one. Fig. 2 shows the diagram of the 10 MHz—500 MHz wide band barretter demodulator. Up to 3 GHz, coaxial demodulators were prepared with conical impedance transformer. For measurements in waveguide system demodulators of X-band are at disposal.

Audio frequency standard attenuator

Because of its extraordinary accuracy, excellent stability and convenient impedance matching, the inductive ratio transformer is the best choice for that purpose.

Phase shifter

After demodulation, some phase difference may occur between the A. F. signals of the two channels depending on the individual barretters and the components of the demodulator circuit. Because of the symmetrical arrangement this phase difference is small and it can be balanced by a simple R..C phase-shifter.

Bridge-transformer

The A.F. signals of the test and of the reference channels are combined on the bridge transformer. The bridge transformer must have a good electrostatic shield so that its leakage current does not load the ratio transformer of non-zero output impedance likely to result in reduction of ratio accuracy. Even in case of double shielded transformer it was necessary to raise the potential of the internal shielding to that of the transformer primary winding for the elimination of the leakage current.

Amplifier and zero indicator

In order to achive a very deep zero a high gain (sensitivity $< 0.1\ \mu V$), narrow band and low noise indicator is necessary.

Phase sensitive detector

Completing the system shown in Fig. 1 with a phase sensitive detector the indication of signals below noise level provides for the extension of dynamic range by about 10 dB. The reference signal of the phase sensitive detector is given by the A.F. modulator. In this case a change of 3 to 4 nV on the ratio transformer (corresponding to 3 to $4 \cdot 10^{-5}$ dB change in attenuation at 0 dB level) can be detected. But such an increase in sensitivity is not reasonable as the short time stability of this simple system is of 10^{-4} dB order [4].

III. Error analysis

Let us consider the possible sources of error characteristic of the A.M. substitution method.

Standard attenuator errors

In this comparative measurement the accuracy of the inductive ratio transformer used as an attenuation standard directly affects the results. This kind of error in case of the given system can be written by [4]

$$\Delta d = 4{,}35 \frac{\alpha_1 - \alpha_2}{\alpha_1 \alpha_2} \Delta\alpha \ (dB) \tag{1}$$

where

$\alpha_1 \alpha_2$ — ratios on the transformer before and after the insertion of the unknown attenuator, respectively,

$\Delta\alpha$ — accuracy of the transformer.

Thus using a commercially available inductive ratio transformer with an accuracy $1 : 10^7$, the error due to the inaccuracy of the attenuation standard is less than 10^{-4} dB up to 20 to 30 dB, one of the main advantages of this method.

Errors due to demodulator and the pertaining circuitry

Deviation from square law for barretters

The resistance of a barretter as a function of the power dissipated on it is given by the equation [3]:

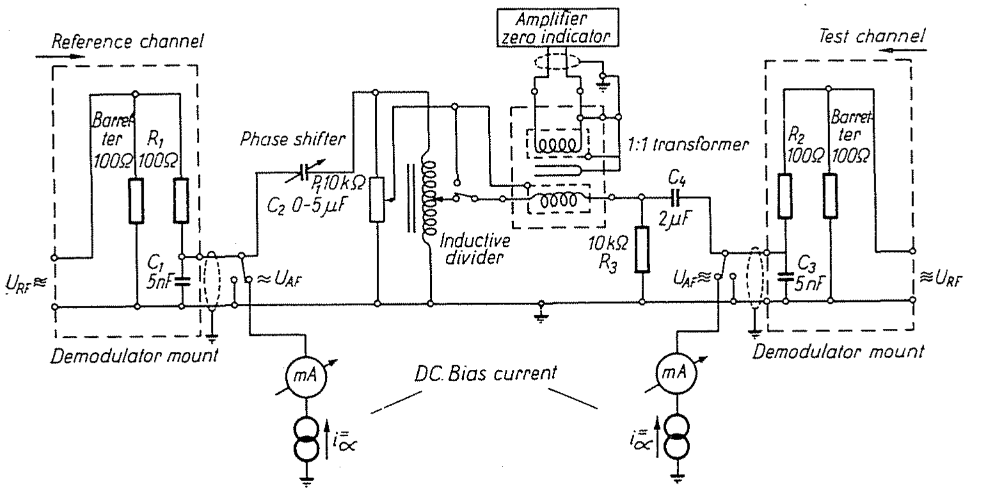

Fig. 2. Diagram of AF. circuitry of audio substitution attenuation measuring set with R.F. barretter demodulators

$$R = R_c + J \cdot P^n \tag{2}$$

where

- R — barretter resistance
- R_c — barretter cold resistance
- J — barretter sensitivity
- n — approximately 0.9 for the usual barretters.

If $n = 1$, the barretter would be a perfect square law detector. In this case the ratio of A.F. output voltages on the output of the demodulator would equal the ratio of R.F. powers on the input of the demodulator. But in the commercially available barretters $n < 1$ therefore an error Δ_l will appear as a function of ratio of R.F. power to D.C. bias power [3].

$$\Delta_l = 2{,}17\,(n-1)\,\frac{P_{RF}}{P_{DC}}\left(\frac{R_0}{R_c}\right)^2 \tag{3}$$

where

- P_{RF} — maximum R.F. power on the barretter
- P_{DC} — D.C. bias power on the barretter
- R_0 — barretter resistance at the operation point.

The square law error can also be determined by measuring the attenuation (e.g. 10 dB) on different R.F. power levels. Fig. 3 shows the comparison of calculated and measured errors. The lines indicate if the nonlinearity error is kept at 0.001 dB order, the R.F. power level on the test barretter cannot exceed 0.1 mW.

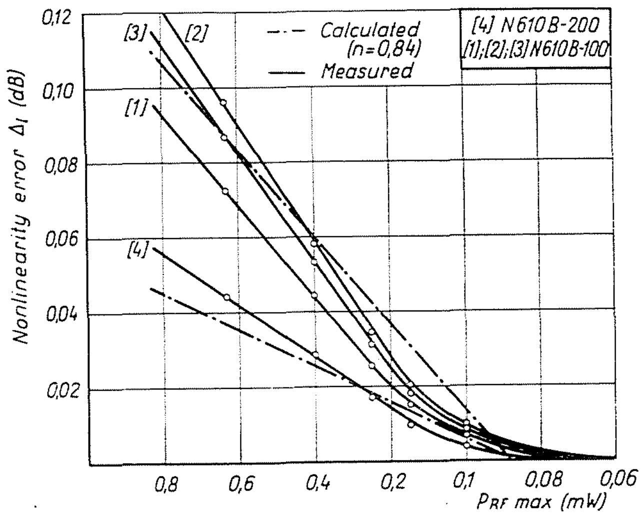

Fig. 3. Comparison of calculated and measured nonlinearity error for barretters

Voltage transfer error

If the input impedance of the following stage is not much higher than the output impedance on the barretter detector Δ_{tr}, the voltage transfer error appears as the detector represents a generator with changing output impedance. This error expressed in dB is [4]:

$$\Delta_{tr} = 4{,}35\,\frac{J(P_{RF_1} - P_{RF_2})}{(1 - I_0^2 J)(R_i + R_0)}\ (dB) \tag{4}$$

where

P_{RF_1}, P_{RF_2} — maximum R.F. power on the barretter before and after the insertion of the unknown attenuator, respectively
I_0 — D.C. bias current through the barretter
R_i — input resistance of the stage following the barretter detector.

If $P_{RF} < 0.1$ mW then in case of usual barretters $\Delta_{tr} < 10^{-4}$ dB.

Errors due to temperature variation

The variation of environmental temperature affects first of all the barretter demodulators. The change in demodulator output voltage level due to differing resistance versus temperature dependences of the reference and test barretters has a statistical character. The spectrum of voltage change is concentrated to the vicinity of some Hz because of the high thermal time constant of barretter mounts and connectors. Thus at modulation frequency in laboratory conditions this source of error is responsible for less than 10^{-4} dB [4].

Errors due to phase shifter

Generally there is small amount of audio frequency phase shift [$\Delta\varphi < 1°$] in the system. If after the insertion of the unknown attenuator a change in phase is necessary to rebalance the audio bridge, then the additional change of amplitude caused by the phase shifter appears as an error in the measurement. The error due to the R.C. phase shifter is easy to calculate and in practice it is by far less than 10^{-3} dB [4].

Errors due to signal source instability

One of the main advantages of the given double channel method is that the instability of the signal source can be neglected in the first approximation. Examining the phenomenon more precisely it is obvious that the change in generator output level results in a small change of barretter operation point. Since the resistance power characteristics of the barretters applied in the reference and test channels are not perfectly identical, the instability of the generator output level does affect the accuracy of the measurement even if secondarily. In knowledge of the barretter sensitivity versus power level function — it can be determined from the R—P characteristics — the error limit due to the instability of the signal source level can be expressed in the following form: [4]

$$\delta g = 4{,}35 \frac{1}{1 - JI_0^2} \left(\frac{\Delta J_1}{J} - \frac{\Delta J_2}{J} \right) (dB) \tag{5}$$

where

$\frac{\Delta J_1}{J}, \frac{\Delta J_2}{J}$ — relative change of sensitivity in case of given level instabilities of the test and reference barretters, respectively.

In case of usual catalog data of barretters and of a power source instability of ± 0.01 dB, (a fairly low requirement) eq. (5) yields $\delta_g = \pm 3 \cdot 10^{-3}$ dB.

These calculations can be controlled by measurements and the results have shown close agreement.

Errors due to instability of D.C. bias current

The operation of the barretter demodulator is based on the principle of getting A.F. signal across the barretter of changing resistance according to the modulated R.F. power if a constant D.C. bias current passes through it. It is evident therefore that a change in bias current results in changing A.F. output signal of the demodulator. The error due to instability of bias current is given by the following equation [4]:

$$\delta_a \cong 4{,}35 \sqrt{2} \frac{1 + I_0^2 J}{1 - I_0^2 J} \frac{\Delta I_0}{I_0} (dB) \tag{6}$$

where

$\frac{\Delta I_0}{I_0}$ the relative stability of D.C. bias current.

The factor $\sqrt{2}$ appears in formula (6) because of the statistical summation of the not correlated random errors of the two channels.

If $\frac{\Delta I_0}{I_0} = 3 \cdot 10^{-5}$ in case of usual barretter and operation point

$$\delta \leqslant \pm 3 \cdot 10^{-4} \text{ dB}$$

Errors due to loss repeatability of connectors and switches

This measuring technique suits to determine a variation in insertion loss as small as about 0.001 dB when connecting and disconnecting attenuators or switching-over and back variable attenuators. Since literature on insertion loss reproducibility [6] is restricted to microwave frequency range, great many measurements were performed on some coaxial connectors and a switch to see insertion loss reproducibility.

Table I

Reproducibility of insertion loss measurements

Connector type	Standard deviation (dB)	
	σ	$\sigma_{corrected}$
GR 874	$0.89 \cdot 10^{-3}$	$0.53 \cdot 10^{-3}$
N-type stainless steel	$2 \cdot 10^{-3}$	$0.7 \cdot 10^{-3}$
Dezifix B	10^{-3}	$0.9 \cdot 10^{-3}$
Rohde-Schwarz coaxial switch	$0.27 \cdot 10^{-3}$	$0.16 \cdot 10^{-3}$

The second column in Table I contains effect of inherent instability of time of the measuring system, too. In the corrected standard deviation of the third column, the system instability is eliminated by means of the method of least squares therefore these results are exclusively characteristic of the connector or switch to be tested.

Errors due to noise and parasitic signals

In the measuring system there are several noise sources: the thermal noise of resistors (Johnson effect), barretter current noise (Schottky effect) and the detector noise. Since the dynamic range of measurement is limited by noise on the low signal side, it is useful to apply a phase locked system to achieve a sensitivity of 10 nV order.

The parasitic signal passing round the unknown attenuator through earth loops or by electro-magnetic radiation results in erroneous indication of the detector. The undesirable effects can be limited by using suitable shielding, noise suppressor, battery operated detectors and appropriate spacing between the exposed units of the system.

Since mismatch errors are the same for the audio substitution system as for any attenuation measuring system, they will not be covered here [7].

Summarizing the above mentioned errors of random and systematic character, according to the theory of probability the estimated total error limits of the dual channel A.F. substitution method can be determined [4].

IV. Measurement results

Control measurements were made on a Rodhe Schwarz variable 50 ohm coaxial attenuator type DPR up to 30 dB at 30 MHz (Table II). The measurements at 20 and 30 dB were performed with an increased RF level, therefore a correction had to be made because of the nonlinearity error of barretter.

Table II

The attenuation of a Rodhe Schwarz variable attenuator at 30 MHz measured by A. F. substitution system

Nominal value) (dB)	Mean of 10 measurements $\bar{x}$ (dB)	Corrected mean value $\bar{x}_c$ (dB)	Standard deviation σ (dB)	Maximum deviation from the mean $\lvert x-x_i \rvert_{max}$ (dB)
1	0.9977		$0.62 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
2	1.9993		$0.88 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
6	6.0074		$1.53 \cdot 10^{-4}$	$3.2 \cdot 10^{-4}$
8	8.0023		$1.51 \cdot 10^{-4}$	$1.9 \cdot 10^{-4}$
10	9.9782		$1.76 \cdot 10^{-4}$	$3.2 \cdot 10^{-4}$
20	19.9435	19.9585	$2.36 \cdot 10^{-4}$	$4.4 \cdot 10^{-4}$
30	29.9243	29.9393	$2.69 \cdot 10^{-4}$	$3.9 \cdot 10^{-4}$

Table II demonstrates the high resolution and reproducibility of the measuring system. Both are of 10^{-4} dB order. Naturally, when calculating the total error limit of the measurements beyond $\frac{3\sigma}{\sqrt{n}}$ which is characteristic to the random error of the mean of set of measurements (n being the number of measurements) also the systematic error has to be taken into consideration.

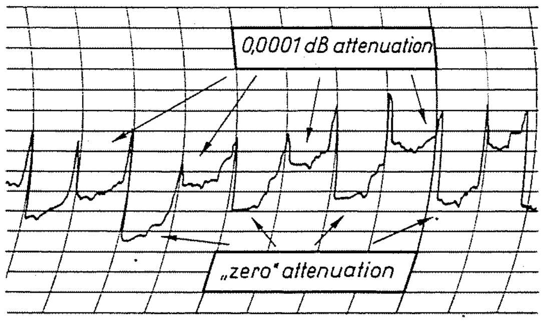

Fig. 4. Resolution of the A.F. substitution system for attenuation measurement

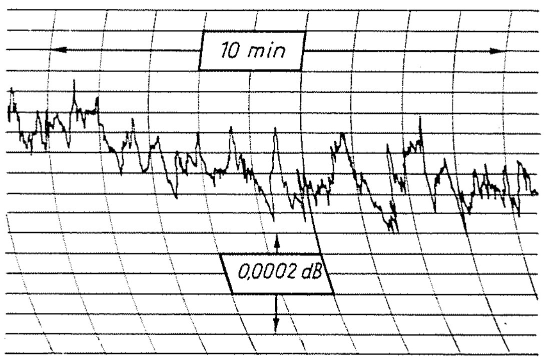

Fig. 5. Short-time stability of the A.F. substitution system for attenuation measurement

(When measuring small attenuations, the only systematic error to be considered is actually the mismatch error.)

In 1971—72 the OMH participated at the international intercomparison of attenuators at 30 MHz and 9 GHz, organized by the Bureau International des Poids et Mesures. The measurements of attenuators under 20 dB were performed by the audio substitution system. Although the organizatory committee took the decision not to permit publication of the results before the accomplishment of the whole measuring cycle, it can be stated in advance that the results of the OMH are in good agreement with the international average represented by well-known institutions using much more sophisticated measuring systems. The deviation of 0.001 dB order in case of 3 dB measurements and less than 0.01 dB up to 20 dB can be attributed first of all to the poor matching conditions.

The resolution and short time stability of the measuring system are shown in Figs 4 and 5, respectively. Both are apxroximately 10^{-4} dB.

V. Conclusions

In case of the audio frequency substitution method, the measurement of attenuation is converted from signal frequency to audio frequency by demodulating the A.M. modulated carrier. Thus the unknown attenuation can be compared against a high precision inductive ratio transformer used as an A.F. reference attenuator. Therefore in the range of R.F.-power level where the A.M. demodulation is linear — this is easily fulfilled in case of measuring small attenuations — a very high accuracy can be achieved. The dual channel version of the method involves moderate requirements for the signal source stability and the zero-indication system especially with phase sensitive detector has a very high resolution.

According to the results of the control measurements and of the error analysis, this simple attenuation measuring system built at the National Office of Measures of Hungary and based on the modified version A.F. substitution method, has an accuracy — depending on the actual circumstances — as follows:

Attenuation (dB)	Uncertainty (dB)
1	$\pm 5—10.10^{-4}$
10	$\pm 2— 5.10^{-3}$
20	$\pm 0.5—1.5 \cdot 10^{-2}$

Acknowledgements

The author is indebted to Mr. H. SZOKOL, head, his deputy Mr. B. PERÉNYI and Mr A. TÖRÖK, senior member of staff Division of Electrical Measurements of OMH, Hungary for their valuable assistance in the design work of the attenuation measuring system and in drawing the conclusions in this paper.

Summary

The paper presents the design of a simple system, measuring attenuation with accuracies from 0.0005 to 0.01 dB over a range of 0.01 to 30 dB from 10 MHz to 10 GHz. The resolution and the stability are of 0.0001 dB order. The system is based on the improved version of the method known as the audio modulation substitution method [2]. The error analysis describes the main sources of error of the method and gives a theoretical estimation for the expected limits of error. Some characteristic results of control and comparison measurements are introduced as well.

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