A NEW METHOD FOR EARTH-POTENTIAL BALANCING OF A. C. BRIDGES

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1. Introduction

A. C. bridges may be classified into two main groups as regards the selection of their earthed point: there are bridges with one of their junctions earthed, and others with their earthed point selected outside the bridge proper.

With respect to the circuit setup and handling it is generally more convenient to have a junction of the bridge available for earthing, but the applicability of this circuit arrangement is restricted by several factors. The impedances of bridges earthed at one of their junctions are enclosed in a single or multiple shielding system connected to suitable points of the bridge. Such shields tend to increase the stray capacitances (a part of these being those termed internal stray impedances) coupled parallel to the bridge arms. This increase of stray capacitances encumbers, or even frustrates the internal compensation of the bridge. Another difficulty is caused by the stray capacitances generally of varying magnitudes introduced by the impedance to be measured, and these stray capacitances are to be compensated separately, which is often very cumbersome, if not entirely unfeasible. Thus, in the case of more exacting measurements, it would be desirable to have also the impedance to be measured enclosed in a special shielding, but this method is in most cases impracticable. All these factors impose serious limitations to the applicability of the system, with respect to accuracy and frequency range. — At higher frequencies, this earthing system is mainly adopted for bridges where a single component determining the characteristic feature of the impedance concerned is to be measured (such as the inductance of a coil).

Devoid of the deficiences of the former earthing system are the bridges with none of their junctions directly earthed. The earthed point is selected outside the bridge (and the shields — if any — enclosing the bridge elements are connected to this external point). With respect to the stray impedances, the adoption of such an external earthed point means that the stray impedances may be divided in two qualitatively different groups with a view to their effect and to how they lend themselves to be compensated. The internal stray impedances coupled parallel to the bridge arms continue to be present, but beside these, the so-called external stray impedances between the elements of the measuring network and the external earthed point also appear. As compared to the bridges earthed at one of their junctions, there is an essential difference, namely the shields connected to the external earthed point do not increase the internal stray impedances, their magnitudes being determined only by the elements of the bridge arms, thus their compensation may generally be achievable up to a much higher frequency limit than in the former case. Another essential difference results from the fact that the stray capacitances of varying magnitudes introduced by the impedance to be measured are coupled with the external stray impedances instead of the bridge arms. This is the reason why a separate shielding of the impedance to be measured may in most cases be dispensed with. Bridges of this type are generally more complicated, because special measures are to be taken for neutralizing the external stray impedances. Nevertheless, their application is still justified, because they are suitable for covering a substantially wider frequency range and for obtaining a higher degree of accuracy. In more exacting types of measuring apparatus this method of earthing is usually adopted, permitting the measurement of both components of the impedance to be measured within a wide frequency range and with an accuracy required. In the paper a new method for neutralizing the external stray impedances will be presented. The method has been developed by the Department for Instruments and Measuring Techniques of the Budapest Technical University.

2. Error introduced by external stray impedances

For analyzing the error due to the external stray impedances a general relation has been deduced. Based on this relation, let us examine first the known methods used for neutralizing the effect of external stray impedances and, then, the circuit arrangement newly developed.

In Fig. 1 the connection diagram of a general a. c. bridge is represented, where $\mathbf{Z}_1 \ldots \mathbf{Z}_4$ are the arm impedances, with $\mathbf{Z}_1$ being the impedance to be measured. The external stray impedances $\mathbf{Z}_a, \ldots \mathbf{Z}_d$ coupled across each junction of the bridge and the external earthed point F are also indicated. Since the neutralization of external stray impedances can only be conceivable up to a certain frequency limit and in cases where these impedances may be reduced to the junctions of the bridge, only such cases will be dealt with in our investigations.

The error due to the external stray impedances has been dealt with by means of a method presented in a paper published earlier [6], introducing the concept of complex error vector. Denoting the complex error vector by $\mathbf{h}$, then, by substituting the impedance to be measured $\mathbf{Z}_1$ by $\mathbf{Z}_1 \cdot (1 - \mathbf{h})$, and setting up the required number of equations for the network and by solving these equations for $\mathbf{h}$, the complex error vector characterizing the error made in the measurement of $\mathbf{Z}_1$ is obtained as follows:

$$\mathbf{h} = \frac{1}{\mathbf{Z}_1} \frac{\left(\frac{\mathbf{Z}_1}{\mathbf{Z}_a} - \frac{\mathbf{Z}_2}{\mathbf{Z}_c}\right) \cdot \left(\frac{\mathbf{Z}_4}{\mathbf{Z}_d} - \frac{\mathbf{Z}_1}{\mathbf{Z}_b}\right)}{\frac{1}{\mathbf{Z}_a} + \frac{1}{\mathbf{Z}_b} + \frac{1}{\mathbf{Z}_c} + \frac{1}{\mathbf{Z}_d}} \tag{1}$$

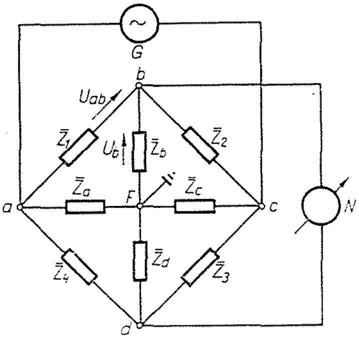

Fig. 1

As demonstrated in our paper referred to above, with the knowledge of complex error vector $\mathbf{h}$, the errors in the real and imaginary parts of impedance $\mathbf{Z}_1$ can easily be determined. Let the relative error of the real part of the impedance be h_{Re} and the imaginary part of the same be h_{Im}, then, with φ_Z denoting the phase angle of the impedance to be measured the errors will be

$$h_{Re} = Re\,[\mathbf{h}] - Im\,[\mathbf{h}] \cdot \operatorname{tg} \varphi_z$$
$$h_{Im} = Re\,[\mathbf{h}] + Im\,[\mathbf{h}] \cdot \frac{1}{\operatorname{tg} \varphi_z} \tag{2}$$

According to Eq. (1), the error caused by the external stray impedances may become zero, if either of the following two equations are satisfied:

$$\frac{\mathbf{Z}_b}{\mathbf{Z}_d} = \frac{\mathbf{Z}_1}{\mathbf{Z}_4} \text{ or } \frac{\mathbf{Z}_a}{\mathbf{Z}_c} = \frac{\mathbf{Z}_1}{\mathbf{Z}_2} \tag{3}$$

Thus, the error introduced by the effect of stray impedances can be eliminated by making the ratio of the stray impedances coupled with either opposite pair of junctions equal to the ratio of the arm impedances connected to the same junctions. The equation also shows that the error becomes zero also in the case, if the value of any pair of the external stray impedances becomes infinite:

$$\mathbf{Z}_b = \mathbf{Z}_d\ \infty, \text{ or } \mathbf{Z}_a = \mathbf{Z}_c\ \infty .$$

If the external stray impedances are pure capacitances, the satisfaction of either equation (3) is only be conceivable, if either $\mathbf{Z}_1/\mathbf{Z}_4$ or $\mathbf{Z}_1/\mathbf{Z}_2$ impedance ratio is real. Even in that case, there is very little probability of spontaneous satisfaction of any of these conditions, therefore some artificial means are generally required for neutralizing the effect of external stray impedances.

Supposing that all external stray impedances are loss-free capacitances, the error given by Eq. (1) will be:

$$h = \frac{1}{\mathbf{Z}_1} j\omega \frac{(C_a\mathbf{Z}_1 - C_c\mathbf{Z}_2)\ (C_d\mathbf{Z}_4 - C_b\mathbf{Z}_1)}{C_a + C_b + C_c + C_d}$$

It can be seen from the equation that the error increases proportionally with frequency even if the arms are pure resistances. If the arms are complex impedances, terms increasing with the frequency according to exponents higher than unity may appear. As verified by measurements performed on various bridges, the external stray capacitances may give rise to considerable errors even in the lower frequency ranges.

The error introduced by the effect of external stray impedances can be given in a form more suitable for general investigations, if expressing the error in terms of the ratio of the voltage difference between a detector-side bridge junction point (e.g. junction b) and earthed point F (e.g. voltage $\mathbf{U}_b$) to the voltage ($\mathbf{U}_{ab}$ in our case) measured across the impedance to be determined. Substituting voltages $\mathbf{U}_b$ and $\mathbf{U}_{ab}$ with orientations as indicated in Fig. 1, from the respective equations applied to the bridge assumed to be balanced, the complex error vector $\mathbf{h}$ can again be expressed as

$$\mathbf{h} = \frac{\mathbf{U}_b}{\mathbf{U}_{ab}} \cdot \left(\frac{\mathbf{Z}_4}{\mathbf{Z}_d} - \frac{\mathbf{Z}_1}{\mathbf{Z}_b}\right) \tag{4}$$

According to this expression, one possible way of eliminating the error caused by the external stray impedances is identical to the condition obtained from Eq. (3), while the other way is to zero voltage $\mathbf{U}_b$. Thus, by means of some method, the potential difference between the junctions connected to the detector and the external earthed point are to be eliminated from the balanced bridge, i.e. the junction points have to be brought to earth potential. This principle is termed "earth-potential balancing".

3. Valuation of known earth-potential balancing circuits

The circuit setups serving for the neutralization of external stray impedances can be divided in two groups: the task may be solved by means of a network containing passive components only and also by such including active components as well. A short survey of the methods known are given in the followings:

I. *Earth-potential balancing circuits containing passive components only.*

The principle followed in setting up the measuring circuit is to add to the bridge a network connected at one suitable point to the external earthed point and by means of its variable impedances this added network is to permit the accomplishment of earth-potential balancing.

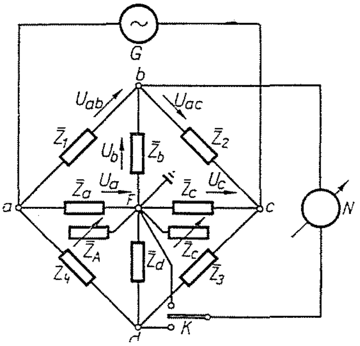

Fig. 2

The generally-known, classical method is the auxiliary-bridge earthing device proposed by WAGNER [1, 2]. As shown in Fig. 2, the bridge is completed with variable impedances $\mathbf{Z}_A$ and $\mathbf{Z}_C$, which are connected parallel to impedances $\mathbf{Z}_a$ and $\mathbf{Z}_c$, respectively. If, by properly adjusting the impedances of the auxiliary bridge, according to the second equation of (3), it can be achieved that the ratio of $\mathbf{Z}_A \times \mathbf{Z}_a$ to $\mathbf{Z}_C \times \mathbf{Z}_c$ be equal to the ratio of bridge impedances $\mathbf{Z}_1/\mathbf{Z}_2$, and the error due to the external stray impedances will become zero. This, of course, is identical also with the condition obtained from Eq. (4), since in this case, the auxiliary bridge extended with the external stray parameters constitutes a similarly balanced bridge with the arms of the balanced main bridge, where the voltage of the detector-side junctions with respect to earth (e.g. $\mathbf{U}_b$) is zero. This also offers the possibility for the proper adjustment of impedances $\mathbf{Z}_A$ and $\mathbf{Z}_C$, the method followed with this auxiliary bridge setup being performed in such a way that detector N is first to be connected to the bridge (to junction d on the figure) by means of switch K and, then after balancing the bridge, the detector is switched over to the earthed point F, the auxiliary bridge is also balanced by varying the elements of the latter. The measurement is considered completed, if the main bridge and auxiliary bridge are jointly balanced.

The Wagner earthing device can be generalized using the notations in Fig. 2. Let impedances $\mathbf{Z}_a \times \mathbf{Z}_A$ and $\mathbf{Z}_c \times \mathbf{Z}_C$ be considered as parts of the power source. Thus, the earth-potential balancing network eliminating the effect of external stray impedances may be regarded as a setting up for the supply of the bridge in a composite power source, one internal point of which is earthed and by which fractional voltages $\mathbf{U}_a$ and $\mathbf{U}_c$ with respect to this earthed point are supplied. If it can be achieved that the fractional voltages of this composite power source be equal to the voltages appearing across the bridge arms, i.e.

$$\mathbf{U}_a = \mathbf{U}_{ab}, \quad \text{and} \quad \mathbf{U}_c = \mathbf{U}_{bc}$$

then $\mathbf{U}_b = 0$, and according to Eq. (4) no error will be introduced by the external stray impedances.

Several circuit arrangements can be set up with passive components which are suitable for satisfying the conditions given above. The parallel elements of a Wagner earthing device may be replaced by series elements, and a number of combinations of these circuit connections may also be devised. Dispensing with a detailed description of these setups, reference is made to the literature [2], noting that in some cases these combined circuits prove more useful than the original Wagner earthing device itself.

The earth-potential balancing circuits containing passive components alone have several disadvantages.

a) The impedances of the auxiliary network can often be realized only up to a certain frequency limit, because of the stray impedances. (If, e.g., an auxiliary bridge arm is to be made resistive, the parallel coupled stray capacitances may be compensated by means of an inductance. In such a case, the frequency limit of the inductance itself constitutes the factor that will impose a limit to the accomplishment of the auxiliary bridge.) It often occurs, when using such an auxiliary bridge setup, that the latter will determine the frequency limit, even if the main bridge itself were suitable for being used at higher frequencies.

b) An inevitable feature of auxiliary-bridge devices is the mutual reaction prevailing between the balancing of the auxiliary bridge and main bridge, therefore the state of total balance, i.e. a simultaneous balanced condition of the main and auxiliary bridges, can only be achieved through several steps by means of an iteration method. This feature renders the measurements extremely lengthy.

II. *Earth-potential balancing circuits containing active elements*

The known methods may be classified into two groups: networks operating with a balancing voltage independent of the measuring system, and those relying upon an automatically produced auxiliary voltage.

A) *Circuits operating with a balancing voltage independent of the measuring system.* According to the generalization outlined in the foregoing section, for neutralizing the effect of external stray impedances a composite power source is required, which would produce fractional voltages $\mathbf{U}_a - \mathbf{U}_c$ (using the notations in Fig. 3) with respect to the fixed earthed point F, where these fractional voltages equal the voltages appearing across the bridge arms be-

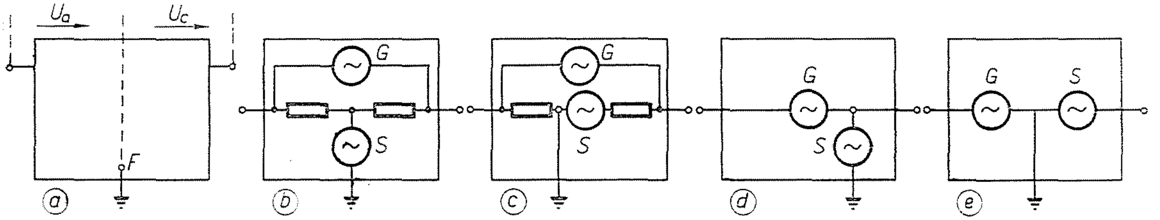

Fig. 3

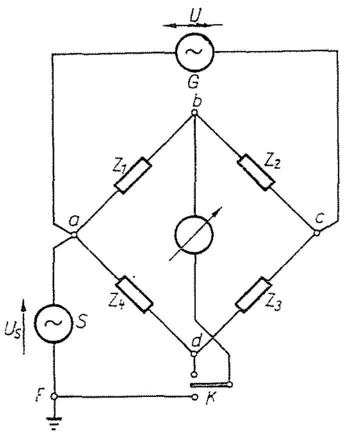

Fig. 4

tween the junctions. The task can be solved by applying an auxiliary power source S (see Fig. 3) supplying a voltage of a frequency identical to that of generator G and of externally variable amplitude and phase angle [3].

Some possible ways of inserting the auxiliary power source are shown in Fig. 3. According to Fig. 3.*b* and 3.*c*, the auxiliary power source may be connected to a suitably selected junction of a compensating network (e.g a Wagner bridge) built up of passive elements. This compensating network composed of passive elements may generally be omitted, and in such a case, the auxiliary power source S may be inserted between a supply point of the bridge and the external earthed point, while generator G, according to Fig. 3.*d*, may either supply the bridge as shown in the original connection or, as indicated in Fig. 3.*e*, it may be connected in series to the auxiliary power source.

In Fig. 4, a connection corresponding to Fig. 3.*d* is presented as an example, where the auxiliary power source is connected to junction a of the bridge. For the sake of perspicuity, the external stray impedances are not shown in the figure. The measurement can be performed with this network in a way similar to that with the Wagner bridge. Connecting switch K, first, to junction d, the bridge can be balanced, then switching over to point F the earth potential may be balanced by adjusting the auxiliary power source.

Inspecting the circuit on the basis of Eq. (4), the quotient of voltages $\mathbf{U}_b$ and $\mathbf{U}_{ab}$ can be expressed in terms of voltage $\mathbf{U}$ of generator G, using the orientations indicated in Fig. 4. After making some reasonable neglections and substituting the voltage quotient into Eq. (4), the complex error vector will be

$$\mathbf{h} = \frac{1}{\mathbf{Z}_1} \cdot \left[\mathbf{Z}_1 - \frac{\mathbf{U}_s}{\mathbf{U}}(\mathbf{Z}_1 + \mathbf{Z}_2)\right] \cdot \left(\frac{\mathbf{Z}_4}{\mathbf{Z}_d} - \frac{\mathbf{Z}_1}{\mathbf{Z}_b}\right) . \tag{5}$$

It is expedient to transform the expression in such a way as to determine first the voltage $\mathbf{U}_{so}$ required for zeroing the error, then, assuming that this voltage can be adjusted only with an error δ, the actual auxiliary voltage will be $\mathbf{U}_S = \mathbf{U}_{so}(1 + \delta)$. Substituting this value into Eq. (5) and performing the reductions, the following relation is obtained:

$$\mathbf{h} = -\delta \left(\frac{\mathbf{Z}_4}{\mathbf{Z}_d} - \frac{\mathbf{Z}_1}{\mathbf{Z}_b}\right) . \tag{6}$$

From this relation, the permissible inaccuracy in the adjustment of the auxiliary power source can be calculated for a given case.

Characteristic features of circuit setups operating with a balancing voltage independent of the measuring system are:

a) The drawback of obtaining the balance only after several iteration steps still remains. The adjustment is "rigid", the changes made in the course of balancing the bridge modify the potential conditions as well, and after each modification a new balancing is to be performed with the auxiliary power source. Neither can this difficulty be avoided by making the voltage of the auxiliary power source vary together with the generator voltage (e.g. by supplying the auxiliary power source from a coil arranged on the supply transformer).

b) In order to reduce the error to an acceptable value, such a high degree of fineness in the adjustment is required, which can only be accomplished with a multi-position, delicate voltage divider. This renders the setup complicated (a multi-position divider free of phase displacement is generally difficult to accomplish), and its handling becomes cumbersome. The difficulties outlined above account for the rare use of this circuit arrangement, confined exclusively to the low frequency range (mainly to 50 c/s).

B) *Circuits operating with an automatically produced balancing voltage.* As power source, an amplifier of $-A$ amplification may be used, with its input terminal connected to a detector-side junction and its output inserted

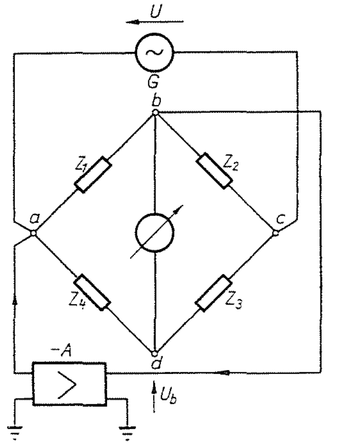

Fig. 5

across the external earthed point and a suitably selected junction of the measuring system, in variants similar to those given for the auxiliary power source indicated in Fig. 3. This arrangement has been proposed first by MAYO. In his setup the amplifier is connected to a Wagner earthing device (similar to the circuit in Fig. 3*b*). Only one practical solution of the proposed system is known from literature, from a paper of KO-HARA and TOSHINO [5]. In their circuit the auxiliary bridge has been omitted, and the output of the amplifier is connected to one of the supply-side junctions of the bridge (as in variants 3*d* or 3*e*).

In the connection of Fig. 5 selected as an example, the amplifier output is connected to junction *a* and its input to the detector-side junction *b*. For the sake of perspicuity, the external stray impedances have been omitted from the drawing.

In this connection diagram, the error due to the effect of external stray impedances have been investigated in a similar way as before. If $\mathbf{U}_b$ is the input voltage of the amplifier, so the voltage appearing at its output will be $(-\mathbf{A} \cdot \mathbf{U}_b)$. With this assumption, and by writing the required number of equations for the network, the voltage quotient $\mathbf{U}_b/\mathbf{U}_{ab}$ can again be expressed. Substituting this quotient into Eq. (4), and making some permissible neglections, the complex error will be

$$\mathbf{h} = \frac{1}{1+\mathbf{A}} \cdot \left(\frac{\mathbf{Z}_4}{\mathbf{Z}_d} - \frac{\mathbf{Z}_1}{\mathbf{Z}_b}\right). \qquad (7)$$

With a sufficiently high degree of amplification the error may be kept within the required limit. The detector-side junctions of the balanced bridge are kept close to earth potential with any setting of the bridge, without requiring any outside intervention. Balancing the system is restricted to balancing the bridge, whereby the measuring time is considerably reduced.

A serious drawback of this system lies in the limitations of its applicability. Since a proportional control is used, some magnitude of residual voltage will inevitably remain ($\mathbf{U}_b \neq 0$). For a given residual voltage, the measuring error will rapidly grow with increasing frequency. Although this error may be reduced by increasing the amplification, this remedy is restricted by stability problems, since the bridge is a feedback network of the amplifier. In practice, two possible compromises may be conceived. To reduce the error to a required low value, the amplification may be increased, but in this case a stable operation can only be expected if the limit frequency is low. The other possibility is to adapt a relatively reduced amplification in order to have a higher limit frequency, but in this case concessions must be made on the magnitude of the measuring error. Beside the stability problems, it can be proved that in the effect exerted by the complex error on the real and imaginary parts of the impedance to be measured a decisive role is played by the phase shift of the amplifier, which imposes increased requirements on the design of the amplifier.

4. The new earth-potential balancing circuit

The essence of the new setup neutralizing the external, stray impedances of a. c. bridges is an active earth-potential balancing circuit jointly containing an amplifier and auxiliary power source, suitably connected to give an output voltage being a linear combination of the amplifier input voltage and the voltage adjusted on the auxiliary power source. As it will be demonstrated in the followings, the joint use of an amplifier and an auxiliary power source offers advantages beyond simple adding-up of their separate favourable featurés, as compared to the known passive and active earth-potential balancing circuits.

An obvious way of connecting an amplifier and an auxiliary power source is shown in Fig. 6, where the auxiliary power source is connected to a second input terminal b_2 of the amplifier. Input terminal b_1 of the amplifier may be connected in the usual way to one of the detector-side junctions of the bridge, and its output terminal k to a suitably selected junction of the measuring network. A few possible variants of making the connections between the control circuit thus arranged and the generator supplying the bridge are shown in Fig. 3.

For the sake of simple comparison with the setups of Figs 4 and 5, in the example shown in Fig. 7, the insertion of the control circuit is again similar to that in Fig. 3*d*. Correspondingly, the amplifier output is connected across

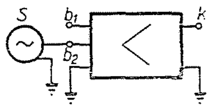

Fig. 6

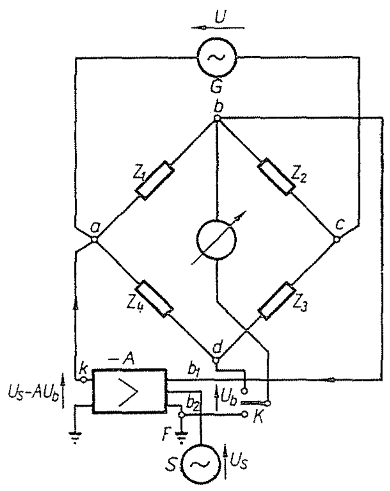

Fig. 7

the external earth and bridge junction a, amplifier input terminal b_1 is connected to bridge junction b, and its input terminal b_2 to auxiliary power source S supplying a frequency equal to that of the generator and provided with means for controlling externally its amplitude and phase angle. Handling of the equipment arranged in this way is similar either to that provided with an auxiliary bridge or to that represented in Fig. 4 containing an auxiliary power source alone. After balancing the bridge and connecting the null detector by means of switch K across a bridge junction (in this case, point b) and earthed point F, the earth potential is balanced by manually controlling the auxiliary power source.

Let the effectiveness of the circuit be investigated again by analyzing the complex error vector. For the sake of simplicity, let the amplification referred to input b_2 be $+1$, thus the voltage appearing at the amplifier output and defining the earth potential of the bridge will be $\mathbf{U}_s - \mathbf{A}\mathbf{U}_b$. With similar considerations as before, if $\mathbf{Z}_1$ is the impedance to be measured in the bridge, then the complex error vector characterizing the error due to the effect of external stray impedances will be:

$$\mathbf{h} = \frac{1}{\mathbf{Z}_1} \cdot \frac{\mathbf{Z}_1 - \frac{\mathbf{U}_S}{\mathbf{U}} (\mathbf{Z}_1 + \mathbf{Z}_2)}{1 + \mathbf{A}} \left(\frac{\mathbf{Z}_4}{\mathbf{Z}_d} - \frac{\mathbf{Z}_1}{\mathbf{Z}_b} \right) \tag{8}$$

This expression is transformed again to obtain voltage $\mathbf{U}_{so}$ required for zeroing the error, then, assuming that this voltage can only be adjusted with an error δ, the value $\mathbf{U}_s = \mathbf{U}_{so}(1 + \delta)$ is substituted into Eq. (8). After suitable reductions, the error will be as follows:

$$\mathbf{h} = -\frac{\delta}{1 + \mathbf{A}} \left(\frac{\mathbf{Z}_4}{\mathbf{Z}_d} - \frac{\mathbf{Z}_1}{\mathbf{Z}_b} \right) \tag{9}$$

From an analysis of this expression it can be seen that the error due to the effect of external stray parameters may be reduced to any desired low value. The advantage as compared to the circuits operating with auxiliary power sources lies in the much less stringent requirement to be raised in respect to the auxiliary power source, the inaccuracy δ of adjustment of the auxiliary voltage appearing with a magnitude reduced in a proportion of $\frac{1}{1 + \mathbf{A}}$ in the relationship describing the error. With a given acceptable measuring error and when an amplification of e.g. $\mathbf{A} = 100$ is accomplished, the accuracy of adjustment required for the auxiliary power source will be by 2 orders of magnitude lower. The functioning of the setup can be interpreted in such a way that, even if an incorrect value is adjusted on the auxiliary power source, the error voltage $\mathbf{U}_b$ fixed by a misadjustment will be reduced in the proportion of $\frac{1}{1 + \mathbf{A}}$. As compared to a setup using an amplifier only, it can be stated that in our case the residual voltage is determined practically by the sensitivity threshold of the detector. Since the residual voltage is usually much lower than that with setups using amplifier only, the error will also be considerably smaller.

As compared to the known circuit arrangements, the new earth-potential balancing method represents a progress, on the one hand, in extending the upper frequency limit and, on the other hand, in the convenience of handling and cutting the measuring time. In the followings the results obtained will be summarized according to these two aspects.

A. Extension of the upper frequency limit:

a) The circuit setup removes the limitations imposed by the difficulties of implementing connections built up of passive components.

b) As opposed to setups using auxiliary power source only, a simple and easily obtainable auxiliary power source may be adopted for the bridge circuit proposed.

c) As compared to the automatic earth-potential balancing circuits operating with amplifier only, where amplification directly affects the error, a qualitative difference is offered by the setup proposed, where the amplification has no direct influence on the error, and it practically facilitates handling. Undoubtedly, an increase of amplification has its advantages also in the proposed setup, yet the requirements are much less exacting than in the case of circuits using amplifier alone. Even a 100-fold amplification will ensure a very convenient operation of the bridge. By means of a compensated amplifier a stable operation can be achieved, giving an upper frequency limit of about two orders of magnitude higher than that obtainable with setups known so far.

d) In contrast to all known bridge circuits the setup jointly incorporating an amplifier and an auxiliary power source eliminates the effect of restricting the upper frequency limit associated with the use of circuits used for neutralizing the influence of external stray impedances. The upper frequency limit of the entire equipment is practically determined by the properties of the bridge used.

B. Convenience of handling, cutting the measuring time:

a) The new setup eliminates the drawback of obtaining total balance through several iteration steps, as in the case of the passive (auxiliary-bridge) methods. The inserted amplifier reduces any voltage appearing across the earth and detector-side junction $\frac{1}{1+A}$ to-th part of its original value. This has the consequence that with the first balancing of the bridge — when the voltage of the auxiliary power source may still considerably deviate from the value pertaining to the totally balanced condition — the measurement will be less wrong than if the auxiliary power source were only included in the circuit, because the detector-side junction will always be kept close to earth potential. After balancing the bridge, performing the earth-potential balancing by means of controlling the voltage of the auxiliary power source, and switching over to the bridge again, generally a minor correction will be required. It is attributable to the stabilizing effect of the amplifier that in the majority of cases the total balancing process is confined to the three steps shown, even in the vicinity of the upper frequency limit.

b) The convergence of auxiliary bridge setups, depending on the impedances used, is often very poor. This means that the balancing of the auxiliary bridge alone, for two components, requires several steps, protracting thereby the time of measurement. In contrast to this feature, the auxiliary power source may be designed so as to permit the required voltage to be combined of two components displaced by 90° with respect to each other. With respect to convergence, this procedure is considered as optimum, manifesting itself in an easy and quick performance of earth-potential balancing.

The joint result of the two effects is the convenience and reduced time requirement in the handling of equipments provided with the new earth-potential balancing circuit, as compared to other auxiliary-bridge setups. A measurement by means of the new arrangement requires practically no longer time than that performed with shielded bridges, where only the bridge is to be balanced. The favourable features of the new setup become especially conspicuous in series measurements of impedances having similar parameters, where any minor deviations are compensated by the amplifier to such an extent that any readjustment of the auxiliary power source from time to time may entirely be dispensed with.

The earth-potential balancing network may be connected to the bridge in several different ways, the most characteristic ones being those shown in Fig. 3, where the auxiliary power source should now be understood as being replaced by the amplifier output. By analyzing the properties of these circuits, it can be stated that the auxiliary-bridge setups are generally unfavourable, the circuits presented in Fig. 3*d* and 3*e* being those of practical importance, where the balancing circuit is directly connected across the earthed point and a supply-side junction of the bridge. The characteristic features of the latter two circuits are briefly summarized in the followings. In the circuit shown in Fig. 3*d*, the supply generator is directly connected to the bridge, therefore its output is independent of the earth, i.e. it is symmetrical. With devices operating at higher frequencies this feature is unfavourable, because usually a symmetrizing supply transformer has to be used. This, in turn, has the drawback of the appearance of increased external stray capacitances of the bridge, in consequence of the inevitable use of shields. By adopting double shielding, stray capacitances may be displaced and concentrated to a less sensitive point of the bridge, but this has again an unwanted effect of increasing the self-capacitance of the transformer, decreasing in turn the limit frequency. In the case of bridges having a wider frequency range, this problem can often be solved at great difficulties when a single transformer is used. In such cases the frequency range is divided into narrower bands and several tapped transformers are to be used. Such a circuit is not only complicated, but several problems associated with shielding and other difficulties are to be coped with. With respect to the earth-potential balancing network, however, this circuit is more favourable, because its current is exclusively determined by the currents flowing through the external stray impedances. This current is usually much lower than that flowing in the bridge arms.

In the connection represented in Fig. 3*e*, one output terminal of the supply generator is connected to earth, i.e. the bridge is asymmetrically supplied by the generator. The main advantage of this circuit arrangement lies in the elimination of the isolating transformer, the generator can directly be connected to the bridge and, thus, the characteristics of the supply transformer have no effect on the applicability of the bridge. With respect to the extension

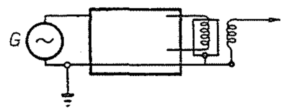

Fig. 8

of the frequency range, this circuit setup offers the additional advantage of having the output capacitances of the generator connected parallel with the generator.

The circuit brings about a favourable situation with respect to the joint earthing of the generator and detector. The detector of the bridge is usually isolated by means of a transformer provided with an earthed shield, the secondary winding of the transformer lending itself to be connected to an electronic instrument having one of its input terminals earthed. With respect to the supply and detector, such a circuit may be regarded as a four-terminal network represented in Fig. 8. Here, one point of the generator is earthed and in balanced condition the detector-side junctions of the bridge are at earth potential. The primary winding being at earth potential is enclosed in an earthed shield, and one point of the secondary winding, i.e. one terminal of the detector, is also earthed. By means of this connection setup, considering the results achieved, the same advantages could be gained as with the use of tripole bridges (such as bridged-T networks or parallel-T networks), the generator and detector having a common earthed point. While, however, the tripole bridges have the serious drawback of being frequency dependent and fail to offer the possibility of direct evaluation, there are some variants among the Wheatstone-type bridges which are suitable for solving various measuring problems and the balancing of which are frequency-independent, providing the possibility of direct evaluation for at least one of the components. A still greater difficulty is encountered in tripole bridges, where the compensation of stray impedances introduced by the various elements is very cumbersome or hardly possible, because of the frequency-dependence of the bridge. In suitably selected circuit arrangements, on the other hand, the internal stray impedances of the Wheatstone-type bridges lend themselves to be compensated very favourably and often independently of the frequency.

The applicability of asymmetrically supplied circuits may be subject to a restriction imposed by the fact that the balancing network — i.e. the output of the amplifier — is required to supply a current practically equal to that of the supply power source.

Summary

For neutralizing the external stray impedances of a.c. bridges provided with an external earthing point the method of earth-potential balancing may be used. The application of the new earth-potential balancing method is justified by the numerous drawbacks of known methods using passive and active elements. The new method permits considerable extension of the upper limit of measuring frequency and highly simplifies to handle the measuring setup.

References

1. WAGNER, K. W.: Zur Messung dielektrischer Verluste mit der Wechselstrombrücke. ETZ. 1911., No. 32., p. 1001, 1912., No. 33.
2. WOLF, H. H.: Wagner-earth and other null instrument capacity neutralizing circuits. Rev. Sci. Instrum. **12**, 1116 (1959).
3. BERGER, B.: A modified earthing device, I. Sci. Instrum. **5**, 184 (1956).
4. BUCKINGHAM—PRICE: Principles of electrical measurements, New York 1957.
5. HARA, K.—TOSHINO, T.: Self-balancing earthing device for precise bridge. Bull. Electrotechn. Lab., **5**, 1 (1963).
6. TÓTH, E.: Computation method for determining the errors of A. C. bridges. Mérés és Automatika **5**, 135 (1966).

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