

# Bridges Supplied by Two Current Sources – New Tool for Impedance Measurements and Signal Conditioning

**Zygmunt L. WARSZA**  
**Institute of Automation and Transportation Telematics**  
**Technical University of Radom**  
**29, Malczewskiego str.**  
**26-600 Radom, Poland**

## ABSTRACT

A new type of measuring circuitry is presented. It is an impedance bridge un conventionally supplied by two current sources connected in parallel to opposite arms of the bridge. This circuit has two independent balance states, when voltage on each output – bridge diagonals – equals zero. If two current sources are ideal and identical, the equality of impedance products of neighboring arms of the output diagonal are the balance conditions. These two relations are different from the one of the classic Wheatstone bridge. The author proposes to call this new type of circuits as: **double current bridge**.

Formulas for currents, voltages and powers of the bridge arms in balance conditions are given. Sensitivities of such circuits and their optimization have been discussed. The method of measurements when current sources are not identical is also proposed. Expressions for output voltages of unbalanced circuit are given. The possibility of simultaneous measurement of two variables by a pair of sensors and measurements of increments of every sensor without disconnecting the bridge are also presented. Some conclusions and directions of future developments in this area are also included.

## 1. INTRODUCTION

Input circuits of the actual autonomic immitance measurement instruments and system transmitters are still mainly analogue one. It is due to two main reasons: first - they directly measure the changes of immitances or indirectly other variables by immitance sensors, second – still it is easier to realize some signal conditioning functions in analogue circuits, such as obtaining output signal from changes of parameters of several sensors.

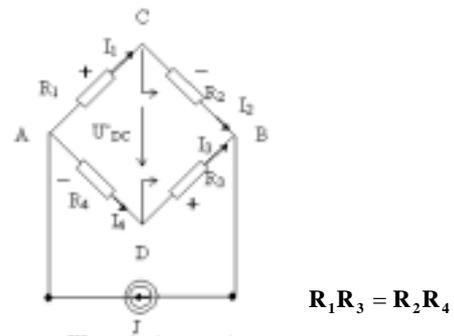
For a couple of last decades many of new input circuits have been developed. They use various differential operational amplifiers [3,4,10], single [10] and double [3,5] stabilized supply sources, many methods of switching (e.g. various integration or successive balancing converters) and supplying of input analogue circuits and AD converter from common source – ratio measurements [3,10]. Classic unbalanced bridges are still very frequently used because of their simplicity and many advantages. They work mainly with the near open circuit voltage output, very rare with current output and deliver measurement signals to high input impedance amplifying circuits.

Many years ago author discovered the idea of the bridge circuit with different then conventional balance conditions [1], but the possibilities of their successful use in practice arising just recently. Because of that author in the few publications [6-9,11] developed the background theory of this circuits and gave some examples of their potential applications, up to now mainly of DC supply. Such knowledge is important for designing these circuits and for programming digital circuits connected with them. Some of the new developments, mainly about optimisation of the initial sensitivity of those bridges are described below.

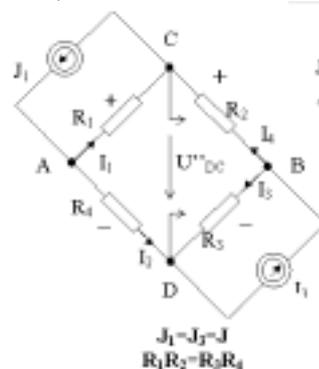
## 2. PRINCIPLES OF OPERATION

On the Fig. 1 resistance bridges circuits differently supplied from current sources are given.

a)



b)



c)

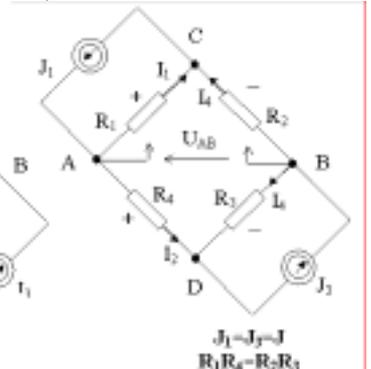


Fig. 1. Resistance measuring circuits with different current supply and their balance conditions:  
 a) – Wheatstone bridge with current supply; b) and c) – bridge circuits supplied from two current sources.

Circuit a) is the classic Wheatstone bridge, but with current supply; circuits b) and c) are supplied unconventionally by two current sources  $J_1$  and  $J_3$  connected parallelly to the opposite arms. These circuits are named below as double current bridges.

The output open circuit voltage of the circuit a) is given by the equation [2]:

$$U'_{DC} = \frac{J(R_1R_3 - R_2R_4)}{\sum R_i}$$

where:  $\sum R_i = R_1 + R_2 + R_3 + R_4$  (1)

If  $U'_{DC} = 0$ , commonly known balance condition is:

$$R_1R_3 = R_2R_4 \quad (1a)$$

The output voltages of the circuits b) and c) are given by such equations:

$$U''_{DC} = J_1 \frac{(R_1R_2 - R_3R_4)}{\sum R_i} - \frac{\Delta J(R_1 + R_4)R_3}{\sum R_i} \quad (2)$$

$$U_{AB} = J_1 \frac{(R_1R_4 - R_2R_3)}{\sum R_i} - \frac{\Delta J(R_1 + R_2)R_3}{\sum R_i} \quad (3)$$

where:  $\Delta J = J_1 - J_3$

Their balance conditions (when  $U''_{DC} = 0$  or  $U_{AB} = 0$ ) depend on current  $J$ .

When the supply sources are equal i.e.  $J_3 = J_1$  and  $\Delta J = 0$ , equations (2) and (3) are simplified to:

$$U''_{DC} = \frac{J(R_1R_2 - R_3R_4)}{\sum R_i} \quad (4)$$

$$U_{AB} = \frac{J(R_1R_4 - R_2R_3)}{\sum R_i} \quad (5)$$

and balance conditions are now as follow:

$$R_1R_2 = R_3R_4 \quad (4a)$$

$$R_1R_4 = R_2R_3 \quad (5a)$$

**Hence, double bridges with equal supply sources are in balance when pairs of the impedance products of the neighbouring arms of the output bridge diagonal (CD or AB) are equal.**

These last formulas completed with condition (1a) set of possible equality of such products of four impedances.

Just recently author developed the new method of measurement using circuit b) or c) with the different supply sources. Output voltages should be measure twice with exchange of sources. In both obtained voltages second components are of the same values, but with opposite sign. Mean value of these two voltages is proportional to the mean value of the source currents as follow:

$$U''_{DC} \acute{s}r = \frac{J_1 + J_3}{2} \frac{(R_1R_2 - R_3R_4)}{\sum R_i} \quad (6)$$

$$U_{AB} \acute{s}r = \frac{J_1 + J_3}{2} \frac{(R_1R_4 - R_2R_3)}{\sum R_i} \quad (7)$$

Even possible is to switch only one current source  $J$ , and in this case sum of these two voltages is proportional to  $J$  and to second component of the equation (6) or (7).

Equations (4) and (5), (6) and (7) of the double current bridges have the similar form to the equation (1) of clas-

sic current bridges, but in these formulas impedances are taking other places dependently of the type of bridge supply.

Let us consider bridges with variable resistances of all arms. Analysis of the metrological characteristics of the circuits from Fig. 1 should be easier if resistances are related to one of them e.g.  $R_{10}$ , and changes of them – to their resistance values in circuit balanced stage. Then:

$$R_i \equiv R_{i0} + \Delta R_i \equiv R_{i0}(1 + \varepsilon_i) \equiv r_{i0} R_{10}(1 + \varepsilon_i) \quad (8)$$

where:  $R_{i0}$  – initial (in balance) value of the  $R_i$  resistance;  $\Delta R_i$ ,  $\varepsilon_i$  – it's absolute and relative increments;  $r_{i0}$  – relative value of resistances in balance conditions.

If the resistances  $R_{10}$ ,  $R_{20}$ ,  $R_{40}$  have the same values in circuits a), b) and c) their  $R_{30}$  resistances of balance are as follow:

$$R'_{30} = r_{20}r_{40}R_{10}; \quad R''_{30} = \frac{r_{20}}{r_{40}}R_{10}; \quad R'''_{30} = \frac{r_{40}}{r_{20}}R_{10}; \quad (9)$$

In general case these resistances are different. Circuits b) and c) are only both in balance when  $r_{20} = r_{40}$  (every one of them is in balance on both diagonals), circuits a) and b) – if  $R_{20} = 1$  and a) and c) if  $R_{40} = 1$ . All three circuits are in balance when  $r_{20} = r_{30} = r_{40} = 1$ , e.g. all balance resistances  $R_{i0}$  are the same.

With the notations given by formulas (8) and after transformation of equation (1), (4) and (5) is possible to obtain:

$$U'_{DC} = J R_{10} \frac{r_{20}r_{40}}{\sum r'_{i0}} \cdot \frac{(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4 + \varepsilon_1\varepsilon_3 - \varepsilon_2\varepsilon_4)}{1 + \frac{\sum r'_{i0}\varepsilon_i}{\sum r'_{i0}}} \equiv T'_0 \cdot f'(\varepsilon_i) \quad (10)$$

$$U''_{DC} = J R_{10} \frac{r_{20}r_{40}}{\sum r''_{i0}} \cdot \frac{(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 + \varepsilon_1\varepsilon_2 - \varepsilon_3\varepsilon_4)}{1 + \frac{\sum r''_{i0}\varepsilon_i}{\sum r''_{i0}}} \equiv T''_0 \cdot f''(\varepsilon_i) \quad (11)$$

$$U_{AB} = J R_{10} \frac{r_{20}r_{40}}{\sum r'''_{i0}} \cdot \frac{(\varepsilon_1 - \varepsilon_2 - \varepsilon_3 + \varepsilon_4 + \varepsilon_1\varepsilon_4 - \varepsilon_2\varepsilon_3)}{1 + \frac{\sum r'''_{i0}\varepsilon_i}{\sum r'''_{i0}}} \equiv T'''_0 \cdot f'''(\varepsilon_i) \quad (12)$$

where:  $T'_0, T''_0, T'''_0$  – initial voltages sensitivities of circuits a), b) and c);

$f'(\varepsilon_i), f''(\varepsilon_i), f'''(\varepsilon_i)$  – their unbalance functions.

Even with the same values of  $r_{20}, r_{40}$ , in three above circuits' denominators of their sensitivities and in unbalance functions are in general case different, because  $r_{30}$  are different according formulas (9).

Currents, voltages and powers of the circuit arms depend of values of all resistances  $R_{i0}$ , and of their relative changes  $\varepsilon_i$ , but in unbalanced classic current bridge – circuit a) always  $I_1 = I_2$  and  $I_3 = I_4$ , when output is not loaded. In unbalanced double current bridges with equal sources  $J_1 = J_3$  currents of the opposite arms are always equal:  $I_1 = I_3$  and  $I_2 = I_4$ . From eq. (10)-(12) it is also obvious, that output voltages in different manner depend from signs of resistance increments. Examples of signs, of these increments changing output in the same direction are given in Fig. 1. If absolute values of these increments are the same, the output voltages are proportional to the number of variable arms (e.g. multiplied by 2 or by 4).

Different conditions of linearity of unbalance functions are briefly discussed in [11]. To the similarity of the form of the equation (10) to (12) it is possible to adopt the accuracy analysis of the classic bridges (e.g. from [5]) for double current bridges accuracy analysis.

### 3. INITIAL VOLTAGE SENSITIVITIES

Let us consider in details relationships between the initial sensitivities and circuit parameters with taking care of limitations existing in practice. For the simplicity in the writing of the equations we put  $r_{20} \equiv m, r_{40} \equiv n$ .

#### 3.1. Sensitivity of the classic current bridge

Initial voltage sensitivity of the bridge classically supplied by current source is:

$$T_0' = JR_{10} \frac{mn}{(I+m)(I+n)} = JR_{10} \left( I + \frac{1}{m} \right)^{-1} \left( I + \frac{1}{n} \right)^{-1} \quad (13)$$

##### Case 1°: $JR_{10} = const.$

Sensitivity  $T_0'$  is the family of hyperbolic functions increasing with  $n$  and  $m$ . When  $n = const.$  they asymptotically increase with  $m \rightarrow \infty$  up to  $T_0' \rightarrow JR_{10} m / (I+m)$ . If  $m = const.$ , they are rising to  $T_0' \rightarrow JR_{10} n / (I+n)$  if  $n \rightarrow \infty$ . Max value for  $n \rightarrow \infty$  and  $m \rightarrow \infty$  is:

$$T_0'_{MAX} = JR_{10} \quad (13a)$$

For maximum sensitivity values of  $n$  and  $m$  should be as large as possible, but they are limited by permissible powers of the bridge arms and by the maximum input voltage and by output bridge resistance.

In the circuit balance stage relations of arm powers are:

$$P_{10} = \left( \frac{n}{I+n} \right)^2 J^2 R_{10} \quad (14)$$

and:  $P_{20} = mP_{10} \quad P_{30} = \frac{m}{n} P_{10} \quad P_{40} = \frac{1}{n} P_{10} \quad (14a)$

**In all conventional bridges** it is possible to formulate general relation: **in the balance stage the maximum power is dissipated in the arm in being in series with the arm of lowest resistance.** E.g. when  $m > I, n > I$  the highest power is in the arm  $R_2$ . If this power is limited to  $P_{20MAX}$  then from (14) and (14a) we have:

$$m_{1max} \leq \left( \frac{n+I}{n} \right)^2 \frac{P_{20MAX}}{I^2 R_{10}} \quad (14b)$$

The maximum values of  $m$  and  $n$  are also limited by given maximum input resistance  $R_{AB} \equiv r_{AB} R_{10}$  and of output resistance  $R_{CD} \equiv r_{10} R_{10}$ , as follows:

$$m_{2max} \leq (r_{AB} - 1) r_{CD} / (r_{CD} - 1) \quad (14c)$$

$$n_{max} \leq (r_{CD} - 1) r_{AB} / (r_{AB} - 1) \quad (14d)$$

The lowest value of  $m_{1max}, m_{2max}$  should be taken.

For example when  $r_{CD} = 10, r_{AB} = 5$  it is:  $m_{2max} = 4,44$ ;

$n_{max} = 1,25$ ;  $m_{1max} \leq 1,19 P_{20MAX} / J^2 R_{10}$ ; and

$T_0' \approx 0,88 JR_{10}$ , (near  $T_0'_{MAX}$ ).

When bridge is symmetric one in respect to diagonal CD: ( $m=I$ ) then:  $n_{max} \leq 2r_{CD} - I$  or

$$n_{max} \leq r_{AB} / (2 - r_{AB}) \text{ if } r_{AB} \leq 2.$$

With all identical resistances  $m=n=I$  should by:

$$P_{i0MAX} \geq \frac{1}{4} J^2 R_{10}, \text{ and sensitivity } T_0' = (1/4) JR_{10}.$$

##### Case 2°: $P_{10} = const., R_{10} = const.$

If maximum power of the first arm  $P_{10MAX}$  and resistance  $R_{CD}$  is given, and source current is find from (14), sensitivity is:

$$T_0' = \frac{m}{I+m} \sqrt{P_{10} R_{10}} \quad (15)$$

where:  $\sqrt{P_{10} R_{10}} = U_{10}$  – voltage of arm  $R_{10}$  in balance

Sensitivity  $T_0'$  is raising like before with  $m$  according homographic function, but is independent from value  $n$ . If  $m \rightarrow \infty, T_0' \rightarrow U_{10}$ . According to (14a) power  $P_{20}$  is proportional to  $m$  and when  $P_{10}$  is equal to  $P_{10MAX}$  (due to adjusting of current  $J$ ) value of  $m$  is limited by  $P_{20MAX}$ , which should be as high as possible. If both these powers are equal sensitivity is  $T_0' = 0,5 \sqrt{P_{10} R_{10}} = U_{10}$ . It does not depend from  $n$ . Level of resistances of lower bridge arms has two limitations. If  $m > I$  lower limit is:

$$n_{1min} > \frac{P_{10MAX}}{m P_{30MAX}} \text{ or } n_{2min} > \frac{P_{10MAX}}{P_{40MAX}}.$$

Higher limit of  $n$  results from permissible input or output bridge resistance like before. Source current  $J$  should be set to value limited by permissible arm powers  $P_{i0MAX}$ .

In this case 2° – it is possible to obtain higher sensitivity  $T_0'$  then with the case 1° when  $J = const.$  and maximum resistance  $R_{AC}$  are too small to rich limited power even in anyone of the bridge arm.

#### 3.2. Sensitivity of circuit b).

Initial sensitivity of double current bridge given on Fig. 1b) is:

$$T_0'' = JR_{10} \frac{mn}{(m+n)(I+n)} \quad (16)$$

##### Case 1°: $JR_{10} = const.$

When  $n = const.$ , initial sensitivity  $T_0''$  is the hyperbolic function of  $m$ . If  $m \rightarrow \infty$ , it is:  $T_0'' \rightarrow JR_{10} n / (I+n)$ . Because of that  $n$  should be as high as possible. When  $m = const.$  sensitivity  $T_0''$  as the function of  $n$  has a flat maximum – see curves on Fig. 2. for  $m=I$  and  $m=5$ .

Sensitivity  $T_0'' = T_0''_{MAX}$  when  $n_e = \sqrt{m}$ , and it is:

$$T_0''_{MAX} = JR_{10} \frac{m}{(I + \sqrt{m})^2} \quad (16a)$$

This sensitivity is increasing with  $m$  – see curve 1 on Fig. 3.

When  $m=I$   $T_0''_{MAX} = JR_{10}/4$ , and if  $m \rightarrow \infty, T_0''_{MAX} \rightarrow JR_{10}$ . That means that  $m$  should be as high as possible. Values of  $n$  and  $m$  are limited by the same reasons as in circuit a). For example maximum sensitivity  $T_0''$  depends on maximal permissible powers  $P_{i0MAX}$  of the bridge arms.

Power  $P_{10}$  is given as before by the equation (14). Relations between it and others powers are here:

$$P_{20} = \frac{m}{n^2} P_{10}; P_{30} = \frac{m}{n} P_{10}; P_{40} = \frac{1}{n} P_{10} \quad (17)$$

If  $J_1 = J_3$  it is possible to formulate different then before general rule, **in balance conditions of double current bridges the maximum power is dissipated in resis-**

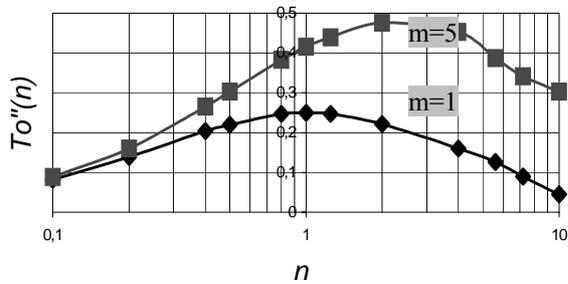


Fig. 2. Initial sensitivity  $T_0''(n)$  of 1b) circuit for  $m=1$ ,  $m=5$ .

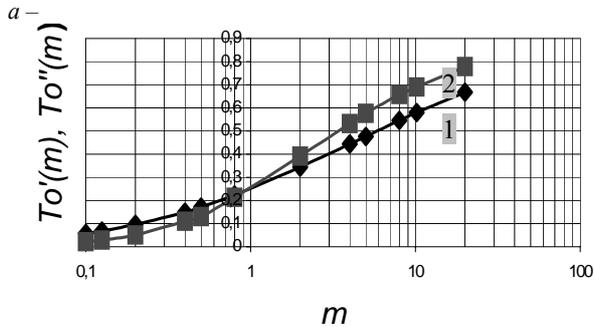


Fig. 3. Maximum initial sensitivity  $T_0''_{MAX}(m)$  of circuit b) when  $n_e=\sqrt{m}$  – curve 1; initial sensitivity  $T_0'(m)$  of circuit a) for  $n=n_e$  – curve 2.

tance in series with the highest one of the paths connecting output terminals of the bridge i.e.  $R_{10}$ ,  $R_{40}$  or  $R_{20}$ ,  $R_{30}$  in the circuit b) and  $R_{10}$ ,  $R_{20}$  or  $R_{30}$ ,  $R_{40}$  in the circuit c). It is so, because opposite arms' currents are equal and voltages of every such path are opposite i.e.  $U_{40} = -U_{10}$ ,  $U_{30} = -U_{20}$  if  $U_{CD}'' = 0$ .

If e.g.  $m > n > 1$ , the most loaded arm is  $R_{30}$ . Limits of  $m$  and  $n$  follow also from permissible voltages of current sources:

$$U_{10}'' = JR_{10}n/(1+n), \text{ or } U_{30}'' = JR_{10}m/(m+n),$$

and from maximum output resistance:

$$R_{CD}'' = R_{10}(1+m)/(n+m)$$

When  $m=n=1$ , sensitivity  $T_0'' = 1/4 JR_{10}$ .

**Case 2°:  $P_{10} R_{10} = const.$**

From equations (14) and (16) it is:

$$T_0'' = \frac{m}{m+n} \sqrt{P_{10}R_{10}} = \frac{1}{1+\frac{n}{m}} \sqrt{P_{10}R_{10}} \quad (18)$$

$$T_{0MAX}'' \rightarrow U_{10} = \sqrt{P_{10}R_{10}} \text{ if } n/m \rightarrow 0, \text{ i.e. when } m \gg n.$$

If power  $P_{10}$  and resistance  $R_{10}$  are given, sensitivity  $T_0''$  is const. when  $m/n = const.$

Source current  $J$  should be set up to such level, for which permissible powers of the bridge arms are not exceeded.

$$\text{If } m = n \text{ sensitivity } T_0'' = 0,5 \sqrt{P_{10}R_{10}} = U_{10}.$$

### 3.3. Sensitivity of circuit c)

Initial voltage sensitivity of double current bridge from Fig. 1c is:

$$T_0''' = JR_{10} \frac{mn}{(m+n)(1+m)} \quad (19)$$

**Case 1°  $JR_{10} = const.$**

When  $m = const.$  sensitivity  $T_0'''$  is increasing also according hyperbolic function of  $n$ ,

If  $n=5$   $m_e=2,24$  and  $T_{0MAX}''' = 0,48 JR_{10}$

If  $n \rightarrow \infty$ ,  $T_0''' \rightarrow JR_{10}m/(1+m)$ .

But when  $n = const.$  sensitivity  $T_0'''$  has the flat extremum

$T_{0MAX}'''$  when  $m_e = \sqrt{n}$  as follow:

$$T_{0MAX}''' = JR_{10} \frac{n}{(1+\sqrt{n})^2} \quad (19a)$$

For example if  $n=1$ , then  $m_e = 1$ , and sensitivity

$T_{0MAX}''' = JR_{10}/4$ . If  $n \rightarrow \infty$  then  $T_{0MAX}''' \rightarrow JR_{10}$ , as before.

Sensitivity  $T_0'''$  of circuit c) is also limited because of restrictions of values of  $m$  and  $n$  resulting of permissible powers of arms, voltages on the current inputs and of output resistance of the bridge. Powers should be found from the following relationships:

$$P_{10} = \left(\frac{n}{1+n}\right)^2 J^2 R_{10} \quad (20)$$

and

$$P_{20} = \frac{1}{m} P_{10}; \quad P_{30} = \frac{n}{m} P_{10}; \quad P_{40} = \frac{n}{m^2} P_{10} \quad (20a)$$

From above relations, if  $m > n > 1$ , the most loaded is  $R_{10}$ . Limitations resulting from sources' permissible voltages are possible to find from formulas;  $U_{10}''' = JR_{10}m/(1+m)$ , or  $U_{30}''' = JR_{10}n/(m+n)$ , and limitations resulting from output resistance – from:  $r_{AB}''' = n(1+m)/(n+m)$ .

**Case 2°:  $P_{10} R_{10} = const.$**

From the equation (20) it is possible to obtain:

$$T_0''' = \frac{n}{m+n} \sqrt{P_{10}R_{10}} = \left(1 + \frac{m}{n}\right)^{-1} U_{10} \quad (21)$$

Sensitivity:  $T_{0MAX}''' \rightarrow U_{10} = \sqrt{P_{10}R_{10}}$  when  $m/n \rightarrow 0$ , that means for  $n \gg m$ .

If  $(m/n) = const.$  sensitivity  $T_0'''$  is also constant.

Limitations of  $m$  and  $n$  are similar like before.

It is worth to notice that double current bridges with  $m=n$  have the same sensitivities of both diagonals.

$$T_0'' = T_0''' = JR_{10} \frac{m}{2(1+m)} \text{ or } T_0'' = T_0''' = \frac{1}{2} \sqrt{P_{10}R_{10}}.$$

Sensitivity  $T_0'$  of the classic current bridge when also

$$m=n \text{ is } T_0' = JR_{10} \frac{m^2}{(1+m)^2} \text{ or } T_0' = \frac{m}{1+m} \sqrt{P_{10}R_{10}}$$

Its means that in both cases:  $JR_{10} = const.$  or  $P_{10}R_{10} = const.$  it is  $T_0' < T_0'' = T_0'''$  if  $m < 1$ .

Pairs of sensitivities of bridges a), b) and c) are related each to other as follows for circuits:

- b) and a)  $T_0'' > T_0'$  if  $m < 1$  –, see curves on Fig. 3;
- c) and a)  $T_0''' > T_0'$  if  $n < 1$
- b) and c)  $T_0'' > T_0'''$  when  $m > n$ . Circuit b) is dissipating slightly higher power then circuit a) when it is more sensitive.

Formulas of current signal outputs of the bridges and also relationships for arms described by conductivity are given in extensive survey paper [11].

#### 4. MEASUREMENT OF TWO VARIABLES

Very frequently in practice the arms' resistances of the bridge depend differently on two variables  $x_1, x_2$ . In such situation the output signals on AB and CD diagonals of the double current bridge are two different functions of above variables. Because of that they could be applied to two parameters simultaneous measurements [7-8,11]. If variable are only two resistances of such bridge, for example as follow:

$$\begin{aligned} \varepsilon_1(x_1, x_2) &= \varepsilon'_1(x_1) + \varepsilon''_1(x_2) \\ \varepsilon_2(x_1, x_2) &= \varepsilon'_2(x_1) - \varepsilon''_2(x_2) \end{aligned} \quad (22)$$

and  $\varepsilon_3 = \varepsilon_4 = 0$  – see Fig. 4a,

furthermore if:

$$\varepsilon'_1(x_1) = \varepsilon'_2(x_1) \equiv \varepsilon' \text{ and } \varepsilon''_1(x_2) = \varepsilon''_2(x_2) \equiv \varepsilon'' \quad (22a)$$

then double current bridge is balanced simultaneously in both diagonals ( $m=n$ ), and its two output signals are as follow:

$$U''_{DC} = JR_{10} \frac{m}{(1+m)} \frac{\varepsilon' + \frac{(\varepsilon')^2 - (\varepsilon'')^2}{2}}{1 + \frac{\varepsilon'}{2} + \frac{\varepsilon''(1-m)}{2(1+m)}} \quad (23)$$

$$U_{AB} = JR_{10} \frac{m}{(1+m)} \frac{\varepsilon''}{1 + \frac{\varepsilon'}{2} + \frac{\varepsilon''(1-m)}{2(1+m)}} \quad (24)$$

Denominators of the above formulas are the same. If  $\varepsilon'$  and  $\varepsilon''$  are not very high, the sum of the last two components of the nominator in equation (23) is negligible. When  $\varepsilon_1 \ll 1, \varepsilon_2 \ll 1$ , these formulas simplified farer up to:

$$U''_{DC} = JR_{10} \frac{m}{1+m} \varepsilon'(x_1) \quad (25)$$

$$U_{AB} = JR_{10} \frac{m}{1+m} \varepsilon''(x_2) \quad (26)$$

Each of the above voltages depends linearly only on one component of the resistance increments, which depends only on one of the influencing variables. If additionally  $\varepsilon'_1(x_1) = k_1 x_1, \varepsilon''_1(x_2) = k_2 x_2$  double current bridge has two voltage signals written in slightly different forms.

$$U''_{CD} = \frac{JR_{10} R_{20}}{\sum R_{i0} + \sum \Delta R_i} 2k_1 x_1 \quad (27)$$

$$U_{AB} = \frac{JR_{10} R_{20}}{\sum R_{i0} + \sum \Delta R_i} 2k_2 x_2 \quad (28)$$

Sensitivities of above two signals are equal and could only slightly depend on:  $x_1, x_2$ , if  $\sum \Delta R_i \neq 0$ .

For higher values of  $\varepsilon', \varepsilon''$  these voltages become their not linear functions, but always their sensitivities are proportional to each other. In such simple method it is possible to realise simultaneous measurement of two variables  $x_1, x_2$  by one or by two pairs of sensors. For higher resistance increments  $0 < |\varepsilon_i| \leq 1$  it is also possible to obtain separately and nearly linear relations of the output voltages of the double bridge, if both components  $\varepsilon'_i(x_1)$  and  $\varepsilon''_i(x_2)$  separately realise linearity conditions.

Such as above futures are not existing in classic bridges. It is also possible to obtain similar relations for circuit a) and only one of circuit b) or c), but in this case supply sources have to be switched like for example in manner described in [10]. With Anderson loop [4] it is possible to obtain two parameters measurements, but only for all similar initial resistances of the sensors. Circuit is also much more complicated, because it includes special double input differential circuit with few operational amplifiers for every one sensor and 7 connection lines.

#### 5. SEPARATE MEASUREMENT OF RESISTANCE INCREMENTS

In some applications separate measurements of resistance increments of the bridge arms are needed. If initial values of all bridge resistances are similar and bridge could be disconnected at least in one terminal, the easiest way in this case is to use the Anderson loop [4], if it is available. But when it is not possible to disconnect the bridge this problem should be solved by other way. It is possible to do it by measurements input resistances between any two terminals of the bridge with others terminals opened or connected shortly by negligibly low resistance. A four arms bridge circuit needs 4 such measurements. In both above cases, non-linear set of equations related to  $\varepsilon_i$  should be solved and it is difficult to obtain good enough accuracy for small increments  $\varepsilon_i$ .

Due to the discovery of double current bridges this problem could be solved in a simpler way. Here also 4 measurements are needed, but different then before. Increments of voltages on both diagonals of the bridge circuits should be measured while they are supplied from current sources by classic method and unconventional one proposed in the begging of this paper. Let us take simple example, when values of initial resistances  $R_{i0}$  are the same, but their increments  $\varepsilon_i$  are different and all possible combinations of products  $\varepsilon_i \varepsilon_j$  ( $i \neq j$ ) are negligible. After the solutions of the set of obtained 4 equations following formulas for all increments are find:

$$\begin{aligned} \varepsilon_1 &= \left( \frac{U_{DC}' + U_{DC}'' + U_{AB} + \delta_{RAB}}{JR_{10}} \right) \frac{1}{1 - \delta_{RAB}} \\ \varepsilon_2 &= \left( \frac{-U_{DC}' + U_{DC}'' - U_{AB} + \delta_{RAB}}{JR_{10}} \right) \frac{1}{1 - \delta_{RAB}} \\ \varepsilon_3 &= \left( \frac{U_{DC}' - U_{DC}'' - U_{AB} + \delta_{RAB}}{JR_{10}} \right) \frac{1}{1 - \delta_{RAB}} \\ \varepsilon_4 &= \left( \frac{-U_{DC}' - U_{DC}'' + U_{AB} + \delta_{RAB}}{JR_{10}} \right) \frac{1}{1 - \delta_{RAB}} \end{aligned} \quad (29)$$

where:  $\delta_{RAB}$  – relative increment of input resistance  $R_{AB}$ . If the increments  $\varepsilon_i$  are small enough or such that  $\delta_{RAB} = 0$  above formulas are simplified to the first fractions in brackets.

By proposed here method it is also possible to measure indirectly at least 4 variables, if any one of them influencing selectively only one arm's resistance or – differently few of them e.g. as described before. This method could be also useful for diagnostics of sensors in the bridge without disconnecting them and for measurements

distribution of fields by few sensors or local distribution of materials parameters.

It is also possible to make another 4 measurements, all

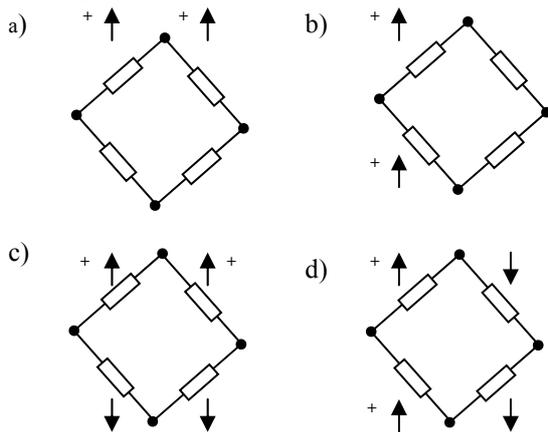


Fig. 4: Examples of resistance changes in four terminal equivalent bridge circuit, measurable if dual current side supply is applied.

only in the double current bridge, without switching sources if they are equal. For that increments of open circuit voltages and short circuit currents should be measured on both outputs. Set of equations obtained here is non-linear too and more difficult to solve.

## 6. GENERAL CONCLUSIONS AND SOME POTENTIAL APPLICATIONS

- Presented above double current supply bridges can successfully used as new type of measuring circuits especially for signal conditioning of immitance sensors. They have balance conditions different in two opposite bridge diagonals, and different then those of classic bridges.
- It is possible to obtain simultaneously two signals differently depended on bridge arms immitance increments from its balance values.
- Equations for the output voltages have the same form like for classic current supply bridge, but immitances of arms take another places in equations according different balance conditions.
- Initial sensitivity depends differently on related immitances than in the classic current bridge.
- In some applications double current bridges could be alternative to existing circuits in others – they give new possibilities. The main application is in measurements of the immitance increments of the bridge and of other topology 4 terminal circuits, which can not be disconnected.
- Increments of the bridge arm resistance of the same signs, as shown on Fig. 4 are not possible to measure so simply by other methods.
- It is also possible to measure indirectly two variables by a pair of non-selective sensors by measuring separately increments any of the bridge arm resistances.
- Double current bridges could be used also in resistance – frequency converters.

- It is possible to create new current output circuits with feedback changing one of the bridge supply current.
- The very large and perspective field of applications of double current bridges is in the domain of AC circuits. For every existing conventional AC bridges it is possible to create 2 (or even 4) such double bridges. Balance could be achieved in 4 arms bridges, which are structurally not balanced for conventional supply because of different phases sum of opposite arms, e.g. in RC bridge AC phase shifter.
- It will be also possible to create new AC measurement circuits of the few variables using a number of various immitance sensors.

Some of these new applications author would like to present at the Symposium and later in other publications.

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