A Quadripolar Parameter-Based Approach of Ideal Gyrators structured on Operational Amplifier Circuits

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Abstract: -. The paper approaches some aspects regarding performances characteristics of gyrators with different circuit topology. The gyrators behavior of a class of two-ports structured on operational amplifiers and resistors is studied. In order to verify the theoretical predictions the analytical quadripolar parameters are bridged with the experimental one numerical by the means of a Pspice simulation. The gyrator equations express the instantaneous behavior of switching power converters, averaged over one switching cycle. Any dc-dc switching power converter meet the requirements of closed-loop control of output voltage or current. There are many ways to design a physical system with gyrator behavior like. Some gyrators are based on various physical effects, like the Hall-effect, other gyrators are created using electronically devices, like operational amplifiers. All these synthesis operate time-continuously.

Key-Words: - gyrator, quadripolar circuits, antireciprocal, , two-ports, operational amplifier.

1 Sumary

A gyrator is two-port whose two-port parameters satisfy a condition, usually referred as the antireciprocity condition. For example, if the short-circuit two-port parameters are considered,

$$\begin{aligned} \underline{I_1} &= G_{11}\underline{U_1} + G_{12}\underline{U_2} \\ \underline{I_2} &= G_{21}\underline{U_1} + G_{22}\underline{U_2} \end{aligned} \quad (1)$$

then the antireciprocity condition involves the transfer short-circuit admittance [1]:

$$G_{12} = - G_{21} \quad (2)$$

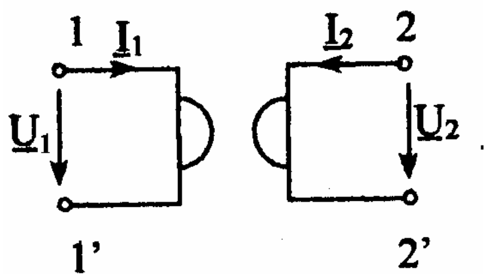

Fig.1. The circuit symbol for a gyrator

The main property of a gyrator is that it converters a one-port network, connected at one port, into the dual network, as seen from the remaining port. Particularly, this means that a capacitor connected at port 2-2' will act as an inductor seen from terminals 1-1'. If the driving point short-circuits admittance vanishes, the gyrator is said to be lossless, or ideal. The instantaneous power transfer through the gyrator network is conserved and is given by:

$$P_1 = U_1 I_1 = G_{12} U_1 U_2 \quad (3)$$

where G_{12} is called the gyration conductance and has the unit of 1/Ω These gyrator equations also describe the instantaneous behavior of switching power converters, averaged over one switching cycle.

Any dc-dc switching power converter can satisfy to by closed- loop control of output voltage or current. Several switching power converters, such as buck, boost, buck-boost, and flyback converter [2], are possible candidates for gyrator realization. In all the realization attempts, an external closed-loop control circuit is required to force the converter circuit to behave as a gyrator. In the following analysis, it is shown that the double bridge converter is naturally a gyrator circuit, without any closed-loop control to force this behavior. There are many ways to build a physical system so that it should behave like a gyrator. Some gyrators are based on various physical affects, like the Hall-effect. Other gyrators are builds using electronically devices, like operational amplifiers [1]. All these realizations operate time-continuously. It has been reported also switched-mode gyrators, based on a reciprocal two-port or a transmission line, sandwiches between two switching bridges. Such devices can be found in a class of dc-dc power converters.

2 Ideal gyrator and lossy gyrator. Literature preview

Ideal gyrator sited in the theory of electric circuits B. D. Tellegen refers to a cuadripolar structure hypothetical antireciprocal without losses [18]. In the ideal gyrator equations, occur only quadripolar transfer parameters. Considering a harmonic feeding regime, ideal gyrator equations are:

$$\begin{aligned} \underline{U_1} &= R_{12}\underline{I_2} \\ \underline{U_2} &= R_{21}\underline{I_1} \end{aligned} \quad \text{or} \quad \begin{aligned} \underline{I_1} &= G_{12}\underline{U_2} \\ \underline{I_2} &= G_{21}\underline{U_1} \end{aligned} \tag{4}$$

in which: $R_{12} = (U_1 / I_2)_{I_1=0} = (R_{to})_2$ no-load transfer resistance for a quadripol feed at terminals 22' is; $R_{21} = (U_1 / I_2)_{I_2=0} = (R_{to})_1$ no-load transfer resistance for a quadripol feed at terminals 11'; $G_{12} = (I_1 / U_2)_{U_1=0} = (G_{tk})_2$ no-load transfer conductance for a quadripol in short circuit feed at terminals $22'$; $G_{21} = (I_2 / U_1)_{U_2=0} = \; = (G_{tk})_1$ no-load transfer conductance for a quadripol in short circuit feed at terminals 11'.

Characteristic for a gyrator is the fact that no-load transfer resistances, respectively no-load transfer conductance for a quadripol in short circuit (rel.4) have always opposite signs:

$$R_{12}R_{21}<0 \quad \text{respectively} \quad G_{12}G_{21}<0 \tag{5}$$

Regarding the numerical values of the quadripolar transfer parameters, usually they are considered equal. In such a case, as there is a only numerical value no-load transfer resistance named gyration resistance R_g, ($|R_{12}| = |R_{21}| = R_g$) and a single transfer conductance in short-circuit G_g, ($|G_{12}| = |G_{21}| = G_g$) called gyration conductance. In this case, gyrator's equations are:

$$\begin{aligned} \underline{U_1} &= R_g\underline{I_2} \\ \underline{U_2} &= -R_g\underline{I_1} \end{aligned} \quad \text{and} \quad \begin{aligned} \underline{I_1} &= -G_g\underline{U_2} \\ \underline{I_2} &= G_g\underline{U_1} \end{aligned} \tag{6}$$

Quadripolar transfer parameters may have, however, and different values, which provide a more general framework of analysis, followed as far as possible and in the paper.

As mentioned, the two transfer parameters have contrary signs. Supposing, for example $R_{12}>0$ it results $R_{21} = -|R_{21}| < 0$ ideal gyrator equations can be write under the form:

$$\begin{aligned} \underline{U_1} &= R_{12}\underline{I_2} \\ \underline{I_1} &= \frac{\underline{U_2}}{R_{21}} = -\frac{\underline{U_2}}{|R_{21}|} \end{aligned} \tag{7}$$

The chain matrix appropriate can be written as:

$$[A] = \begin{bmatrix} 0 & R_{12} \\ \dfrac{-1}{|R_{21}|} & 0 \end{bmatrix} \tag{8}$$

If we notes the load impedance with connected to the gyrator terminals 22' $\underline{Z_S}$ out relations (7) it result the input equivalent impedance:

$$\underline{Z_{e1}} = \frac{\underline{U_1}}{\underline{I_1}} = \frac{|R_{12}R_{21}|}{\underline{Z_S}} = |R_{12}R_{21}|\underline{Y_S} \tag{9}$$

in which was taken into account the association rule at the receivers at both terminals, $\underline{Z_S} = -\underline{U_2} / \underline{I_2}$.

When the quadripolar transfer parameters are equal in numeric values, the input equivalent impedance is:

$$\underline{Z_{e1}} = R_g^2 \frac{1}{\underline{Z_S}} \tag{10}$$

This expression of (rel.9, rel.10), input equivalent impedance reveals the simple a gyrator property of reversing the impedances. It is a characteristic gyratoars property, which has important technical applications. If, for example, the task is represented by a condenser of the capacity C, input equivalent impedance corresponds to a inductivity and vice versa.

Thus, if $\underline{Z_S} = 1 / j\omega C$, the simulated inductivity for an ideal gyrator characterized by resistance of gyration R_g, is the equation $L = R_g^2 C$, and if transfer quadripolar resistance are not equal it results $L = |R_{12}R_{21}|C$.

Regarding the relation 9, may be said that a gyrator has input equivalent impedance proportional to load admittance $\underline{Y_S}$. When we refer to gyrator equations depending of conductance parameters, analog we obtain:

$$\underline{Z_{e1}} = \frac{1}{|G_{12}G_{21}|}\frac{1}{\underline{Z_S}} \tag{11}$$

Comparing the relations (9), (11) it results also:

$$|R_{12}R_{21}| = \frac{1}{|G_{12}G_{21}|} \tag{12}$$

relationship valid only for ideal gyrator. If gyrator is not ideal, the relation between no-load transfer parameters and transfer parameters in short-circuit is more complicated. It may be noted in this context known fact that reversing impedances is obtain, in the case of electric lines, a length of quarter wavelength [19, 20]. Distinct of this possibility, reversing impedances with a gyrator has the advantage of being practically independent of frequency.

As result of reversing property of the gyrator impedances, in literature, the gyrator is also known as an impedance inverter [21, 22]. In these works, equivalent impedance input of impedance inverter is defined by the equation:

$$\underline{Z}_{e1} = M \frac{1}{\underline{Z}_S} \tag{13}$$

where M= A_{12}/A_{21} and A_{12} şi A_{21} are elements of the secondary diagonal of chain matrix of ideal gyrator. Taking into account the ideal gyrator chain matrix (rel.8**)** and substituting the relations M in eq. (13) is obtain the same expression of input equivalent impedance previously established (rel.9).

Quadripolar equivalent scheme of a ideal gyrator, in accordance with the quadripolar equations (rel.4) contains two sources of the current command in voltage, as is shown in Fig. 2.

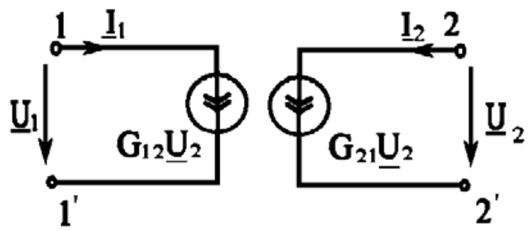

Fig.2 Scheme of an ideal qudripolar equivalent gyrator

Referring to the technical gyrators we note that in principle can not be achieved gyrator based Hall effect, which is ideal because of the large losses that occur in the semiconductor Hall plate. In return can be achieved ideal gyrator with AO and that, simply by sizing a proper topology of resistance gyrator. Additional clarifications on gyrators ideal with AO will be made in following.

If gyrator quadripolar parameters defined for each of the two terminals in particular schemes regimes of no load and empty short-circuit are not zero, gyrator is not ideal, and we say is with losses. Referring to the quadripolar parameters resistance and conductance, the equations of lossy gyrator can be written:

$$\begin{aligned} \underline{U_1} &= R_{11}\underline{I_1} + R_{12}\underline{I_2} \\ \underline{U_2} &= R_{21}\underline{I_1} + R_{22}\underline{I_2} \end{aligned} \quad \text{and} \quad \begin{aligned} \underline{I_1} &= G_{11}\underline{U_1} + G_{12}\underline{U_2} \\ \underline{I_2} &= G_{21}\underline{U_1} + G_{22}\underline{U_2} \end{aligned} \tag{14}$$

whom correspond the resistance or conductance matrix:

$$[R] = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \text{ and } [G] = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \tag{15}$$

It is observable that if gyrator is not ideal, in addition to the transfer parameters (R_{12}; R_{21}; G_{12}; G_{21}) intervening in the equations and quadripolar parameters R_{11}, R_{22}, G_{11}, G_{22} that are called also own parameters defined at the two terminals to distinguish from the transfer parameters and also by terminology.

The significance of these parameters are as follows: $R_{11} = \left(\underline{U_1}/\underline{I_1}\right)_{I_2=0} = R_{10}$ and $R_{22} = \left(\underline{U_2}/\underline{I_2}\right)_{I_1'=0} = R_{20}$ are the no-laod resistance at the two terminals, the gyrator being feed by the terminals 11', respectively 22', and conductances in short circuit at the two terminals, $G_{11} = \left(\underline{I_1}/\underline{U_1}\right)_{U_2=0} = G_{1k}$ and $G_{22} = \left(\underline{I_2}/\underline{U_2}\right)_{U_1=0} = G_{2k}$ the gyrator being feed by the terminals 11', respectively 22 /. These parameters are always positive magnitudes.

In the lossy gyrator case is desirable that the quadripolar transfer parameters to be as higher compared to other parameters. A global parameter, we can say quality parameter of gyrator, which it is noted with k and take into account all the parameters quadripolar is:

$$k = \frac{|R_{12}R_{21}|}{R_{11}R_{22}} = \frac{|G_{12}G_{21}|}{G_{11}G_{22}} \tag{16}$$

In quadripolar theory can show that the global parameter *k* has the following significance [24]:

$$k = \left(\frac{U_2}{U_1}\right)_{I_2=0} \cdot \left(\frac{U_1}{U_2}\right)_{I_1=0} \tag{17}$$

in which $\left(U_2/U_1\right)_{I_2=0}$ is the ratio of voltage to the terminals 22' in no-load regime (I_2 = 0) and power supply U_1, and $\left(U_1/U_2\right)_{I_1=0}$ is the ratio of the output voltage to the terminals in no-load regime (I1 = 0) and voltage applied to the terminals 22'.

As range, ratio *k* is varying widely. Informative, if at Hall gyrator, in the usual design, this global parameter values has under unit, at gyrator with AO attain k = 10^2-10^6. In connection with the k may be noted that it is involved in other expressions of the gyrators study. For example, the maximum yield of a lossy gyrator can be expressed as follows:

$$\eta_M = \frac{\sqrt{1+k}-1}{\sqrt{1+k}+1} \quad (18)$$

which is used specifically in the case Hall generator, which is a lossy gyrator.

3 Analysis of a gyrator with operational amplifiers

An example of gyrator with operational amplifiers (OA) is shown in fig.3, [2, 3].

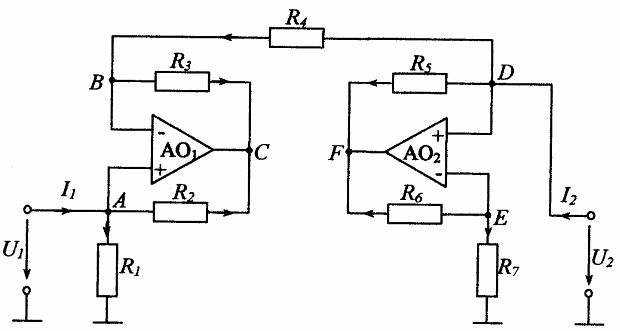

Fig.3 Antoniou gyrator schematic

Admitting that amplification is infinite for the two OA we have following equations:

$$I_1 = U_1\left(G_1 - \frac{G_2G_4}{G_3}\right) + U_2\frac{G_2G_4}{G_3}$$
$$I_2 = -U_1G_4 + U_2\left(G_4 - \frac{G_5G_7}{G_6}\right) \quad (19)$$

Based on relations (1) we note that: $G_{12} = G_2G_4/G_3$, $G_{21} = -G_4$ and the result of transfer conductance in short-circuit is negative $G_{12}G_{21}<0$, thus the schematic behaves like a gyrator. Based on equation (1), we analyze different situations depending on resistances $R_{1...}R_7$. Taking into account the parameters involved in quadripolar expressions, according to conductance G_1 ... G_7 analysis scheme may be different cases gyrators depending on the values of these items charge. Thus, in order to obtain a gyrator to be ideal (G_{11} = $=G_{22}=0$) condition is: $G_1G_3 = G_2G_4$ and G_4G_6 = $=G_5G_7$. This condition can be obtained either by picking all conductances scheme of equal ($G_1=G_2=$ $=G_3=$ … $=G_7=G$), in which case the transfer parameters will be equal (G_{12}=G and G_{21} = - G), or choosing certain values for the two of conductances ($G_1=G_2=$ …$=G_6=G_7=G^{/}$ and $G_3=G_4$ $=G^{//}$) where the parameters of the transfer will result in different values ($G_{12}=G^{/}$ and G_{21}= - $G^{//}$). Similarly, it may consider choosing conductances from the scheme to obtain gyrator who is not ideal ($G_{11}\neq0$, $G_{22}\neq0$). For example, if we choose $G_2=G_3=G_5=G_7=G$ and G_1, G_4, G_7, are chosen to fulfill the inequality $G_1>G_4>G_7$, G_{11} and G_{22} parameters will result positive and different from zero, and quadripolar transfer parameters in short circuit will be of numerical values equal ($G_{12}=G_4$, G_{21}= - G_4). In particular, must be mentioned the possibility to obtain ideal gyrators with AO, which principally in Hall gyrators case it is not possible. If gyrators are ideal, do not appear loss corresponding parameters G_{11} and G_{22}, which is certainly beneficial. In correlation with gyrators with AO, regarded as ideal by computation, some clarifications should be made. Thus, in a real scheme a gyrator considered ideal in theory these quadripolar parameters (G_{11} and G_{22}) are not void because the actual operational amplifiers used in the scheme are not rigorously ideal, as assumed in the calculation. These quadripolar parameters are not quite negligible, in the case of quality operational amplifier is usually around 10^2-10^3 less than the transfer quadripolar parameters**.**

4 The powers, voltage and currents ratios at the two ports of gyrator

Let's consider an ideal gyrator with AO, having different values for transfer in short circuit conductance (G_{12}, G_{21}) and closed on an load impedance, $\underline{Z_S}$, fig.4.

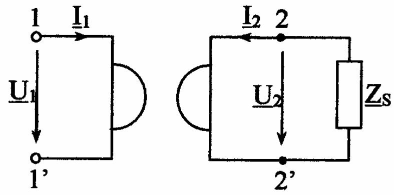

Fig. 4 Gyrator ideal closed on a load impedance $\underline{Z_S}$.

Equations ideal gyrator are:

$$\underline{I_1} = G_{12}\underline{U_2}$$
$$\underline{I_2} = -|G_{21}|\underline{U_1} \quad (20)$$

and $\underline{U_2} = -\underline{Z_S}\ \underline{I_2}$.

Gyrator's equations are written on the assumption $G_{12}>0$ and G_{21}= -$|G_{21}|$<0. Taking into account these equations can be written:

$$\underline{I_1} = G_{12}\underline{U_2} = G_{12}\left(-\underline{Z_S}\ \underline{I_2}\right) = G_{12}|G_{21}|\underline{Z_S}\ \underline{U_1} \quad (21)$$

Also, it can write:

$$\underline{U_2} = -\underline{Z_S}\ \underline{I_2} = \underline{Z_S}|G_{21}|\underline{U_1} \quad (22)$$

With these expressions (20, 21, 22) can calculate the apparent power in complex ($\underline{S_1}$ and $\underline{S_2}$) from the two ports of gyrator, obtaining:

$$\underline{S_1} = \underline{U_1^*}\ \underline{I_1} = P_1 - jQ_1 = G_{12}|G_{21}|\underline{Z_S}U_1^2 \quad (23)$$

$$\underline{S_2} = \underline{U_2^*}\ \underline{I_2} = P_2 - jQ_2 = -|G_{21}|^2\,\underline{Z_S^*}U_1^2 \quad (24)$$

From which it results:

$$P_1 = G_{12}|G_{21}|U_1^2\Re_e\underline{Z_S}$$

$$P_2 = -|G_{21}|^2U_1^2\Re_e\underline{Z_S^*} \quad (25)$$

respectively,

$$Q_1 = -G_{12}|G_{21}|U_1^2\Im_m\underline{Z_S}$$

$$Q_2 = |G_{21}|^2U_1^2\Im_m\underline{Z_S^*} \quad (26)$$

In relation (26) we consider:

$$\Re_e(\underline{Z_S}) = \Re_e(\underline{Z_S^*}) \text{ and } \Im_m(\underline{Z_S}) = -\Im_m(\underline{Z_S^*}) \quad (27)$$

From relations (25) and (26) to get the expressions of active and reactive powers ratio:

$$\frac{P_2}{P_1} = -\frac{|G_{21}|}{G_{12}} \text{ and } \frac{Q_2}{Q_1} = \frac{|G_{21}|}{G_{12}} \quad (28)$$

We can notice that powers ratios (rel.28) depend only on transfer quadripolar parameters of gyrator (G_{12}, G_{21}), being independent of load impedance. It should be mentioned that the powers of these relations are received at the two ports by gyrator.

The voltage ratio the terminals at the two ports can be expressed under the form:

$$\frac{\underline{U_2}}{\underline{U_1}} = |G_{21}|\underline{Z_S} \quad (29)$$

observing that this ratio depends on load impedance and the quadripolar $|G_{21}|$. In particular case $\underline{Z_S} = R_S$ is obtained:

$$\frac{\underline{U_2}}{\underline{U_1}} = |G_{21}|R_S = \frac{|G_{21}|}{G_S} > 0 \quad (30)$$

This ratio is positive, voltage at the two terminals are in phase.

As regards the ratio of current to obtain the expression:

$$\frac{\underline{I_2}}{\underline{I_1}} = -\frac{1}{G_{12}\underline{Z_S}} \quad (31)$$

which also depends on the load impedance. Considering case of a task resistive ($\underline{Z_S} = R_S = 1/G_S$), the ratio of current becomes:

$$\frac{\underline{I_2}}{\underline{I_1}} = -\frac{1}{G_{12}R_S} < 0 \quad (32)$$

If this ratio is negative, the two currents are in opposition. These results on reports of powers (active and reactive), the terminal voltages and currents at the two ports are important characteristics of an ideal gyrator.

5 The condition of passivity of gyrator with operational amplifiers

Since gyrators with AO contain in addition to passive elements of circuit and active circuit elements (AO), it is significant to know the conditions in which a gyrator behaves as of passive or active circuit, which may be based on the condition of passivity [4, 5]. The condition of passivity of a quadripol two-port is that total energy received at the two ports to be equal to or greater than zero, namely:

$$E(t) = \int_0^t P_t dt + E(t_o) \geq 0 \quad (33)$$

For the total power is received at the two ports, and if it is considered $E(t_0)=0$, resulting:

$$E(t) = \int_0^t P_t dt = \int_0^t (U_1I_1 + U_2I_2)dt \geq 0 \quad (34)$$

These forms take into account that the give respectively provided power of a receiver connected to the output terminals of quadripol is equal and opposite sign of power received by quadripol outside at those terminals. For example, we will consider the case of a ideal gyrator resist. Analysis in terms of the conditions of passivity will be made in the following three specific cases:

a) $G_{12}=|G_{21}|$
b) $G_{12}>|G_{21}|$
c) $G_{12}<|G_{21}|$

where we consider that gyrator analyzed behavior respect the conditions $G_{12}>0$ şi $G_{21}<0$.

In terms of the powers involved in a gyrator with AO we note that in addition to the powers P_1 and P_2 at the two ports, intervenes the power P_{AO} developed operational amplifiers and power dissipated P_R inevitably in the scheme resistance. To determine these two powers (P_{AO}, P_R) should be known currents and the potential at the nodes A, B, C, D, E, F of the gyrator scheme (fig.3) which are:

$$V_A = V_B = U_1$$

$$V_C = \frac{U_1(G_3 + G_4) - U_2G_2}{G_3} \quad (35)$$

$$V_D = V_E = U_2$$

$$V_F = \frac{U_2\left(G_4 + G_5\right)}{G_6}$$

Case a) Taking into account that $P_1 = G_{12}U_1U_2$ and $P_2 = G_{21}U_1U_2 = -\left|G_{21}\right|U_1U_2$ the total power P_t occurring in the condition of passivity is null.

$$P_t = U_1U_2\left(G_{12} - \left|G_{21}\right|\right) = 0 \quad (36)$$

So, gyrator considered ideal in this case (rel.36) acts as a passive quadripolar circuit. The fact that the gyrator with AO behave as a passive circuit if it satisfies the condition $\left(G_{12} + G_{21}\right) \geq 0$ represents a real advantage in terms of stability circuit, [6].

Potential VC and VF nodes in this case are:

$$V_C = 2U_1 - U_2$$

$$V_F = 2U_2 \quad (37)$$

Potentials $V_A=V_B=U_1$ and $V_D=V_E=U_2$ remain unchanged.

Computing the currents for the scheme gyrator with equal resistances, the power dissipated in the resistances P_R we find the expression:

$$P_R = G\left(4U_1^2 + 6U_2^2 - 6U_1U_2\right) \quad (38)$$

and for power P_{AO} developed by AO shows the same expression that is.

$$P_{AO} = G\left(4U_1^2 + 6U_2^2 - 6U_1U_2\right)$$

Balance of the four powers P_1, P_2, P_{AO}, P_R is written in the evident form:

$$P_1 + P_{AO} = \left|P_2\right| + P_R \quad (39)$$

expressing the fact that the amount of power P_1 received gyrator at terminals and power P_{AO} developed by operational amplifiers is equal to the amount of power transferred from gyrator on the output terminals and power dissipated in the resistances P_R.

In the case considered we see that the powers at the two ports are equal and $P_1 = \left|P_2\right|$ also $P_{AO} = P_R$, which means that power developed by AO fully covers power dissipated in the scheme resistances. As for coverage of power dissipated in the resistors is not consumed any of the power received gyrator at terminals, in this one case can say that gyrator acts as an undissipative element. Under the said the gyrator with AO operates in optimal conditions, being the case most often encountered in literature.

Case b) Because in this case ($G_{12} > \left|G_{21}\right|$) the total power P_t received by gyrator at the two ports is positive: in this case:

$$P_t = U_1U_2\left(G_{12} - \left|G_{21}\right|\right) > 0 \quad (40)$$

that, conform to the passivity condition, gyrator behaves still as a passive circuit. Achieving this case involves the choice of resistance scheme as follows: $R_1=R_2=R_6=R_7=R^{/}$, $R_3=R_4=R_5=R^{//}$; $G^{/}=1/R^{/}$ and $G^{//}=1/R^{//}$, also $G^{/}>G^{//}$.

Quadripol parameters are:

$G_{11}=G_{22}=0$ şi $G_{12}=G^{/}$, $G_{21}= - G^{//}$ thus $G_{12} > \left|G_{21}\right|$ (41)

For potential V_C and V_F in this case are obtain the expressions:

$$V_C = 2U_1 - U_2\frac{G_{12}}{\left|G_{21}\right|}\ ;\ V_F = 2U_2\frac{G_{12}}{\left|G_{21}\right|} \quad (42)$$

Computing now the dissipated power and the power of P_R P_{AO} developed by AO, to obtain the final relations:

$$P_R = \left(G_{12} + \left|G_{21}\right|\right)\left(2U_1^2 + 3U_2^2 - 2U_1U_2\right) - 2\left|G_{21}\right|U_1U_2 \quad (43)$$

Taking into account the powers at terminals expressions, it results in this case $P_1 > \left|P_2\right|$ and the difference between the two powers is $P_1 - \left|P_2\right| = \left(G_{12} - \left|G_{21}\right|\right)U_1U_2 > 0$. The same relation we obtain in this case and if is made the difference between PR and expressions powers P_{AO} (rel.43), which is in accordance with the balance of powers, which can be written under the form:

$$P_1 - \left|P_2\right| = P_R - P_{AO}$$

In addition that the gyrator acts as a passive circuit, and power at output terminal is lesser than power P_1 at input terminal, the gyrator has a dissipative like behavior because power P_R dissipated in resistors is covered by a part of power P_1 ($P_R = P_1 + P_{AO} - \left|P_2\right|$).

Case c) In this case total power received by gyrator on the ports is negative:

$$P_t = U_1U_2\left(G_{12} - \left|G_{21}\right|\right)\ 0 \quad (44)$$

Because $G_{12} < \left|G_{21}\right|$.

So gyrator will behave as an active ($\left|P_2\right| > P_1$).

To achieve this case resistance scheme shall be selected as in the case b $G^{/} < G^{//}$, in the aim to result $G_{12} < \left|G_{21}\right|$ The powers P_R and P_{AO} will have the same expression as in the previous case (b). By distinguishing between these powers is found that produces the same expression $\left(\left|G_{21}\right| - G_{12}\right)U_1U_2 > 0$ as the difference between $\left|P_2\right|$ and P_1 Power developed by AO covers power dissipated P_R and the difference P_2 and P_1, to be precise, $P_{AO} = P_R + \left(\left|P_2\right| - P_1\right)$, relation also with the powers balance. Analysis of the three cases (a, b, c) was considering a ideal gyrator. If gyrator is not ideal ($G_{11} \neq 0$, $G_{22} \neq 0$), the total power P_t received at the two ports must fulfill the passivity condition:

$$P_t = \left(G_{11}U_1^2 + G_{22}U_2^2\right) + U_1U_2\left(G_{12} - |G_{21}|\right) \geq 0 \quad (45)$$

Observing that in this more generally case, in the expression of total power is involved a supplementary term compared to the ideal gyrator, which is always positive, ($G_{11}U_1^2 + G_{22}U_2^2$ >0).

If gyrator is not ideal, the conclusion of passive circuit (rel.45) remain valid in cases a and b, with the remark that the losses occurring in the first case (a). As regards the case c, to see if the gyrator behavior is active must be verify whether this additional term of total power is negative. Analysis of these cases characteristic (a, b, c) will be listed below, make a check of the results obtained in paper and the calculation based on PSPICE.

6 The driving point impedance for a gyrator. Some special cases

The driving-point impedance (input equivalent impedance) expression for a loaded two-port network [15] takes the special form

$$\underline{Z_{e1}} = R_{11} - \frac{R_{12}R_{21}}{\underline{Z_S} + R_{22}} = R_{10} - \frac{R_{12}R_{21}}{\underline{Z_S} + R_{20}} \quad (46)$$

if the network is a gyrator, where $\underline{Z_S}$ is the load impedance and $R_{11}=R_{10}$, $R_{22}=R_{20}$ are the open-circuit driving point resistances of the gyrator. In the deriving eq. (46) we considered at both the input port as well as at the output port the passive rule for port current and voltage, rule that is very convenient for the analysis of antireciprocal two-ports.

Equation (46), alternatively, may be represented as follows:

$$\underline{Z_{e1}} = R_{10} + \frac{|R_{12}R_{21}|}{\underline{Z_S} + R_{20}} \quad (47)$$

explicited form which takes into account the negative sign of the antireciprocity condition. An analogue expression can be written for the input admittance:

$$\underline{Y_{e1}} = G_{11} - \frac{G_{12}G_{21}}{\underline{Y_S} + G_{22}} = G_{1k} + \frac{|G_{12}G_{21}|}{\underline{Y_S} + G_{2k}} \quad (47')$$

where $G_{11}=G_{1k}$ and $G_{22}=G_{2k}$ are, respectively, the short-circuit driving-point conductances of the gyrator.

In contrast, for a resistive and reciprocal two-port, by taking explicitly into account the sign that accompanies the reciprocity condition, the input impedance, respectively admittance, are:

$$\underline{Z_{e1}} = R_{10} - \frac{|R_{12}R_{21}|}{\underline{Z_S} + R_{20}} \quad (48)$$

$$\underline{Y_{e1}} = G_{1k} - \frac{|G_{12}G_{21}|}{\underline{Y_S} + G_{2k}} \quad (49)$$

Equations (47, 47') and (48, 49), allows us to make a simple and quick difference between a gyrators and a reciprocal two-port network, as will be shown further.

Taking into account that $\underline{Z_{e1}} = 1/\underline{Y_{e1}}$, it follows eq. (46, 47) that for a gyrator:

$$\frac{R_{10}\left(\underline{Z_S} + R_{20}\right) + |R_{12}R_{21}|}{R_{20} + \underline{Z_S}} = \frac{G_{2k} + \underline{Y_S}}{G_{1k}\left(G_{2k} + \underline{Y_S}\right) + |G_{12}G_{21}|} \quad (50)$$

and respectively, from eq. (48, 49) for a reciprocal two-port:

$$\frac{R_{10}\left(\underline{Z_S} + R_{20}\right) - |R_{12}R_{21}|}{R_{20} + \underline{Z_S}} = \frac{G_{2k} + \underline{Y_S}}{G_{1k}\left(G_{2k} + \underline{Y_S}\right) - |G_{12}G_{21}|} \quad (51)$$

For a lossless two-port, from eq. (50, 51) follows the simple and interesting relation:

$|R_{12}R_{21}| = 1/|G_{12}G_{21}|$

A special case occurs if $\underline{Z_S} = 0$ (short-circuit at the output port). In this case, eq. (13) becomes:

$$\underline{Z_{e1}} = R_{1k} = R_{10} + \frac{|R_{12}R_{21}|}{R_{20}} > R_{10} \quad (52)$$

It can be seen from eq. (52) that, for a gyrator, the short - circuit input resistance R_{1k} is always greater than the open-circuit input resistance R_{10}. This is an unusual condition, as for a reciprocal two-port the opposite condition holds. Therefore, the difference between a gyrator and a reciprocal two-port is deeper than a formal change of sign.

A more significant parameter, that can be used to emphasize this behaviour, is the ratio $T_{k0} = R_{1k}/R_{10}$ which for a gyrator is always greater then 1:

$$T_{k0} = \frac{R_{1k}}{R_{10}} = 1 + \frac{|R_{12}R_{21}|}{R_{10}R_{20}} = 1 + k > 1 (k>0) \quad (53)$$

This ratio is seen as a kind of a quality factor for a gyrator. Indeed, for an ideal gyrator, $T_{k0} \to \infty$ and therefore a high T_{k0} means a good performing gyrator.

$$T_{k0} = \frac{\det[R]}{R_{11}R_{22}} = \frac{\det[G]}{G_{11}G_{22}} = \frac{A_{12}A_{21}}{A_{11}A_{22}} \quad (54)$$

Table 1 shows a classification of two-ports depending on the value of T_{k0} as compared with the unity.

Table 1

T_{k0}	Two-port network
<1	Reciprocal
=1	Unidirectional
>1	Antireciprocal (gyrator)

The transition from a reciprocal two-port to an antireciprocal one, via a unidirectional two-port is not surprisingly, as it is known that an unidirectional two-port can be synthesized by combining a resistive reciprocal and an antireciprocal two-port.

Additional useful information about the driving-point impedance of a gyrator can be gathered by analyzing the locus of this network function. Specifically, the case of a capacitively loaded gyrator (fig.5a) is of great interest, as such networks are used to simulate high Q inductance's [15]. This application is based on the impedance inversion property of a gyrator. We will consider the more general case of a lossy gyrator, with different numerical values for the transfer parameters. In this case, for a purely capacitive load ($\underline{Z_S} = X_C$), eq. (46) becomes:

$$\underline{Z_{e1}} = R_{10} + \frac{|R_{12}R_{21}|}{R_{20}^2 + X_C^2} R_{20} + j\frac{|R_{12}R_{21}|}{R_{20}^2 + X_C^2} X_C . = \mathrm{R}_{e1} + jX_{e1} \tag{55}$$

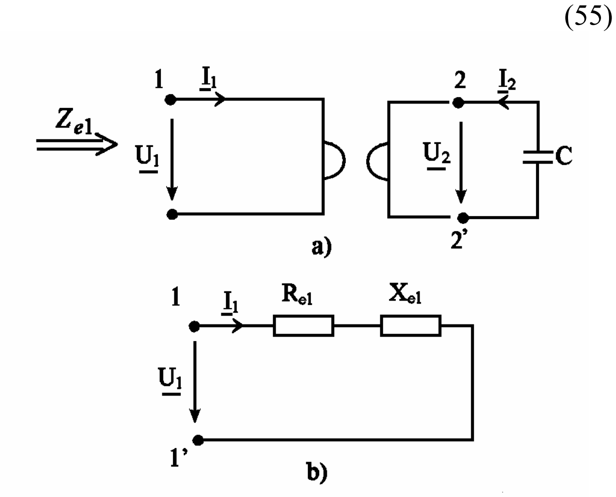

Fig. 5 a) Capacitively - loaded gyrator; b) Dipolar equivalent circuit

The inductive nature of the impedance is clearly revealed this expression. The corresponding equivalent circuit is shown in fig.5b. Making the substitution $X_C = 1/\omega C$, eq. (55) can be transformed to:

$$\underline{Z_{e1}} = \left(R_{10} + \frac{|R_{12}R_{21}|\omega^2 C^2}{1+\omega^2 C^2 R_{20}^2} R_{20} \right) + j\frac{\omega C |R_{12}R_{21}|}{1+\omega^2 C^2 R_{20}^2} \tag{56}$$

from which the expression of the simulated inductance at the input of the loss gyrators follows:

$$L_{e1} = \frac{C|R_{12}R_{21}|}{1+\omega^2 C^2 R_{20}^2} . \tag{57}$$

For a lossless gyrator, R_{20}=0 and therefore $L_{e1}^{*} = C|R_{12}R_{21}|$, a well known result. To approach

This ideal situation, a loss gyrator must satisfy the condition $(\omega C R_{20})^2$<<1, which follows straightforward from eq. (57). This needs a ratio T_{k0} of about 10^4 to 10^6, which can be easily obtained by using OA gyrators.

In the following we will find the locus of the input impedance of a lossy gyrator, assuming a variable load reactance X_C. Taking into account that $X_C = X_{e1}R_{20}/(R_{e1} - R_{10})$, eq. (55) can be written in the form:

$$(R_{e1} - R_{11})^2 + X_{e1}^2 - \frac{|R_{12}R_{21}|}{R_{22}}(R_{e1} - R_{11}) = 0 \tag{58}$$

Further, this equation can be but in the form:

$$\left[R_{e1} - \left(R_{11} + \frac{|R_{12}R_{21}|}{2R_{22}} \right) \right]^2 + X_{e1}^2 = \frac{|R_{12}R_{21}|^2}{4R_{22}^2} \tag{59}$$

which represents the equation of a circle lying in the complex (R_{e1}, X_{e1}) plane, having the centre on the "R_{e1}" axis, at the distance $d_0 = R_{10} + |R_{12}R_{21}|/2R_{20}$ from the origin and a radius $r = |R_{12}R_{21}|/2R_{20}$, (fig.6). If X_C varies from 0 to ∞, the current point the circle moves on the semicircle lying in the first quadrant of the plane. The circle crosses the real axis on the point R_{10} and R_{1k}, which represent the open circuit and the short circuit resistances, respectively. The graph shows that indeed $R_{1k} > R_{10}$, a defining property for a gyrator already mentioned.

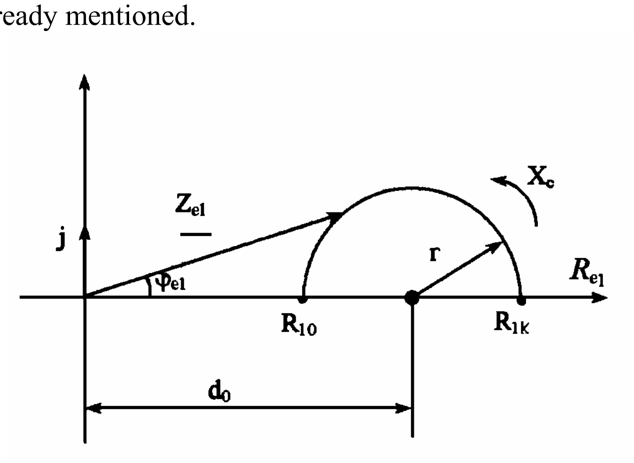

Fig. 6 Locus of the equivalent input impedance of a gyrator

Related to the equivalent input impedance, an interesting dipolar equivalent circuit for a capacitively - load lossy gyrator can be derived as follows. Substituting $\underline{Z_C} = 1/j\omega C$ into the relation:

$$\underline{Z_{e1}} = \frac{G_{2k}\underline{Z_C} + 1}{G_{1k} + \det[G]\underline{Z_C}} \tag{60}$$

known from the two-port theory, after a few algebraic transformation we get:

$$\underline{Z}_{e1} = \frac{1}{G_{11} + \dfrac{1}{\dfrac{G_{22}}{|G_{12}G_{21}|} + \dfrac{1}{|G_{12}G_{21}|\underline{Z}_C}}} = \frac{1}{G_{11} + \dfrac{1}{\dfrac{G_{22}}{|G_{12}G_{21}|} + j\omega L_{e1}^*}} \quad (61)$$

The equivalent dipolar circuit which corresponds to eq. (61) is shown in fig. 7, where $j\omega L_{e1}^*$ represents the equivalent inductive input reactance of an ideal gyrator. It is interesting to note that the losses are implemented in this equivalent circuit by two resistances: $R_S = G_{2k} / |G_{12}G_{21}|$ is connected in series with the simulated ideal inductance, whereas $R_p = 1/G_{1k}$ is connected in derivation with the gyrator's input nodes. As compared with this last equivalent circuit, in the circuit shown in fig.5b there is no separation of the losses; they are disseminated into R_{e1} and X_{e1}.

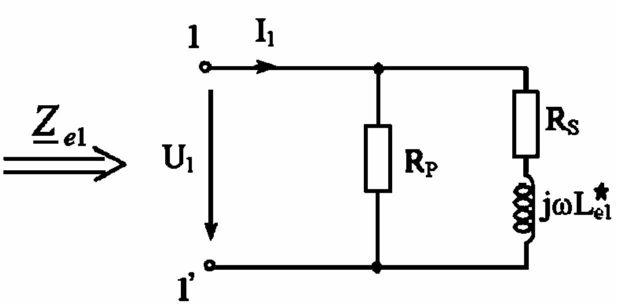

Fig. 7 A dipolar equivalent circuit for a capacitively-loaded lossy gyrator

7 Expression of input equivalent impedance in no-load regime and short-circuit. Experimental results

Taking account of resistive behavior of gyrator analyzed in paper [7], the input equivalent impedance is:

$$\underline{Z}_{e1} = R_{11} + \frac{|R_{12}R_{21}|}{R_{22} + \underline{Z}_S} \quad (62)$$

and similarly we may write:

$$\underline{Y}_{e1} = G_{11} + \frac{|G_{12}G_{21}|}{G_{22} + \underline{Y}_S} \quad (63)$$

In order to $\underline{Z}_{e1}=1/\underline{Y}_{e1}$ and taking account of relations (62) and (63) it results:

$$\frac{R_{11}(\underline{Z}_S + R_{22}) + |R_{12}R_{21}|}{\underline{Z}_S + R_{22}} = \frac{\underline{Y}_S + G_{22}}{G_{11}(\underline{Y}_S + G_{22}) + |G_{12}G_{21}|} \quad (64)$$

which reveals the relation between $|R_{12}R_{21}|$ and $|G_{12}G_{21}|$. It is obvious that in case of real quadripol this relation becomes quite complicate. The relation simplified in the case of ideal antireciprocal quadripol

$$|R_{12}R_{21}| = 1/|G_{12}G_{21}| \quad (65)$$

The quadripolar transfer parameters R_{12} and R_{21} are referring at no-load regime whereas the transfer parameters G_{12} and G_{21} are referring at short-circuit regime. A peculiar interest presents the expression of input equivalent impedance (rel.62, rel.63). Considering the antireciprocal quadripol in short-circuit ($\underline{Z}_S$=0), from relation (63) we obtain the expression of resistance in short-circuit:

$$R_{1k} = R_{11} + \frac{|R_{12}R_{21}|}{R_{22}} \quad (66)$$

from which it results and ratio $T_{k0} = R_{1k} / R_{10}$

$$T_{ko} = \frac{R_{1k}}{R_{10}} = 1 + \frac{|R_{12}R_{21}|}{R_{11} + R_{22}} = 1 + \eta > 1 \quad (67)$$

which clearly reveals a behavior of antireciprocal quadripol in which the resistance in short-circuit R_{1k} is always bigger that resistance in no-load regime R_{10}, and it is considered that η is a quality parameter of gyrator:

$$\eta = \frac{|R_{12}R_{21}|}{R_{11}R_{22}} = \frac{|G_{12}G_{21}|}{G_{11}G_{22}} \quad (68)$$

It is verified and relation:

$$T_{k0} = R_{1k} / R_{10} = R_{2k} / R_{20} \quad (69)$$

If we consider a reciprocal quadripol by corresponding, in short-circuit it is obtained:

$$T_{ko} = \frac{R_{1k}}{R_{10}} = 1 - \frac{|R_{12}R_{21}|}{R_{11} + R_{22}} = 1 - \eta < 1 \quad (70)$$

thus in this case short-circuit resistance is lesser than now-load resistance. These results (rel.67 and rel.70) totally separate an antireciprocal quadripol from a reciprocal quadripolar. In the theory of electrical quadripol depending on different parameters system of independent parameters quadripolar, for the ratio between short-circuit resistance and no-load resistance, we get:

$$T_{k0} = \frac{\det[R]}{R_{11}R_{22}} = \frac{\det[G]}{G_{11}G_{22}} = \frac{A_{12}A_{21}}{A_{11}A_{22}} \quad (71)$$

which correspond with the results obtained. For different values of resistances we verify the quadripolar parameters R_{11}, R_{12}, R_{21}, R_{22} using a simulation PSpice. Based on rel.(70) it is determined the ratio T_{k0} in every case. In table 2 shows a synthesis of these results.

Table 2

Analytical	Experimental f=950Hz, U=1V	PSpice	Gyra-tor

$G_{11}=0$ $G_{12}=1\cdot 10^{-3}$ $G_{21}=-1\cdot 10^{-3}$ $G_{22}=0$	$G_{11}=0{,}18\cdot 10^{-3}$ $G_{12}=0{,}99\cdot 10^{-3}$ $G_{21}=-0{,}88\cdot 10^{-3}$ $G_{22}=0{,}16\cdot 10^{-3}$	$G_{11}=0{,}0007\cdot 10^{-3}$ $G_{12}=1\cdot 10^{-3}$ $G_{21}=-1\cdot 10^{-3}$ $G_{22}=0{,}0005\cdot 10^{-3}$	ideal
$R_{11}=0$ $R_{12}=-1\cdot 10^{3}$ $R_{21}=1\cdot 10^{3}$ $R_{22}=0$	$R_{11}=0{,}18\cdot 10^{3}$ $R_{12}=-1{,}1\cdot 10^{3}$ $R_{21}=0{,}98\cdot 10^{3}$ $R_{22}=0{,}2\cdot 10^{3}$	$R_{11}=0{,}0005\cdot 10^{3}$ $R_{12}=-1\cdot 10^{3}$ $R_{21}=1\cdot 10^{3}$ $R_{22}=0{,}0007\cdot 10^{3}$	
$G_{11}=0$ $G_{12}=2\cdot 10^{-3}$ $G_{21}=-1\cdot 10^{-3}$ $G_{22}=0$	$G_{11}=0{,}3\cdot 10^{-3}$ $G_{12}=1{,}99\cdot 10^{-3}$ $G_{21}=-0{,}89\cdot 10^{-3}$ $G_{22}=0{,}12\cdot 10^{-3}$	$G_{11}=0{,}0014\cdot 10^{-3}$ $G_{12}=2\cdot 10^{-3}$ $G_{21}=-1\cdot 10^{-3}$ $G_{22}=0{,}0005\cdot 10^{-3}$	ideal
$R_{11}=0$ $R_{12}=-1\cdot 10^{3}$ $R_{21}=0{,}5\cdot 10^{3}$ $R_{22}=0$	$R_{11}=0{,}07\cdot 10^{3}$ $R_{12}=-1{,}09\cdot 10^{3}$ $R_{21}=0{,}49\cdot 10^{3}$ $R_{22}=0{,}19\cdot 10^{3}$	$R_{11}=0{,}0002\cdot 10^{3}$ $R_{12}=-1\cdot 10^{3}$ $R_{21}=0{,}5\cdot 10^{3}$ $R_{22}=0{,}0007\cdot 10^{3}$	
$G_{11}=0$ $G_{12}=0{,}25\cdot 10^{-3}$ $G_{21}=-110^{-3}$ $G_{22}=0$	$G_{11}=0{,}046\cdot 10^{-3}$ $G_{12}=0{,}24\cdot 10^{-3}$ $G_{21}=-0{,}92\cdot 10^{-3}$ $G_{22}=0{,}041\cdot 10^{-3}$	$G_{11}=0{,}00016\cdot 10^{-3}$ $G_{12}=0{,}25\cdot 10^{-3}$ $G_{21}=-1\cdot 10^{-3}$ $G_{22}=0{,}00049\cdot 10^{-3}$	ideal
$R_{11}=0$ $R_{12}=-1\cdot 10^{3}$ $R_{21}=4\cdot 10^{3}$ $R_{22}=0$	$R_{11}=0{,}18\cdot 10^{3}$ $R_{12}=-1{,}07\cdot 10^{3}$ $R_{21}=3{,}99\cdot 10^{3}$ $R_{22}=0{,}2\cdot 10^{3}$	$R_{11}=0{,}0019\cdot 10^{3}$ $R_{12}=-1\cdot 10^{3}$ $R_{21}=4\cdot 10^{3}$ $R_{22}=0{,}0006\cdot 10^{3}$	
$G_{11}=1{,}5\cdot 10^{-3}$ $G_{12}=0{,}5\cdot 10^{-3}$ $G_{21}=-0{,}5\cdot 10^{-3}$ $G_{22}=0{,}25\cdot 10^{-3}$	$G_{11}=1{,}57\cdot 10^{-3}$ $G_{12}=0{,}5\cdot 10^{-3}$ $G_{21}=-0{,}48\cdot 10^{-3}$ $G_{22}=0{,}24\cdot 10^{-3}$	$G_{11}=1{,}5\cdot 10^{-3}$ $G_{12}=0{,}5\cdot 10^{-3}$ $G_{21}=-0{,}5\cdot 10^{-3}$ $G_{22}=0{,}25\cdot 10^{-3}$	real
$R_{11}=0{,}4\cdot 10^{3}$ $R_{12}=-0{,}8\cdot 10^{3}$ $R_{21}=0{,}8\cdot 10^{3}$ $R_{22}=2{,}4\cdot 10^{3}$	$R_{11}=0{,}39\cdot 10^{3}$ $R_{12}=-0{,}8\cdot 10^{3}$ $R_{21}=0{,}77\cdot 10^{3}$ $R_{22}=2{,}5\cdot 10^{3}$	$R_{11}=0{,}4\cdot 10^{3}$ $R_{12}=-0{,}8\cdot 10^{3}$ $R_{21}=0{,}8\cdot 10^{3}$ $R_{22}=2{,}4\cdot 10^{3}$	
$G_{11}=2{,}83\cdot 10^{-3}$ $G_{12}=0{,}5\cdot 10^{-3}$ $G_{21}=-1\cdot 10^{-3}$ $G_{22}=0{,}87\cdot 10^{-3}$	$G_{11}=2{,}92\cdot 10^{-3}$ $G_{12}=0{,}52\cdot 10^{-3}$ $G_{21}=-1{,}02\cdot 10^{-3}$ $G_{22}=0{,}89\cdot 10^{-3}$	$G_{11}=2{,}83\cdot 10^{-3}$ $G_{12}=0{,}5\cdot 10^{-3}$ $G_{21}=-1\cdot 10^{-3}$ $G_{22}=0{,}87\cdot 10^{-3}$	real
$R_{11}=293{,}72$ $R_{12}=-168{,}80$ $R_{21}=337{,}59$ $R_{22}=955{,}43$	$R_{11}=283{,}70$ $R_{12}=-165{,}13$ $R_{21}=323{,}03$ $R_{22}=926{,}60$	$R_{11}=294{,}00$ $R_{12}=-168{,}00$ $R_{21}=336{,}00$ $R_{22}=951{,}00$	
$G_{11}=1{,}33\cdot 10^{-3}$ $G_{12}=2\cdot 10^{-3}$ $G_{21}=-1\cdot 10^{-3}$ $G_{22}=0{,}5\cdot 10^{-3}$	$G_{11}=1{,}34\cdot 10^{-3}$ $G_{12}=2{,}01\cdot 10^{-3}$ $G_{21}=-1{,}02\cdot 10^{-3}$ $G_{22}=0{,}51\cdot 10^{-3}$	$G_{11}=1{,}33\cdot 10^{-3}$ $G_{12}=2\cdot 10^{-3}$ $G_{21}=-1\cdot 10^{-3}$ $G_{22}=0{,}5\cdot 10^{-3}$	real
$R_{11}=187{,}61$ $R_{12}=-750{,}46$ $R_{21}=375{,}24$ $R_{22}=499{,}06$	$R_{11}=185{,}52$ $R_{12}=-728{,}15$ $R_{21}=371{,}05$ $R_{22}=485{,}43$	$R_{11}=187{,}50$ $R_{12}=-750{,}00$ $R_{21}=375{,}00$ $R_{22}=500{,}00$	

Conclusions

The checking up of simulation, experimental and analytical, shows a good concordance, the transfer quadripolar parameters (G_{12}, G_{21}, R_{12}, R_{21}) obtain by two ways have rigorous same values. Quadripolar parameters defined at ports (G_{11}, G_{22}, R_{11}, R_{22}) obtained by PSpice simulation are not null, their value in ratio with corresponding transfer parameters being approximately 10^{-3} lesser. These results verify the hypothesis of ideal gyrator with operational amplifiers.

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