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AUTOMATIC GENERATION OF LINEAR QUADRUPOLE PARAMETERS

Razvan ASANACHE[1], Cristina Mihaela TURCU[2], Mihai IORDACHE[3]

The paper presents the automatic generation, using dedicated simulation software programs, of $\underline{Z}$, $\underline{Y}$ and $\underline{T}$ parameters for the linear or non-linear two-port circuits, but linearized on portions. Based on these parameters, the parameters that characterize the analog filters are determined, and the passing and stop frequency bands for these filters are calculated. The obtained results from the definition relations are compared with those ones obtained as functions of $\underline{S}$ parameters. As the results obtained with the two procedures coincide, it proves that at high and very high frequencies it is indicated to use the procedures with $\underline{S}$ parameters.

Keywords: quadrupole, analog filter, S-parameters, symbolic analysis

1. Introduction

In order to describe linear analog circuits in harmonic behavior at low and medium frequencies, one may use impedance parameters $\underline{Z}$, admittance parameters $\underline{Y}$ and transfer (fundamental) parameters $\underline{T}$ [1-11].

For higher frequencies, these parameters can no longer be used since their measurements require special arrangements. For instance, to compute impedance parameters of a two-port network (2PN), the output port must be short-circuited, which makes impossible the measurement at higher frequencies. In this case, the equipment is not able to measure the actual voltage and the actual current at the 2PN's gates. Moreover, many active devices cannot operate by a stable manner when short-circuits or open circuits occur. The transverse waves should be used at these frequencies, [2, 4, 6].

At low frequencies, the transfer coefficients matrix and the ones for impedances or admittances are commonly used, but at high and very high frequency domains, they are difficult to be measured and for this reason at high frequencies the scattering parameters $\underline{S}$ are preferred. The $\underline{S}$ parameters are

[1] PhD Student, Faculty of Electrical Engineering Faculty, University POLITEHNICA of Bucharest, Romania, e-mail: rasanache@yahoo.com
[2] PhD Student, Faculty of Electrical Engineering Faculty, University POLITEHNICA of Bucharest, Romania, e-mail: mihaela.turcu@telekom.ro
[3] Prof., Faculty of Electrical Engineering Faculty, University POLITEHNICA of Bucharest, Romania, e-mail: mihai.iordache@upb.ro

measured with a VNA (Vector Network Analyzer) HP 8720D, which can measure $\underline{S}$ parameters for frequency values between 50 MHz and 40 GHz, [1-7].

In the specialized literature, [4-12], there are conversion formulas between the $\underline{S}$ parameters and the classical parameters of the circuit theory ($\underline{Z}$ impedances, $\underline{Y}$ admittances, fundamental (transfer) parameters $\underline{T}$ ($\underline{A}$, $\underline{B}$, $\underline{C}$ and $\underline{D}$) etc.), [4-12].

The automatic generation of $\underline{S}$ parameters, for various structures of two-ports, linear passive or non-linear but linearized on portions, can be used either the modified nodal equations, generated by the application software *CSAP* – *C*ircuit *S*ymbolic *A*nalysis *P*rogram, [14-16], or the state equations, generated by the software program *SYSEG* – *SY*mbolic *S*tate *E*quation *G*eneration, [14-16].

Using dedicated simulation software programs, this paper presents the automatic generation of $\underline{Z}$, $\underline{Y}$, and $\underline{T}$ parameters for linear or non-linear but linearized on portions quadrupoles. Based on these parameters there are determined the parameters which characterize the analogue filters and calculated the pass and stop frequency bands for the analyzed filters and obviously the nature of these filters. The obtained results are compared with the ones obtained using the $\underline{S}$ parameters.

At the end, based on developed procedures, in MAPLE and MATLAB programming environments have been implemented routines, in order to calculate all the parameters mentioned above and to be able to compare the results obtained by simulation with those ones existing in the specialized literature and with the experimental ones.

2. Automatic generation of $\underline{Z}$, $\underline{Y}$, $\underline{T}$ and $\underline{S}$ parameters and their use in the analysis of the two-port electric circuits

This paragraph, using the electrical circuits theory and dedicated software applications, presents, starting from the definition expressions, the $\underline{\boldsymbol{Z}}$, $\underline{\boldsymbol{Y}}$ and $\underline{\boldsymbol{T}}$ matrices, used in the analog filter analysis. Then, the $\underline{\boldsymbol{S}}$ matrix of scattering parameters is generated and based on them, the $\underline{\boldsymbol{Z}}$, $\underline{\boldsymbol{Y}}$ and $\underline{\boldsymbol{T}}$ matrices are calculated at high and very high frequencies. The impedances equations (in complex) of a passive linear quadrupole have the following expressions, [16]:

$$\begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} = \begin{bmatrix} \underline{Z}_{11} & \underline{Z}_{12} \\ \underline{Z}_{21} & \underline{Z}_{22} \end{bmatrix} \begin{bmatrix} \underline{I}_1 \\ \underline{I}_2 \end{bmatrix} \tag{1}$$

where the transfer complex impedances are defined as follows:

$$\underline{Z}_{11} \overset{d}{=} \left.\frac{\underline{U}_1}{\underline{I}_1}\right|_{\underline{I}_2=0} = \underline{Z}_{ii}; \quad \underline{Z}_{12} \overset{d}{=} \left.\frac{\underline{U}_1}{\underline{I}_2}\right|_{\underline{I}_1=0} = \underline{Z}_{io}; \quad \underline{Z}_{21} \overset{d}{=} \left.\frac{\underline{U}_2}{\underline{I}_1}\right|_{\underline{I}_2=0} = \underline{Z}_{oi}; \quad \underline{Z}_{22} \overset{d}{=} \left.\frac{\underline{U}_2}{\underline{I}_2}\right|_{\underline{I}_1=0} = \underline{Z}_{oo} \tag{2}$$

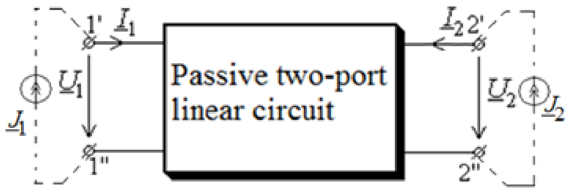


Fig. 1. A passive linear quadrupole circuit.

The passive linear quadrupole circuit shown in Fig. 1 is equivalent with the circuit presented below, in Fig. 2, where $\underline{E}_G$ is the voltage provided by the generator, $\underline{Z}_G$ is the generator impedance and $\underline{Z}_L$ is the load impedance.

The input impedance (from the port *i' – i''*) $\underline{Z}_{in}$ is defined as follows:

$$\underline{Z}_{in} = \left.\frac{\underline{U}_1}{\underline{I}_1}\right|_{\underline{E}_G=0, \underline{U}_2=-\underline{Z}_L \underline{I}_2} \tag{3}$$

Considering the impedances equations of the two-port circuit (1), there can be obtained:

$$\underline{Z}_{in} = \underline{Z}_{11} - \frac{\underline{Z}_{12}\underline{Z}_{21}}{\underline{Z}_L + \underline{Z}_{22}} \tag{4}$$

The output impedance (from the port *o' – o''*) $\underline{Z}_{out}$ is defined as follows:

$$\underline{Z}_{out} = \left.\frac{\underline{U}_2}{\underline{I}_2}\right|_{\underline{E}_G=0, \underline{U}_1=-\underline{Z}_G \underline{I}_1} \tag{5}$$

Considering the impedances equations for the two-port circuit, there is obtained:

$$\underline{Z}_{out} = \underline{Z}_{22} - \frac{\underline{Z}_{12}\underline{Z}_{21}}{\underline{Z}_G + \underline{Z}_{11}} \tag{6}$$

For the analytical calculation of complex impedances, to the input and output ports of the two-port circuit, from Fig. 1, will be connected independent ideal current sources with the current intensities $\underline{J}_1$, respectively $\underline{J}_2$, and then this circuit is analyzed symbolically with the *CSAP* program, [14 - 16], and there can be computed, starting from their definition, the complex impedances of the two-port circuit (2).

The admittances equations (in complex) of a passive linear quadrupole circuit have the following expressions:

$$\begin{bmatrix} \underline{I}_1 \\ \underline{I}_2 \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{12} \\ \underline{Y}_{21} & \underline{Y}_{22} \end{bmatrix} \begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \end{bmatrix} \tag{7}$$

where the transfer complex admittances are defined as follows:

$$\underline{Y}_{11} \stackrel{d}{=} \left.\frac{\underline{I}_1}{\underline{U}_1}\right|_{\underline{U}_2=0} = \underline{Y}_{ii}; \quad \underline{Y}_{12} \stackrel{d}{=} \left.\frac{\underline{I}_1}{\underline{U}_2}\right|_{\underline{U}_1=0} = \underline{Y}_{io}; \quad \underline{Y}_{21} \stackrel{d}{=} \left.\frac{\underline{I}_2}{\underline{U}_1}\right|_{\underline{U}_2=0} = \underline{Y}_{oi}; \quad \underline{Y}_{22} \stackrel{d}{=} \left.\frac{\underline{I}_2}{\underline{U}_2}\right|_{\underline{U}_1=0} = \underline{Y}_{oo} \quad (8)$$

By connecting to the input and output ports of the two-port circuit, from Fig. 1, independent ideal voltage sources, with voltages $\underline{E}_1$, respectively $\underline{E}_2$, and then analyzing symbolically this circuit with the *CSAP* program, [14 - 16], there can be computed, starting from their definition, the complex admittances of the two-port circuit (8).

The equations of a passive linear quadrupole circuit (Fig. 4), based on the fundamental (transfer) parameters, have the following expressions, [15]:

$$\begin{bmatrix} \underline{U}_1 \\ \underline{I}_1 \end{bmatrix} = \begin{bmatrix} \underline{A} & \underline{B} \\ \underline{C} & \underline{D} \end{bmatrix} \begin{bmatrix} \underline{U}_2 \\ \underline{I}_2 \end{bmatrix} \quad (9)$$

The fundamental parameters have, by definition, the following expressions:

$$\underline{A} \stackrel{d}{=} \left.\frac{\underline{U}_1}{\underline{U}_2}\right|_{\underline{I}_2=0} = \frac{1}{\underline{A}_{oi}}; \quad \underline{B} \stackrel{d}{=} \left.\frac{\underline{U}_1}{\underline{I}_2}\right|_{\underline{U}_2=0} = \frac{1}{\underline{Y}_{oi}};$$
$$\underline{C} \stackrel{d}{=} \left.\frac{\underline{I}_1}{\underline{U}_2}\right|_{\underline{I}_2=0} = \frac{1}{\underline{Z}_{oi}}; \quad \underline{D} \stackrel{d}{=} \left.\frac{\underline{I}_1}{\underline{I}_2}\right|_{\underline{U}_2=0} = \frac{1}{\underline{B}_{oi}} \quad (10)$$

For the analytical calculations, by example, for the one of the transfer factor (amplification) in voltage from the input to the output, $\underline{A}$, there is calculated the transfer factor (amplification) in voltage, from the output to the input of the two-port circuit from Fig. 1, $\underline{A}_{oi}$, by connecting to the terminals 1' - 1" an ideal voltage independent source, with the voltage $\underline{E}_1$, and the output terminals 2' – 2" are left not connected, then this circuit is analyzed symbolically with the *CSAP* software program, [14, 15].

The characteristic (iterative) impedances of a passive linear quadrupole circuit are defined as follows, [16]:

$$\underline{Z}_{c1} \stackrel{d}{=} \left.\frac{\underline{U}_1}{\underline{I}_1}\right|_{\underline{Z}_s=\underline{Z}_{c1}}; \quad \underline{Z}_{c2} \stackrel{d}{=} \left.\frac{\underline{U}_2}{\underline{I}_2}\right|_{\underline{Z}_i=\underline{Z}_{c2}} \quad (11)$$

and the image impedances have the following expressions:

$$\underline{Z}_{i1} \stackrel{d}{=} \left.\frac{\underline{U}_1}{\underline{I}_1}\right|_{\underline{Z}_s=\underline{Z}_{i2}}; \quad \underline{Z}_{i2} \stackrel{d}{=} \left.\frac{\underline{U}_2}{\underline{I}_2}\right|_{\underline{Z}_i=\underline{Z}_{i1}} \quad (12)$$

The expressions of the characteristic impedances, depending on the fundamental (transfer) parameters of the quadrupole are as follows, [12, 15]:

$$\underline{Z}_{c1} = \frac{1}{2\underline{C}}\left[\left(\underline{A} - \underline{D}\right) \pm \sqrt{\left(\underline{A} - \underline{D}\right)^2 + 4\underline{B}\underline{C}}\right],$$
$$\underline{Z}_{c2} = \frac{1}{2\underline{C}}\left[\left(\underline{D} - \underline{A}\right) \pm \sqrt{\left(\underline{D} - \underline{A}\right)^2 + 4\underline{B}\underline{C}}\right]. \tag{13}$$

Impedance images, depending on the fundamental (transfer) parameters of the quadrupole, have the following expressions:

$$\underline{Z}_{i1} = \pm\sqrt{\frac{\underline{A}\underline{B}}{\underline{C}\underline{D}}}, \quad \underline{Z}_{i2} = \pm\sqrt{\frac{\underline{D}\underline{B}}{\underline{C}\underline{A}}} \tag{14}$$

If the quadrupole is symmetric, equations (13) and (14) become as follows:

$$\underline{Z}_{c1} = \underline{Z}_{c2} = \underline{Z}_{i1} = \underline{Z}_{i2} = \pm\sqrt{\frac{\underline{B}}{\underline{C}}} \tag{15}$$

The transfer factors for the characteristic impedances and, respectively, for the image impedances, depending on the transfer parameters, are given by the following expressions:

$$\underline{\gamma}_c = \ln\left(\frac{1}{2}\left[\left(\underline{A} + \underline{D}\right) + \sqrt{\left(\underline{A} + \underline{D}\right)^2 - 4}\right]\right),$$
$$\underline{\gamma}_i = \ln\left(\sqrt{\underline{A}\underline{D}} + \sqrt{\underline{B}\underline{C}}\right). \tag{16}$$

If the quadrupole is symmetric, equations (16) become as follows:

$$\underline{\gamma}_c = \underline{\gamma}_i = \ln\left(\underline{A} + \sqrt{\underline{B}\underline{C}}\right) \tag{17}$$

For the reciprocal and no loss filters, the passing (stop) intervals consist of all frequencies for which the following inequality is (is not) satisfied:

$$0 \le AD \le 1 \tag{18}$$

The attenuation constant a and the phase constant b have, in the filter passing intervals, the following expressions:

$$a = 0, \quad b = arcctg\frac{1}{\sqrt{\frac{1}{AD} - 1}} + k\pi = \arccos\sqrt{AD} + k\pi \tag{19}$$

and in the stop intervals these constants are given by the following relations:

$$a = \arg cth\frac{1}{\sqrt{1 - \frac{1}{AD}}} = \mathrm{argch}\sqrt{AD}, \quad b = \begin{cases} \pm\frac{\pi}{2} & AD \le 0 \\ 0 \text{ sau } 1 & AD \ge 1 \end{cases} \tag{20}$$

The generation of $\underline{S}$ parameters for linear analog circuits and for non-linear analog circuits, but linearized on portions around an operating point, under precise polarization and temperature conditions of electronic devices, can be performed through small signal simulations, [3, 16].

For the generation of $\underline{S}$ parameters for nonlinear circuits, there is utilized the LSSP simulator - Large-Signal S-Parameter Simulation [5], which uses the *harmonic balance* analysis method. The simulation based on the harmonic balance method is a *large signal* simulation, for which the solutions include also the effects of nonlinearities of electronic components. Parameters $\underline{S}$ of both small and large signals are defined as ratios between incident waves and the reflected ones, [1, 5].

There can be easily demonstrated the following:

- The complex impedances matrix, $\underline{\boldsymbol{Z}}$, can have an expression depending on the $\underline{\boldsymbol{S}}$ parameters matrix, by the following relation, [4, 8, 12, 15]:

$$\underline{\boldsymbol{Z}} = \left(\boldsymbol{I}_2 - \underline{\boldsymbol{S}}\right)^{-1} \times \left(\boldsymbol{I}_2 + \underline{\boldsymbol{S}}\right) Z_0 \tag{21}$$

where $\underline{\boldsymbol{Z}} = \begin{bmatrix} \underline{Z}_{11} & \underline{Z}_{12} \\ \underline{Z}_{21} & \underline{Z}_{22} \end{bmatrix}$, $\underline{\boldsymbol{S}} = \begin{bmatrix} \underline{S}_{11} & \underline{S}_{12} \\ \underline{S}_{21} & \underline{S}_{22} \end{bmatrix}$, $\boldsymbol{I}_2$ is the unit matrix of second order.

- The $\underline{\boldsymbol{S}}$ matrix is expressed as a function of the $\underline{\boldsymbol{Z}}$ matrix as follows:

$$\underline{\boldsymbol{S}} = \left(\underline{\boldsymbol{Z}} - Z_0 \underline{\boldsymbol{I}}_2\right) \times \left(\underline{\boldsymbol{Z}} + Z_0 \underline{\boldsymbol{I}}_2\right)^{-1} \tag{22}$$

- The transfer parameters matrix, $\underline{\boldsymbol{T}} = \begin{bmatrix} \underline{A} & \underline{B} \\ \underline{C} & \underline{D} \end{bmatrix}$, has the following expression depending on the $\underline{\boldsymbol{Z}}$ matrix elements:

$$\underline{\boldsymbol{T}} = \frac{1}{\underline{Z}_{21}} \begin{bmatrix} \underline{Z}_{11} & -\underline{Z}_{11} \cdot \underline{Z}_{22} + \underline{Z}_{12} \cdot \underline{Z}_{21} \\ 1 & -\underline{Z}_{22} \end{bmatrix} \tag{23}$$

- The $\underline{\boldsymbol{Z}}$ matrix expression, depending on the parameters $\underline{A}$, $\underline{B}$, $\underline{C}$ and $\underline{D}$ is as follows, [12]:

$$\underline{\boldsymbol{Z}} = \frac{1}{\underline{C}} \begin{bmatrix} \underline{A} & -\underline{A} \cdot \underline{D} + \underline{B} \cdot \underline{C} \\ 1 & -\underline{D} \end{bmatrix} \tag{24}$$

- The complex admittance matrix $\underline{\boldsymbol{Y}} = \begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{12} \\ \underline{Y}_{21} & \underline{Y}_{22} \end{bmatrix}$ can be expressed as a function of the $\underline{\boldsymbol{Z}}$ matrix elements as follows:

$$\underline{\boldsymbol{Y}} = \frac{1}{\underline{Z}_{11}\underline{Z}_{22} - \underline{Z}_{12}\underline{Z}_{21}} \begin{bmatrix} \underline{Z}_{22} & -\underline{Z}_{12} \\ -\underline{Z}_{21} & \underline{Z}_{11} \end{bmatrix} \quad (25)$$

In [1, 5] are presented the definition relations, expressed as functions of $\underline{S}$ parameters, for the reflection coefficients from: generator $\underline{\Gamma}_G$, load $\underline{\Gamma}_L$, input $\underline{\Gamma}_{in}$ and output $\underline{\Gamma}_{out}$.

The system consisting of two resonators (two coils) magnetically coupled and used for the wireless transfer of the electromagnetic power, can be considered as a passive linear two-port circuit and it is presented in Fig. 2.

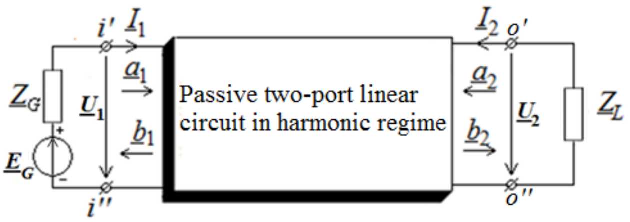


Fig. 2. Linear passive two-port circuit connected to the generator and load.

The active power generated (delivered) on the output port *o' – o''*, by the two-port circuit from the Fig. 2, has the following expression:

$$P_2 = P_L = -\operatorname{Re}\left(\underline{V}_2 \cdot \underline{I}_2^*\right) = -\left|\underline{a}_2\right|^2 + \left|\underline{b}_2\right|^2 \quad (26)$$

The loss of power is given by the difference between the powers P_1 and P_2:

$$P_{loss} = P_1 - P_2 = \left|\underline{a}_1\right|^2 + \left|\underline{a}_2\right|^2 - \left|\underline{b}_1\right|^2 - \left|\underline{b}_2\right|^2 = \left(\underline{\boldsymbol{a}}^*\right)^t \cdot \underline{\boldsymbol{a}} - \left(\underline{\boldsymbol{b}}^*\right)^t \cdot \underline{\boldsymbol{b}} \quad (27)$$

where $\underline{\boldsymbol{a}} = \begin{bmatrix} \underline{a}_1 \\ \underline{a}_2 \end{bmatrix}$ and $\underline{\boldsymbol{b}} = \begin{bmatrix} \underline{b}_1 \\ \underline{b}_2 \end{bmatrix}$.

If we consider that $\underline{\boldsymbol{b}} = \underline{\boldsymbol{S}} \cdot \underline{\boldsymbol{a}}$ with $\underline{\boldsymbol{S}} = \begin{bmatrix} \underline{S}_{11} & \underline{S}_{12} \\ \underline{S}_{21} & \underline{S}_{22} \end{bmatrix}$, the efficiency of the active power transmission from the emitting coil (from the input port *i' – i''*) to the load (to the output port *o' – o''*) can be calculated with the following relations:

$$\eta_{21} = \frac{P_2}{P_1}\cdot 100 = \frac{P_1 - P_{loss}}{P1}\cdot 100 \qquad (28)$$

The efficiency of signals transmission from input (from the input port *i' – i''*) to the load (to the output port *o' – o''*) has the expression:

$$\eta_{21\_\underline{S}_{21}} = \underline{S}_{21}\cdot\underline{S}_{21}^{*}\cdot 100 = \left|\underline{S}_{21}\right|^{2}\cdot 100 \qquad (29)$$

and the efficiency of signals transmission from output (from the output port *o' – o''*) to the generator (to the input port *i' – i''*) is calculated with the relation:

$$\eta_{12\_\underline{S}_{12}} = \underline{S}_{12}\cdot\underline{S}_{12}^{*}\cdot 100 = \left|\underline{S}_{12}\right|^{2}\cdot 100 \qquad (30)$$

According to maximum power transfer theorem, the load receives the maximum power if $\underline{Z}_L = \underline{Z}_{out}^{*}$ and it has the expression:

$$P_{L\_\max} = \frac{V_{Thef}^{2}}{4\cdot \mathrm{Re}\left(\underline{Z}_{out}\right)} \qquad (31)$$

The parameters of the Thévenin equivalent circuit, $\underline{V}_{Thev} = \underline{U}_{L0} = \underline{U}_2\big|_{\underline{Z}_L\to\infty}$, $\underline{I}_{2sc} = \underline{I}_{Lsc} = \underline{I}_2\big|_{\underline{Z}_L=0}$ and $\underline{Z}_{out} = \underline{Z}_{L0} = \underline{U}_{L0} / \underline{I}_{Lsc}$ can be determined, easily, as follows: there is analyzed the given circuit, calling the *CSAP* software program, [14 - 16], in the full or partial symbolic form (obviously, the parameters of the circuit branch in relation to which the equivalent Thévenin circuit is calculated, are considered symbolic), then there are calculated the expressions of these parameters, using the definition relations for the Thévenin equivalent circuit parameters, as presented above.

$\underline{S}$ parameters allow to study the two-port circuits using the Smith diagram [18].

3. Examples

Example 3.1: There are considered two magnetically coupled printed coils, having the SPICE equivalent scheme obtained with the ANSYS EXTRACTOR Q3D software program [9], which is given in Fig. 3.

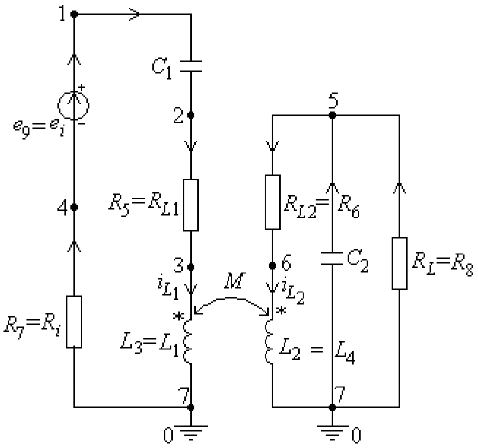


Fig. 3. The equivalent SPICE circuit obtained with the EXTRACTOR Q3D program.

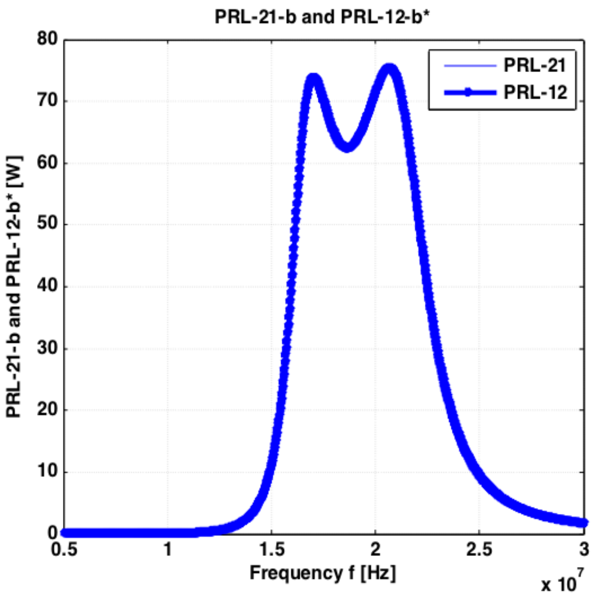
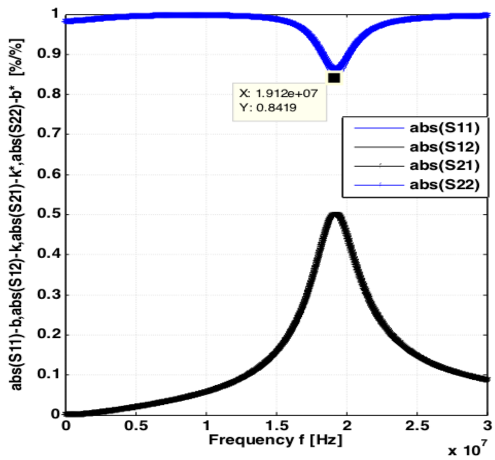


Fig. 4. P_{RL_21} and P_{RL_12} vs frequency.

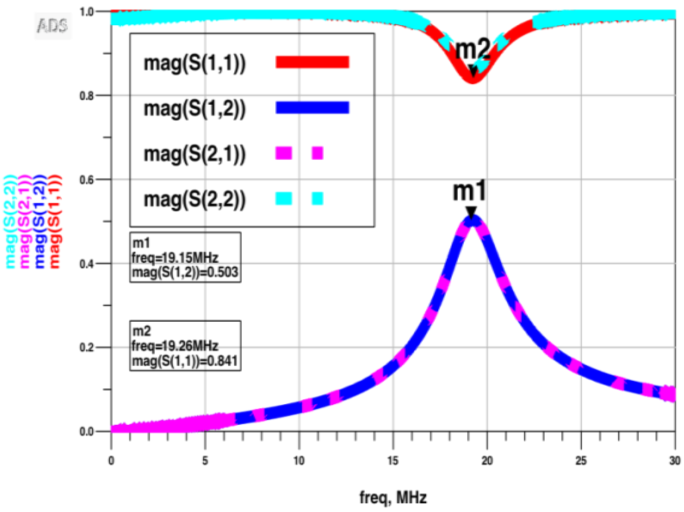
The numerical values of the parameters for the circuits shown in the Fig. 3 are as follows: L_1 = 2.925 μH; L_2 = 2.445 μH ;M = 0.66856 μH; R_{L1} = 0.55 Ω; R_{L2} = 0.45; C_1 = 25.0 pf; C_2 = 31.0 pF; E_i = 124.0 V; R_c = 50.0 Ω; $R_i = R_c$; $R_L = R_c$ and f_0 = 18.454988 MHz.

Running the routines implemented in MATLAB, for the considered example, the results were obtained, as follows. Fig. 4 shows the frequency variations of: the active power transmitted from the input to the output P_{RL_21} and, respectively, the active power transmitted from the output to the input P_{RL_12}, for SWTP (System Wireless Transfer Power). Variations with the frequency for the two powers are identical, because the two-port circuit corresponding to the two magnetically coupled coils from Fig. 3 is symmetrical (the two resonators are practically identical).

Figs. 5, a and b show variations with the frequency for the magnitudes of scattering parameters $\underline{S}_{11}$, $\underline{S}_{12}$, $\underline{S}_{22}$ and $\underline{S}_{21}$ obtained with the *SCAP* software program, [14 - 16], respectively with the *ADS* software application, [9, 10]. There is observed that the variations for the magnitudes of $\underline{S}_{11}$ and $\underline{S}_{22}$ ($\underline{S}_{12}$ and $\underline{S}_{21}$) parameters are identical, and the STWP in Fig. 3 is symmetrical. Figs. 5, a and b highlight the correctness of the procedures used to calculate the $\underline{S}$ parameters with the *SCAP* software program, respectively *ADS*, because the values obtained with the two software applications are identical.



(a)



(b)

Fig. 5. Mag($\underline{S}_{11}$), mag($\underline{S}_{12}$), mag($\underline{S}_{21}$), and mag($\underline{S}_{22}$) vs frequency: a) With *CSAP*; b) With *ADS*.

Variations with the frequency for the magnitudes for the coefficients of reflection from the generator $\underline{\Gamma}_G$, from the load $\underline{\Gamma}_L$, from the input $\underline{\Gamma}_{in}$ and the output $\underline{\Gamma}_{out}$ have been shown in Fig. 6. Because the two-port circuit corresponding to the two magnetically coupled resonators in Fig. 3 is symmetrical (the two magnetically coupled resonators are identical), the variations with the frequency for the magnitudes of the reflection coefficients $\underline{\Gamma}_{in}$ and $\underline{\Gamma}_{out}$ overlap.

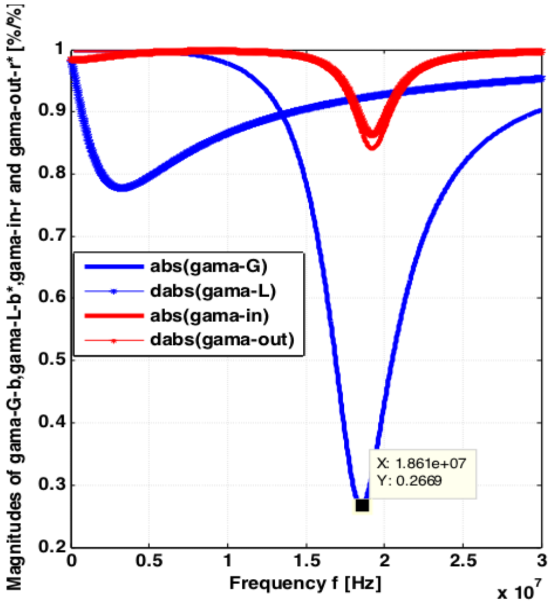


Fig. 6. Mag($\underline{\Gamma}_G$), mag($\underline{\Gamma}_L$), mag($\underline{\Gamma}_{in}$) and mag($\underline{\Gamma}_{out}$) vs frequency.

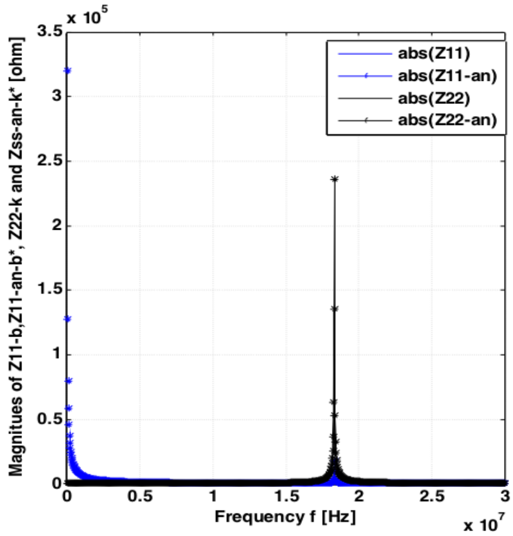


Fig. 7. Mag($\underline{Z}_{11}$), mag($\underline{Z}_{11\_an}$), mag ($\underline{Z}_{22}$) and mag($\underline{Z}_{22\_an}$) vs frequency.

Variations with the frequency for the complex impedance magnitudes $\underline{Z}_{11}$ and $\underline{Z}_{22}$ are calculated by formula (2) (the analytical ones) and with the relation (17). There can be observed, from Fig. 7, that variations with the frequency for the two impedance magnitudes, calculated with formulas (2) and (17), certify the validity of the proposed calculation procedures.

Fig. 8 shows variations with the frequency for the efficiencies η_{21}, η_{21_S21}, C_p*100, η_{12_S12}. From Fig. 8 there is observed that the variations of the transmissions efficiency for the active power and for the signals, from the input to the output, are identical with those ones transmitted from the output to the input, because the two-port circuit, with the two magnetically coupled resonators, from Fig. 3, is a symmetrical two-port circuit.

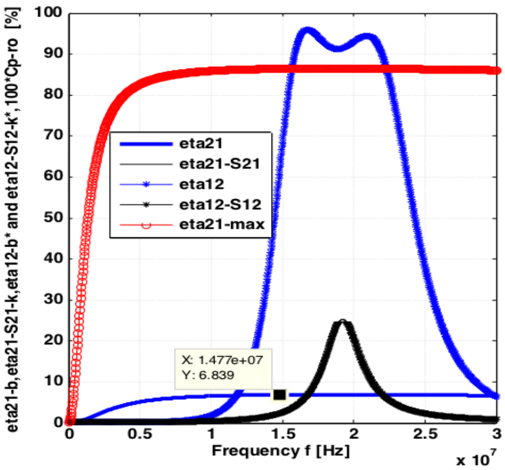


Fig. 8. Efficiencies vs frequency.

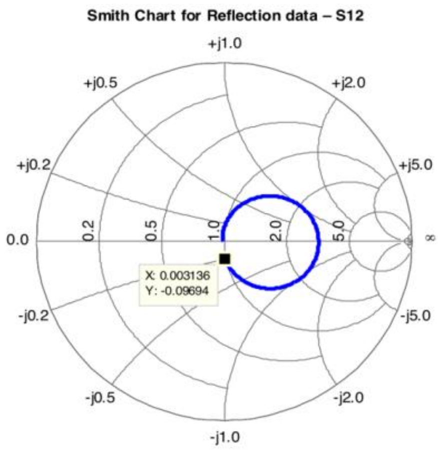


Fig. 9. Smith Diagram for $\underline{S}_{11}$ parameters corresponding to SWTP_SS from Fig. 3.

Figs. 9 and 10 show the variations with frequency on the Smith Diagram of $\underline{S}_{11}$ and $\underline{S}_{12}$ parameters, calculated with the *CSAP* software program, and in Fig. 11 are shown $\underline{S}$ parameters calculated with the *ADS* software application. The studied system of the two magnetically coupled resonators, being symmetrical, the Smith Diagrams of parameters $\underline{S}_{11}$ and $\underline{S}_{22}$ ($\underline{S}_{12}$ and $\underline{S}_{21}$) are identical.

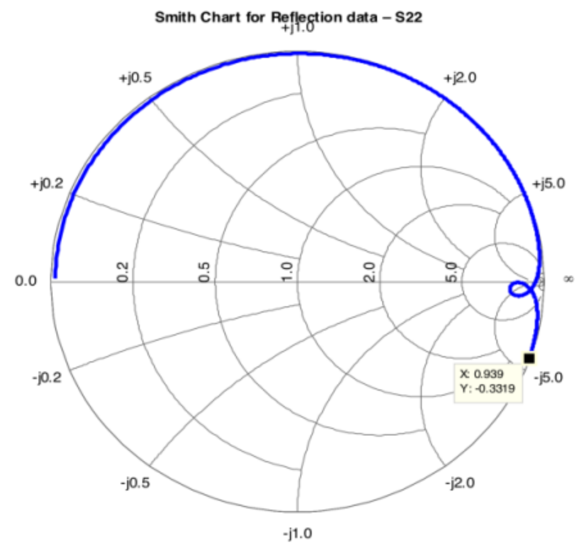


Fig. 10. Smith Diagram for $\underline{S}_{22}$ parameters calculated with *CSAP*.

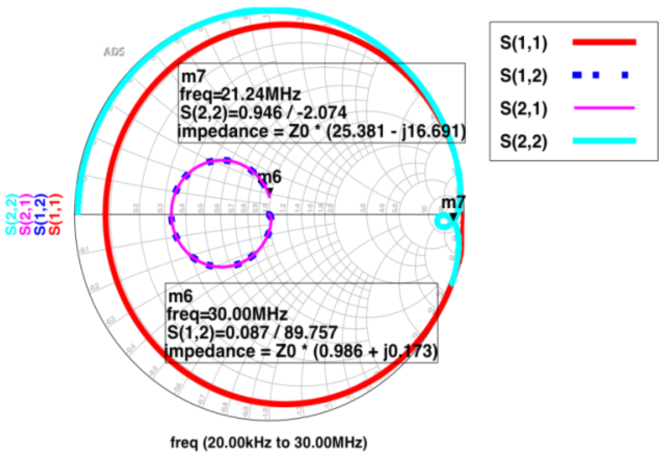


Fig. 11. Smith Diagram for $\underline{S}$ parameters calculated with *ADS*.

From Figs. 9 and 10, there is noticed that variations with the frequency for $\underline{S}_{11}$ and $\underline{S}_{12}$ parameters, on the Smith Diagram, calculated with the *CSAP* software program and, respectively, with the *ADS* software application, overlap, confirming once again the validity of the simulation procedures used.

Example 3.2: To study the *m* type filter from Fig. 12. The *CSAP* software program [14 - 16] is called again to analyze the non-dissipative filter from Fig. 12.

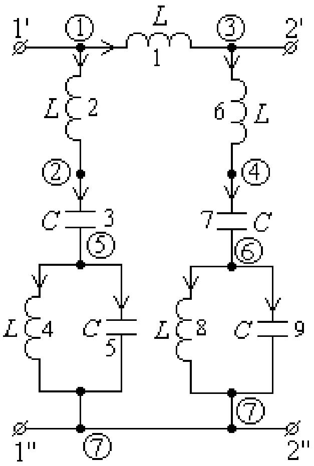


Fig. 12. M type filter scheme.

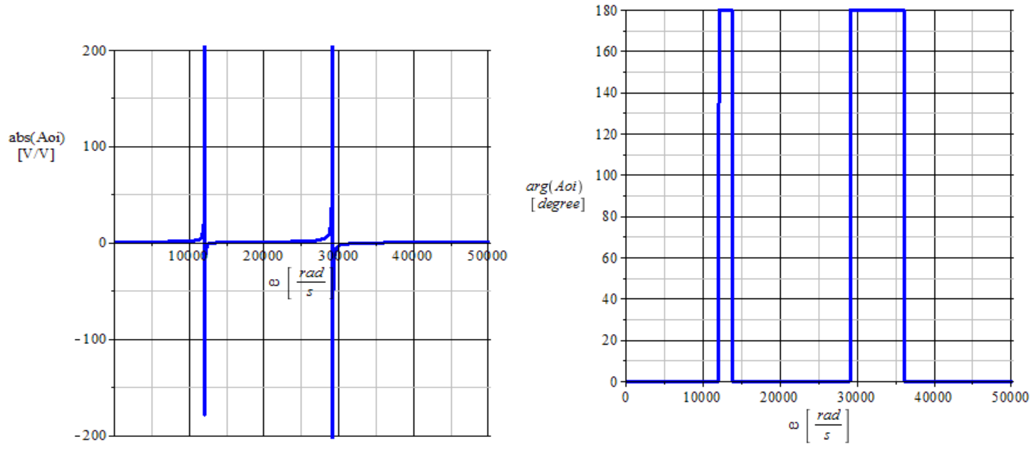
After generating the $\underline{S}$ parameters, all the parameters described in paragraph 2 can be calculated. For example, for numerical values L = 1mH and C = 2.0 μF, the fundamental (transfer) parameters matrix $\underline{\boldsymbol{T}}$ has the following structure:

$$T := \begin{bmatrix} \frac{2.\,(\omega^4 - 0.1\ 10^{10}\ \omega^2 + 0.125\ 10^{18})}{0.25\ 10^{18} - 0.15\ 10^{10}\ \omega^2 + \omega^4} & 0.001\ I\ \omega \\ \frac{-1000.\ I\ \omega\,(3.\ \omega^6 - 0.5\ 10^{10}\ \omega^4 + 0.225\ 10^{19}\ \omega^2 - 0.25\ 10^{27})}{\omega^8 - 0.30\ 10^{10}\ \omega^6 + 0.275\ 10^{19}\ \omega^4 - 0.75\ 10^{27}\ \omega^2 + 0.625\ 10^{35}} & \frac{2.\,(\omega^4 - 0.1\ 10^{10}\ \omega^2 + 0.125\ 10^{18})}{0.25\ 10^{18} - 0.15\ 10^{10}\ \omega^2 + \omega^4} \end{bmatrix} \quad (27)$$

From the expression (27) there is noticed that the filter from Fig. 12 is symmetrical ($\underline{A} = \underline{D}$). The transfer (amplification) factor of the filter, Aoi_f = 1.0/A, has, depending on the frequency, the following expression:

$$Aoi\_f := \frac{1.0\,(0.622155\ 10^{-14}\, f^4 - 0.236630\ 10^{-6}\, f^2 + 1.)}{0.124431\ 10^{-13}\, f^4 - 0.315507\ 10^{-6}\, f^2 + 1.} \quad (28)$$

The variation with the frequency for the amplitude (phase) of the transfer (amplification) factor in voltage, A_{oi} is shown in Fig. 13, a (Fig. 13, b).



(a) (b)

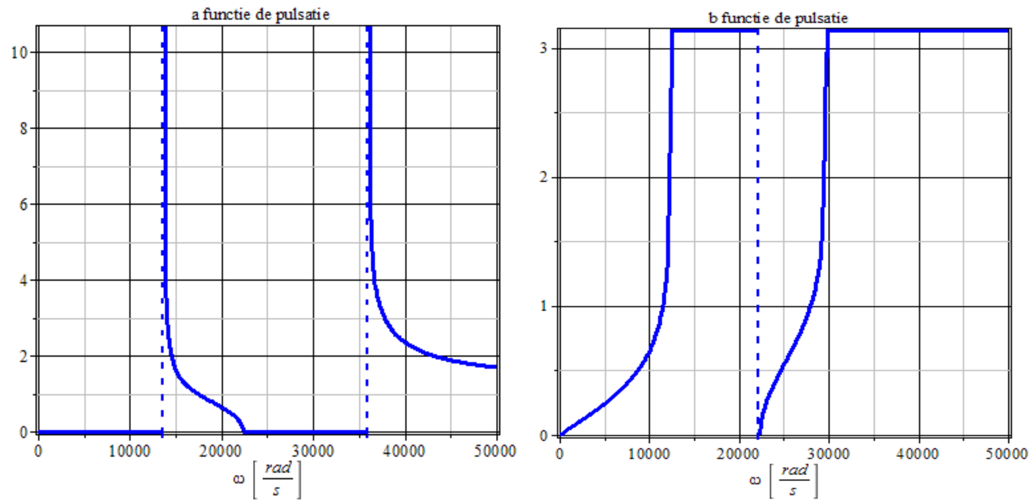
Fig. 13. a) The variation with the frequency for Aoi_f magnitude; b) The variation with the frequency for A_{oi_f} phase.

Using the expressions (18), (19) and (20), there can be calculated the passing and stop intervals for the filter and, implicitly its nature:

$$w \in \left[0,\ 12909.944\right] \cup \left[22360.68,\ 31622.777\right] \text{ - passing intervals and} \quad (29)$$

$$w \in \left(12909.944,\ 22360.68\right) \cup \left(31622.777,\ \infty\right) \text{ - stop intervals.}$$

Therefore, the filter shown in Fig. 12 is a *m* type filter. The variations with the ω pulse for the attenuation factor *a* and for the phase constant *b* are shown in Fig. 14, a and respectively in Fig. 14, b.



(a) (b)

Fig. 14. a) The variation with the ω pulse for the attenuation factor *a*; b) The variation with the ω pulse for the phase constant *b*.

4. Conclusions

The paper presents the automatic generation, using dedicated simulation software programs, of $\underline{Z}$, $\underline{Y}$, and $\underline{T}$ parameters for the linear or non-linear quadrupoles, but linearized on portions. Based on these parameters, the parameters that characterize the analog filters are determined, and the passing and stop frequency bands for the analyzed filters are calculated and obviously, implicitly the nature of these filters is determined. The obtained results from the definition relations are compared with those ones obtained as functions of $\underline{S}$ parameters. As the results obtained with the two procedures coincide, it proves that at high and very high frequencies it is indicated to use the procedures with $\underline{S}$ parameters, because these parameters can be easily measured at high frequencies.

Considering the two magnetically coupled coils, used as basic elements in the construction of wireless power transfer systems, as a passive linear two-port circuit in harmonic regime, all parameters mentioned above are determined, depending on the parameters $\underline{S}$. The paper presents the practical use of these parameters in the streamlining of processes related to the transmission and propagation of the information and to the transfer of the active power from the input (output) to the output (input).

For the analysis of linear analog circuits and non-linear analog circuits, but linearized on portions around to an operating point, there were implemented routines, based on the elaborated procedures, in the MAPLE and MATLAB programming environments, in order to calculate all the parameters mentioned above and to be able to compare the results obtained by simulation with those ones existing in the specialized literature and with the experimental ones.

The correct definition, based on the electrical circuits' theory, of the $\underline{S}$ parameters allowed their automatic generation, using the state equations or the modified nodal equations. Once the $\underline{S}$ parameters have been generated, for a set of frequencies there can be generated: $\underline{\boldsymbol{T}}$, $\underline{\boldsymbol{Z}}$ and $\underline{\boldsymbol{Y}}$ matrices; the reflection coefficients $\underline{\Gamma}_G$, $\underline{\Gamma}_L$, $\underline{\Gamma}_{in}$ and $\underline{\Gamma}_{out}$; active power transmission efficiencies η_{21} and η_{12}; signal transmission efficiencies η_{21_S21} and η_{12_S12}; input and output impedances $\underline{Z}_{\text{in}}$ and $\underline{Z}_{\text{out}}$ and the gain (efficiency) of the power transfer G_p, also called the operating gain and the Smith Diagrams for $\underline{S}$ parameters.

Comparing the variations with the frequency variations for the active power transmission efficiency η_{21} with the ones of the signal transmission η_{21_S21} and η_{12_S12}, there can be noticed that the frequencies corresponding to the extreme points are identical. Due to the symmetry, variations with the frequency for the signal transmission efficiencies η_{21_S21} and η_{12_S12} are identical.

The accuracy of $\underline{S}$ parameters definition, based on the theory of analog circuits in complex harmonic regime, is confirmed by the results obtained with the

ADS software program, provided with specific subroutines for $\underline{S}$ parameters generation.

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