Chapter 8

Two-Port Parameters of Autotransformer Discrete Alternating Voltage Regulators

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ABSTRACT

The present paper is dedicated to an unusual analysis of an autotransformer discrete alternating voltage regulator presented as a two-port with a load. The main purpose of the study is to determine the different sets of parameters (matrices) of this two-port – ABCD, B–, H-, G-, Z-, and Y-parameters and the characteristic parameters. A Matlab simulation model of the autotransformer discrete alternating voltage regulator with four commutators, realized by thyristor switches, corresponding to different supply voltages, is used for the analysis. The non-linearities of the regulator's circuit have been considered in the model.

The received results were experimentally verified in the case of an active load and a good coincidence of less than 1% was achieved. These parameters can be used for quick and accurate analysis of such a device in case of an arbitrary type of load – active, inductive, or capacitive. The obtained results could be used to improve the methodologies for designing such regulators.

Keywords: autotransformer discrete alternating voltage regulator, two-port, transmission matrix, hybrid parameters, G-parameters, Z-parameters, characteristic parameters.

1 INTRODUCTION

The autotransformer discrete alternating voltage regulators (ADAVR) are widely used in regulating the input supply voltage of household consumers https://www.collinsdictionary.com/dictionary/english/in_1https://www.collinsdictionary.com/dictionary/english/order to improve the quality of the electrical energy and to prevent damage to electrical equipment in emergency modes of power grids [1-8]. This type of regulator has been the subject of many years of research in various scientific publications [9-24]. Their precise analysis and simulation is usually very difficult task. The purpose of the present study is to examine an ADAVR with four switching levels at different values of the input voltage as a two-port (TP) and to obtain its ABCD parameters, B – parameters, hybrid parameters (H-parameters), G-parameters, Z-parameters, Y-parameters and the characteristic parameters (characteristic impedances, propagation constant, attenuation constant and phase constant) and the specific systems of equations at the arbitrary type of the load – active, inductive or capacitive. This new approach for research of such devices allows their quick and accurate analysis at any type of their load.

The scheme of the studied regulator, which includes four semiconductor commutating elements $S_1 \div S_4$ (thyristor switches), is shown in Fig. 1 [25]. The replacement circuit of the ADAVR as a TP is given in Fig. 2, where:

- The input terminals are (1) and (1’);
- The output terminals are (2) and (2’);
- $\dot{I}_1$ and $\dot{U}_1$ are the phasors of the input current and the input voltage;
- $\dot{I}_2$ and $\dot{U}_2$ are the phasors of the output current and the output voltage;
- $\dot{E}_1$ is the phasor of the supply voltage of the input source;
- Z_L is the impedance of the load.

Fig. 1. Equivalent circuit of ADAVR with four levels of switching according to the values of the input supply voltage.

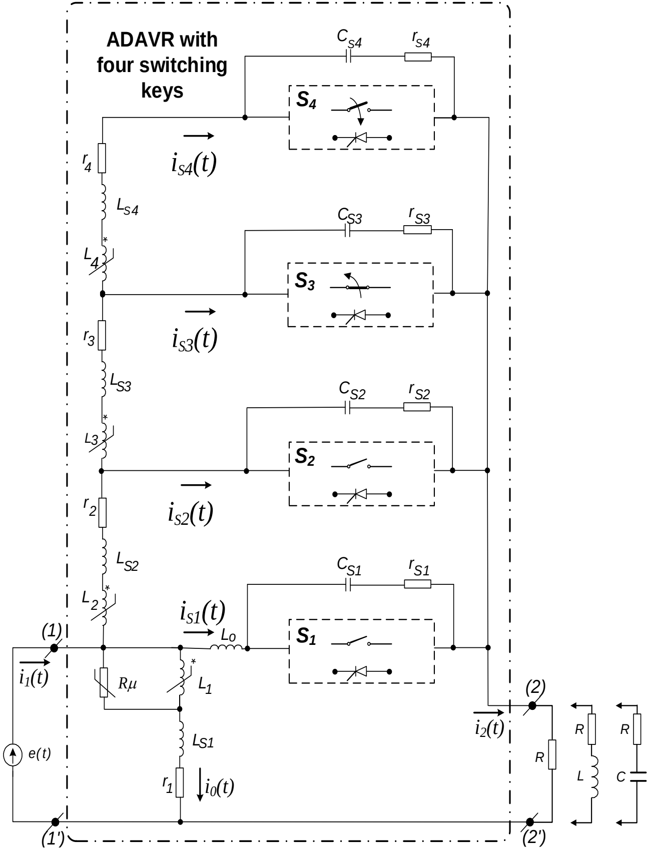
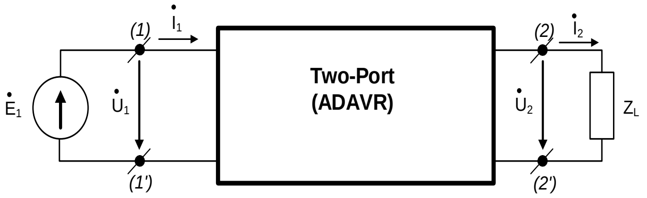


Fig. 2. Replacement circuit of an ADAVR explored as a TP at forward transmission.



Here, the study is carried out in the case of forward transmission of the TP.

For the investigated ADAVR the input and the output quantities (currents and voltages) had been determined at different loads and values of the supply voltage in previous research by conducting simulations and experiments [11-13, 21, 22]. The simulations were performed in the environment of MATLAB by using a previously created non-linear model by the authors [15-19]. The final results were compared with the experimental data and the achieved correspondence was very good. The following peculiarities were taken into account in the study of the explored regulator:

- the ferromagnetic core of the autotransformer;
- the commutation groups;
- the switch-off assemblies;
- the separate sections of the winding.

The existing non-linearity caused by the ferromagnetic core of the autotransformer was also considered.

2 RESULTS

There is a great practical interest to determine the ABCD parameters of the transmission equations, which form the corresponding transmission system of equations (1) of the TP (the so-called A – a system of equations) for the case of forward transmission [25]:

$$\left| \begin{array}{l} \dot{U}_1 = A\dot{U}_2 + B\dot{I}_2 \\ \dot{I}_1 = C\dot{U}_2 + D\dot{I}_2 \end{array} \right. \tag{1}$$

System (1) allows the determination of the input current and voltage of the TP at known values of the phasors of the output current and voltage.

The ABCD parameters of the A-matrix can be calculated with the help of the input impedances at two different regimes:

a) when there is an open circuit at the output terminals of the TP - $Z_{1\ O.C.}$ (2);

b) when there is a short circuit at the output terminals of the TP - $Z_{1\ S.C.}$ (3):

$$Z_{1O.C.} = Z_{1-1'}\big|_{Z_L=\infty} = Z_{input}\big|_{Z_L=\infty} \tag{2}$$

$$Z_{1S.C.} = Z_{1-1'}\Big|_{Z_L=0} = Z_{input}\Big|_{Z_L=0} \tag{3}$$

The connections between the two impedances and the ABCD parameters of the A-matrix are as follows:

$$\left| \begin{array}{l} A = C \cdot Z_{1O.C.} \\ B = D \cdot Z_{1S.C.} \end{array} \right. \tag{4}$$

After replacing (4) in (1) the following formulas for the ABCD parameters can be extracted:

$$\left| \begin{array}{l} A = \dfrac{Z_{1O.C.}(Z_{1S.C.}\dot{I}_1 - \dot{U}_1)}{(Z_{1S.C} - Z_{1O.C.})\dot{U}_2} \\ B = \dfrac{Z_{1S.C.}(\dot{U}_1 - Z_{1O.C.}\dot{I}_1)}{(Z_{1S.C} - Z_{1O.C.})\dot{I}_2} \\ C = \dfrac{Z_{1S.C.}\dot{I}_1 - \dot{U}_1}{(Z_{1S.C} - Z_{1O.C.})\dot{U}_2} \\ D = \dfrac{\dot{U}_1 - Z_{1O.C.}\dot{I}_1}{(Z_{1S.C} - Z_{1O.C.})\dot{I}_2} \end{array} \right. \tag{5}$$

The analysis of the explored ADAVR as a TP at the different levels of commutation was done with the help of the conditional linearization method.

The B-system of equations for forward transmission of the TP is the following:

$$\left| \begin{array}{l} \dot{U}_2 = B_{11}\dot{U}_1 + B_{12}\dot{I}_1 \\ \dot{I}_2 = B_{21}\dot{U}_1 + B_{22}\dot{I}_1 \end{array} \right. \tag{6}$$

The B-matrix can also be obtained by the ABCD parameters by (7):

$$[B] = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} = \frac{1}{\Delta A}\begin{bmatrix} D & -B \\ -C & A \end{bmatrix} = \frac{1}{AD - BC}\begin{bmatrix} D & -B \\ -C & A \end{bmatrix} \tag{7}$$

The H - parameters and equations are also important because the considered devices are objects of the power electronics and it is necessary to know or to be able to determine quickly their parameters such as current and voltage gains and others. Since the H-parameters do not provide the complete set of parameters from a practical point of view, it is convenient to find the G-parameters, as well.

The hybrid system of equations of the two-port (the so-called H - system) in case of forward transmission is the next one (8) [26, 27]:

$$\left| \begin{array}{l} \dot{U}_1 = H_{11} \cdot \dot{I}_1 + H_{12} \cdot \dot{U}_2 \\ \dot{I}_2 = H_{21} \cdot \dot{I}_1 + H_{22} \cdot \dot{U}_2 \end{array} \right. . \tag{8}$$

System (8) gives the opportunity, if we know the input voltage $\dot{U}_1$ and the load Z_L, to be determined the input current $\dot{I}_1$, the output current $\dot{I}_2$, and the output voltage $\dot{U}_2$ of the two-port.

The hybrid parameters of the H - matrix are the following [27]:

$$\left| \begin{array}{l} H_{11} = Z_{1S.C.} \\ H_{12} = \dfrac{(Z_{1O.C.} - Z_{1S.C.}) \cdot (Z_{1S.C.}\dot{I}_1 - \dot{U}_1)}{(Z_{1S.C.} - Z_{1O.C.}) \cdot \dot{U}_2} \\ H_{21} = \dfrac{(Z_{1S.C.} - Z_{1O.C.}) \cdot \dot{I}_2}{(\dot{U}_1 - Z_{1O.C.} \cdot \dot{I}_1)} \\ H_{22} = \dfrac{(\dot{U}_1 - Z_{1S.C.}\dot{I}_1) \cdot \dot{I}_2}{(\dot{U}_1 - Z_{1O.C.}\dot{I}_1) \cdot \dot{U}_2} \end{array} \right. \tag{9}$$

From an engineering point of view, important basic parameters of such an electronic device are the current and voltage forward gains during operation under load. Determining the H-parameters makes it possible to determine these two coefficients by (10) and (11) [27].

$$\dot{K}_{I_{21L}} = \frac{H_{21}}{1 - H_{22} \cdot Z_L} \tag{10}$$

$$\dot{K}_{U_{21L}} = \frac{Z_L \cdot H_{21}}{H_{11} - (H_{11} \cdot H_{22} - H_{12} \cdot H_{21}) \cdot Z_L} \tag{11}$$

Therefore, for the output load current $\dot{I}_{2L}$, the following is obtained:

$$\dot{I}_{2L} = \dot{K}_{I_{21L}} \cdot \dot{I}_1 = \frac{H_{21} \cdot \dot{E}}{H_{11} - (H_{11} \cdot H_{22} - H_{12} \cdot H_{21}) \cdot Z_L} \tag{12}$$

The H-system can be used also to determine the input impedance of the investigated device at a known load impedance:

$$Z_{IN} = H_{11} + \frac{H_{12} \cdot H_{21} \cdot Z_L}{1 - H_{22} \cdot Z_L} \tag{13}$$

The determination of the H-parameters allows being found the G-parameters of the studied two-port (14).

$$[G] = \frac{1}{\Delta H} \begin{bmatrix} H_{22} & -H_{12} \\ -H_{21} & H_{11} \end{bmatrix} = \frac{1}{H_{11} \cdot H_{22} - H_{12} \cdot H_{21}} \begin{bmatrix} H_{22} & -H_{12} \\ -H_{21} & H_{11} \end{bmatrix} \tag{14}$$

And the G-system of equations has the following form:

$$\left| \begin{array}{l} \dot{I}_1 = G_{11} \cdot \dot{U}_1 + G_{12} \cdot \dot{I}_2 \\ \dot{U}_2 = G_{21} \cdot \dot{U}_1 + G_{22} \cdot \dot{I}_2 \end{array} \right. \tag{15}$$

The Z-parameters and the characteristic parameters of any TP are also very important characteristics, which allow quick analysis of the explored device without very complex calculations. Except that, they provide very important (generalized) information about the properties of the investigated circuit [28].

The Z - system of the TP for the studied case at forward transmission is:

$$\left|\begin{array}{l} \dot{U}_1 = Z_{11}\dot{I}_1 + Z_{12}\dot{I}_2 \\ -\dot{U}_2 = Z_{21}\dot{I}_1 + Z_{22}\dot{I}_2 \end{array}\right. \tag{16}$$

Here, Z_{11} is the open circuit input impedance; Z_{12} and Z_{21} are the open circuit transfer impedances; Z_{22} is the open circuit output impedance.

The Z-parameters are calculated according to a set of equations (16) by using the parameters of the TP at 2 modes of the explored ADAVR at the output of the circuit – equations (2) and (3):

$$\left|\begin{array}{c} Z_{11} = Z_{1O.C.} \\ Z_{12} = \dfrac{\left(\dot{U}_1 - Z_{1O.C.}\dot{I}_1\right)}{\dot{I}_2} \\ Z_{21} = \dfrac{\left(Z_{1O.C.} - Z_{1S.C.}\right)\dot{U}_2}{\left(Z_{1S.C.}\dot{I}_1 - \dot{U}_1\right)} \\ Z_{22} = \dfrac{\left(\dot{U}_1 - Z_{1O.C.}\dot{I}_1\right)\dot{U}_2}{\left(Z_{1S.C.}\dot{I}_1 - \dot{U}_1\right)\dot{I}_2} \end{array}\right. \tag{17}$$

The Y - a system of the studied TP at forward transmission is:

$$\left|\begin{array}{l} \dot{I}_1 = Y_{11}\dot{U}_1 - Y_{12}\dot{U}_2 \\ \dot{I}_2 = Y_{21}\dot{U}_1 - Y_{22}\dot{U}_2 \end{array}\right. \tag{18}$$

The determination of the Z-parameters allows being found the Y-parameters of the studied TP (19).

$$[Y] = \frac{1}{\Delta Z}\begin{bmatrix} Z_{22} & -Z_{12} \\ -Z_{21} & Z_{11} \end{bmatrix} = \frac{1}{Z_{11}\cdot Z_{22} - Z_{12}\cdot Z_{21}}\begin{bmatrix} Z_{22} & -Z_{12} \\ -Z_{21} & Z_{11} \end{bmatrix} \tag{19}$$

The characteristic parameters of the studied ADAVR were also determined. They can be used for receiving the electrical parameters of the regulator by using the hyperbolic form of the A-matrix of the TP. Here:

$$\gamma = \alpha + j\beta = \alpha\left[Np\right] + j\beta\left[rad\right] = \ln(\sqrt{AD} + \sqrt{BC}) \tag{20}$$

$$Z_{C1} = \sqrt{\frac{AB}{CD}} \tag{21}$$

$$Z_{C2} = \sqrt{\frac{DB}{CA}} \tag{22}$$

$$\left| \begin{aligned} \dot{U}_1 &= \sqrt{\frac{Z_{c1}}{Z_{c2}}}\left[\left(ch\gamma\right)\dot{U}_2 + \left(Z_{c2}sh\gamma\right)\dot{I}_2\right] \\ \dot{I}_1 &= \sqrt{\frac{Z_{c2}}{Z_{c1}}}\left[\left(\frac{sh\gamma}{Z_{c2}}\right)\dot{U}_2 + \left(ch\gamma\right)\dot{I}_2\right] \end{aligned} \right. \tag{23}$$

where:

- Z_{c1} and Z_{c2} are the characteristic impedances, *Ω;*
- γ is the propagation constant;
- α is the attenuation constant, *Np;*
- β is the phase constant, *rad.*

The results for the values of the phasors of the input and the output currents and voltages for four intervals of the input supply voltage, which correspond to different closed switches (S_1÷S_4) are presented in an exponential form in Table 1 [27]. These results were verified experimentally with the help of a series of vector measurements [17, 18].

Table 1. Input and output quantities of ADAVR for the different commutation levels at R_L=3,4921Ω [27]

Closed switch	***S₁***		***S₂***		***S₃***		***S₄***	
Supply voltag *E*, V	220	200,1	200	180,1	180	160,1	160	150
Input current $\dot{I}_1$, A	$63{,}114\,e^{-j0{,}867^\circ}$	$57{,}405\,e^{-j0{,}867^\circ}$	$69{,}02\,e^{-j2{,}0437^\circ}$	$62{,}152\,e^{-j2{,}0437^\circ}$	$74{,}851e^{-j9{,}875^\circ}$	$66{,}576e^{-j9{,}875^\circ}$	$70{,}039\,e^{-j34{,}661^\circ}$	$65{,}662\,e^{-j34{,}661^\circ}$
The input voltage $\dot{U}_1$, V	$220e^{j0^\circ}$	$200{,}1e^{j0^\circ}$	$200{,}1e^{j0^\circ}$	$180{,}1e^{j0^\circ}$	$180{,}1e^{j0^\circ}$	$160{,}1e^{j0^\circ}$	$160{,}1e^{j0^\circ}$	$150{,}1e^{j0^\circ}$
Output curren $\dot{I}_2$, A	$63\,e^{-j3{,}782.10^{-15}{}^\circ}$	$57{,}301\,e^{-j3{,}782.10^{-15}{}^\circ}$	$62{,}741e^{-j1{,}5601^\circ}$	$56{,}498e^{-j1{,}5601^\circ}$	$61{,}428e^{-j9{,}652^\circ}$	$54{,}637e^{-j9{,}6522^\circ}$	$51{,}041\,e^{-j34{,}57^\circ}$	$47{,}851\,e^{-j34{,}57^\circ}$
The output voltage $\dot{U}_2$ V	$220\,e^{-j3{,}782.10^{-15}{}^\circ}$	$200{,}1\,e^{-j3{,}782.10^{-15}{}^\circ}$	$219{,}1e^{-j1{,}5601^\circ}$	$197{,}3e^{-j1{,}5601^\circ}$	$214{,}51e^{-j9{,}652^\circ}$	$190{,}79e^{-j9{,}6522^\circ}$	$178{,}24e^{-j34{,}57^\circ}$	$167{,}1\,e^{-j34{,}57^\circ}$
	$3{,}486\,e^{j0{,}867^\circ}$		$2{,}898e^{j2{,}044^\circ}$		$2{,}405e^{j9{,}875^\circ}$		$2{,}284e^{j34{,}661^\circ}$	

The values of the ABCD parameters of the A-matrix were calculated based on the received results for the input and the output currents and voltages of the TP for the different intervals of the input supply voltage, when only one of the switches $S_1 \div S_4$ is closed – Table 2 [25].

Table 2. ABCD parameters of the A-system at R_L=3,4921Ω

Closed switch	$\boldsymbol{S_1}$	$\boldsymbol{S_2}$	$\boldsymbol{S_3}$	$\boldsymbol{S_4}$
Supply voltage E, V	200,1V÷220V	180,1V÷200V	160,1V÷180V	150÷160V
A	$1e^{j7{,}1498.10^{-16}\circ}$	$0{,}91044e^{j3{,}101.10^{-3}\circ}$	$0{,}82219e^{j9{,}1346.10^{-3}\circ}$	$0{,}73038e^{j1{,}1988.10^{-2}\circ}$
B, Ω	$1{,}8206.10^{-15}e^{j173{,}61^\circ}$	$8{,}6923.10^{-2}e^{j85{,}206^\circ}$	$0{,}49118e^{j87{,}936^\circ}$	$1{,}7783e^{j89{,}009^\circ}$
C, S	$4{,}3674.10^{-3}e^{-j83{,}591^\circ}$	$2{,}482.10^{-3}e^{-j81{,}921^\circ}$	$1{,}4216.10^{-3}e^{-j73{,}469^\circ}$	$8{,}3447.10^{-4}e^{-j65{,}781^\circ}$
D	$1e^{j1{,}42.10^{-5}\circ}$	$1{,}0988e^{-j3{,}6694.10^{-2}\circ}$	$1{,}2171e^{j5{,}4838.10^{-4}\circ}$	$1{,}371e^{j1{,}9191.10^{-2}\circ}$

The A-matrix was used for the analysis of I_1, U_2, and I_2 at values of the load resistance R_L= 35,552Ω; 11Ω; 5,5Ω; 3,4921Ω for the interval of the input supply voltage $E=U_1$=220V÷160V and especially for E=220V, E=200V, E=180V, E=160V. The simulation results, which were received, coincide with those of the physical experiments with an accuracy of less than 1%.

The results for the B-parameters are shown in Table 3.

Table 3. Elements of the B-matrix at R_L=3,4921Ω

Closed switch	$\boldsymbol{S_1}$	$\boldsymbol{S_2}$	$\boldsymbol{S_3}$	$\boldsymbol{S_4}$
Supply voltage E , V	200,1V÷220V	180,1V÷200V	160,1V÷180V	150÷160V
B_{11}	$1e^{-j2{,}594.10^{-16}\circ}$	$1{,}0986e^{-j2{,}3856.10^{-3}\circ}$	$1{,}2171e^{j8{,}5338.10^{-4}\circ}$	$1{,}371e^{j2{,}1504.10^{-2}\circ}$
B_{12}, Ω	$1{,}8206.10^{-15}e^{j6{,}3939^\circ}$	$8{,}6907.10^{-2}e^{-j94{,}76^\circ}$	$0{,}4912e^{-j92{,}064^\circ}$	$1{,}7784e^{-j90{,}988^\circ}$
B_{21}, S	$4{,}3674.10^{-3}e^{j96{,}409^\circ}$	$2{,}4815.10^{-3}e^{j98{,}113^\circ}$	$1{,}4216.10^{-3}e^{j106{,}53^\circ}$	$8{,}3448.10^{-4}e^{j114{,}22^\circ}$
B_{22}	$1e^{-j1{,}42.10^{-5}\circ}$	$0{,}9103e^{j3{,}7409.10^{-2}\circ}$	$0{,}8222e^{j9{,}4398.10^{-3}\circ}$	$0{,}7304e^{j1{,}4301.10^{-2}\circ}$

The H- and G- parameters are presented in Table 4 and Table 5 [27].

Table 4. Elements of the H-system at R_L=3,4921Ω

Closed switch	$\boldsymbol{S_1}$	$\boldsymbol{S_2}$	$\boldsymbol{S_3}$	$\boldsymbol{S_4}$
Supply voltage E , V	200,1V÷220V	180,1V÷200V	160,1V÷180V	150÷160V
H_{11}, *Ω*	$1{,}8206.10^{-15}e^{j173{,}61^\circ}$	$7{,}9107.10^{-2}e^{j85{,}242^\circ}$	$0{,}40356e^{j87{,}935^\circ}$	$1{,}2971e^{j88{,}99^\circ}$
H_{12}	$1e^{j2{,}5941.10^{-16}\circ}$	$0{,}91025e^{j2{,}3856.10^{-3}\circ}$	$0{,}82163e^{-j8{,}5358.10^{-4}\circ}$	$0{,}72938e^{-j2{,}1504.10^{-2}\circ}$
H_{21}	$1e^{-j1{,}42.10^{-5}\circ}$	$0{,}91007e^{j3{,}6694.10^{-2}\circ}$	$0{,}82162e^{-j5{,}4838.10^{-4}\circ}$	$0{,}72939e^{-j1{,}9191.10^{-2}\circ}$
H_{22}, *S*	$4{,}3674.10^{-3}e^{j96{,}409^\circ}$	$2{,}2588.10^{-3}e^{j98{,}116^\circ}$	$1{,}1681.10^{-3}e^{j106{,}53^\circ}$	$6{,}0865.10^{-4}e^{j114{,}2^\circ}$

Table 5. Elements of the G-system at R_L=3,4921Ω

Closed switch	S_1	S_2	S_3	S_4
Supply voltage E , V	200,1 V÷220V	180,1V÷ 200V	160,1V ÷180V	150÷160 V
G_{11}, *S*	$4,3674.10^{-3}e^{-j83,591°}$	$2,7261.10^{-3}e^{-j81,924°}$	$1,7291.10^{-3}e^{-j73,478°}$	$1,1425.10^{-3}e^{-j65,793°}$
G_{12}	$1e^{j1,42.10^{-5}\circ}$	$1,0986e^{-j3,7409.10^{-2}\circ}$	$1,2163e^{-j9,4398.10^{-3}\circ}$	$1,3691e^{-j1,4301.10^{-2}\circ}$
G_{21}	$1e^{-j7,1499.10^{-16}\circ}$	$1,0984e^{-j3,101.10^{-3}\circ}$	$1,2163e^{-j9,1346.10^{-3}\circ}$	$1,3692e^{-j1,1988.10^{-2}\circ}$
G_{22}, *Ω*	$1,8206.10^{-15}e^{-j6,3939°}$	$9,5474.10^{-2}e^{-j94,797°}$	$0,5974e^{-j92,073°}$	$2,4348e^{-j91,003°}$

The received values of the Z- and Y-parameters are presented in Table 6 [28] and Table 7.

Table 6. Parameters of the Z-matrix at R_L=3,4921Ω

Closed switch	S_1	S_2	S_3	S_4
Supply voltage E , V	200,1V÷220V	180,1V÷200V	160,1V÷180V	150÷160V
Z_{11}, *Ω*	$228,97e^{j83,591°}$	$366,82e^{j81,924°}$	$578,34e^{j73,478°}$	$875,25e^{j65,793°}$
Z_{12}, *Ω*	$228,97e^{-j96,409°}$	$402,98e^{-j98,113°}$	$703,42e^{-j106,53°}$	$1198,4e^{-j114,22°}$
Z_{21}, *Ω*	$228,97e^{-j96,409°}$	$402,9e^{-j98,079°}$	$703,41e^{-j106,53°}$	$1198,4e^{-j114,22°}$
Z_{22}, *Ω*	$228,97e^{j83,591°}$	$442,71e^{j81,884°}$	$856,13e^{j73,469°}$	$1643e^{j65,8°}$

Table 7. Parameters of the Y-matrix at R_L=3,4921Ω

Closed switch	S_1	S_2	S_3	S_4
Supply voltage E , V	200,1V÷220V	180,1V÷200V	160,1V÷180V	150÷160V
Y_{11}, *S*	$5,4926.10^{14}e^{-j173,61°}$	$12,641e^{-j85,242°}$	$2,4779e^{-j87,935°}$	$0,7709e^{-j88,99°}$
Y_{12}, *S*	$5,4926.10^{14}e^{-j173,61°}$	$11,507e^{-j85,24°}$	$2,036e^{-j87,936°}$	$0,5623e^{-j89,012°}$
Y_{21}, *S*	$5,4926.10^{14}e^{-j173,61°}$	$11,504e^{-j85,206°}$	$2,0359e^{-j87,936°}$	$0,5623e^{-j89,009°}$
Y_{22}, *S*	$5,4926.10^{14}e^{-j173,61°}$	$10,474e^{-j85,203°}$	$1,6739e^{-j87,927°}$	$0,4107e^{-j88,997°}$

The characteristic parameters of the studied ADAVR are presented in Table 8 [28].

Table 8. Characteristic parameters of the ADAVR

Case / **Para-meter**	S_1 ***– switched on***	S_2 ***- switched on***	S_3 ***- switched on***	S_4 ***- switched on***
Z_{c1}, *Ω*	$6,456.10^{-7}e^{-j51,401°}$	$5,3868e^{j83,583°}$	$15,277e^{j80,707°}$	$33,649e^{j77,391°}$
Z_{c2}, *Ω*	$6,456.10^{-7}e^{-j51,401°}$	$6,503e^{j83,543°}$	$22,615e^{j80,698°}$	$63,249e^{j77,399°}$
α, Np	$-1,998.10^{-6}$	$1,478.10^{-2}$	$2,622.10^{-2}$	$3,772.10^{-2}$
β, rad	$1,259.10^{-7}$	$1,259.10^{-4}$	$3,324.10^{-3}$	$7,731.10^{-3}$

3 ANALYSIS

In the case, when the switch S_1 is closed, from the results obtained in Table 2 ÷ Table 7, it can be noted that the condition for reciprocity of the TP is fulfilled ($AD-BC=1+j2,4784.10^{-7}\approx 1$, $B_{11}\cdot B_{22}$ - $B_{12}\cdot B_{21}=1$, $H_{12}\approx H_{21}$, $G_{12}\approx G_{21}$, $Z_{12}\approx Z_{21}$, $Y_{12}\approx Y_{21}$). Since $A\approx D$, $B_{11}\approx B_{22}$, $-H_{11}\cdot H_{22}+H_{12}\cdot H_{21}=-1$, $-\det G\approx 1$, $Z_{11}=Z_{22}$, $Y_{11}\approx Y_{22}$ and $Z_{C1}=Z_{C2}$ it can be noted that the explored TP is symmetrical one.

In the cases of closed switches S_2, S_2 or S_4 the conditions for reciprocity are satisfied for the obtained A-matrices, but in these cases the TP is not symmetrical.

From the results, obtained for the A - matrices of the ADAVR considered as a TP in Table 2, the following dependences are observed:

- The module of the parameter A decreases from 1 to 0,73038 and the phase of the same parameter A increases from $7,1498.10^{-16\circ}$ to $1,1988.10^{-2\circ}$;
- The module of the parameter B increases from $1,8206.10^{-15}\Omega$ to $1,7783\Omega$ and the phase of B decreases from 173,61° to about 85 ÷ 89°;
- The module of the parameter C decreases from 4,3674S to $8,3447.10^{-4}$S and the phase of C decreases from -83,591° to -65,781°;
- The module of the parameter D increases from 1 to 1,371, and the phase of D changes from -3,6694.$10^{-2\circ}$ to $1,9191.10^{-2\circ}$.

From the results, obtained for the B - matrices of the ADAVR considered as a TP in Table 3, the following dependences are observed:

- The module of B_{11} increases from 1 to 1,371 and the phase of the parameter changes from $-2,3856.10^{-3\circ}$ and $2,1504.10^{-2\circ}$;
- The module of B_{12} increases from $1,8206.10^{-15}$ Ω to 1,7784 Ω and the phase of B_{12} changes from -6,3939° and -94,776°;
- The module of B_{21} decreases from $4,3674.10^{-3}$ S to $8,3448.10^{-4}$ S and the phase of B_{21} increases from 96,409° to 114,22°;
- The module of B_{22} decreases from 1 to 0,7304, and the phase of B_{22} increases from $-1,42.10^{-5\circ}$ to $1,4301.10^{-2\circ}$.

From the ADAVR, at decreasing the supply voltage from 200V to 150V, the following dependences are observed (Table 4 and Table 5):

- The absolute value of H_{11} rises from $1,8206.10^{-15}\Omega$ till $1,2971\Omega$ and its exponent reduces from 173,61° till 85°÷89°;
- The absolute value of H_{12} reduces from 1 till 0,72938 and its phase changes in the range from $2,1504.10^{-2\circ}$ till $2,3856.10^{-2\circ}$;
- The absolute value of H_{21} reduces from 1 till 0,72939 and its exponent changes in the range from $1,9191.10^{-2\circ}$ to $3,6694.10^{-2\circ}$;

- The absolute value of H_{22} reduces from $4,3674.10^{-3}$ S till $6,0865.10^{-4}$ S and its exponent rises from 96,409° till 114,2°;
- The absolute value of G_{11} reduces from $4,3674.10^{-3}$ S till $1,1425.10^{-3}$ S and its exponent rises from -83,591° till -65,793°;
- The absolute value of G_{12} rises from 1 till 1,3691 and its exponent changes in the range from $1,42.10^{-5\circ}$ till $-3,7409.10^{-2\circ}$;
- The absolute value of G_{21} rises from 1 till 1,3692 and its exponent reduces from $-7,1499.10^{-16\circ}$ till $-1,1988.10^{-2\circ}$;
- The absolute value of G_{22} rises from $1,8206.10^{-15}$ Ω till 2,4348 Ω and its exponent changes in the range from -6,3939° till -94,797°.

From the received Z-matrices in Table 6 the following conclusions can be made:

- The modulus of Z_{11} (the open circuit input impedance) increases from 228,97 Ω to 875,25 Ω; the phase of the same parameter goes down from 83,591° to 65,793°;
- The modulus of Z_{12} (the open-circuit transfer impedance) increases from 228,97 Ω to 1198,4 Ω and the phase of the same parameter decreases from -96,409° to -114,22°;
- The modulus of Z_{21} (the open-circuit transfer impedance) increases from 228,97 Ω to 1198,4 Ω and the phase of the same parameter decreases from -96,409° to -114,22°;
- The modulus of Z_{22} (the open circuit output impedance) increases from 228,97 Ω to 1643 Ω and the phase of the same parameter decreases from 83,591° to 65,8°.

From the received Y-matrices in Table 7 the following conclusions can be made:

- The modulus of Y_{11} decreases from $5,4926.10^{14}$ S to 0,7709 S; the phase of the same parameter changes from -173,61° to -85,242°;
- The modulus of Y_{12} decreases from $5,4926.10^{14}$ S to 0,5623 S and the phase of the same parameter changes from -173,61° to -85,24°;
- The modulus of Y_{21} decreases from $5,4926.10^{14}$ S to 0,5623 S and the phase of the same parameter changes from -173,61° to -85,206°;
- The modulus of Y_{22} decreases from $5,4926.10^{14}$ S to 0,4107 S and the phase of the same parameter changes from -173,61° to -85,203°.

Having in mind the results for the characteristic parameters in Table 8, the next features can be noticed:

- The modulus of the characteristic impedance Z_{C1} increases from $6,456.10^{-7}$ Ω to 33,649 Ω and the phase of the same parameter changes in the range from -51,401° to 83,583°;
- The modulus of the characteristic impedance Z_{C2} increases from $6,456.10^{-7}$ Ω to 63,249 Ω and the phase of the same parameter changes in the range from -51,401° to 83,543°;
- The attenuation constant α increases from $-1,998.10^{-6}$ Np to $3,772.10^{-2}$ Np;

The obtained values of the characteristic impedances Z_{c1} and Z_{c2}, as well as the parameters of the propagation constant γ (the attenuation - α and the phase constant - β), give a more complete picture of the features of ADAVR, considered as a TP. Together with the Z-parameters, they complement the general configuration of all parameters of the studied regulator as a TP - something that is mandatory for a complete analysis of the properties of this class of devices.

A comparison among the values of the input and the output quantities of the TP, obtained by simulations and by physical experiments at several values of the load resistance, is presented in Table 9. The simulation results, which were received, coincide with those of the physical experiments with an accuracy of less than 1% [25, 27].

Table 9. Comparison between experimental and simulation results

		Simulations			**Experiments**		
R_L, Ω	**U_1, V**	**I_1, A**	**I_2, A**	**U_2, V**	**I_1, A**	**I_2, A**	**U_2, V**
115,79	160	2,6724	1,8908	218,94	2,69	1,9	220
61,798	160	4,9306	3,5397	218,75	4,94	3,56	220
35,552	160	8,4945	6,1401	218,29	8,45	6,16	219

4 CONCLUSIONS

From the results of the explored ADAVR, considered as a TP, it can be summarized the following:

- At supply voltage in the range $E=U_1$=220V÷200,1V, the TP is symmetrical, and for the interval $E=U_1$=200V÷150V, the TP is not symmetrical.
- Due to the use of the conditional linearization method at the separate intervals of the input supply voltage, the reciprocity principle is valid for the obtained matrices, even though the general model of the explored ADAVR is non-linear.
- The TP-systems of equations of the explored ADAVR allow quick and accurate determination of the input or output quantities and parameters of such devices, which facilitate their practical application.
- The TP parameters of the explored ADAVR can be used not only in cases when the load is active but also when it is inductive or capacitive. That makes the proposed new approach more universal and useful.
- The obtained TP parameters of equations allow fast and precise analysis of the parameters of the ADAVR, the current, and voltage gains. This facilitates the calculation procedures connected with the design and the practical application of ADAVR.
- The analysis and the design of voltage regulators require the examination of the characteristics and parameters of these devices from different aspects, to determine their reliability and efficiency because these are devices that are subjected to severe operating conditions during continuous operation. The use of

the theory of the two ports is one of the good possibilities for solving these complex modern technical problems.

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