Constructor University Bremen
Spring Semester 2023

Natural Science Laboratory
Electrical Engineering Module II

Lab Report 2 - Two Port Networks

Author of the report: **Getuar Rexhepi**

Experiment Conducted By:
Mr. Getuar Rexhepi
Mr. Joan Collaku
Mr. Obaro Rexon Elebe

Conducted on: **April 13, 2023**

1. Introduction

The concept of a port in electrical networks refers to a pair of terminals through which current can enter or leave the network. This can be seen in two-terminal devices such as resistors, capacitors, and inductors, which result in one-port networks. In contrast, two-port networks have two separate ports for input and output and are commonly used in various fields including communications, control systems, power systems, and electronics. The two ports act as access points to the network, with the current entering one terminal leaving through the other terminal so that the net current entering the port equals zero.

The six sets of parameters that relate to the terminal quantities of a two-port network are derived to characterize it. Two of these parameters are independent, and the various terms that relate these voltages and currents are called parameters. By knowing the parameters of a two-port network, we can connect them in series, parallel, or cascade, and apply the concepts to the analysis of transistor circuits and the synthesis of ladder networks.

Out of 6, in this experiment, 3 parameters are studied: Z Parameters (Impedance), Y Parameters (Admittance), and ABCD Parameters (Transmission).

Z Parameters:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{1.1}$$

$$V_1 = Z_{11} I_1 + Z_{12} I_2$$

$$V_2 = Z_{21} I_1 + Z_{22} I_2$$

Y Parameters:

$$\begin{bmatrix} I_1 \\ V_1 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} I_2 \\ V_2 \end{bmatrix} \tag{1.2}$$

$$I_1 = Y_{11} V_1 + Y_{12} V_2$$

$$I_2 = Y_{21} V_1 + Y_{22} V_2$$

ABCD Parameters:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \tag{1.3}$$

$$V_1 = AV_2 - BI_2$$

$$I_1 = CV_2 - DI_2$$

2. Execution

2.0.1 Part 1 : Two-port Z / Y Network

Tools and equipment:

Elabo multimeter
Breadboard and electrical components
Tektronix TBS1072B Oscilloscope
TENMA multimeter
Function generator

Preparation:

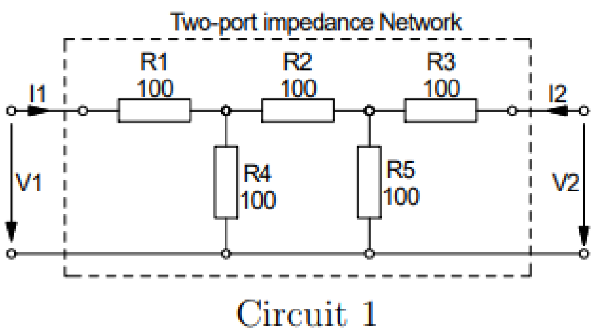

Figure 2.1: Circuit 1 used in the first part of the experiment to measure Z parameters

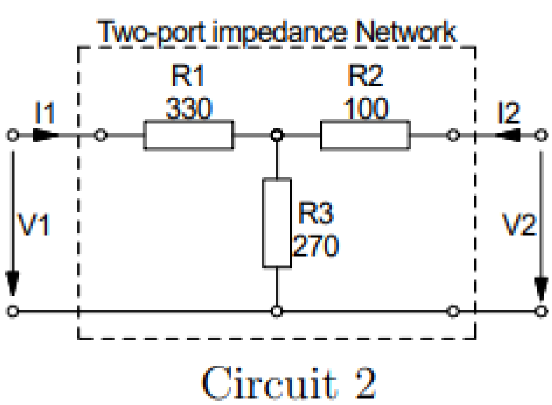

Figure 2.2: Circuit 2 used in the first part of the experiment to measure Y parameters

After the circuits in figure 2.1 and 2.2 were assembled, the supply voltage was set to 5V, and Elabo multimeter was used to measure voltage, with the best range. To measure the impedances, no voltage was supplied to either ports, and the respective current and voltages were measured so the impedances were determined using Ohm's Law. For the admittances, the output was short-circuited to measure the first Y Parameters (Y11 and Y12), and conversely the input was short circuited to measure Y22 and Y21, again using Ohm's Law.

Execution:
Firstly Z or Impedance Parameters were determined, using the circuit shown in figure 2.1 (All 5 resistors of 100Ω), and suitable methods! Z_{11} and Z_{22} were directly measured using the TENMA multimeter, and for the Z_{12} and Z_{21}, the formulas (1.1) were used. The results can be seen in the below table:

Z parameters	[Ω]	Measurements	
Z11	1.663e+2	V_1 [V]	1.008e+0
Z12	3.329e+1	V_2 [V]	1.007e+0
Z21	3.333e+1	I_1 [A]	3.024e-2
Z22	1.663e+2	I_2 [A]	3.028e-2

Table 2.1: Resulting Z parameters determined from measuring respective Currents and Voltages also shown as measurements

Similarly Y or Admittance Parameters were determined, using the circuit shown in figure 2.2. Y_{11} and Y_{22} were measured directly using TENMA multimeter, while Y_{12} and Y_{21} , the formulas (1.2) were used. The results can be seen in the table 2.2 (Measured Values are shown in the left side, with their respectve units V1,V2,I1, I2):

Y parameters	[S]	Measurements	
Y11	2.473e-3	V_1 [V]	5.047e+00
Y12	-1.815e-3	V_2 [V]	5.052e+00
Y21	-1.797e-3	I_1 [A]	-9.170e-03
Y22	4.028e-3	I_2 [A]	-9.067e-03

Table 2.2: Resulting Y parameters determined from measuring respective Currents and Voltages also shown as measurements

After circuits in figure 2.1 and figure 2.2 were connected to a voltage supply of 5V, a load of 1kΩ was used at the output. All voltages and currents at both ports, for both circuits were measured, and results are summarized in the table 2.3:

Circuit 1		Circuit 2	
V1 [V]	5.069e+0	V1 [V]	5.072e+0
V2 [V]	8.731e-1	V2 [V]	1.819e+0
I1 [A]	3.061e-2	I1 [A]	9.314e-3
I2 [A]	-8.780e-4	I2 [A]	-1.824e-3

Table 2.3: Resulting currents and voltages, after 5V were supplied to both circuits

To be clear, the currents were not directly measured, but instead only voltages were measured and then Ohms Law was used to determine the currents:

$$I = \frac{V}{R}$$

2.0.2 Part 2 : Interconnection of Two-port Networks

In this part two two-port networks were connected in parallel and then its properties were observed! The circuit shown in figure 2.3 was assembled and then Z parameters were measured:

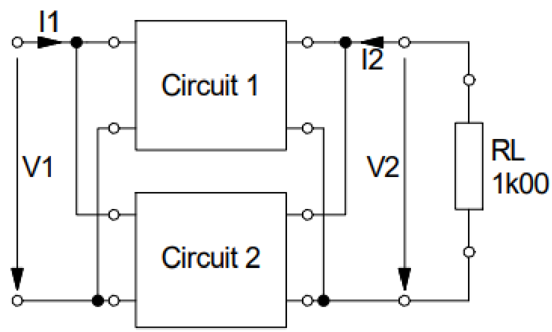

Figure 2.3: Parallel interconnection of circuit 1 and ciruit 2 used in the second part of the experiment to measure Z/Y parameters

Similarly to the previous part, the first two parameters were determined by measuring the impedance directly, while Z_12 and Z_21 were determined using Ohm's Law, by firstly measuring the voltage, and then determining the current. After that using the load, we can find the abovementioned Z parameters:

Z parameters	[Ω]	Measurements	
Z11	1.276e+2	V_1 [V]	1,7742e+0
Z12	3.806e+1	V_2 [V]	1,5069e+0
Z21	3.797e+1	I_1 [A]	3,9678e-2
Z22	1.084e+2	I_2 [A]	4,6616e-2

Table 2.4: Resulting Z parameters of parallel network determined from measuring respective Currents and Voltages also shown as measurements

After this 5V was supplied to the circuit in figure 2.3, and a load of 1kΩ was used at the output. All voltages and currents at both ports for the parallel network were measured and the results are summarized in the table 2.5:

Parallel circuit	
V1 [V]	5.066e+0
V2 [V]	1.372e+0
I1 [A]	4.005e-2
I2 [A]	-1.372e-3

Table 2.5: Resulting currents and voltages, after 5V were supplied to the parallel network

2.0.3 Part 3 : Complex Two-port Networks / Cascading

For the next part, complex two-port networks are going to be analyzed. Namely the ones shown in figure 2.4:

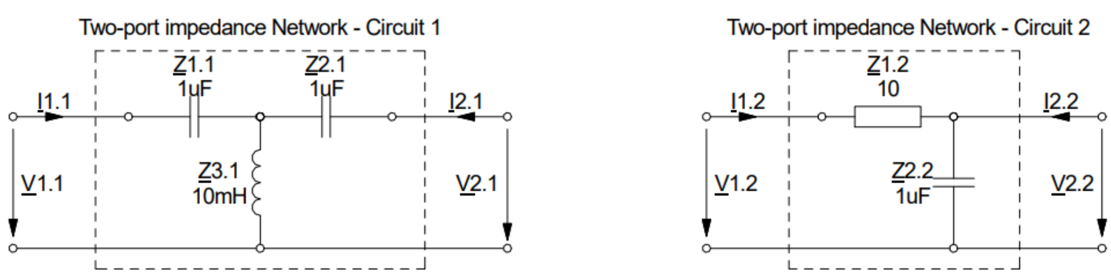

Figure 2.4: Circuit 1 and Circuit 2 used in the third part of the experiment to measure ABCD parameters

After the circuits in figure 2.4 were assembled they were cascaded like the circuit in figure 2.5:

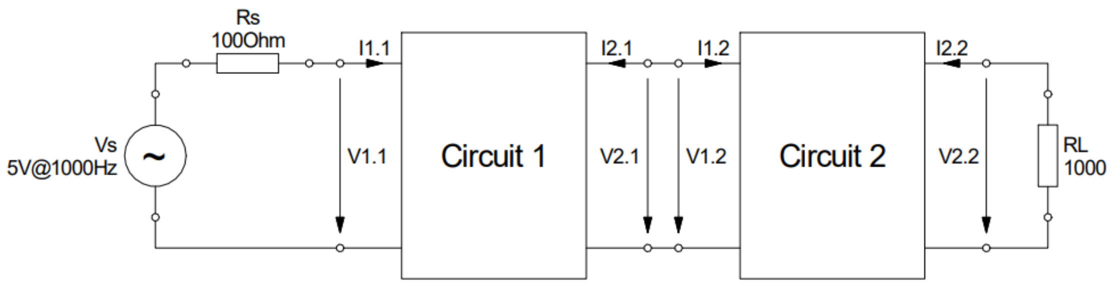

Figure 2.5: Circuit 1 and Circuit 2 cascaded used in the third part of the experiment to measure ABCD parameters

The resulting two-port network was connected to a voltage supply from the function generator with parameters: $\hat{v} = 5V_{pp}$, at 1000Hz frequence, sine wave. In adittion, a 100Ω resistor was used to determine current. Moreover, oscilloscope was used to measure voltages and currents shown in figure 2.5. It is worth to mention that $\hat{v}1.1$ was used as a reference voltage, from which other values were measured! The hard copy used to determine v1.1 and i1.1 is shown below:

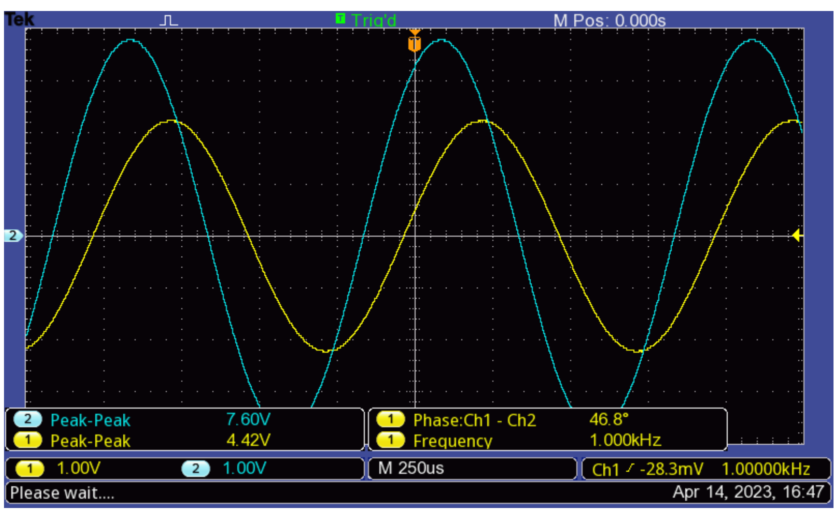

Figure 2.6: Hard-copy showing the reference voltage in yellow and the source voltage in blue

The hard copy used to determine v2.2 and i2.2 is shown below:

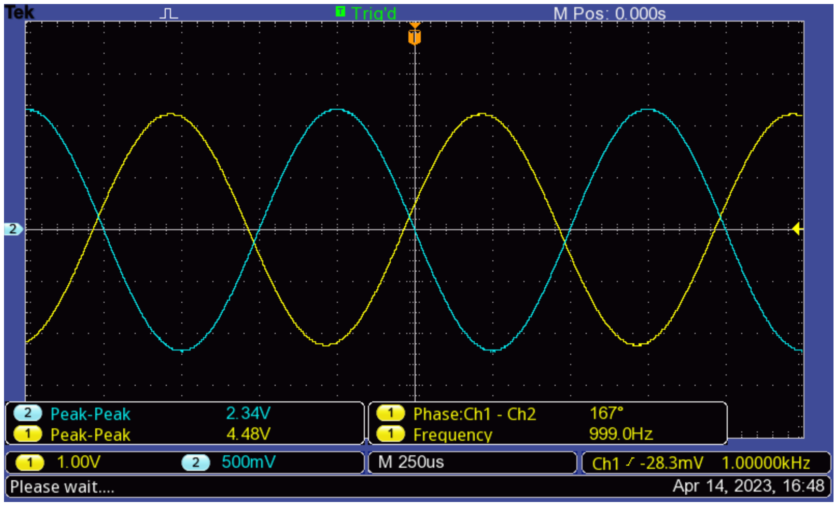

Figure 2.7: Hard-copy showing the reference voltage in yellow and the source voltage in blue

Keep in mind that the phase of $\hat{v}1.1$ is taken as 0°. Now from figures 2.6 and 2.7 we can find all values that we are interested in. These values are summarized in the below table:

Vs	V1.1	I1.1	V2.2	I2.2
$7.60\angle 46.8°$	$4.42\angle 0°$	$0.056\angle 81.96°$	$2.34\angle 167°$	$-0.0023\angle 167°$

Table 2.6: Values of voltages and currents mesaured with the oscilloscope

To clarify the currents I1.1 and I1.2 were found using KCL and circuit in figure 2.5:

$$\sum_i I_i = 0 \implies \frac{Vs - V1.1}{100\Omega} = I1.1 \qquad \frac{V2.2 - 0}{1000\Omega} = I2.2$$

Notice the sign in front of the current I2.2, that's because we took care of the polarity from the circuit in figure 2.5!

Finally the impedance in the format Z = R+jX, were measured using the RLC Meter. The measurements of the 5 components is summarized in the table 2.7:

RLC METER	Ohm	Phasor
Z1,1 (CAP)	0.35814-158.43i	$158.43 \angle -89.87°$
Z2,1 (CAP)	0.22141-149.89i	$149.89 \angle -89.915°$
Z3,1 (IND)	4.0827+64.213i	$64.34 \angle 86.362°$
Z2,1 (RES)	9.57+0.16666i	$9.57 \angle 0.99°$
Z2,2 (CAP)	0.24286-157.15i	$157.43 \angle -89.915°$

Table 2.7: Impedances measured at the RLC Meter in the format Z = R+jX, also shown in polar format

For the reference the figure below was used to compute the Z parameters of the circuit in figure 2.2:

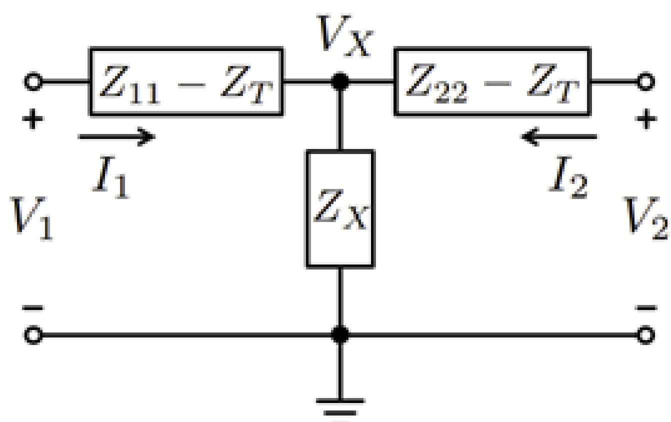

Figure 2.8: Smart shortcut to calculate the Z parameters for the characteristic circuit

3. **Evaluation**

3.0.1 Part 1 : Two-port Z / Y Network

To calcualate the Z Parameters of circuit 1 and circuit 2, from the given resistors seen in figure 2.1 and figure 2.2, we have used MATLAB. The script is shown below:

```
%% Z Parameters
% Circuit 1 resistor values in Ohm
R1 = 100;
R2 = 100;
R3 = 100;
R4 = 100;
R5 = 100;
% Calculate Z parameters of circuit 1
Z11 = R1 + (R4*(R2+R5))/(R4+R2+R5);
Z12 = R3*(R5/(R2+R4+R5));
Z21 = R1*(R4/(R2+R4+R5));
Z22 = R3+(R5*(R2+R4))/(R3+R2+R4);
Z = [Z11, Z12; Z21, Z22];
```

To find the Z parameters, resistive circuit analysis techniques were used, seen in the code above (Resistance simplification). This code gives the Z parameters for circuit 1:

$$Z1 = \begin{bmatrix} 166.6667 & 33.3333 \\ 33.3333 & 166.6667 \end{bmatrix}$$

Similarly the Z parameters for the circuit 2, were easily calculated since the circuit 2 is a characteristic two-port network for which Z parametersc can be easily found using some nice tricks:

```
% Circuit 2 resistor values in Ohm
R1 = 330;
R2 = 100;
R3 = 270;
% Calculate Z parameters of circuit 2
Z = [R1+R3, R3; R3, R2+R3];
```

This gives us the Z parameters for the second circuit:

$$Z2 = \begin{bmatrix} 600 & 270 \\ 270 & 370 \end{bmatrix}$$

To find the Y parameters for the first and second circuit, we can first find the Z parameters use the results to find Y parameters, since we know that all parameters are,in someway, related to each other:

```
%Y parameters for the circuit 1
% using Z parameters
Y11 = Z22 / det(Z);
Y12 = -Z12 / det(Z);
Y21 = -Z21 / det(Z);
Y22 = Z11 / det(Z);
Y = [Y11, Y12; Y21, Y22];
disp(Y);
% Use resulting Z  from above to calculate Y parameters for circuit 2
Y11 = Z(2,2)/det_Z;
Y12 = -Z(1,2)/det_Z;
Y21 = -Z(2,1)/det_Z;
Y22 = Z(1,1)/det_Z;
Y = [Y11, Y12; Y21, Y22];
disp(Y)
```

This code gives us two matrices in the form of :

$$Y1 = \begin{bmatrix} 0.0062 & -0.0012 \\ -0.0012 & 0.0062 \end{bmatrix}$$

$$Y2 = \begin{bmatrix} 0.0025 & -0.0018 \\ -0.0018 & 0.0040 \end{bmatrix}$$

As we can see these two Matrices' (Z1 and Y2) entries are not that differenent from the measured Parameters in table 2.1 and 2.2. For the Z parameters Z1, the values seems to be almost exactly the same, and for the Y parameters Y2, there seems to be a more distinguished error, even though the values are stilll very accurate! The innaccuracy in this case comes mainly from the instruments used,and the resistance of the components themselves!
To verify the voltages and currents measured, we can use Z parameters determined and formulas 1.1.

Because of the tidious calculations we used MATLAB to find these values:

```
%Verify V1,V2 measured with Z parameters
I1 = 0.030605;
I2 = -0.000878;
V1 = Z11*I1 + Z12*I2
V2 = Z21*I1 + Z22*I2
```

This gives us :

$$V1 = 5.0716 \qquad\qquad V2 = 0.8738$$

Similarly to verify the voltages and currents measured, we can use Y parameters determined and formulas 1.2. Because of the tidious calculations we used MATLAB to find these values:

```
%Verify I1,I2 measured with Y parameters
V1 = 5,072;
V2 = 1,820;
I1 = Y11*V1 + Y12*V2
I2 = Y21*V1 + Y22*V2
```

This gives us:

$$I1 = 0.0093 \qquad\qquad I2 = -0.0019$$

As we can see the values from table 2.3 (measured values) are very close to the determined values shown above, for V1, V2 and I1, I2. This shows us that our methods are correct, even though the instrumental error is still present.

3.0.2 Part 2 : Interconnection of Two-Port Networks

To compute the Z parameters of the parallel combination of circuit 1 and circuit 2, we have used Y parameters of each circuit, and then combined them, because in a parallel interconnection we have that the Total Y parameters are:

$$Y = Ya + Yb$$

We have both Matrices Ya and Yb from the first part, so we have just to combine them and find that (MATLAB was used again, full script shown in Appendix):

$$Y = \begin{bmatrix} 0.0087 & -0.0030 \\ -0.0030 & 0.0102 \end{bmatrix}$$

And then to find the Z parameters from here we have:

```
Y = YA + YB
det_Y = det(Y);
% to find Z parameters we have
Z11 = Y(2,2)/det_Y;
Z12 = -Y(1,2)/det_Y;
Z21 = -Y(2,1)/det_Y;
Z22 = Y(1,1)/det_Y;
Z = [Z11, Z12; Z21, Z22];
```

This gives us the Z parameters of the parallel interconnection:

$$Z_p = \begin{bmatrix} 127.5114 & 37.9424 \\ 37.9424 & 108.8512 \end{bmatrix}$$

To compare these values with the measured ones we have:

Z parameters	Measured[Ω]	Calculated [Ω]
Z11	1.276e+2	1.275e+2
Z12	3.806e+1	3.794e+1
Z21	3.797e+1	3.794e+1
Z22	1.084e+2	1.088e+2

Table 3.1: Resulting Z parameters of parallel network compared to the calculated parameters

As we can see from table 3.1, the calculaeted and values determined from measurements are very accurate, which again verifies that our methods were effective, but there is some instrumental error, becuase of the instruments and devices used (as always)!
To verify the measured V1, V2 and I1, I2 values, similarly to the first part, we have:

```
%Verify V1,V2 measured with Z parameters
I1 = 0.04005;
I2 = -0.001372;
V1 = Z11*I1 + Z12*I2
V2 = Z21*I1 + Z22*I2

%Verify I1,I2 measured with Y parameters
V1 = 5.066;
V2 = 1.3722;
I1 = Y(1,1)*V1 + Y(1,2)*V2
I2 = Y(2,1)*V1 + Y(2,2)*V2
```

From this we get:

$$V1 = 5.0548 \qquad V2 = 1.3702$$

and

$$I1 = 0.0401 \qquad I2 = -0.0014$$

which compared with values in table 2.5, again verifies that the values calculated are correct and very accurate, with the measured values!

	Measured	Calculated
V1 [V]	5.066e+0	5.0548e+0
V2 [V]	1.372e+0	1.3702e+0
I1 [A]	4.005e-2	4.01e-2
I2 [A]	-1.372e-3	-1.40e-3

Table 3.2: Measured currents and voltages, and calculated values

For a series interconnection of two two-port networks, it is theoretically possible to determine the Z-parameters of the combined network by combining the Z-parameters of the individual networks. However, it should be noted that this approach assumes that the input voltage across the combined network is zero, which may not be the case in practical situations (like in our lab). This is because we most likely will have a voltage drop more than 0V. In a parallel interconnection of two two-port networks, we didn't face this issue because the input voltage is the same across both networks, while the output current of the combined network is the sum of the output currents of the individual networks.

3.0.3 Part 3 : Interconnection of Two-Port Networks

To determine the Z parameters of the first complex Two-port Network MATLAB and the shortcut shown in figure 2.8 was used:

```
% Measured values of impedances
% Define the complex numbers in rectangular form
z1 = 0.35814 - 158.43i;
z2 = 0.22141 - 149.89i;
z3 = 4.0827 + 64.213i;
z4 = 9.57 + 0.16666i;
z5 = 0.24286 - 157.15i;

% from the shortcut learned in class
%Z parameters of first circuit
Z11_1 = z1 + z3;
Z12_1 = z3;
Z21_1 = z3;
Z22_1 = z3 + z2;
Z1 = [Z11_1, Z12_1; Z21_1, Z22_1]
%phasor form
cart2pol_matrix(Z1);
```

This gives us the Z parameters which were converted to phasor form (using a function that we defined on MATLAB):

$$Z1 = \begin{bmatrix} 94.3216\angle-87.3014^\circ & 64.3427\angle 86.3620^\circ \\ 64.3427\angle 86.3620^\circ & 85.7850\angle-87.1241^\circ \end{bmatrix}$$

In the same way we found the Z parameters for the second circuit which were also converted to phasor form:

```
%Z parameters of second circuit
Z11_2 = z4 + z5;
Z12_2 = z5;
Z21_2 = z5;
Z22_2 = z5+0;
Z2 = [Z11_2, Z12_2; Z21_2, Z22_2]
%phasor form
cart2pol_matrix(Z2);
```

which gives us:

$$Z2 = \begin{bmatrix} 157.2897\angle-86.4232^\circ & 157.1502\angle-89.9115^\circ \\ 157.1502\angle-89.9115^\circ & 157.1502\angle-89.9115^\circ \end{bmatrix}$$

To calculate the transmission parameters (ABCD) we can convert both Z parameters to ABCD parameters and then multiply those matrices, since they are cascaded in the circuit shown in figure 2.5:

```
% To determine ABCD parameters
A1 = Z11_1/Z21_1;
B1 = det_Z1/Z21_1;
C1 = 1/Z21_1;
D1 = Z22_1/Z21_1;
ABCD1 = [A1, B1; C1, D1];

A2 = Z11_2/Z21_2;
B2 = det_Z2/Z21_2;
C2 = 1/Z21_2;
D2 = Z22_2/Z21_2;
ABCD2 = [A2, B2; C2, D2];
%Casceded ABCD Parameters
ABCD = ABCD1*ABCD2
% Convert complex matrix to polar form
cart2pol_matrix(ABCD);
```

The above code gives us the final ABCD parameters converted to phasor form:

$$ABCD = \begin{bmatrix} 1.8713\angle-167.5365^\circ & 69.5193\angle123.2646^\circ \\ 0.0240\angle-83.1211^\circ & 1.3464\angle-167.1460^\circ \end{bmatrix}$$

To verify the currents and voltages measured V1, V2, and I1, I2, we can use the above ABCD parameters and formula 1.3, to find that:

```
%measured current
I22mag = -0.0023;
I22ang = deg2rad(167);
%meausred voltage
V22mag = 2.34;
V22ang = deg2rad(167);
```

```
%convert to rectangular form for calulations
real_part_I22 = I22mag * cos(I22ang);
imag_part_I22 = I22mag * sin(I22ang);
real_part_V22 = V22mag * cos(V22ang);
imag_part_V22 = V22mag * sin(V22ang);
I22 = real_part_I22 + imag_part_I22*1i;
V22 = real_part_V22 + imag_part_V22*1i;
%calculate V11 and I11
V11_I11 = ABCD * [V22; -I22];
V11 = V11_I11(1);
I11 = V11_I11(2);
```

where we have used the equality:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \tag{3.1}$$

and found that:

$$V_1 = 4.4382\angle -2.4665^\circ \qquad I_1 = 0.0567\angle 80.7629^\circ$$

From table 2.6 we can see that the measured values of V_1 and I_1 were:

$$V_1 = 4.42\angle 0^\circ \qquad I_1 = 0.056\angle 81.96^\circ$$

which are clearly very close the the determined values using the ABCD Parameters.
We can notice that the phase of the voltage is slightly off. Remember that V_1 was the reference voltage shown in figure 2.6, which we used to determine other values. However, the phase shift is reasonable, since we measured the components at the RLC meter in the room 54, which even though was calibrated, it was on for a long time. This together with other instrumental errors may have contributed to this phase of the voltage, which again is very close to 0. As for the magnitudes of voltages we can clearly see that they are correct up to the second decimal. The current phase is also very close the the measured one. It is worthy to mention that in the phase determination, the oscilloscope attenuation may have also contributed to the error.

4. Conclusion

In this lab experiment the properties of two-port networks were measure and analyzed. In particular, Z and Y parameters of different two-port networks, were measured and calculated, networks were combined to form more complex circuits, and verifying measured values using the calculated parameters.

In part 1, the Z and Y parameters of two resistive circuits are calculated and compared with the measured values. Any differences between the calculated and measured values are discussed. In part 2, the Z parameters of parallel connected resistive circuits are calculated by combining the measured Z or Y parameters from part 1. The combined values are compared to directly measured ones, and the validity of using Z or Y parameters to verify measured values is discussed. In part 3, the Z parameters of two complex circuits are determined, and the resulting cascaded ABCD parameters are calculated using these Z parameters. The calculated values are compared to the measured values, and differences are discussed. It is important to note that the measured values in this experiment were correctly measured. Any differences between the calculated and measured values are likely due to instrumental errors, rather than measurement errors. Instrumental errors include imperfections in the RLC meter, oscilloscope attenuation, and the resistance of other components! Overall, the experiment was carried out correctly and satisfactory results were obtained.

5. Bibliography

[1] Alexander, C. K., & O., S. M. N. (2021). Fundamentals of Electric Circuits. McGraw-Hill Education.

[2] Pagel, U. (April, 2023) http://uwp-raspi-lab.jacobs.jacobs-university.de/01.0.generaleelab/01.2.generaleelab2/20230118-ch-211-b-manual.pdf.

[3] Matlab. MathWorks. Retrieved April 21, 2023, from https://www.mathworks.com/products/matlab.html

[4] Abreu, G. T. F. (2021). Two port networks [Lecture notes]. Gen EE I. Constructor Univeristy Bremen

6. Appendix

MATLAB script used during the evaluation of the report, includind comments and explainations, and a function that converts rectangular entries of a matrix to polar form. Code is divided in sections for convenience:

```
%% Circuit 1
%close all
%clear all
% Circuit 1 resistor values in Ohm
R1 = 100;
R2 = 100;
R3 = 100;
R4 = 100;
R5 = 100;
% Calculate Z parameters of circuit 1
Z11 = R1 + (R4*(R2+R5))/(R4+R2+R5);
Z12 = R3*(R5/(R2+R4+R5));
Z21 = R1*(R4/(R2+R4+R5));
Z22 = R3+(R5*(R2+R4))/(R3+R2+R4);
Z = [Z11, Z12; Z21, Z22]
%Y parameters for the circuit 1
Y11 = Z22 / det(Z);
Y12 = -Z12 / det(Z);
Y21 = -Z21 / det(Z);
Y22 = Z11 / det(Z);
Y = [Y11, Y12; Y21, Y22]

%Verify V1,V2 measured with Z parameters
I1 = 0.030605;
I2 = -0.000878;
V1 = Z11*I1 + Z12*I2
V2 = Z21*I1 + Z22*I2

%% Circuit 2
% Circuit 2 resistor values in Ohm
R1 = 330;
R2 = 100;
R3 = 270;

% Calculate Z parameters of circuit 2
Z = [R1+R3, R3; R3, R2+R3]
det_Z = det(Z);
```

```
% Use results to calculate Y parameters
Y11 = Z(2,2)/det_Z;
Y12 = -Z(1,2)/det_Z;
Y21 = -Z(2,1)/det_Z;
Y22 = Z(1,1)/det_Z;
Y = [Y11, Y12; Y21, Y22]

%Verify I1,I2 measured with Y parameters
V1 = 5.072;
V2 = 1.8195;
I1 = Y11*V1 + Y12*V2
I2 = Y21*V1 + Y22*V2
%% Parameters of Parallel connection
%Y = [YA] + [YB]
% Convert Z parameters from Circuit 1 to Y parameters
Z = [166.6667, 33.3333; 33.3333, 166.6667];
det_Z = det(Z);
Y11a = Z(2,2)/det_Z;
Y12a = -Z(1,2)/det_Z;
Y21a = -Z(2,1)/det_Z;
Y22a = Z(1,1)/det_Z;
YA = [Y11a, Y12a; Y21a, Y22a]
%from above we have
YB = [0.0025, -0.0018; -0.0018, 0.0040]
Y = YA + YB
det_Y = det(Y);
% to find Z parameters we have
Z11 = Y(2,2)/det_Y;
Z12 = -Y(1,2)/det_Y;
Z21 = -Y(2,1)/det_Y;
Z22 = Y(1,1)/det_Y;
Z = [Z11, Z12; Z21, Z22]

%Verify V1,V2 measured with Z parameters
I1 = 0.04005;
I2 = -0.001372;
V1 = Z11*I1 + Z12*I2
```

```
V2 = Z21*I1 + Z22*I2

%Verify I1,I2 measured with Y parameters
V1 = 5.066;
V2 = 1.3722;
I1 = Y(1,1)*V1 + Y(1,2)*V2
I2 = Y(2,1)*V1 + Y(2,2)*V2
%% Complex Two Port
% Measured values of impedances
% Define the complex numbers in rectangular form
z1 = 0.35814 - 158.43i;
z2 = 0.22141 - 149.89i;
z3 = 4.0827 + 64.213i;
z4 = 9.57 + 0.16666i;
z5 = 0.24286 - 157.15i;

% from the shortcut learned in class
%Z parameters of first circuit
Z11_1 = z1 + z3;
Z12_1 = z3;
Z21_1 = z3;
Z22_1 = z3 + z2;
Z1 = [Z11_1, Z12_1; Z21_1, Z22_1]
%phasor form
cart2pol_matrix(Z1);
det_Z1 = det(Z1);
%Z parameters of second circuit
Z11_2 = z4 + z5;
Z12_2 = z5;
Z21_2 = z5;
Z22_2 = z5+0;
Z2 = [Z11_2, Z12_2; Z21_2, Z22_2]
%phasor form
cart2pol_matrix(Z2);
det_Z2 = det(Z2);

% To determine ABCD parameters
A1 = Z11_1/Z21_1;
```

```
B1 = det_Z1/Z21_1;
C1 = 1/Z21_1;
D1 = Z22_1/Z21_1;
ABCD1 = [A1, B1; C1, D1];

A2 = Z11_2/Z21_2;
B2 = det_Z2/Z21_2;
C2 = 1/Z21_2;
D2 = Z22_2/Z21_2;
ABCD2 = [A2, B2; C2, D2];

%Casceded ABCD Parameters
ABCD = ABCD1*ABCD2

% Convert complex matrix to polar form
cart2pol_matrix(ABCD);

%measured current
I22mag = -0.0023;
I22ang = deg2rad(167);
%meausred voltage
V22mag = 2.34;
V22ang = deg2rad(167);
%convert to rectangular form for calulations
real_part_I22 = I22mag * cos(I22ang);
imag_part_I22 = I22mag * sin(I22ang);
real_part_V22 = V22mag * cos(V22ang);
imag_part_V22 = V22mag * sin(V22ang);
I22 = real_part_I22 + imag_part_I22*1i;
V22 = real_part_V22 + imag_part_V22*1i;
%calculate V11 and I11
V11_I11 = ABCD * [V22; -I22];
V11 = V11_I11(1);
I11 = V11_I11(2);

fprintf('V11 = %.4f < %.4f°  \n', abs(V11), rad2deg(angle(V11)));
fprintf('I11 = %.4f < %.4f°  \n', abs(I11), rad2deg(angle(I11)));
```

```
function [Result] = cart2pol_matrix(ABCD)
    [angle_ABCD, rho_ABCD] = cart2pol(real(ABCD), imag(ABCD));
    D = rad2deg(angle_ABCD);
    Result = zeros(size(rho_ABCD, 1), 2*size(rho_ABCD, 2));
    Result(:,1:2:end) = rho_ABCD;
    Result(:,2:2:end) = D;
    % Display the result in mag<angle format
    for i = 1:size(Result,1)
        for j = 1:size(Result,2)/2
            mag = Result(i,2*j-1);
            angle_deg = Result(i,2*j);
            fprintf('%.4f < %.4f°  ', mag, angle_deg);
        end
        fprintf('\n');
    end
end
```

Data from previous experiment:

Component	[Ω]	ELABO range [$k\Omega$]
R4	8223	20
R3	2196	20
R1	2199	200

Table 6.1: Part 1.1 Measurements

Component	[Ω]
Dekade value	81900
Measured decade(with ELABO) (200k[Ω])	82340

Table 6.2: Part 1.2 Measurements

Range [V]	Elabo voltage [V]	Vout [V]	Range [mV]
20	1.0073	-0.219	40
200	10	-0.241	400

Table 6.3: Part 2.1 Measurements

Component	[kΩ]	Range
Z1	5,595	2
Z4	8,185	2

Table 6.4: Part 3.1 Measurements

Calculated	Decade	RLC meter
Radj = 485 Ohm	Radj = 485 Ohm	Z4 = 488-6.8182
Cadj = 22.3 nF	Cadj = 23.3 nF	

Table 6.5: Part 3.1 Measurements