Chapter 9

TWO-PORT NETWORKS

Chapter Outline

- Admittance Parameters
- Impedance Parameters
- Hybrid Parameters
- Transmission Parameters
- Parameter Conversions
- Interconnection of Two-Ports

Admittance Parameters

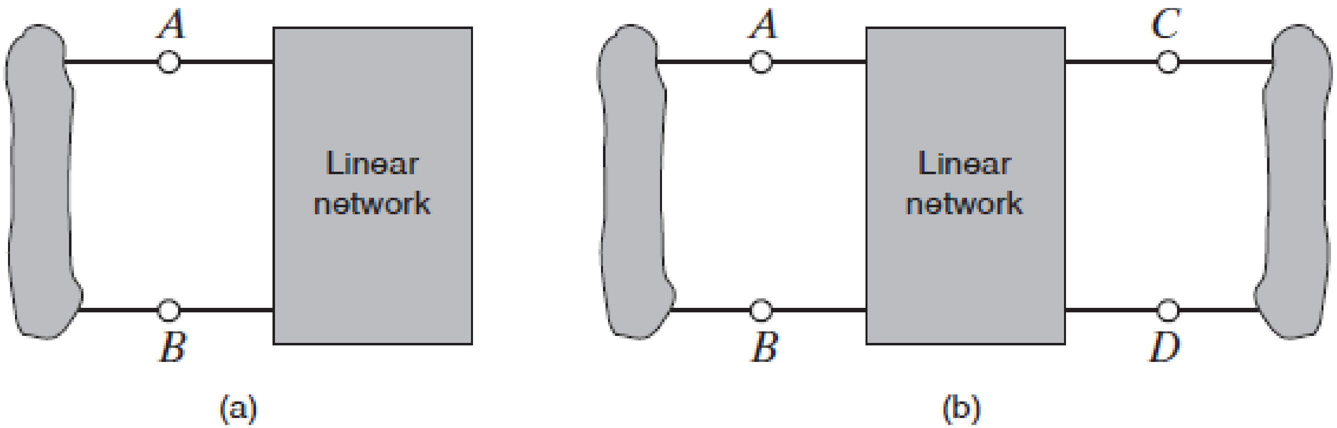


Figure 10.1: (a) Single-port network; (b) two-port network.

Admittance Parameters

- The linear network in Fig. 10.1a has a single *port*—that is, a single pair of terminals.
- The pair of terminals A-B that constitute this port could represent a single element (e.g., R, L, or C), or it could be some interconnection of these elements. The linear network in Fig. 10.1b is called a two-port. As a general rule the terminals A-B represent the input port, and the terminals C-D represent the output port.

Admittance Parameters

- In the two-port network shown in Fig. 10.3, it is customary to label the voltages and currents as shown; i.e, the upper terminals are positive with respect to the lower terminals, the currents are into the two-port at the upper terminals, and, because KCL must be satisfied at each port, the current is out of the two-port at the lower terminals. Since the network is linear and contains no independent sources, the principle of superposition can be applied to determine the current I_1 which can be written as the sum of two components, one due to V_1 and one due to V_2. Using this principle, we can write

Admittance Parameters

- $I_1 = y_{11}V_1 + y_{12}V_2$
- Where y_{11} and y_{12} are essentially constants of proportionality with units of siemens.

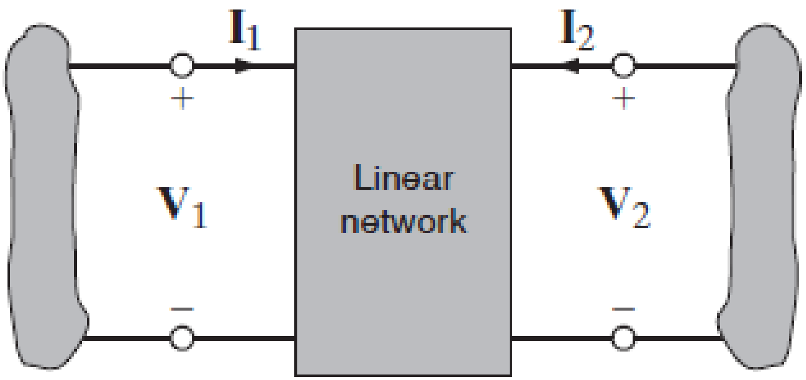


Figure 10.3; Generalized two-port network.

Admittance Parameters

- In a similar manner I_2 can be written as
- $I_2 = y_{21}V_1 + y_{22}V_2$
- These two equations describe the two port network and can be written in matrix form as:
- $\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$
- Note that subscript 1 refers to the input port and subscript 2 refers to the output port, and the equations describe what we will call the Y *parameters* for a network. If these parameters are known, the input/output operation of the two-port is completely defined.

Admittance Parameters

- From the equations y_{11} is equal to I_1 divided by V_1 with the output short-circuited (1.e $V_2 = 0$)
- $y_{11} = \left.\frac{I_1}{V_1}\right|_{V_2=0}$
- Since y_{11} is an admittance at the input measured in siemens with the output short-circuited, it is called the *short-circuit input admittance*. The equations indicate that the other Y parameters can be determined in a similar manner.
- $y_{12} = \left.\frac{I_1}{V_2}\right|_{V_1=0}$; $y_{21} = \left.\frac{I_2}{V_1}\right|_{V_2=0}$; and $y_{22} = \left.\frac{I_2}{V_2}\right|_{V_1=0}$

- $y_{12}\ \ y_{21} and$ are called the *short-circuit transfer admittances*, and y_{22} is called the *short-circuit output admittance*. As a group, the Y parameters are referred to as the *short-circuit admittance parameters*.

Admittance Parameters

- **Example**
- We wish to determine the Y parameters for the two-port network shown in Fig. 10.4a. Once these parameters are known, we will determine the current in a 4 Ω load, which is connected to the output port when a 2-A current source is applied at the input port

Admittance Parameters

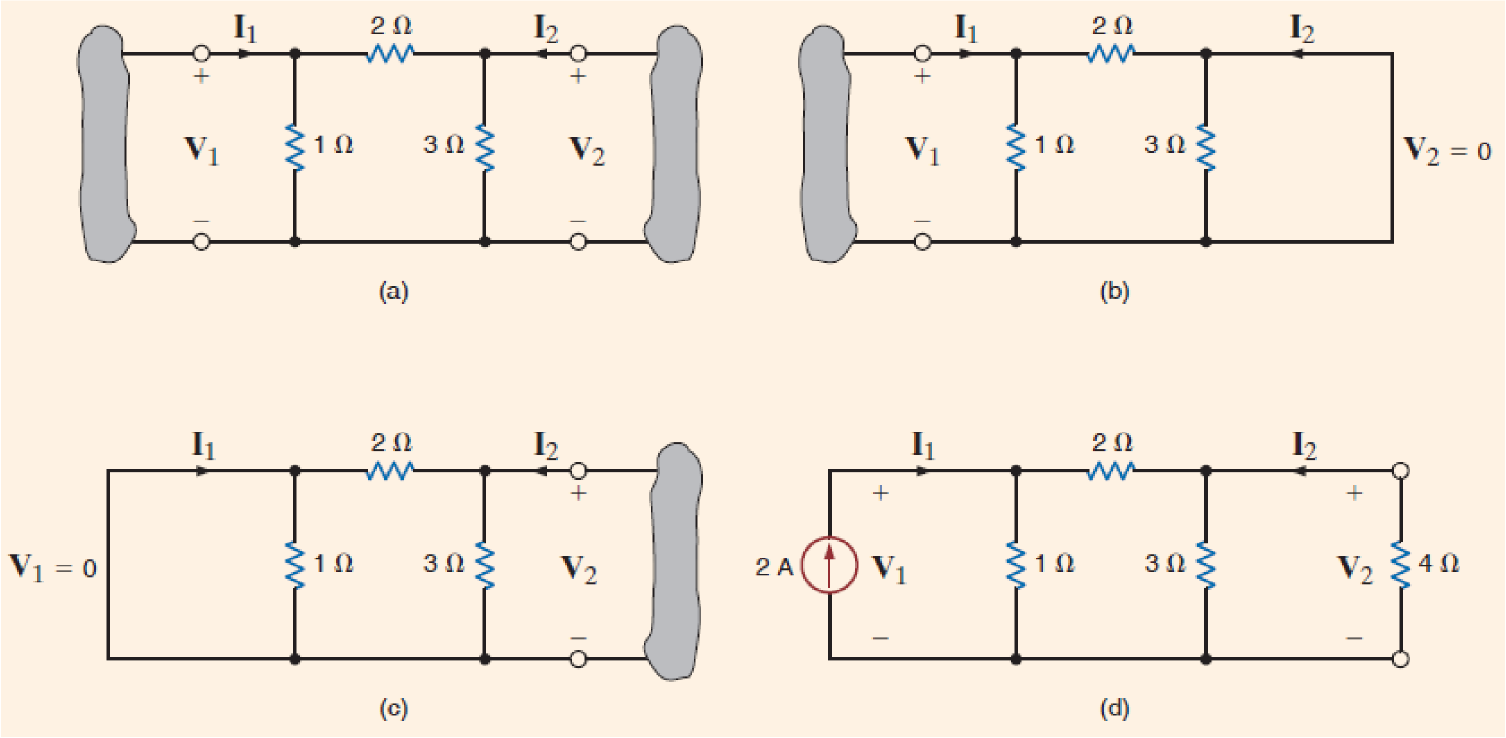


Figure 10.4

Admittance Parameters

- **Solution**
- From Fig. 10.4b,
- $I_1 = V_1\left(\frac{1}{1} + \frac{1}{2}\right)$ Thus $y_{11} = \frac{3}{2}S$
- As shown in Fig. 10.4c
- $I_1 = -\frac{V_2}{2}$ And hence $y_{12} = -\frac{1}{2}S$
- And also y_{21} is computed from fig 10.4b using the equation
- $I_2 = -\frac{V_1}{2}$ And therefore $y_{21} = -\frac{1}{2}S$

Admittance Parameters

- From Fig. 10.4c
- $I_2 = V_2\left(\frac{1}{3} + \frac{1}{2}\right)$ And $y_{22} = \frac{5}{6} S$
- Therefore, the equations that describe the two-port itself are:
- $I_1 = \frac{3}{2} V_1 - \frac{1}{2} V_2$ $\qquad$ $I_2 = -\frac{1}{2} V_1 + \frac{5}{6} V_2$

Admittance Parameters

- These equations can now be employed to determine the operation of the two-port for some given set of terminal conditions. The terminal conditions we will examine are shown in Fig. 10.4d. From this figure we note that
- $I_1 = 2A \quad and \;\; V_2 = -4\,I_2$
- Combining these with the preceding two-port equations yields
- $2 = \frac{3}{2}V_1 - \frac{1}{2}V_2$ $\qquad\qquad 0 = -\frac{1}{2}V_1 + \frac{13}{12}V_2$

Admittance Parameters

- Or in matrix form
- $$\begin{bmatrix} \frac{3}{2} & -\frac{1}{2} \\ -\frac{1}{2} & \frac{13}{12} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \end{bmatrix}$$
- Note carefully that these equations are simply the nodal equations for the network in Fig. 10.4d. Solving the equations, we obtain V_2 = 8/11 V and therefore I_2 = -2/11 A .

Admittance Parameters

- **Exercise**
- Find the Y parameters for the two-port network shown in Fig. 10.4

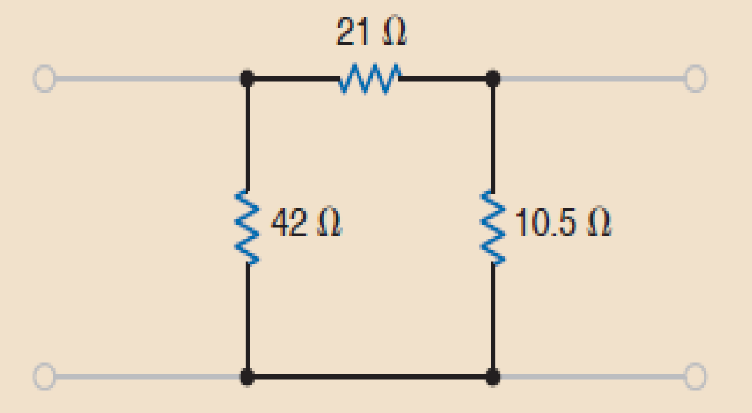


Figure 10.4

- $\left(y_{11} = \frac{1}{14}S, y_{12} = y_{21} = -\frac{1}{21}S;\ y_{22} = \frac{1}{7}S\right)$

If a 10-A source is connected to the input of the two-port network in Fig. 10.4, find the current in a 5Ω resistor connected to the output port. (-4.29 A)

Impedance Parameters

- Once again, if we assume that the two-port network is a linear network that contains no independent sources, then by means of superposition we can write the input and output voltages as the sum of two components, one due to I_1 and one due to I_2.
- $V_1 = z_{11}I_1 + z_{12}I_2$
- $V_2 = z_{21}I_1 + z_{22}I_2$
- These equations, which describe the two-port network, can also be written in matrix form as
- $\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$

Impedance Parameters

- Like the Y parameters, these Z *parameters* can be derived as follows:
- $z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2=0}$ $z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1=0}$ $z_{21} = \left.\frac{V_2}{I_1}\right|_{I_2=0}$ and $z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1=0}$
- In the preceding equations, setting I_1 or $I_2 = 0$ is equivalent to open-circuiting the input or output port.
- Therefore, the Z parameters are called the *open-circuit impedance parameters*. z_{11} is called the *open-circuit input impedance*, z_{22} is called the *open-circuit output impedance*, and $\mathbf{z}_{12}$ and $\mathbf{z}_{21}$ are termed *open-circuit transfer impedances.*

Example

- We wish to find the Z parameters for the network in Fig. 10.5a. Once the parameters are known, we will use them to find the current in a 4-Ω resistor that is connected to the output terminals when a $12\angle 0^0 - V$ source with an internal impedance of *1+j0 Ω* is connected to the input.

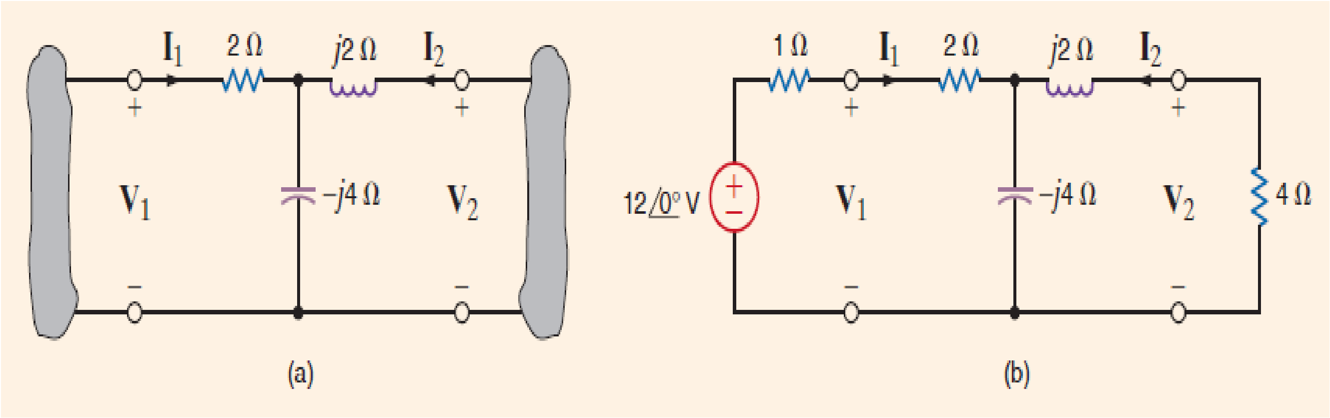


Figure 10.5

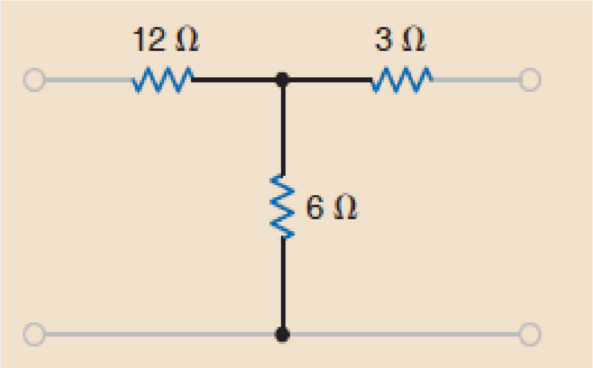
Impedance Parameters

- **Solution**
- From Fig. 10.5a we note that
- $z_{11} = 2 - j4\ \Omega, \quad z_{12} = -j4\ \Omega, \quad z_{21} = -j4\ \Omega, \quad z_{22} = -j4 + j2 = -j2\ \Omega$
- The equations for the two-port network are, therefore,
- $V_1 = (2 - j4)I_1 = j4I_2$
- $V_2 = -j4I_1 - j2I_2$
- The terminal conditions for the network shown in Fig. 10.5b are
- $V_1 = 12\angle 0^0 - (1)I_1 \quad and \quad V_2 = -4I_2$

- Combining these with the two-port equations yields
- $12\angle 0^0 = (3 - j4)I_1 - j4I_2$
- $0 = -j4I_1 + (4 - j2)I_2$
- It is interesting to note that these equations are the mesh equations for the network. If we solve the equations for I_2 we obtain $I_2 = 1.61\angle 137.73^0$ A which is the current in the 4 Ω load.

Impedance Parameters

- **Exercise**
- Find the Z parameters for the network in Fig. 10.6. Then compute the current in a 4Ω load if a $112\angle 0^0\ V$ source is connected at the input port.



- *Figure 10.6*
- $(I_2 = -0.73\angle 0^0)$

Impedance Parameters

- Determine the Z parameters for the two-port network shown in Fig. 10.7

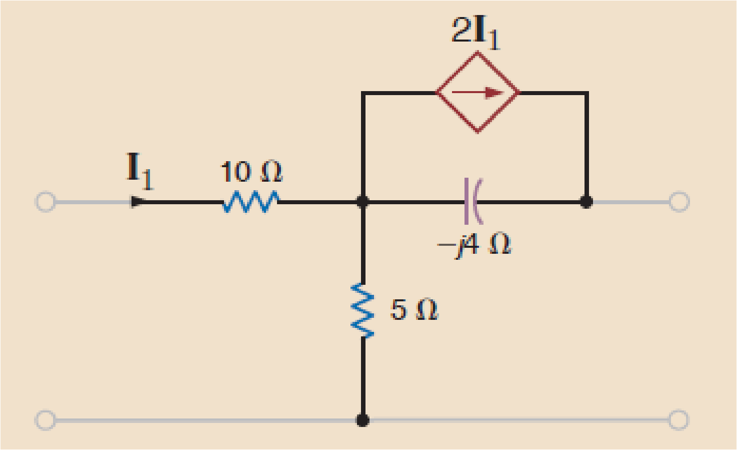


Figure 10.7

$$(z_{11} = 15\Omega;\ z_{12} = 5\Omega;\ z_{21} = 5 - j8\ \Omega;\ \ z_{22} = 5 - j4\ \Omega)$$

Hybrid Parameters

- Under the assumptions used to develop the Y and Z parameters, we can obtain what are commonly called the *hybrid parameters*. In the pair of equations that define these parameters, V_1 and I_2 are the independent variables. Therefore, the two-port equations in terms of the hybrid parameters are
- $V_1 = h_{11}I_1 + h_{12}V_2$
- $I_2 = h_{21}I_1 + h_{22}V_2$
- Or in matrix form
- $\begin{bmatrix} V_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ V_2 \end{bmatrix}$

Hybrid Parameters

- These parameters are especially important in transistor circuit analysis. The parameters are determined via the following equations:
- $h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$ $\quad h_{12} = \left.\frac{V_1}{V_2}\right|_{I_1=0}$ $\quad h_{21} = \left.\frac{I_2}{I_1}\right|_{V_2=0}$ $\quad and \quad h_{22} = \left.\frac{I_2}{V_2}\right|_{I_1=0}$

- The parameters h_{11}, h_{12}, h_{21} and h_{22} represent the *short-circuit input impedance*, the *open-circuit reverse voltage gain*, the *short-circuit forward current gain*, and the *opencircuit output admittance*, respectively. Because of this mix of parameters, they are called *hybrid parameters*. In transistor circuit analysis, the parameters h_{11}, h_{12}, h_{21} and h_{22} are normally labeled h_i, h_r, h_f, and h_o.

Example

- An equivalent circuit for the op-amp in Fig. 10.8a is shown in Fig. 10.8b. We will determine the hybrid parameters for this network.

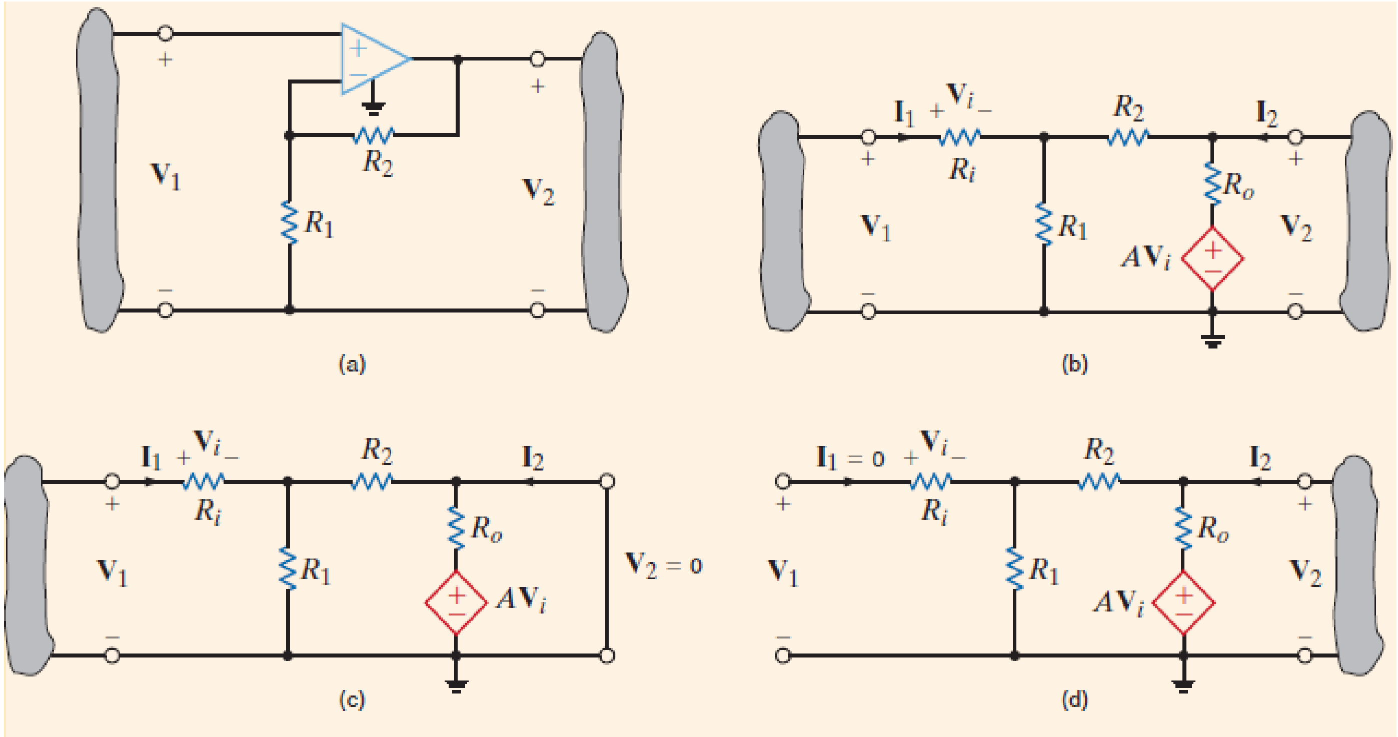


Figure 10.8

Hybrid Parameters

- Parameter h_{11} is derived from Fig. 10.8c. With the output shorted, h_{11} is a function of only R_i, R_1 and R_2 and
- $h_{11} = R_i + \frac{R_1 R_2}{R_1 + R_2}$
- Fig. 10.8d is used to derive h_{12}. Since I_1=0 V, V_i=0 and the relationship between V_1 and V_2 is a simple voltage divider.
- $V_1 = \frac{V_2 R_1}{R_1 + R_2}$
- And thus $h_{12} = \frac{R_1}{R_1 + R_2}$

- KVL and KCL can be applied to Fig. 10.8c to determine h_{21}.
- $V_i = I_1 R_i$
- $I_2 = \frac{-AV_i}{R_0} - \frac{I_1 R_1}{R_1+R_2}$
- Therefore $h_{21} = -\left(\frac{AV_i}{R_0} + \frac{R_1}{R_1+R_2}\right)$
- Finally, from Fig. 10.8d is
- $\frac{V_2}{I_2} = \frac{R_0(R_1+R_2)}{R_0+R_1+R_2}$
- And thus $h_{22} = \frac{R_0+R_1+R_2}{R_0(R_1+R_2)}$

- The network equations are, therefore,
- $V_1 = \left(R_i + \frac{R_1R_2}{R_1+R_2}\right)I_1 + \frac{R_1}{R_1+R_2}V_2$
- $I_2 = -\left(\frac{AR_i}{R_0} + \frac{R_1}{R_1+R_2}\right)I_1 + \frac{R_0+R_1+R_2}{R_0(R_1+R_2)}V_2$

Hybrid Parameters

- **Exercise**
- Find the hybrid parameters for the network shown in Fig. 10.7.
- $\left(h_{11} = 14\,\Omega;\ h_{12} = \frac{2}{3};\quad h_{21} = -\frac{2}{3};\ \ h_{22} = \frac{1}{9}S\right)$

Transmission Parameters

- The final parameters we will discuss are called the *transmission parameters*. They are defined by the equations
- $V_1 = AV_2 - BI_2$
- $I_1 = CV_2 - BDI_2$
- or in matrix form,
- $\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix}$
- These parameters are very useful in the analysis of circuits connected in cascade, as we will demonstrate later.

Transmission Parameters

- $A = \left.\frac{V_1}{V_1}\right|_{I_2=0}$ $B = \left.\frac{V_1}{-I_2}\right|_{V_2=0}$ $C = \left.\frac{I_2}{V_2}\right|_{I_2=0}$ and $D = \left.\frac{I_2}{-I_2}\right|_{V_2=0}$
- **A**, **B**, **C**, and **D** represent the *open-circuit voltage ratio*, the *negative short-circuit transfer impedance*, the *open-circuit transfer admittance*, and the *negative short-circuit current ratio*, respectively. For obvious reasons the transmission parameters are commonly referred to as the ABCD *parameters*.

Example

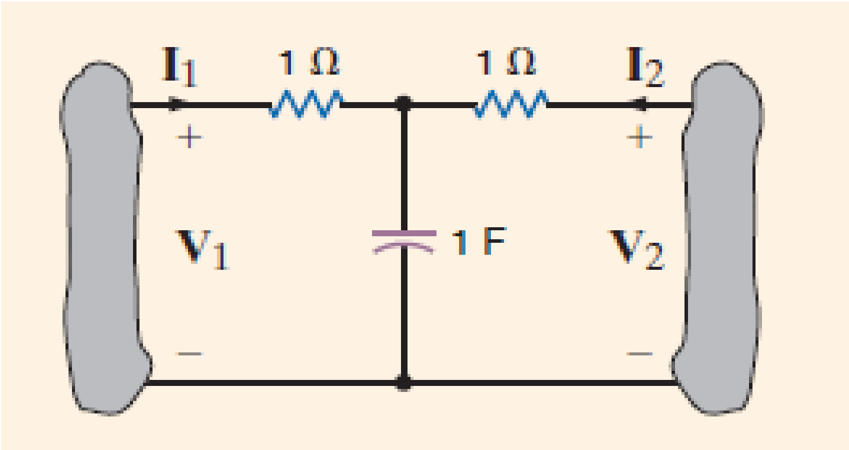


Figure 10.9

We will now determine the transmission parameters for the network in Fig. 10.9.

Solution

- Let us consider the relationship between the variables under the conditions stated in the parameters For example, I_2 = 0, V_2 with can be written as
- $V_2 = \frac{V_1}{1+1/j\omega}\left(\frac{1}{jw}\right) \quad or \quad A = \frac{V_1}{V_1}\Big|_{I_2=0} = 1 + J\omega$
- Similarly, with V_2=0 the relationship between I_2 and V_1 is
- $-I_2 = \frac{V_1}{1+\frac{1/j\omega}{1+1/J\omega}}\left(\frac{1/J\omega}{1+1/J\omega}\right) \quad or \;\; B = \frac{V_1}{-I_2}\Big|_{V_2=0} = 2 + j\omega$
- In a similar manner, we can show that $c = j\omega \;\; and \; D = 1 + j\omega$

Exercise

- Compute the transmission parameters for the two-port network in Fig. 10.4 .
- $(A = 3;\ \ B = 21\Omega;\ \ C = \frac{1}{6}S;\ \ D = \frac{3}{2})$
- Find the transmission parameters for the two-port network shown in Fig. 10.7.

$$\begin{pmatrix} A = 0.843 + j1.348; \quad B = 4.61 + j3.37\ \Omega; \\ C = 0.056 + J0.09\ S; \quad D = 0.64 + j0.225 \end{pmatrix}$$

Parameter Conversions

- If all the two-port parameters for a network exist, it is possible to relate one set of parameters to another since the parameters interrelate the variables V_1, I_1, V_2 and I_2 and Table 10.1 lists all the conversion formulas that relate one set of two-port parameters to another. Note that $\Delta_Z, \Delta_Y, \Delta_H$ *and* Δ_T refer to the determinants of the matrices for the Z, Y, hybrid and ABCD parameters, respectively. Therefore, given one set of parameters for a network, we can use Table 10.1 to find others.

Parameter Conversions

$\begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix}$	$\begin{bmatrix} \frac{y_{22}}{\Delta_Y} & \frac{-y_{12}}{\Delta_Y} \\ \frac{-y_{21}}{\Delta_Y} & \frac{y_{11}}{\Delta_Y} \end{bmatrix}$	$\begin{bmatrix} \frac{A}{C} & \frac{\Delta_T}{C} \\ \frac{1}{C} & \frac{D}{C} \end{bmatrix}$	$\begin{bmatrix} \frac{\Delta_H}{h_{22}} & \frac{h_{12}}{h_{22}} \\ \frac{-h_{21}}{h_{22}} & \frac{1}{h_{22}} \end{bmatrix}$
$\begin{bmatrix} \frac{z_{22}}{\Delta_Z} & \frac{-z_{12}}{\Delta_Z} \\ \frac{-z_{21}}{\Delta_Z} & \frac{z_{11}}{\Delta_Z} \end{bmatrix}$	$\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix}$	$\begin{bmatrix} \frac{D}{B} & \frac{-\Delta_T}{B} \\ -\frac{1}{B} & \frac{A}{B} \end{bmatrix}$	$\begin{bmatrix} \frac{1}{h_{11}} & \frac{-h_{12}}{h_{11}} \\ \frac{h_{21}}{h_{11}} & \frac{\Delta_H}{h_{11}} \end{bmatrix}$
$\begin{bmatrix} \frac{z_{11}}{z_{21}} & \frac{\Delta_Z}{z_{21}} \\ \frac{1}{z_{21}} & \frac{z_{22}}{z_{21}} \end{bmatrix}$	$\begin{bmatrix} \frac{-y_{22}}{y_{21}} & \frac{-1}{y_{21}} \\ \frac{-\Delta_Y}{y_{21}} & \frac{-y_{11}}{y_{21}} \end{bmatrix}$	$\begin{bmatrix} A & B \\ C & D \end{bmatrix}$	$\begin{bmatrix} \frac{-\Delta_H}{h_{21}} & \frac{-h_{11}}{h_{21}} \\ \frac{-h_{22}}{h_{21}} & \frac{-1}{h_{21}} \end{bmatrix}$
$\begin{bmatrix} \frac{\Delta_Z}{z_{22}} & \frac{z_{12}}{z_{22}} \\ \frac{-z_{21}}{z_{22}} & \frac{1}{z_{22}} \end{bmatrix}$	$\begin{bmatrix} \frac{1}{y_{11}} & \frac{-y_{12}}{y_{11}} \\ \frac{y_{21}}{y_{11}} & \frac{\Delta_Y}{y_{11}} \end{bmatrix}$	$\begin{bmatrix} \frac{B}{D} & \frac{\Delta_T}{D} \\ -\frac{1}{D} & \frac{C}{D} \end{bmatrix}$	$\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$

TABLE 10.1: Two-port parameter conversion formulas

Parameter Conversions

- **Example**
- Determine the Y parameters for a two-port if the Z parameters are
- $Z = \begin{bmatrix} 18 & 6 \\ 6 & 9 \end{bmatrix}$
- $\left(y_{11} = \frac{1}{14}S;\ y_{12} = y_{21} = -\frac{1}{21}S;\ y_{22} = \frac{1}{7}S\right)$

Interconnection of Two-Ports

- Interconnected two-port circuits are important because when designing complex systems it is generally much easier to design a number of simpler subsystems that can then be interconnected to form the complete system.
- If each subsystem is treated as a two-port network, the interconnection techniques described in this section provide some insight into the manner in which a total system may be analyzed and/or designed.

Interconnection of Two-Ports

- Thus, we will now illustrate techniques for treating a network as a combination of subnetworks. We will, therefore, analyze a two-port network as an interconnection of simpler two-ports.
- Although two-ports can be interconnected in a variety of ways, we will treat only three types of connections: parallel, series, and cascade.

Interconnection of Two-Ports

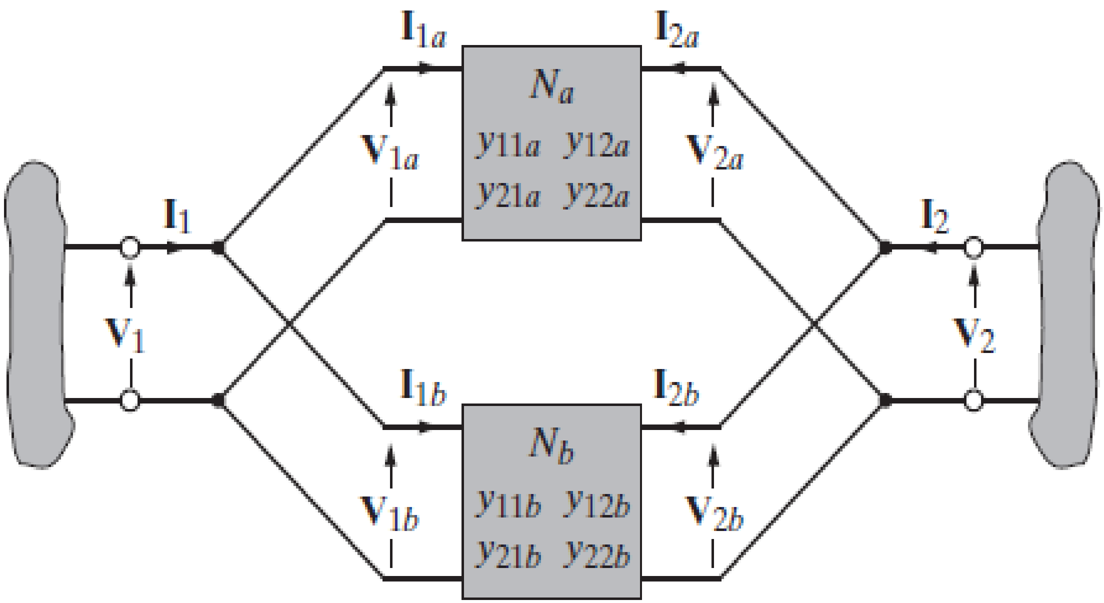


Figure 10.10: *Parallel interconnection of two-ports.*

- In the parallel interconnection case, a two-port N is composed of two-ports N_a and N_b and connected as shown in Fig. 10.10. *Provided that the terminal characteristics of the two networks N_a and N_b are not altered by the interconnection illustrated in the figure*, then the Y parameters for the total network are
- $\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} = \begin{bmatrix} y_{11a} + y_{11b} & y_{12a} + y_{12b} \\ y_{21a} + y_{21b} & y_{22a} + y_{22b} \end{bmatrix}$
- and hence to determine the Y parameters for the total network, we simply add the Y parameters of the two networks N_a and N_b.

Interconnection of Two-Ports

- Likewise, if the two-port N is composed of N_a and N_b the series connection of and as shown in Fig. 10.8, then *once again, as long as the terminal characteristics of the two networks* N_a *and* N_b *are not altered by the series interconnection*, the Z parameters for the total network are
- $$\begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} = \begin{bmatrix} z_{11a} + & z_{11b} & z_{12a} + & z_{12b} \\ z_{21a} + & z_{21b} & z_{22a} + & z_{22b} \end{bmatrix}$$
- Therefore, the Z parameters for the total network are equal to the sum of the Z parameters for the networks N_a and N_b .

Interconnection of Two-Ports

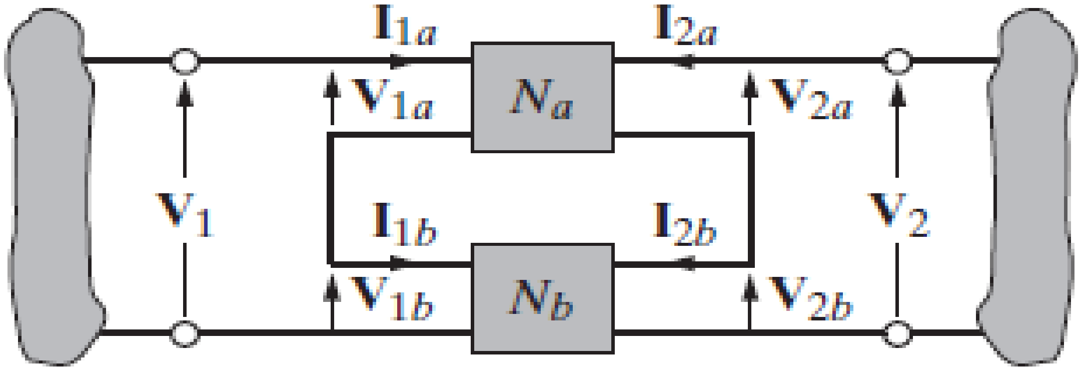


Figure 10.11: Series interconnection of two-ports.

Interconnection of Two-Ports

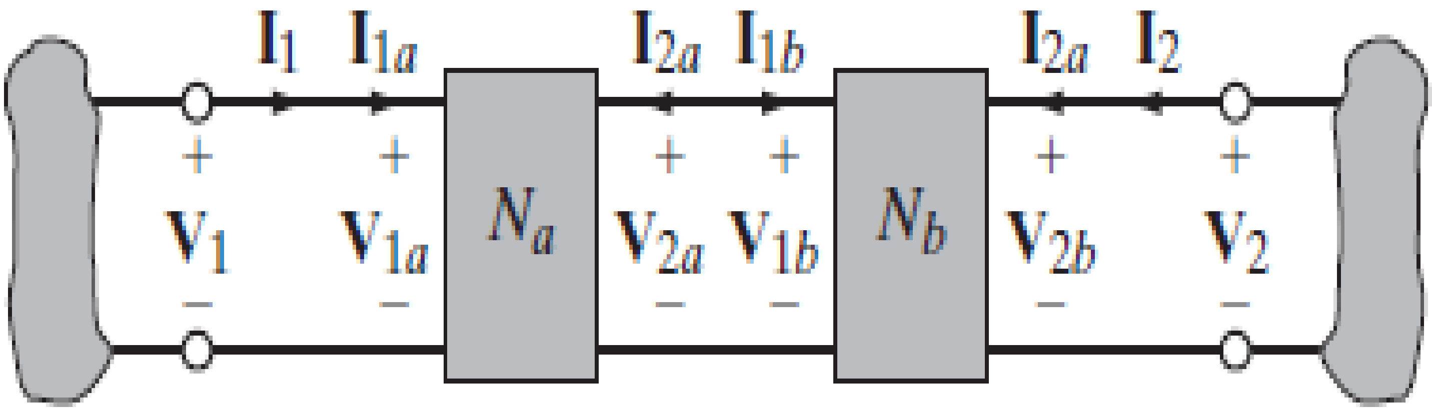


Figure 10.12: Cascade interconnection of networks.

Interconnection of Two-Ports

- Finally, if a two-port N is composed of a cascade interconnection of N_a and N_b as shown in Fig. 10.9, the equations for the total network are
- $$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A_a & B_a \\ C_a & D_a \end{bmatrix} \begin{bmatrix} A_b & B_b \\ C_b & D_b \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix}$$
- Hence, the transmission parameters for the total network are derived by matrix multiplication as indicated previously. The order of the matrix multiplication is important and is performed in the order in which the networks are interconnected.

Interconnection of Two-Ports

- The cascade interconnection is very useful. Many large systems can be conveniently modeled as the cascade interconnection of a number of stages. For example, the very weak signal picked up by a radio antenna is passed through a number of successive stages of amplification—each of which can be modeled as a two-port subnetwork.

Interconnection of Two-Ports

- **Example**
- We wish to determine the Y parameters for the network shown in Fig. 10.13a by considering it to be a parallel combination of two networks as shown in Fig. 10.13b. The capacitive network will be referred to as N_a and the resistive network will be referred to as N_b.

Interconnection of Two-Ports

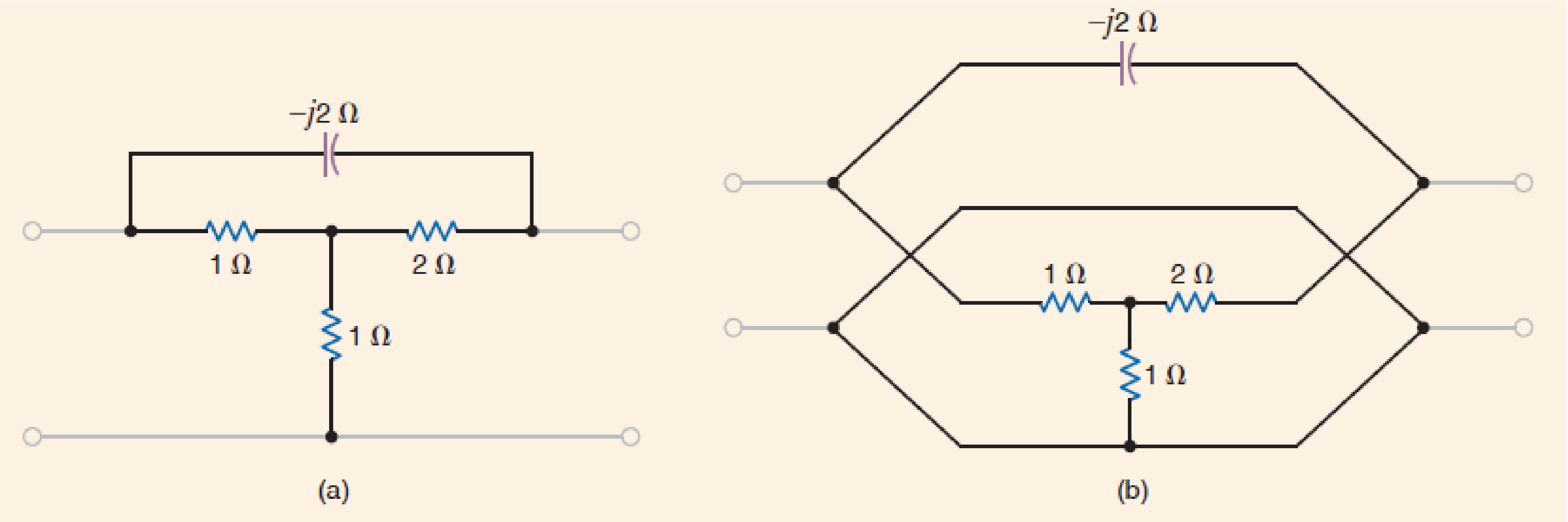


Figure 10.13: *Network composed of the parallel combination of two subnetworks.*

Interconnection of Two-Ports

- The Y parameters for N_a are
- $y_{11a} = j\frac{1}{2}S$ $\quad$ $y_{12a} = -j\frac{1}{2}S$
- $y_{21a} = -j\frac{1}{2}S$ $\quad$ $y_{22a} = j\frac{1}{2}S$
- And the Y parameters for N_b are:
- $y_{11b} = \frac{3}{5}S$ $\quad$ $y_{12b} = -\frac{1}{5}S$
- $y_{21b} = -\frac{1}{5}S$ $\quad$ $y_{22b} = \frac{2}{5}S$

Interconnection of Two-Ports

- Hence, the Y parameters for the network in Fig. 10.10 are
- $y_{11} = \frac{3}{5} + j\frac{1}{2}S$ $\qquad y_{12} = -\left(\frac{1}{5} + j\frac{1}{2}\right)S$
- $y_{21} = -\left(\frac{1}{5} + j\frac{1}{2}\right)S$ $\qquad y_{22} = \frac{2}{5} + j\frac{1}{2}S$
- To gain an appreciation for the simplicity of this approach, you need only try to find the Y parameters for the network in Fig. 10.13a directly.

Example

- Let us derive the two-port parameters of the network in Fig. 10.14 by considering it to be a cascade connection of two networks as shown in Fig. 10.9
- The ABCD parameters for the identical T networks were calculated in Example 16.4 to be
- $A = 1 + J\omega \quad B = 2 + j\omega \ \ , c = j\omega \ \ and\, D = 1 + j\omega$
- Therefore, the transmission parameters for the total network are
- $\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 + 4j\omega - 2\omega^2 & 4 + 6j\omega - 2\omega^2 \\ 2j\omega - 2\omega^2 & 1 + 4j\omega - 2\omega^2 \end{bmatrix}$

Interconnection of Two-Ports

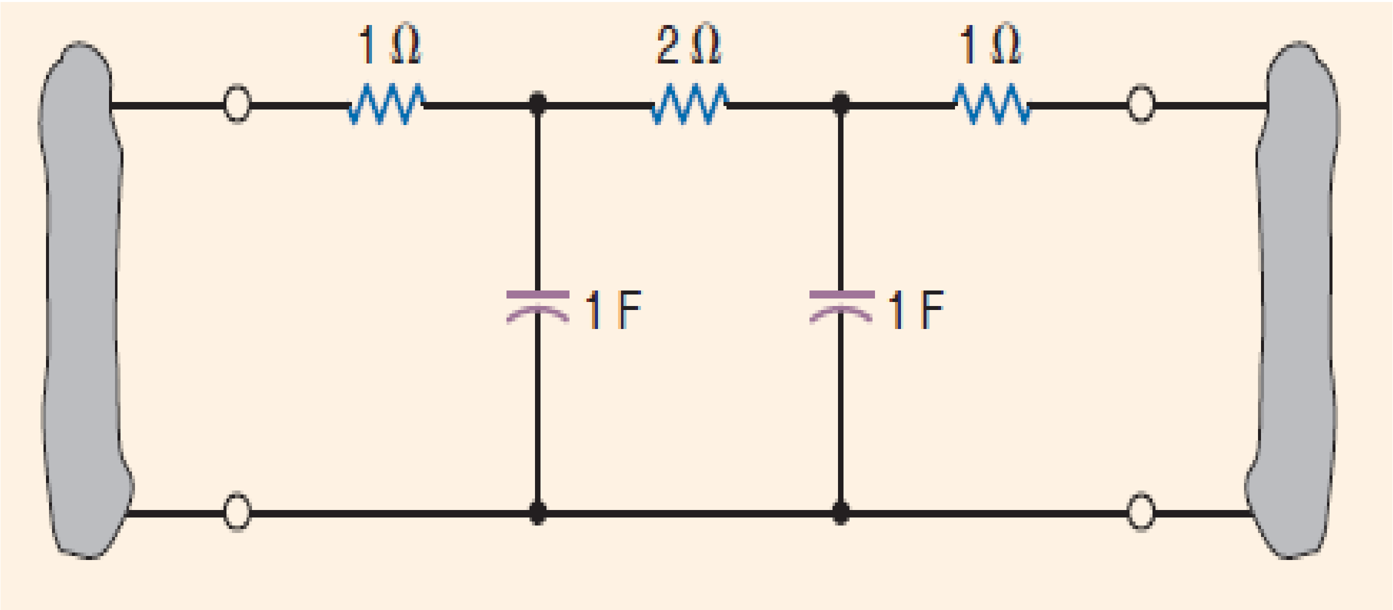


Figure 10.14