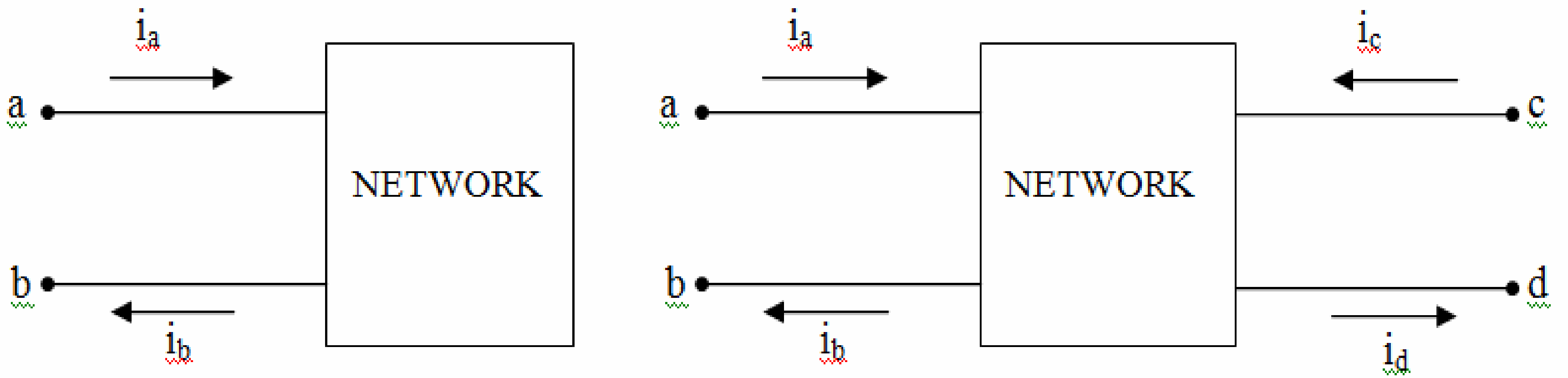
# TWO PORT NETWORKS

A pair of terminals at which a signal may enter (or) leave a network is called a port, and a network having only one such pair of terminals is called a one-port network (or) simply a one-port. Now connections may be made to any other nodes interval to the one-port, and it is there fore evident that '$i_a$' must be equal to '$i_b$' in the one port network shown in figure. When more than on pair of terminals is present, the network is known as a multi-port network.
In this case $i_a = i_b$ and $i_c = i_d$.




A two-port network is a special case of multi-port network. Each port consists of two terminals, one for entry and other for exit. From the definition of a pot, the current at entry is equal to that at the exit terminal of a port.

**Examples:-** Transforms, Power Transmission lines, Bridge circuits, Filters etc., Let us consider a network having six terminals to which external connections can be made …….

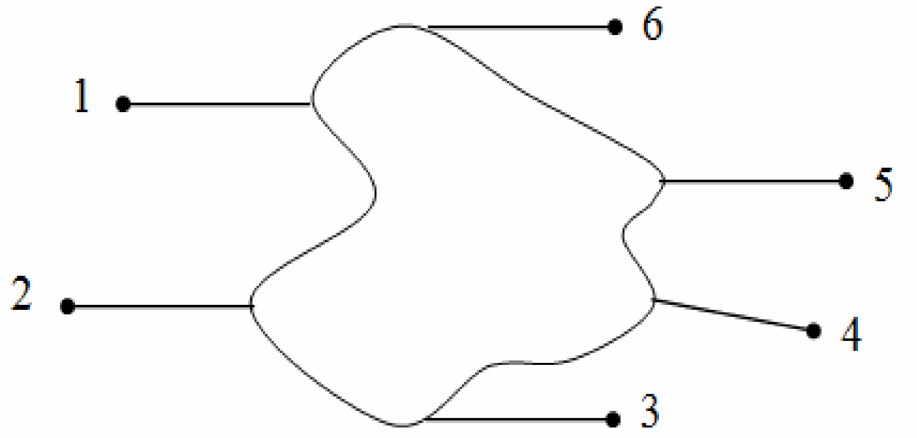



Fig. Six – Terminal network

The special methods of analysis which have been developed for two-port networks, the current and voltage relationships at the terminals of the networks and existing at the specific nature of the currents & voltage within the networks.

# RELATIONSHIP OF TWO-PORT VARIABLES

In the two-port network as shown in figure.

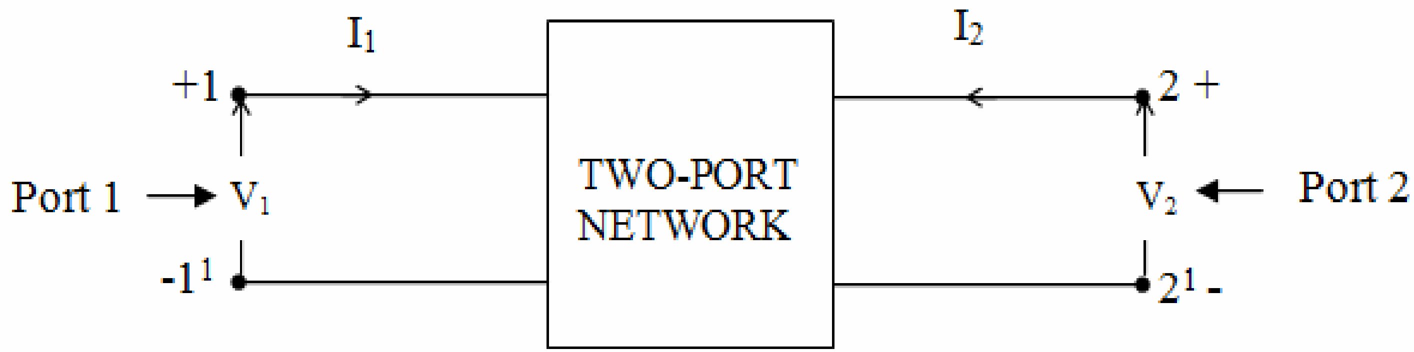



Fig. Two-port network

Here four variables i.e., two voltages and two currents. There are other voltages and currents that are present inside the box. The box enclosing the network has the function of indicating that other voltages and currents are not available for measurement (or) are not important. We assume that the variables are transform quantities and use '$V_1$' and '$I_1$' as variables at the input i.e., port 1, and $V_2$ and $I_2$ as the variables at output port 2. Now only two of the four variables are independent, and the specification of any two of them determines the remaining two. For example, if $V_1$ and $V_2$ are specified, the $I_1$ and $I_2$ are determined. The dependence of two of the four variables on the other two is described in a number of ways, depending on which of the variables are choosen to be the independent variables.

| NAME | FUNCTION | | EQUATION |
| --- | --- | --- | --- |
| | EXPRESS | INTERMS OF | |
| OPEN CIRCUIT IMPEDANCE [Z-PARAMETERS] | $V_1, V_2$ | $I_1, I_2$ | $V_1 = Z_{11} I_1 + Z_{12} I_2$ <br> $V_2 = Z_{21} I_1 + Z_{22} I_2$ |
| SHORT CIRCUIT ADMITTANCE [Y-PARAMETERS] | $I_1, I_2$ | $V_1, V_2$ | $I_1 = Y_{11} V_1 + Y_{12} V_2$ <br> $I_2 = Y_{21} V_1 + Y_{22} V_2$ |
| TRANSMISSION [ABCD-PARAMETERS] | $V_1, I_1$ | $V_2, I_2$ | $V_1 = AV_2 - BI_2$ <br> $I_1 = CV_2 - DI_2$ |
| INVERSE TRANSMISSION [$A^1B^1C^1D^1$-PARAMETERS] | $V_2, I_2$ | $V_1, I_1$ | $V_2 = A^1 V_1 - B^1 I_1$ <br> $I_2 = C^1 V_1 - D^1 I_1$ |
| HYBRID [h-PARAMETERS] | $V_1, I_2$ | $I_1, V_2$ | $V_1 = h_{11} I_1 + h_{12} V_2$ <br> $I_1 = h_{21} I_1 + h_{22} V_2$ |
| INVERSE HYBRID [g-PARAMETERS] | $I_1, V_2$ | $V_1, I_2$ | $I_1 = g_{11} V_1 + g_{12} I_2$ <br> $V_2 = g_{21} V_1 + g_{22} I_2$ |

# OPEN CIRCUIT IMPEDANCE – PARAMETERS (OR) Z-PARAMETERS

$(V_1, V_2) = f(I_1, I_2)$  $V_1 = Z_{11} I_1 + Z_{12} I_2 \longrightarrow (1)$

$V_2 = Z_{21} I_1 + Z_{22} I_2 \longrightarrow (2)$

Putting in matrix form,

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

## Determination of Z-parameters:

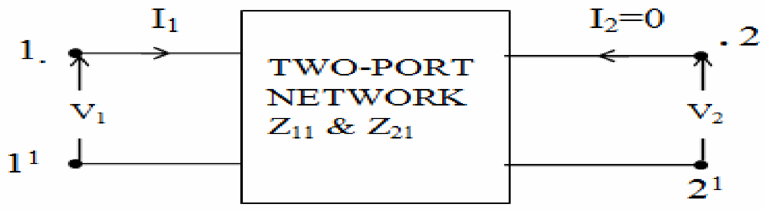



Fig (a)

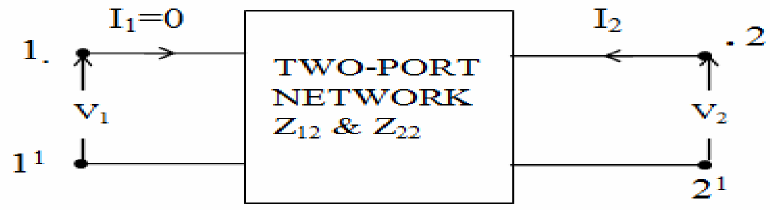



Fig (b)

Mathematically,

$Z_{11} = \left.\frac{V_1}{I_1}\right|_{I_2 = 0} \longrightarrow$ Input driving point impedance with out put port open circuited.

$Z_{12} = \left.\frac{V_1}{I_2}\right|_{I_1 = 0} \longrightarrow$ Reverse transfer function impedance with input port open circuited.

$Z_{21} = \left.\frac{V_2}{I_1}\right|_{I_2 = 0} \longrightarrow$ Forwarded transfer function impedance with put port open circuited.

$Z_{22} = \left.\frac{V_2}{I_2}\right|_{I_1 = 0} \longrightarrow$ Output driving point impedance with input port open circuited.

The Z-parameters equivalent circuit corresponding to equations (1) & (2) is shown in figure (c). The voltage sources $V_1 = Z_{12} I_2$ & $V_2 = Z_{21} I_1$ are called current controlled voltage sources [CCVS] as their voltages are dependent on current $I_1$ and $I_2$ respectively.

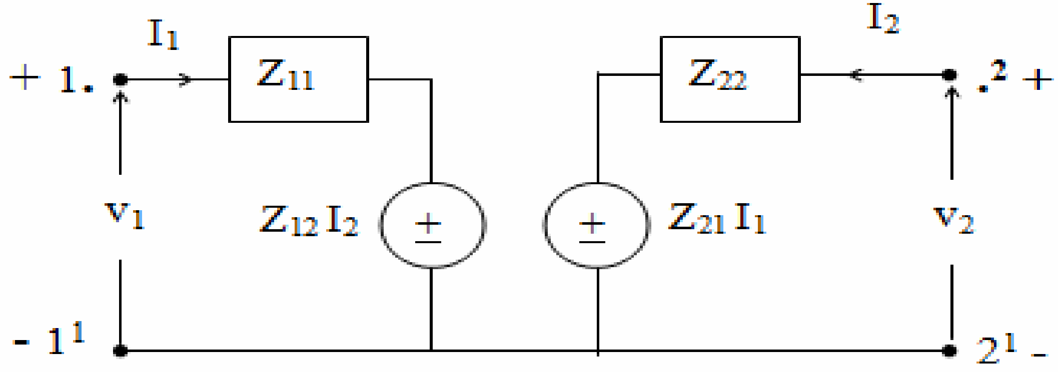



Fig (c) : Two Generator Equivalent circuit using Z-parameters

Writing equation as

$$V_1 = (Z_{11} - Z_{12}) I_1 + Z_{12} (I_1 - I_2) \longrightarrow (3)$$

$$V_2 = (Z_{21} - Z_{12}) I_1 + (Z_{22} - Z_{12}) I_2 + Z_{12} (I_1 + I_2) \longrightarrow (4)$$

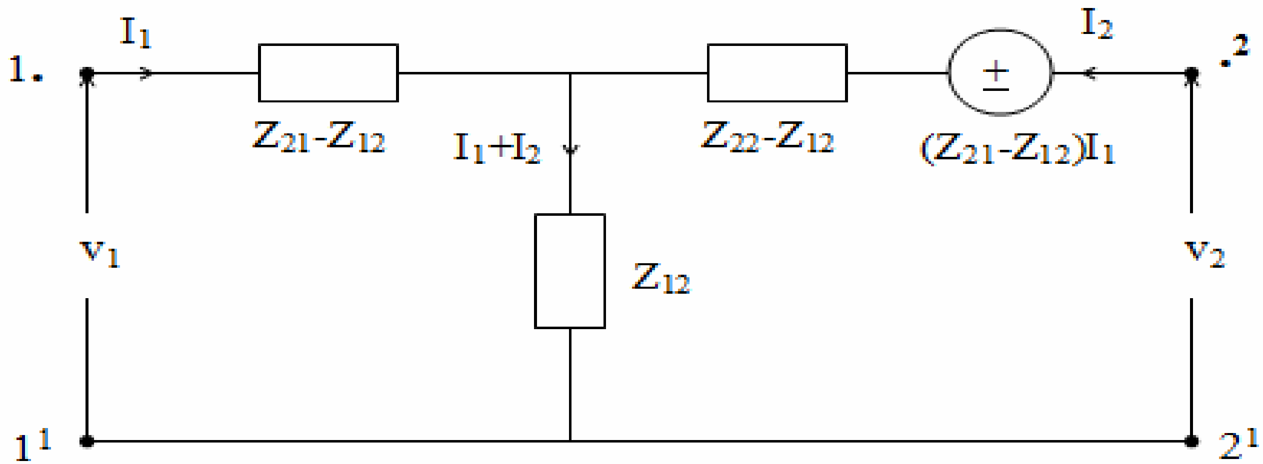



Fig. (d) : One Generator equivalent circuit

## SHORT – CIRCUIT ADMITTANCE – PARAMETERS (OR) Y-PARAMETERS

$(I_1, I_2) = f(V_1, V_2)$ $\quad I_1 = Y_{11} V_1 + Y_{12} V_2 \longrightarrow (1)$

$I_2 = Y_{21} V_1 + Y_{22} V_2 \longrightarrow (2)$

Putting in matrix form,

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

### Determination of Y-parameters:

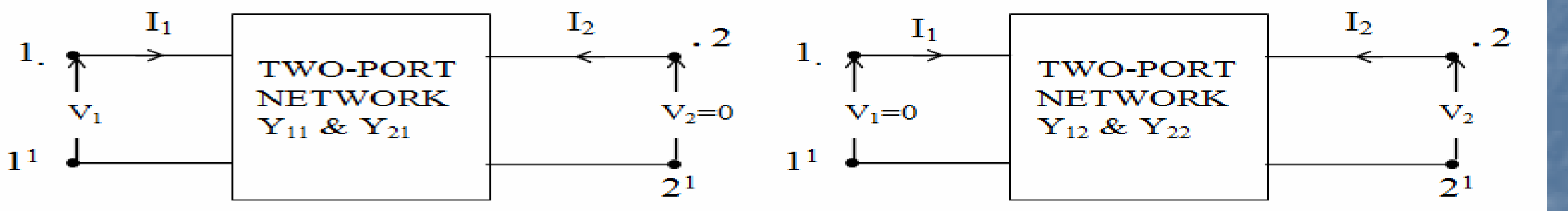



Fig (a) Fig (b)

Mathematically,

$Y_{11} = \left.\frac{I_1}{V_1}\right|_{V_2 = 0} \longrightarrow$ Input driving point admittance with out put port short-circuited.

$Y_{12} = \left.\frac{I_1}{V_2}\right|_{V_1 = 0} \longrightarrow$ Reverse transfer admittance with input port short-circuited.

$Y_{21} = \left.\frac{I_2}{V_1}\right|_{V_2 = 0} \longrightarrow$ Forwarded transfer admittance with out put port short-circuited.

$Y_{22} = \left.\frac{I_2}{V_2}\right|_{V_1 = 0} \longrightarrow$ Output driving point admittance with input port short-circuited.

**NOTE:** [Short circuit admittance matrix] = [Open circuit impedance matrix] $^{-1}$

And $Y_{ij} \neq \frac{1}{Z_{ij}}$ i.e., $Y_{11} \neq \frac{1}{Z_{11}}$ & $Y_{12} \neq \frac{1}{Z_{12}}$ etc., The Y-parameters equivalent circuit corresponding to equations (1) & (2) is shown in figure (c). The current sources $I_1 = Y_{12} V_2$ & $I_2 = Y_{21} V_1$ are called voltage controlled current sources [VCCS] as the values of their currents are dependent on voltages $V_1$ and $V_2$ respectively.

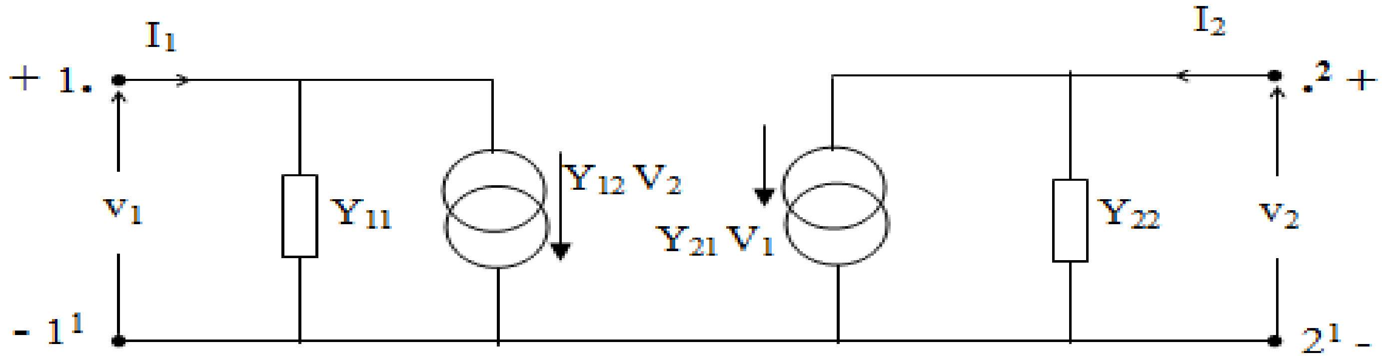



Fig (c) : Two Generator Equivalent circuit using Y-parameters

$$I_1 = (Y_{11} + Y_{12}) V_1 - Y_{12} (V_1 - V_2) \longrightarrow (3)$$

$$I_2 = (Y_{21} - Y_{12}) V_1 + (Y_{22} + Y_{12}) V_2 - Y_{12} (V_2 - V_1) \longrightarrow (4)$$

From which the following equivalent circuit is obtain as shown in figure (d)

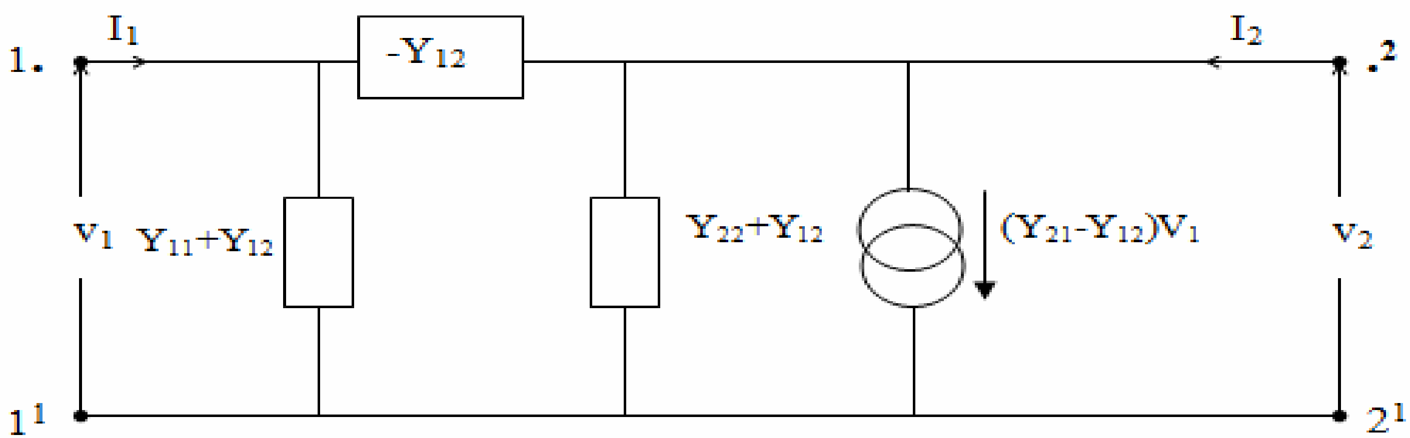



Fig. (d) : One Generator equivalent circuit

# HYBRID – PARAMETERS (OR) h -PARAMETERS

The hybrid parameters are wide usage in electronic circuits, especially in constructing models for transistors. In this case, voltage of the input port and the current of the output port are expressed in terms of the current of the input port and the voltage of the output port. The parameters are dimensionally mixed and due to this reason, these parameters are called as "Hybrid Parameters".

$(V_1, I_2) = f(I_1, V_2)$ $\qquad V_1 = h_{11} I_1 + h_{12} V_2 \longrightarrow$ (1)

$I_2 = h_{21} I_1 + h_{22} V_2 \longrightarrow$ (2)

Putting in matrix form,

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

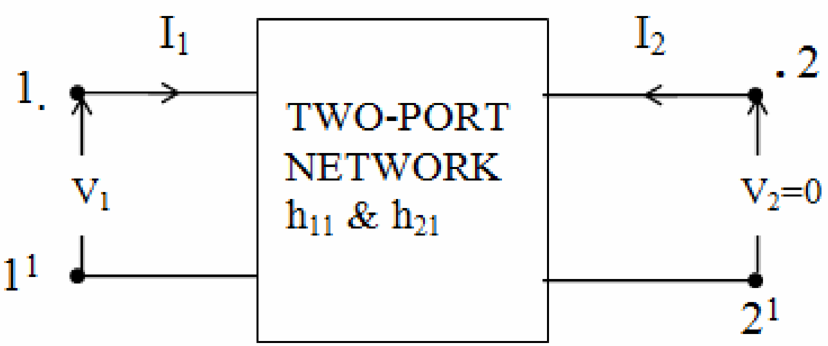



Fig (a)

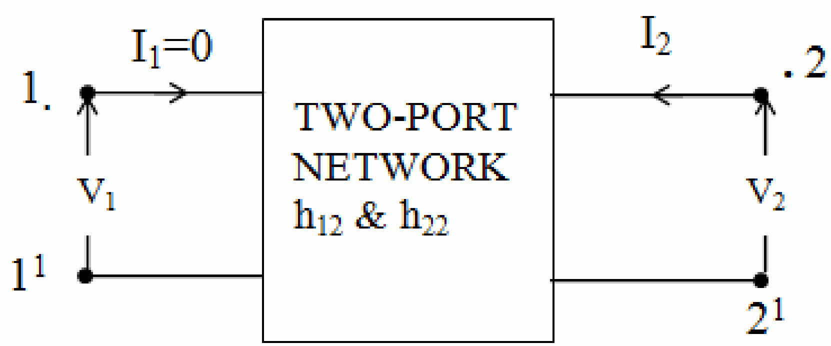



Fig (b)

Mathematically,

$$h_{11} = \frac{V_1}{I_1}\bigg|_{V_2 = 0}$$ ⟶ Input impedance with the out put port short-circuited.

$$h_{12} = \frac{V_1}{V_2}\bigg|_{I_1 = 0}$$ ⟶ Reverse voltage with the input port open circuited.

$$h_{21} = \frac{I_2}{I_1}\bigg|_{V_2 = 0}$$ ⟶ Forward current gain with the out put port short-circuited.

$$h_{22} = \frac{I_2}{V_2}\bigg|_{I_1 = 0}$$ ⟶ Output admittance with the input port open circuited.

The h-parameters equivalent circuit corresponding to equations (1) & (2) is shown in figure (c). Where $V_1 = h_{12} V_2$ & $I_2 = h_{21} I_1$ are voltage controlled voltage sources [VCVS] and currents controlled current source [CCCS] respectively.

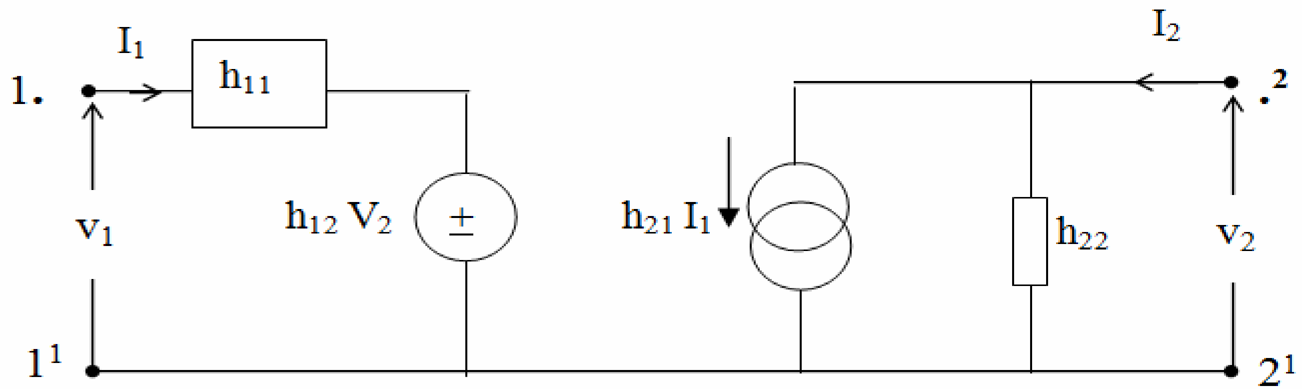



Fig (c) : h-parameters equivalent network

# INVERSE - HYBRID – PARAMETERS (OR) g -PARAMETERS

The hybrid parameters and inverse hybrid parameters are dual of each other like Z and Y-parameters.

$$[g] = [h]^{-1}$$

$(I_1, V_2) = f(V_1, I_2)$

$$I_1 = g_{11} V_1 + g_{12} I_2 \longrightarrow (1)$$

$$V_2 = g_{21} V_1 + g_{22} I_2 \longrightarrow (2)$$

## Determination of g-parameters:

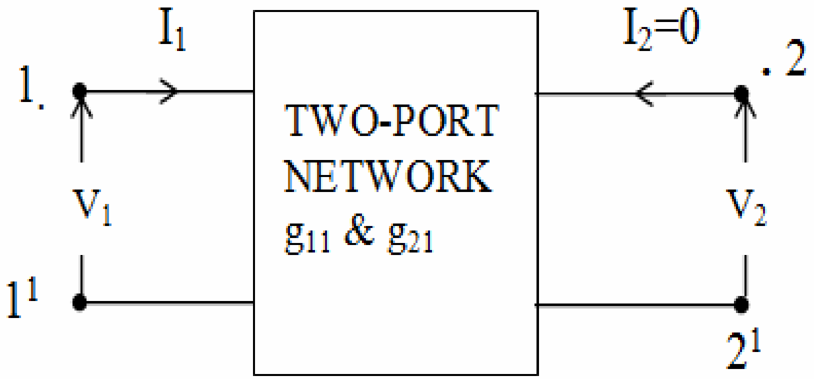



Fig (a)

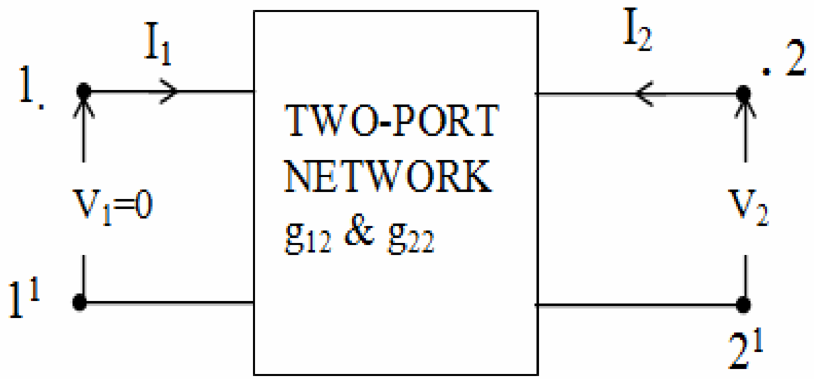



Fig (b)

Mathematically,

$$g_{11} = \left.\frac{I_1}{V_1}\right|_{I_2 = 0} \longrightarrow$$ Input admittance with out put port open circuited.

$$g_{12} = \left.\frac{I_1}{I_2}\right|_{V_1 = 0} \longrightarrow$$ Reverse current gain with input port short-circuited.

$$g_{21} = \left.\frac{V_2}{V_1}\right|_{I_2 = 0} \longrightarrow$$ Forward voltage with out put port open circuited.

$$g_{22} = \left.\frac{V_2}{I_2}\right|_{V_1 = 0} \longrightarrow$$ Output impedance with input port short-circuited.

The g-parameters equivalent circuit corresponding to equations (1) & (2) is shown in figure (c). Where $I_1 = g_{12} I_2$ & $V_2 = g_{21} V_1$ are current controlled current sources [CCCS] and Voltage controlled voltage source [VCVS] respectively.

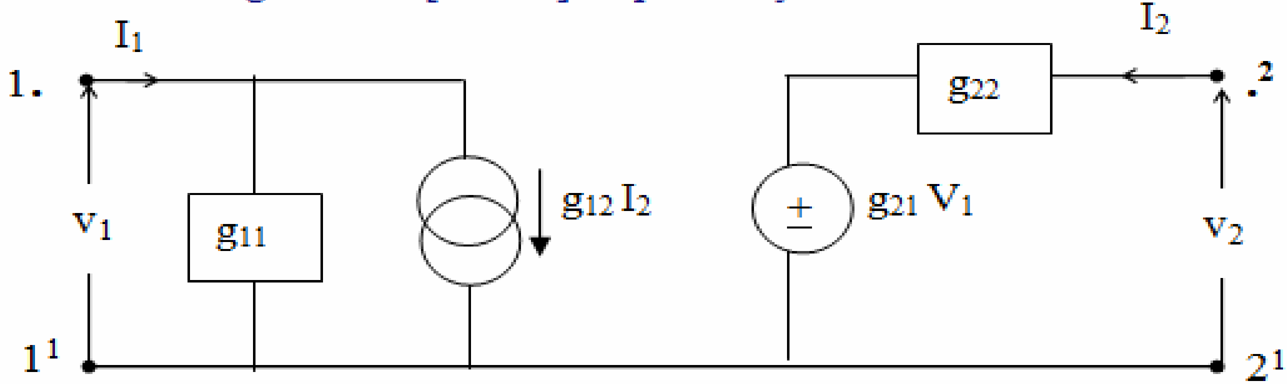



Fig (c) : Equivalent circuit of g-parameters

**TRANSMISSION [T] (OR) CHAIN (OR) ABCD-PARAMETERS (OR) GENERAL CIRCUIT PARAMETERS:**

The transmission 'T' (or) Chain (or) ABCD – Parameters can be expressed as

$(V_1, I_1) = f(V_2, I_2)$ $\quad$ $V_1 = AV_2 - B I_2 \longrightarrow (1)$

$I_1 = CV_2 - D I_2 \longrightarrow (2)$

Putting in matrix form,

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

**Determination of ABCD (or) T-parameters:**

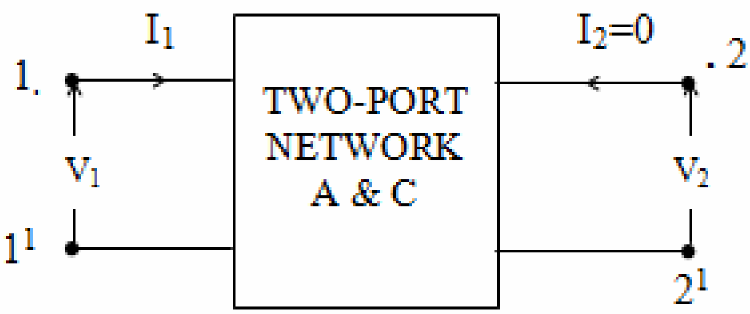



Fig (a)

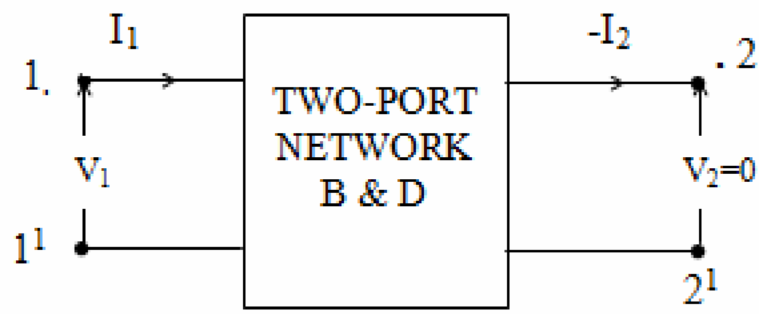



Fig (b)

In order to determine the T-Parameters, open and short the circuit output port [receiving end] and applied some voltage '$V_1$' to input port [sending end] as shown in figure (a) & (b) to obtain A,C and B,D respectively.

Mathematically,

$$A = \left.\frac{V_1}{V_2}\right|_{I_2 = 0} \longrightarrow$$ Reverse voltage ratio with the receiving end open circuited.

$$B = \left.\frac{V_1}{-I_2}\right|_{V_2 = 0} \longrightarrow$$ Reverse transfer impedance with the receiving end short-circuited.

$$C = \left.\frac{I_1}{V_2}\right|_{I_2 = 0} \longrightarrow$$ Reverse transfer admittance with the receiving end open circuited.

$$D = \left.\frac{I_1}{-I_2}\right|_{V_2 = 0} \longrightarrow$$ Reverse current ratio with the receiving end short-circuited.

**NOTE:** For passive network the all the four T-parameters are positive, since $I_2$ is itself negative (or) $-I_2$ is positive.

## INVERSE TRANSMISSION (OR) INVERSE ABCD (OR) $T^1$ - PARAMETERS:

$T^1$- parameters can be expressed as output variables in terms of input port variables i.e.,

$(V_2, I_2) = f(V_1, I_1)$  $V_2 = A^1 V_1 - B^1 I_1$ ⟶ (1)

$I_2 = C^1 V_1 - D^1 I_1$ ⟶ (2)

Putting in matrix form,

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} A^1 & B^1 \\ C^1 & D^1 \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix}$$

The equivalent circuit of a two port network is also not possible in terms of $T^1$ – Parameters.

## Determination of $T^1$-parameters:

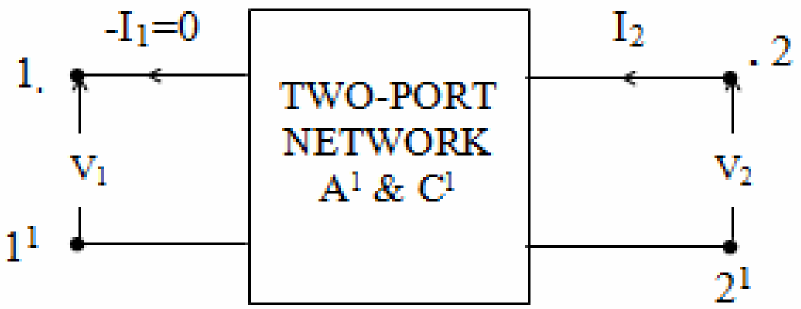



Fig (a)

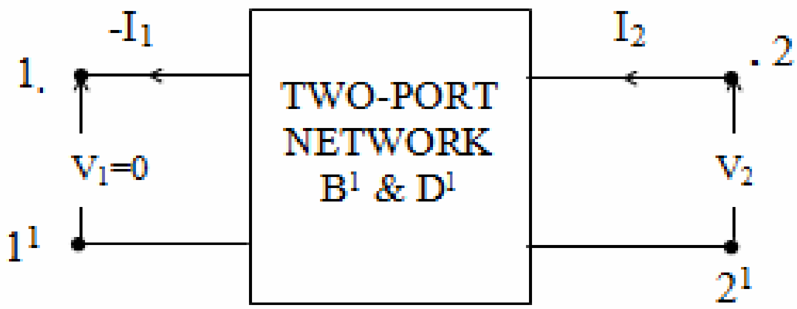



Fig (b)

Mathematically,

$$A^1 = \frac{V_2}{V_1}\bigg|_{I_1 = 0} \longrightarrow$$ Forwarded voltage ratio with sending end open circuited.

$$B^1 = \frac{V_2}{-I_1}\bigg|_{V_1 = 0} \longrightarrow$$ Forward transfer impedance with sending end short-circuited.

$$C^1 = \frac{I_2}{V_1}\bigg|_{I_1 = 0} \longrightarrow$$ Forward transfer admittance with sending end open circuited.

$$D^1 = \frac{I_2}{-I_1}\bigg|_{V_1 = 0} \longrightarrow$$ Forwarded current ratio with sending end short-circuited.

**NOTE: -** For passive network in the case also all the four $T^1$-parameters are positive, as $I_1$ is itself negative (or) $-I_1$ is positive.

## INTER RELATION SHIPS BETWEEN PARAMETERS SETS

If we want to express 'α'-parameters in terms of 'β'-parameters, we have to write 'β'-parameters equations & then the algebraic manipulation, rewrite the equations as needed for 'α'-parameters.

### Z-PARAMETERS IN TERMS OF OTHER PARAMETERS

**Z-parameters in terms of Y-parameters**

We know that Y-parameters as

$$I_1 = Y_{11} V_1 + Y_{12} V_2 \longrightarrow (1)$$

$$I_2 = Y_{21} V_1 + Y_{22} V_2 \longrightarrow (2)$$

Putting in matrix form,

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

$$\Rightarrow \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}^{-1} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

$$\therefore [Z] = [Y]^{-1}$$

i.e., $$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}^{-1} = \frac{1}{\Delta Y} \begin{bmatrix} Y_{22} & -Y_{12} \\ -Y_{21} & Y_{11} \end{bmatrix}$$

Where $\Delta Y = Y_{11} Y_{22} - Y_{12} Y_{21}$

$$\therefore Z_{11} = \frac{Y_{22}}{\Delta Y}; \quad Z_{12} = \frac{-Y_{12}}{\Delta Y}; \quad Z_{21} = \frac{-Y_{21}}{\Delta Y}; \quad Z_{22} = \frac{Y_{11}}{\Delta Y}$$

## Z-parameters in terms of T-parameters

We know that T-parameters as

$$V_1 = AV_2 - B I_2 \longrightarrow (1)$$

$$I_1 = CV_2 - D I_2 \longrightarrow (2)$$

From equation (2), $V_2 = \frac{I_1}{C} + \frac{D}{C} I_2$

$$\therefore Z_{22} = \frac{D}{C}; \quad Z_{21} = \frac{1}{C}$$

Substituting $V_2$ in equation (1)

$$V_1 = A\left[\frac{I_1}{C} + \frac{D}{C}\right] I_2 - BI_2 = \frac{A}{C} I_1 + \frac{(AD - BC)}{C} I_2$$

Put $\Delta T = AD-BC$

$$V_1 = \frac{A}{C} I_1 + \frac{\Delta T}{C} I_2$$

$$\therefore Z_{11} = \frac{A}{C}; \quad Z_{12} = \frac{\Delta T}{C}$$

## Z-parameters in terms of $T^1$-parameters

We know that $T^1$-parameters as

$$V_2 = A^1 V_1 - B^1 I_1 \longrightarrow (1)$$

$$I_2 = C^1 V_1 - D^1 I_1 \longrightarrow (2)$$

From equation (2), $V_1 = \frac{I_2}{C^1} + \frac{D^1}{C^1} I_1 = \frac{D^1}{C^1} I_1 + \frac{I_2}{C^1}$

$$\therefore Z_{11} = \frac{D^1}{C^1}; \quad Z_{12} = \frac{1}{C^1}$$

Substituting $V_2$ in equation (1)

$$V_2 = A^1\left[\frac{D^1}{C^1} I_1 + \frac{1}{C^1} I_2\right] - B^1 I_1 = \frac{(A^1 D^1 - B^1 C^1)}{C^1} I_1 + \frac{A^1 I_2}{C^1}$$

Put $\Delta T^1 = A^1 D^1 - B^1 C^1$

$$V_2 = \frac{\Delta T^1}{C^1} I_1 + \frac{A^1 I_2}{C^1}$$

$$\therefore Z_{21} = \frac{\Delta T^1}{C^1}; \quad Z_{22} = \frac{A^1}{C^1}$$

## Z-parameters in terms of h-parameters

We know that h-parameters as

$$V_1 = h_{11} I_1 + h_{12} V_2 \longrightarrow (1)$$

$$I_2 = h_{21} I_1 + h_{22} V_2 \longrightarrow (2)$$

From equation (2) we have

$$V_2 = \frac{I_2}{h_{22}} - \frac{h_{21}}{h_{22}} I_1 = \frac{-h_{21}}{h_{22}} I_1 + \frac{1}{h_{22}} I_2$$

$$\therefore Z_{21} = \frac{-h_{21}}{h_{22}}; \quad Z_{22} = \frac{1}{h_{22}}$$

Substituting $V_2$ in equation (1)

$$V_1 = h_{11} I_1 + h_{12}\left[\frac{-h_{21}}{h_{22}} I_1 + \frac{I_2}{h_{22}}\right] = \frac{\Delta h}{h_{22}} I_1 + \frac{h_{12}}{h_{22}} I_2$$

Put $\Delta h = h_{11} h_{22} - h_{12} h_{21}$

$$\therefore Z_{11} = \frac{\Delta h}{h_{22}}; \quad Z_{12} = \frac{h_{12}}{h_{22}}$$

## Z-parameters in terms of g-parameters

We know that g-parameters as

$$I_1 = g_{11} V_1 + g_{12} I_2 \longrightarrow (1)$$

$$V_2 = g_{21} V_1 + g_{22} I_2 \longrightarrow (2)$$

From equation (1) we have

$$V_1 = \frac{I_1}{g_{11}} - \frac{g_{12}}{g_{11}} I_2$$

$$\therefore Z_{11} = \frac{1}{g_{11}}; \quad Z_{12} = \frac{-g_{12}}{g_{11}}$$

Substituting $V_1$ in equation (2)

$$V_2 = g_{21}\left[\frac{I_1}{g_{11}} - \frac{g_{12}}{g_{11}} I_2\right] + g_{22}\ I_2 = \frac{g_{21}}{g_{11}} I_1 + \frac{\Delta g}{g_{11}} I_2$$

Put $\Delta g = g_{11} g_{22} - g_{12} g_{21}$

$$V_2 = \frac{g_{21}}{g_{11}} I_1 + \frac{\Delta g}{g_{11}} I_2$$

$$\therefore \ Z_{21} = \frac{g_{21}}{g_{11}}; \ Z_{22} = \frac{\Delta g}{g_{11}}$$

## Y-PARAMETERS IN TERMS OF OTHER PARAMETERS

### Y-parameters in terms of Z-parameters

We know that Z-parameters as

$$V_1 = Z_{11} I_1 + Z_{12} I_2 \longrightarrow (1)$$

$$V_2 = Z_{21} I_1 + Z_{22} I_2 \longrightarrow (2)$$

Putting in matrix, we have

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

$$\Rightarrow \quad \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}^{-1} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

$$\therefore [Y] = [Z]^{-1}$$

i.e., $\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}^{-1} = \frac{1}{\Delta Z} \begin{bmatrix} Z_{22} & -Z_{12} \\ -Z_{21} & Z_{11} \end{bmatrix}$

Where $\Delta Z = Z_{11} Z_{22} - Z_{12} Z_{21}$

$$\therefore Y_{11} = \frac{Z_{22}}{\Delta Z}; \quad Y_{12} = \frac{-Z_{12}}{\Delta Z}; \quad Y_{21} = \frac{-Z_{21}}{\Delta Z}; \quad Y_{22} = \frac{Z_{11}}{\Delta Z}$$

## Y-parameters in terms of T-parameters

We know that T-parameters as

$$V_1 = AV_2 - B I_2 \longrightarrow (1)$$

$$I_1 = CV_2 - D I_2 \longrightarrow (2)$$

From equation (1), we have

$$I_2 = \frac{AV_2}{B} - \frac{V_1}{B} = \frac{-1}{B}V_1 + \frac{A}{B}V_2$$

$$\therefore \quad Y_{21} = \frac{-1}{B}; \; Y_{22} = \frac{A}{B}$$

Substituting $I_2$ in equation (2)

$$I_1 = CV_2 - D\left[\frac{-1}{B}V_1 + \frac{A}{B}V_2\right] = \frac{D}{B}V_1 + \frac{(-(AD - BC))}{B}V_2$$

Put ΔT = AD-BC

$$I_1 = \frac{D}{B}V_1 - \frac{\Delta T}{B}V_2$$

$$\therefore Y_{11} = \frac{D}{B}; \quad Y_{12} = \frac{-\Delta T}{B}$$

## Y-parameters in terms of $T^1$-parameters

We know that the $T^1$-parameters as

$$V_2 = A^1V_1 - B^1 I_1 \longrightarrow (1)$$

$$I_2 = C^1V_1 - D^1 I_1 \longrightarrow (2)$$

From equation (1), we have

$$I_1 = \frac{A^1}{B^1}V_1 - \frac{1}{B^1}V_2$$

$$\therefore Y_{11} = \frac{A^1}{B^1}; \quad Y_{12} = \frac{-1}{B^1}$$

Substituting $I_1$ in equation (2)

$$I_2 = C^1V_1 - D^1\left[\frac{A^1}{B^1}V_1 - \frac{V_2}{B^1}\right] = \frac{-(A^1D^1 - B^1C^1)}{B^1}V_1 + \frac{D^1}{B^1}V_2$$

Put $\Delta T^1 = A^1D^1 - B^1C^1$

$$I_2 = \frac{-\Delta T^1}{B^1}V_1 + \frac{D^1}{B^1}V_2$$

$$\therefore Y_{21} = \frac{-\Delta T^1}{B^1}; \quad Y_{22} = \frac{D^1}{B^1}$$

## Y-parameters in terms of h-parameters

We know that h-parameters as

$$V_1 = h_{11} I_1 + h_{12} V_2 \longrightarrow (1)$$

$$I_2 = h_{21} I_1 + h_{22} V_2 \longrightarrow (2)$$

From equation (1), we have

$$I_1 = \frac{V_1}{h_{11}} - \frac{h_{12}}{h_{11}} V_2$$

$$\therefore Y_{11} = \frac{1}{h_{11}}; \quad Y_{12} = \frac{-h_{12}}{h_{11}}$$

Substituting $I_1$ in equation (2)

$$I_2 = h_{21}\left[\frac{V_1}{h_{11}} - \frac{h_{12}}{h_{11}} V_2\right] + h_{22} V_2 = \frac{h_{21}}{h_{11}} V_1 + \frac{(h_{11}h_{22} - h_{12}h_{21})}{h_{11}} V_2$$

Put $\Delta h = h_{11} h_{22} - h_{12} h_{21}$

$$I_2 = \frac{h_{21}}{h_{11}} V_1 + \frac{\Delta h}{h_{11}} V_2$$

$$\therefore Y_{21} = \frac{h_{21}}{h_{11}}; \quad Y_{22} = \frac{\Delta h}{h_{11}}$$

## Y-parameters in terms of g-parameters

We know that g-parameters as

$$I_1 = g_{11} V_1 + g_{12} I_2 \longrightarrow (1)$$

$$V_2 = g_{21} V_1 + g_{22} I_2 \longrightarrow (2)$$

From equation (2) we have

$$I_2 = \frac{-g_{21}}{g_{22}} V_1 + \frac{V_2}{g_{22}}$$

$$\therefore \quad Y_{21} = \frac{-g_{21}}{g_{22}}; \quad Y_{22} = \frac{1}{g_{22}}$$

Substituting $I_2$ in equation (1)

$$I_1 = g_{11} V_1 + g_{12}\left[\frac{-g_{21}}{g_{22}} V_1 + \frac{V_2}{g_{22}}\right] = \frac{(g_{11} g_{22} - g_{12} g_{21})}{g_{22}} V_1 + \frac{g_{12}}{g_{22}} V_2$$

Put $\Delta g = g_{11} g_{12} - g_{12} g_{21}$

$$I_1 = \frac{\Delta g}{g_{22}} V_1 + \frac{g_{12}}{g_{22}} V_2$$

$$\therefore \quad Y_{11} = \frac{\Delta g}{g_{22}}; \quad Y_{12} = \frac{g_{12}}{g_{22}}$$

## T-PARAMETERS IN TERMS OF OTHER PARAMETERS

### T-parameters in terms of Z-parameters

We know that Z-parameters as

$$V_1 = Z_{11} I_1 + Z_{12} I_2 \longrightarrow (1)$$

$$V_2 = Z_{21} I_1 + Z_{22} I_2 \longrightarrow (2)$$

From Equation (2), we have

$$I_1 = \frac{V_2}{Z_{21}} - \frac{Z_{22}}{Z_{21}} I_2$$

$$\therefore C = \frac{1}{Z_{21}}; \quad D = \frac{Z_{22}}{Z_{21}}$$

Substituting $I_1$ in equation (1)

$$V_1 = Z_{11}\left[\frac{V_2}{Z_{21}} - \frac{Z_{22}}{Z_{21}} I_2\right] + Z_{12} I_2$$

$$= \frac{Z_{11}}{Z_{21}} V_2 - \frac{\Delta Z}{Z_{21}} I_2$$

Where $\Delta Z = Z_{11} Z_{22} - Z_{12} Z_{21}$

$$\therefore A = \frac{Z_{11}}{Z_{21}}; \quad B = \frac{\Delta Z}{Z_{21}}$$

## T-parameters in terms of Y-parameters

We know that Y-parameters as

$$I_1 = Y_{11} V_1 + Y_{12} V_2 \longrightarrow (1)$$

$$I_2 = Y_{21} V_1 + Y_{22} V_2 \longrightarrow (2)$$

From Equation (2), we have

$$V_1 = \frac{-Y_{22}}{Y_{21}} V_2 + \frac{1}{Y_{21}} I_2$$

$$\therefore\ A = \frac{-Y_{22}}{Y_{21}};\ B = \frac{-1}{Y_{21}}$$

Substituting $V_1$ in equation (1)

$$I_1 = Y_{11}\left[\frac{-Y_{22}}{Y_{21}} V_2 + \frac{1}{Y_{21}} I_2\right] + Y_{12} V_2$$

$$= \frac{-\Delta Y}{Y_{21}} V_2 + \frac{Y_{11}}{Y_{21}} I_2$$

Where $\Delta Y = Y_{11} Y_{22} - Y_{12} Y_{21}$

$$\therefore C = \frac{-\Delta Y}{Y_{21}};\quad D = \frac{-Y_{11}}{Y_{21}}$$

## T-parameters in terms of $T^1$-parameters

We know that the $T^1$-parameters as

$$V_2 = A^1 V_1 - B^1 I_1 \longrightarrow (1)$$

$$I_2 = C^1 V_1 - D^1 I_1 \longrightarrow (2)$$

Putting in matrix form,

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} A^1 & B^1 \\ C^1 & D^1 \end{bmatrix} \begin{bmatrix} V_1 \\ -I_1 \end{bmatrix}$$

Rewriting the above equation,

$$\begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} = \begin{bmatrix} A^1 & -B^1 \\ -C^1 & D^1 \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A^1 & -B^1 \\ -C^1 & D^1 \end{bmatrix}^{-1} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix}$$

$$\therefore [T] \neq [T^1]^{-1}$$

i.e. $$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A^1 & -B^1 \\ -C^1 & D^1 \end{bmatrix}^{-1} = \frac{1}{\Delta T^1}\begin{bmatrix} D^1 & B^1 \\ C^1 & A^1 \end{bmatrix}$$

Where $\Delta T^1 = A^1 D^1 - B^1 C^1$

$$\therefore A = \frac{D^1}{\Delta T^1};\quad B = \frac{B^1}{\Delta T^1};\quad C = \frac{C^1}{\Delta T^1};\quad D = \frac{A^1}{\Delta T^1}$$

**NOTE:** $\therefore [T] \neq [T^1]^{-1}$

## T-parameters in terms of h-parameters

We know that h-parameters as

$$V_1 = h_{11} I_1 + h_{12} V_2 \longrightarrow (1)$$

$$I_2 = h_{21} I_1 + h_{22} V_2 \longrightarrow (2)$$

From equation (2), we have

$$I_1 = \frac{-h_{22}}{h_{21}} V_2 + \frac{1}{h_{21}} I_2$$

$$\therefore\ C = \frac{-h_{22}}{h_{21}};\ D = \frac{-1}{h_{21}}$$

Substituting $I_1$ in equation (1)

$$V_1 = h_{11}\left[\frac{-h_{22}}{h_{21}} V_2 + \frac{1}{h_{21}} I_2\right] + h_{12} V_2$$

$$= \frac{-\Delta h}{h_{21}} V_2 + \frac{h_{11}}{h_{21}} I_2$$

Put $\Delta h = h_{11} h_{22} - h_{12} h_{21}$

$$\therefore\ A = \frac{-\Delta h}{h_{21}};\quad B = \frac{-h_{11}}{h_{21}}$$

## T-parameters in terms of g-parameters

We know that g-parameters as

$$I_1 = g_{11} V_1 + g_{12} I_2 \longrightarrow (1)$$

$$V_2 = g_{21} V_1 + g_{22} I_2 \longrightarrow (2)$$

From equation (2) we have

$$V_1 = \frac{V_2}{g_{21}} - \frac{g_{22}}{g_{21}} I_2$$

$$\therefore\ A = \frac{1}{g_{21}};\ B = \frac{g_{22}}{g_{21}}$$

Substituting $V_1$ in equation (1)

$$I_1 = g_{11}\left[\frac{V_2}{g_{21}} - \frac{g_{22}}{g_{21}} I_2\right] + g_{12} I_2$$

$$= \frac{g_{11}}{g_{21}} V_2 - \frac{\Delta g}{g_{21}} I_2$$

Put $\Delta g = g_{11} g_{22} - g_{12} g_{21}$

$$\therefore\ C = \frac{g_{11}}{g_{21}};\ D = \frac{\Delta g}{g_{21}}$$

## $T^1$-PARAMETERS IN TERMS OF OTHER PARAMETERS

### $T^1$-parameters in terms of Z-parameters

We known, that the Z-parameters as

$$V_1 = Z_{11} I_1 + Z_{12} I_2 \longrightarrow (1)$$

$$V_2 = Z_{21} I_1 + Z_{22} I_2 \longrightarrow (2)$$

From Equation (1), we have

$$I_2 = \frac{V_1}{Z_{12}} - \frac{Z_{11}}{Z_{12}} I_2$$

$$\therefore C^1 = \frac{1}{Z_{12}}; \quad D^1 = \frac{Z_{11}}{Z_{12}}$$

Substituting $I_2$ in equation (2)

$$V_2 = Z_{21} I_1 + Z_{22}\left[\frac{V_1}{Z_{12}} - \frac{Z_{11}}{Z_{12}} I_1\right]$$

$$= \frac{Z_{22}}{Z_{12}} V_1 - \frac{\Delta Z}{Z_{12}} I_1$$

Where $\Delta Z = Z_{11} Z_{22} - Z_{21} Z_{12}$

$$\therefore A^1 = \frac{Z_{22}}{Z_{12}}; \quad B^1 = \frac{\Delta Z}{Z_{12}}$$

## $T^1$-parameters in terms of Y-parameters

We known, the Y-parameters as

$$I_1 = Y_{11} V_1 + Y_{12} V_2 \longrightarrow (1)$$

$$I_2 = Y_{21} V_1 + Y_{22} V_2 \longrightarrow (2)$$

From Equation (1), we have

$$V_2 = \frac{I_1}{Y_{12}} - \frac{Y_{11}}{Y_{12}} V_1 = \frac{-Y_{11}}{Y_{12}} V_1 + \frac{I_1}{Y_{12}}$$

$$\therefore A^1 = \frac{-Y_{11}}{Y_{12}}; \quad B^1 = \frac{-1}{Y_{12}}$$

Putting $V_2$ in equation (2)

$$I_2 = Y_{21} V_1 + Y_{22}\left[\frac{-Y_{11}}{Y_{12}} V_1 + \frac{I_1}{Y_{12}}\right]$$

$$= \frac{-\Delta Y}{Y_{12}} V_1 + \frac{Y_{22}}{Y_{12}} I_1$$

Where $\Delta Y = Y_{11} Y_{22} - Y_{12} Y_{21}$

$$\therefore C^1 = \frac{-\Delta Y}{Y_{12}}; \quad D^1 = \frac{-Y_{22}}{Y_{12}}$$

## $T^1$-parameters in terms of T-parameters

We know that the T-parameters as

$$V_1 = AV_2 - B I_2 \longrightarrow (1)$$

$$I_1 = CV_2 - D I_2 \longrightarrow (2)$$

Putting in matrix form,

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

Rewriting the above equation,

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

$$\Rightarrow \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} A & -B \\ -C & D \end{bmatrix}^{-1} \begin{bmatrix} V_1 \\ -I_1 \end{bmatrix}$$

$$\therefore [T^1] \neq [T]^{-1}$$

i.e. $$\begin{bmatrix} A^1 & B^1 \\ C^1 & D^1 \end{bmatrix} = \begin{bmatrix} A & -B \\ -C & D \end{bmatrix}^{-1} = \frac{1}{\Delta T}\begin{bmatrix} D & B \\ C & A \end{bmatrix}$$

Where $\Delta T = AD-BC$

$$\therefore A^1 = \frac{D}{\Delta T}; \quad B^1 = \frac{B}{\Delta T}; \quad C^1 = \frac{C}{\Delta T}; \quad D^1 = \frac{A}{\Delta T}$$

**NOTE:** $\therefore [T^1] \neq [T]^{-1}$

## $T^1$-parameters in terms of h-parameters

We know that h-parameters as

$$V_1 = h_{11} I_1 + h_{12} V_2 \longrightarrow (1)$$

$$I_2 = h_{21} I_1 + h_{22} V_2 \longrightarrow (2)$$

From equation (1), we have

$$V_2 = \frac{V_1}{h_{12}} - \frac{h_{11}}{h_{12}} I_1$$

$$\therefore \quad A^1 = \frac{1}{h_{12}}; \quad B^1 = \frac{h_{11}}{h_{12}}$$

Putting $V_2$ in equation (2)

$$I_2 = h_{21} I_1 + h_{22}\left[\frac{V_1}{h_{12}} - \frac{h_{11}}{h_{12}} I_1\right]$$

$$= \frac{h_{22}}{h_{12}} V_1 - \frac{\Delta h}{h_{12}} I_1$$

Put $\Delta h = h_{11} h_{22} - h_{12} h_{21}$

$$\therefore \quad C^1 = \frac{h_{22}}{h_{12}}; \quad D^1 = \frac{\Delta h}{h_{12}}$$

## $T^1$-parameters in terms of g-parameters

We know that g-parameters as

$$I_1 = g_{11} V_1 + g_{12} I_2 \longrightarrow (1)$$

$$V_2 = g_{21} V_1 + g_{22} I_2 \longrightarrow (2)$$

From equation (1), we have

$$I_2 = \frac{I_1}{g_{12}} - \frac{g_{11}}{g_{12}} V_1 = \frac{-g_{11}}{g_{12}} V_1 + \frac{1}{g_{12}} I_1$$

$$\therefore \quad C^1 = \frac{-g_{11}}{g_{12}}; \quad D^1 = \frac{-1}{g_{12}}$$

Putting $I_2$ in equation (2)

$$V_2 = g_{21} V_1 + g_{22}\left[\frac{-g_{11}}{g_{12}} V_1 + \frac{1}{g_{12}} I_1\right]$$

$$= \frac{-\Delta g}{g_{12}} V_2 + \frac{g_{22}}{g_{12}} I_1$$

Put $\Delta g = g_{11} g_{22} - g_{12} g_{21}$

$$\therefore A^1 = \frac{-\Delta g}{g_{12}}; \quad B^1 = \frac{-g_{22}}{g_{12}}$$

## h-PARAMETERS IN TERMS OF OTHER PARAMETERS

### h-parameters in terms of Z-parameters

We know that Z-parameters as

$$V_1 = Z_{11} I_1 + Z_{12} I_2 \longrightarrow (1)$$

$$V_2 = Z_{21} I_1 + Z_{22} I_2 \longrightarrow (2)$$

From Equation (2), we have

$$I_2 = \frac{V_2}{Z_{22}} - \frac{Z_{21}}{Z_{22}} I_1 = -\frac{Z_{21}}{Z_{22}} I_1 + \frac{V_2}{Z_{22}}$$

$$\therefore h_{21} = \frac{-Z_{21}}{Z_{22}}; \quad h_{22} = \frac{1}{Z_{22}}$$

Put $I_2$ in equation (1)

$$V_1 = Z_{11} I_1 + Z_{12}\left[\frac{-Z_{21}}{Z_{22}} I_1 + \frac{V_2}{Z_{22}}\right]$$

$$= \frac{\Delta Z}{Z_{22}} I_1 + \frac{Z_{12}}{Z_{22}} V_2$$

$$\because \Delta Z = Z_{11} Z_{22} - Z_{12} Z_{21}$$

$$\therefore \quad h_{11} = \frac{\Delta Z}{Z_{22}}; \quad h_{12} = \frac{Z_{12}}{Z_{22}}$$

## h-parameters in terms of Y-parameters

We know, Y-parameters as

$$I_1 = Y_{11} V_1 + Y_{12} V_2 \longrightarrow (1)$$

$$I_2 = Y_{21} V_1 + Y_{22} V_2 \longrightarrow (2)$$

From Equation (1), we have

$$V_1 = \frac{I_1}{Y_{11}} - \frac{Y_{12}}{Y_{11}} V_2$$

$$\therefore \quad h_{11} = \frac{-1}{Y_{11}}; \quad h_{12} = \frac{-Y_{12}}{Y_{11}}$$

Put $V_1$ in equation (2)

$$I_2 = Y_{21}\left[\frac{I_1}{Y_{11}} - \frac{Y_{12}}{Y_{11}} V_2\right] + Y_{22} V_2$$

$$= \frac{Y_{21}}{Y_{11}} I_1 + \frac{\Delta Y}{Y_{11}} V_2$$

$$\because \Delta Y = Y_{11} Y_{22} - Y_{12} Y_{21}$$

$$\therefore \quad h_{21} = \frac{Y_{21}}{Y_{11}}; \quad h_{22} = \frac{\Delta Y}{Y_{11}}$$

## h-parameters in terms of T-parameters

We know that the T-parameters as

$$V_1 = AV_2 - B I_2 \longrightarrow (1)$$

$$I_1 = CV_2 - D I_2 \longrightarrow (2)$$

From equation (2), we have

$$I_2 = \frac{CV_2}{D} - \frac{I_1}{D} = -\frac{I_1}{D} + \frac{C}{D} V_2$$

$$\therefore h_{21} = -\frac{1}{D}; \quad h_{22} = \frac{C}{D}$$

Put $I_2$ in equation (1)

$$V_1 = AV_2 - B\left[\frac{-I_1}{D} + \frac{C}{D} V_2\right] = \frac{B}{D} I_1 + \frac{\Delta T}{D} V_2$$

$$\because \Delta T = AD - BC$$

$$\therefore h_{11} = \frac{B}{D}; \quad h_{12} = \frac{\Delta T}{D}$$

## h-parameters in terms of T¹-parameters

We know that the T¹-parameters as

$$V_2 = A^1 V_1 - B^1 I_1 \longrightarrow (1)$$

$$I_2 = C^1 V_1 - D^1 I_1 \longrightarrow (2)$$

From equation (1), we have

$$V_1 = \frac{V_2}{A^1} + \frac{B^1}{A^1} I_1 = \frac{B^1}{A^1} I_1 + \frac{1}{A^1} V_2$$

$$\therefore\ h_{11} = \frac{B^1}{A^1}; \quad h_{12} = \frac{1}{A^1}$$

Put $V_1$ in equation (2)

$$I_2 = C^1\left[\frac{B^1}{A^1} I_1 + \frac{1}{A^1} V_2\right] - D^1 I_1 = \frac{-\Delta T}{A^1} I_1 + \frac{C^1}{A^1} V_2$$

$$\because \Delta T^1 = A^1 D^1 - B^1 C^1$$

$$\therefore\ h_{21} = \frac{-\Delta T^1}{A^1}; \quad h_{22} = \frac{C^1}{A^1}$$

## h-parameters in terms of g-parameters

We know that the g-parameters as

$$I_1 = g_{11} V_1 + g_{12} I_2 \longrightarrow (1)$$

$$V_2 = g_{21} V_1 + g_{22} I_2 \longrightarrow (2)$$

Putting in matrix, we have

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

$$\Rightarrow \begin{bmatrix} V_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix}^{-1} \begin{bmatrix} I_1 \\ V_2 \end{bmatrix}$$

$$\therefore [h] = [g]^{-1}$$

i.e., $$\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix}^{-1} = \frac{1}{\Delta g}\begin{bmatrix} g_{22} & -g_{12} \\ -g_{21} & g_{11} \end{bmatrix}$$

$$\because \Delta g = g_{11} g_{22} - g_{12} g_{21}$$

$$\therefore h_{11} = \frac{g_{22}}{\Delta g}; \quad h_{12} = \frac{-g_{12}}{\Delta g}; \quad h_{21} = \frac{-g_{21}}{\Delta g}; \quad h_{22} = \frac{g_{11}}{\Delta g}$$

# g-PARAMETERS IN TERMS OF OTHER PARAMETERS

## g-parameters in terms of Z-parameters

We know, Z-parameters as

$$V_1 = Z_{11} I_1 + Z_{12} I_2 \longrightarrow (1)$$

$$V_2 = Z_{21} I_1 + Z_{22} I_2 \longrightarrow (2)$$

From Equation (1), we have

$$I_1 = \frac{V_1}{Z_{11}} - \frac{Z_{12}}{Z_{11}} I_2$$

$$\therefore g_{11} = \frac{1}{Z_{11}}; \quad g_{12} = \frac{-Z_{12}}{Z_{11}}$$

Substituting $I_1$ in equation (2)

$$V_2 = Z_{21}\left[\frac{V_1}{Z_{11}} - \frac{Z_{12}}{Z_{11}} I_2\right] + Z_{22} I_2$$

$$= \frac{Z_{21}}{Z_{11}} V_1 + \frac{\Delta Z}{Z_{11}} I_2$$

$$\because \Delta Z = Z_{11} Z_{22} - Z_{12} Z_{21}$$

$$\therefore \quad g_{21} = \frac{Z_{21}}{Z_{11}}; \quad g_{22} = \frac{\Delta Z}{Z_{11}}$$

## g-parameters in terms of Y-parameters

We know, Y-parameters as

$$I_1 = Y_{11} V_1 + Y_{12} V_2 \longrightarrow (1)$$

$$I_2 = Y_{21} V_1 + Y_{22} V_2 \longrightarrow (2)$$

From Equation (2), we have

$$V_2 = \frac{I_2}{Y_{22}} - \frac{Y_{21}}{Y_{22}} V_1 = -\frac{Y_{21}}{Y_{22}} V_1 + \frac{1}{Y_{22}} I_2$$

$$\therefore \; g_{21} = \frac{-Y_{21}}{Y_{22}}; \quad g_{22} = \frac{1}{Y_{22}}$$

Put $V_2$ in equation (1)

$$I_1 = Y_{11} V_1 + Y_{12}\left[-\frac{Y_{21}}{Y_{22}} V_1 + \frac{1}{Y_{22}} I_2\right]$$

$$= \frac{\Delta Y}{Y_{22}} V_1 + \frac{Y_{12}}{Y_{22}} I_2$$

$$\because \; \Delta Y = Y_{11} Y_{22} - Y_{12} Y_{21}$$

$$\therefore \; g_{11} = \frac{\Delta Y}{Y_{22}}; \quad g_{12} = \frac{Y_{12}}{Y_{22}}$$

## g-parameters in terms of T-parameters

We know that the T-parameters as

$$V_1 = AV_2 - B I_2 \longrightarrow (1)$$

$$I_1 = CV_2 - D I_2 \longrightarrow (2)$$

From equation (1), we have

$$V_2 = \frac{V_1}{A} + \frac{B}{A} I_2$$

$$\therefore \; g_{21} = \frac{1}{A}; \quad g_{22} = \frac{B}{A}$$

Put $V_2$ in equation (2)

$$I_1 = C\left[\frac{V_1}{A} + \frac{B}{A} I_2\right] - DI_2 = \frac{C}{A} V_1 + \frac{\Delta T}{A} I_2$$

$$\because \Delta T = AD - BC$$

$$\therefore \; g_{11} = \frac{C}{A}; \quad g_{12} = \frac{-\Delta T}{A}$$

## g-parameters in terms of $T^1$-parameters

We know that the $T^1$-parameters as

$$V_2 = A^1 V_1 - B^1 I_1 \longrightarrow (1)$$

$$I_2 = C^1 V_1 - D^1 I_1 \longrightarrow (2)$$

From equation (2), we have

$$I_1 = \frac{C^1}{D^1} V_1 - \frac{I_2}{D^1}$$

$$\therefore \; g_{11} = \frac{C^1}{D^1}; \quad g_{12} = \frac{-1}{D^1}$$

Put $I_1$ in equation (1)

$$V_2 = A^1 V_1 - B^1 \left[ \frac{C^1}{D^1} V_1 + \frac{I_2}{D^1} \right] = \frac{\Delta T}{D^1} V_1 + \frac{B^1}{D^1} I_2$$

$$\because \Delta T^1 = A^1 D^1 - B^1 C^1$$

$$\therefore \; g_{21} = \frac{\Delta T^1}{D^1}; \quad g_{22} = \frac{B^1}{D^1}$$

## g-parameters in terms of h-parameters

We know that the h-parameters as

$$V_1 = h_{11} I_1 + h_{12} V_2 \longrightarrow (1)$$

$$I_2 = h_{21} I_1 + h_{22} V_2 \longrightarrow (2)$$

Putting in matrix, we have

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

$$\Rightarrow \quad \begin{bmatrix} I_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}^{-1} \begin{bmatrix} V_1 \\ I_2 \end{bmatrix}$$

$$\therefore [g] = [h]^{-1}$$

i.e., $$\begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}^{-1} = \frac{1}{\Delta h} \begin{bmatrix} h_{22} & -h_{12} \\ -h_{21} & h_{11} \end{bmatrix}$$

$$\because \Delta h = h_{11} h_{22} - h_{12} h_{21}$$

$$\therefore g_{11} = \frac{h_{22}}{\Delta h}; \quad g_{12} = \frac{-h_{12}}{\Delta h}; \quad g_{21} = \frac{-h_{21}}{\Delta h}; \quad g_{22} = \frac{h_{11}}{\Delta h}$$

| Parameters | [Z] | [Y] | [T] | [$T^1$] | [h] | [g] |
|---|---|---|---|---|---|---|
| [Z] | $\begin{matrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{matrix}$ | $\begin{matrix} \frac{Y_{22}}{\Delta Y} & \frac{-Y_{12}}{\Delta Y} \\ \frac{-Y_{21}}{\Delta Y} & \frac{Y_{11}}{\Delta Y} \end{matrix}$ | $\begin{matrix} \frac{A}{C} & \frac{\Delta T}{C} \\ \frac{1}{C} & \frac{D}{C} \end{matrix}$ | $\begin{matrix} \frac{D^1}{C^1} & \frac{1}{C^1} \\ \frac{\Delta T^1}{C^1} & \frac{A^1}{C^1} \end{matrix}$ | $\begin{matrix} \frac{\Delta h}{h_{22}} & \frac{h_{12}}{h_{22}} \\ \frac{-h_{21}}{h_{22}} & \frac{1}{h_{22}} \end{matrix}$ | $\begin{matrix} \frac{1}{g_{11}} & \frac{-g_{12}}{g_{11}} \\ \frac{g_{21}}{g_{11}} & \frac{\Delta g}{g_{11}} \end{matrix}$ |
| [Y] | $\begin{matrix} \frac{Z_{22}}{\Delta Z} & \frac{-Z_{12}}{\Delta Z} \\ \frac{-Z_{21}}{\Delta Z} & \frac{Z_{11}}{\Delta Z} \end{matrix}$ | $\begin{matrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{matrix}$ | $\begin{matrix} \frac{D}{B} & \frac{-\Delta T}{B} \\ \frac{-1}{B} & \frac{A}{B} \end{matrix}$ | $\begin{matrix} \frac{A^1}{B^1} & \frac{-1}{B^1} \\ \frac{-\Delta T^1}{B^1} & \frac{A^1}{B^1} \end{matrix}$ | $\begin{matrix} \frac{1}{h_{11}} & \frac{-h_{12}}{h_{11}} \\ \frac{h_{21}}{h_{11}} & \frac{\Delta h}{h_{11}} \end{matrix}$ | $\begin{matrix} \frac{\Delta g}{g_{22}} & \frac{g_{12}}{g_{22}} \\ \frac{-g_{21}}{g_{22}} & \frac{1}{g_{22}} \end{matrix}$ |
| [T] | $\begin{matrix} \frac{Z_{11}}{Z_{21}} & \frac{\Delta Z}{Z_{21}} \\ \frac{1}{Z_{21}} & \frac{Z_{22}}{Z_{21}} \end{matrix}$ | $\begin{matrix} \frac{-Y_{22}}{Y_{21}} & \frac{-1}{Y_{21}} \\ \frac{-\Delta Y}{Y_{21}} & \frac{-Y_{11}}{Y_{21}} \end{matrix}$ | $\begin{matrix} A & C \\ C & D \end{matrix}$ | $\begin{matrix} \frac{D^1}{\Delta T^1} & \frac{B^1}{\Delta T^1} \\ \frac{C^1}{\Delta T^1} & \frac{A^1}{\Delta T^1} \end{matrix}$ | $\begin{matrix} \frac{-\Delta h}{h_{21}} & \frac{-h_{11}}{h_{21}} \\ \frac{-h_{22}}{h_{21}} & \frac{-1}{h_{21}} \end{matrix}$ | $\begin{matrix} \frac{1}{g_{21}} & \frac{g_{22}}{g_{21}} \\ \frac{g_{11}}{g_{21}} & \frac{\Delta g}{g_{21}} \end{matrix}$ |
| [$T^1$] | $\begin{matrix} \frac{Z_{22}}{Z_{12}} & \frac{\Delta Z}{Z_{12}} \\ \frac{1}{Z_{12}} & \frac{Z_{11}}{Z_{12}} \end{matrix}$ | $\begin{matrix} \frac{-Y_{11}}{Y_{12}} & \frac{-1}{Y_{12}} \\ \frac{-\Delta Y}{Y_{12}} & \frac{-Y_{22}}{Y_{12}} \end{matrix}$ | $\begin{matrix} \frac{D}{\Delta T} & \frac{B}{\Delta T} \\ \frac{C}{\Delta T} & \frac{A}{\Delta T} \end{matrix}$ | $\begin{matrix} A^1 & C^1 \\ C^1 & D^1 \end{matrix}$ | $\begin{matrix} \frac{1}{h_{12}} & \frac{h_{11}}{h_{12}} \\ \frac{h_{22}}{h_{12}} & \frac{\Delta h}{h_{12}} \end{matrix}$ | $\begin{matrix} \frac{-\Delta g}{g_{12}} & \frac{-g_{22}}{g_{12}} \\ \frac{-g_{11}}{g_{12}} & \frac{-1}{g_{12}} \end{matrix}$ |
| [h] | $\begin{matrix} \frac{\Delta Z}{Z_{22}} & \frac{Z_{12}}{Z_{22}} \\ \frac{-Z_{21}}{Z_{22}} & \frac{1}{Z_{22}} \end{matrix}$ | $\begin{matrix} \frac{1}{Y_{11}} & \frac{-Y_{12}}{Y_{11}} \\ \frac{Y_{21}}{Y_{11}} & \frac{\Delta Y}{Y_{11}} \end{matrix}$ | $\begin{matrix} \frac{B}{D} & \frac{\Delta T}{D} \\ \frac{-1}{D} & \frac{C}{D} \end{matrix}$ | $\begin{matrix} \frac{B^1}{A^1} & \frac{1}{A^1} \\ \frac{-\Delta T^1}{A^1} & \frac{C^1}{A^1} \end{matrix}$ | $\begin{matrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{matrix}$ | $\begin{matrix} \frac{g_{22}}{\Delta g} & \frac{-g_{12}}{\Delta g} \\ \frac{-g_{21}}{\Delta g} & \frac{g_{11}}{\Delta g} \end{matrix}$ |
| [g] | $\begin{matrix} \frac{1}{Z_{11}} & \frac{-Z_{12}}{Z_{11}} \\ \frac{Z_{21}}{Z_{11}} & \frac{\Delta Z}{Z_{11}} \end{matrix}$ | $\begin{matrix} \frac{\Delta Y}{Y_{22}} & \frac{Y_{12}}{Y_{22}} \\ \frac{-Y_{21}}{Y_{22}} & \frac{1}{Y_{22}} \end{matrix}$ | $\begin{matrix} \frac{C}{A} & \frac{-\Delta T}{A} \\ \frac{1}{A} & \frac{B}{A} \end{matrix}$ | $\begin{matrix} \frac{C^1}{D^1} & \frac{-1}{D^1} \\ \frac{\Delta T^1}{D^1} & \frac{B^1}{D^1} \end{matrix}$ | $\begin{matrix} \frac{h_{22}}{\Delta h} & \frac{-h_{12}}{\Delta h} \\ \frac{-h_{21}}{\Delta h} & \frac{h_{11}}{\Delta h} \end{matrix}$ | $\begin{matrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{matrix}$ |

# INTER CONNECTION OF TWO-PORT NETWORKS

Two-port networks may be inter connected in various configurations, such as series, parallel, cascade, series-parallel and parallel-series connection, resulting in new two port networks. For each configuration certain set of parameters may be more useful than others to describe the network.

## SERIES – CONNECTION

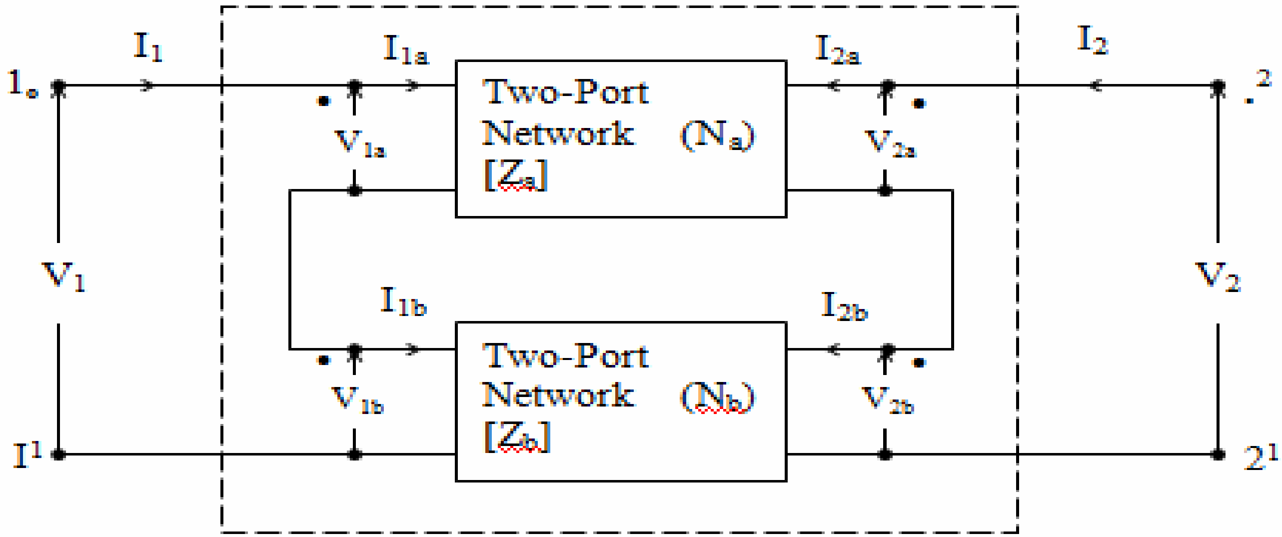



Fig. Series – Connection of Two Two – Port Networks

Figure shows a series-connection of two two-port networks $N_a$ and $N_b$ with open circuit impedance (or) Z-parameters $Z_a$ and $Z_b$ respectively.

i.e., for network $N_a$,

$$\begin{bmatrix} V_{1a} \\ V_{2a} \end{bmatrix} = \begin{bmatrix} Z_{11a} & Z_{12a} \\ Z_{21a} & Z_{22a} \end{bmatrix} \begin{bmatrix} I_{1a} \\ I_{2a} \end{bmatrix}$$

Similarly, for network $N_b$,

$$\begin{bmatrix} V_{1b} \\ V_{2b} \end{bmatrix} = \begin{bmatrix} Z_{11b} & Z_{12b} \\ Z_{21b} & Z_{22b} \end{bmatrix} \begin{bmatrix} I_{1b} \\ I_{2b} \end{bmatrix}$$

Then, their series connection requires that

$I_1 = I_{1a} = I_{1b}$; $I_2 = I_{2a} = I_{2b}$; $V_1 = V_{1a} + V_{1b}$; $V_2 = V_{2a} + V_{2b}$

Now,

$$V_1 = V_{1a} + V_{1b} = (Z_{11a} I_{1a} + Z_{12a} I_{2a}) + (Z_{11b} I_{1b} + Z_{12b} I_{2b})$$
$$= (Z_{11a} + Z_{11b}) I_1 + (Z_{12a} + Z_{12b}) I_2$$
$$\because \quad I_1 = I_{1a} = I_{1b} \ \& \ I_2 = I_{2a} = I_{2b}$$

Similarly

$$V_2 = V_{2a} + V_{2b} = (Z_{21a} I_{1a} + Z_{22a} I_{2a}) + (Z_{21b} I_{1b} + Z_{22b} I_{2b})$$
$$= (Z_{21a} + Z_{21b}) I_1 + (Z_{22a} + Z_{22b}) I_2$$
$$\because \quad I_1 = I_{1a} = I_{1b} \ \& \ I_2 = I_{2a} = I_{2b}$$

So, in matrix form the Z-parameters of the series-connected combined network can be written as

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

Where $Z_{11} = Z_{11a} + Z_{11b}$

$Z_{12} = Z_{12a} + Z_{12b}$

$Z_{21} = Z_{21a} + Z_{21b}$

$Z_{22} = Z_{22a} + Z_{22b}$

[or] $[Z] = [Z_a] + [Z_b]$

This result may be generalized for any number of two-port networks connected in series. "The overall Z-parameter matrix for series connected two-port networks is simply the sum of Z-parameter matrices of each individual two-port network connected in series". The series connection is also called series-series connection.

# PARALLEL – CONNECTION

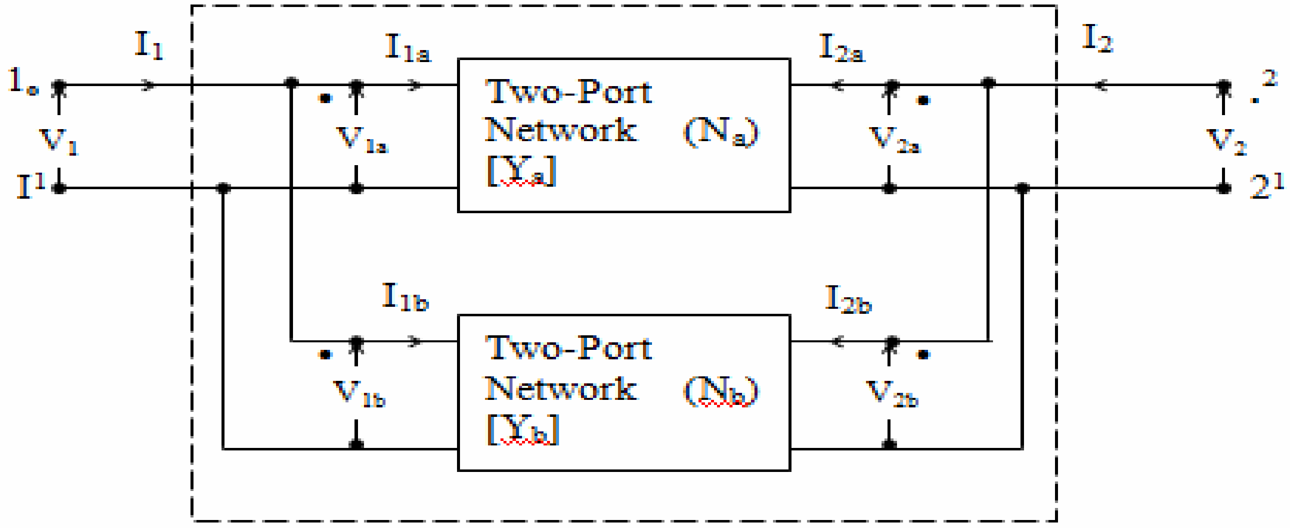



Fig. Parallel Connection of Two Two – Port Networks

Figure shows a parallel-connection of two two-port networks $N_a$ and $N_b$ with short-circuited admittance (or) Y-parameters $Y_a$ and $Y_b$ respectively.

for network $N_a$,

$$\begin{bmatrix} I_{1a} \\ I_{2a} \end{bmatrix} = \begin{bmatrix} Y_{11a} & Y_{12a} \\ Y_{21a} & Y_{22a} \end{bmatrix} \begin{bmatrix} V_{1a} \\ V_{2a} \end{bmatrix}$$

Similarly, for network $N_b$,

$$\begin{bmatrix} I_{1b} \\ I_{2b} \end{bmatrix} = \begin{bmatrix} Y_{11b} & Y_{12b} \\ Y_{21b} & Y_{22b} \end{bmatrix} \begin{bmatrix} V_{1b} \\ V_{2b} \end{bmatrix}$$

Then, their parallel connection requires that

$V_1 = V_{1a} = V_{1b}$; $I_1 = I_{1a} = I_{1b}$; $V_2 = V_{2a} = V_{2b}$; $I_2 = I_{2a} + I_{2b}$

Now,

$$I_1 = I_{1a} + I_{1b} = (Y_{11a} V_{1a} + Y_{12a} V_{2a}) + (Y_{11b} V_{1b} + Y_{12b} V_{2b})$$
$$= (Y_{11a} + Y_{11b}) V_1 + (Y_{12a} + Y_{12b}) V_2$$
$$\because \quad V_1 = V_{1a} = V_{1b} \;\&\; V_2 = V_{2a} = V_{2b}$$

Similarly

$$I_2 = I_{2a} + I_{2b} = (Y_{21a} V_{1a} + Y_{22a} V_{2a}) + (Y_{21b} V_{1b} + Y_{22b} V_{2b})$$

$$= (Y_{21a} + Y_{21b}) V_1 + (Y_{22a} + Y_{22b}) V_2$$

$$\because \quad V_1 = V_{1a} = V_{1b} \ \& \ V_2 = V_{2a} = V_{2b}$$

So, in matrix form the Y-parameters of the parallel-connected combined network can be written as

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

Where $Y_{11} = Y_{11a} + Y_{11b}$

$Y_{12} = Y_{12a} + Y_{12b}$

$Y_{21} = Y_{21a} + Y_{21b}$

$Y_{22} = Y_{22a} + Y_{22b}$

[or] $[Y] = [Y_a] + [Y_b]$

This result may be generalized for any number of two-port networks connected in parallel.

"The overall Y-parameter matrix for parallel connected two-port networks is simply the sum of Y-parameter matrices of each individual two-port network connected in parallel". The parallel connection is also called parallel-parallel connection.

# CASCADE-CONNECTION

The simplest possible inter connection of two-port network is cascade (or) Tandem-connection. Two Two port networks are said the connected in cascade if the output port of the first becomes the input port of the second as shown in figure.

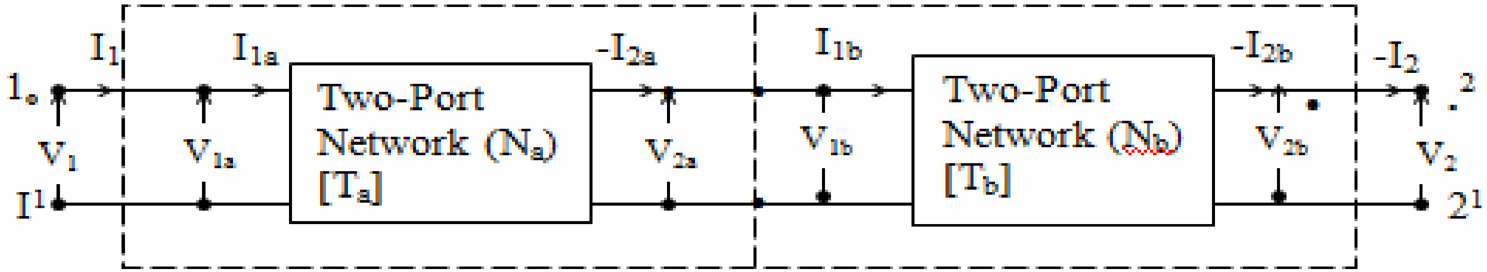



Fig. Cascade Connection of Two two port networks

## FOR T-PARAMETERS

If the $T_a$ and $T_b$ are the T-parameters of the network $N_a$ and $N_b$ respectively. Then, for network $N_a$,

$$\begin{bmatrix} V_{1a} \\ I_{1a} \end{bmatrix} = \begin{bmatrix} A_a & B_a \\ C_a & D_a \end{bmatrix} \begin{bmatrix} V_{2a} \\ -I_{2a} \end{bmatrix}$$

Similarly, for network $N_b$,

$$\begin{bmatrix} V_{1b} \\ I_{1b} \end{bmatrix} = \begin{bmatrix} A_b & B_b \\ C_b & D_b \end{bmatrix} \begin{bmatrix} V_{2b} \\ -I_{2b} \end{bmatrix}$$

Then, their cascade connection requires that

$I_1 = V_{1a}$ $\quad$ $-I_{2a} = I_{1b}$; $\quad$ $I_{2b} = I_2$

$V_1 = V_{1a}$ $\quad$ $V_{2a} = V_{1b}$; $\quad$ $V_{2b} = V_2$

Now,

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} V_{1a} \\ I_{1a} \end{bmatrix} = \begin{bmatrix} A_a & B_a \\ C_a & D_a \end{bmatrix} \begin{bmatrix} V_{2a} \\ -I_{2a} \end{bmatrix}$$

$$= \begin{bmatrix} A_a & B_a \\ C_a & D_a \end{bmatrix} \begin{bmatrix} V_{1b} \\ I_{1b} \end{bmatrix} \quad \because V_{2a} = V_{1b}; \qquad -I_{2a} = I_{1b}$$

$$= \begin{bmatrix} A_a & B_a \\ C_a & D_a \end{bmatrix} \begin{bmatrix} A_b & B_b \\ C_b & D_b \end{bmatrix} \begin{bmatrix} V_{2b} \\ -I_{2b} \end{bmatrix}$$

$$= \begin{bmatrix} A_a & B_a \\ C_a & D_a \end{bmatrix} \begin{bmatrix} A_b & B_b \\ C_b & D_b \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix}$$

So, in matrix form the T-parameters of the cascade connected combined network can be written as

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

Where

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_a & B_a \\ C_a & D_a \end{bmatrix} \begin{bmatrix} A_b & B_b \\ C_b & D_b \end{bmatrix}$$

(or) $[T] = [T_a]\,[T_b]$

(or) In the equation form

$A = A_a A_b + B_a C_b$

$B = A_a B_b + B_a D_b$

$C = C_a A_b + D_a C_b$

$D = C_a B_b + D_a D_b$

This result may be generalized for any number of two-port networks connected in cascade.

"The overall T-parameter matrix for cascade connected two-port networks is simply the matrix product of the T-parameter matrices of each individual two-port network in cascade".

## FOR $T^1$-PARAMETERS

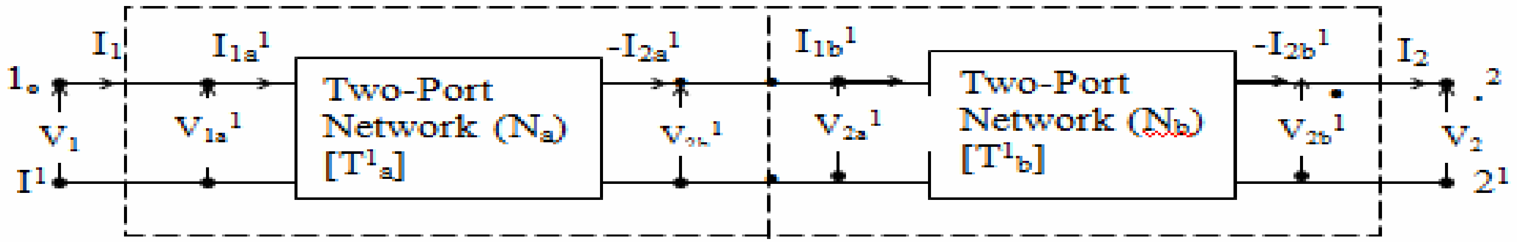



Fig. Cascade Connection of Two two port networks

If the $T_a^1$ and $T_b^1$ are the $T^1$-parameters of the network $N_a$ and $N_b$ respectively. Then, for network $N_a$,

$$\begin{bmatrix} V_{2a}^1 \\ I_{2a}^1 \end{bmatrix} = \begin{bmatrix} A_a^1 & B_a^1 \\ C_a^1 & D_a^1 \end{bmatrix} \begin{bmatrix} V_{1a}^1 \\ -I_{1a}^1 \end{bmatrix}$$

Similarly, for network $N_b$,

$$\begin{bmatrix} V_{2b}^1 \\ I_{2b}^1 \end{bmatrix} = \begin{bmatrix} A_b^1 & B_b^1 \\ C_b^1 & D_b^1 \end{bmatrix} \begin{bmatrix} V_{1b}^1 \\ -I_{1b}^1 \end{bmatrix}$$

Then, their cascade connection requires that

$I_1 = I_{1a}^1$; $\quad -I_{2a}^1 = I_{1b}^1$; $\quad I_2 = I_{2b}^1$

$V_1 = V_{1a}^1$ ; $\quad V_{2a}^1 = V_{1b}^1$; $\quad V_2 = V_{2b}^1$

Now,

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} V_{2b}^1 \\ I_{2b}^1 \end{bmatrix} = \begin{bmatrix} A_b^1 & B_b^1 \\ C_b^1 & D_b^1 \end{bmatrix} \begin{bmatrix} V_{1a}^1 \\ -I_{1a}^1 \end{bmatrix}$$

$$= \begin{bmatrix} A_b^1 & B_b^1 \\ C_b^1 & D_b^1 \end{bmatrix} \begin{bmatrix} V_{2a}^1 \\ I_{2a}^1 \end{bmatrix} \qquad \because V_{2a}^1 = V_{1b}^1; \qquad -I_{2a}^1 = I_{1b}^1$$

$$= \begin{bmatrix} A_b^1 & B_b^1 \\ C_b^1 & D_b^1 \end{bmatrix} \begin{bmatrix} A_a^1 & B_a^1 \\ C_a^1 & D_a^1 \end{bmatrix} \begin{bmatrix} V_{1b}^1 \\ -I_{1b}^1 \end{bmatrix}$$

$$= \begin{bmatrix} A_b^1 & B_b^1 \\ C_b^1 & D_b^1 \end{bmatrix} \begin{bmatrix} A_a^1 & B_a^1 \\ C_a^1 & D_a^1 \end{bmatrix} \begin{bmatrix} V_1 \\ -I_1 \end{bmatrix} \because V_1 = V_{1a}^1; \qquad I_1 = I_{1a}^1$$

So, in matrix form the $T^1$-parameters of the cascade connected combined network can be written as

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} A^1 & B^1 \\ C^1 & D^1 \end{bmatrix} \begin{bmatrix} V_1 \\ -I_1 \end{bmatrix}$$

Where

$$\begin{bmatrix} A^1 & B^1 \\ C^1 & D^1 \end{bmatrix} = \begin{bmatrix} A_b^1 & B_b^1 \\ C_b^1 & D_b^1 \end{bmatrix} \begin{bmatrix} A_a^1 & B_a^1 \\ C_a^1 & D_a^1 \end{bmatrix}$$

(or) $[T^1] = [T_a^1]\,[T_b^1]$

(or) In the equation form

$A^1 = A_b^1\,A_a^1 + B_b^1\,C_a^1$

$B^1 = A_b^1\,B_a^1 + B_b^1\,D_a^1$

$C^1 = C_b^1\,A_a^1 + D_b^1\,C_a^1$

$D^1 = C_b^1\,B_a^1 + D_b^1\,D_a^1$

This result may be generalized for any number of two-port networks connected in cascade.

"The overall $T^1$-parameter matrix for cascade connected two-port networks is simply the matrix product of the $T^1$-parameter matrices of each individual two-port networks in cascade".

## SERIES –PARALLEL-CONNECTION

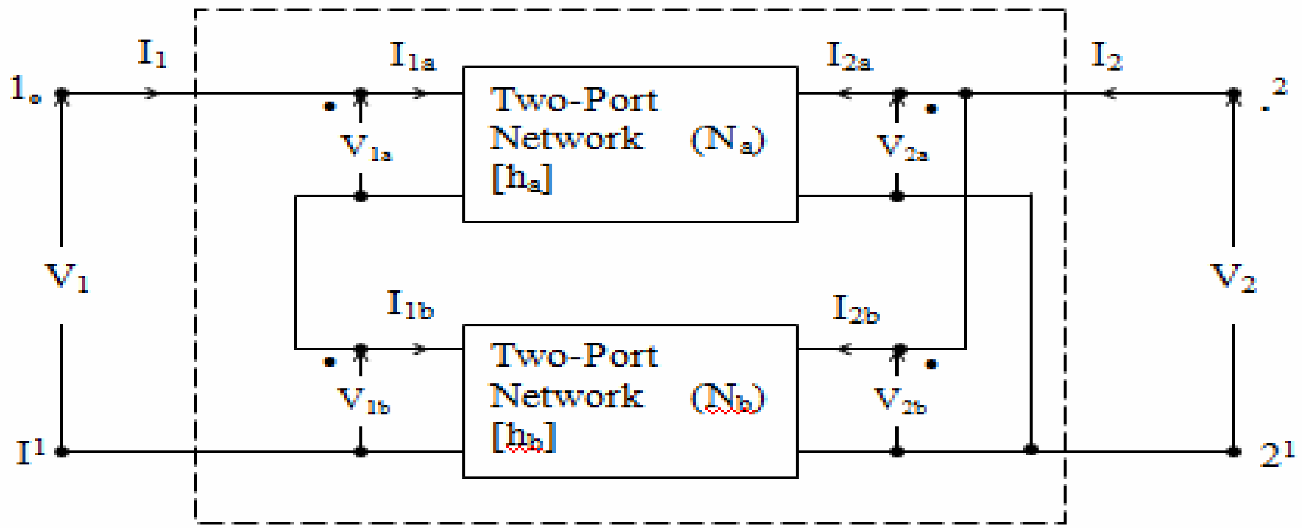



Fig. Series – Parallel Connection of Two Two – Port Networks

Two two-ports are connected in series while the output ports are connected in parallel as shown in figure. Then, the connections require that

$$V_1 = V_{1a} + V_{1b} ; \qquad I_1 = I_{1a} = I_{1b} ;$$
$$V_2 = V_{2a} = V_{2b} ; \qquad I_2 = I_{2a} + I_{2b} ;$$

For network, Na

$$\begin{bmatrix} V_{1a} \\ I_{2a} \end{bmatrix} = \begin{bmatrix} h_{11a} & h_{12a} \\ h_{21a} & h_{22a} \end{bmatrix} \begin{bmatrix} I_{1a} \\ V_{2a} \end{bmatrix}$$

Similarly, for network $N_b$,

$$\begin{bmatrix} V_{1b} \\ I_{2b} \end{bmatrix} = \begin{bmatrix} h_{11b} & h_{12b} \\ h_{21b} & h_{22b} \end{bmatrix} \begin{bmatrix} I_{1b} \\ V_{2b} \end{bmatrix}$$

Now,

$$\begin{bmatrix} V_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} V_{1a} \\ I_{2a} \end{bmatrix} + \begin{bmatrix} V_{1b} \\ I_{2b} \end{bmatrix} = \begin{bmatrix} h_{11a} + h_{11b} & h_{12a} + h_{12b} \\ h_{21a} + h_{21b} & h_{22a} + h_{22b} \end{bmatrix} \begin{bmatrix} I_1 \\ V_2 \end{bmatrix}$$

$\because$ $I_1 = I_{1a} = I_{1b}$ & $V_2 = V_{2a} = V_{2b}$

So, in matrix form the h-parameters of the series-parallel-connection can be written as

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

Where $h_{11} = h_{11a} + h_{11b}$

$h_{12} = h_{12a} + h_{12b}$

$h_{21} = h_{21a} + h_{21b}$

$h_{22} = h_{22a} + h_{22b}$

[or] $[h] = [h_a] + [h_b]$

This result may be generalized for any number of two-port networks connected in series-parallel.

"The overall h-parameters matrix for series-parallel-connected two-port networks is simply the sum of h-parameter matrices of each individual two-port network connected in series-parallel".

# PARALLEL-SERIES-CONNECTION

Figure shows a parallel-series-connection of two two-port networks $N_a$ and $N_b$ with g-parameters $g_a$ and $g_b$ respectively. In this case input ports are connected in parallel while the output ports are connected in series. Then the connection requires that,

$V_1 = V_{1a} = V_{1b}$ ;     $I_1 = I_{1a} + I_{1b}$ ;

$V_2 = V_{2a} + V_{2b}$ ;     $I_2 = I_{2a} = I_{2b}$ ;

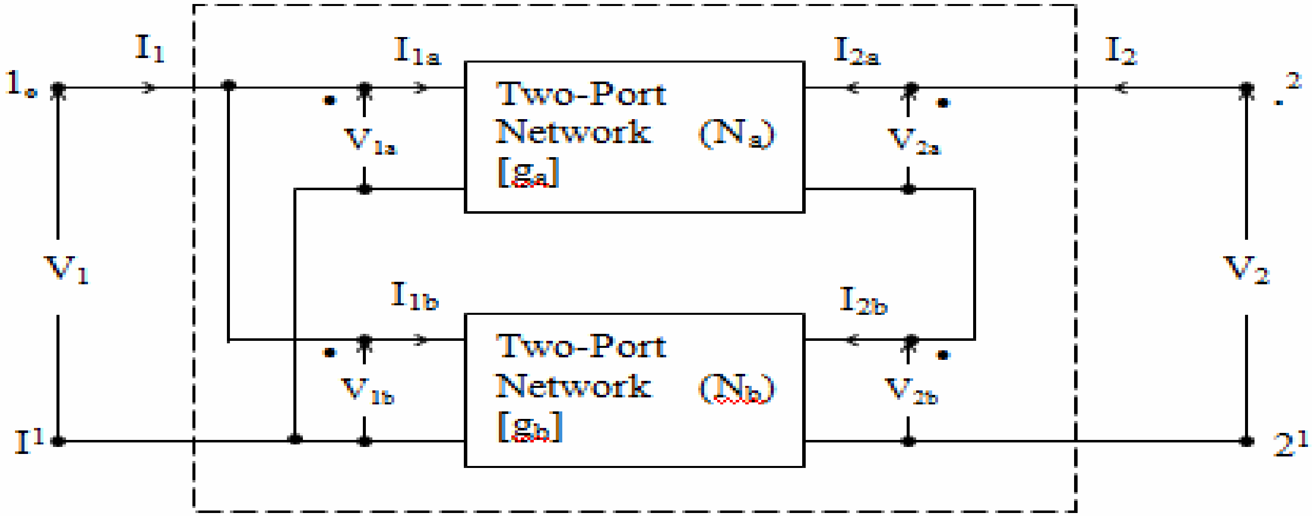



Fig. Parallel-Series Connection of Two Two – Port Networks

For network, Na

$$\begin{bmatrix} I_{1a} \\ V_{2a} \end{bmatrix} = \begin{bmatrix} g_{11a} & g_{12a} \\ g_{21a} & g_{22a} \end{bmatrix} \begin{bmatrix} V_{1a} \\ I_{2a} \end{bmatrix}$$

Similarly, for network $N_b$,

$$\begin{bmatrix} I_{1b} \\ V_{2b} \end{bmatrix} = \begin{bmatrix} g_{11b} & g_{12b} \\ g_{21b} & g_{22b} \end{bmatrix} \begin{bmatrix} V_{1b} \\ I_{2b} \end{bmatrix}$$

Now,

$$\begin{bmatrix} I_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} I_{1a} \\ V_{2a} \end{bmatrix} + \begin{bmatrix} I_{1b} \\ V_{2b} \end{bmatrix} = \begin{bmatrix} g_{11a}+g_{11b} & g_{12a}+g_{12b} \\ g_{21a}+g_{21b} & g_{22a}+g_{22b} \end{bmatrix} \begin{bmatrix} V_1 \\ I_2 \end{bmatrix}$$

$\because \quad V_1 = V_{1a} = V_{1b}$ & $I_2 = I_{2a} = I_{2b}$

So, in matrix form the g-parameters of the parallel-series-connection network can be written as

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

Where $g_{11} = g_{11a} + g_{11b}$

$g_{12} = g_{12a} + g_{12b}$

$g_{21} = g_{21a} + g_{21b}$

$g_{22} = g_{22a} + g_{22b}$

[or] $[g] = [g_a] + [g_b]$

This result may be generalized for any number of two-port networks connected in parallel- series.

"The overall g-parameters matrix for parallel-series connected two-port networks is simply the sum of g-parameter matrices of each individual two-port network connected in parallel- series".

| Inter Connection | Individual Parameters Matrix | Overall Parameter matrix |
|---|---|---|
| Series-Series | $[Z_a]$, $[Z_b]$ | $[Z] = [Z_a] + [Z_b]$ |
| Parallel-Parallel | $[Y_a]$, $[Y_b]$ | $[Y] = [Y_a] + [Y_b]$ |
| Cascade (or) Tandem [T] | $[T_a]$, $[T_b]$ | $[T] = [T_a] * [T_b]$ |
| $[T^1]$ | $[T^1{}_a]$, $[T^1{}_b]$ | $[T^1] = [T^1{}_a] * [T^1{}_b]$ |
| Series-Parallel | $[h_a]$, $[h_b]$ | $[h] = [h_a] + [h_b]$ |
| Parallel-Series | $[g_a]$, $[g_b]$ | $[g] = [g_a] + [g_b]$ |