2 Edition
Revised & Updated

A Handbook on

Instrumentation Engineering

Contains well illustrated formulae & key theory concepts

for

GATE, PSUs

& OTHER COMPETITIVE EXAMS

MADE EASY PUBLICATIONS

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A Handbook on Instrumentation Engineering

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Director's Message


B. Singh (Ex. IES)

During the current age of international competition in Science and Technology, the Indian participation through skilled technical professionals have been challenging to the world. Constant efforts and desire to achieve top positions are still required.

I feel every candidate has ability to succeed but competitive environment and quality guidance is required to achieve high level goals. At MADE EASY, we help you discover your hidden talent and success quotient to achieve your ultimate goals. In my opinion GATE & PSUs exams are tools to enter in to the main stream of Nation serving. The real application of knowledge and talent starts, after you enter in to the working system. Here at MADE EASY you are also trained to become winner in your life and achieve job satisfaction.

MADE EASY alumni have shared their winning stories of success and expressed their gratitude towards quality guidance of MADE EASY. Our students have not only secured All India First Ranks in GATE and PSUs entrance examinations but also secured top positions in their career profiles. Now, I invite you to become an alumnus of MADE EASY to explore and achieve ultimate goal of your life. I promise to provide you quality guidance with competitive environment which is far advanced and ahead than the reach of other institutions. You will get the guidance, support and inspiration that you need to reach the peak of your career.

I have a true desire to serve the Society and the Nation easing path of the education for the people of India.

After a long experience of teaching Electronics Engineering over a period of time, MADE EASY team realised that there is a need of a good *Handbook* which can provide the crux of Instrumentation Engineering in a concise form to the student to brush up the formulae and important concepts required for GATE, PSUs and other competitive examinations. This *handbook* contains all the formulae and important theoretical aspects of Instrumentation Engineering. It provides much needed revision aid and study guidance before examinations.

B. Singh (Ex. IES)
CMD, MADE EASY Group

A Handbook on

Instrumentation Engineering

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Contents

Electrical Circuits

1

I Basic Definitions and Circuits Element

Definitions

1. **Charge:** It is an electrical property of an atomic particle of which the matter consists of and its unit is Coulombic (C).

   It can be positive or negative,

   $$\text{Charge of } 1e^- = 1.6 \times 10^{-19}\ \text{C}$$

2. **Current:** The flow of electron or the time rate of change of charge is called current.

   $$\boxed{i = \frac{dq}{dt}} \quad \text{Ampere}$$

3. **Voltage:** It is an external force required to move the electron from one point to another in a particular direction in an electrical circuit. This force is provided by the electromotive force (emf).

   $$\boxed{V = \frac{dw}{dq}} \quad \text{J/C or Voltage}$$

4. **Power:** It is the time rate of change of energy.

   $$\boxed{P = \frac{dw}{dt} = v(t) \cdot i(t)}$$

   Its unit is watts.

5. **Law of Conservation of Charge:** It states that the charge can neither be created nor be destroyed. It can only be transferred from one body to another body.

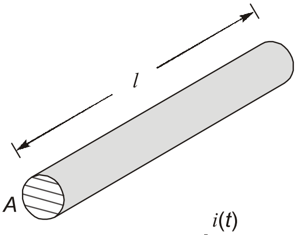
6. **Law of Conservation of Energy:** The sum of total instantaneous power in a circuit must be equal to zero.

   $$\Sigma P = 0$$

Electrical Network Components

Resistor

It is the property of a substance due to which it opposes the flow of current (i.e. electrons) through it.

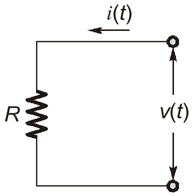


Resistance, $R = \rho \dfrac{l}{A}$, Ohm (Ω)

where, $l \rightarrow$ Length of conductor, metre (m)

$A \rightarrow$ Area of cross-section, m^2

$\rho \rightarrow$ Resistivity of the material, Ω-m



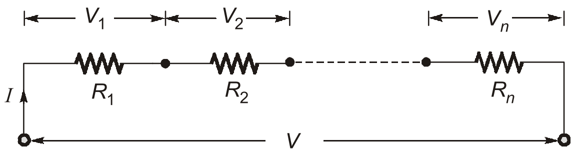
$v(t) = Ri(t)\,; \quad i(t) = \dfrac{1}{R} v(t) \cdots$ in time domain

$V(s) = RI(s)\,; \quad I(s) = \dfrac{1}{R} V(s) \cdots$ in s-domain

- Power loss in resistor, $p(t) = v(t)\, i(t) = i^2(t) = \dfrac{v^2(t)}{R}$
- Energy dissipated in resistor, $E_R = \int_{t_1}^{t_2} p(t)\, dt$

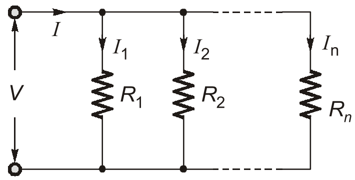
Combination of Resistors

Resistors in series



$$V = I R_{eq} \quad ; \quad R_{eq} = R_1 + R_2 + \ldots\ldots + R_n$$

Resistors in parallel



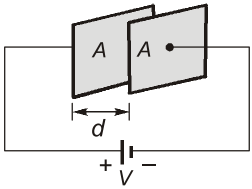
$$I = \frac{V}{R_{eq}}$$

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots\ldots \frac{1}{R_n}$$

Capacitor

The circuit element that stores energy in the form of electric field is a capacitor or capacitance.

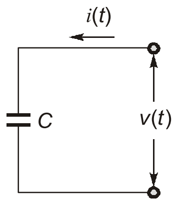
Capacitance $C = \dfrac{\epsilon_0 \epsilon_r A}{d}$ Farad(F)



where $\epsilon_0 \rightarrow$ Permittivity of free space, F/m , $\epsilon_r \rightarrow$ Relative permittivity of the dielectric ; $A \rightarrow$ Cross-sectional area of parallel plates, m^2
$d \rightarrow$ Separation of plates, m

Note:
When the capacitance is removed from source, the capacitor retains the charge and the electric field until a discharge path is provided.

$$v(t) = \frac{1}{C}\int_0^t i(t)\, dt \;;\; i(t) = C\frac{dv(t)}{dt} \cdots \text{in time domain}$$

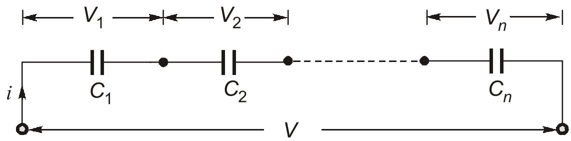


Power in capacitance, $p(t) = v(t)\, i(t) = Cv(t)\dfrac{dv(t)}{dt}$

Energy stored in capacitance, $E_c = \dfrac{1}{2}Cv^2$

Combination of Capacitors

- **Capacitors in series**

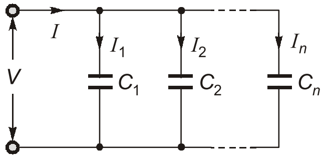


$$V = \frac{1}{C_{eq}}\int_0^t i\, dt \quad ; \quad \frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots\ldots + \frac{1}{C_n}$$

- **Capacitors in parallel**

$$I = C_{eq}\frac{dv}{dt}$$

$$C_{eq} = C_1 + C_2 + C_3 + \ldots\ldots\ldots + C_n$$



Note:

☑ Under steady state condition for D.C. supply capacitor acts as open circuit.

☑ Capacitor doesn't allow sudden change of voltage, until impulse of current is applied.

- ☑ If unit impulse of current is applied then at $t = 0^+$ it stores $\frac{1}{2C}$ Joules energy.
- ☑ Power dissipation in ideal capacitor is zero.

Inductor

The circuit element that stores energy in the form of a magnetic field is an inductor or inductance.

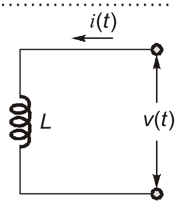
Inductance $L = \frac{\mu_0 N^2 A}{l}$ Henry (H)

where $\mu_0 \rightarrow$ Permeability of free space, H/m ; $N \rightarrow$ Total number of turns in coil ; $A \rightarrow$ Cross-sectional area of coil, m^2 ; $l \rightarrow$ Length of coil, m

Note:

When the inductance is removed from the source, the magnetic field will collapse i.e. no energy is stored without a connected sources.

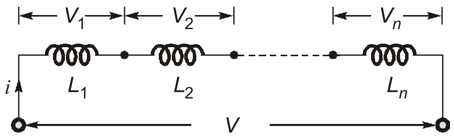
$$v(t) = L\frac{di(t)}{dt} \; ; \; i(t) = \frac{1}{L}\int_0^{\infty} v(t)dt \quad \text{..... in time domain}$$



- Power in inductance, $p(t) = v(t)\, i(t) = Li(t)\frac{di(t)}{dt(t)}$
- Energy stored in an inductance, $E_L = \frac{1}{2}Li^2(t)$

Combination of Inductor

- **Inductors in series**

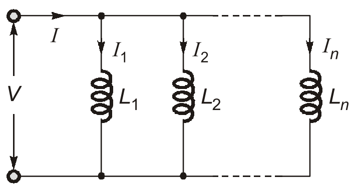


$$V = L_{eq}\frac{di}{dt} \quad ; \quad L_{eq} = L_1 + L_2 + L_3 + \ldots\ldots + L_n$$

- **Inductors in parallel**

$$I = \frac{1}{L_{eq}}\int_0^t v dt$$

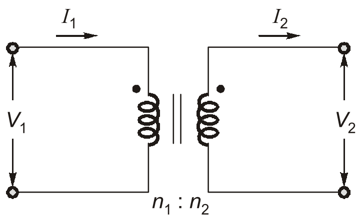
$$\frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots\ldots + \frac{1}{L_n}$$



Note:

- ☑ Under steady state condition for D.C. supply, inductor acts as short circuit.
- ☑ Inductor doesn't allow sudden change of voltage, until impulse of voltage is applied.
- ☑ If unit impulse of voltage is applied across it then at $t = 0^+$ it stores energy $= \frac{1}{2L}$ Joules.
- ☑ Power dissipation in ideal inductor is zero.

Ideal Transformer



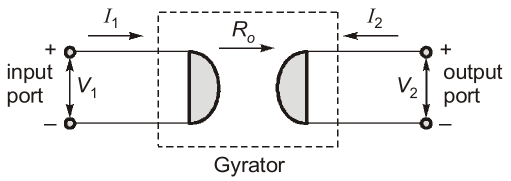
$$\frac{V_2}{V_1} = \frac{n_2}{n_1} = \frac{I_1}{I_2}$$

If $n_1 < n_2$, step up transformer

and $n_1 > n_2$, step down transformer

Gyrator

Gyrator shows an impedance inversion.



$$V_1 = +R_o I_2$$
$$V_2 = -R_o I_1$$

where, $R_o \rightarrow$ Coefficient of gyrator and it depends upon

(i) Op-amp parameter (ii) Externally connected R and C values

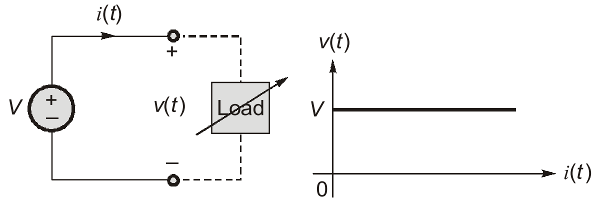
Remember:

- ☑ Linear network is one which holds the principle of superposition and principle of homogeneity both.
- ☑ Element which conducts in both directions is called bilateral element.
- ☑ A network containing circuit elements without any energy source is called passive network. e.g. R, L, C.
- ☑ A network containing energy source together with other circuit elements is called active network. e.g. Op-Amp, transistors.

Ideal Sources

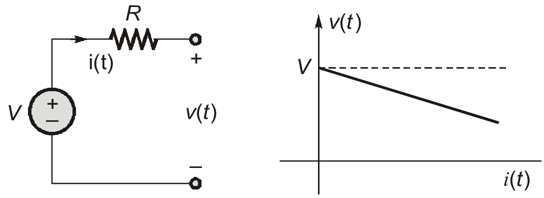
Ideal Voltage Source

Voltage always remains constant for any value of current passing through it.



Practical Voltage Source

It has small internal resistance. Voltage across the element varies with respect to current.

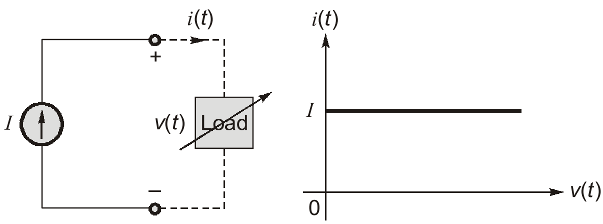


Note:

- ☑ The current through any voltage source is purely arbitrary. It will depend upon
  - (a) The current source which is connected in series with it.
  - (b) The load resistance which is connected in parallel with it.
- ☑ We cannot write KCL equation at a load with which any voltage source is connected as the current through this voltage source is purely arbitrary.

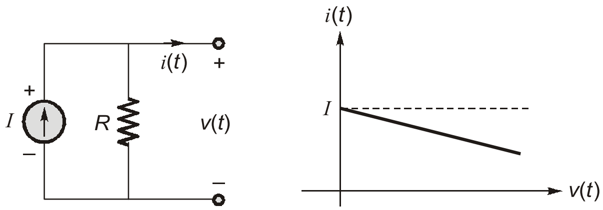
Ideal current source

Current always remains constant for any value of voltage across it



Practical current source

It has large value of internal resistance. Current varies with respect to the voltage across the element.

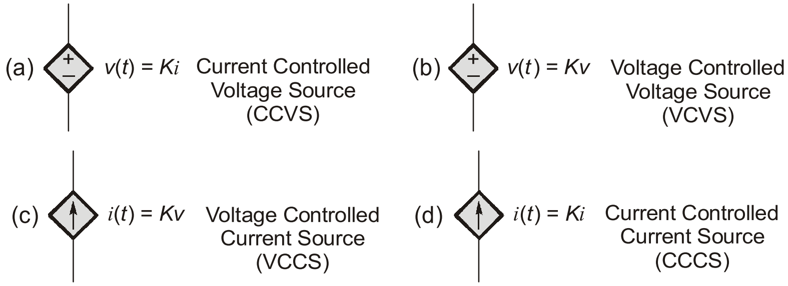


Note:

☑ The voltage across current source is purely arbitrary. It will depend upon
- (a) Voltage source which is connected in parallel with it.
- (b) The load resistance which is connected in series with it.

☑ We cannot write any KVL equation in a loop in which a current source is present as the voltage across the current source is purely arbitrary.

Dependent Sources



where, K is a constant.

Classification of Circuit Elements

Linear and non linear: Elements which obey Ohm's law are linear elements. Ex: R, L, C.

Elements which do not follow Ohm's law are non-linear.
Ex. Diode, transistor.

Active and passive: Elements which supply finite power for infinite time are active. Ex: ideal voltage and current sources.

Elements which either absorbs or supplies finite power only for finite time. Ex. R, L, C.

Unilateral and bilateral: Elements which allow flow of current only in one direction are unilateral. Ex. diode.

Elements which allow current flow in both the directions. Ex. R, *L*, *C*.

Properties of Periodic Signal

For periodic signal *y*(*t*):

- Average value, $Y_{av} = \frac{1}{T}\int_0^T y(t)dt$

  where T is the time period of periodic function $y(t)$

- RMS or effective value, $Y_{rms} = \sqrt{\frac{1}{T}\int_0^T [y(t)]^2 dt}$

  If $y(t) = a_0 + (a_1 \cos\omega t + a_2 \cos 2\omega t + ...) + (b_1 \sin\omega t + b_2 \sin 2\omega t + ...)$

$$Y_{rms} = \sqrt{a_0^2 + \frac{1}{2}(a_1^2 + a_2^2 + ...) + \frac{1}{2}(b_1^2 + b_2^2 + ...)}$$

- Form factor, $FF = \frac{Y_{rms}}{Y_{av}} = \frac{\sqrt{\frac{1}{T}\int_0^T [y(t)]^2 dt}}{\frac{1}{T}\int_0^T y(t)dt}$

- Peak factor, $PF = \frac{Y_{max}}{Y_{rms}}$

Remember:

-

	Pure sine wave	Half-wave rectified waveform	Full-wave rectified waveform
Y_{av}	0	$\frac{Y_{max}}{\pi}$	$\frac{2Y_{max}}{\pi}$
Y_{rms}	$\frac{Y_{max}}{\sqrt{2}}$	$\frac{Y_{max}}{\sqrt{2}}$	$\frac{Y_{max}}{\sqrt{2}}$
FF	$\frac{\pi}{2\sqrt{2}}$	$\frac{\pi}{2}$	$\frac{\pi}{2\sqrt{2}}$
PF	$\sqrt{2}$	2	$\sqrt{2}$

- $\sin\omega t = \frac{e^{j\omega t} - e^{-j\omega t}}{2j}$ and $\cos\omega t = \frac{e^{j\omega t} + e^{-j\omega t}}{2}$

  $\sinh\omega t = \frac{e^{\omega t} - e^{-\omega t}}{2}$ and $\cosh\omega t = \frac{e^{\omega t} + e^{-\omega t}}{2}$

II Network Laws and Theorems

Ohm's Law

The ratio of potential difference (V) between any two points on a conductor to the current (I) flowing through them is constant, provided the temperature of the conductor does not change.

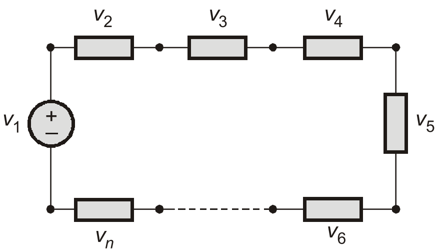
$$\frac{V}{I} = \text{constant} \quad \text{or} \quad \frac{V}{I} = R$$

Where, R is the resistance of the conductor between the two points considered.

Kirchhoff's Laws

Kirchhoff's Voltage Law (KVL)

For any closed path in a network, the algebraic sum of the voltages is zero.

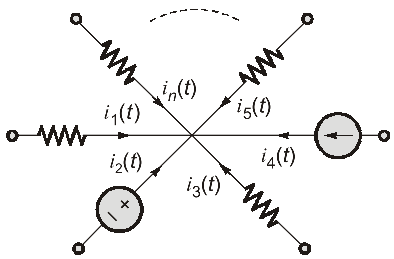


$$\sum_{k=1}^{n} v_k(t) = 0 \quad \text{.... in a closed loop}$$

where, v_k is the voltage drop or voltage gain across k^{th} element

Kirchhoff's Current Law (KCL)

The algebraic sum of the currents at a node is zero. Alternatively the sum of the currents entering a node is equal to the sum of the currents leaving that node.



$$\sum_{k=1}^{n} i_k(t) = 0 \quad \text{..... at any node}$$

where $i_k(t)$ is the current through kth branch

Note:

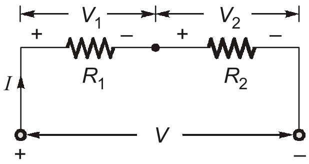
☑ A network is an interconnection of elements or devices, whereas a circuit is a network providing one or more closed paths.

☑ Number of KVL equations = $b - (n - 1)$

- ☑ Number of KCL equations = $(n - 1)$
  where, b is number of branches and n is number of nodes.
- ☑ KVL is based on the law of conservation of energy.
- ☑ KCL is based on the law of conservation of charge.
- ☑ KVL and KCL are applicable to lumped networks.

Voltage Division Equations

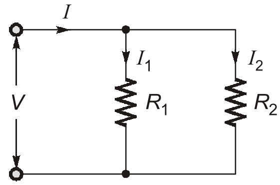
$$V_1 = \frac{R_1}{R_1 + R_2} V \quad ; \quad V_2 = \frac{R_2}{R_1 + R_2} V$$



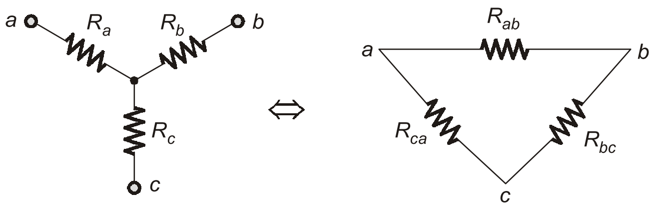
Current Division Equations

$$I_1 = \frac{R_2 \, I}{R_1 + R_2}$$

$$I_2 = \frac{R_1 \, I}{R_1 + R_2}$$



Star to Delta Transformation



$$R_{ab} = \frac{\Delta}{R_c}, \quad R_{bc} = \frac{\Delta}{R_a}, \quad R_{ca} = \frac{\Delta}{R_b}$$

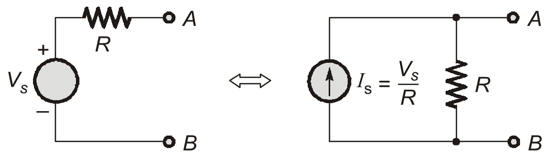
where, $\Delta \rightarrow (R_aR_b + R_bR_c + R_cR_a)$

Delta to Star Transformation

$$R_a = \frac{R_{ca}R_{ab}}{R_{ab} + R_{bc} + R_{ca}} \quad ; \quad R_b = \frac{R_{ab}R_{bc}}{R_{ab} + R_{bc} + R_{ca}} \quad ; \quad R_c = \frac{R_{bc}R_{ca}}{R_{ab} + R_{bc} + R_{ca}}$$

Source Transformation

Transformation of a resistive voltage source to a resistive current source or vice-versa.



Network Theorems

Superposition Theorem

The response in any element of a linear, bilateral RLC network containing more than one independent voltage or current source is the algebraic sum of responses produced by the independent source when each of them is acting alone with

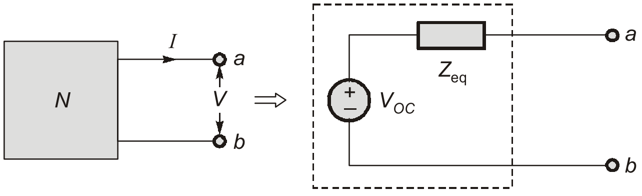
(a) All other independent voltage sources are short circuited (S.C.).
(b) All other independent current sources are open circuited (O.C.).
(c) All dependent voltage and current sources remain as they are and therefore, they are neither S.C. nor O.C.

Note:

☑ The theorem is not applicable to the network containing
  (a) Non linear elements.
  (b) Unilateral elements such as diode or BJT.
☑ The theorem is not applicable to power since it is a non linear parameter.
☑ The theorem is also applicable for circuit having initial condition.

Thevenin's Theorem

A linear active RLC network which contains one or more independent or dependent voltage or current sources can be replaced by a single voltage source V_{OC} in series with equivalent impedance Z_{eq}.



where, V_{OC} → Open circuit voltage between a and b (when I = 0).
Z_{eq} → Equivalent impedance between a and b, when
(a) All independent sources are replaced by their internal impedances.
(b) All dependent voltage and current sources remain as they are.

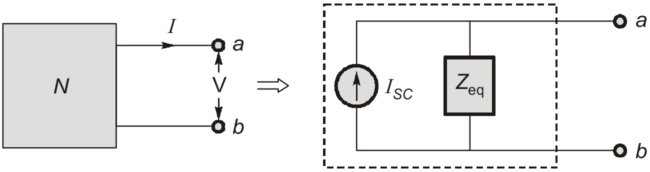
Note:

Theorem is not applicable to the network containing :

- Non linear element.
- Unilateral element.

Norton's Theorem

A linear, active RLC network which contains one or more independent or dependent voltage or current sources can be replaced by a single current source I_{SC} in shunt with equivalent impedance Z_{eq}.

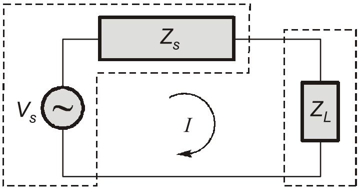


where, $I_{SC} \rightarrow$ Short circuit current between *a* and *b* (when $V = 0$)

$Z_{eq} \rightarrow$ Same as that of Thevenin's theorem

Maximum Power Transfer Theorem

In any linear bilateral network, the power transferred to the load will be maximum when the load resistance is equal to Thevenin's equivalent resistance.



$Z_L = Z_s^*$ ......for maximum power transfer

Case 1: If $Z_s = R_s + jX_s$ and $Z_L = R_L + jX_L$

then $R_L = R_s$ and $X_L = -X_s$

Case 2: If $Z_s = R_s + jX_s$ and $Z_L = R_L$ then $R_L = \sqrt{R_s^2 + X_s^2}$

Case 3: If $Z_L = R_L$ and $Z_s = R_s$ then $R_L = R_s$

Note:

☑ Efficiency at maximum power transfer is 50%.

☑ If Z_s(source resistance) is varied then maximum power is transferred to the load if $Z_s = 0$.

Tellegen's Theorem

- In any network, the sum of instantaneous power consumed by various elements of the branches is always equal to zero.
- Total power supplied by different voltage sources is equal to total power consumed by various passive elements in various branches of the network.

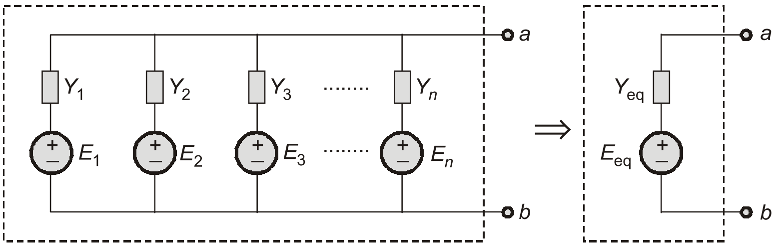
$$\sum_{k=1}^{b} v_k \cdot i_k = 0$$ where, $b \rightarrow$ Number of branches

Note:

☑ The theorem is valid for any type of network as long as KVL and KCL equations are valid.

Millman's Theorem

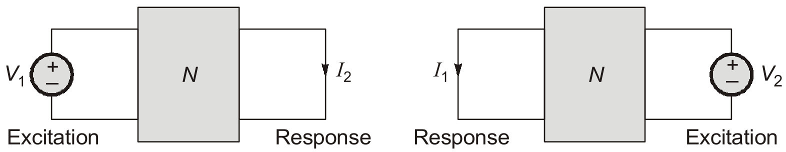
When number of voltage sources ($E_1, E_2 \cdots E_n$) are in parallel with internal resistances $\left(\frac{1}{Y_1}, \frac{1}{Y_2} \cdots \frac{1}{Y_n}\right)$, the arrangement can be replaced by a single equivalent voltage source E_{eq} with an equivalent series resistance $\left(\frac{1}{Y_{eq}}\right)$.



$$E_{eq} = \frac{\sum_{i=1}^{n} E_i Y_i}{\sum_{i=1}^{n} Y_i} \quad \text{and} \quad Y_{eq} = \sum_{i=1}^{n} Y_i$$

Reciprocity Theorem

In a linear bilateral single source network, the ratio of excitation to the response is constant even when the position of excitation and response are interchanged.



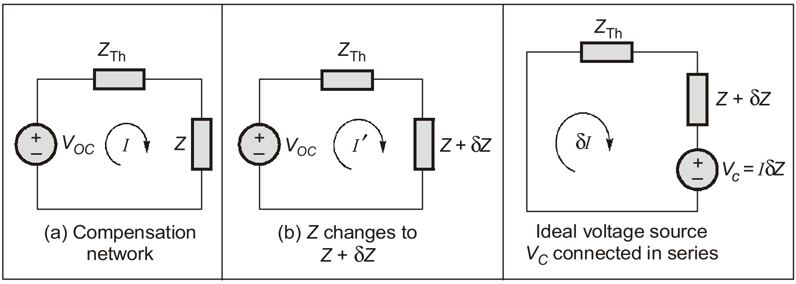
$$\frac{V_1}{I_2} = \frac{V_2}{I_1} \;;\; z_{12} = z_{21}$$

Note:

- ☑ The basis of the theorem is the symmetry of impedance or admittance of matrix.
- ☑ The theorem is valid for network in which linear and bilateral elements are present.
- ☑ The theorem is valid only when single independent voltage or current source is present.
- ☑ The initial conditions are assumed to be zero in reciprocity theorem.

Compensation Theorem

If impedance 'Z' of any branch of a network is changed by 'δZ', then the incremental current 'δI' in such branch is that which will be produced by a compensating voltage source $V_c = I\,\delta Z$ introduced in the same branch with polarity opposing the original direction of current I.



(a) Compensation network (b) Z changes to $Z + \delta Z$ Ideal voltage source V_C connected in series

Substitution Theorem

Any branch of a bilateral network may be substituted by a different branch without disturbing the voltages and current in the entire network, provided the new branch has the same set of terminal voltage and current as the original branch.