

HANDBOOK & FORMULA BOOK

ELECTRICAL ENGINEERING

GATE, IES & PSU's

NETWORK THEORY CONTROL SYSTEM DIGITAL ELECTRONICS & CIRCUITS MICROPROCESSOR
ELECTRONIC DEVICES & CIRCUITS ANALOG ELECTRONICS SIGNAL AND SYSTEM COMMUNICATION SYSTEM
ELECTROMAGNETIC THEORY MEASUREMENT & INSTRUMENTATION ELECTRICAL MACHINES
POWER SYSTEMS POWER ELECTRONICS ELECTRICAL MATERIALS

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- COMPLETE revision before the EXAM in short time.
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HANDBOOK & FORMULA BOOK

for
GATE, IES, JTO, PSU's & SSC

ELECTRICAL ENGINEERING

Published by Engineers Institute of India



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A WORD TO THE STUDENTS



Er. R.K. Rajesh
(DIRECTOR)

GATE and Engineering Services Examinations are the most prestigious competitive examinations conducted for graduate engineers. Over the past few years, they have become more competitive as more and more numbers of aspirants are increasingly becoming interested in post graduate qualifications & government jobs for a secured and bright career.

This Formula Book consists of well-illustrated concepts, important formulae and diagrams, which will be highly beneficial at the last leg of candidate's preparation.

It includes all the subjects of Electrical Engineering, which are required for all type of competitive examinations. Adequate emphasis has been laid down to all the major topics in the form of Tips / Notes, which will be highly lucrative for objective and short answer type questions.

Proper strategy and revision is a mandatory requirement for clearing any competitive examination. This book covers short notes and formulae for Electrical Engineering. This book will help in quick revision before the GATE, IES & all other PSUs.

This book has been designed after considering the current demand of examinations.

It would be very fruitful if the students go through this book every day. We are presenting this book by considering all the facts which is required to get success in the competition.

With best wishes for future career

R. K. Rajesh

Director

Engineers Institute of India

eii.rkrajesh@gmail.com

**This book is dedicated to all
Electrical Engineers
Preparing for GATE, IES, JTO, SSC
& Public sector examinations.**

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Why IES?

Indian engineering services (IES) constitute of engineers that work under the govt. of India to manage a large segment of public sector economy which constitutes of Railroads, Public works, Power, Telecommunications, etc. IES remain the most sought-after careers for the engineering graduates in India. A combined competitive examination is conducted by UPSC for recruitment to the Indian Engineering Services. The exam constitutes of a written exam followed by an interview for personality test.

Why GATE?

In the present competitive scenario, where there is mushrooming of universities and engineering colleges, the only yardstick to measure and test the calibre of engineering students is the GATE.

The GATE Advantage

Many public sector undertakings such as BHEL, IOCL, NTPC, BPCL, HPCL, BARC and many more PSUs are using the GATE score for selecting candidates for their organizations. Students who qualify in GATE are entitled to a stipend of Rs 8,000 per month during their M.Tech. course. Better remuneration is being offered for students of M.Tech./ME as compared to those pursuing B.Tech/B.E. A good rank assures a good job. After joining M.Tech. at IITs and IISc, one can look at a salary package ranging from Rs 7lakh to 30lakh per annum depending upon specialization and performance. Qualifying GATE with good marks is also an eligibility clause for the award of JRF in CSIR Laboratories.

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NETWORK THEORY

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1. NETWORK BASICS

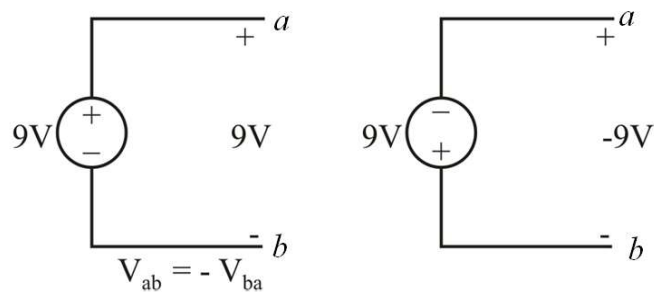
Current: Electric current is the time rate of change of charge flow.

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

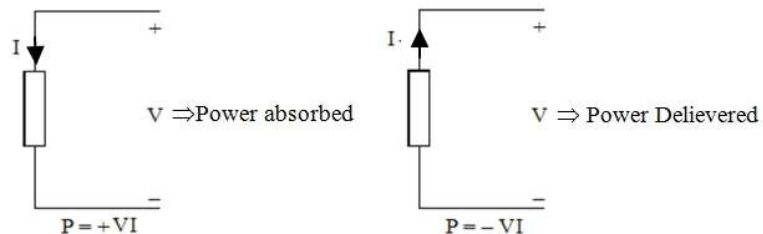
Charge transferred between time t_o and t $q = \int_{t_o}^t i dt$

Sign Convention: A negative current of $-5A$ flowing in one direction is same as a current of $+5A$ in opposite direction.

Voltage: Voltage or potential difference is the energy required to move a unit charge through an element, measured in volts.



Power: It is time rate of expending or absorbing energy.



- Law of conservation of energy must be obeyed in any electric circuit.
- Algebraic sum of power in a circuit, at any instant of time, must be zero.
i.e. $\sum P = 0$

Circuit Elements:

Resistor: Linear and bilateral (conduct from both direction)

In time domain $V(t) = I(t)R$

In s domain $V(s) = RI(s)$

$$R = \frac{\rho l}{A} \text{ ohm}$$

l = length of conductor, ρ = resistivity, A = area of cross section

- Extension of wire to n times results in increase in resistance: $R' = n^2 R$

- Compression of wire results in decrease in resistance:

$$R' = \frac{R}{n^2}$$

Capacitor: All capacitors are linear and bilateral, except electrolytic capacitor which is unilateral.

Time Domain: $i(t) = \frac{Cdv(t)}{dt}$ $v(t) = \frac{1}{C} \int_{-\infty}^t i(t)dt$

$$I(s) = sCV(s)$$

In s-domain: $V(s) = \frac{1}{sC} I(s)$

- Capacitor doesn't allow sudden change of voltage, until impulse of current is applied.
- It stores energy in the form of electric field and power dissipation in ideal capacitor is zero.

- Impedance $Z_c = -jX_c \Omega$ & $X_c = \frac{1}{\omega C}$; $X_c \rightarrow$ Capacitive reactance ; $\omega = 2\pi f$

Inductor: Linear and Bilateral element

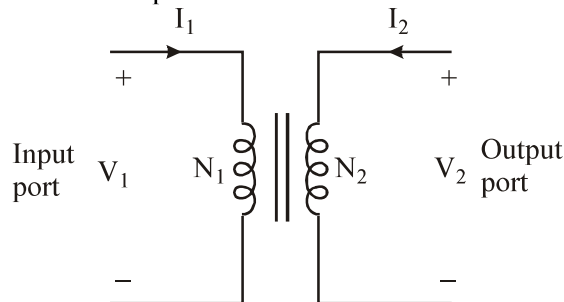
Time Domain: $v(t) = L \frac{di(t)}{dt}$ $i(t) = \frac{1}{L} \int_{-\infty}^t v(t)dt$

Impedance $Z_L = jX_L \Omega$ & $X_L = \omega L \Omega$

In s-domain $V(s) = sL I(s)$ $I(s) = \frac{1}{sL} V(s)$

- Inductor doesn't allowed sudden change of current, until impulse of voltage is applied.
- It stores energy in the form of magnetic field.
- Power dissipation in ideal inductor is zero.

Transformer: 4 terminal or 2-port device.



$N_1 > N_2$: Step down transformer

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

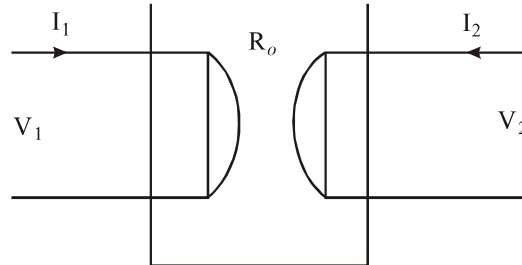
$N_2 > N_1$: Step up transformer

$$\frac{I_1}{I_2} = \frac{N_2}{N_1}$$

Where $\frac{N_1}{N_2} = K \rightarrow$ Turns ratio.

Transformer doesn't work as amplifier because current decreases in same amount power remain constant.

Gyrator:



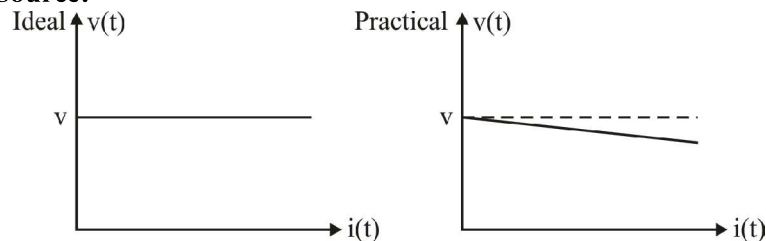
$R_o \rightarrow$ Coefficient of Gyrator

$$V_1 = R_o I_2$$

$$V_2 = -R_o I_1$$

- If load is capacitive then input impedance will be inductive and vice versa.
- If load is inductive then input impedance will be capacitive.
- It is used for simulation of equivalent value of inductance.

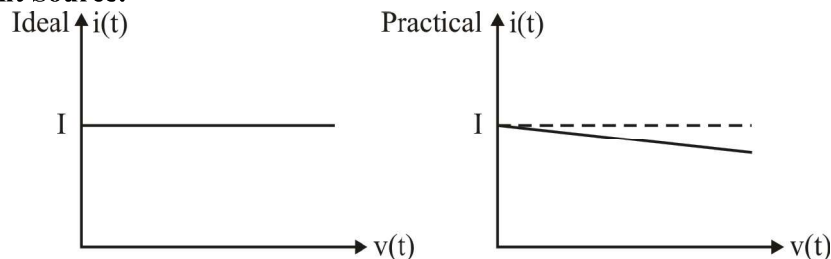
Voltage Source:



In practical voltage source, there is small internal resistance, so voltage across the element varies with respect to current.

- **Ideal voltmeter, $R_V \rightarrow \infty$ (Internal resistance)**

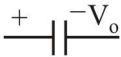
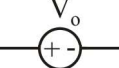
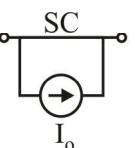
Current Source:



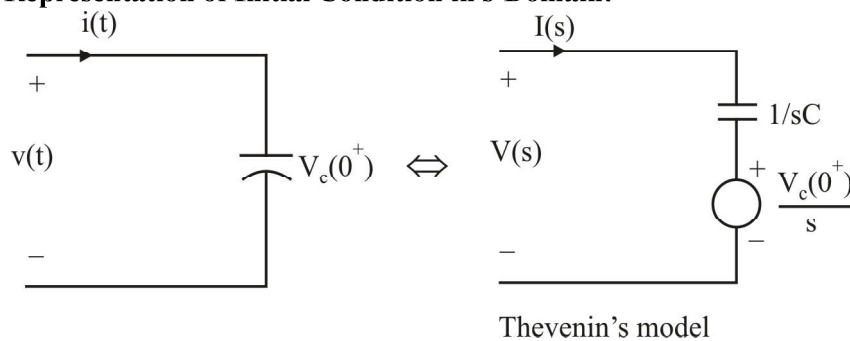
In practical current source, there is small internal resistance, so current varies with respect to the voltage across element.

5. TRANSIENTS

- Initially at $t = 0$ (when uncharged) the capacitor acts as a short circuit and the inductor acts as an open circuit.
- At $t = \infty$ (steady state condition) the capacitor acts as open circuit and inductor acts as a short circuit.
- At $t = 0$, any capacitor with initial voltage acts as a constant voltage source and any inductor with initial current as a constant current source.
- The above relations are valid for d.c. source only.

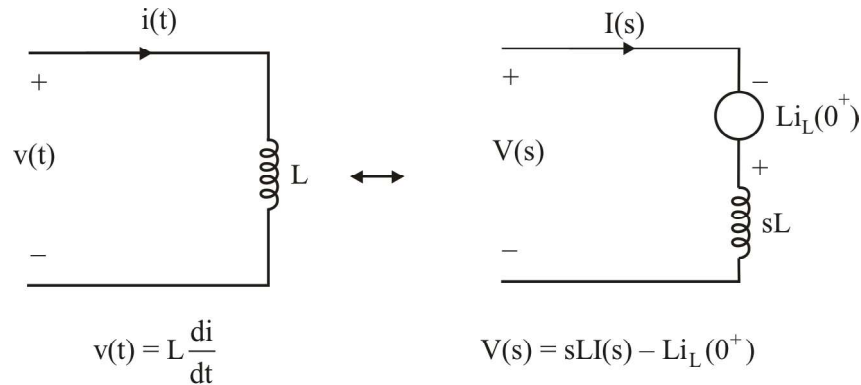
Element	Initial condition $t = 0^+$	Steady State $t = \infty$
		
		
		
		

Representation of Initial Condition in s-Domain:



$$i(t) = C \frac{dV(t)}{dt}$$

$$V(s) = \frac{I(s)}{sC} + \frac{V_c(0^+)}{s}$$

Inductor:

Transient Current through inductor at any time t :

$$i_L(t) = I_f - (I_f - I_i)e^{-\frac{R_{eq}t}{L}}$$

$I_f \rightarrow$ Steady state current through L, $I_i \rightarrow$ Initial current through L

$R_{eq} \rightarrow$ Thevenin's equivalent resistance seen across L for $t > 0$

Transient Voltage across capacitor at any time t :

$$v_C(t) = V_f - (V_f - V_i)e^{-\frac{t}{R_{eq}C}}$$

$V_f \rightarrow$ Steady state voltage across C, $V_i \rightarrow$ Initial voltage across C

$R_{eq} \rightarrow$ Thevenin's equivalent resistance seen across C for $t > 0$

In general:

$$x(t) = x(\infty) + [x(t_0^+) - x(\infty)]e^{-\frac{(t-t_0)}{\tau}}$$

- Just before closing the switch and after just opening of switch, the voltages and current are same through capacitor and inductors respectively i.e.

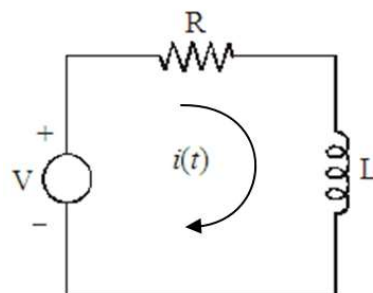
$$I_L(0^+) = I_L(0^-) \quad \& \quad V_C(0^+) = V_C(0^-)$$

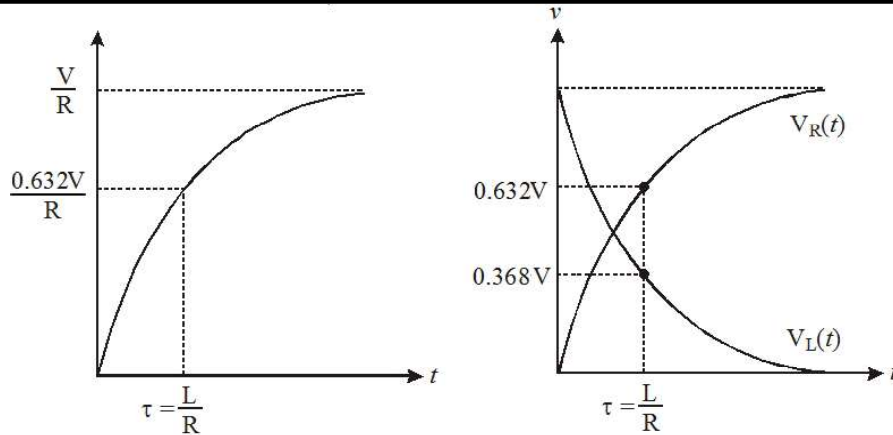
Basic R – L Circuit:

$$i(t) = \frac{V}{R} \left(1 - e^{-\frac{R}{L}t} \right)$$

$$v_L(t) = Ve^{-\frac{R}{L}t}$$

$$v_R(t) = V(1 - e^{-\frac{R}{L}t})$$

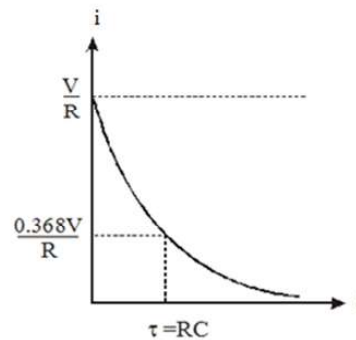
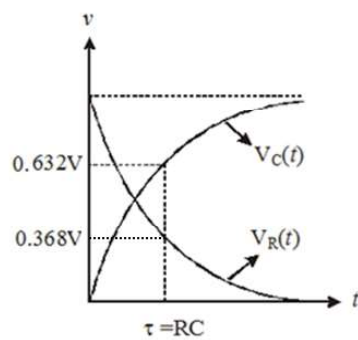
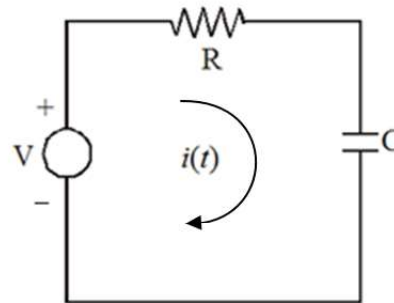


**Basic R-C Circuit:**

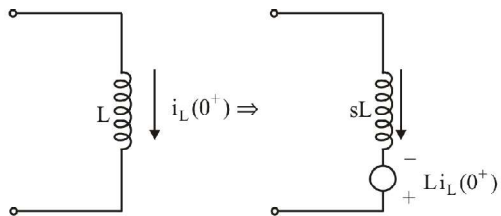
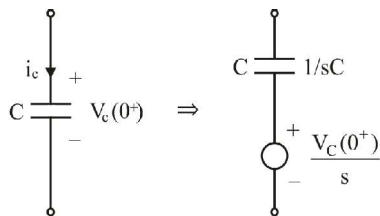
$$v_C(t) = V(1 - e^{-\frac{t}{RC}})$$

$$i(t) = \frac{V}{R} e^{-\frac{t}{RC}}$$

$$v_R(t) = V e^{-\frac{t}{RC}}$$



To find $i(t)$ and $V(t)$ for $t > 0$:



- Always take a particular direction shown both for capacitor and inductor.

(vii) Bandwidth increases

(viii) No effect on type and error

(ix) Transient characteristics improves (x) $\left(\frac{S}{N}\right)$ and e_{ss} decreases

Proportional + Integral:

(i) Adds an open loop pole, so stability decreases

(ii) M_p, t_r, t_d increases.

(iii) PM and GM decreases

(iv) ξ decreases

(v) ω_{gc}, ω_{pc} decreases

(vi) Bandwidth decreases

(vii) Type and order are increased by one

(viii) Steady state characteristics improves

(ix) $\left(\frac{S}{N}\right)$ increases and e_{ss} decreases by huge amount

Effect of adding a pole to Root Locus:

- Root locus tends towards real axis.
- Number of asymptotes increases
- Root locus shifts towards right half of s -plane
- Stability reduces and BW reduces.
- Its properties are almost same to proportional + derivative controller.

Effect of adding a zero to Root Locus:

- Number of asymptotes decreases.
 - Root locus shifts towards left half of s -plane.
 - Stability increases and BW increases.
 - Its properties are almost same to proportional + integral controller.
-

10. STATE SPACE ANALYSIS

General Representation of State Model:

State Equation $\dot{X} = AX + BU$
 $Y = CX + DU$

$\dot{X}$ = Velocity Vector ($n \times 1$) U = Input Vector ($m \times 1$)
 X = State vector ($n \times 1$) Y = Output Vector ($P \times 1$)
 A = System Matrix ($n \times n$) B = Input matrix ($n \times m$)
 C = Output matrix ($p \times n$) D = Transmission ($p \times m$) matrix
 n = Number of state variables
 p = Number of outputs
 m = Number of inputs

(i) State Space Representation of n th order Differential Equation:

$$\frac{d^n y}{dt^n} + a_1 \frac{d^{n-1} y}{dt^{n-1}} + \dots \text{any} = u(t)$$

$$\begin{aligned} \dot{X} &= AX + BU \\ \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \vdots \\ \dot{x}_n \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ -a_n & -a_{n-1} & \dots & \dots & -a_1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix} U \\ &\& \quad Y = [1 \ 0 \ 0 \ \dots \ 0] \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \end{aligned}$$

(ii) T.F. from State Model: $\dot{x}(t) = A x(t) + Bu(t)$
 $y(t) = C x(t) + Du(t)$

$$\frac{Y(s)}{U(s)} = C[sI - A]^{-1}B + D$$

(iii) Controllability and Observability:

For Controllability $Q_c = [B: AB: A^2B: \dots : A^{n-1}B]$
 $|Q_c| \neq 0$ (for controllability)

For Observability $Q_o = [C^T: A^T C^T: (A^T)^2 C^T: \dots : (A^T)^{n-1} C^T]$
 $|Q_o| \neq 0$ (for observability)

(iv) Solution of State Equation: (State Transition Matrix)

$$e^{AT} = L^{-1}(sI - A)^{-1}$$

Forced Response:

$$x(t) = \underbrace{L^{-1}[(sI-A)^{-1}]x[0]}_{\text{Free Response } \phi(t)} + \underbrace{L^{-1}[(sI-A)^{-1}]Bu(s)}_{\text{Forced Response } \theta(t)}$$

Properties of State Transition Matrix:

- (i) $\phi^{-1}(t) = \phi(-t)$
 - (ii) $\phi(t_1 + t_2) = \phi(t_1) \cdot \phi(t_2) = \phi(t_2) \cdot \phi(t_1)$
 - (iii) $[\phi(t)]^n = \phi[nt]$
 - (iv) $\phi(t_2 - t_1) \cdot \phi(t_1 - t_0) = \phi(t_2 - t_0) = \phi(t_1 - t_0) \phi(t_2 - t_1)$
-
-

3

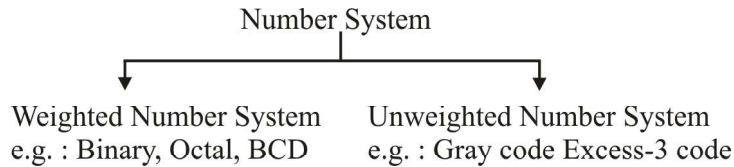
DIGITAL ELECTRONICS AND CIRCUITS

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1. NUMBER SYSTEM & CODES

Number System and Codes:



A number system with base ' r ', contains ' r ' different digits and they are from 0 to $r - 1$.

Decimal to other codes conversions: To convert decimal number into other system with base ' r ', divide integer part by r and multiply fractional part with r .

Other codes to Decimal Conversions: $(x_2x_1x_0 \cdot y_1y_2)_r \rightarrow (A)_{10}$

$$A = x_2r^2 + x_1r + x_0 + y_1r^{-1} + y_2r^{-2}$$

Hexadecimal to Binary: Convert each Hexadecimal digit into 4 bit binary.

$$(5AF)_{16} \rightarrow \frac{(0101)}{5} \frac{1010}{A} \frac{1111}{F}_2$$

Binary to Hexadecimal: Grouping of 4 bits into one hex digit.

$$(110101.11)_2 \rightarrow \underbrace{0011}_{3} \underbrace{0101}_{5} . \underbrace{1100}_{C} \rightarrow (35.C)_{16}$$

Octal to Binary and Binary to Octal: Same procedure as discussed above but here group of 3 bits is made.

Codes:

Binary coded decimal (BCD):

- In BCD code each decimal digit is represented with 4 bit binary format.

$$Eg : (943)_{10} \rightarrow \left(\underbrace{1001}_9 \underbrace{0100}_4 \underbrace{0011}_9 \right)_{BCD}$$

- It is also known as 8421 code

Invalid BCD codes

Total Number possible $\rightarrow 2^4 \Rightarrow 16$

Valid BCD codes $\rightarrow 10$

Invalid BCD codes $16 - 10 \Rightarrow 6$

These are 1010, 1011, 1100, 1101, 1110, and 1111

Excess-3 code: (BCD + 0011)

- It can be derived from BCD by adding '3' to each coded number.
- It is unweighted and self-complementing code.

4

MICROPROCESSORS

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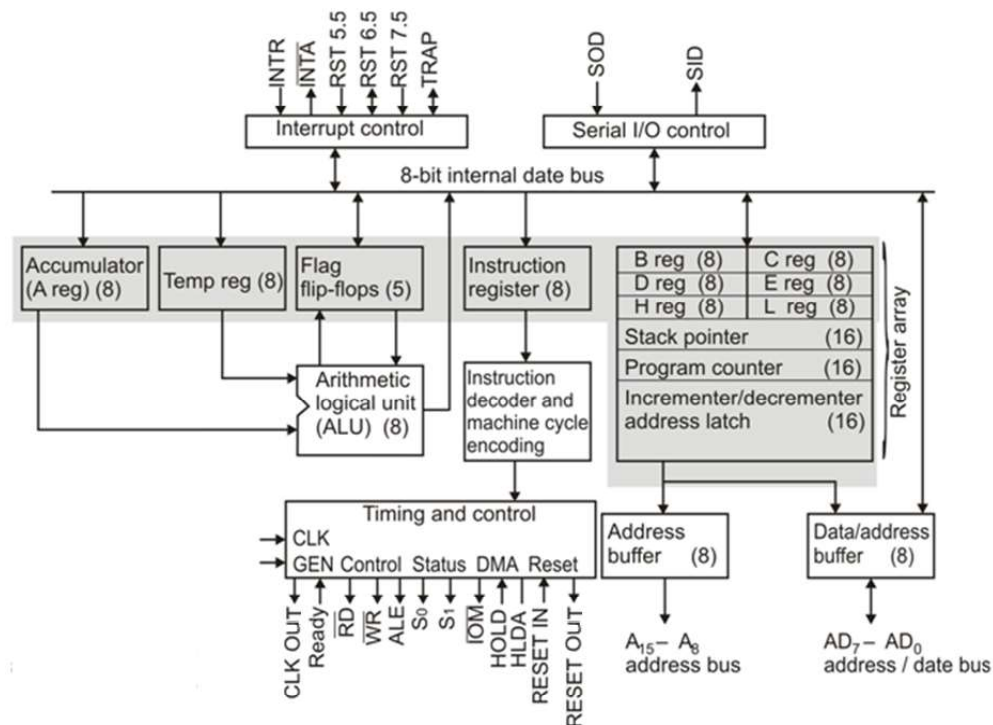
1. MICROPROCESSOR BASICS

A **Microprocessor** includes ALU, register arrays and control circuits on a single chip.

Microcontroller:

A device that includes microprocessor, memory and input and output signal lines on a single chip, fabricated using VLSI technology.

Architecture of 8085 Microprocessor



1. 8085 MPU:

- 8 bit general – purpose microprocessor capable of addressing 64 K of memory.
- It has 40 pins, requires a +5V single power supply and can operate with 3 – MHz single phase clock.

2. 8085 programming model:

It has six general purpose register to store – 8 bit data. These are B, C, D, E, H and L. It can be combined as BC, DE, and HL to perform 16 bit operations.

B, D, H → high order register and C, E, L → low order register.

Accumulator: Is an 8 bit register that is used to perform arithmetic and logic functions.

Flags: 5 flags

Flag Register:

D_7	D_6	D_5	D_4	D_3	D_2	D_1	D_0
S	Z		AC		P		CY

Carry Flag (CY): If an arithmetic operation result in a carry or borrow, the CY flag is set, otherwise it is reset.

Parity Flag (P):

If the result has an even number of 1s, the flag is set, otherwise the flag is reset.

Auxiliary Carry (AC): In an arithmetic operation

- If carry is generated by D_3 and passed to D_4 flag is set.
- Otherwise it is reset.

Zero Flag (Z): Zero Flag is set to 1, when the result is zero otherwise it is reset.

Sign Flag (S): Sign Flag is set if bit D_7 of the result is 1. Otherwise it is reset.

Program counter (PC): It is used to store the 16 bit address of the next byte to be fetched from the memory or address of the next instruction to be executed.

Stack Pointer (SP): It is 16 bit register used as a memory pointer. It points to memory location in Read/Write memory which is called as stack.

8085 Signals:

Address lines:

There are 16 address lines $AD_0 - AD_7$ and $A_8 - A_{15}$ to identify the memory locations.

Data lines/ Multiplexed address lines:

Multiplexed address lines: The signal lines $AD_7 - AD_0$ are bi-directional i.e. they serve dual purpose. The $AD_7 - AD_0$ address lines are shared with the data lines. The ALE signal is used to distinguish between address lines and data lines.

Control and Status Signals:

Address Latch Enable (ALE): This is positive going pulse generated every time and indicates that the $AD_7 - AD_0$ bits are address bits.

$\overline{RD}$: This is active low signal indicates that the selected I/O or memory device is to be read.

$\overline{WR}$: Active low signal indicates that data on data bus are to be written into a selected memory or I/O location.

$IO/\overline{M}$:

When this signal is high, it indicates an I/O operation.

When it is low it indicates memory operation.

S_1 and S_0 : These are status signals.

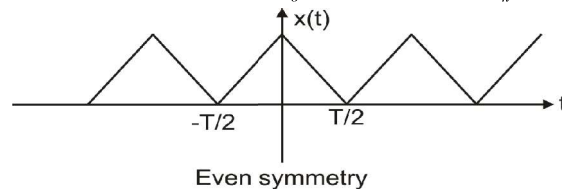
Integration Property

$$y(t) = \int_{-\infty}^t x(\tau) d\tau \quad b_k = \frac{1}{jk\omega_o} a_k \quad |b_k| = \frac{1}{k\omega_o} |a_k|$$

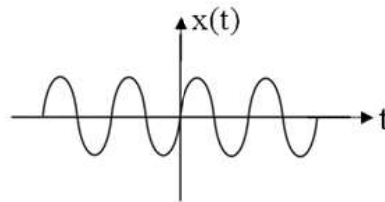
$$\angle b_k = \frac{-\pi}{2} + \angle a_k$$

Symmetry in Fourier series:

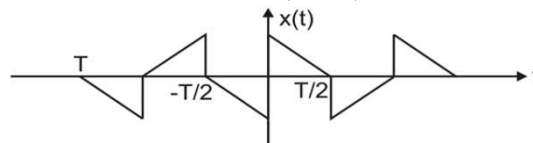
(i) **Even Symmetry:** $x(-t) = x(t)$ $a_o \neq 0$ $\angle a_k = 0^\circ$ or $\pm 180^\circ$



(ii) **Odd Symmetry:** $x(-t) = -x(t)$ $a_o = 0$ $\angle a_k = \pm 90^\circ$



(iii) **Half wave Symmetry:** $x(t) = -x\left(t \pm \frac{T}{2}\right)$ $a_o = 0$ $a_k = 0; k = \text{even}$



Even and Half wave: $x(-t) = x(t)$ and $x(t) = -x\left(t \pm \frac{T}{2}\right)$
 $a_o = 0$ $a_k = 0, k = \text{even}$ $\angle a_k = 0, \pm 180^\circ$

Odd and Half wave: $x(-t) = -x(t)$ and $x\left(t + \frac{T}{2}\right) = -x(t)$
 $a_o = 0$ $a_k = 0, k = \text{even}$ $\angle a_k = \pm 90^\circ$

Parseval's Theorem: $\frac{1}{2T} \int_{-T}^T |x(t)|^2 dt = \sum_{k=-\infty}^{\infty} |a_k|^2$ used for power calculation.

It is used for power calculation.

The term $|a_k|^2$ for $k = 0, 1, 2, \dots$ is the distribution of power as a function of frequency and so it is called power density spectrum or power spectral density of the periodic signal.

4. FOURIER TRANSFORM

Fourier Transform: It is the special case of Laplace transform evaluated on $j\omega$ axis.

$$X(j\omega) = \int_{-\infty}^{\infty} x(t)e^{-j\omega t} dt$$

Inverse Fourier transform: $x(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(j\omega) e^{j\omega t} d\omega$

Fourier Transform Properties:

Linearity Property: $ax_1(t) + bx_2(t) \longleftrightarrow aX_1(j\omega) + bX_2(j\omega)$

Time shifting: $x(t - t_0) \xrightarrow{\text{FT}} e^{-j\omega t_0} X(j\omega) \quad x(t + t_0) \xrightarrow{\text{FT}} e^{j\omega t_0} X(j\omega)$

Time reversal: $x(-t) \xrightarrow{\text{FT}} X(-j\omega)$

Time scaling: $x(at) \longleftrightarrow \frac{1}{|a|} X\left(\frac{j\omega}{a}\right)$

Frequency shifting property:

$$e^{j\omega_0 t} x(t) \longleftrightarrow X(j(\omega - \omega_0)) \quad e^{-j\omega_0 t} x(t) \longleftrightarrow X(j(\omega + \omega_0))$$

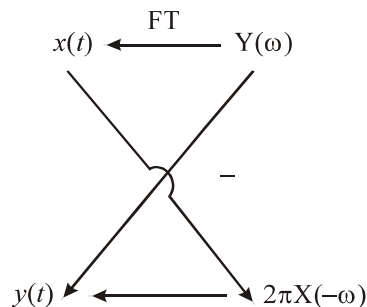
Differentiation and Integration:

$$\frac{d}{dt} x(t) \xrightarrow{\text{F.T.}} j\omega X(j\omega)$$

$$\int_{-\infty}^t x(\tau) d\tau \xrightarrow{\text{F.T.}} \frac{1}{j\omega} X(j\omega) + \pi x(0) \delta(\omega)$$

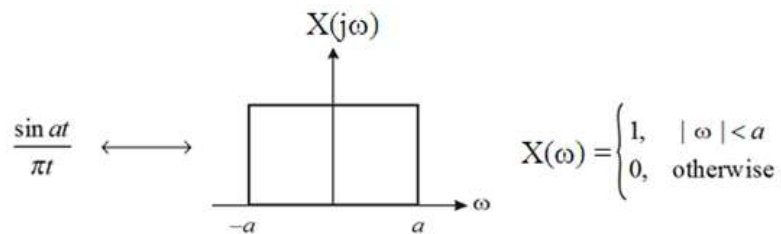
Differentiation in Frequency Domain: $t x(t) \xrightarrow{\text{F.T.}} j \frac{dX(j\omega)}{d\omega}$

Duality property:

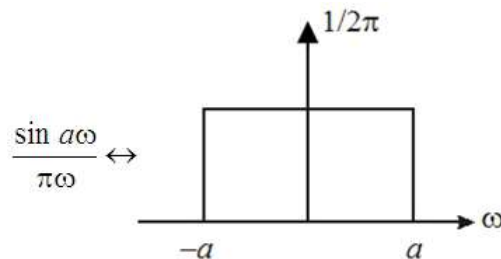


Fourier Transform of some useful functions:

- $e^{-at}u(t), a > 0 \xleftrightarrow{\text{F.T.}} \frac{1}{a + j\omega}$ $e^{-a|t|} \longleftrightarrow \frac{2a}{a^2 + \omega^2}$
 - $e^{at}u(-t), a > 0 \xleftrightarrow{\text{F.T.}} \frac{1}{a - j\omega}$
 - $\delta(t) \xleftrightarrow{\text{F.T.}} 1$
 - $1 \xleftrightarrow{\text{F.T.}} 2\pi\delta(\omega)$
 - $\text{sgn}(t) \longleftrightarrow \frac{2}{j\omega}$
 - $u(t) \rightarrow \frac{1}{j\omega} + \pi\delta(\omega)$
- $X(j\omega) \quad X(\omega) =$



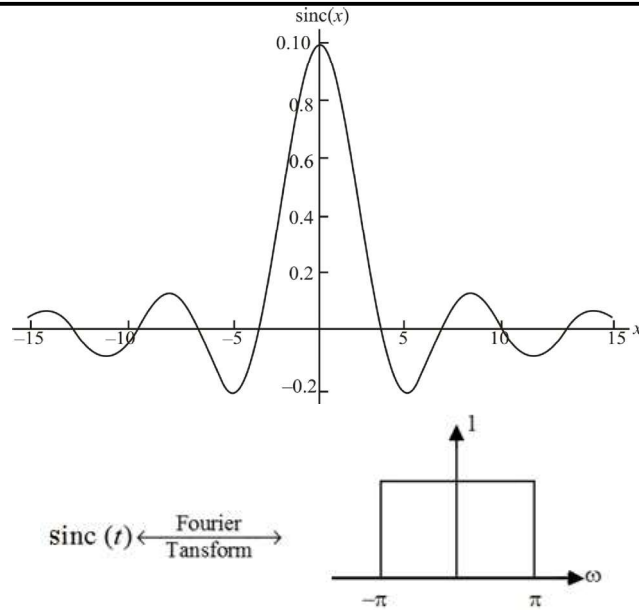
•



- $\frac{1}{a + jt} \leftrightarrow 2\pi e^{a\omega} u(-\omega)$
- $\sin \omega_0 t \leftrightarrow \frac{\pi}{j} [\delta(\omega - \omega_0) - \delta(\omega + \omega_0)]$
- $\cos \omega_0 t \leftrightarrow \pi [\delta(\omega - \omega_0) + \delta(\omega + \omega_0)]$

Sinc Function: $\text{sinc}(\theta) = \frac{\sin \pi\theta}{\pi\theta}$ $\frac{\sin \omega t}{\pi t} = \frac{\omega}{\pi} \text{sinc}\left(\frac{\omega T}{\pi}\right)$

Representation of sinc Function $x(t) = A \text{sinc}(t)$



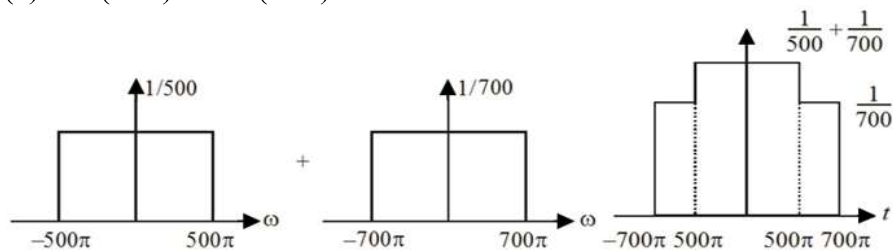
(i) It is an even function of x .

(ii) $\text{sinc}(0) = 1$

(iii) $\text{sinc}(x) = 0$ except at $x = 0$, for $x = \pm 1, \pm 2, \dots$

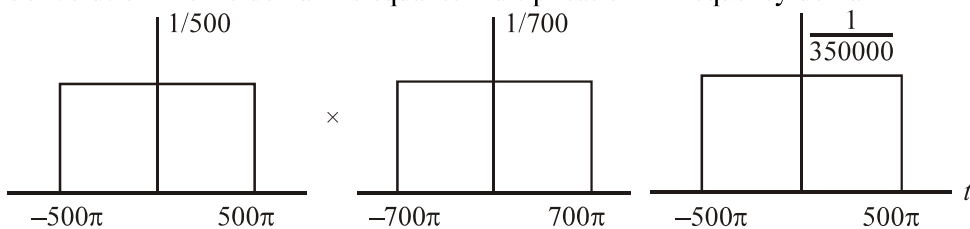
Operation of sinc function

(1) $\text{sinc}(500t) + \text{sinc}(700t)$

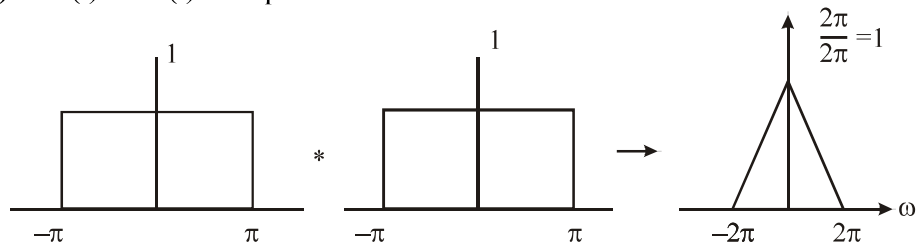


(2) $\text{sinc}(500t) * \text{sinc}(700t)$ convolution

Convolution in time domain is equal to multiplication in frequency domain

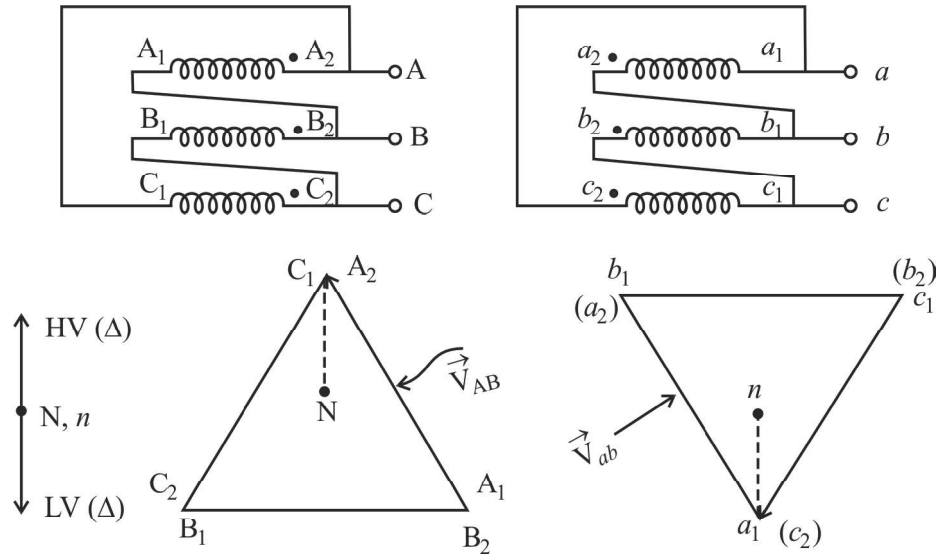


(3) $\text{sinc}(t) \cdot \text{sinc}(t)$ multiplication

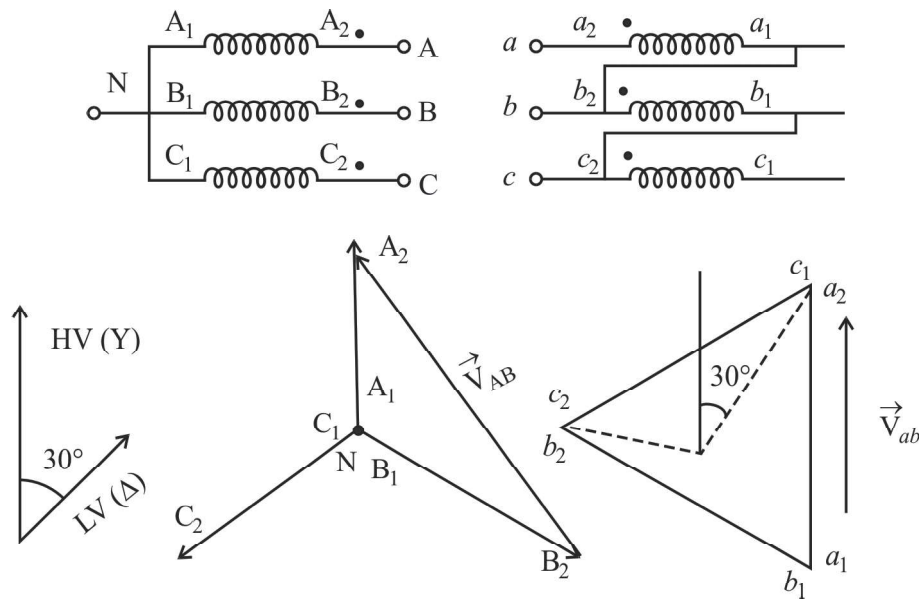


Convolution

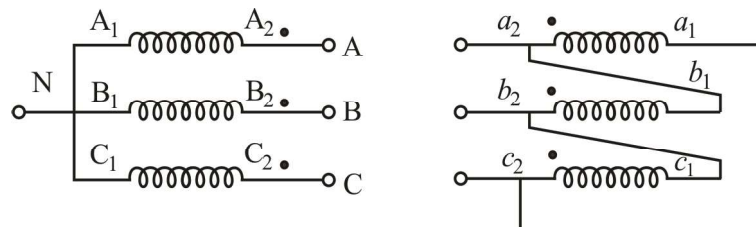
4. Dd 6

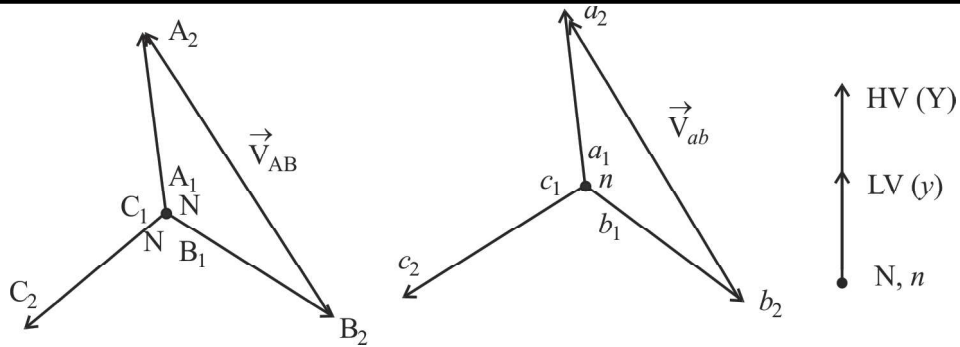


5. Yd 1

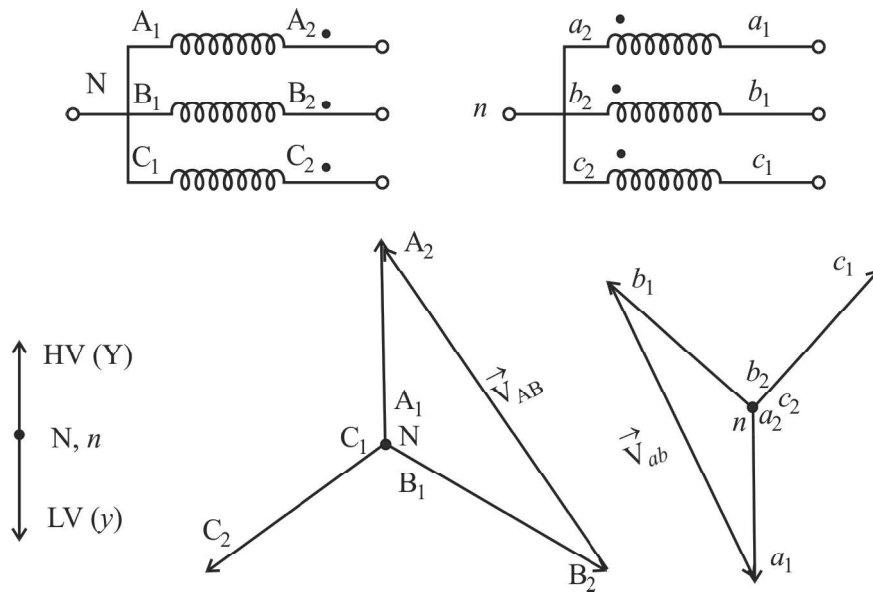


6. Yd 11

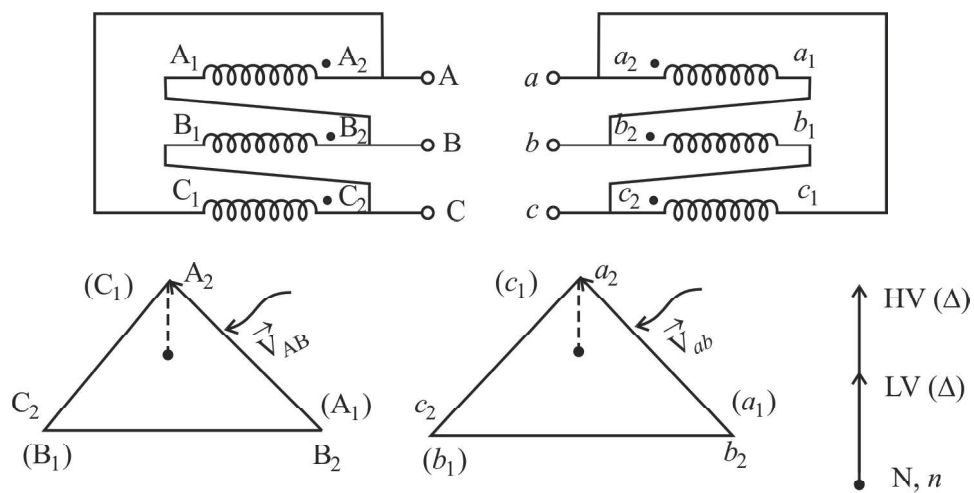




2. Yy 6



3. Dd 0



Note: If in a $\Delta-\Delta$ connection with $3-\phi$ bank of $1-\phi$ transformer, one transformer develops fault, then remaining 2 transformer can still feed the load at a reduced capacity.

Phasor Groups:

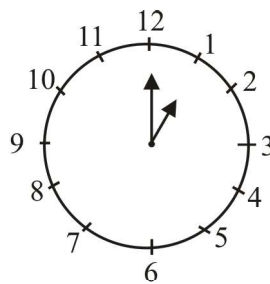
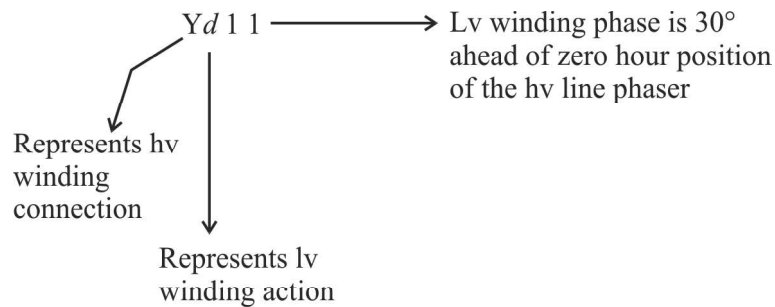
Group 1: $0^\circ \rightarrow Yy0, Dd0$

Group 2: $180^\circ \rightarrow Yy6, Dd6$

Group 3: $-30^\circ \rightarrow Yd1, Dy1$

Group 4: $+30^\circ \rightarrow Yd11, Dy11$

Note:

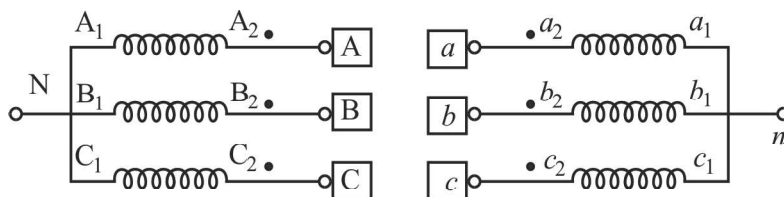


Yd_1 or Dr_1

$L.v$ lags by 30° with $h.v$

Representation:

1. $Yy0$



Note that here Z_1 and Z_2 are expressed in ohms.

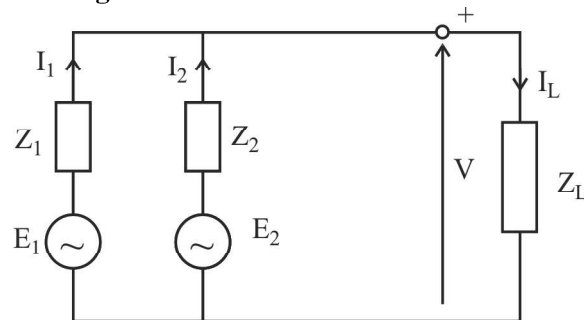
Important Point:

1. Pu loading of any transformer is inversely proportional to its p.u. impedance on its own base which implies that the transformer which has minimum p.u. impedance on its own base has maximum p.u. load sharing.

2. For proportional sharing of load, $(Z_1)_{pu} = (Z_2)_{pu}$

Where the Pu values are on their own base.

Case-2: Unequal Voltage Ratio



We use Millman's theorem in such cases.

Steps to be followed in such problems:

1. Write $\vec{V} = \vec{I}_{sc} \vec{Z}_q$

where, $\vec{I}_{sc} = \sum_{k=1}^n \frac{\vec{E}_k}{\vec{Z}_k}$ and $\frac{1}{\vec{Z}_q} = \frac{1}{\vec{Z}_L} + \sum_{k=1}^n \frac{1}{\vec{Z}_k}$

2. $\vec{I}_k = \frac{\vec{E}_k - \vec{V}}{\vec{Z}_k}$ where, $k = 1, 2, 3, 4, \dots, n$

3. $\vec{S}_K = \vec{V} \vec{I}_k^*$

3 ϕ T/F Connection:

Key Points:

1. A star connection is used for high voltage, low capacity applications

Delta is used for high capacity low voltage application

Which implies that, $\Delta - Y \Rightarrow$ Step up application

$Y - \Delta \Rightarrow$ Step down application

Note:

In distribution transformers, there are 3 ϕ and 1 ϕ loads as well which requires a line to neutral voltage. Hence, in such cases we use $\Delta - Y$ connection.

2. Y - Y connections are not used without a tertiary Δ due to problems related with magnetizing current and unbalanced loads.

3. $\Delta - \Delta$ connections are used where mixed loading is not required.

$$4. \text{ Ratio of conductive transfer to total transfer} = \frac{1}{a_{(\text{auto})}}$$

$$5. \text{ Ratio of inductive transfer to total transfer} = 1 - \frac{1}{a_{\text{auto}}}$$

Note: Advantages of auto transformer are at best when $a_{(\text{auto})}$ is close to one.

PARALLEL OPERATION OF TRANSFORMERS:

Conditions for Parallel Operation

I. For 1 ϕ and 3 ϕ Transformers:

(a) Must conditions:

- (i) Same polarity
- (ii) Same phase sequence
- (iii) Zero relative phase difference

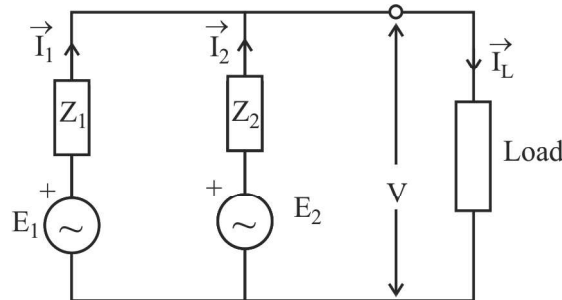
Note: (ii) and (iii) only for 3 ϕ transformers.

(b) Desirable condition:

- (i) Same voltage ratio
- (ii) Same Pu impedance
- (iii) Same $\left(\frac{X}{R}\right)$ ratio

Sharing of Load by Transformers in Parallel Operation:

Case-I: Equal Voltage Ratio



$$\text{Let } E_1 = E_2 = E$$

$$\text{By current division rule, } \vec{I}_1 = \left(\frac{Z_2}{Z_1 + Z_2} \right) \vec{I}_L \quad \dots(i)$$

$$\vec{I}_2 = \left(\frac{Z_1}{Z_1 + Z_2} \right) \vec{I}_L \quad \dots(ii)$$

$$\begin{aligned} \text{Multiplying equation (i) by } V \quad \vec{S}_1^* &= \vec{V}^* \vec{I}_1 \\ \vec{S}_1^* &= V^* \left(\frac{Z_2}{Z_1 + Z_2} \right) \vec{I}_L \quad \vec{S}_1^* = \left(\frac{Z_2}{Z_1 + Z_2} \right) (\vec{S}_L^*) \end{aligned}$$

$$\text{Similarly, } \vec{S}_2^* = \left(\frac{Z_1}{Z_1 + Z_2} \right) (\vec{S}_L^*)$$

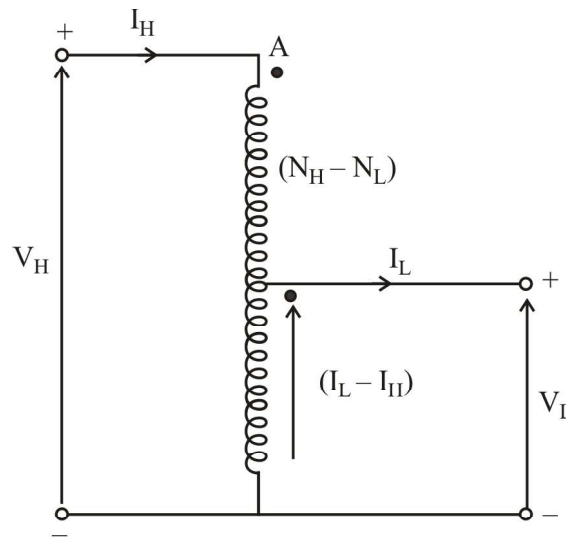
Where, j represents loading.

For example for 20% loading,
$$S_{\eta_{\max}} = S_{20\%} \sqrt{\frac{P_i}{P_{Cu}(20\%)}}$$

All day efficiency,
$$\eta_{\text{all day}} = \frac{\text{Output KWhr for 24 hours}}{\text{Input KWhr for 24 hours}}$$

Auto Transformer:

When the primary and secondary winding are electrically connected so that a part of the winding is common to both high voltage and low voltage sides, the transformer is called auto transformer.



mmf balance equation states: $(N_H - N_L) I_H = N_L (I_L - I_H)$

$$N_H I_H = N_L I_L \quad \frac{I_L}{I_H} = \frac{N_H}{N_L}$$

and as per turn voltage is same
$$\frac{V_H}{N_H} = \frac{V_L}{N_L}$$

$$\Rightarrow \frac{V_H}{V_L} = \frac{N_H}{N_L} = \frac{I_L}{I_H} = a_{(\text{auto})}$$

Comparison of auto transformer with two winding transformer:

1. $\frac{Cu_{(\text{auto})}}{Cu_{(2\text{Wdg})}} = \left[1 - \frac{1}{a_{\text{auto}}} \right]$
2. $\frac{S_{(\text{auto})}}{S_{(2\text{Wdg})}} = \frac{a_{(\text{auto})}}{a_{(\text{auto})} - 1}$
3. % Cu saving = $\frac{1}{a_{(\text{auto})}} \times 100$

Transformer Losses: Transformer losses are of two types:

(i) Core Loss: These are of two types

(a) Hysteresis Loss: $P_h = K_h f B_m^x$

Where, K_h = Proportionality constant that depends upon the core and its volume.

B_m = Maximum flux density in the core.

f = Frequency of the flux.

x = Steinmetz constant (1.5 to 2.5)

(b) Eddy Current Loss: $P_e = K_e f^2 B_m^2 t^2$

Where, K_e = Proportionality constant which depends on the volume and resistivity of the core, thickness of laminations

t = thickness of insulation

(ii) Copper Loss: It occurs in the primary and secondary winding resistance

$$P_{cu} = I^2 R_{eq}$$

$$\text{Efficiency } (\eta) : \eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}} = \frac{\text{Input} - \text{Losses}}{\text{Input}}$$

$$\eta = \frac{x \cdot KVA \cos \phi}{x \cdot kVA \cos \phi + x^2 P_{cu} + P_i}$$

Where,

P_i = Iron loss,

P_{cu} = Copper loss

x = loading factor;

P_{cu} = Full load cu-loss; P_i = Iron loss

If 20 KVA transformer is used at 15KW, 8pf lag.

Then

$x = ?$

$$\boxed{KW = KVA \cdot p.f.}$$

$$KVA = \frac{15 KW}{8} = \frac{150}{8} = 18.75$$

$$\therefore x = \frac{18.75}{20} = 0.9375$$

Condition for Maximum Efficiency:

Variable loss = Constant loss

$$\boxed{\text{Copper loss} = \text{Iron loss}}$$

$$P_i = P_{Cu} = I^2 r_{eq} \Rightarrow (I_{\eta \max}) = \sqrt{\frac{P_i}{r_{eq}}}$$

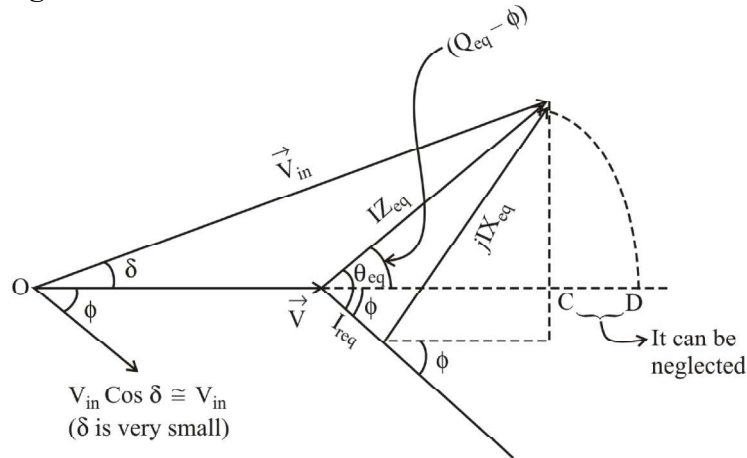
If we multiply both sides by V,

$$V \cdot I_{\eta \max} = V \cdot \sqrt{\frac{P_i}{r_{eq}}}$$

Multiplying and dividing RHS by I_j ,

$$S_{\eta \max} = V I_j \sqrt{\frac{P_i}{I_j^2 r_{eq}}}$$

$$S_{\eta \max} = S_j \sqrt{\frac{P_i}{P_{Cu}(j)}}$$

Voltage Regulation Derivation:

Approximate voltage regulation derivation

$$= \frac{OC - OA}{OA} = \left(\frac{I Z_{eq}}{V} \right) \cos(\theta_{eq} - \phi) = Z_{pu} \cos(\theta_{eq} - \phi)$$

Which can be written as, voltage regulation

$$\begin{aligned} VR^n &= Z_{pu} \cos(\theta_{eq} - \phi) = Z_{pu} [\cos \theta_{eq} \cdot \cos \phi + \sin \theta_{eq} \sin \phi] \\ &= (Z_{pu} \cos \theta_{eq}) \cdot \cos \phi + (Z_{pu} \sin \theta_{eq}) \sin \phi \end{aligned}$$

$$\boxed{V.R^n = R_{pu} \cos \phi + X_{pu} \sin \phi}$$

Note: Replace $\phi \rightarrow -\phi$ for leading pf.

(i) Maximum Regulation: $V_R^n = Z_{pu} \cos(\theta_{eq} - \phi)$

V_R^n is maximum when $\cos(\theta_{eq} - \phi) = 1 \Rightarrow \theta_{eq} = \phi$ (lagging)

$$\boxed{Pf = \cos \phi = \cos \theta_{eq} = \frac{R_{eq}}{Z_{eq}}}$$

(ii) Zero Regulation: $\theta_{eq} - \phi = 90^\circ$

$$\phi = \theta_{eq} - 90^\circ \quad \phi = -(90^\circ - \theta_{eq})$$

$$\phi = (90^\circ - \theta_{eq}) \text{ (Leading)}$$

$$Pf = \cos \phi = \cos(90^\circ - \theta_{eq}) = \sin \theta_{eq} = \frac{X_{eq}}{Z_{eq}}$$

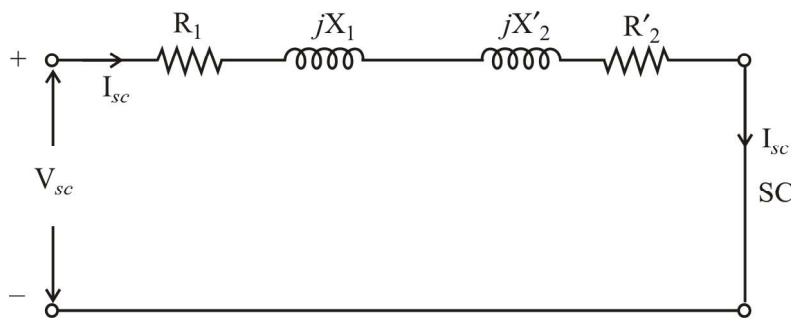
Note:

- Zero voltage regulation is possible only at leading power factor.
- Maximum voltage regulation is possible for lagging power factor.
- R_{pu} signifies the p.u full load cu-loss
- Z_{pu} signifies the maximum p.u voltage regulation

Point to Remember:

- (i) Short circuit test is carried out at rated current to know about the full copper loss.
- (ii) Rated frequency is not required in SC test.
- (iii) The test is done by placing the instruments on HV side while LV side is short circuited.

Note: The voltage required to circulate full load current under short circuit conditions is very small, so, I_o is also very small. Hence, the shunt branch is easily neglected for studies.

**Calculations:**

Reading of wattmeter = P_{sc}

Reading of voltmeter = V_{sc}

Reading of Ammeter = I_{sc}

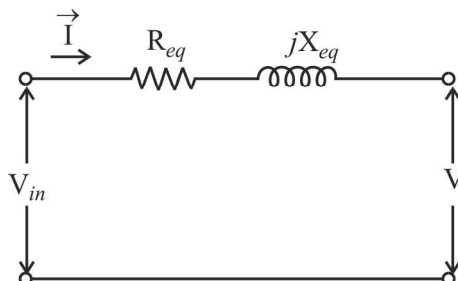
Hence, $Z_{eq} = (R_1 + R_2) + j(X_1 + X_2)$

$Z_{eq} = R_{eq} + jX_{eq}$ is given by $\vec{Z}_{eq} = |Z_{eq}| \angle \theta_{eq}$

$$Z_{eq} = \frac{V_{sc}}{I_{sc}} \angle \cos^{-1} \left(\frac{P_{sc}}{V_{sc} \cdot I_{sc}} \right) = R_{eq} + jX_{eq}$$

Voltage Regulation:

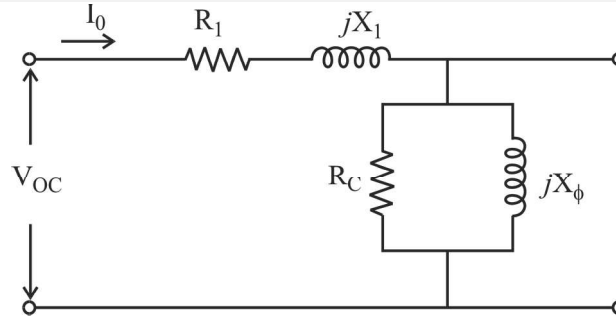
$$\text{Voltage regulation} = \frac{(\text{No load voltage} - \text{Full load voltage})}{\text{Full load voltage}} \text{ pu}$$



$$\text{Exact voltage regulation} = \frac{|V_{in}| - |V|}{|V|} \text{ pu}$$

Points to Remember:

- (i) Open circuit is carried out to calculate no load loss of transformer.
- (ii) OC test is carried out with high voltage side open circuited and measuring instruments on low voltage side.
- (iii) OC test is carried out at rated voltage and frequency.
- (iv) As the HV side is open circuited, I_o current flows in LV side which is only (at maximum) 5% of full load current, hence power measured by wattmeter can be considered to be core loss.
- (v) The circuit looks like



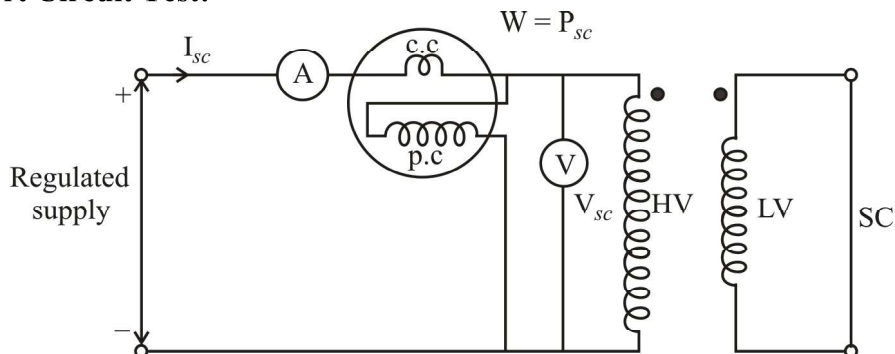
- (vi) R_1 and X_1 can be easily neglected without much error.
- (vii) The OC test is done to calculate the values of R_C and X_ϕ
- (viii) Let the wattmeter reads P_{OC} voltmeter reads V_{OC} ammeter reads I_{OC}

Then, (i) $R_C = \frac{(V_{OC})^2}{P_{OC}}$

(ii) No Load power factor angle, $\phi_o = \cos^{-1} \left(\frac{P_{OC}}{V_{OC} I_{OC}} \right)$

(iii) $X_\phi = \frac{R_C}{\tan \phi_o}$

Note: In OC test, ϕ_o is too small, hence low Pf watt-meter is used.

Short Circuit Test:

Here, R_2' represented the resistance of secondary winding referred to primary

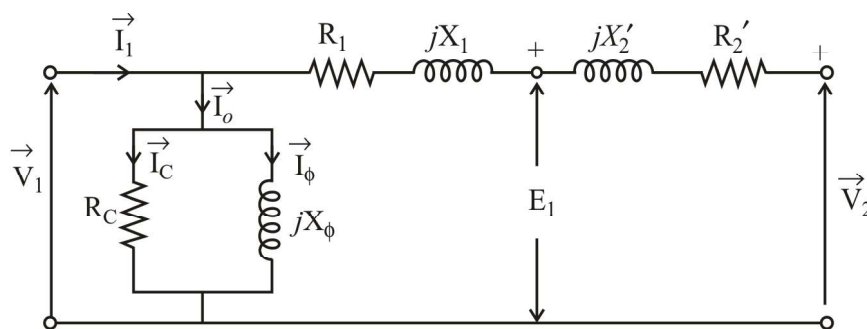
Similarly, X_2' and $\vec{V}_2'$ represents reactance and voltage of secondary referred to primary.

Let the no. of turns on primary be N_1 and secondary be N_2

$$\begin{aligned} \text{Hence, } R_2' &= R_2 \left(\frac{N_1}{N_2} \right)^2 & X_2' &= X_2 \left(\frac{N_1}{N_2} \right)^2 \\ V_2' &= V_2 \left(\frac{N_1}{N_2} \right) & I_2' &= I_2 \left(\frac{N_2}{N_1} \right) \end{aligned}$$

Note:

- No load current (I_o) = 2% to 3% of full load current. This property of $\vec{I}_o$ leads to further approximate circuits which are:
- The voltage drop due to I_o in $(R_1 + jX_1)$ is so small that it can be neglected.

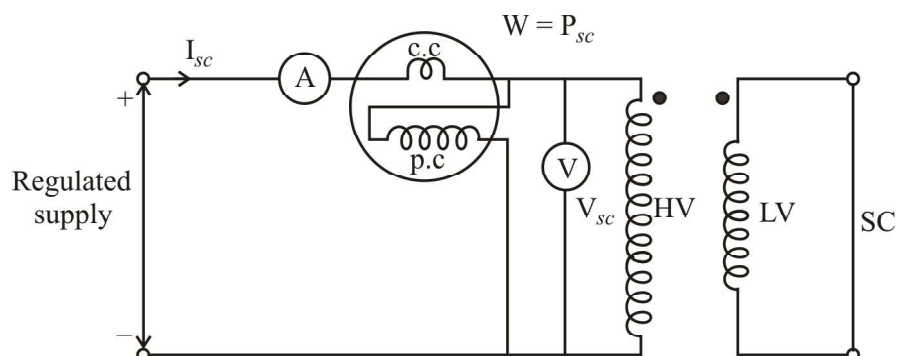


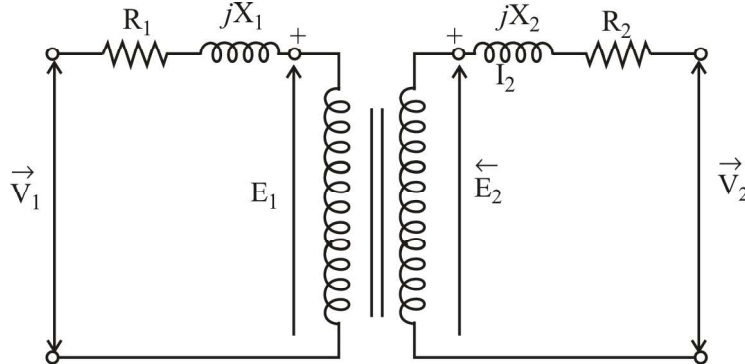
Cantilever 1st approximate circuit

Note: Due to low value of $\vec{I}_o$ the magnetizing branch is sometimes totally ignored.

OC and SC tests on Transformer:

Open Circuit Test:



Circuit Representation of a practical Transformer

The KVL equations Read:

$$\vec{E}_2 = \vec{V}_2 + \vec{I}_2 R_2 + j \vec{I}_2 X_2$$

$$\vec{V}_1 = \vec{E}_1 + \vec{I}_1 R_1 + j \vec{I}_1 X_1$$

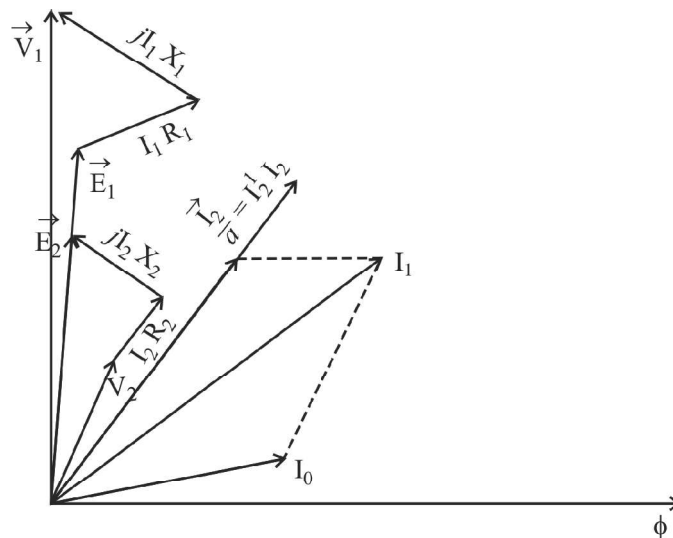


Figure: Transformer at Lagging Power Factor Load.

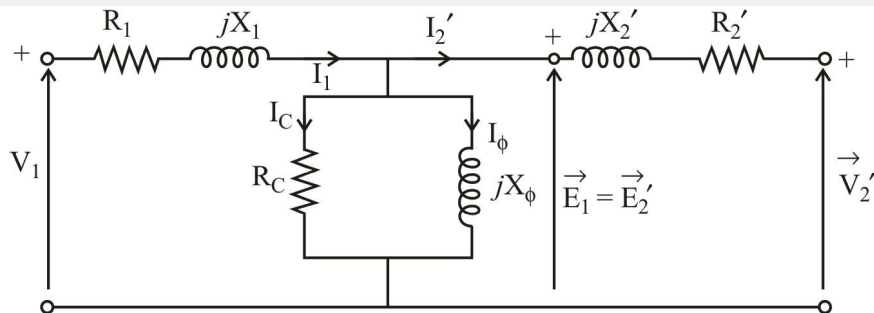
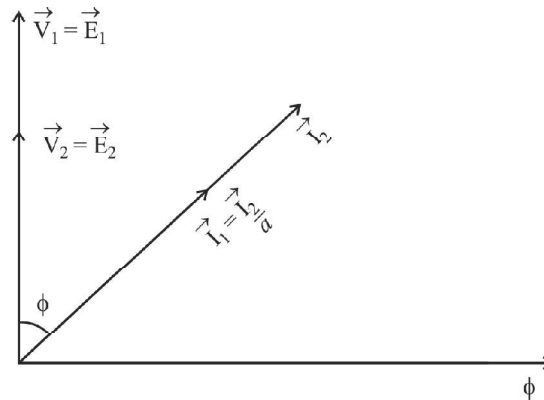
Equivalent circuit of Transformer:

Figure: Exact equivalent circuit referred to primary side.

Phasor diagram of a Ideal Transformer (At Lagging pf load):

Note: As per IEEE, the turns ratio (a) = $\frac{N_{HV}}{N_{LV}}$

Where, N_{HV} = Number of turns of HV winding
 N_{LV} = Number of turns of LV winding

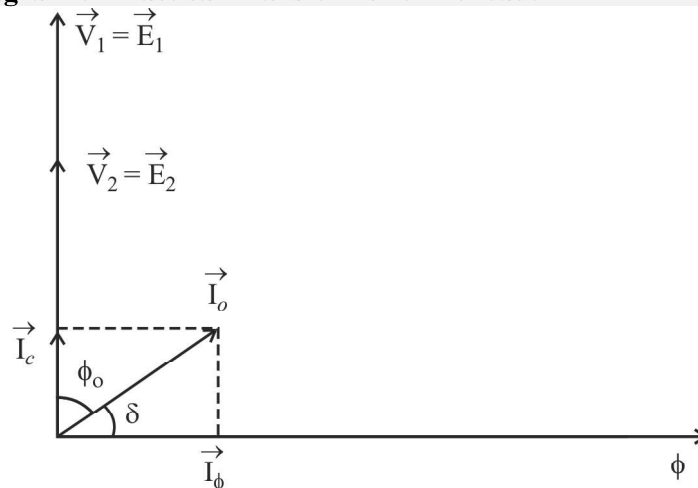
**Practical Transformer ($\mu \neq \infty$)**

In case of a practical transformer, I_o current is required to produce flux in the core and to compensate the core losses.

The mmf balance equation reads: $N_1 \vec{I}_1 - N_2 \vec{I}_2 = N_1 \vec{I}_o$

$$\Rightarrow \vec{I}_1 = \left(\frac{N_2}{N_1} \right) \vec{I}_2 + \vec{I}_o \quad \vec{I}_1 = \vec{I}_2' + \vec{I}_o$$

Where I_o is the exciting current/no load current.

Phasor Diagram of Practical Transformer on no load:

Here, $\vec{I}_c$ = core loss component of $\vec{I}_o$
 $\vec{I}_\phi$ = magnetizing component of $\vec{I}_o$

Note: Hysteresis angle (δ) shows us the lagging nature of ϕ w.r.t. I_o

$$(E_2)_{\text{rms}} = \sqrt{2} \pi f N_2 \phi_m \quad \dots(ii)$$

From equation (i) and (ii), $\frac{E_1}{N_1} = \frac{E_2}{N_2}$

i.e., voltage per turns are equal in primary and secondary windings.

From figure (i) we have, $E_1 = V_1$ and $E_2 = V_2$

Hence, $\frac{V_1}{V_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2} = a = \frac{I_2}{I_1}$

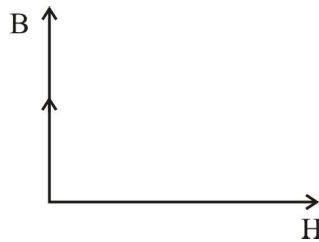
Key Points:

1. Emf induced in the windings are $\left(\frac{\pi}{2}\right)$ radians ahead by the core flux.
2. Any change in the secondary current of the transformer causes a change in primary current so that the flux remains constant.
3. Infinite permeability of the core signifies that no magnetizing current is required for establishment of flux.

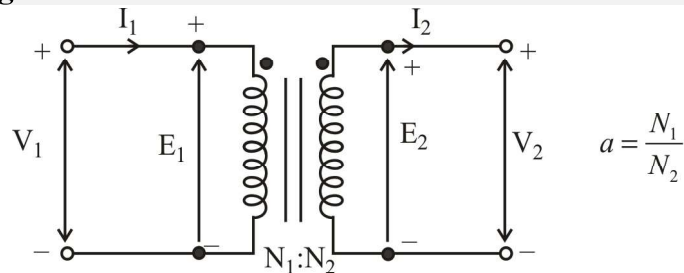
Ideal Transformer:

Properties

- (i) Resistance of the windings of transformer is zero.
- (ii) Magnetic leakage flux is zero.
- (iii) The permeability of the core of transformer is infinite.
- (iv) Efficiency is 100%.



Phasor diagram of an ideal transformer:



mmf balance equation: $N_1 \vec{I}_1 - N_2 \vec{I}_2 = 0$

$$\Rightarrow \vec{I}_1 = \left(\frac{N_2}{N_1} \right) \vec{I}_2 = \frac{\vec{I}_2}{a} = \vec{I}_2'$$

I_2' = Secondary current referred to primary.

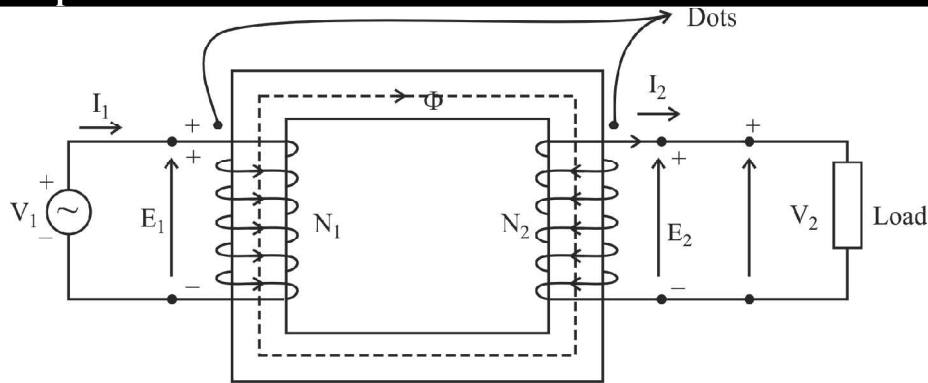
Principle of Transformer Action:

Figure (i)

- A transformer works on the principle of electromagnetic induction between two (or more) coupled circuits or coils. According to Faraday's law of electromagnetic induction, an emf is induced in a coil if it links to changing flux.
- The direction of induced emf is given by Lenz's law which states that emf will be induced in such a way that it opposes the cause which has produced it.
- In transformer electrical energy is transferred due to mutual induction between primary and secondary winding.

Emf equation of Transformer:

Referring to figure (i), E_1 = emf induced in the primary winding

E_2 = emf induced in the secondary winding

and N_1, N_2 are the winding turns.

Let the flux ϕ is represented as, $\phi = \phi_m \sin \omega t$

By Faraday's law of electromagnetic induction,

Emf induced in primary winding, $E_1 = N_1 \frac{d\phi}{dt}$

$$\Rightarrow E_1 = N_1 \frac{d}{dt} (\phi_m \sin \omega t) \quad E_1 = N_1 \omega \phi_m \cos \omega t$$

$$E_1 = (E_1)_m \sin(\omega t + 90^\circ)$$

rms value of emf induced in primary winding

$$(E_1)_{\text{rms}} = \frac{(E_1)_m}{\sqrt{2}}$$

$$(E_1)_{\text{rms}} = \sqrt{2} \pi f N_1 \phi_m \quad \dots(i)$$

Similarly, emf induced in secondary winding $E_2 = N_2 \frac{d\phi}{dt}$

$$E_2 = N_2 \omega \phi_m \sin(\omega t + 90^\circ)$$

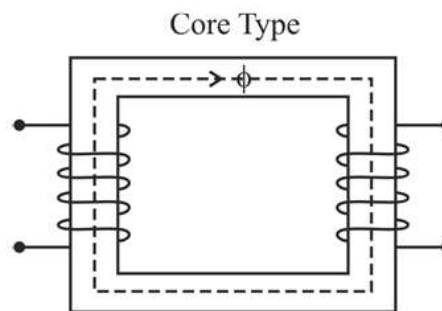
$$(E_2)_{\text{rms}} = \left(\frac{N_2 \omega \phi_m}{\sqrt{2}} \right)$$

1. TRANSFORMER

Definition: A transformer is a static device that transfers electrical energy from one electrical circuit to another electrical circuit through the medium of magnetic field and without the change of frequency.

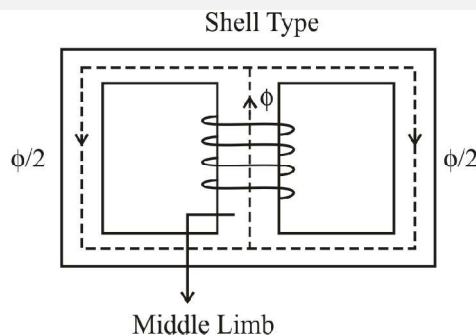
Construction of Transformer:

Core Type:



1. In core type construction, both the limbs are provided with windings and the core is surrounded by windings.
 2. For a given output and voltage rating, it requires less iron but more copper.
 3. Cross-section area of both limbs is equal.
 4. These are used for high power applications.
 5. These are suited for high voltage, small kVA rating.
- For example:** 15 kVA, 2200 / 1100 V
6. Cost of insulation is less.

Shell Type:



1. In shell type, only middle limb is provided with winding and the windings are surrounded by core.
 2. Amount of copper required is less.
 3. Cross-sectional area of the middle limb is twice to that of outer limbs.
 4. These are used for low power applications.
 5. These are suited for large kVA ratings but low voltage.
- For Example:** 150 kVA, 400/230 V

11

ELECTICAL MACHINES

CONTENTS

1.	TRANSFORMER.....	310-330
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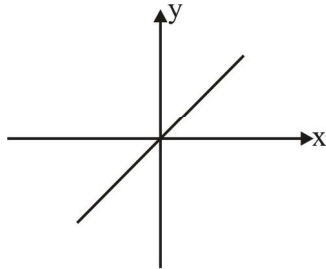
Note: Here vertical Maxima = Vertical minima

Measurement of Phase and Frequency:

Lissajous Pattern

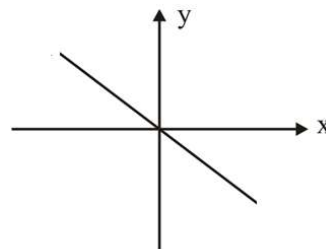
$X = A \sin \omega t$; $Y = A \sin (\omega t + \phi)$; where ϕ is phase difference.

(i)



Phase difference = 0°

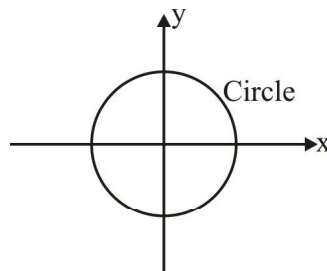
(ii)



Phase difference = 180°

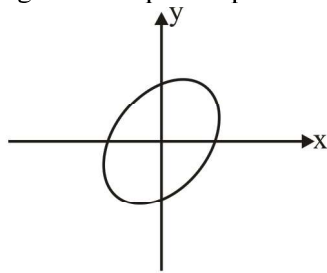
- In figure (i) and (ii), both signals are having same amplitude and frequency.

(iii)

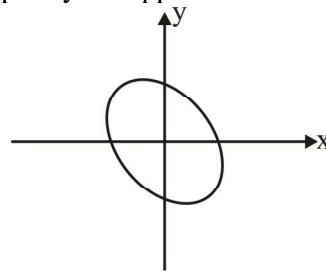


Phase difference = 90° or 270°

(iv) If voltages of unequal amplitude and same frequency are applied



$0^\circ < \phi < 90^\circ$ or $270^\circ < \phi < 360^\circ$



$90^\circ < \phi < 180^\circ$ or $180^\circ < \phi < 270^\circ$

Key points:

- General Rule,**
 $0 < \phi < 180^\circ \rightarrow$ CW direction.
 $180^\circ < \phi < 360^\circ \rightarrow$ ACW direction.
- Generalised form**
 $|\phi| < 90^\circ \rightarrow$ Ellipse in 1st & 3rd quadrant.
 $|\phi| > 90^\circ \rightarrow$ Ellipse in 2nd & 4th quadrant.

8. CRO (CATHODE RAY OSCILLOSCOPE)

- Input impedance of **CRO** is very high (1 MΩ). So loading effect is negligible.

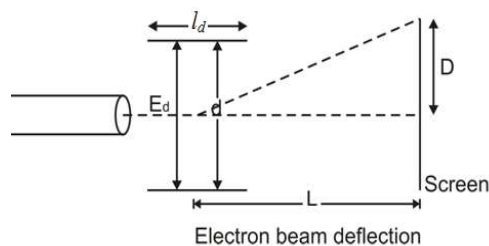
Modes of CRO:

Normal mode: In this mode horizontal deflecting plates are connected to output of sweep generator and vertical deflecting plates are connected to input channel.

Dual or XY mode: In this mode vertical deflecting plates are connected to Y input channel and horizontal deflecting plates are connected to X-input channel.

Deflection:

$$D = \frac{L l_d E_d}{2d E_a}$$



Where, L = Distance between screen and the center of deflecting plates; m

l_d = Length of deflecting plates; m

E_d = Potential between deflecting plates; V

d = Distance between deflecting plates; m

E_a = Voltage of pre-accelerating anode; V

Deflection Sensitivity:

$$S = \frac{D}{E_d} = \frac{L l_d}{2d E_a} \text{ m/V}$$

Rise time of vertical amplifier:

$$t_r = \frac{0.35}{BW}$$

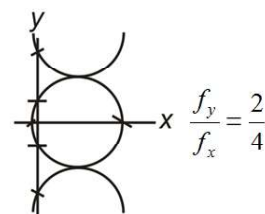
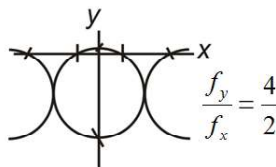
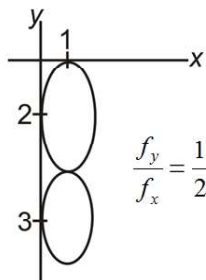
BW = Bandwidth

Measurement of frequency with CRO:

The CRO is operated in dual or XY mode and frequency is determined by using following formula:

$$\frac{f_y}{f_x} = \frac{\text{Number of intersections of the horizontal line with curve}}{\text{Number of intersections of the vertical line with curve}}$$

Example:



Output of thermocouple can be detected by using PMMC or using dc potentiometer.

Sensitivity: Thermistor > RTD > Thermocouple

Linearity: RTD > Thermocouple > Thermistor

Temperature range: Thermocouple > RTD > Thermistor

Temperature range: 0° C to 2500° C

Thermocouple	Type	Temp range
Copper - Constantan	T	– 200°C to 350°C
Platinum - Rhodium+Platinum	R	0 to 1000°C
Iridium - Rhodium+Iridium	–	1200°C to 2000°C
Iron - Constantan	J	– 200°C to 850°C
Chromel - Alumel	K	–200°C to 1100°C

MISCELLANEOUS

- **Venturi meter, Orifice and Rotameter** are used for measurement of **liquid flow**.
- **Pirani gauge** measures pressure within range of 10^{-5} to 10^{-3} mm of Hg.
- **Hall Effect** is weakest in metal and strongest in extrinsic semiconductor.
- **Radiation Pyrometer** measures temperature in range 1200° C to 3500° C.
- **Hot wire anemometer** measures air flow (Gas velocity).
- Generally, if input impedance is high, **loading effect** become minimum.

$$\text{Voltage Regulation} = \frac{|V_{RO}| - |V_{RL}|}{|V_{RL}|} \times 100$$

$|V_{RO}|$ = Magnitude of no load receiving end voltage.

$|V_{RL}|$ = Magnitude of full load receiving end voltage.

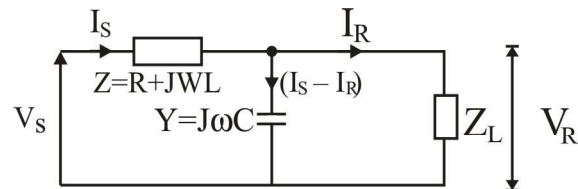
$$\%VR = \frac{|I_R| (R \cos \phi_R \pm X \sin \phi_R)}{V_R} \times 100$$

$\left[\begin{array}{l} + \text{ for lagging load} \\ - \text{ for leading load} \end{array} \right]$

- VRⁿ will be zero for leading p.f.
- VRⁿ will be maximum for lagging p.f.

(2) Medium transmission line ($100 < l < 250\text{Km}$)

(i) End condenser network

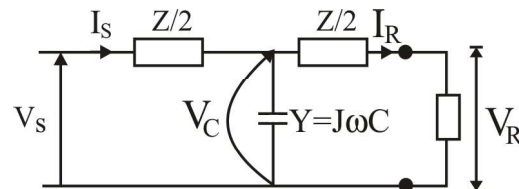


Z = total series impedance / phase

Y = total shunt admittance / phase to neutral

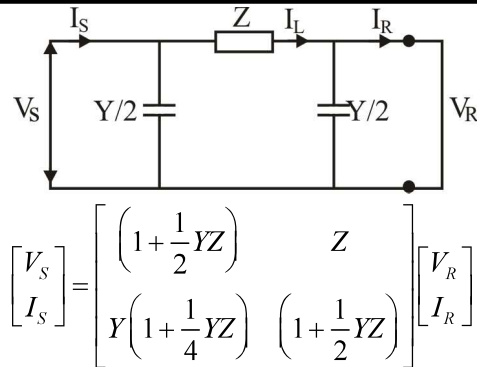
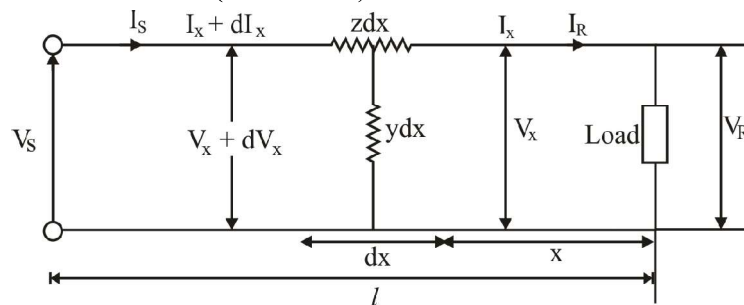
$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 + YZ & Z \\ Y & 1 \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

(ii) Nominal-T model



$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \left(1 + \frac{1}{2}YZ\right) & Z\left(1 + \frac{1}{4}YZ\right) \\ Y & \left(1 + \frac{1}{2}YZ\right) \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

(iii) Nominal- π model

(3) Long transmission line ($l > 250$ Km)Where Z = Series impedance / unit length / phase Y = Shunt admittance / unit length / phase

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & Z_c \sinh l \\ \frac{1}{Z_c} \sinh \gamma l & \cosh l \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

where $\gamma = \sqrt{YZ} =$ propagation constant

$$Z_c = \left(\frac{Z}{Y}\right)^{1/2} = \text{characteristic impedance}$$

 l = length of transmission line

$$\text{Voltage regulation} = \frac{\left| \frac{V_S}{A} \right| - |V_R|}{|V_R|} \times 100$$

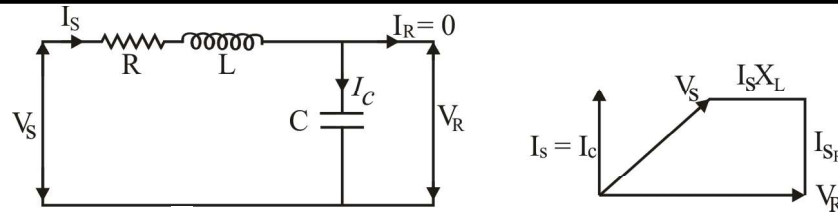
where A is one of ABCD parameter $A = 1 + YZ$ (for end condenser)

$$A = 1 + \frac{1}{2}YZ \quad (\text{for nominal-T model})$$

$$A = 1 + \frac{1}{2}YZ \quad (\text{for nominal-}\pi \text{ model})$$

$$A = \cos \sqrt{YZ}l = (\text{for long transmission})$$

Ferranti effect: Under no load or light load condition receiving end voltage become more than sending end voltage. This is due to capacitance between line and earth.



$$\Delta V_R = V_R - V_S \approx (\omega^2 LC)V_S$$

where ω = frequency in rad

L = Total inductance

C = Total capacitance

Note: Ferranti effect can be avoided by using shunt reactor.

The value of shunt reactor to maintain $V_S = V_R$

$$L_{sh} = \frac{V_R}{I_R} = \frac{B}{1 - A}$$

Where A, B are line model parameter.

Surge Impedance (Z_s):

Characteristic impedance of lossless line is referred to as surge impedance.

$$Z_s = \sqrt{\frac{L}{C}} \text{ (purely resistive)}$$

Overhead line $Z_s = 400 - 600\Omega$

Cable $Z_s = 40 - 60\Omega$

Note: Z_s is independent of the length of the transmission line.

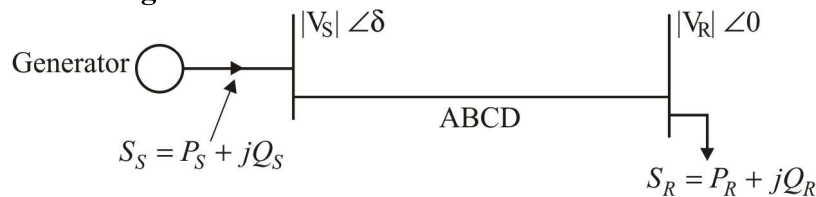
Surge Impedance loading (SIL): Power delivered by a line to purely resistive load equal to the surge impedance.

It is also capacity of a T-line.

$$SIL = \frac{|V_R|^2}{Z_s} \text{ watt}$$

$|V_R|$ = Line to line voltage

Power flow though a transmission line



A two bus system

If $A = |A| \angle \alpha$ & $B = |B| \angle \beta$

$$P_R = \frac{|V_R| |V_S|}{|B|} \cos(\beta - \delta) - \frac{|A| |V_R|^2}{|B|} \cos(\alpha - \beta)$$

$$Q_R = \frac{|V_S| |V_R|}{|B|} \sin(\beta - \delta) - \frac{|A| |V_R|^2}{|B|} \sin(\alpha - \beta)$$

Special Case: Short transmission line

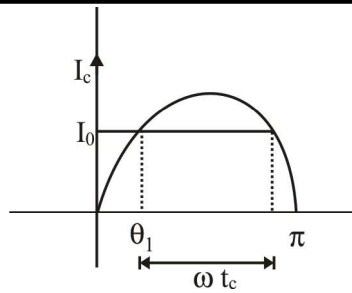
$$A = D = 1 \angle 0 \quad B = Z = |Z| \angle \theta$$

$$P_R = \frac{|V_S| |V_R|}{|Z|} \cos(\theta - \delta) - \frac{|V_R|^2}{|Z|} \cos \theta$$

$$Q_R = \frac{|V_S| |V_R|}{|Z|} \sin(\theta - \delta) - \frac{|V_R|^2}{|Z|} \sin \theta$$

If series resistance is neglected then $Z = |X| \angle 90^\circ$

$$\begin{aligned} P_R &= \frac{|V_S| |V_R|}{X} \sin \delta \\ Q_R &= \frac{|V_R|}{X} (|V_S| \cos \delta - |V_r|) \end{aligned} \Big|_{\text{Imp.}}$$



$$I_0 = I_{cp} \sin \theta_1$$

$$\sin \theta_1 = \frac{I_0}{I_{cp}}$$

$$I_{cp} > I_0$$

$$I_{cp} = x I_0$$

$$\therefore \sin \theta_1 = \frac{1}{x}$$

$$\sqrt{\frac{C}{L}} = \frac{x I_0}{V_s} \quad \sqrt{LC} = \frac{t_c}{2 \cos^{-1} \left(\frac{1}{x} \right)}$$

$$t_c > t_q$$

$$t_c = (S.F) t_a$$

S.F = safety factor

t_q = device turn off time

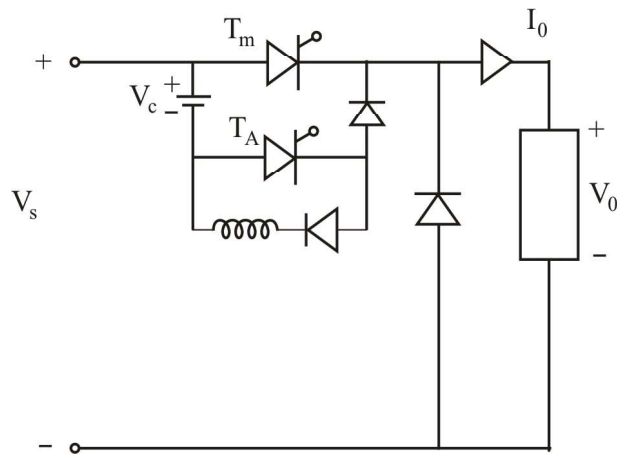
→ x minimum is equal to 1.5

→ Peak capacitor voltage

$$V_{cp} = V_s + I_0 \sqrt{\frac{L}{C}}$$

→ Peak current through main thyristor is ' I_0 '

❖ CLASS D/VOLTAGE COMMUTATED CHOPPER:



→ Circuit turn off time (t_c)

$$t_{cm} = \frac{CV_s}{I_0}$$

→ Peak current through main thyristor

$$(I_T)_{peak} = I_0 + V_s \sqrt{\frac{C}{L}}$$

→ Voltage commutated chopper can't be operated at no load.

$$I_{cp} \leq I_0$$

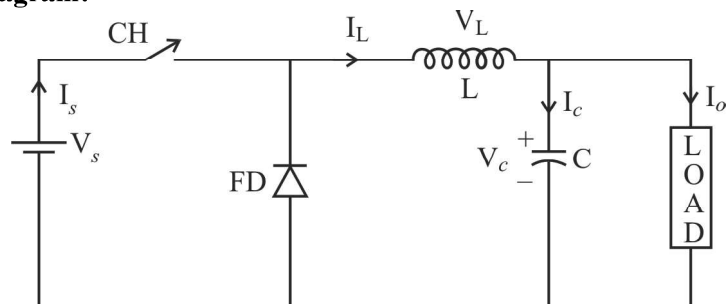
$$V_s \sqrt{\frac{C}{L}} \leq I_0$$

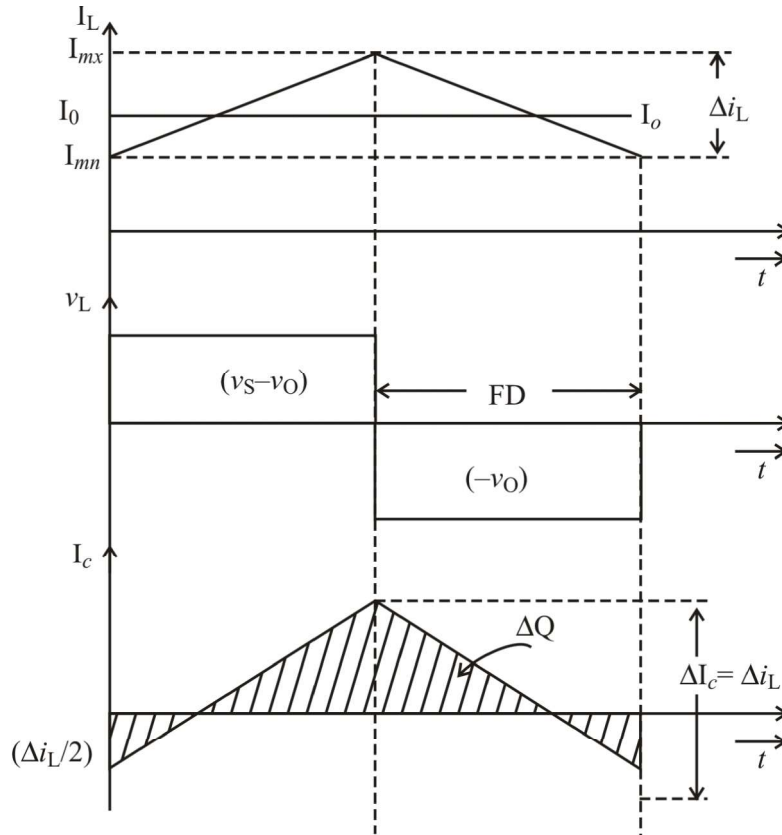
$$L \leq \left(\frac{V_s}{I_0} \right)^2 \cdot C$$

$$\rightarrow (T_{on})_{effective} = \alpha T + 2t_{cm}$$

1. Buck Regulator (Step down Chopper)

Circuit Diagram:



Related Waveforms:**Important Formulas : (Buck Converter)**

1. Output voltage, $V_o = \alpha V_s$ Where, $\alpha = \left(\frac{T_{ON}}{T} \right)$; referred to as duty cycle.
2. Inductor current ripple, $\Delta i_L = \frac{\alpha(1-\alpha)V_s}{fL}$
3. Output voltage ripple, $\Delta V_c = \frac{\alpha(1-\alpha)V_s}{8f^2 LC}$

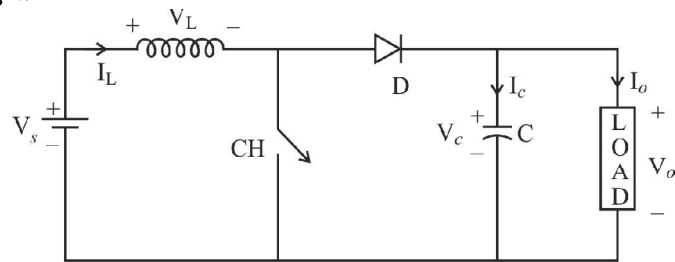
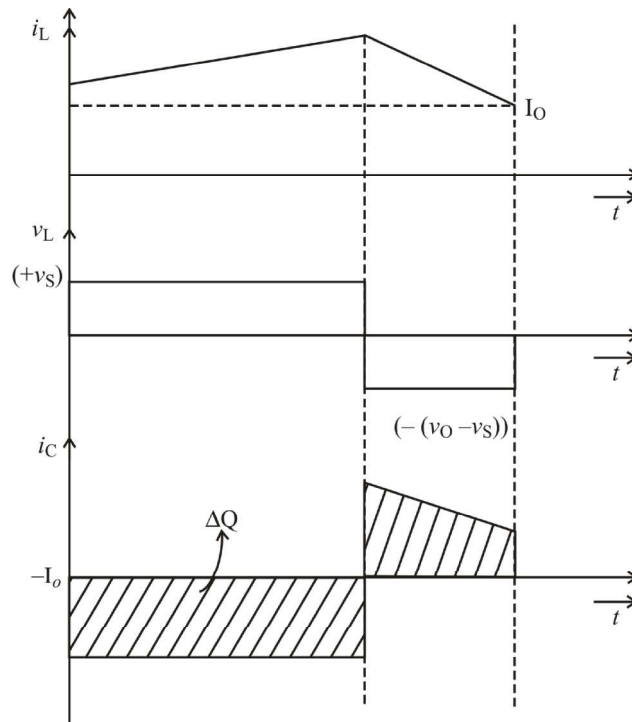
Note:

(a) Critical Inductance (L_c): Refers to value of inductance at which inductor current waveform is just discontinuous.

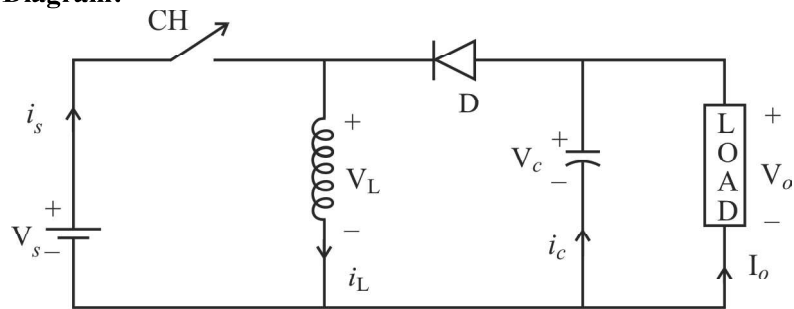
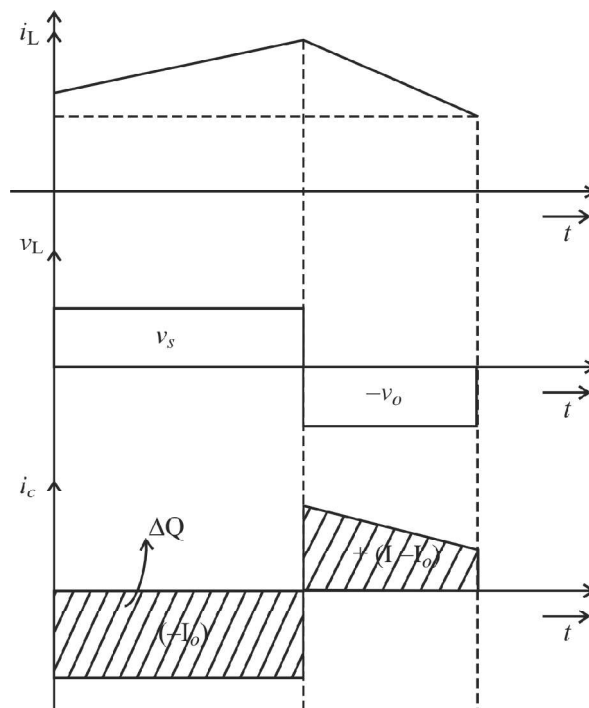
$$\text{Critical inductance, } L_c = \frac{(1-\alpha)R}{2f}$$

(b) Critical Capacitance (C_c): Refers to the value of capacitance at which voltage waveform is just discontinuous.

$$\text{Critical capacitance, } C_c = \frac{(1-\alpha)}{16f^2 L_c}$$

Boost Regulator (Step up Chopper)**Circuit Diagram****Related Waveforms****Important Formula: (Boost Converter)**

1. Output voltage,
$$V_o = \left(\frac{V_s}{1 - \alpha} \right)$$
2. Inductor current ripple,
$$\Delta i_L = \frac{\alpha V_s}{f L}$$
3. Output voltage ripple,
$$\Delta V_C = \frac{\alpha I_o}{f C}$$
4. Critical inductance,
$$L_C = \frac{\alpha(1 - \alpha) R}{2 f}$$
5. Critical capacitance,
$$C_C = \frac{\alpha}{2 f R}$$

Buck-Boost Regulator (Step down/up Chopper):**Circuit Diagram:****Waveforms:****Important Formula:**

1. Output voltage, $V_o = \left(\frac{\alpha}{1-\alpha} \right) V_s$
2. Inductor current ripple, $\Delta i_L = \frac{\alpha V_s}{f L}$
3. Output voltage ripple, $\Delta V_c = \frac{\alpha I_o}{f C}$
4. Critical inductance, $L_c = \frac{(1-\alpha) R}{2 f}$
5. Critical capacitance, $C_c = \frac{\alpha}{2 f R}$