Synchronous and Induction Machines

Synchronous and Induction Machines
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by

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KNOWLEDGE IS POWER

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Module 3 - Overview

1. Theory of Salient Pole Machine
   - Blondel's Two Reaction Theory
   - Phasor Diagram
   - Slip test (Determination of X_d & X_q)
2. Parallel Operation of Alternators
   - Requirements for Parallel Operation
   - Methods of Synchronisation
     - Dark Lamp Method
     - Bright Lamp Method
     - Synchroscope
   - Effects of Changing Excitation
   - Load Sharing between Two Alternators

Theory of Salient Pole Machine

- **Cylindrical rotor** → uniform air-gap → same reactance irrespective of the spatial position of rotor → Synchronous reactance,X_s(constant for all postions of field poles w.r.t. armature.)
- **Salient pole machine** → non-uniform air-gap → reactance varies with rotor position.
- Two axes of geometry
  1. **Direct Axis** - Field pole axis
  2. **Quadrature Axis** - axis through the centre of interpolar space

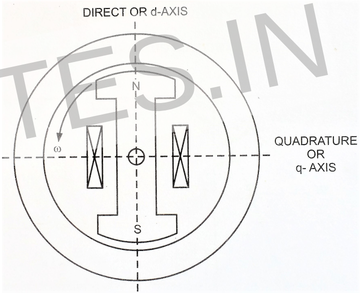

Figure 1 : Salient pole machine

Theory of Salient Pole Machine

- Reluctance of magnetic path → different along direct and quadrature axes.
- Reluctance of direct axis magnetic path is due to → yoke, teeth of stator, air-gap, pole, core of rotor etc.
- Reluctance of quadrature axis magnetic path is mainly due to → large air-gap in interpolar space
- Due to non-uniformity of reluctance of magnetic paths, armature mmf has two components
  1. Direct acting component
  2. Quadrature component

Theory of Salient Pole Machine

Armature reaction:

- Unity pf → cross magnetising or distorting effect → armature mmf acts at right angles to the axis of salient pole
- ZPF lagging → demagnetizing effect → armature mmf acts directly upon magnetic path though salient pole → directly opposing
- ZPF leading → magnetizing effect → armature mmf acts directly upon magnetic path though salient pole → directly aiding

In general, if $0 < \theta < 90$

- armature mmf has both direct acting and quadrature component.
- Direct component $\propto I_d \propto Sin\theta$
- Quadrature component $\propto I_q \propto Cos\theta$
  where $\theta =$ angle between armature current and excitation voltage(E_o)

Theory of Salient Pole Machine

- Two reactance concept and synchronous impedance concept
- **Synchronous impedance concept** → Effect of armature reaction is taken into account by means of equivalent armature reactance voltage.
- Due to the difference in reluctance of magnetic paths, **two reactance concept** replaces effect of armature reaction by two fictitious voltages.
- Reactance voltages are $I_d X_{ad}$ and $I_q X_{aq}$

Theory of Salient Pole Machine

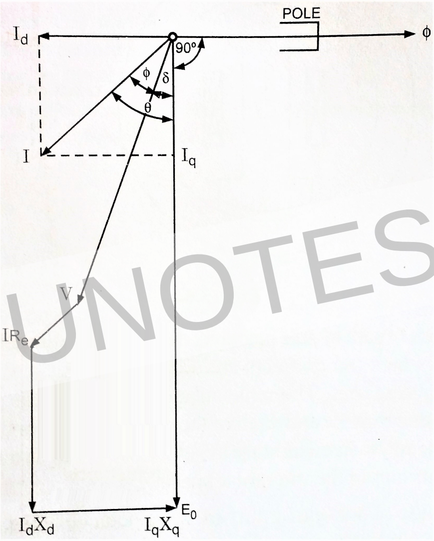

Figure 2 : Phasor diagram

Theory of Salient Pole Machine

Assuming same armature leakage flux along direct and quadrature axes,

- Direct axis synchronous reactance, $X_d = X_{ad} + X_L$
- Quadrature axis synchronous reactance, $X_q = X_{aq} + X_L$

Blondel's Two Reaction Theory

- Two reaction theory proposed by **Blondel**.
- Owing to the difference in magnetic paths,
  - Armature current can be resolved into two components, I_d and I_q
    - $I_d \perp E_o$
    - I_q along E_o
  - Armature reactance has two components
    - Direct axis armature reactance(X_{ad}) associated with I_d
    - Quadrature axis armature reactance(X_{aq}) associated with I_q

Theory of Salient Pole Machine

- Voltage equation for each phase based on two-reactance concept

$$\overrightarrow{V} = \overrightarrow{E_o} - \overrightarrow{I} R_e - \overrightarrow{I_d} X_d - \overrightarrow{I_q} X_q$$

- Salient pole machine, $X_q = 0.6$ to 0.7 times X_d
- Cylindrical rotor machine, $X_q = X_d$

Slip test (Determination of X_d & X_q)

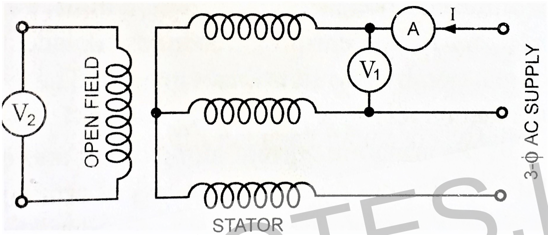

Figure 3 : Slip Test Circuit

- Apply a balanced reduced external voltage(V_1) to an unexcited machine at low speed little less than N_s(Slip $<$ 1%)
- Applied voltage(V_1), armature current(I) and induced voltage in the field(V_2) are measured by oscillographs.

Slip test (Determination of X_d & X_q)

- $V_1 \rightarrow I \rightarrow$ stator mmf
- stator mmf moves slowly relative to poles and induces emf in the field winding
- The physical poles and armature reaction mmf are alternatively in-phase and out, change occurring at slip frequency
- When axis of poles and axis of armature reaction mmf wave coincides, armature mmf acts through field magnetic circuit. $\Longrightarrow$ Applied voltage will be equal to the drop caused by direct axis component of armature reaction and leakage reactance.
- When armature reaction mmf is in quadrature with the field poles, applied voltage is equal to drop due to cross magnetising component of armature reaction and leakage reactance.

Slip test (Determination of X_d & X_q)

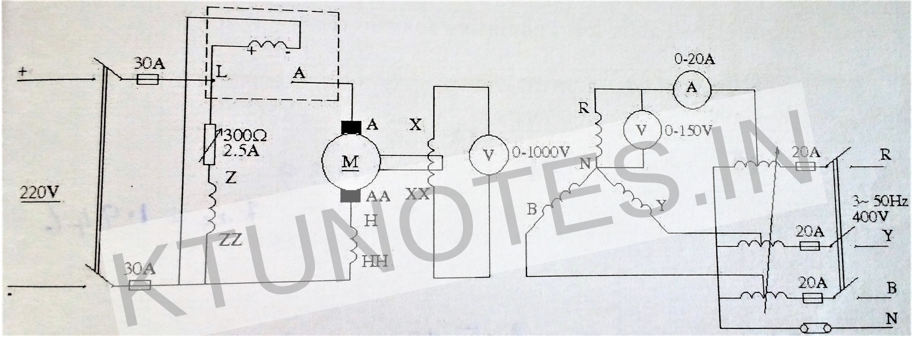

Figure 4 : Connection diagram - Slip Test

Slip test (Determination of X_d & X_q)

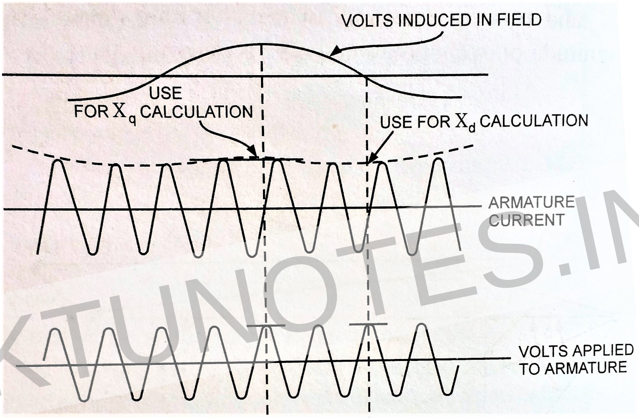

Figure 5 : Slip Test - waveforms

$$X_d = \frac{Maximum\ voltage}{Minimum\ current}, \quad X_q = \frac{Minimum\ voltage}{Maximum\ current}$$

Slip test (Determination of X_d & X_q)

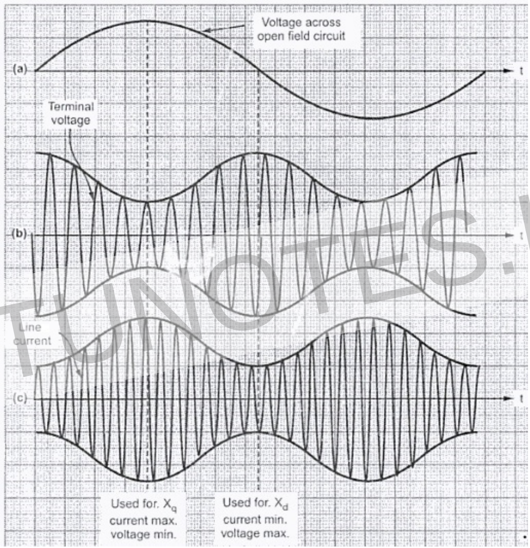

Figure 6 : Slip Test - waveforms

Power Developed by an Alternator

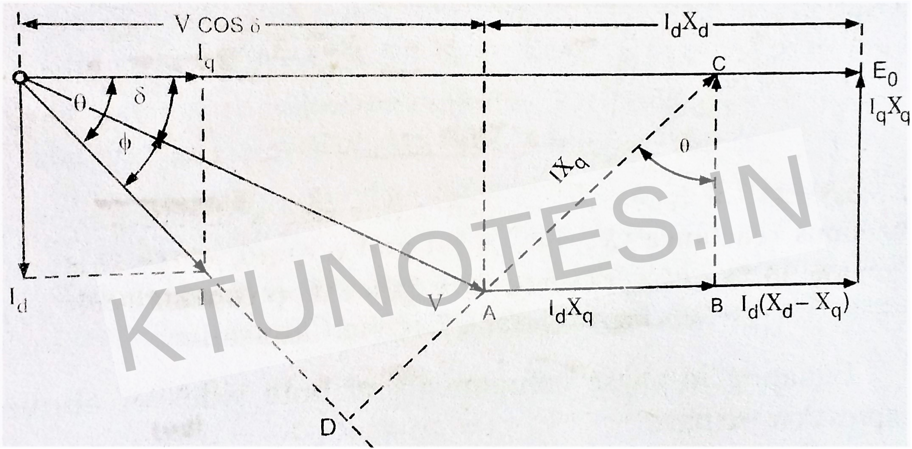

Figure 7 : Phasor diagram

Power Developed by an Alternator

- Power developed per phase(P_d) = Power output(P_{out}) per phase (provided R is negligible)

$$\begin{aligned} P_d &= P_{out} = VICos\Phi \\ I_qX_q &= VSin\delta \\ I_dX_d &= E_o - VCos\delta \\ ICos\Phi &= I_dSin\delta + I_qCos\delta \\ P_d &= VI_dSin\delta + VI_qCos\delta \\ &= \frac{E_oV}{X_d}Sin\delta + \frac{V^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]Sin2\delta \end{aligned}$$

- Total power developed

$$P = \frac{3E_oV}{X_d}Sin\delta + \frac{3V^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]Sin2\delta$$

Power Developed by an Alternator

- First term → power due to field excitation
- Second term → reluctance power(power due to saliency)
- For cylindrical machine, power due to saliency $= 0$ ($\because X_d = X_q$)
- For Alternator, $\delta = +$ve
- For synchronous motor, $\delta =$ -ve

M3 - Tutorial 1

Q1. A star connected salient pole alternator is driven at a speed near synchronous speed with field circuit open and stator is supplied from a three phase supply. Voltmeter connected across the line gave minimum and maximum readings of 2800V and 2820V. The line current fluctuated between 360A and 275A. Find X_d and X_q per phase. Neglect R_e.

Ans:

$$X_d = \frac{Maximum\ voltage}{Minimum\ current}, \quad X_q = \frac{Minimum\ voltage}{Maximum\ current}$$

$$X_{d-line} = \frac{2820}{275} = 10.25\Omega, \quad X_{d-phase} = \frac{10.25}{\sqrt{3}} = 5.92\Omega$$

$$X_{q-line} = \frac{2800}{360} = 7.78\Omega, \quad X_{q-phase} = \frac{7.78}{\sqrt{3}} = 4.5\Omega$$

M3 - Tutorial 1

Q2. A 2.2kV, 50Hz, three phase star connected alternator has $R_e = 0.5\Omega$ per phase. A field current of 30A produced full load current of 200A on short-circuit test and line to line emf of 1.1kV on open circuit test. Determine (a) power angle of alternator when it delivers full load at 0.8pf lag (b) Short circuit ratio(SCR) of the alternator.

Ans:

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{2200}{\sqrt{3}} = 1270.2V$$

$$Full\ load\ current, I = 200A$$

$$Synchronous\ impedance\ per\ phase, Z_s = \frac{E_{o-phase}}{I_{sc-phase}} = \frac{(1100/\sqrt{3})}{200} = 3.175\Omega$$

$$Synchronous\ reactance\ per\ phase, X_s = \sqrt{Z_s^2 - R_e^2}$$

$$= \sqrt{3.175^2 - 0.5^2} = 3.136\Omega$$

M3 - Tutorial 1

$$When\ delivering\ full\ load\ current,$$

$$Open\ circuit\ voltage\ per\ phase, E = \sqrt{(VCos\Phi + IR_e)^2 + (VSin\Phi + IX_s)^2}$$

$$= \sqrt{(1270.2 \times 0.8 + 200 \times 0.5)^2 + (1270.2 \times 0.6 + 200 \times 3.136)^2} = 1782V$$

$$Total\ power\ output = 3V_{ph}I_{ph}Cos\Phi = 3 \times \frac{2200}{\sqrt{3}} \times 200 \times 0.8 = 609681W$$

$$(Assuming\ non-salient\ pole\ alternator\ and\ neglecting\ losses)$$

$$Total\ power\ developed = \frac{3E_oV}{X_s}Sin\delta$$

$$\implies Sin\delta = \frac{PX_s}{E_oV} = \frac{609681 \times 3.136}{3 \times 1782 \times 1270.2} = 0.2816$$

$$\therefore Power\ angle, \delta = Sin^{-1}(0.2816) = 16.35^o$$

$$SCR = \frac{1}{X_s} = \frac{1}{3.316} = 0.319$$

Parallel Operation of Alternators

- Efficiency
- Reliability or Continuity of Service
- Maintenance and Repair
- Physical Size

Requirements for Parallel Operation

- Alternators must have same output voltage rating
- Speeds of the machines should be such as to generate same frequency
- Alternators should be of same type so as to generate voltages of same waveform
- Prime movers of the alternators should have same speed-load characteristics
- Alternators should have reactances in their armature

Conditions for Synchronising

* **Synchronising** - The process of connecting an alternator in parallel with another alternator or with the common bus bar.
* **Running machine** - Alternators which are in operation and sharing the load
* **Incoming machine** - Alternator which is to be connected in parallel to the running machines.
* For satisfactory operation,

- The terminal voltage of incoming machine must be exactly equal to that of running machines or common bus bar
- The speed of incoming machine must be such that its frequency $\left(f = \frac{PN}{120}\right)$ equals to bus bar frequency
- Phase of incoming machine voltage must be the same as that of the bus bar voltage relative to the load.
- For three phase alternator, the phase sequence of incoming machine must be same as that of bus bar.

Methods of Synchronisation

- Synchronising of single phase alternators
    1. Dark Lamp Method
    2. Bright Lamp Method
- Synchronising of three phase alternators
    1. Three Dark Lamp Method
    2. Two Bright and One Dark Lamp Method
    3. Synchroscope

Dark Lamp Method

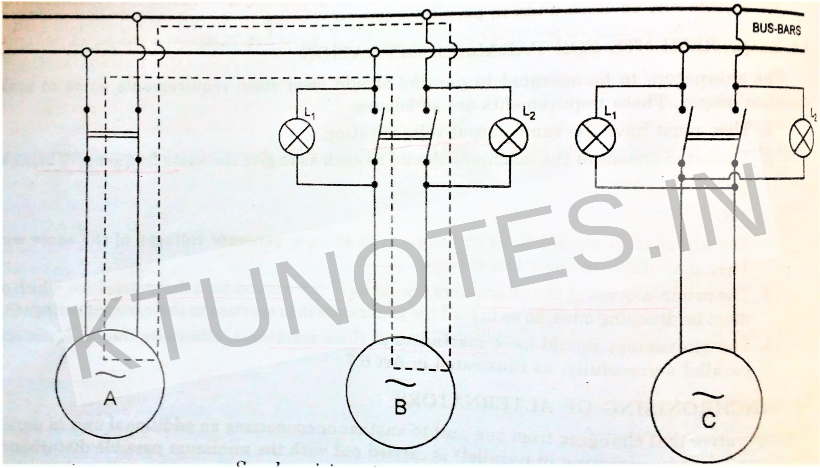

Figure 8 : Synchronising of single phase alternators

Dark Lamp Method

- Equality of terminal voltages can be determined by connecting voltmeters to the incoming and running alternators.
- Equality of frequency and phasing can be determined with the help of synchronising lamps.

Let alternator B is to be paralleled with alternator A,

- Prime mover of Alternator B is started and brought up close to the rated speed.
- Alternator B is excited and its voltage is raised by increasing the excitation.
- If frequencies of alternators A & B are exactly same and their terminal voltages w.r.t local series circuit → no resultant voltage will act across lamps L_1 and L_2 → Lamps will remain dark.
- If frequencies of A & B are not equal → flickering of lamps.
- Frequency of flickering = Difference of frequencies of two alternators. $\implies$ greater the difference in frequencies, greater will be the frequency of flickering.

Dark Lamp Method

- Synchronising is done at the middle of dark period.

”At the time of synchronising of alternators, the speed of the incoming machine is adjusted until the lamps go in and out very slowly, the terminal voltage of the incoming alternator is made equal to bus bar voltage by adjusting the excitation of the incoming alternator and then switch of incoming alternator is closed in the middle of the dark period.”

- But it is not so easy to judge the middle of dark period.

Bright Lamp Method

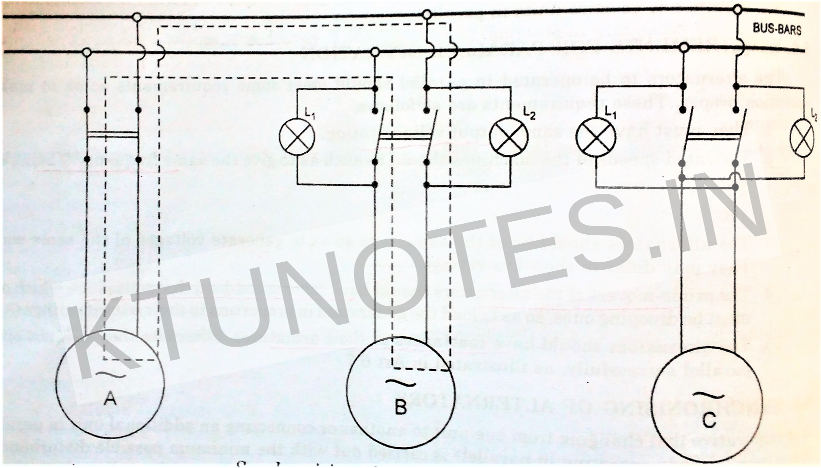

Figure 9 : Synchronising of single phase alternators

Bright Lamp Method

- Easy to judge the middle of bright period
- In **Bright lamp method**, lamps are cross-connected.
- Maximum voltage across lamps will occur when alternator C is in phase opposition with alternator A.
- Magnitude of maximum voltage that can exist across a lamp is double that of the voltage of one machine.
- After doing the adjustments, the synchronising switch is closed at the middle of bright period.

Synchronization of 3-Phase Alternators

"Phasing out the alternator" → The process of checking the phase sequence and getting it correct

1. Three Dark Lamp Method
2. Two Bright and One Dark Lamp Method
3. Using Synchroscope

Three Dark Lamp Method

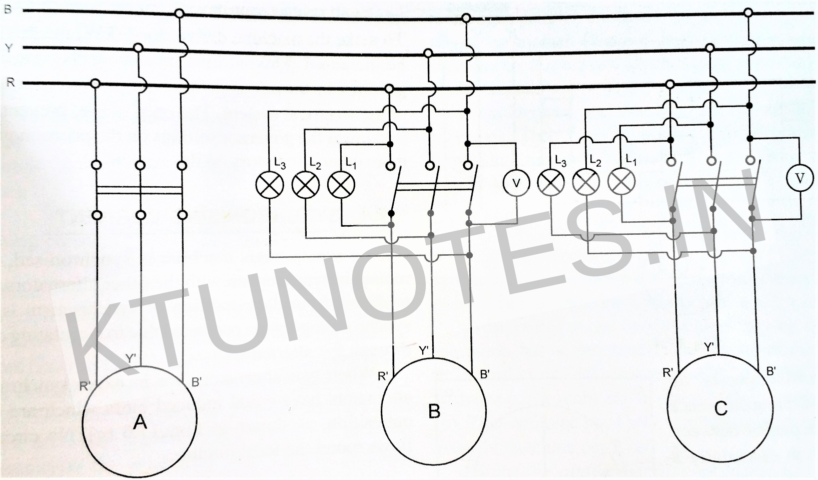

Figure 10 : Synchronising of 3-Phase Alternators

Three Dark Lamp Method

- Prime mover of alternator B is started and brought up close to the rated speed.
- Then alternator B is excited and its voltage is raised by increasing the excitation.
- If the incoming alternator B is properly connected, all the three lamps should become bright and dark together.
- If they bright and dim in sequence $\Longrightarrow$ incoming alternator B is not properly connected with the bus-bars and the phase sequence of incoming alternator B must be reversed relative to the system.(Interchange any two leads on either the alternator side or the line side of the switch)
- The speed of incoming machine is further adjusted until the lamps flicker at a very rate and voltage is made equal to the bus bar voltage by adjusting the excitation.
- The synchronising switch is closed at the instant all the three lamps are dark.

Two Bright and One Dark Lamp Method

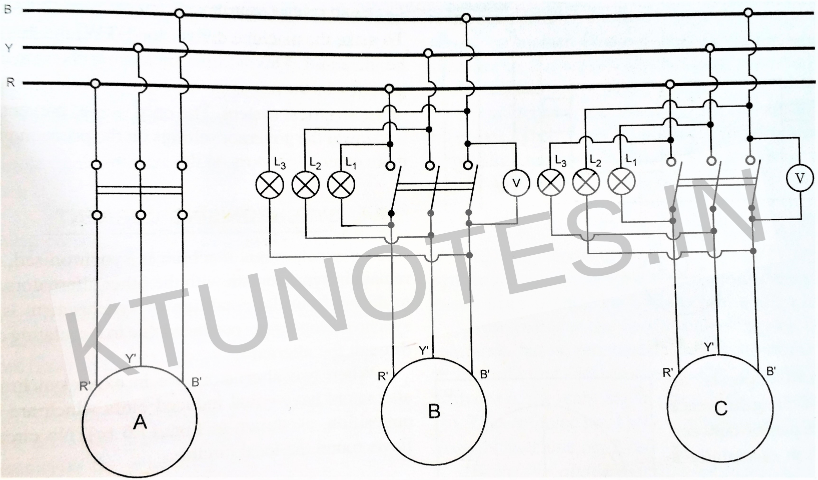

Figure 11 : Synchronising of 3-Phase Alternators

Two Bright and One Dark Lamp Method

- When incoming alternator is in synchronism with running machine, lamps L_1 and L_3 are bright and L_2 is dark.
- Since near the point of synchronism, the brightness of one lamp increases and of another decreases. The instant at which the incoming machine is in synchronism with the bus-bars can be accurately determined and the paralleling switch will be closed at this instant.
- If the incoming machine is too fast $\rightarrow$ voltage across L_3 decreases, L_1 increases and L_2 decreases.
- If the incoming machine is too slow $\rightarrow$ voltage across L_3 increases, L_1 decreases and L_2 increases.
- Hence when the three lamps are placed in a ring, a light wave travelling in counter-clockwise direction indicates that the incoming machine is slow and light wave travelling in clockwise direction indicates that the incoming machine is fast.
- Synchronising switch is closed when changes in light are very slow and at the instant the lamp L_2 is dark.

Using Three Limbed Transformer and Lamp

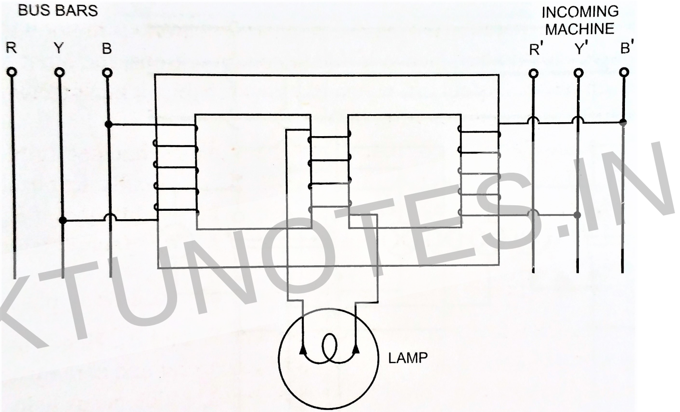

Figure 12 : Three Limbed Transformer and Lamp

Using Three Limbed Transformer and Lamp

- The two primary windings on the outer limbs are connected to bus-bar and incoming alternator.
- secondary winding on the central limb is connected to the lamp
- The correct moment for closing paralleling switch is the middle of dark period if primaries are each connected the same way round, and the middle of the bright period if the connections of one winding are reversed.

Synchroscope

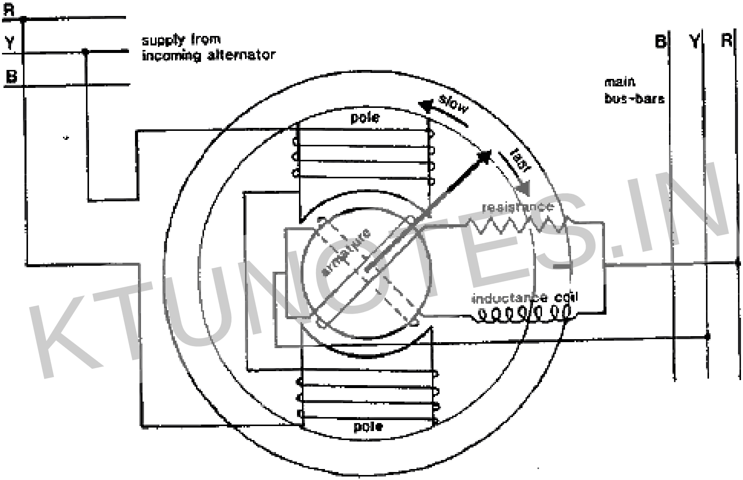

Figure 13 : Synchroscope

Synchroscope

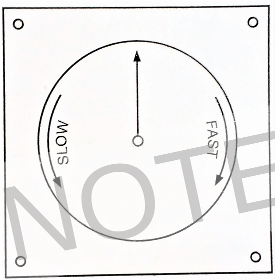

Figure 14 : Synchroscope-Dial

Synchroscope

- Synchroscope → Instrument indicating the difference of phase and frequency between two voltages.
- Its a split-phase motor
- Torque is developed if the frequencies of the two voltages differ.
- Voltages from corresponding phases of incoming and running alternators are applie to synchroscope.
- When frequencies are equal, no torque is exerted on the pointer and the pointer stops at the middle of the dial.
- When pointerstops at vertical position, the frequencies are equal, the voltages are in phase and the paralleling switch can be closed.

Synchronising Current

- Once synchronisation is done, the machine will try to remain in synchronism with other alternators.
- Any tendency to depart from synchronism is opposed by synchronising torque produced due to circulating current flowing through the alternators.

Synchronising Current

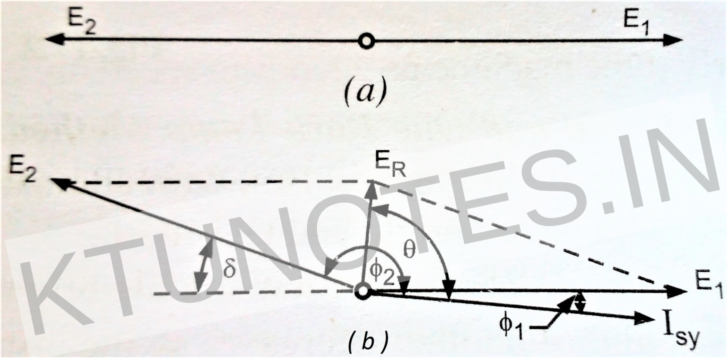

Figure 15 : Voltage Phasors

Synchronising Current

- When two alternators are in synchronism → have equal emfs in exact phase opposition → no circulating current (Fig. (a))
- When induced emfs are equal in magnitude but not in exact phase opposition → resultant emf around the local circuit ≠ zero → causes flow of current → **Synchronising current(I_{sy})**

→ Let alternator-2 tends to retard,

- E_2 falls back by a phase angle δ electrical degrees
- $|E_1| = |E_2| = E$
  but phase difference = 180 - δ

Synchronising Current

→ Resultant emf(E_R)

$$
\begin{aligned}
E_R &= 2ECos\left(\frac{180-\delta}{2}\right) \\
&= 2ECos\left(90-\frac{\delta}{2}\right) \\
&= 2ESin\frac{\delta}{2} \\
&= 2E \times \frac{\delta}{2} \\
&= E\delta
\end{aligned}
$$

→ Synchronising current(I_{sy})

$$I_{sy} = \frac{E_R}{Z_{cs}} = \frac{E\delta}{Z_{cs}}$$

where Z_{cs}=combined synchronous impedance/phase of the 2 alternators

Synchronising Current

- I_{sy} lags behind E_R by an angle θ
- If $R_{ce} <<< X_{cs}$,

$$I_{sy} = \frac{E_R}{X_{cs}}$$

$\implies$ I_{sy} lags E_R by 90^o $\implies$ almost in phase with E_1

- $I_s y$ → generating current w.r.t machine 1 and motoring current w.r.t machine 2
- I_{sy} sets up synchronising torque(T_{sy}) which tends to accelerate machine no.2 and decelerate machine no.1
- Any departure from synchronism results in development of synchronising torque which tends to keep the machines in synchronism

Synchronising Power

- Power supplied by Machine no.1 $= E_1 I_{sy} Cos\Phi_1$
- Power received by Machine no.2 $= E_2 I_{sy} Cos\left(180 - \Phi_2\right)$
- Power supplied by Machine no.1 = Power received by Machine no.2 + copper losses
- Power supplied by Machine no.1 is called as **Synchronising power**(P_{sy})

$$\begin{aligned} P_{sy} &= E_1 I_{sy} Cos\Phi_1 \\ &= E_1 I_{sy} \\ &= E \times \frac{E\delta}{X_{cs}} \\ &= \frac{\delta E^2}{X_{cs}} \end{aligned}$$

- Total synchronising power $= 3P_{sy} = \frac{3\delta E^2}{X_{cs}}$

Synchronising Torque

$$3P_{sy} = T_{sy} \times \frac{2\pi N_s}{60}$$

Therefore Synchronising torque,

$$T_{sy} = \frac{3P_{sy} \times 60}{2\pi N_s}$$

where N_s is the synchronous speed in rpm

Effects of Changing Excitation

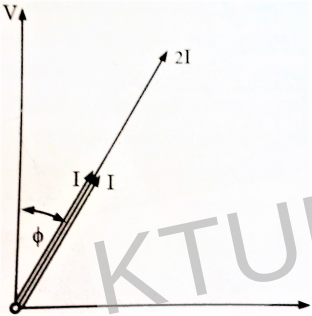

Figure 16 : (a)

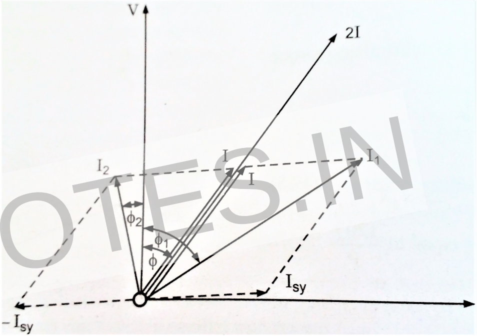

Figure 17 : (b)

Effects of Changing Excitation

- Let two identical alternators are sharing equally a load of pf $Cos\Phi$
  - If both the machines have same excitation, $\implies |I_1| = |I_2| = \mathrm{I}$ Also I_1 & I_2 are in phase(Fig. (a))
- If the excitation of alternator 1 is increased,(Fig. (b))
  - $|E_1| > |E_2| \implies I_{sy}$ flows
  - I_{sy} is almost in quadrature with V
  - Output current of alternator 1, $\overrightarrow{I_1} = \overrightarrow{I} + \overrightarrow{I_{sy}}$
  - Output current of alternator 2, $\overrightarrow{I_2} = \overrightarrow{I} - \overrightarrow{I_{sy}}$
  - For alternator 1, $\Phi_1 > \Phi \implies Cos\Phi_1 < Cos\Phi \implies$ pf decreases.
  - For alternator 2, $\Phi_2 < \Phi \implies Cos\Phi_2 > Cos\Phi \implies$ pf improves.
  - **By changing the excitation, the power factors of alternators are changed.**

Effects of Changing Excitation

- I_{sy} doesn't change wattful(active) components but changes the wattless(reactive) components.
- Due to change in excitation, the output current of alternators changes with no appreciable change in it's active power(kW).

- During parallel operation of two alternators, increase in excitation of alternator 1 causes,

- increase in terminal voltage of alternator 1
- increase in reactive power supplied by alternator 1
- decrease in reactive power supplied by alternator 2

Load Sharing between Two Alternators

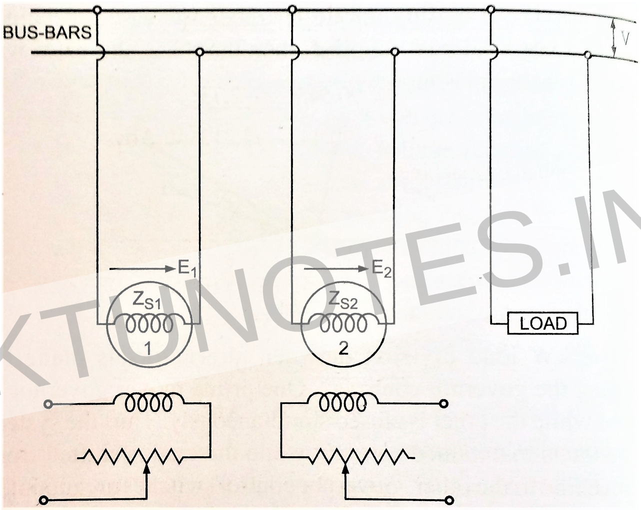

Figure 18 : Load sharing

Load Sharing between Two Alternators

- Consider two Alternators(A_1 and A_2) with identical speed-load characteristics running in parallel.

Let,

- V = Common terminal voltage in volts
- Z = Load impedance
- E_1 = Generated emf of A_1
- E_2 = Generated emf of A_2
- Z_{s1} = Synchronous impedance per phase of A_1
- Z_{s2} = Synchronous impedance per phase of A_2

Load Sharing between Two Alternators

- Terminal voltage of A_1

$$V = E_1 - I_1 Z_{s1}$$

$$\implies I_1 = \frac{E_1 - V}{Z_{s1}}$$

- Terminal voltage of A_2

$$V = E_2 - I_2 Z_{s2}$$

$$\implies I_2 = \frac{E_2 - V}{Z_{s2}}$$

Therefore,

$$I_1 + I_2 = \frac{E_1 - V}{Z_{s1}} + \frac{E_2 - V}{Z_{s2}}$$

Load Sharing between Two Alternators

- Voltage across load

$$V = IZ = (I_1 + I_2)Z$$

$$\implies \frac{V}{Z} = \frac{E_1 - V}{Z_{s1}} + \frac{E_2 - V}{Z_{s2}}$$

$$\implies V\left(\frac{1}{Z_{s1}} + \frac{1}{Z_{s2}} + \frac{1}{Z}\right) = \frac{E_1}{Z_{s1}} + \frac{E_2}{Z_{s2}}$$

$$\implies V = \frac{\left(\frac{E_1}{Z_{s1}} + \frac{E_2}{Z_{s2}}\right)}{\left(\frac{1}{Z_{s1}} + \frac{1}{Z_{s2}} + \frac{1}{Z}\right)}$$

M3 - Tutorial 2

Q1. Two single phase alternators with emfs $E_1 = 100V$ & $E_2 = 110V$ and synchronous impedances $Z_{s1} = (0.2 + j1)\,\Omega$ & $Z_{s2} = (0.2 + j1)\,\Omega$ operate in parallel on a load impedance of $Z = (3 + j4)\,\Omega$. Determine the terminal voltage and power output of each machine.

Ans:

V = 96 - j3.87V

I_1 = 5.457∠-34.64A

I_2 = 14.24∠-63.24A

P_1 = 443W

P_2 = 664.8W

M3 - Tutorial 2

Q2. Two alternators running in parallel supply a lighting load of 2000kW and a motor load of 4000kW at pf 0.8 lagging. One machine is loaded to 2400kW at pf 0.95 lagging. What is the output and power factor of the second machine.

Ans:
$P_2 = 3600kW$
$Q_2 = 2211.16kVAR$
$pf_2 = 0.8521$ lagging

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Thank You