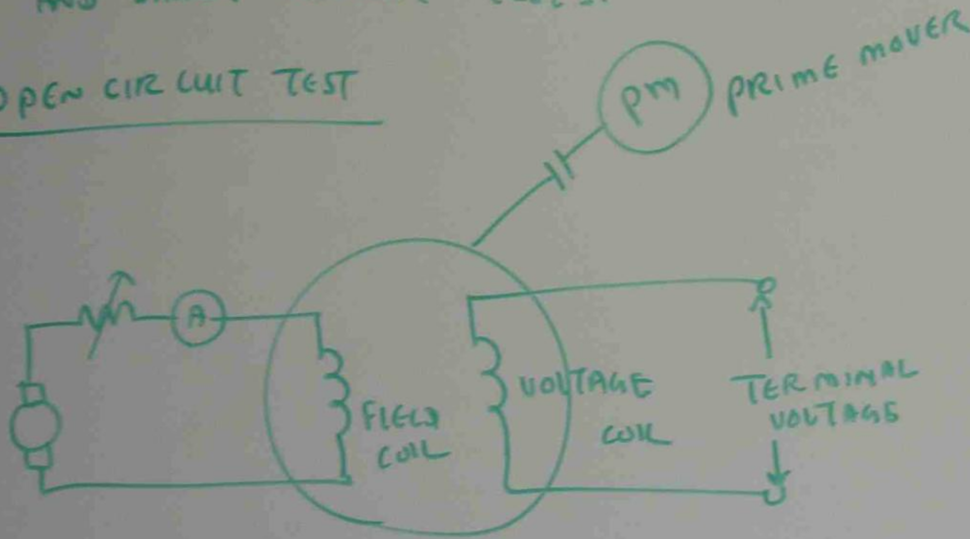
# DETERMINATION OF SYNCHRONOUS IMPEDANCE

THE OHMIC VALUE OF THE SYNCHRONOUS IMPEDANCE AT A GIVEN VALUE OF EXCITATION MAY BE DETERMINED BY OPEN CIRCUIT AND SHORT CIRCUIT TESTS.

## OPEN CIRCUIT TEST



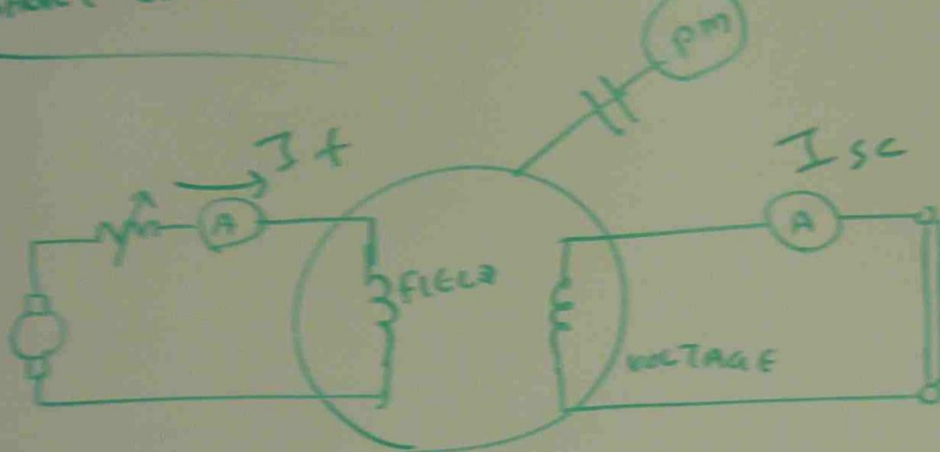


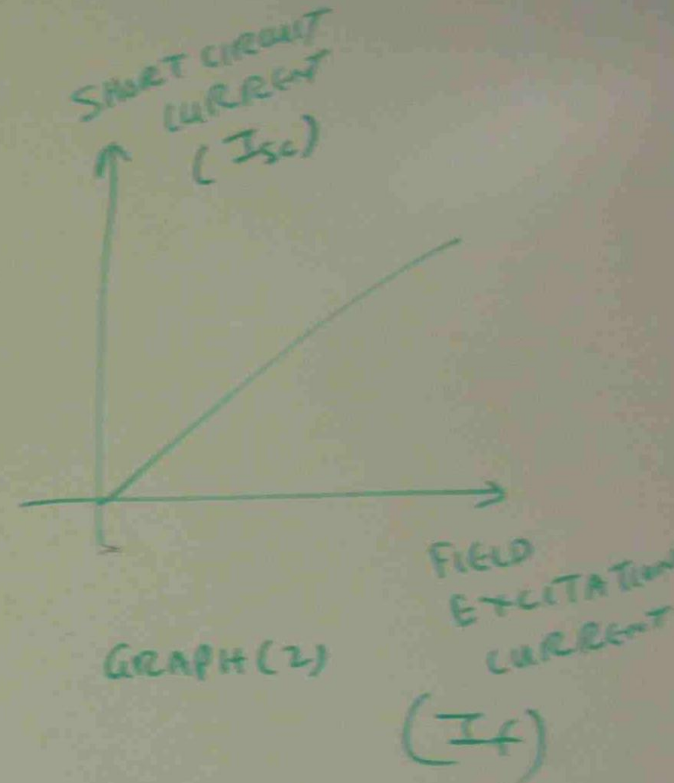
GRAPH(1)

GENERATOR TERMINALS ARE OPEN. DRIVE THE MACHINE, INCREASE THE FIELD EXCITATION CURRENT AND MEASURE TERMINAL VOLTAGE.

STOP THE MACHINE

SHORT CIRCUIT TEST



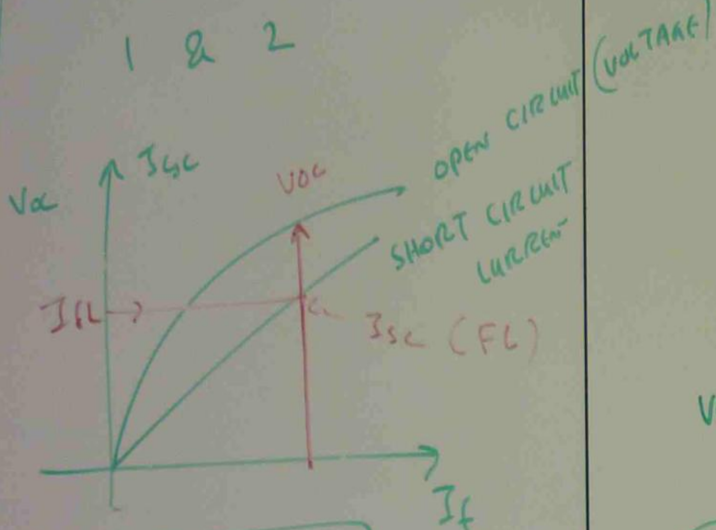




GRAPH (2)

GENERATOR TERMINALS ARE SHORT CIRCUITED. SET EXCITER TO ZERO. DRIVE THE MACHINE. INCREASE EXCITATION AND MEASURE SHORT CIRCUIT CURRENT UNTIL IT REACHES THE FULL LOAD CURRENT MAGNITUDE.

THEN COMBINE GRAPH

1 & 2




$$\boxed{Z_s = \frac{V_{oc}}{I_{sc}(FL)}}$$

$E_f$ = GENERATED VOLTAGE

V = TERMINAL VOLTAGE

$$E_f = V + I Z_s$$

$$Z_s = \frac{E_f - V}{I}$$

$$\text{VOLTAGE REGULATION} = \frac{E_f - V}{V} \times 100$$

Pb 49 MODIFIED

A 3ϕ STAR CONNECTED ALTERNATOR HAS A RESISTANCE OF 0.5Ω AND SYNCHRONOUS REACTANCE OF 5Ω PER PHASE. IT IS EXCITED TO GIVE 6600V LINE ON OPEN CIRCUIT.

CALCULATE (a) SYNCHRONOUS IMPEDANCE

(b) SHORT CIRCUIT CURRENT.

WHEN OPEN CIRCUIT VOLTAGE IS 500V AT TERMINAL

IF FIELD EX

SUCH SHORT CI

10 AMP, C

CURRENT AT

CURRENT VA

$Z_s = 0$

$V_{oc}(ph) =$

Z

$E_F$ = GENERATED VOLTAGE

$V$ = TERMINAL VOLTAGE

$$E_F = V + I Z_S$$

$$Z_S = \frac{E_F - V}{I}$$

$$\text{VOLTAGE REGULATION} = \frac{E_F - V}{V} \times 100$$

49 MODIFIED

A $3\phi$ STAR CONNECTED ALTERNATOR HAS A RESISTANCE OF $0.5\,\Omega$ AND SYNCHRONOUS REACTANCE OF $5\,\Omega$ PER PHASE. IT IS EXCITED TO GIVE 6600V LINE ON OPEN CIRCUIT.

CALCULATE (a) SYNCHRONOUS IMPEDANCE

(b) SHORT CIRCUIT CURRENT.

WHEN OPEN CIRCUIT VOLTAGE IS 500V AT TERMINAL

IF FIELD EXCITATION CURRENT AT SUCH SHORT CIRCUIT ~~CURRENT~~ CURRENT MAGNITUDE IS 10 AMP, CALCULATE THE FIELD EXCITATION CURRENT AT $\frac{1}{10}$ OF SHORT CIRCUIT CURRENT VALUE.

$$Z_S = 0.5 + j5 = \sqrt{0.5^2 + 5^2}$$

$$= 5.02\,\Omega$$

$$V_{oc}(ph) = \frac{500}{\sqrt{3}} = 288.6\ V$$

$$Z_S = \frac{V_{oc}}{I_{sc}}$$

$$I_{sc} = \frac{V_{oc}}{Z_S} = \frac{288.6}{5.02} = 57.5\ \text{Amp}$$

WH

IF FIELD EXCITATION CURRENT AT SUCH SHORT CIRCUIT CURRENT MAGNITUDE IS 10 AMP, CALCULATE THE FIELD EXCITATION CURRENT AT $\frac{1}{10}$ OF SHORT CIRCUIT CURRENT VALUE.

$$Z_s = 0.5 + j5 = \sqrt{0.5^2 + 5^2}$$

$$= 5.02\ \Omega$$

$$V_{oc(ph)} = \frac{500}{\sqrt{3}} = 288.6\ V$$

$$Z_s = \frac{V_{oc}}{I_{sc}}$$

$$I_{sc} = \frac{V_{oc}}{Z_s} = \frac{288.6}{5.02} = 57.5\ Amp$$

AT TERMINAL

WHEN $I_{sc} = 57.5A \longrightarrow I_f = 10A$

$\frac{1}{10} \times 57.5 \longrightarrow ?$

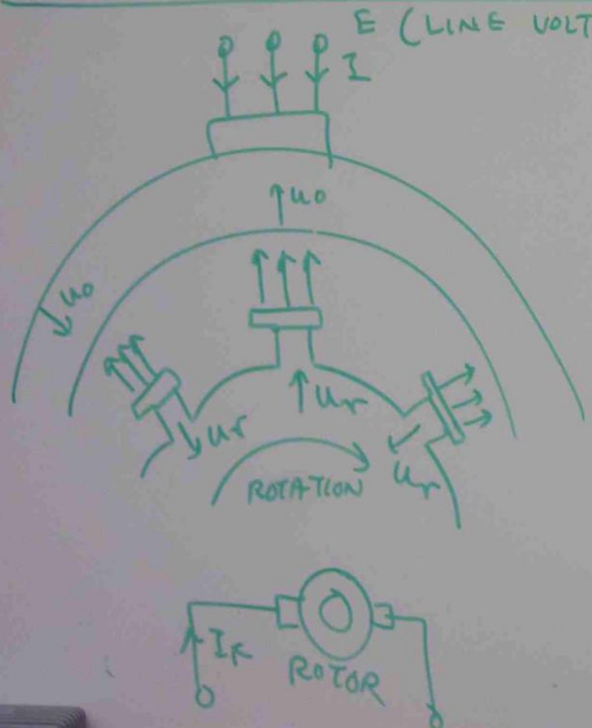
$$= \frac{10}{10} = 1\ Amp$$

WHEN $I_{sc} = 57.5\,A \longrightarrow I_f = 10A$

$\underline{\quad\quad\quad} \frac{1}{10} \times 57.5 \underline{\quad\quad\quad} ?$

$= \frac{10}{10} = 1\,Amp$

## EXCITATION AND REACTIVE POWER




* LINE VOLTAGE "E" IS FIXED

* LINE CURRENT "I" PRODUCES MAGNETO MOTIVE FORCE $U_0$

* ROTOR PRODUCES MAGNETO MOTIVE FORCE $U_r$

* TOTAL FLUX $\phi$ IS PRODUCED BY COMBINED ACTION OF $U_0$ & $U_r$

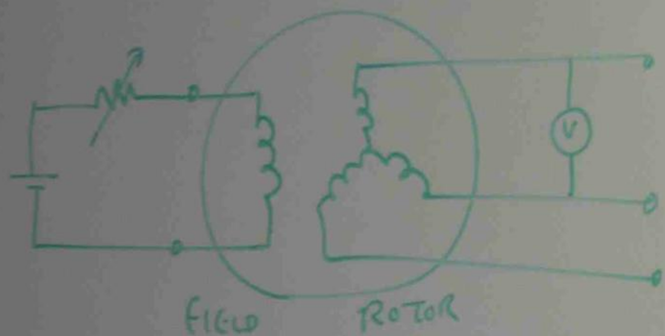
* IF ROTOR EXCITATION IS INSUFFICIENT (UNDER EXCITATION), THE STATOR ABSORBS THE REACTIVE POWER FROM SUPPLY TO PRODUCE ENOUGH FLUX. IT IS UNDER EXCITATION AND P.F IS LAGGING.

* IF ROTOR EXCITATION IS MORE THAN REQUIRED VALUE (OVER EXCITATION), THE STATOR DELIVERS THE REACTIVE POWER INTO SUPPLY WHILE IT IS PRODUCING FLUX. DELIVERING REACTIVE POWER TO SUPPLY IS LEADING P.F.

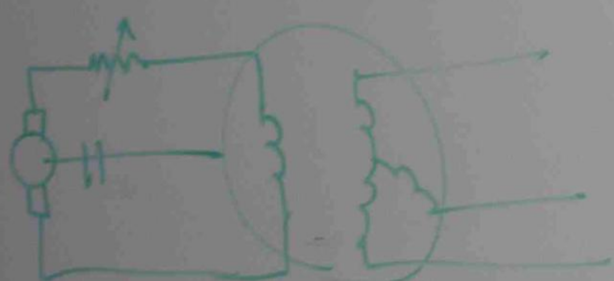
mp

# EXCITATION METHODS

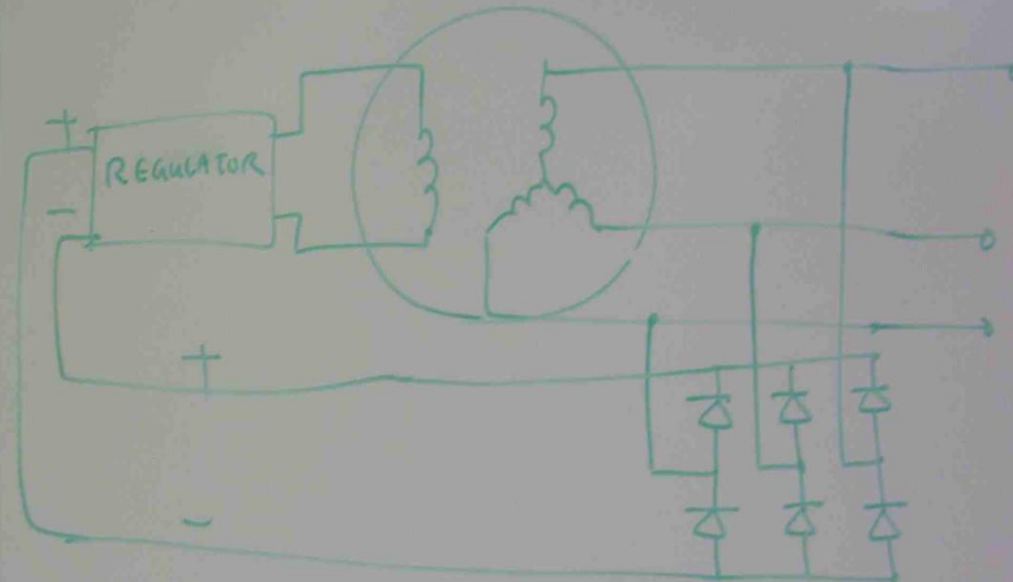
## BATTERY EXCITATION



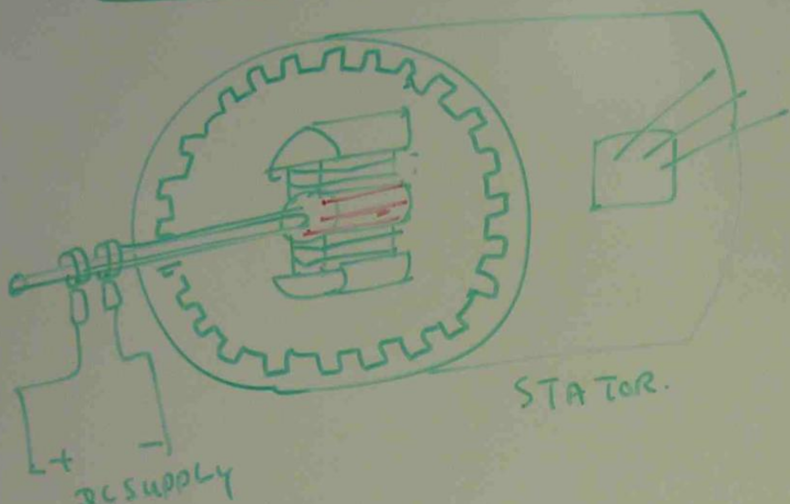

## SMALL DC GENERATOR



## SELF EXCITATION BY 3$\phi$ RECTIFIER BRIDGE



## CONSTRUCTION OF SYNCHRONOUS MOTOR



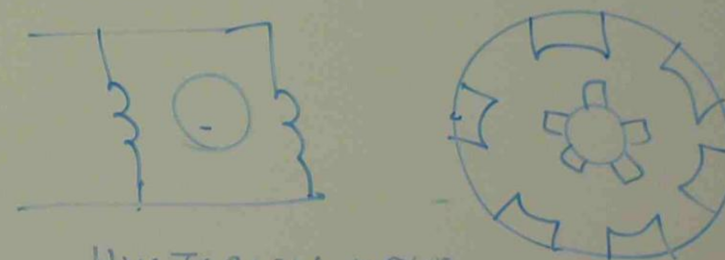

- THE STATOR HAS 3φ WINDING
- ROTOR IS SALIENT POLE
- AT THE STARTING, THERE IS ONLY REVOLVING MAGNETIC FIELD IN STATOR
- ROTOR NEEDS TO BE TURNED BY SMALL MOTOR

(OR) INSERT THE COPPER BARS INTO ROTOR SURFACE AND STARTS WITH INDUCTION MOTOR ACTION.

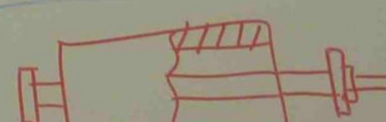
## CYLINDERICAL ROTOR MACHINE

1φ SYNCHRONOUS MOTOR

RELUCTANCE MOTOR



HYSTERESIS MOTOR



### APPLICATION

ELECTRIC CLOCK
SERVO SYSTEM
WIRELESS RADIO
RECORDING DEVICE

Pb (51) A 500 HP 720 RPM SYNCHRONOUS MOTOR CONNECTED TO A 3980V 3φ LINE GENERATES AN EXCITATION VOLTAGE $E_F$ OF 1790V (LINE TO NEUTRAL) WHEN THE DC EXCITATION CURRENT IS 25 Amp. THE SYNCHRONOUS REACTANCE IS 22 Ω THE TORQUE ANGLE BETWEEN $E_F$ AND V IS 30°.

CALCULATE (a) THE VALUE OF IMPEDANCE DROP $E_Z$

(b) AC LINE CURRENT.

(c) POWER FACTOR OF THE MOTOR.

(d) THE APPROPRIATE HORSE POWER DEVELOPED BY THE MOTOR

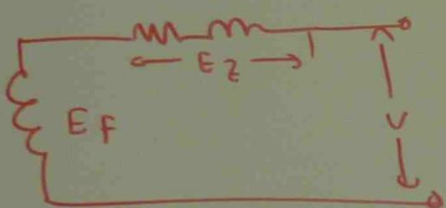
(d) THE APPROPRIATE HORSE POWER DEVELOPED AT THE SHAFT.

(e) THE APPROPRIATE TORQUE DEVELOPED

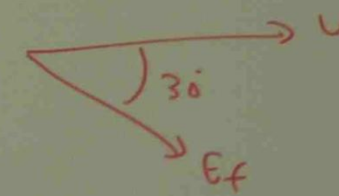
$$V_{(ph)} = \frac{3980}{\sqrt{3}} = 2300V$$

$$V = E_f + E_z$$

(a)




$$2300\angle 0 = 1790\angle -30 + E_Z$$




$$E_Z = 2300\angle 0 - 1790\angle -30$$

$$= 2300 - \left(1790\cos(-30) + j\,1790\sin(-30)\right)$$

$$= 2300 - 1550 + j895$$

$$= 750 + j895$$

$$E_Z = \sqrt{750^2 + 895^2} \angle \tan^{-1}\frac{895}{750}$$

$$E_Z = 1168 \angle 50 \quad V$$

(b) $$I = \frac{E_Z}{Z_S} = \frac{1168\angle 50}{0 + j22} = \frac{1168\angle 50}{22\angle 90} = 53\angle -40 \ A$$

(c) $pf = \cos(-40)$ LAGGING

$= 0.766$ LAGGING

(d) OUTPUT POWER $= 3 V I \cos\theta$

$= 3 \times 2300 \times 53 \cos 40$

$=$ 280142 WATT

$$Hp = \frac{WATT}{746} = \frac{280142}{746} = 375\ HP$$

(e) $$T = \frac{9.55\ P}{n} = \frac{9.55 \times 280142}{720} = 3715\ N\text{-}m$$

## POWER AND TORQUE

$$P = \frac{E_f \times V}{X_s} \sin\delta$$

$P$ = MECHANICAL POWER OF MOTOR | PHASE (WATT)

$E_f$ = LINE TO NEUTRAL VOLTAGE INDUCED BY EXCITATION CURRENT (VOLT)

$V$ = LINE TO NEUTRAL VOLTAGE OF THE SOURCE (V)

$X_s$ = SYNCHRONOUS REACTANCE | PHASE ($\Omega$)

$\delta$ = ANGLE BETWEEN $E_f$ & $V$ (ELECTRICAL DEGREE)

$$T = \frac{9.55\,P}{n_s}$$

$T$ = TORQUE (N-m)

$P$ = MECHANICAL POWER | PHASE (W)

$n_s$ = SYNCHRONOUS SPEED (RPM)

$$n_s = \frac{120 f}{p}$$

Pb 52 MODIFIED

A 15 kW, 1200 RPM 460V 3$\phi$ SYNCHRONOUS MOTOR HAS A SYNCHRONOUS REACTANCE OF 0.8$\Omega$/PHASE IF THE EXCITATION VOLTAGE $E_f$ IS FIXED AT 300V/ph

DETERMINE THE FOLLOWINGS

(a) MECHANICAL POWER/PHASE

(b) TORQUE

(c) $\delta$

$$V_{(ph)} = \frac{460}{\sqrt{3}} = 266V$$

(a) $$P = \frac{E_f\ V}{X_s} \sin\delta$$

$$= \frac{300 \times 266}{0.8} \sin\delta$$

$$= 99750 \sin\delta$$

(b) $$T = \frac{9.55 \times P}{n_s}$$

$$= \frac{9.55 \times 15 \times 10^3}{1200}$$

$$= 119.375 \text{ N-m}$$

NEGLECT POWER LOSSES

$$P_{mech} = 15 \text{ kW}$$

$$99750 \sin\delta = 15000$$

$$\sin\delta = \frac{15000}{99750}$$

$$\sin\delta = 0.15$$

$$\delta = \sin^{-1} 0.15 = 8.62^\circ$$

## RELATION BETWEEN MECHANICAL AND ELECTRICAL ANGLE

$$\delta = \frac{P\alpha}{2}$$

$\delta$ = ELECTRICAL ANGLE (TORQUE ANGLE)

$\alpha$ = MECHANICAL ANGLE

$P$ = NO. OF POLES

Pb 53 A 3$\phi$ 6000 kW, 4 kV, 180 RPM 60 Hz MOTOR HAS A SYNCHRONOUS REACTANCE OF 1.2$\Omega$. AT FULL LOAD, THE ROTOR POLES ARE DISPLACED BY MECHANICAL ANGLE OF 1 DEGREE FROM THEIR NO LOAD POSITION. IF THE LINE TO NEUTRAL EXCITATION $E_f$ = 2.4 kV, CALCULATE THE MECHANICAL POWER DEVELOPED.

$$P = \frac{E_f V}{X_s} \sin\delta$$

$E_f = 2400\,V$

$V_{(ph)} = \frac{4000}{\sqrt{3}} = 2309\,V$

$X_s = 1.2\,\Omega$

$$N = \frac{120f}{P}$$

$$180 = \frac{120 \times 60}{P}$$

$$P = \frac{120 \times 60}{180}$$

$$= 40$$

$$\delta = \frac{P\alpha}{2}$$

$$= \frac{40 \times 1}{2}$$

$$= 20^{\circ}$$

$$P = \frac{E_f V}{X_s} \sin\delta$$

$$= \frac{2400 \times 2309}{1.2} \sin 20$$

$$= 1573 \text{ kw}$$

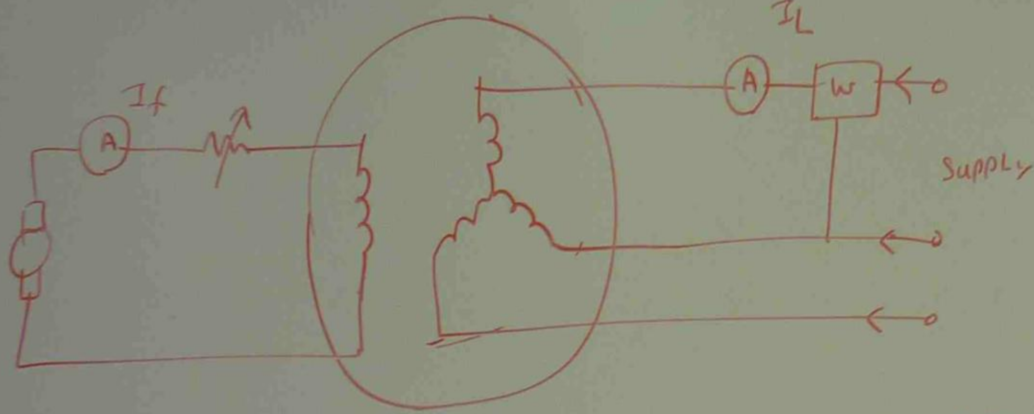
$3\phi$ power $= 3 \times 1573$

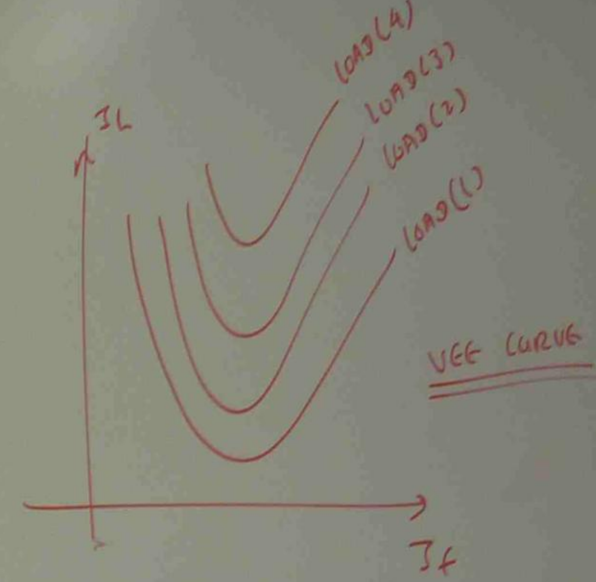
$= 4719$ kw

$$HP = \frac{4719}{0.746}$$

$$= 6300 \text{ HP}$$

# SYNCHRONOUS MOTOR VEE CURVE CHARACTERISTICS



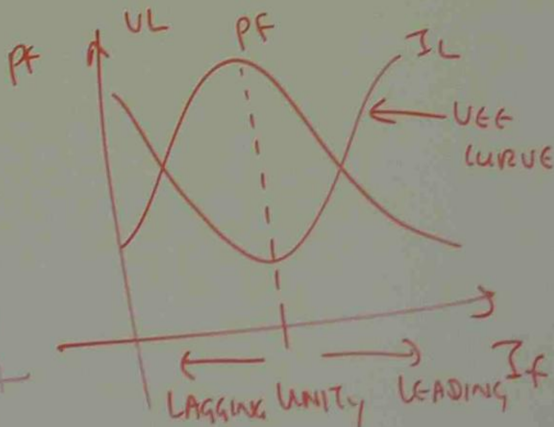




RUN THE MOTOR, ADJUST FIELD RHEOSTAT, NOTE $I_f$ & $I_L$

$I_f$ = FIELD EXCITATION CURRENT

$I_L$ = LINE CURRENT

| $I_f$ | $I_L$ | W | $PF = \frac{W}{\sqrt{3} V I_L}$ |
|---|---|---|---|
| | | | |



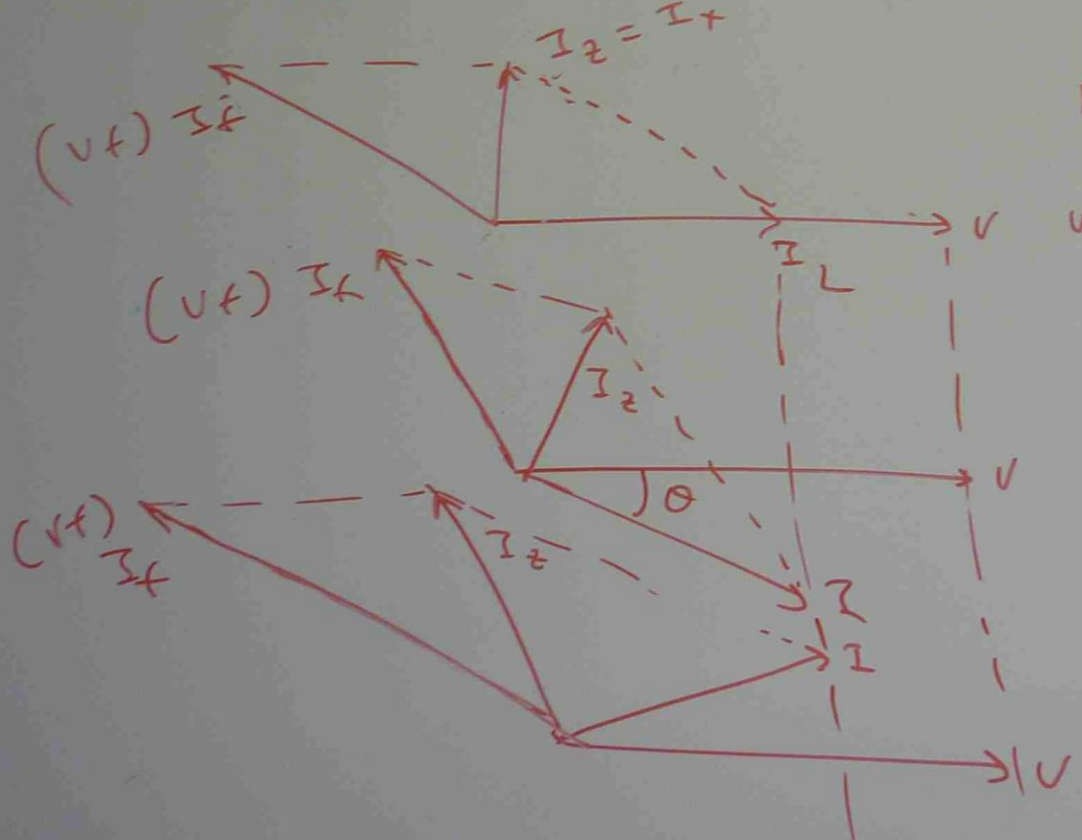

PLOT (i) $I_L$ VS $I_f$

(ii) PF VS $I_f$

# EFFECT OF VARYING FIELD EXCITATION

IF THE LOAD APPLIED TO A SYNCHRONOUS MOTOR IS CONSTANT, THE POWER INPUT TO THE MOTOR IS ALSO CONSTANT.

WHEN THE ROTOR FIELD EXCITATION IS VARIED, THE INDUCED VOLTAGE IN EACH STATOR WINDING IS ALSO ALTERED.




$R_S \simeq 0$

UNITY PF

LAGGING PF

LEADING PF

IF THE EXCITATION OF A SYNCHRONOUS MOTOR ON A CONSTANT LOAD IS VARIED FROM A LOW TO A HIGHER VALUE, THEN

1. STATOR CURRENT GRADUALLY DECREASES, REACHES A MINIMUM AND THEN INCREASES AGAIN

2. THE POWER FACTOR, AT FIRST LAGGING, GRADUALLY INCREASES BECOMES UNITY WHEN THE STATOR CURRENT IS MINIMUM. THEN DECREASES AGAIN, BUT BECOMES LEADING.