SYNCHRONOUS MACHINE-II

CONTENTS

Synchronous Machine II:

- Two Reaction Theory
- Power flow equations of cylindrical and salient pole machines
- Operating Characteristics

Synchronous Motor:

- Starting methods
- Effect of varying field current at different loads
- V- Curves
- Hunting & damping
- synchronous condenser

Power flow out of a Synchronous Machine

δ = Load angles

$$E\angle\delta = V_t\angle 0 + I_L\angle\phi .\ jX_s$$

Ia

In practical synchronous machines, except for small ones, $X_s >> R_a$ so we could assume that $Z_s = jX_s$ in the analysis.
Therefore we get $E = V_t + jI_LX_s$

Power flow out of a Synchronous Machine

h

Ia

Power = $VI\cos\phi$

Considering the diagram $h = I_L X_s \cos\phi = E\sin\delta$

Therefore $I_L X_s \cos\phi = E\sin\delta$

Power flow out of a Synchronous Machine

Esino

Xs

N *ov»* Pout = l.JTc o s ¢-

from the tw o equations *vve* can get Pout= Esino / Xs **V**

EV / Xs sin o

For maximum power sinδ = 1

Therefore δ = 90

In which case

$$\boxed{\text{Pout}= \frac{EV}{X_s}}$$

STARTING SYNCHRONOUS MOTORS

1 – Starting by Reducing Electrical Frequency

- If stator B rotate at low enough speed, there will be no problem for rotor to accelerate & will lock in with stator
- Speed of B_s then can be increased gradually to normal 50 or 60 Hz
- Shortcoming: how to provide a variable electrical frequency source, this needs a dedicated generator

STARTING SYNCHRONOUS MOTORS

- Today, (as described in ch. 3) rectifier-inverter & cycloconverter can be used to convert a constant frequency to any desired output frequency
- With modern solid-state variable frequency drive packages, it is perfectly possible to continuously control electrical frequency applied to motor from a fraction of Hz up to and above rated frequency
- If such a variable-frequency drive unit included in motor-control circuit to achieve speed control, then starting syn. motor is very easy
- When syn. Motor operated at ➔ a speed lower than rated speed, its internal generated voltage $E_A=K\phi\omega$ will be smaller than normal
- & If E_A reduced, voltage applied to motor must reduced to keep stator current at safe levels
- Voltage in any variable-frequency drive (or variable-frequency starter cct) must vary roughly linearly with applied frequency

STARTING SYNCHRONOUS MOTORS

2- Starting With an External Prime Mover

- Attaching an external motor to it to bring syn. Machine up to full speed
- Then syn. Machine be paralleled with its power system as a generator.
- Now starting motor can be detached from machine shaft, then its slow down
- B_R fall behind B_{net} & machine change its mode to be motor
- Once paralleling completed syn. Motor can be loaded

STARTING SYNCHRONOUS MOTORS

- Since starting motor should overcome inertia of syn. machine without a load & starting motor can have much smaller rating
- since most syn. motors have brushless excitation systems mounted on their shaft, often these exciters can be used as starting motors
- For many medium-size to large syn. motors, an external starting motor or starting by using exciter may be the only possible solution , because the connected power system source may not be able to feed the required starting current for amortisseur winding (next)

STARTING SYNCHRONOUS MOTORS

3- Starting by Using Amortisseur Windings

- most popular method is to employ amortisseur or damper winding
- armortisseur windings are special bars laid into notches carved in face of a syn. motor's rotor & then shorted out on each end by a large shorting ring

shown in next slide

- pole face
- To understand what a set of amortisseur windings does in a syn. motor, examine salient 2 pole rotor shown next

STARTING SYNCHRONOUS MOTORS

- Simplified diagram of salient 2 pole machine

0

- Not a way normal machines work

-however, reason

illustrate

for its

application

0

STARTING SYNCHRONOUS MOTORS

- Assume initially main rotor field winding is disconnected & that a 3 phase set of voltages applied to stator
- assume when power is first applied at t=0, Bs is vertical as shown, & as Bs sweeps along in counter-clockwise direction, it induces a voltage in bars of amortisseur winding :
- $e_{ind}=(v \times B) \cdot l$

v=velocity of bar relative to B

B=magnetic flux density vector

l=length of conductor magnetic field

STARTING SYNCHRONOUS MOTORS

- Development of a unidirectional with syn. torque

Motor amortisseu r winding s

e ind and i
out of page

●

●

e ind and i
into page
©©

c
a

W -----+-----
..lioo
B w
B 5
T_{ind} d =counterclockwise

T_{ind} =O

Bw
...,.

._...

T_{ind} =O

©©
eind and
into page
t=O

t= 1/240 s

a •
eind and i
out of page
t=l/120 s

t=3/240 s

STARTING SYNCHRONOUS MOTORS

- 1- at t=0

  Bars at top of rotor moving to right relative to magnetic field stator, so of induced voltage is out of page
- And similarly induced voltage in bottom bars into page
- Voltages produced a current flow out of top bars & into bottom bars, therefore this winding (bars) magnetic field B_W pointing to right
- Employing induced torque equation:
- $T_{ind}=k B_W \times B_S$
- Direction of resulting torque on bars (& rotor) counterclockwise

2- at t=1/240 s,

B_S now rotated 90°, while rotor has barely moved (simply can not speed up in short a time), since v is in parallel with B no induced voltage & current is zero

STARTING SYNCHRONOUS MOTORS

3- at t=1/120 s

- stator magnetic field rotated 90◦ and is downward, and rotor still not moved
- Induced voltage in damping winding out of page in bottom bars & into page in top bars
- Resulting current also out of page in bottom bars & into page at top bars which cause B_W pointing to left

is counterclockwise

STARTING SYNCHRONOUS MOTORS

4- at t=3/240 s

- Here as t=1/240 induced torque is zero
- Note: during these four steps, sometimes torque is counterclockwise & sometimes zero, however always
- unidirectional and the net is nonzero, motor speed
- up

Although rotor speed up, never reach syn. Speed

Since if rotor turn at syn. Speed, there would be no relative motion between rotor and Bs consequently induced voltage

STARTING SYNCHRONOUS MOTORS

- In Real Machines, field windings not open-circuited during starting procedure
- If field windings were O.C. then very high voltages would be produced during starting
- If field winding be shorted During starting no dangerous voltage developed, and induced field current contribute extra torque to motor

- Starting procedure for machines with amortisseur winding:

- 1- disconnect field windings from dc power source & sh. Them
- 2- apply a 3 phase voltage to stator winding, let rotor accelerate up near-syn. Speed, motor should have no load to get close to n_{syn}
- 3- connect dc field circuit to its power source, after this motor get to syn. Speed and loads then may be added to shaft

STARTING SYNCHRONOUS MOTORS

- Effects of Amortisseur Windings on Motor Stability
- There is another advantage when there is an armortisseur winding, i.e.
- increase machine stability
- Stator magnetic field rotates at a constant speed n_{syn} which varies only when system frequency varies
- If rotor turns at n_{syn} amortisseur winding have no induced voltage
- If rotor turn slower than n_{syn} there will be relative motion between rotor & B_s & a voltage will be induced, consequently current pass and magnetic field produced that develop a torque which tend to speed machine up again
- On the other hand if rotor turn faster than B_s a torque develop to slow rotor down
- These windings dampen out load or other transients on machine

SYNCHRONOUS MACHINE SUMMARY

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~ ~~~ r

~ ''' ~ ~ ' ~ \.ml '--' '

- Motors and Generators

1- syn. Gen.: E_A lies ahead of V_φ while for motor: E_A lies behind V_φ

2- machine supplying Q have $E_A \cos\delta >$ V_φ (regardless of being motor or generator) and machine consuming reactive power Q has $E_A \cos\delta < V_\varphi$

Synchronous motors commonly used for low speed , high power loads

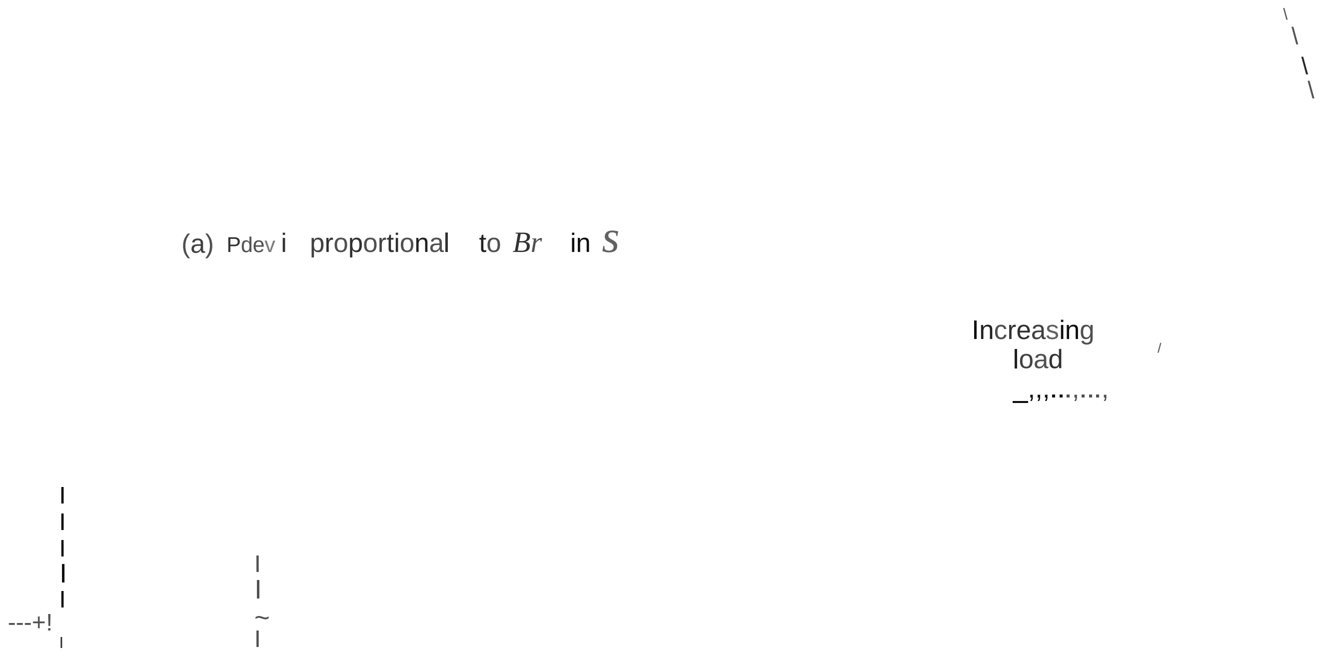
When connected to power system, frequency and terminal voltage of syn. motor is fixed

$n_m = n_{sync} = 120\ f_e / p$

$P_{max} = 3\ V_\varphi\ E_A\ /\ X_S$

this is maximum power of machine and if exceeded, motor slip

Effect of Load Change (Field constant)



(a) Pdev i proportional to *Br* in *S*

(b) Pdcv i. proportional to *Ia* co. *()and* to *Er*. in *O*

(c) Phas or diagram with increa. ing load and con. tarn field current

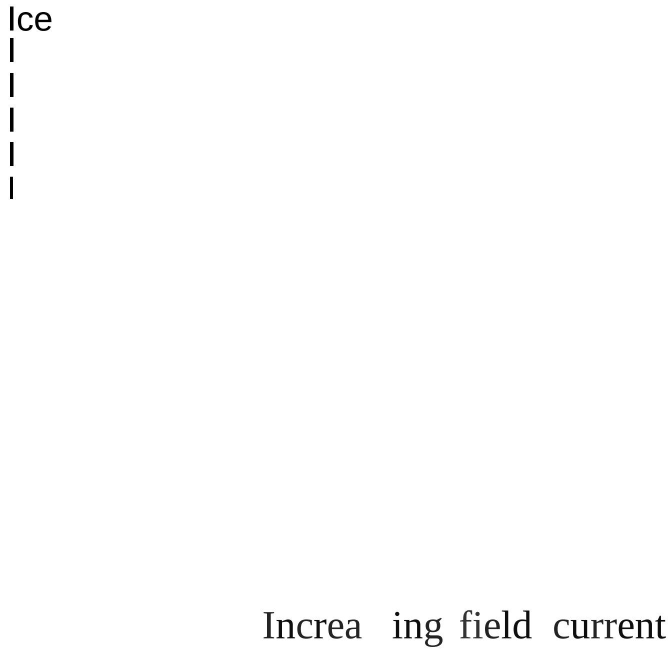
Figure 17.21 **Phasor diagrams for a synchronous motor**

Note: E_r same as E_f

V_a same as V_t

R_a has been neglected

Effect of Field Change (Load constant)



Note: E_r same as E_f
V_a same as V_t
R_a has been neglected

Figure 17.22 Phasor diagram for constant developed power and increasing field current.

Question: 1)Why is the loci of stator current and excitation voltage moves on a straight line?

2) What is happening to power factor as field is changed?

V curves

Lagging
power factor ~

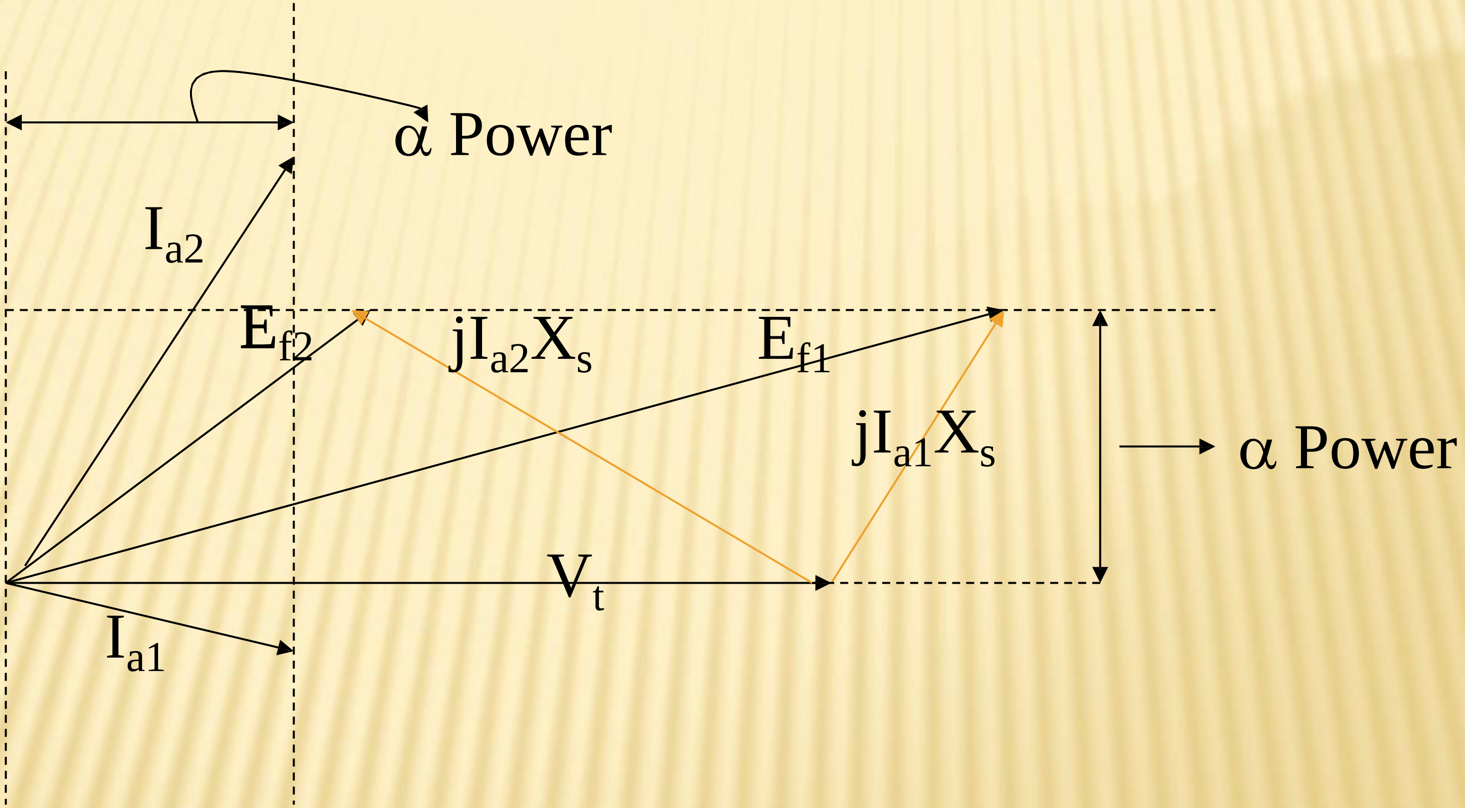
Unity
power
factor

Leading
power factor

to magnetic
aturaton

Figure 17.23 V curves for a synchronous motor with variable excitation.

Effect of Field Change (Load constant) for a generator



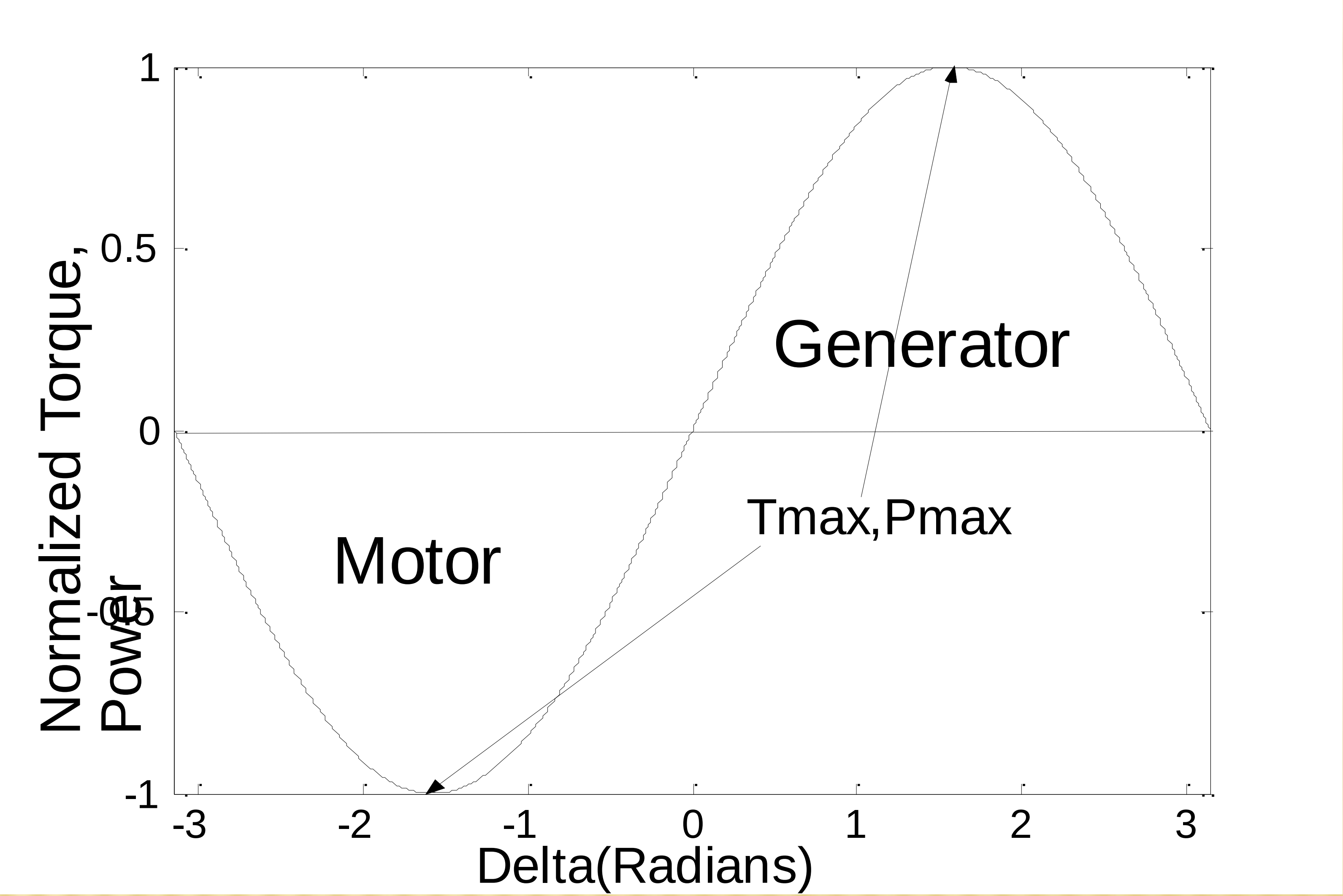
Conclusion for effect for field change with constant load on power factor

- For motor with increased (decreased)excitation power factor becomes leading (lagging)

- For generator with increased (decreased) excitation power factor becomes lagging (leading)

- *Unloaded* overexcited synchronous motors are sometimes used to improve power factor. They are known as *synchronous condensers*

Torque versus Electrical Load Angle



Torque versus Speed

Figure 17.26 Torque-speed characteristic of synchronous motors.

Example 2

An eight-pole, 240 V-rms, 60 Hz, delta connected synchronous motor operates with a constant developed power of 50 hp and a torque angle of 15^o and unity power factor. Suppose the field current is increased by 20%. Find the new torque angle and power factor. Is the new power factor lagging or leading? Assume linear magnetic characteristics.

SPSM and the concept of Direct and Quadrature Axes

- Since in the salient pole machine the reluctance of the machine varies with the position of the pole, flux due to armature reaction varies with power factor. Thus X_{ar} alone is no longer sufficient for the equivalent circuit.

- Reluctance is minimum along polar (direct) axis. Hence component of the armature reaction acting along this axis produce maximum flux. Let this component be Φ_{ad}.

- Reluctance is maximum along the inter-polar (quadrature)axis. Hence the component of the armature reaction acting along this axis produce minimum flux. Let this component be Φ_{aq}.

SPSM and the concept of Direct and Quadrature Axes (2)

- $X_d = X_{ad} + X_{al}$=(d)irect axis synchronous reactance)
- $X_q = X_{aq} + X_{al}$= (q)uadrature axis synchronous reactance)
- X_{ad}= d(irect) axis armature reactance $=\omega L_{ad}$
- X_{aq} = (q)uadrature axis armature reactance$=\omega L_{aq}$
- X_{al} = leakage reactance

- $\Phi_{ad} = L_{ad} I_d$
- $\Phi_{aq} = L_{aq} I_q$
- I_d= d(irect) axis component of the armature current
- I_q = (q)uadrature axis component of the armature current
- $I_a = \mathrm{I}_q \pm \mathrm{j} I_d$

Explaining d-q axes using diagrams

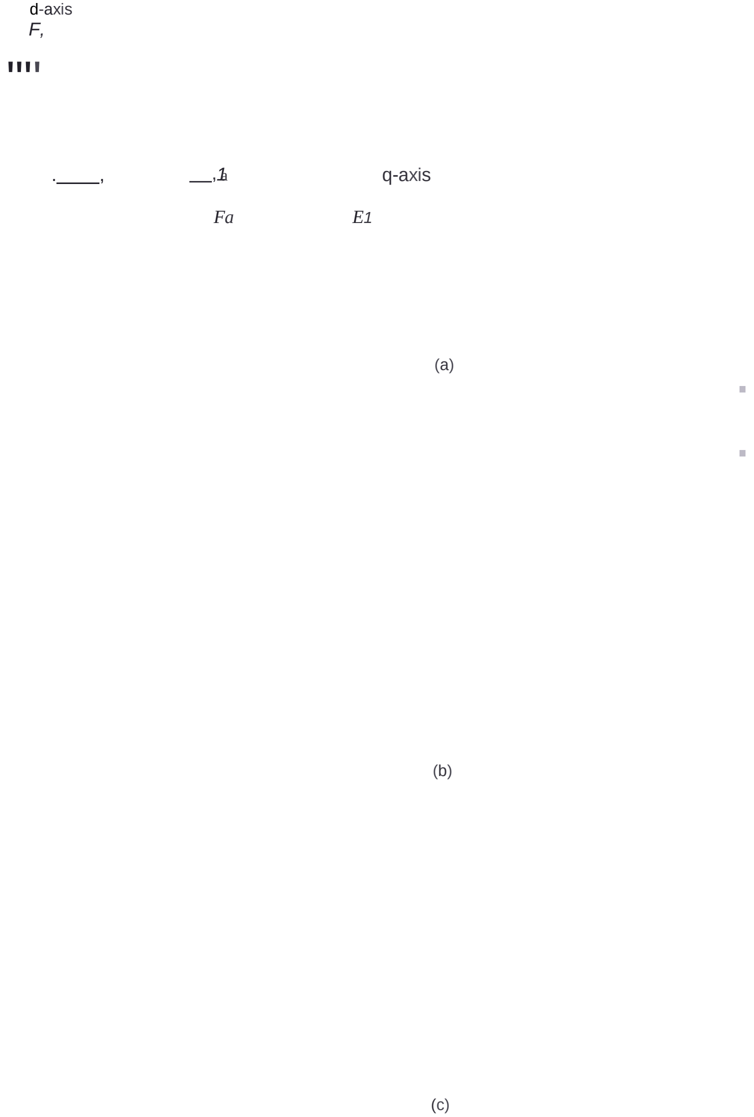


FIGURE 6.26 MMF and flux in salient pole synchronous machine.

Equivalent circuits of SPSM

(a)

(b)

/ /

k)

W >

FIGURE 6.27 Equivalent circuit and phasor diagrams for the salient pole syn• chronous machine. (a),(b),(c) ~Generator action. (d) 4 Motor action.

Power Angle Characteristics of SPSM

Power

Resultant power

P_1, power due to field excitation

P_r, power due to saliency

-----Motor----+.----Generator-----

FIGURE 6.28 Power-angle characteristic of a salient pole synchronous machine.

Power

$E_1 = 1.5$ per unit

$E_1 = 1$

$E_1 = 0.5$

,,._.a..-- $E_1 = 0$

$-180°$

----Motor----....,.,__--Generator-----

FIGURE 6.29 Power-angle characteristics for various field currents.