GENERATOR SINKRON
DAN
MOTOR SINKRON

Mesin Listrik Lanjut

GENERATOR SINKRON

- Jenis generator yg paling banyak dipakai
- Nilai output voltage sebanding dengan arus eksitasi
- Frekuensi output voltage sebanding dengan kecepatan putar dan jumlah pole
- Frekuensi generator sinkron

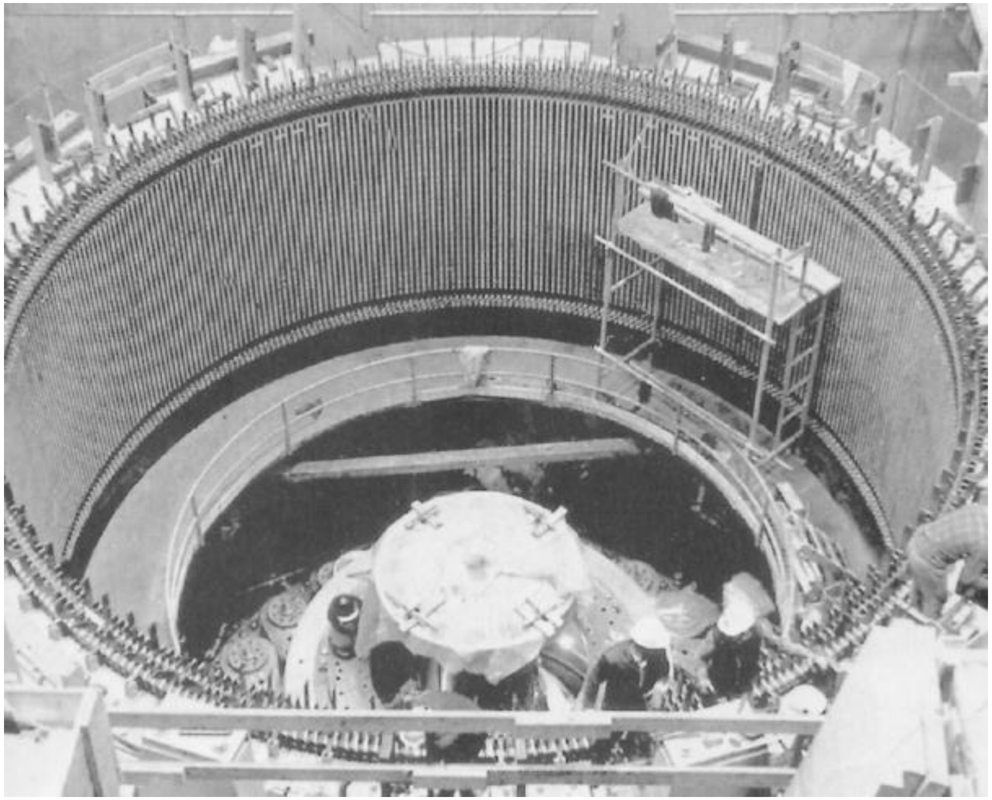
$$f = \frac{pn}{120} \qquad (16.1)$$

where

f = frequency of the induced voltage [Hz]
p = number of poles on the rotor
n = speed of the rotor [r/min]

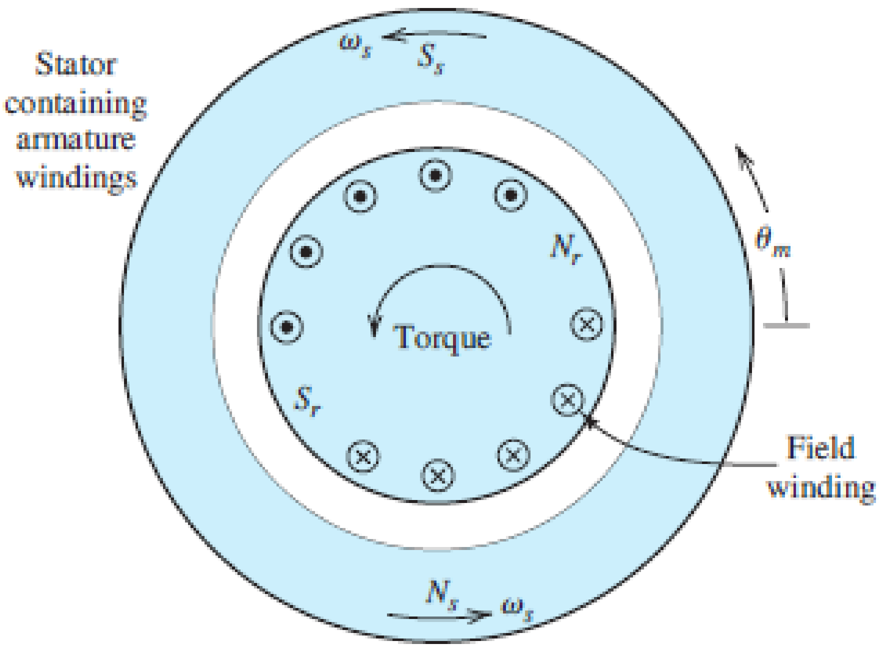
Stator

- Identik dengan stator pada motor induksi
- Coil stator terhubung koneksi star

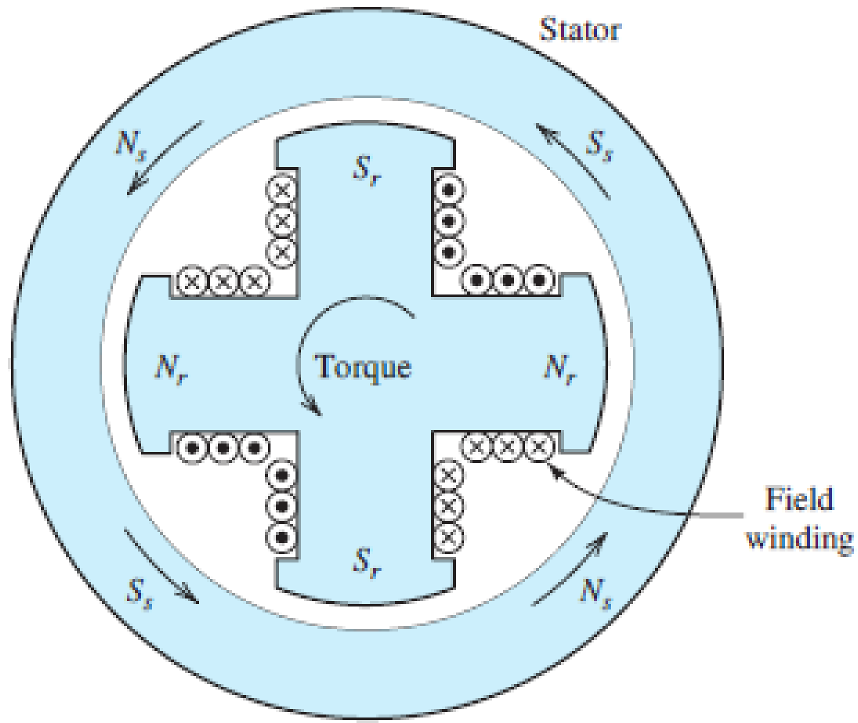


Rotor

- Ada 2 tipe: salient pole dan cylindrical
- Salient pole dipakai untuk kec rendah seperti pada turbin hidrolik. Untuk menghasilkan frekuensi output 50-60 Hz dari sumber mechanical speed 50-300rpm maka jenis ini memiliki pole yg banyak
- Cylindrical dipakai pada kecepatan tinggi seperti genset
  - Lebih effisient
  - Kerena kec tinggi maka polenya sedikit, biasanya 2 &4



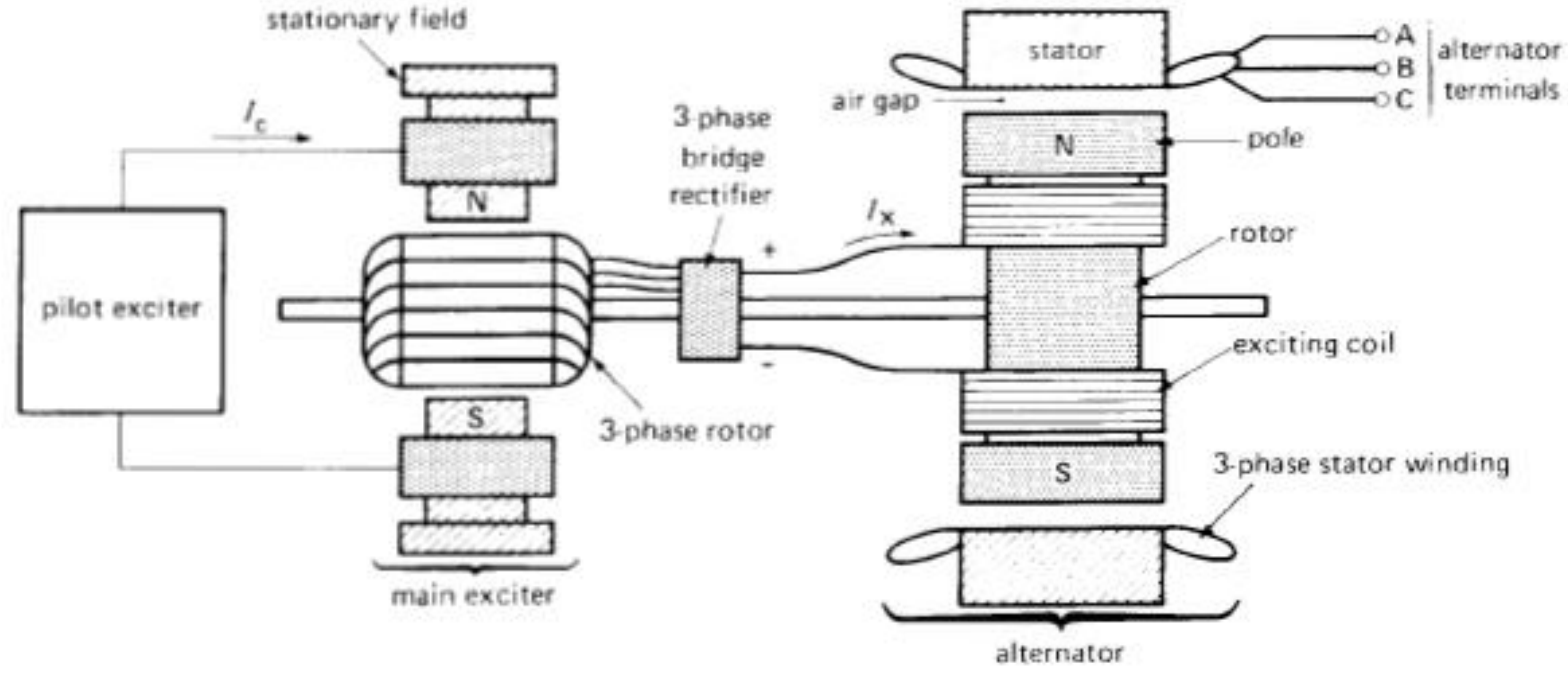
cylindrical



salient pole

Excitation

- Berfungsi untuk menghasilkan medan magnet pada rotor sehingga kecepatan sinkron rotor-stator tetap terjaga



Batasan Dimensi Gen Sinkron

- Semakin besar size dimensi gen sinkron, maka effisiensinya semakin baik
- 1 kW gen sinkron effisiensinya 50 %
- 10 MW gen sinkron effisiensinya 90 %
- Jika gen 1 kW beratnya 20 kg maka power output 50 W/kg
- Jika gen 10 MW beratnya 20 ton maka power outputnya 500 W/kg
- Permasalahan, semakin besar dimensi gen, maka cooling semakin rumit
- Gen speed rendah, dimensinya besar karena tidak ada masalah dengan cooling

Sinkronisasi Beberapa Generator

- Load yg besar biasanya disupply lebih dari 1 gen
- Misal load 30 MW disuply dengan 3 gen 10 MW. Ketika full load maka 3 gen menyala, ketika load rendah hanya 1 gen yg menyala. Mekanisme ini akan lebih efisien dibanding dengan menggunakan 1 gen 30 MW.
- Beberapa gen tadi akan terhubung dengan sebuah bus

- Agar dapat dihubungkan generator harus ter-sinkronisasi
- Syarat kondisi sinkron
  - Frek gen = Frek sistem
  - Volt gen = Volt sistem
  - Phase voltage gen = Phase voltage sistem
  - Phase sequence gen = Phase sequence sistem

- Sinkronisasi gen dilakukan dengan cara

1) Atur kec sehingga frek sama
2) Atur eksitasi sehingga out voltage sama
3) Samakan phase voltage dengan bantuan **synchroscope**

Infinite Bus

- Ketika banyak gen terhubung ke dalam sebuah bus, maka bus tersebut disebut infinite bus
- Kondisi floating adalah kondisi ketika gen terhubung ke bus tetapi tidak ada daya yg disalurkan

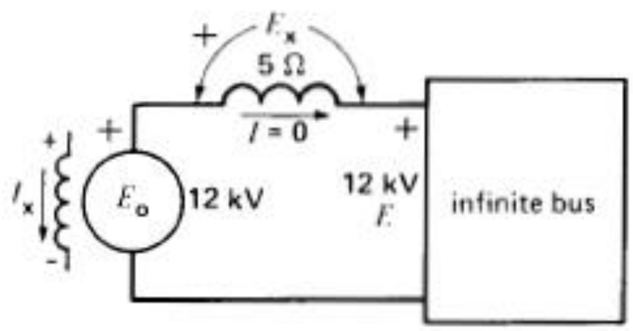


Figure 16.26a
Generator *floating* on an infinite bus.

Efek eksitasi pada gen yg terhubung ke bus

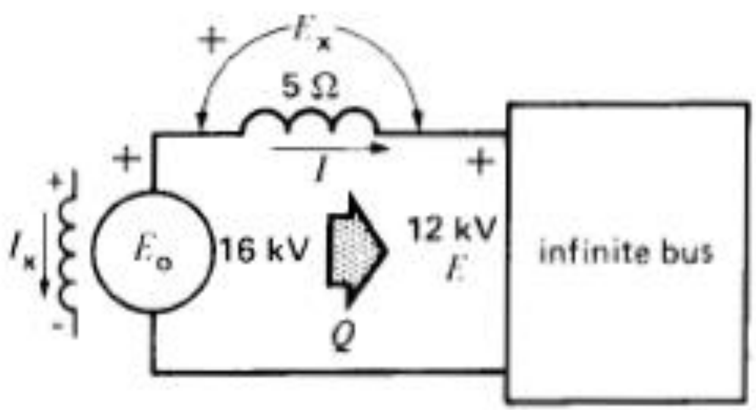


Figure 16.26b
Over-excited generator on an infinite bus.

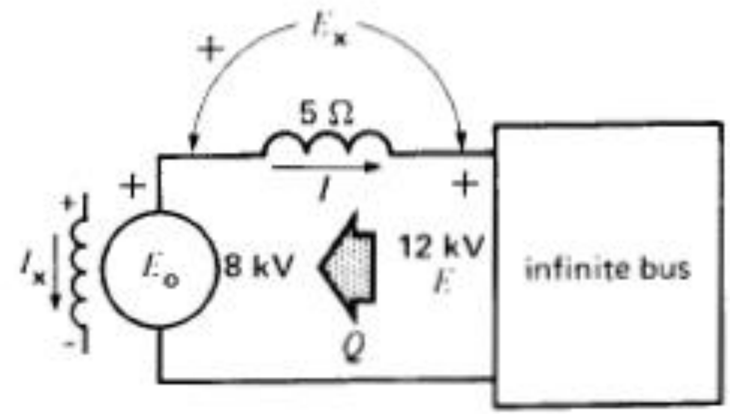
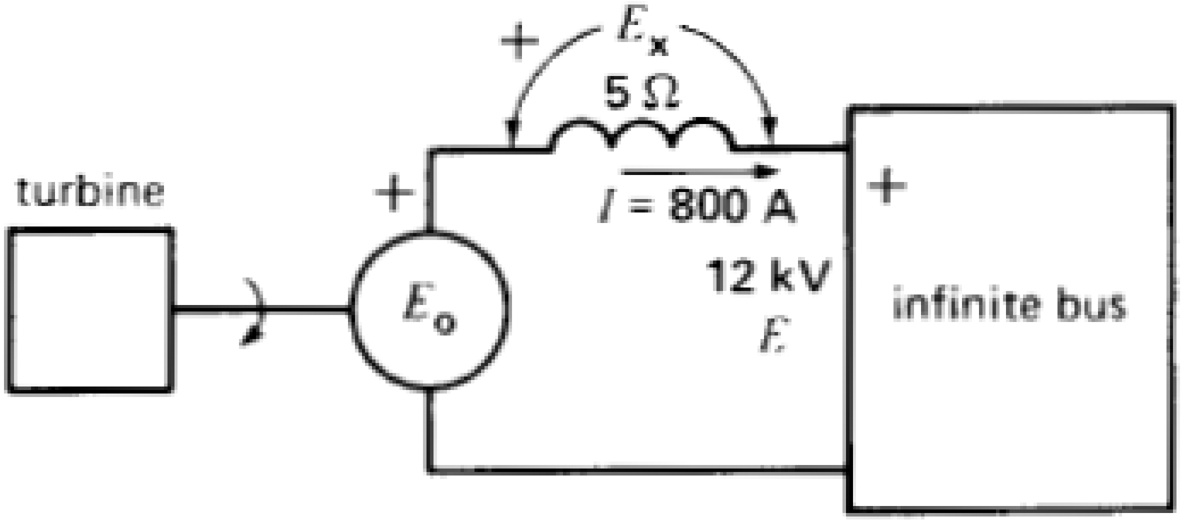


Figure 16.26c
Under-excited generator on an infinite bus.

Efek perubahan torsi pada gen yg terhubung ke bus

- Jika torsi naik, maka terjadi beda fase antara Eo(voltage internal gen) dan E (voltage di terminal gen). Beda fase akan menyebabkan beda potensial sehingga arus listrik mengalir.

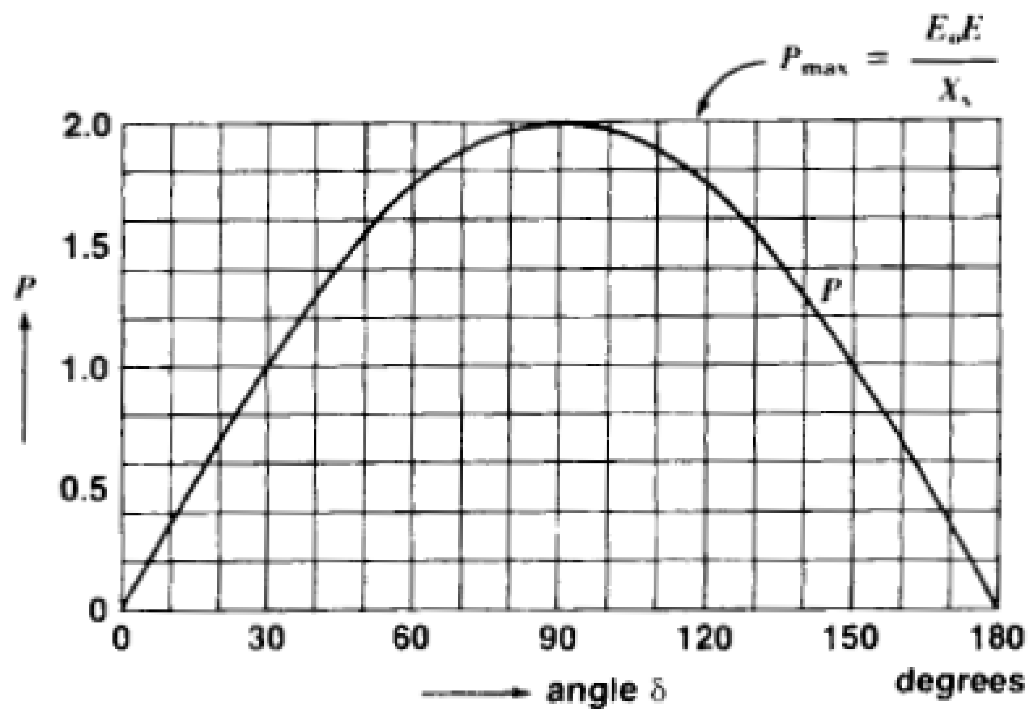


Daya Aktif Generator

$$P = \frac{E_o E}{X_s} \sin \delta \qquad (16.5)$$

where

P = active power, per phase [W]
E_o = induced voltage, per phase [V]
E = terminal voltage, per phase [V]
X_s = synchronous reactance per phase [Ω]
δ = torque angle between E_o and E [°]



- Jika EoE/Xs konstan, maka P tergandung pada delta
- Pmax ketika delta=90 derajad

Example 16-7

A 36 MVA, 21 kV, 1800 r/min, 3-phase generator connected to a power grid has a synchronous reactance of 9 Ω per phase. If the exciting voltage is 12 kV (line-to-neutral), and the system voltage is 17.3 kV (line-to-line), calculate the following:

a. The active power which the machine delivers when the torque angle δ is 30° (electrical)
b. The peak power that the generator can deliver before it falls out of step (loses synchronism)

Solution

a. We have

$$E_o = 12 \text{ kV}$$
$$E = 17.3 \text{ kV}/\sqrt{3} = 10 \text{ kV}$$
$$\delta = 30°$$

The active power delivered to the power grid is

$$P = (E_oE/X_s) \sin \delta$$
$$= (12 \times 10/9) \times 0.5$$
$$= 6.67 \text{ MW}$$

The total power delivered by all three phases is

$$(3 \times 6.67) = 20 \text{ MW}$$

b. The maximum power, per phase, is attained when δ = 90°.

$$P = (E_oE/X_s) \sin 90$$
$$= (12 \times 10/9) \times 1$$
$$= 13.3 \text{ MW}$$

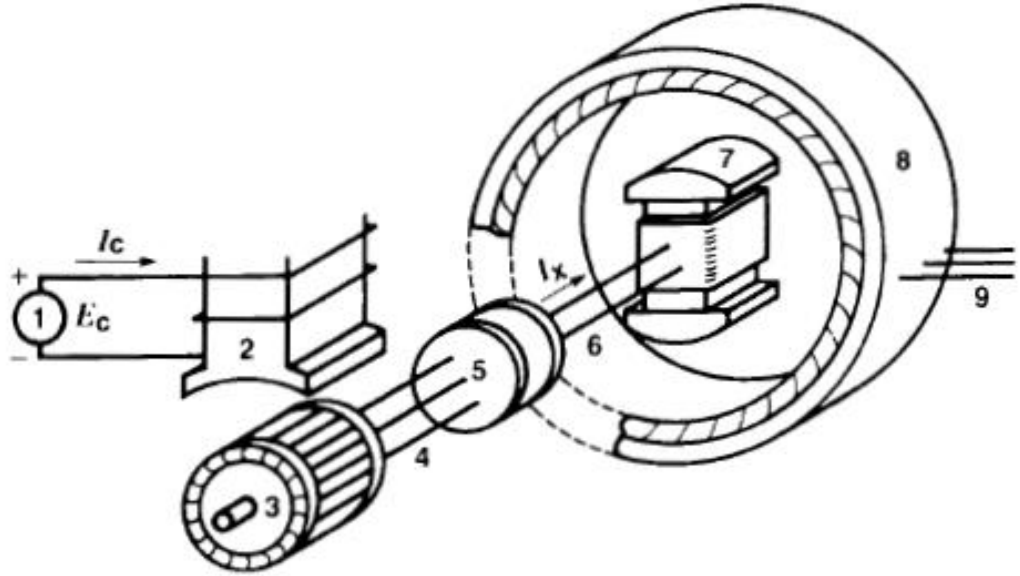
The peak power output of the alternator is, therefore,

$$(3 \times 13.3) = 40 \text{ MW}$$

Motor Sinkron

- Gen sinkron dapat dioperasikan sebagai motor sinkron
- Jarang dipakai karena kecepatannya konstan dan perlu tambahan exciter
- Kecepatan sinkron

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



1 - dc control source

2 - stationary exciter poles

3 - alternator (3-phase exciter)

4 - 3-phase connection

5 - bridge rectifier

6 - dc line

7 - rotor of synchronous motor

8 - stator of synchronous motor

9 - 3-phase input to stator

Figure 17.3

Diagram showing the main components of a brushless exciter for a synchronous motor. It is similar to that of a synchronous generator.

- Motor sinkron tidak dapat start sendiri, oleh kerena itu ditambahakan sangkar tupai(squirel cage) pada rotornya, sehingga ketika start awal motor sinkron bekerja seperti motor induksi. Eksitasi baru masuk setelah motor berputar.
- Arah putar motor dapat diubah dengan mengubah koneksi 3 phase di terminal.
- Effisiensi motor sinkron lebih besar dibanding effisiensi motor induksi kerena tidak ada slip

Pembebanan Motor

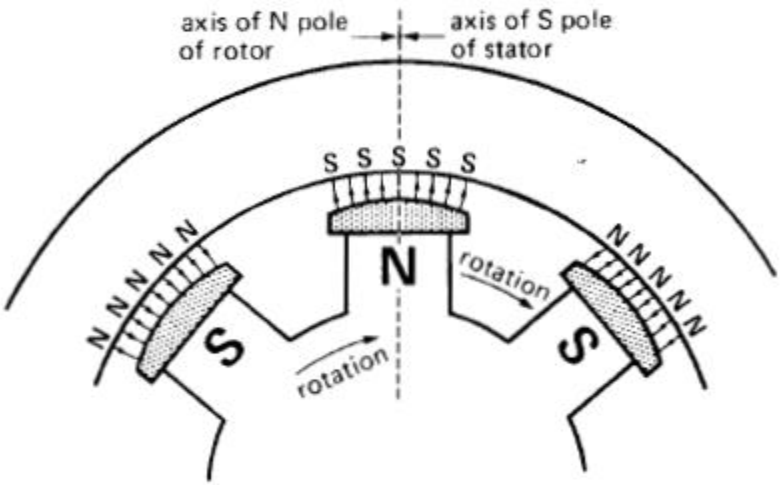


Figure 17.5
The poles of the rotor are attracted to the opposite poles on the stator. At no-load the axes of the poles coincide.

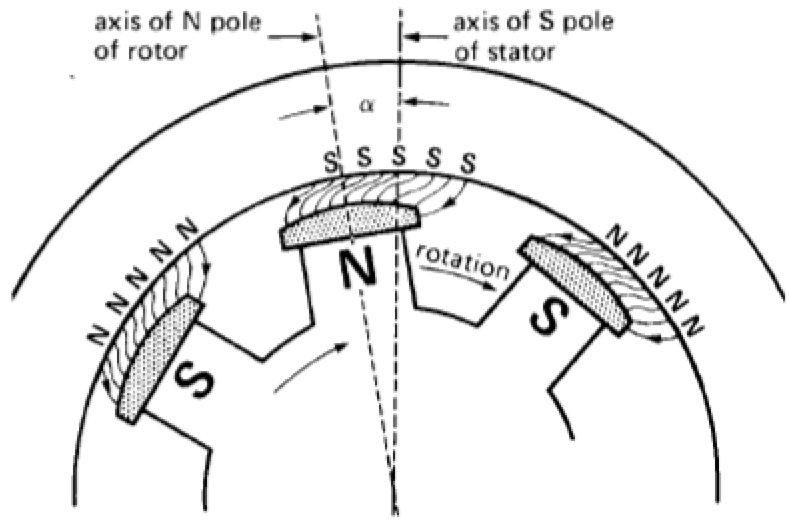


Figure 17.6
The rotor poles are displaced with respect to the axes of the stator poles when the motor delivers mechanical power.

$$\delta = p\alpha/2$$

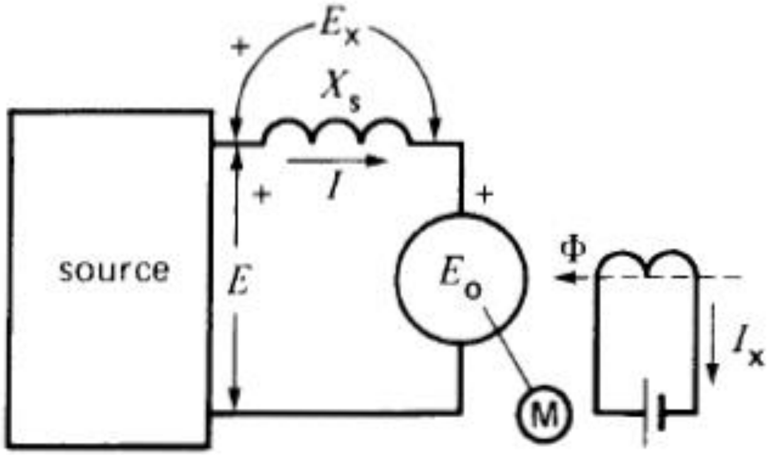


Figure 17.7a
Equivalent circuit of a synchronous motor, showing one phase.

Figure 17.7b
Motor at no-load, with E_o adjusted to equal E.

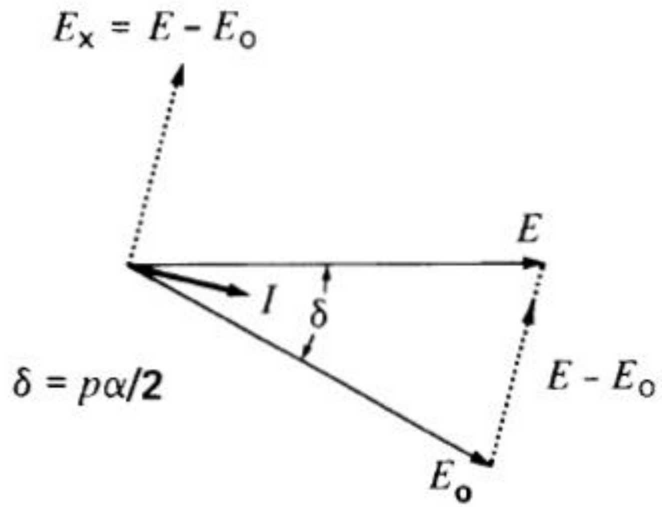


Figure 17.7c
Motor under load E_o has the same value as in Fig. 17.7b, but it lags behind E.

Example 17-2b

The motor in Example 17-2a has a stator resistance of 0.64 Ω per phase and possesses the following losses:

I^2R losses in the rotor:	3.2 kW
Stator core loss:	3.3 kW
Windage and friction loss:	1.5 kW

Calculate

a. The actual horsepower developed
b. The actual torque developed at the shaft
c. The efficiency of the motor

Solution

a. Power input to the stator is 280.1 kW

Stator I^2R losses $= 3 \times 53^2 \times 0.64\ \Omega = 5.4$ kW
Total stator losses $= 5.4 + 3.3 = 8.7$ kW
Power transmitted to the rotor $= 280.1 - 8.7$
$= 271.4$ kW

The power at the shaft is the power to the rotor minus the windage and friction losses. The rotor I^2R losses are supplied by an external dc source and so they do not affect the mechanical power.

Power available at the shaft:

$$P_o = 271.4 - 1.5 = 269.9 \text{ kW}$$
$$= \frac{269.9 \times 10^3}{746} = 361.8 \text{ hp}$$

This power is very close to the approximate value calculated in Example 17-2a.

b. The corresponding torque is:

$$T = \frac{9.55 \times P}{n} = \frac{9.55 \times 269.9 \times 10^3}{720}$$
$$= 3580 \text{ N·m}$$

c. Total losses $= 5.4 + 3.3 + 3.2 + 1.5 = 13.4$ kW

Total power input $= 280.1 + 3.2 = 283.3$ kW
Total power output $= 269.9$ kW
Efficiency $= 269.9/283.3 = 0.9527 = 95.3$ %

Note that the stator resistance of 0.64 Ω is very small compared to the reactance of 22 Ω. Consequently, the true phasor diagram is very close to the phasor diagram of Fig. 17.8b.

Daya dan Torsi

$$P = \frac{E_o E}{X_s} \sin \delta \qquad (17.2)$$

where

P = mechanical power of the motor, per phase [W]

E_o = line-to-neutral voltage induced by I_x [V]

E = line-to-neutral voltage of the source [V]

X_s = synchronous reactance per phase [Ω]

δ = torque angle between E_o and E [electrical degrees]

$$T = \frac{9.55\,P}{n_s} \qquad (17.4)$$

where

T = torque, per phase [N·m]

P = mechanical power, per phase [W]

n_s = synchronous speed [r/min]

9.55 = a constant [exact value = $60/2\pi$]

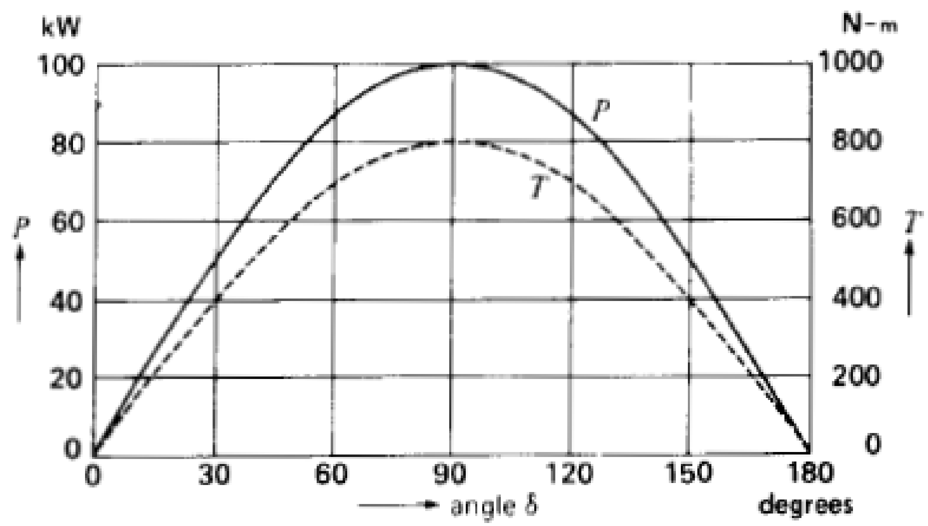


Figure 17.9
Power and torque per phase as a function of the torque angle δ. Synchronous motor rated 150 kW (200 hp), 1200 r/min, 3-phase, 60 Hz. See Example 17-3.

Eksitasi dan Daya Reaktif (Q)

- Flux yg dipakai untuk menghasilkan gaya gerak pada motor sinkron dibangkitkan oleh medan magnet stator maupun medan magnet rotor
- Ketika eksitasi kecil, maka hampir semua flux dibangkitkan oleh stator, sehingga banyak daya reaktif yg diserap dari sumber 3 phase untuk menghasilkan medan magnet
- Semakin besar eksitasi, maka semakin kecil daya reaktif yg diserap dari jaringan. Bahkan ketika eksitasi melebihi batas motor akan mensuply daya reaktif ke jaringan
- Sifat ini dimanfaatkan untuk perbaikan faktor daya di jaringan listrik

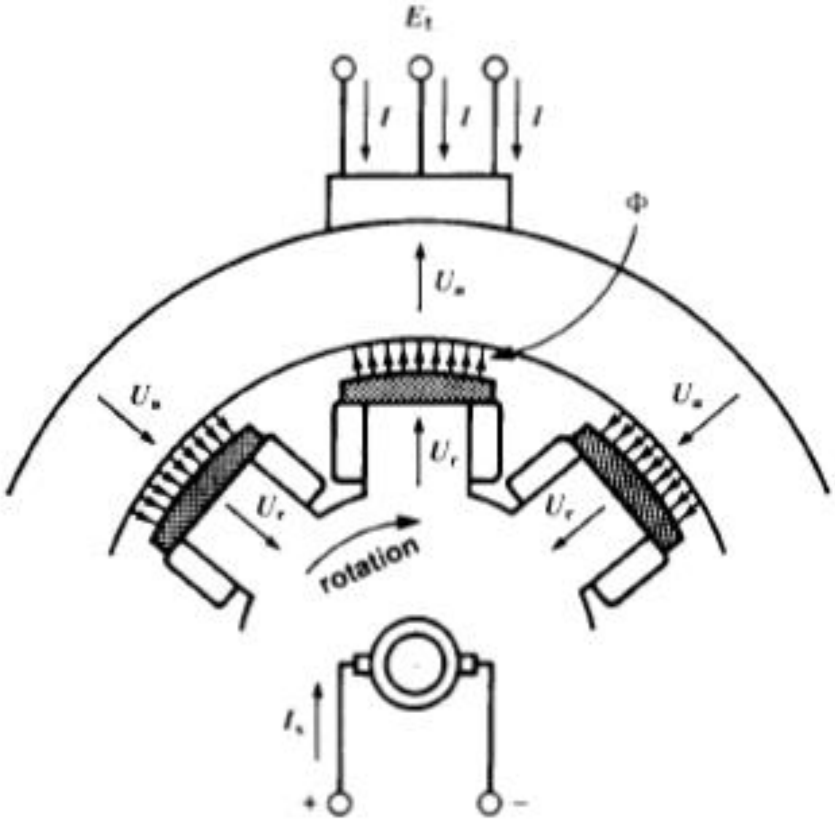


Figure 17.13
The total flux Φ is due to the mmf produced by the rotor (U_r) plus the mmf produced by the stator (U_a). For a given E_L, the flux Φ is essentially fixed.

Power factor rating

Figure 17.14
Unity power factor synchronous motor and phasor diagram at full-load.

$$I_p = 0.8\ I_s \qquad (17.7)$$

$$I_q = 0.6\ I_s \qquad (17.8)$$

The active power P is given by

$$P = E_{ab}I_p = 0.8\ E_{ab}I_s \qquad (17.9)$$

The reactive power delivered by the motor is

$$Q = E_{ab}I_q = 0.6\ E_{ab}I_s \qquad (17.10)$$

Figure 17.15
80 percent power factor synchronous motor and phasor diagram at full-load.

Is = Ip
========================
Is=1.25 Ip

Ketika pf turun, semakin besar arus yg dipakai

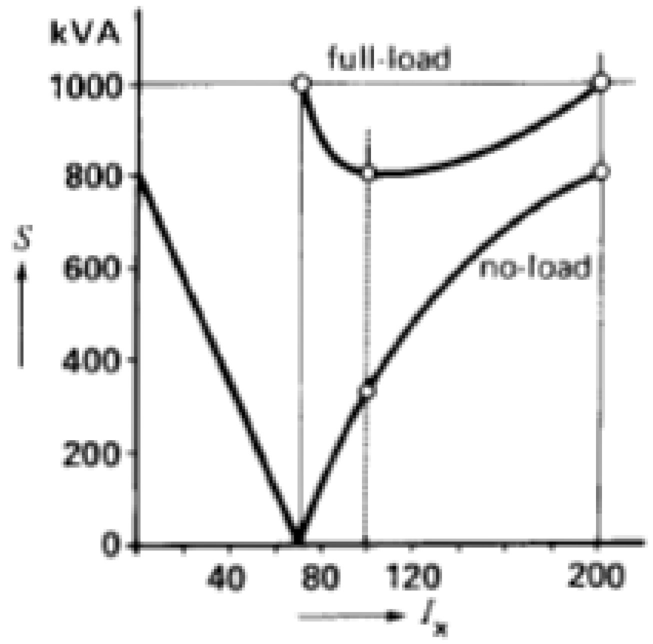


Figure 17.19
No-load and full-load V-curves of a 1000 hp synchronous motor.

- Jika pf<1 atau pf>1 maka daya semu akan naik
- Pf<1 motor menyerap daya reaktif
- Pf>1 maka memberikan daya reaktif

Pengereman

- Regeneratif braking
  - Men-sort kan terminal 3 phase, full exitation
  - Menghubungkan terminal 3 phase dgn resistor, full excitation
- Mechanical brake
  - Memutus sumber listrik dan memberikan beban ke motor

Capasitor Sinkron

- Pemanfaatan motor sinkron untuk perbaikan faktor daya
- Motor sinkron bisa bersifat induktif atau kapasitif tergantung eksitasinya
- Motor sinkron dapat menghasilkan daya reaktif 20-200 Mvar

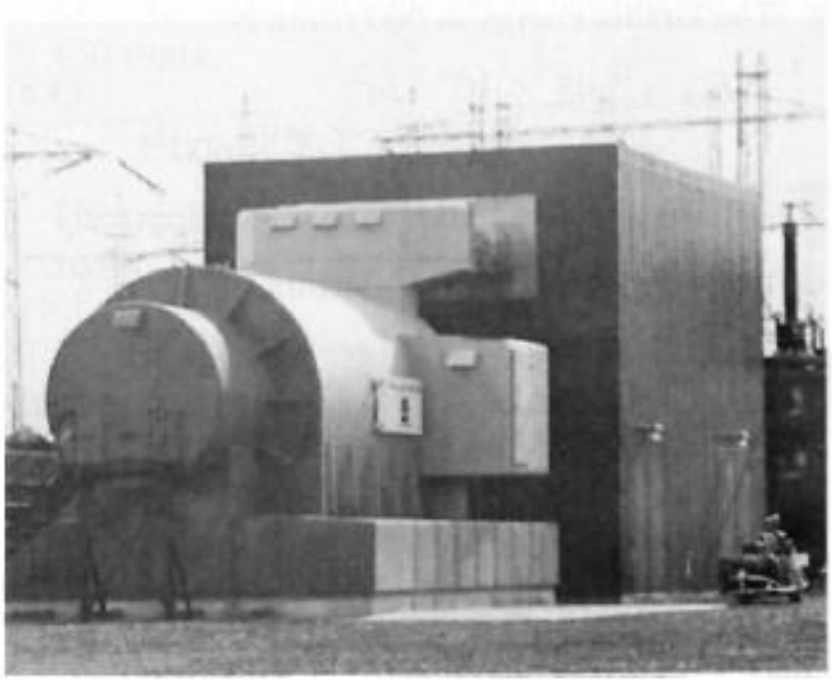


Figure 17.24b
Synchronous capacitor enclosed in its steel housing containing hydrogen under pressure (300 kPa, or about 44 lbf/in^2).
(*Courtesy of Hydro-Québec*)

AC motor kontrol

- Kendali motor DC: variasi voltase
- Kendali motor AC: variasi voltase dan frekuensi
- Kelebihan motor AC

1. AC machines have no commutators and brushes; consequently, they require less maintenance.
2. AC machines cost less (and weigh less) than dc machines.
3. AC machines are more rugged and work better in hostile environments.
4. AC machines can operate at much higher voltages: up to 25 kV. DC machines are limited to about 1000 V.
5. AC machines can be built in much larger sizes: up to 50 000 kW. DC machines are limited to about 2000 kW.
6. AC machines can run at speeds up to 100 000 r/min, whereas large dc machines are limited to about 2000 r/min.

Tipe AC drive

- Static frequency changers
  - Dipakai di motor sinkron dan motor induksi
  - Dapat dilakukan dengan cycloconverter

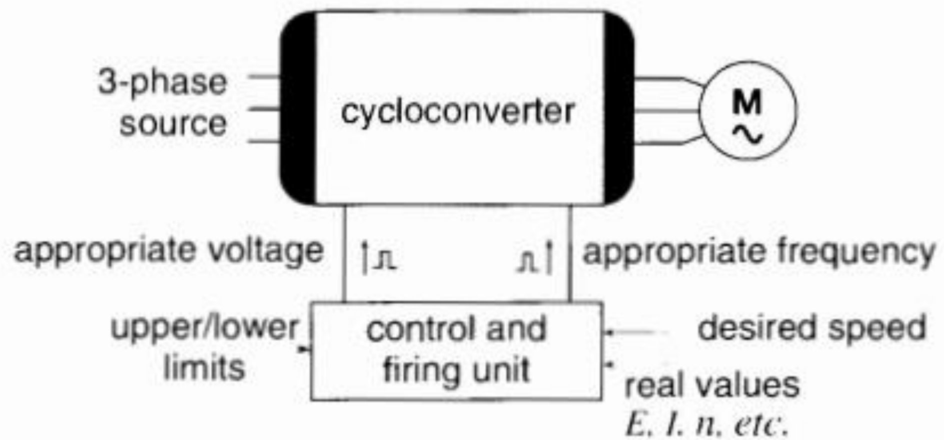


Figure 23.1
Variable-speed drive system using a cycloconverter (see Sections 23.3 and 23.5).

- Static voltage controller
  - Dipakai soft start motor induksi

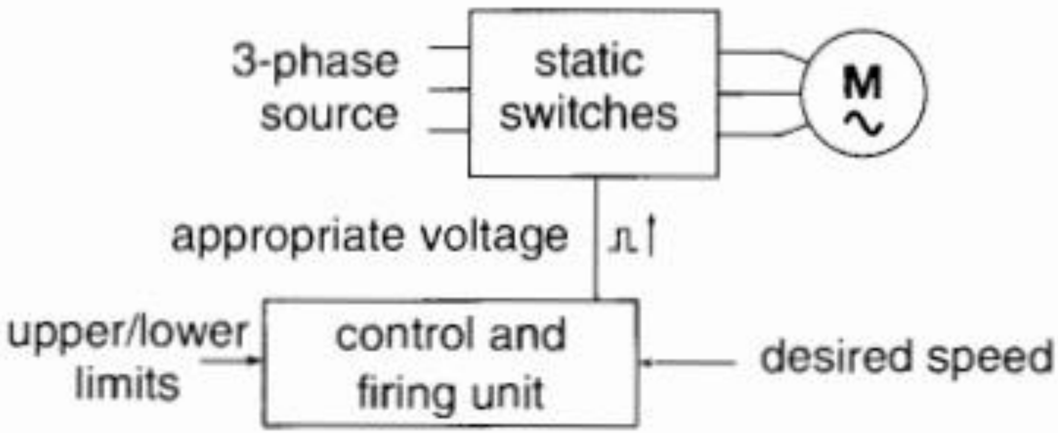


Figure 23.2
Variable-speed drive using a static switch (see Section 23.6).

- Rectifier-inverter system with line commutation
  - Dipakai pada motor sinkron dan motor induksi
  - Frek sistem mengikuti line freq

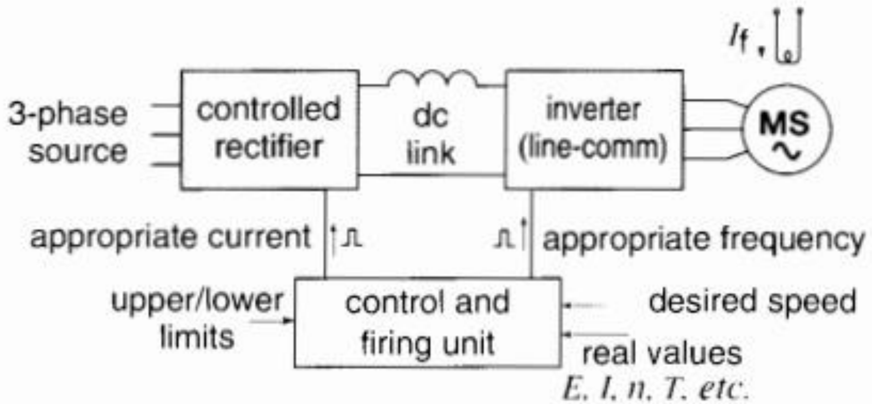


Figure 23.3
Variable-speed synchronous motor drive using a controlled rectifier and a line-commutated inverter fed from a dc link current source (see Section 23.2).

- Rectifier-inverter system with self commutation
  - Dipakai pada motor induksi
  - Frek sistem ditentukan sistem sendiri

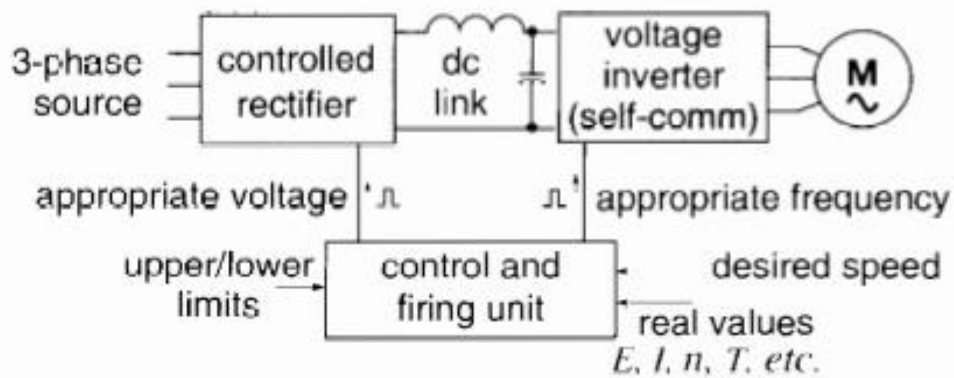


Figure 23.6
Variable-speed drive using a controlled rectifier and a self-commutated inverter fed from a dc link voltage source (see Section 23.10).

- Pulse-width modulation system
  - Variasi voltase dan frekuensi dilakukan oleh inverter

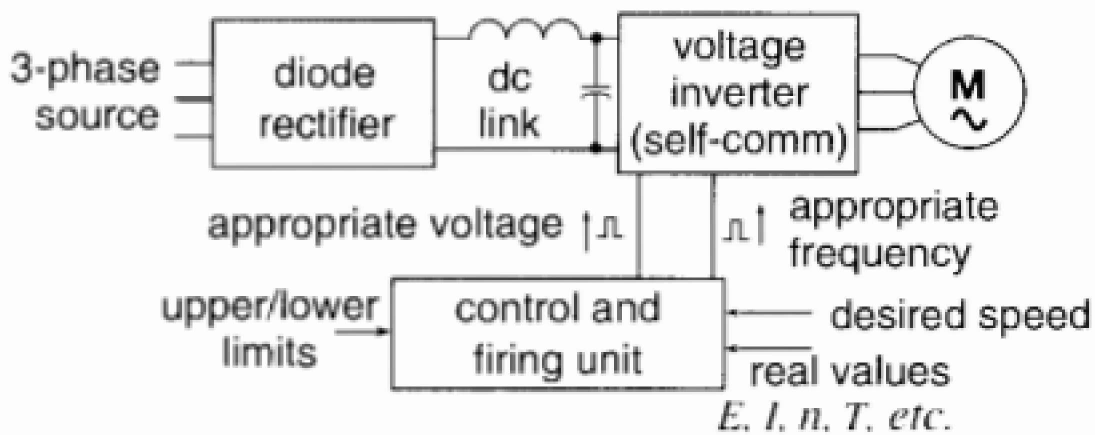


Figure 23.7
Variable-speed drive using a diode rectifier and a self-commutated PWM inverter fed from a dc link voltage source (see Section 23.13).

Kendali Motor Sinkron

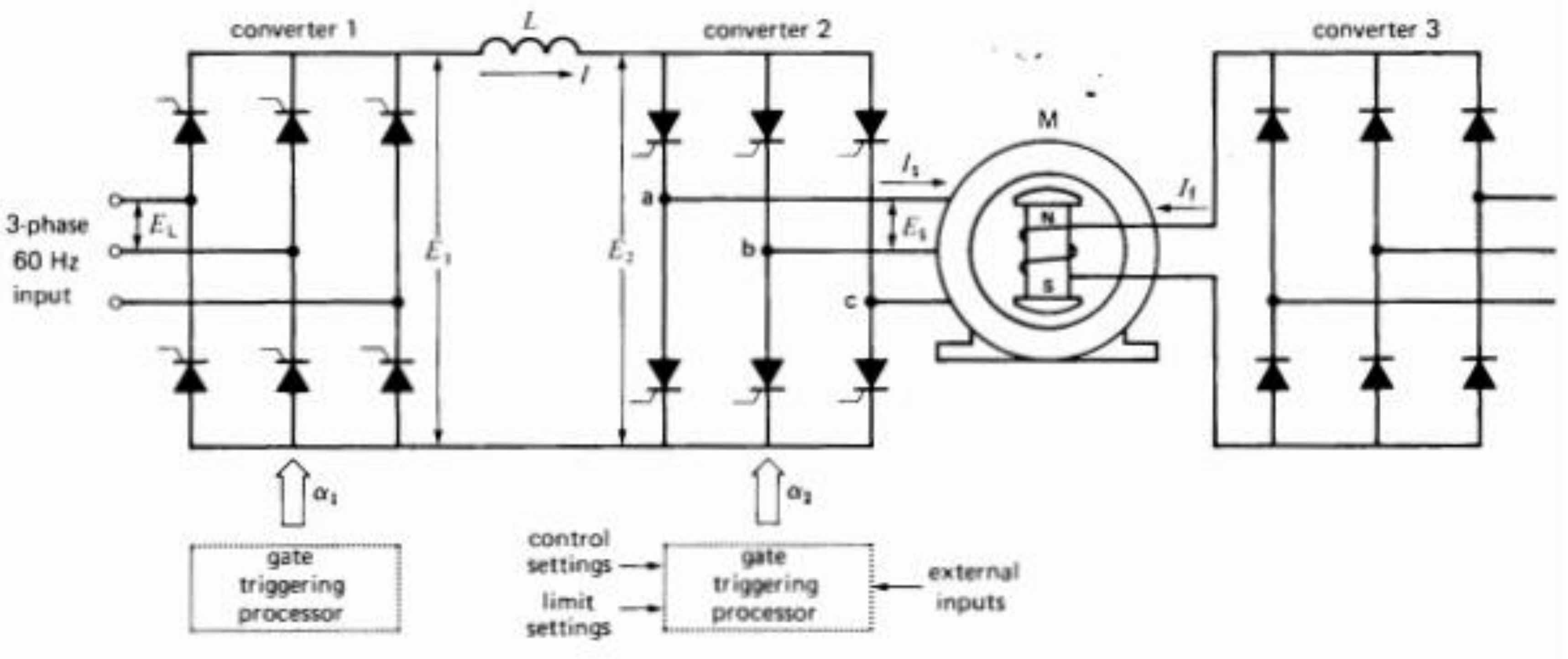


Figure 23.8
Synchronous motor driven by a converter with a dc link. The output frequency can be considerably greater than 60 Hz, thus permitting high speeds.

Stator voltage E_s produces a dc emf E_2 given by

$$E_2 = 1.35\ E_s \cos \alpha_2 \qquad (21.13)$$

where

E_2 = dc voltage generated by converter 2 [V]
E_s = effective line-to-line stator voltage [V]
α_2 = firing angle of converter 2 [°]

Similarly, the voltage produced by converter 1 is given by

Regenerative braking is accomplished by shifting the gate-firing pulses so that converter 2 acts as a rectifier while converter 1 operates as an inverter. The polarity of E_2 and E_1 reverses, but the link current continues to flow in the same direction. Power is, therefore, pumped back into the 3-phase, 60 Hz line and the motor slows down. During this period the motor functions as an ac generator.

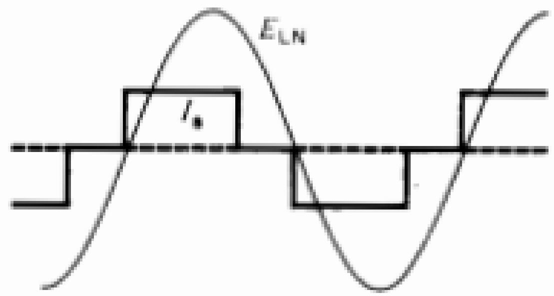


Figure 23.9
Typical voltage and current waveshapes in Fig. 23.8.

Contoh soal

Example 23-1

A 3-phase synchronous motor rated at 200 kW, 480 V, 60 Hz, 450 r/min, is connected to a drive similar to that shown in Fig. 23.8. The three-phase electric utility voltage is 600 V, 60 Hz.

The motor runs at a speed of 535 r/min. The effective terminal voltage is 511 V and the motor draws an effective line current I_s of 239 A at a power factor of 95 %. The motor has an efficiency of 93 %. Neglecting the losses in the converters, calculate:

a. the frequency applied to the stator
b. the fundamental component of the stator current I_s
c. the current I flowing in the dc link
d. the firing angle α_2 of converter 2
e. the voltage E_2 of the dc link
f. the firing angle α_1 of converter 1
g. the reactive power supplied to converter 1
h. the mechanical power developed by the motor

Solution

a. The frequency applied to the motor is proportional to its speed. Because the rated speed is 450 r/min at a frequency of 60 Hz, the frequency at 535 r/min is:

$$f = \frac{535 \text{ r/min}}{450 \text{ r/min}} \times 60 \text{ Hz} = 71.3 \text{ Hz}$$

b. Fundamental component of the stator current:

$$I_F = 0.955\, I_s \qquad (21.8)$$

$$= 0.955 \times 239 = 228 \text{ A}$$

c. Current in the dc link:

$$I_d = \frac{I_F}{0.78} \qquad (21.7)$$

$$= \frac{228}{0.78} = 293 \text{ A}$$

d. Firing angle α_2:

Converter 2 acts as an inverter, consequently:

$$\alpha_2 = -\text{ arccos } FP = -\text{ arccos } 0.95$$
$$= 180° - 18.2° = 161.8°$$

e. Voltage E_2 of the dc link:

$$E_2 = 1.35 E_s \cos \alpha_2 \qquad (21.4)$$
$$= 1.35 \times 511 \times \cos 161.8° = -655 \text{ V}$$

The dc voltage drop across inductor L is negligible, consequently, $E_1 = E_2 = 655$ V

f. Firing angle α_1:

Converter 1 acts as a rectifier, hence:

$$E_1 = 1.35 E_L \cos \alpha_1 \qquad (21.4)$$
$$655 = 1.35 \times 600 \times \cos \alpha_1$$
$$\alpha_1 = \text{arccos } 0.808 = 36.0°$$

g. Active power supplied to converter 1:

$$P = E_1 I = 655 \times 293 = 191\,915 \text{ W} = 192 \text{ kW}$$

Displacement power factor of converter 1:

$$PF = \cos \alpha_1 = \cos 36.0° = 0.809 = 80.9\ \%$$

Apparent power absorbed by converter 1:

$$S = 192 \text{ kW}/0.809 = 237 \text{ kVA}$$

Reactive power absorbed by converter 1:

$$Q = \sqrt{S^2 - P^2}$$
$$= \sqrt{237^2 - 192^2} = 139 \text{ kvar}$$

h. Mechanical power developed by the motor:

$$P_m = 192 \text{ kW} \times 0.93 = 179 \text{ kW} \approx 240 \text{ hp}$$

Cycloconverter Drive

- Kelebihan
  - Torsi starting besar
  - Kecepatan starting kecil
- Kekurangan
  - Tidak cocok dipakai untuk frek 1.5x dari fek nominal

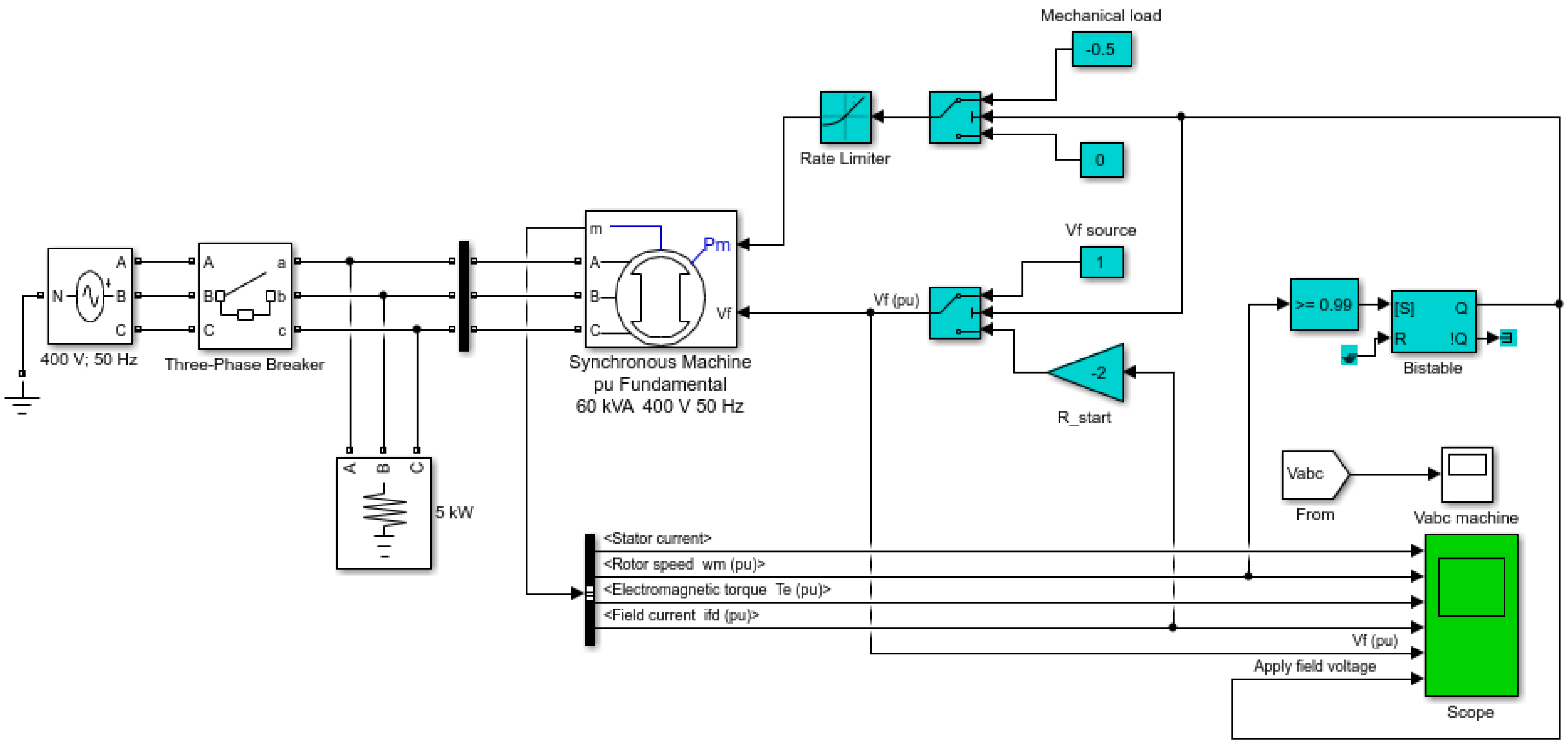
Simulasi Motor Sinkron

Starting a Synchronous Motor

This example shows the starting procedure for a synchronous motor.

Richard Gagnon (Hydro-Quebec)

Open Model



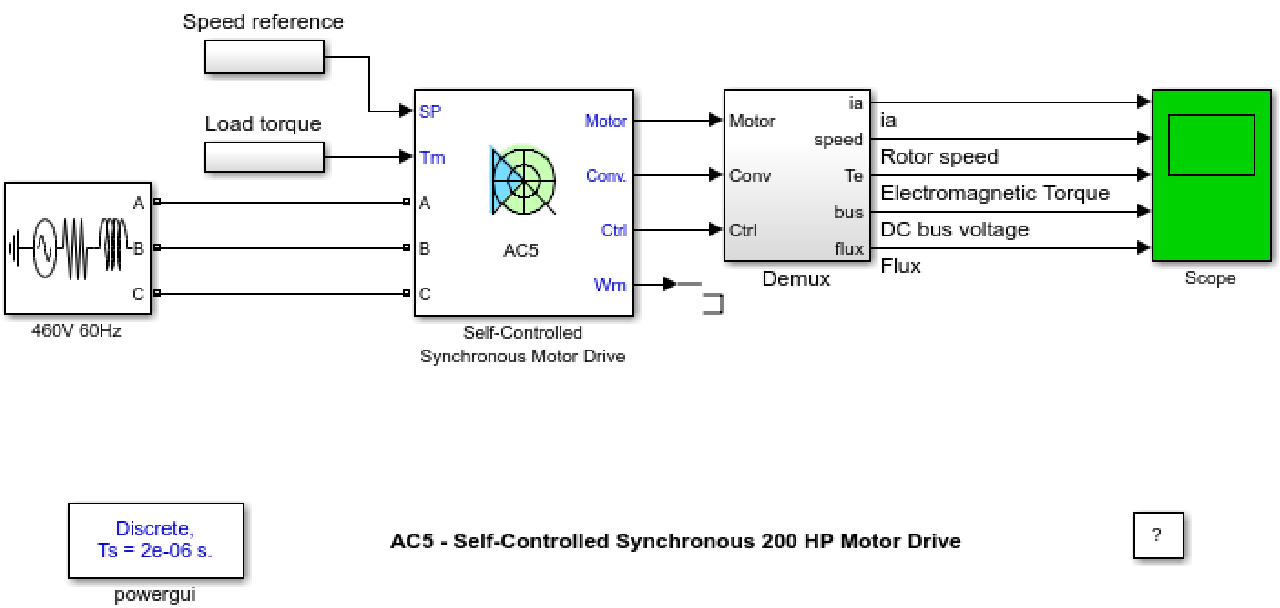
Kendali Motor Sinkron

AC5 - Self-Controlled Synchronous 200 HP Motor Drive

This example shows the AC5 Self-Controlled Synchronous motor drive during speed regulation.

H.Blanchette, L.-A. Dessaint (Ecole de technologie superieure, Montreal)

Open Model



Aplikasi Genset Sederhana

Emergency Diesel-Generator and Asynchronous Motor

This example shows the Machine Load Flow tool of Powergui block to initialize an induction motor/diesel-generator system.

G. Sybille (Hydro-Quebec), Tarik Zabaiou (ETS)

Open Model