EN 206 - Power Electronics and Machines

Synchronous Machine

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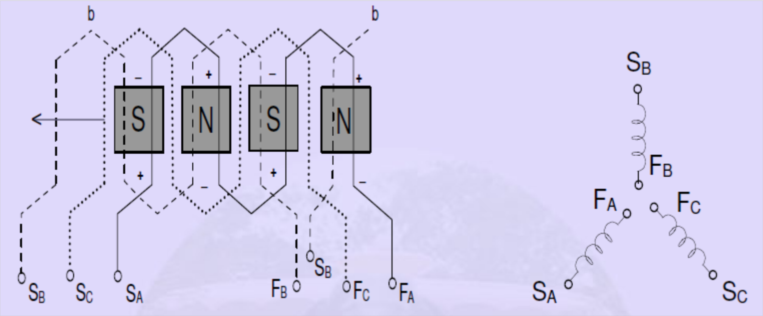
Lecture Organization - Modules

- Introduction and Power Semiconductor Switches
- Module 1: Transformers
- Module 2: AC/DC converter / Rectifier
- Module 3: DC machines and Drives
- Module 4: DC/DC converter
- Module 5: Induction Machine
- Module 6: DC/AC converter / Inverter
- Module 7: AC/AC converter / Cyclo converter
- Module 8: Synchronous Machine
- Module 9: Special Topics: Machines, HVDC, APF

Construction

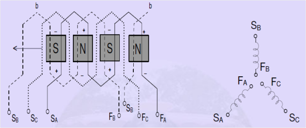
- Synchronous Motor/Generator
  - Field is rotating (large size machines)
  - Armature is stationary
- Rotor
  - Salient pole (Low Speed- Hydro turbine)
  - Non-Salient pole (High Speed Steam turbine)
- Field is excited by 'dc' supply
  - DC generator
  - Power Electronic converter
  - Brush less excitation
- AC voltage is available across armature/stationary conductors
  - Concentrated winding
  - Distributed winding

EMF Generation in Synchronous Machine



- Assume : The poles are moving to left, then relative motion of conductors is to the right
- Identical magnetic conditions will be seen by coil A followed by C and followed by B.
- Induces EMF with phase sequence of ACB

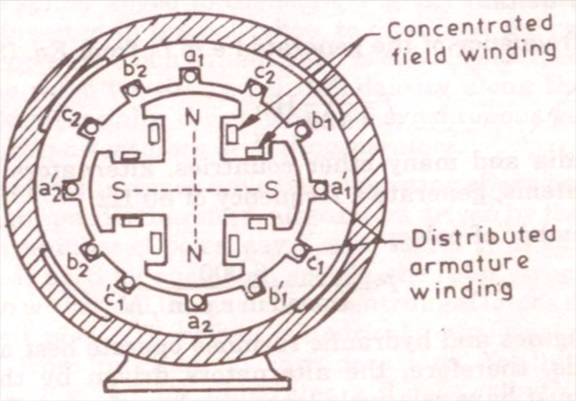
Frequency in Synchronous Generator



- In one revolution
    1. Two pole machine generates one full waveform (one cycle)
    2. Four pole machine generates two full waveforms (two cycles)
- Electrical degrees = pole pair * mechanical degree of rotation
- For one revolution/sec, the frequency of emf wave = pole pair
- Frequency = (P/2)*(N/60)=(PN)/120

Construction - Generator

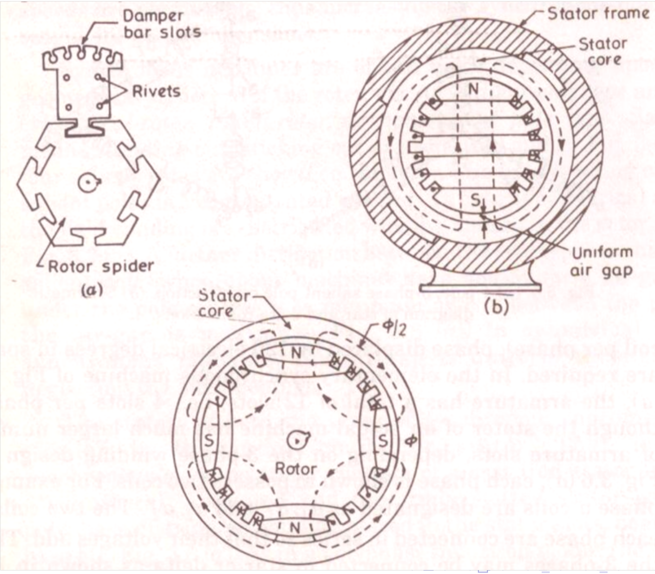
- Salient Pole Rotor
  - 4 pole, three phase salient pole rotor with concentric field windings.



Connections - Generator

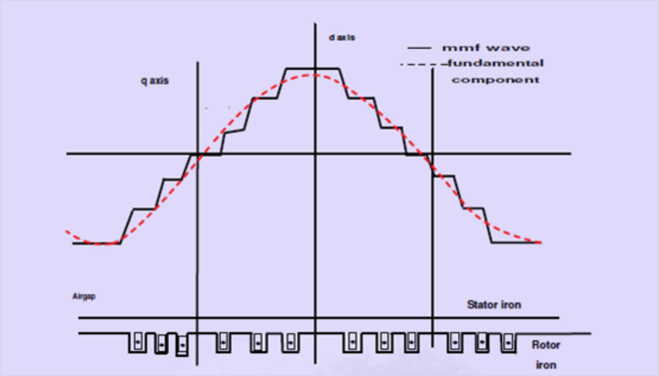
- Distributed armature winding
  - Three phase armature winding is distributed in 12 slots - 4 slots per pole.

Rotor Structures



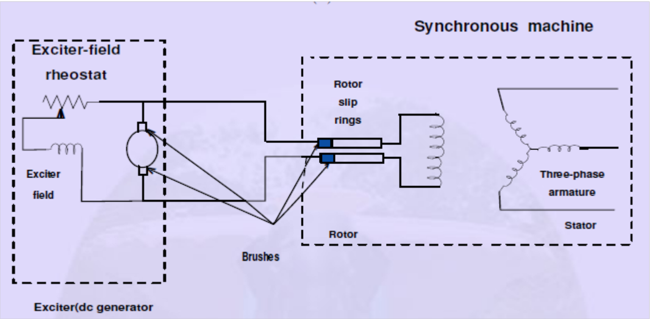
Rotor MMF

Cylindrical rotor mmf wave and its fundamental of a synchronous machine

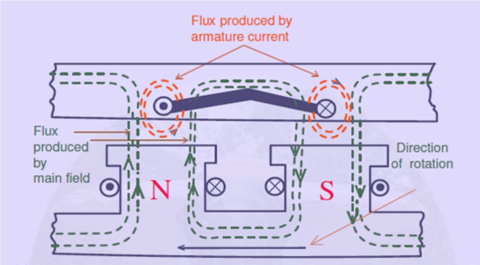


Excitation Systems

- Field ac or dc?
- Adjustment of field current can be either automatic or manual based on complexity of system it is connected to.
- Voltage is up to 125V for 50kW system and higher voltage for higher system rating.

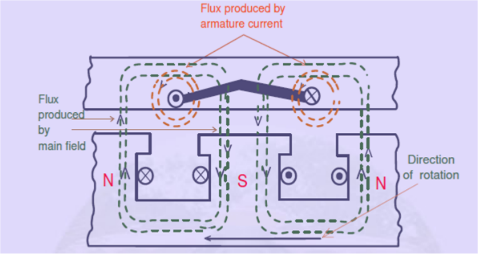


Loaded Generator - UPF



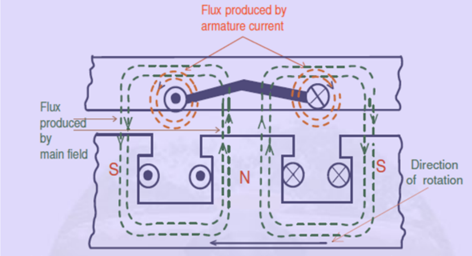
- Assume: A conductor induces maximum emf when it is under direct influence of pole.
- Current and emf magnitude are maximum at same instant in case of purely resistive loads.
- The flux produced by the armature is demagnetizing under north pole and magnetizing under south pole.
- The next flux remains same in the airgap.

Loaded Generator - ZPF (lagging)



- Assume: A conductor induces maximum emf when it is under direct influence of pole.
- Current is maximum when voltage is minimum.
- The flux produced by the armature is demagnetizing under both north pole and south pole.
- The next flux in the airgap reduces.

Loaded Generator - ZPF (leading)

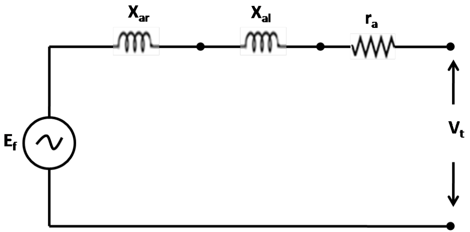


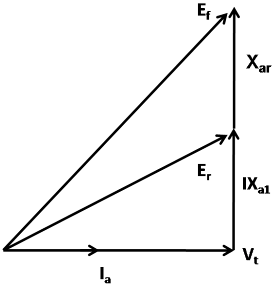
- Assume: A conductor induces maximum emf when it is under direct influence of pole.
- Current is maximum when voltage is minimum.
- The flux produced by the armature is magnetizing under both north pole and south pole.
- The next flux in the airgap increases.

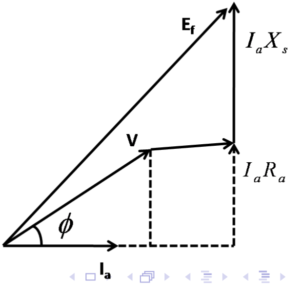
Armature and Field mmf

- If I_a lags emf by 90^0 (zero power factor) then it can be proven the F_a is entirely demagnetizing F_f.
- If I_a leads emf by 90^0 (zero power factor) then it can be proven the F_a is entirely magnetizing F_f.
- For motoring operation the same analysis is applicable by substituting I_a in place of I_a
- If armature current lags emf by 90^0, the nature of armature mmf is
  - demagnetizing in an alternator
  - magnetizing in a synchronous motor
- If armature current leads emf by 90^0, the nature of armature mmf is
  - magnetizing in an alternator
  - demagnetizing in a synchronous motor

Phasor Diagram-Resistive and inductive load







Characteristics of Synchronous Generator

- Open circuit and short circuit characteristics are useful to determine the parameters of a synchronous machine
- OCC: The alternator is driven at rated speed and open circuit voltage reading is noted as the field current is increased. The final value of E_f should be 125% of the rated voltage
- OCC is also called as no-load, saturation or magnetization characteristic and is not straight line because of saturation in the iron part of magnetic circuit.
- SCC: The machine is driven at rated synchronous speed and the armature terminals are short-circuited through an ammeter. The field current is varied till the armature current reading is 125 to 150% of rated value.
- SCC is a straight line through origin. Saturation does not occur as F_a is demagnetizing in nature

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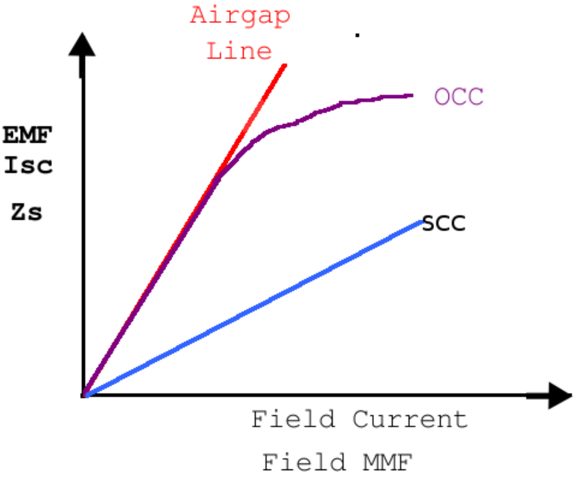


Voltage Regulation of Synchronous Generator

- It is defined as change in terminal voltage expressed as a percentage of the rated voltage, when the load at a given power factor is removed.
- In case of small machines, this test can be directly performed
- In case of large machines, it is not economical or technically feasible to perform voltage regulation test at laboratory
- Voltage regulation helps in
  - determining the voltage levels - insulation level
  - Automatic voltage regulator equipment design
  - Steady state short-circuit condition and stability are effected by the voltage regulation
  - Parallel operation of one alternator with other alternator, is effected considerable by voltage regulation

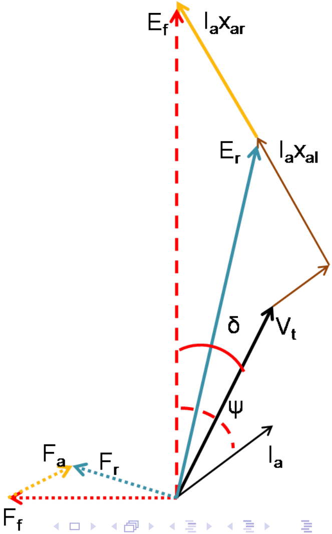
Methods - Determine Voltage Regulation

- EMF method or synchronous impedance method (Pessimistic approach)
  - Applicable for cylindrical rotor machines
  - The lowest values of Z_s obtained from largest value of SCC is used in computation
  - SCC: The effect of armature flux is demagnetizing and hence the flux density is much less than the flux density in actual condition - an unsaturated value of Z_s is obtained.
- Mmf method (Optimistic Approach)
- ZPF method (Potier traingle)
- New ASA method
- Saturated synchronous reactance method

EMF Method - Cylindrical rotor

Field mmf F_f generates E_f lagging it by 90^0

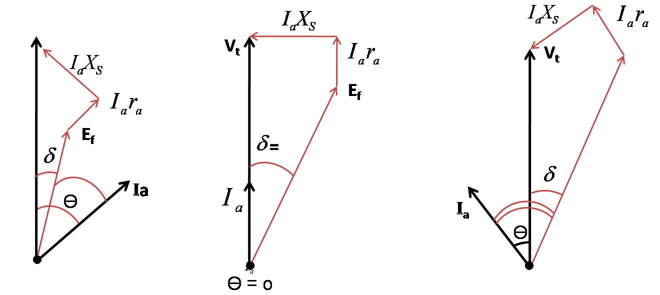
- Resultant mmf F_r generates E_r lagging it by 90^0. Armature reaction mmf F_r generates E_{ar} lagging it by 90^0
- X_{ar} is armature reaction reactance, it is a fictitious reactance which accounts for the voltage E_{ar} generated by armature reaction mmf E_a.
- The term $r_a + jX_s = Z_s$ is called synchronous impedance, $X_s = X_{al} + X_{ar}$



Synchronous Motor - Phasor Diagram

The analysis of synchronous machine can be carried out by using phasor diagram

For an alternator, phasor E_f is always ahead of phasor V_t, and for a synchronous motor, phasor E_f is always behind phasor V_t



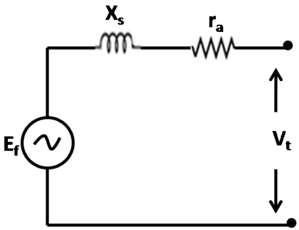
Lagging pf　　upf　　Leading pf

For a cylindrical rotor machine
Generator

- $P_{ig} = \frac{E_f V_t}{Z_s} sin(\delta - \alpha_z) + \frac{E_f^2}{Z_s^2} r_a$
- $P_{og} = \frac{E_f V_t}{Z_s} sin(\delta + \alpha_z) - \frac{V_t^2}{Z_s^2} r_a$
- $Q_{og} = \frac{E_f V_t}{Z_s} cos(\delta + \alpha_z) - \frac{V_t^2}{Z_s^2} X_s$

Motor

- $P_{im} = \frac{E_f V_t}{Z_s} sin(\delta - \alpha_z) + \frac{V_t^2}{Z_s^2} r_a$
- $P_{om} = \frac{E_f V_t}{Z_s} sin(\delta + \alpha_z) - \frac{E_f^2}{Z_s^2} r_a$
- $Q_{im} = -\frac{E_f V_t}{Z_s} cos(\delta - \alpha_z) + \frac{V_t^2}{Z_s^2} X_s$



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A synchronous machine has been synchronized with an infinite bus. Now, without changing the field current, the machine is made to deliver real power to the bus. Will it, at the same time, generate or consume reactive power?

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A synchronous generator is running overexcited with $E_F = 1.40pu$. This machine, with a synchronous reactance of 1.20pu is delivering a synchronous power of 0.5pu to the bus. If the primemover torque is increased by 1%, by how much will the active power P and reactive power Q change?

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- $\frac{dQ}{dP} = -tan\delta = \tan(25.4) = -0.475$, therefore dQ=-0.475x1% = -0.475%

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"1% increase in primemover torque leads to 1% increase in real power but 0.475% decrease in reactive power."

Reactive Power Flow

Generator

- When $E_f cos\delta > V_t$ (over excited), Q_{og} is positive and delivers reactive power, alternator operates at lagging pf
- When $E_f cos\delta = V_t$ (normal excited), Q_{og} is zero and alternator operates at unity pf
- When $E_f cos\delta < V_t$ (under excited), Q_{og} is negative and absorbs reactive power, alternator operates at leading pf

Motor

- When $E_f cos\delta > V_t$ (over excited), Q_{im} is negative and delivers reactive power, motor operates at leading pf
- When $E_f cos\delta = V_t$ (normal excited), Q_{im} is zero and alternator operates at unity pf
- When $E_f cos\delta < V_t$ (under excited), Q_{im} is positive and absorbs reactive power, motor operates at lagging pf

Problem

A 3300V, star connected synchronous motor has synchronous impedance of 0.4+j0.5 ohm/phase. For an excitation emf of 4000V and motor input power of 1000kW at rated voltage, compute the line current and power factor.

Solution

Given Data:
$V_t = 3300/\sqrt{3} = 1905.3V$,$\alpha_z = tan^{-1}(0.4/5) = 4.57^o$,
$E_f = 4000/\sqrt{3} = 2309.5V$, $Z_s = \sqrt{0.4^2 + 5^2} = 5.016$
Input power (per phase) for the machine is given by

- $P_{im} = \frac{E_f V_t}{Z_s} sin(\delta - \alpha_z) + \frac{V_t^2}{Z_s^2} r_a$, substituting

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- $sin(\delta - \alpha_z) = 0.314$, $\delta = 18.31 + 4.57 = 22.88^o$

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From the vector diagram

- $I_a Z_s =$
  $\sqrt{1905.3^2 + 2309.5.3^2 - 2x1905.3x2309.5xcos(22.88)}$

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- $E_f cos\delta = 2309.5xcos(22.88) = 2127.87 > 1905.3$

Solution

Given Data:

$V_t = 3300/\sqrt{3} = 1905.3V, \alpha_z = tan^{-1}(0.4/5) = 4.57^o$,
$E_f = 4000/\sqrt{3} = 2309.5V,\ Z_s = \sqrt{0.4^2 + 5^2} = 5.016$

Input power (per phase) for the machine is given by

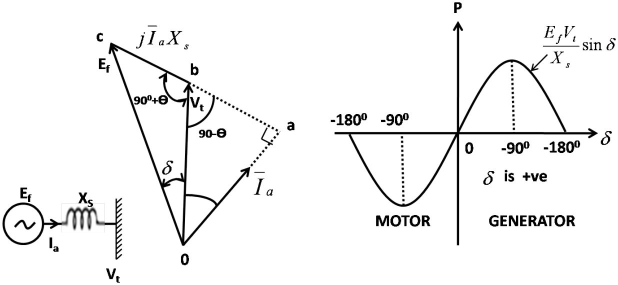
- $P_{im} = \frac{E_f V_t}{Z_s} sin(\delta - \alpha_z) + \frac{V_t^2}{Z_s^2} r_a$, substituting
- $1000000/3 = \frac{1905.3x2309.5}{5.016} sin(\delta - \alpha_z) + \frac{1905.3^2}{5.016^2} x0.4$
- $sin(\delta - \alpha_z) = 0.314,\ \delta = 18.31 + 4.57 = 22.88^o$

From the vector diagram

- $I_a Z_s = \sqrt{1905.3^2 + 2309.5.3^2 - 2x1905.3x2309.5xcos(22.88)}$
- $I_a = 184.43A$
- $3V_t I_a cos(\theta) = 1000kW$
- $cos\theta = \frac{1000000}{3x1905.3x184.43} = 0.9486$
- $E_f cos\delta = 2309.5xcos(22.88) = 2127.87 > 1905.3$

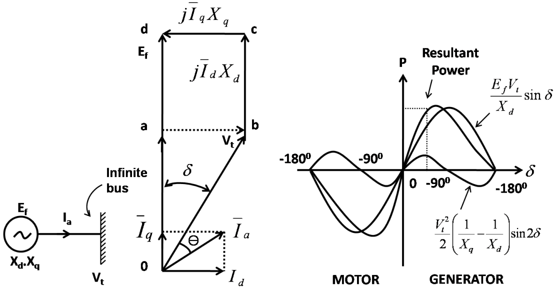
The motor is operating at a leading power factor of 0.9486.

Cylindrical rotor machine



- Resistance of synchronous machine is usually small and hence neglected
- Power delivered to infinite bus $(P) = V_t I_a cos\theta$
- From figure, $I_a X_s cos\theta = E_f sin\delta$
- $P = \frac{E_f V_t}{X_s} sin\delta$

Synchronous machine connected to infinite bus
Salient pole machine



- The per phase power delivered is given by $P = I_d(V_t sin\delta) + I_q(V_t cos\delta)$
- $V_t sin\delta = ab = bc = I_q X_q$ and $V_t cos\delta = oa = od - ad = od - bc = E_f - I_d X_d$
- $I_d = \frac{E_f - V_t cos\delta}{X_d}$

The per phase power transferred to the bus is given by:

$$P = \frac{E_f V_t}{X_d} sin\delta + \frac{V_t^2}{2}(\frac{1}{X_q} - \frac{1}{X_d})sin2\delta$$

- It is a combination of fundamental component and second harmonic component
- The first term (identical to cylindrical rotor machine) is termed as electromagnetic power
- The armature reaction flux passes through low reluctance path (i.e., field pole axis or direct axis)
- The second component is mainly due to reluctance of both d and q axes and hence termed as reluctance power.
- Motor may continue to rotate as reluctance motor even when field excitation is reduced to zero.