EE-565 - W13 SYNCHRONOUS MACHINES

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SYNCHRONOUS MACHINES

The SM are AC machines having similiarities with induction machines, but not quite the same

Asynchronous machines – rotor revolves at speed slightly slower than synchronous speed

Synchronous machines – rotor revolves at synchronous speed

$$n_s = \frac{60 f_s}{p}$$

f_s - stator frequency, p - number of pole pairs

Stator of SM:

- magnetic circuit and windings are rather the same as for IM

Rotor of SM:

- wound rotor with excitation winding supplied by DC – externally controlled flux
- permanent magnets build into rotor structure – built in flux

SYNCHRONOUS MACHINES

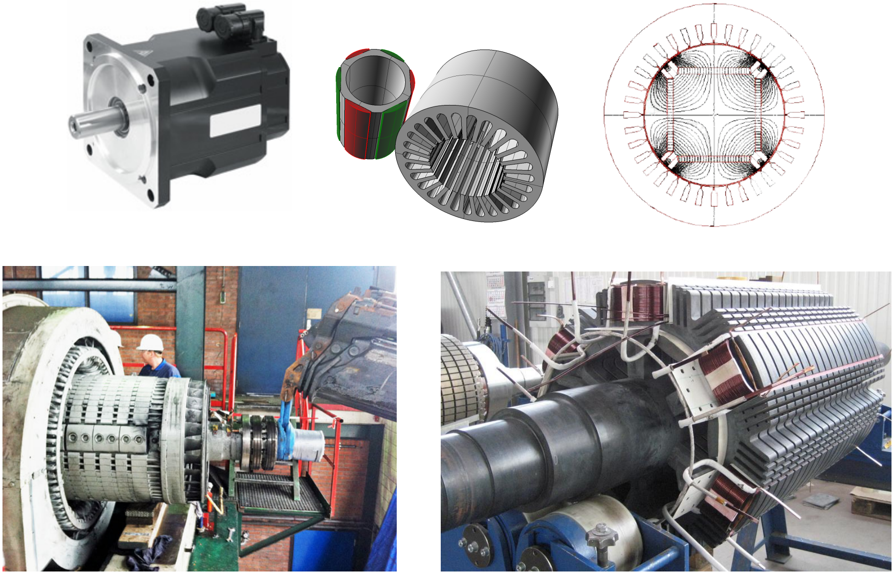


Figure 1 Synchronous machines - various parts.

SM – PRINCIPLE OF OPERATION

Like with IM, stator windings are supplied with AC currents

- stator currents create the stator magnetomotive force which revolves at synchronous speed
- synchronous speed is defined by stator excitation frequency and pole pair number
- stator magnetomotive force creates the stator flux
- stator flux vector rotates at the synchronous speed - the same for IM and SM
- rotor flux is established independently from the stator flux (excitation winding or magnets)
- rotor flux position is determined by the rotor mechanical position
- rotor flux vector rotates at the rotor speed
- both, stator flux and rotor flux rotate at the same speed
- the torque and power are dependent on the vector product of the two flux vectors
- the vector product depends on the angle between two vectors
- as they rotate at the same speed, angle between is constant in steady state

Synchronous Machines have been predominantly used as Synchronous Generators

Synchronous Motors are found today in many applications - always driven by power electronic converters

SM – STATOR WINDINGS

Three-phase stator windings:

- Star (left floating) or Delta connected windings
- sinusoidal distribution with 120° spatial displacement
- synchronous speed is determined as: $\omega_s = \omega_e / p$
- AC currents create rotating magnetomotive force
- Stator flux rotates at the same speed
- Leakage flux – part of a stator flux which does not reach rotor
- Mutual flux or air gap flux – part of a stator flux that reaches rotor
- Total air-gap flux of the machine has also contribution from the rotor

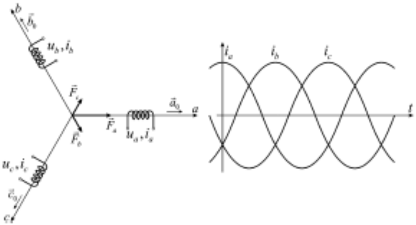


Figure 2 Three-phase stator winding of synchronous machine.

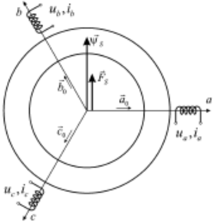


Figure 3 Vectors of the stator magnetomotive force and flux.

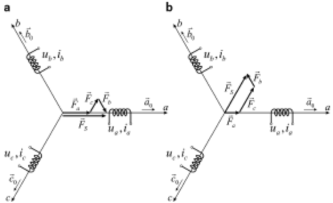


Figure 4 Spatial orientation of the stator magnetomotive force.

SM – TORQUE GENERATION

Torque generation is related to:

- presence of stator magnetomotive force and stator flux
- built-in or externally provided rotor magnetomotive force and rotor flux
- The torque can be expressed as vector product:

$$T_{em} = k_t \overrightarrow{\Psi_r} \times \overrightarrow{F_s}$$

- for a constant torque, relative position of vectors should stay constant
- stator mmf is related to stator current

$$T_{em} = k_t N_s \Phi_r I_s sin(\xi)$$

- ξ is the angle between the rotor flux vector and stator current
- to maximize Torque-per-Ampere:

$$\xi = \pm\pi/2$$

- ideally, we want to invest the lowest possible stator current
- magnetomotive force should be perpendicular to the rotor flux
- to achieve that, control action is needed

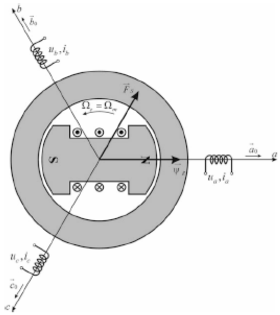


Figure 5 Position of rotor flux vector and stator magnetomotive force.

SM – STATOR CONSTRUCTION

Stator is made of feromagnetic material of suitable shape.

- laminated sheets are used to reduce eddy current losses
- hot rolled sheets provide isotropic behaviour – the same properties in all directions
- windings are placed into slots
- between slots are teeths, where flux is directed since reluctance is lower

$$R_\mu = \frac{l}{\mu_0 \mu_r A}$$

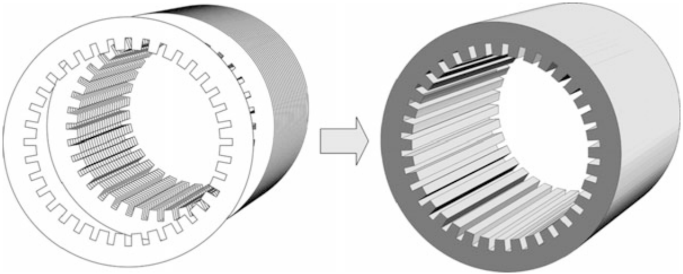


Figure 6 Stator magnetic circuit is made by stacking iron sheets.

Rotor construction of SM is quite different from rotor of IM

- Permanent Magnets: provide rotor flux without external excitation
- Excitation Windings: provide controlled rotor flux from external source

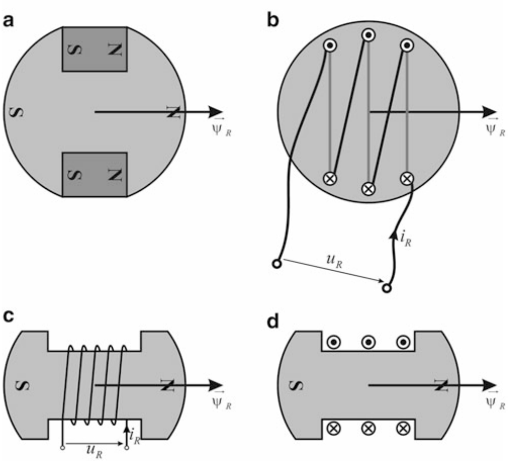


Figure 7 a) Rotor with permanent magnets. b) Rotor with excitation winding. c) Rotor with excitation winding and salient poles. d) Common symbol for denoting the rotor in figures and diagrams.

SM – ROTOR CONSTRUCTION (II)

Permanent Magnet SM

- there is no rotor magnetomotive force that could be controlled externally
- Permanent Magnets have relatively high remanent induction B, which defines the rotor flux
- rotor flux is therefore obtained in a loss-less manner
- construction is simplified
- losses are reduced
- efficiency is increased
- yet, penalty is that rotor flux cannot be changed and Field Weakening is virtually impossible

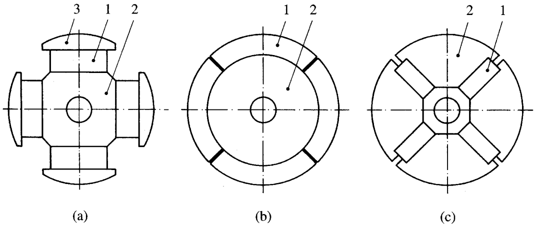


Figure 8 SM Rotor possibilities: a) Salient pole (wound) rotor, b) Surface (exterior) mounted magnets, c) Burried (interior) mounted magnets.

SM – EXCITATION WINDING

Wound Rotor SM has excitation windings on the rotor, accesible from the outside:

- N turns on rotor carry DC current
- magnetomotive force of the excitation winding is:

$$F_r = N_r I_r$$

- excitation flux is determined as:

$$\Phi_r = N_r I_r / R_\mu$$

- total flux of excitation winding is:

$$\Psi_r = N_r \Phi_r = (N_r^2 / R_\mu) I_r = L_r I_r$$

- small amount of total flux does not reach stator magnetic circuit – excitation leakage flux
- major part of total flux reaches stator – mutual flux
- excitation windings are usually made as Salient poles
- small air gap and low magnetic resistance along the path of excitation flux
- larger air gap and higher magnetic resistance in direction perpendicular to flux path
- controllable flux, but increased losses and more complex construction

Two common way to supply excitation winding are:

Direct Excitation:

- slip rings mounted on rotor shaft, connecting excitation windings
- DC current is provided through the brushes from external DC source
- good control of flux but mechanical wear and arcing are problematic

Brushless Excitation:

- rotating transformer mounted on the rotor shaft
- primary (static) side is suppied from external AC source
- secondary side rotates with rotor and has diodes connected for rectification
- high reliability and low maintenance

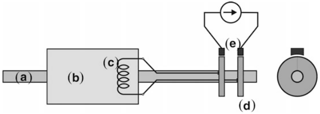


Figure 9 Passing the excitation current by the system with slip rings and brushes. (a) Shaft. (b) Magnetic circuit of the rotor. (c) Excitation winding. (d) Slip rings. (e) Brushes.

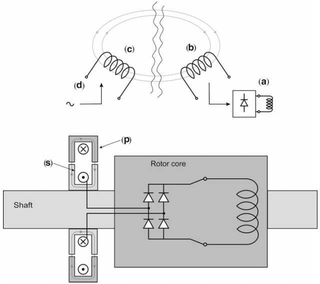
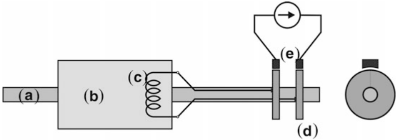


Figure 10 Contactless excitation system with rotating transformer. (a) Diode rectifier on the rotor side. (b) Secondary winding. (c) Primary winding. (d) Terminals of the primary fed from the stator side. (P) Stator part of the magnetic circuit. (S) Rotor part of the magnetic circuit



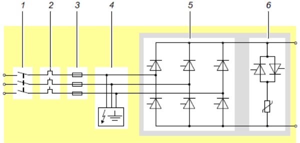
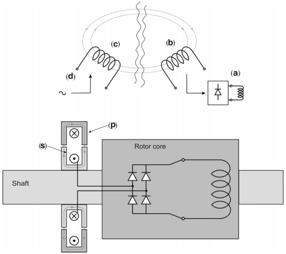


Figure 1 Block diagram of EXU type ED5V

1 Circuit breaker
2 Thermal overcurrent protection
3 Fuses
4 Earth fault detection (option)
5 Thyristor bridge of DCS800-S01 type D4
6 Overvoltage protection

Figure 11 Direct Excitation



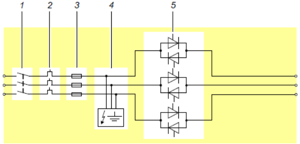


Figure 3 Block diagram of EXU type EB5R

1 Circuit breaker
2 Thermal overcurrent protection
3 Fuses
4 Earth fault detection (option)
5 DCS800-S03 power controller type D4

Figure 12 Brushless Excitation

Permanent magnets offer certain advantages:

- only a part of rotor assembly is filled with magnets, while remaining part is made out of iron
- Permanent Magnets can be mounted differently
- Surface mounted permanent magnets
- Interior mounted (buried) permanent magnets
- mounting method has effect on stator inductance (inversely proportional to magnetic resistance)
- machine's losses are significantly reduced due to absence of rotor supply

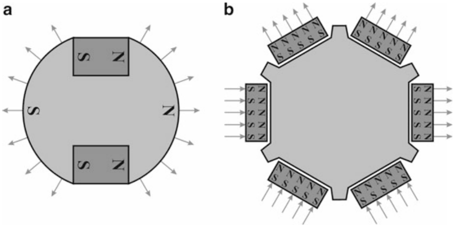


Figure 13 PMSM: (a) Rotor with interior magnets. (b) Surface-mounted magnets

Magnetizing characteristics

- remanent induction B_r exists without external excitation
- $B_R > 1T$ for PM
- $B_R \approx 0.3T$ for Ferrites
- $B_R > 50mT$ for iron sheets
- opposite external field H may reduce magnetic induction
- if Coercitive field is reached, PM could be damaged (knee point is critical for operation)
- in the first quadrant of B-H characterists all magnetic dipoles are already oriented
- differential permeability of permanent magnets is roughly equal to that of air or vacuum

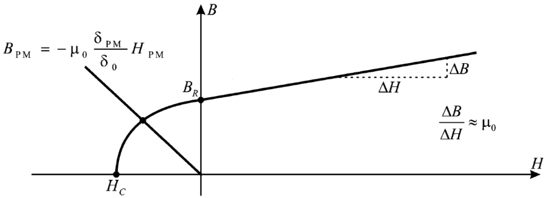


Figure 14 Magnetizing characteristic of permanent magnet

SM – PERMANENT MAGNETS MOUNTING

Stator flux is made out of:

- component due to rotor flux - Ψ_{mr}
- component due to stator currents - $L_s I_s$
- iron permeability is very high and field H in iron is negligible
- stator self-inductance depends on the magnetic resistance

Surface Mounted PM:

- thickness of magnets is several times the air gap thickness
- equivalent gap is therefore high
- magnetic resistance is therefore high
- stator self-inductance is very low – 1$\%$

Interior Mounted PM

- magnets are placed deeper into rotor iron, closer to the shaft
- equivalent gap is identical to air gap and is small
- magnetic resistance is therefore low
- stator self-inductance is high – 10$\%$ to 70$\%$

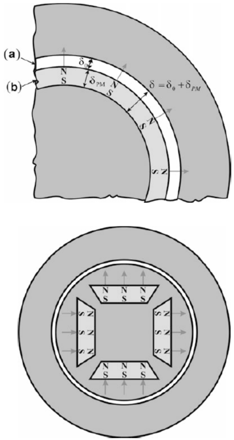


Figure 15 (top) Surface mounted PM; (bottom) Interior mounted PM