Synchronous Generators

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Synchronous Generators

- Synchronous generator is the common type used in generating stations.
- It runs at constant speed and generates constant frequency output.
- The field poles are on the rotor side and the armature is on stator side.
- The armature winding is placed in the slots on stator core.
- Field poles are excited with a dc supply.
- DC supply to the field poles are given through a pair of slip rings.
Types of Construction

Salient Pole type

Cylindrical Rotor type
Why Armature on Stator?

- Power in the field system is much less compared to the generated power, which is easily handled by the slip rings.

- When the armature is on the stator side, generated power is directly taken out without the help of slip rings.
Relation between Speed and Frequency

2 Pole

1 revolution per second (RPS) makes 1 Hertz

4 Pole

1 revolution per second (RPS) makes 2 Hertz

General case

\[ RPS = \frac{2f}{P} \]

where \( f \) is the frequency and \( P \) is the number of poles

\[ RPM, \quad N = \frac{120f}{P} \]
Synchronous Speed

- Synchronous speed is the speed at which the generator should run to produce a constant frequency.

\[
\text{Number of cycles per revolution} = \frac{P}{2}
\]

\[
\text{Revolution per second} = \frac{N}{60}
\]

\[
\text{Cycles per second} = \frac{P \times N}{2 \times 60} \quad \Rightarrow \quad f = \frac{P \times N}{2 \times 60}
\]

\[
\text{RPM}, \quad N = \frac{120f}{P}
\]

- \(f\) - frequency
- \(P\) - number of poles
- \(N\) - speed in RPM
Three Phase Generator

- There will be three sets of similar windings
- Windings are placed 120 degrees apart
- Practically each phase winding will be distributed across several slots
Practical Winding

Stator Windings Partially Completed

Stator Windings Completed
Single Layer Winding
Winding example (Full pitch)

No of poles: 2, No of slots: 12, Double layer    \[\Rightarrow\]    Slots/pole/phase = 12/(2\times3) = 2
Winding example (Full pitch)

3 phase
2 pole
12 slot
Double layer winding
Winding example (Short Chorded)

No of poles: 2, No of slots: 12, Double layer → Slots/pole/phase = 12/(2x3) = 2
Winding example (Short Chorded)

3 phase
2 pole
12 slot
Double layer winding
Features of Short Chording

- Saves copper in end connections
- Improve wave shape (reduce harmonics)
- Reduce losses – both copper loss and core loss
- Reduced voltage compared to full pitch
Slot Angle

Slot angle = \frac{180}{\text{Slots/pole}}

In this case (2 pole, 12 slot):

Slot angle = \frac{180}{6} = 30^\circ

For a 4 pole 36 slot machine:

Slot angle = \frac{180}{9} = 20^\circ
Pitch Factor

Let the voltage induced in a conductor is $E$

If the coil is full pitched,
Total induced voltage in a coil $= 2E$

If the coil is short pitched by an angle $\alpha$
Total induced voltage $= 2E \cos \frac{\alpha}{2}$
Pitch Factor

Also known as coil span factor

Let the voltage induced in a conductor is $E$

If the coil is full pitched,
Total induced voltage in a coil = $2E$

If the coil is short pitched by an angle $\alpha$
Total induced voltage = $2E \cos \frac{\alpha}{2}$

Pitch factor, $K_c = \frac{\text{Resultant emf of chorded coil}}{\text{Resultant emf of full piched coil}}$

$$= \frac{2E \cos \frac{\alpha}{2}}{2E} = \cos \frac{\alpha}{2}$$
Distribution factor

Distribution factor, $K_d = \frac{\text{emf with distributed winding}}{\text{emf with concentrated winding}}$

Slot angle, $\beta = \frac{180}{\text{Slots/pole}}$

$m = \text{Slots/pole/phase}$

$m\beta = \text{phase spread angle}$
Distribution factor

Distribution factor, \( K_d = \frac{\text{emf with distributed winding}}{\text{emf with concentrated winding}} \)

Arithmetic sum = \( m \cdot 2r \sin \frac{\beta}{2} \)

Vector sum = \( 2r \sin \frac{m\beta}{2} \)

\[
K_d = \frac{2r \sin \frac{m\beta}{2}}{m \cdot 2r \sin \frac{\beta}{2}} = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}}
\]

\( AB = 2r \sin \frac{\beta}{2} \)
Example

For a 3 phase 36 slot 4 pole winding find the distribution factor

Slot angle, $\beta = \frac{180}{\text{Slots per pole}} = \frac{180}{9} = 20^\circ$

Slots/pole/phase, $m = \frac{36}{4 \times 3} = 3$

Distribution factor, $K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}} = \frac{\sin \frac{3 \times 20}{2}}{3 \sin \frac{20}{2}} = 0.956$
EMF Equation

Z = Number of coil sides in series per phase
P = Number of poles
f = Frequency
N = Speed in RPM
Φ = Flux per pole

In one revolution each conductor is cut by ΦP webers

\[ d\Phi = \Phi P \quad dt = \frac{60}{N} \]

Average emf induced = \[ \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi NP}{60} \] volts

Substituting for \( N \)

Average emf induced = \[ \frac{\Phi P}{60} \times \frac{120 f}{P} = 2 f \Phi \] volts
EMF Equation

For the total winding, average emf \( = 2f\Phi Z \)
\[ = 4f\Phi T \]

RMS value \( = 4.44f\Phi T \)

Considering pitch factor and distribution factor,

RMS value of per phase voltage, \( E = 4.44 K_c K_d \Phi f T \) volts

\[ K_c = \cos \frac{\alpha}{2} \]
\[ K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}} \]
Example

A 4 pole 3 phase star connected alternator having 60 slots with 4 conductor per slot runs at 1500 rpm. Coils are short pitched by 3 slots. If the phase spread is 60 degrees, find the line voltage induced fir for a flux per pole of 0.75 Wb distributed sinusoidally in space. All turns per phase are in series.

Slots/pole/phase, \( m = \frac{60}{4 \times 3} = 5 \)

Slot angle, \( \beta = \frac{180}{\text{Slots/pole}} = \frac{180}{15} = 12^\circ \)

Coil pitch = \((15 - 3) \times 12 = 144^\circ\)    Short chording angle, \( \alpha = (180 - 144) = 36^\circ \)
Number of turns, \( T = \frac{60 \times 4}{2 \times 3} = 40 \)

\[
K_c = \cos \frac{\alpha}{2} = \cos \frac{36}{2} = 0.951
\]

\[
K_d = \frac{\sin \frac{m \beta}{2}}{m \sin \frac{\beta}{2}} = \frac{\sin \frac{5 \times 12}{2}}{5 \times \sin \frac{12}{2}} = 0.957
\]

Per phase voltage = \( 4.44 \times K_c \times K_d \times \Phi \times f \times T \)

\[
= 4.44 \times 0.951 \times 0.957 \times 0.75 \times 50 \times 40 = 6061.3 \text{ volts}
\]

Line voltage = \( \sqrt{3} \times V_{\text{ph}} \)

\[
= \sqrt{3} \times 6061.3 = 10498.5 \text{ volts}
\]
Harmonics

- Defined as sinusoidal voltages and currents at frequencies other than the fundamental frequency.
- Harmonic frequencies are integer multiples of the fundamental frequency

\[ f(x) = a_0 + \sum_{n=0}^{\infty} [a_n \cos(nx) + b_n \sin(nx)] \]
\( K_c \) and \( K_d \) for Harmonic Frequencies

\[
K_{cn} = \cos \frac{n\alpha}{2} \\
K_{dn} = \frac{\sin \frac{mn\beta}{2}}{m \sin \frac{n\beta}{2}}
\]

where \( n \) is the harmonic order

if \( n = 5 \) and \( \alpha = 36^\circ \) \( K_{c5} = \cos \frac{5 \times 36}{2} = 0 \)

Short chording can help to eliminate harmonics
Line voltage with harmonics in generated emf

\[ V_{RY} = V_R - V_Y \]
Line voltage with harmonics in generated emf

\[ V_{RY} = V_R - V_Y \]

Phase voltage

Third Harmonic voltages

Line voltage

Third harmonics cancel in line voltage
Slot Harmonics

- Distortion of flux occur due to variation of reluctance between the slot area and tooth area.
- Distortion of flux produce distortion in voltage waveform which is known as slot harmonics.
- Slot harmonics is reduced either by skewing of field poles or by incorporating fractional slot winding.
Methods for Elimination of Harmonics

- 120 Degrees phase spread
  - Eliminates 3rd order harmonics

- Short Chording
  - Eliminates 5th and 7th order harmonics

- Fractional slot winding
  - Eliminates slot harmonics

- Skewing of field poles
  - Eliminates slot harmonics

- Star connection
  - Eliminates triplen (order 3, 9, 15 etc) harmonics
120 Degree Phase Spread Winding
Fractional Slot Winding
Example

Calculate the rms value of induced voltage per phase of a 3 phase, 10 pole, 50 Hz, alternator with 2 slots per pole per phase and 4 conductor per slot in 2 layers. The coil span is 150 degrees. Flux per pole has a fundamental component of 0.12 Wb and a 20% third harmonic component. Also find the line voltage.

Slots/pole/phase, \( m = 2 \)  

Slot angle, \( \beta = \frac{180}{\text{Slots/pole}} = \frac{180}{6} = 30^\circ \)

Short chording angle, \( \alpha = (180 - 150) = 30^\circ \)

Number of turns, \( T = \frac{10 \times 2 \times 4}{2} = 40 \)
\[ K_c = \cos \frac{\alpha}{2} = \cos \frac{30}{2} = 0.966 \]
\[ K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}} = \frac{\sin \frac{2 \times 30}{2}}{2 \times \sin \frac{30}{2}} = 0.966 \]

Per phase fundamental voltage = \[4.44 \times K_c \times K_d \times \Phi \times f \times T\]
\[= 4.44 \times 0.966 \times 0.966 \times 0.12 \times 50 \times 40 = 995 \text{ volts}\]

\[ K_{c3} = \cos \frac{3\alpha}{2} = \cos \frac{3 \times 30}{2} = 0.707 \]
\[ K_{d3} = \frac{\sin \frac{mn\beta}{2}}{m \sin \frac{n\beta}{2}} = \frac{\sin \frac{2 \times 3 \times 30}{2}}{2 \times \sin \frac{3 \times 30}{2}} = 0.707 \]
\[
\Phi_3 = \frac{0.2 \times 0.12}{3} = 0.008 \text{ Wb} \quad \quad \quad \quad \quad f_3 = 150 \text{ Hz}
\]

Per phase third harmonic voltage:
\[
4.44 K_{c_3} K_{d_3} \Phi_3 f_3 T = 4.44 \times 0.707 \times 0.707 \times 0.008 \times 150 \times 40 = 106 \text{ volts}
\]

Per phase voltage:
\[
\sqrt{E_1^2 + E_3^2} = \sqrt{995^2 + 106^2} = 1000 \text{ volts}
\]

Line voltage:
\[
\sqrt{3 \times 995} = 1723.4 \text{ volts}
\]
Thank You