Electric Machinery III

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References for Electric Machinery III

Text: A. E. Fitzgerald, Charles Kingsley, Jr And Stephen D. Umans, *Electric Machinery*. Mc Graw Hill, 7th Edition

Reference 1: P.C. Sen, *Principles of Electric Machines and Power Electronics*. Wiley, 3rd Edition

Reference 2: P.S. Bimbhra, *Electrical Machinery* . Khanna Publication

Electrical Machine III Syllabus

1. Introduction

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2. Introduction to Rotating Machines

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3. Generation of Sinusoidal Voltage in a Synchronous Generator
   - Rotor Winding Factors
   - Stator Winding Factors
     - Stator Distribution Winding Factor
     - Stator Pitch Winding Factor
     - Generator Connections

4. Synchronous-Machine Analyses

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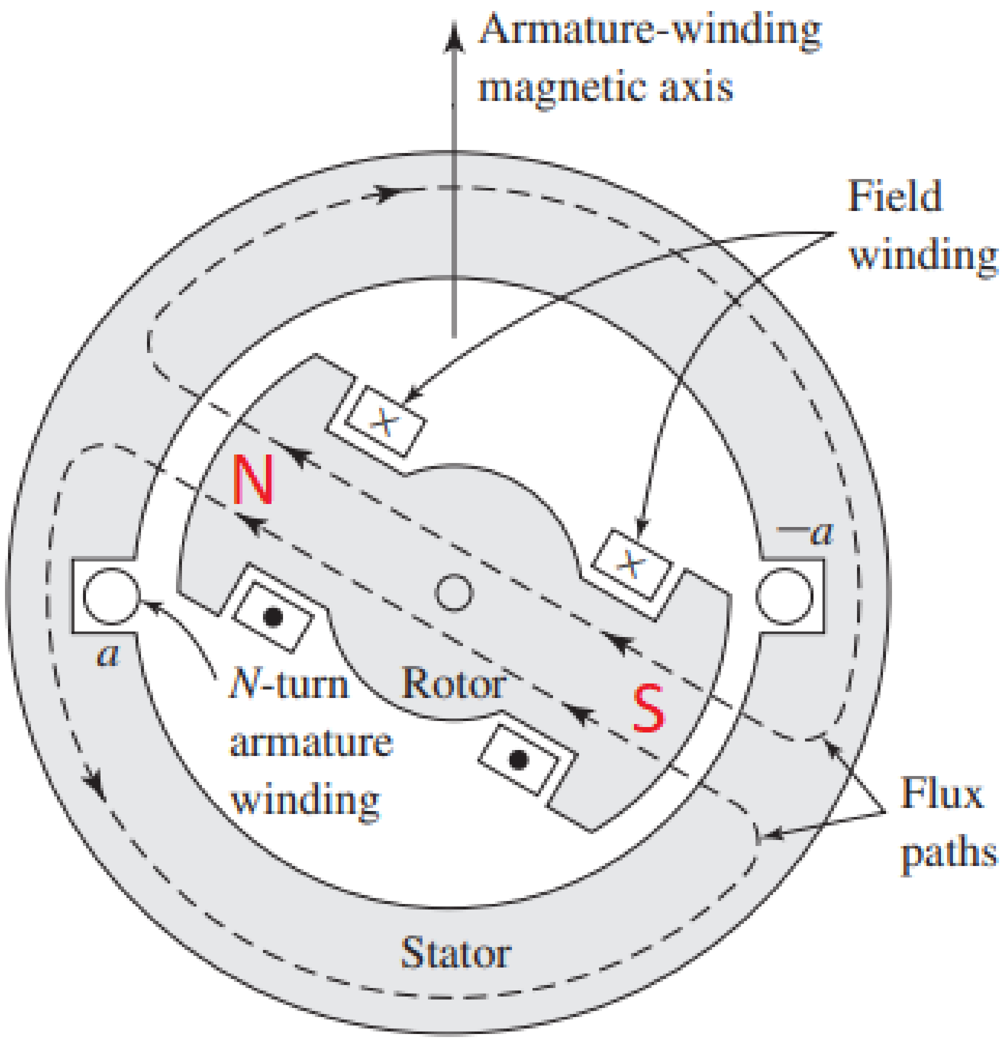
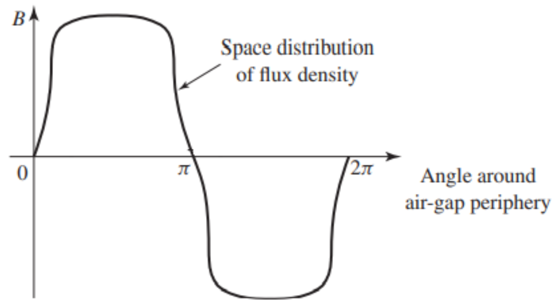
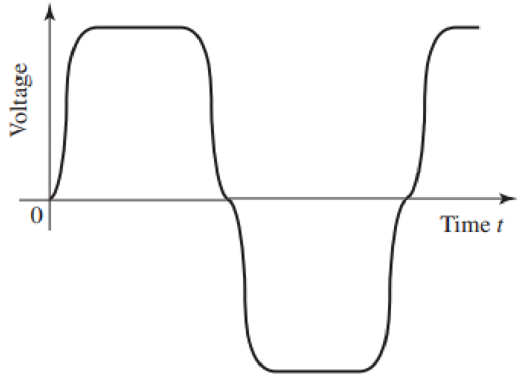
Generation of Sinusoidal Voltage in a Synchronous Generator



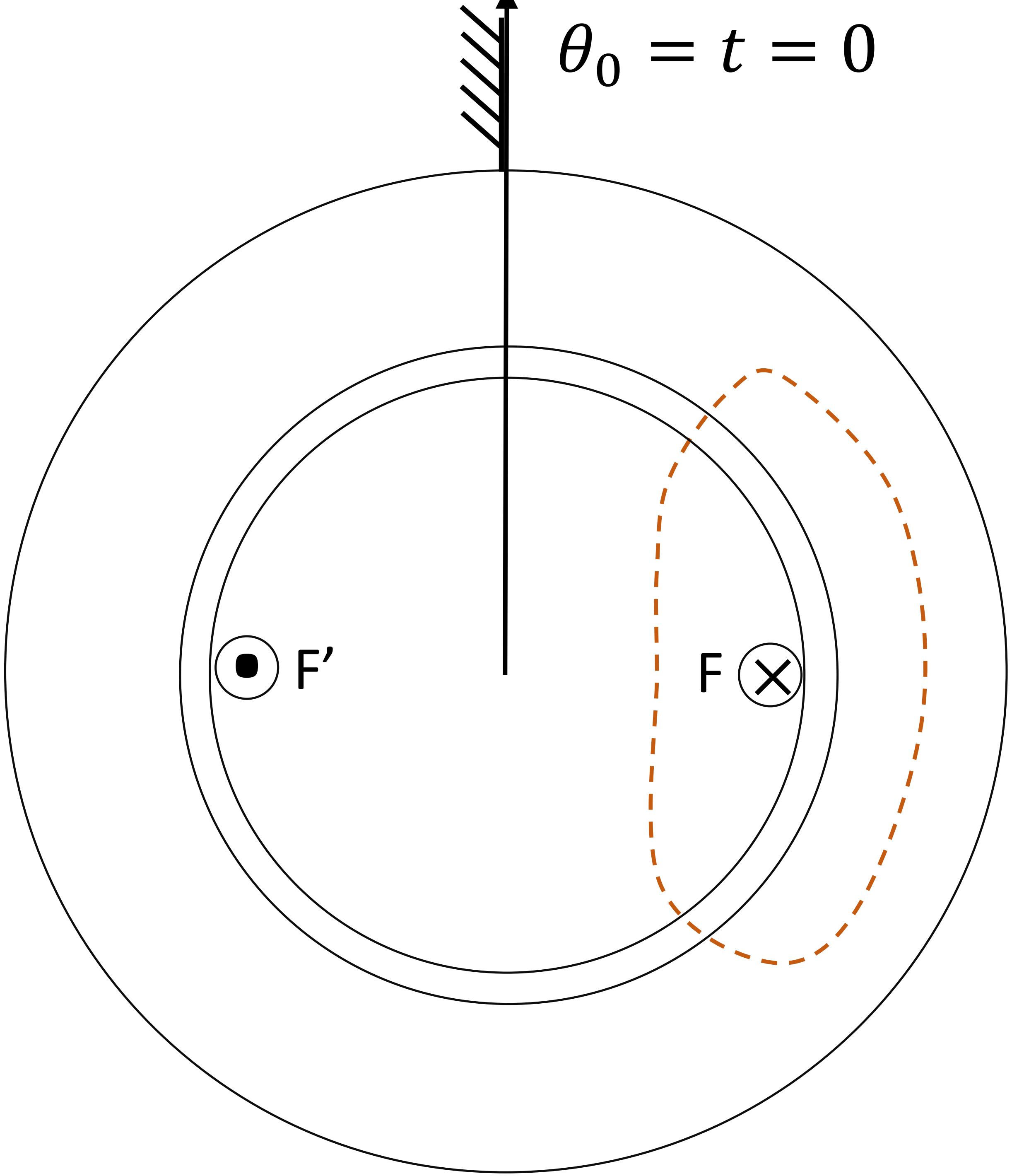


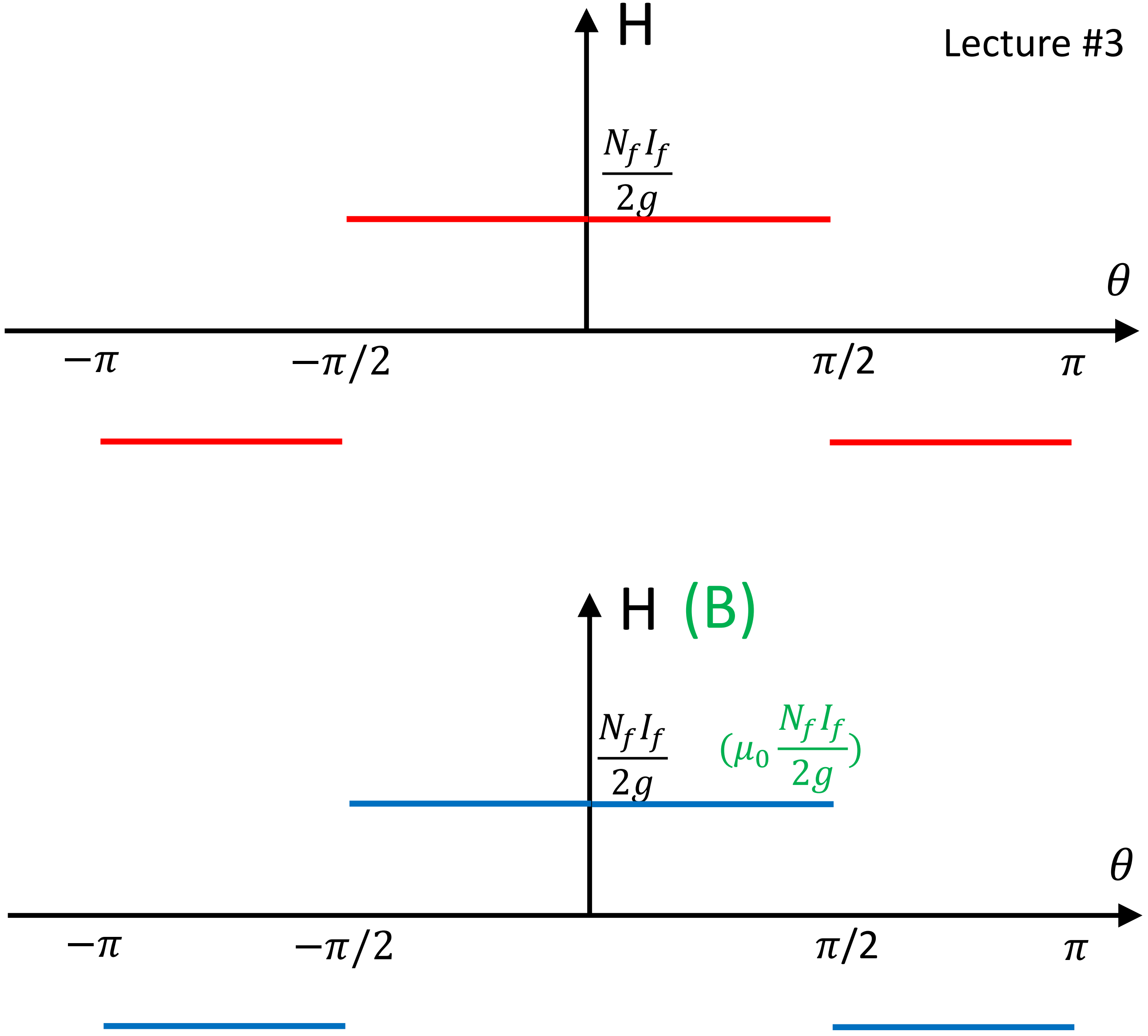
$e_a = ?$



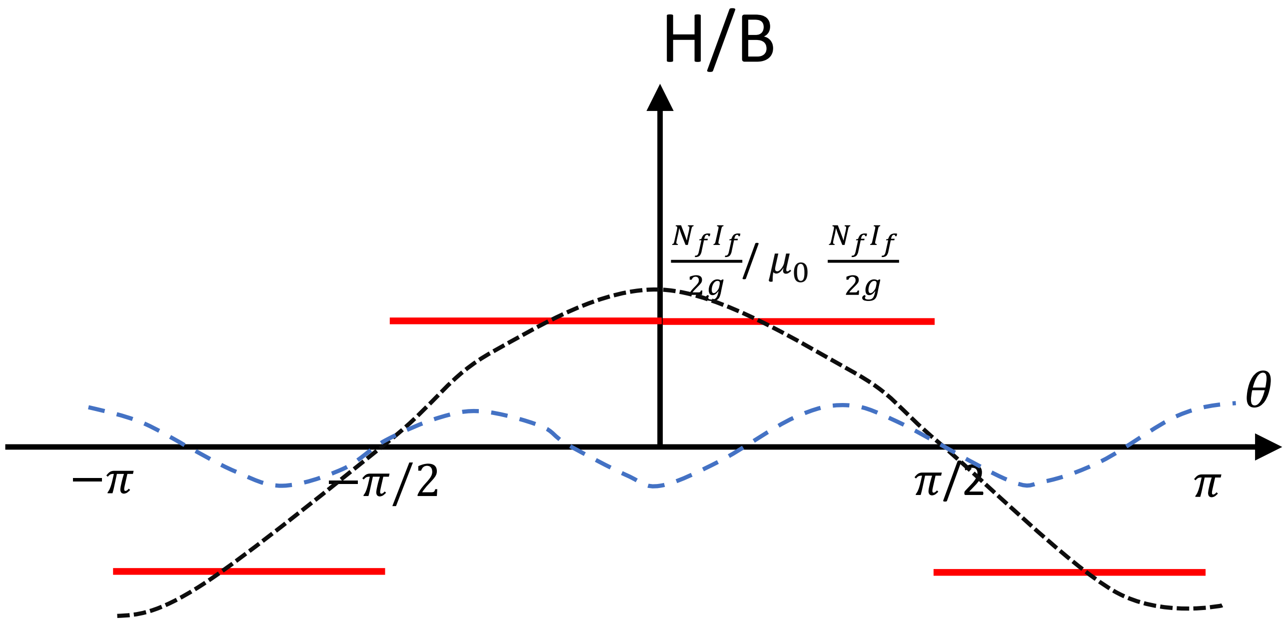
Does sinusoidal voltage?

How can we make it sinusoidal?


$\theta_0 = t = 0$
F'
F

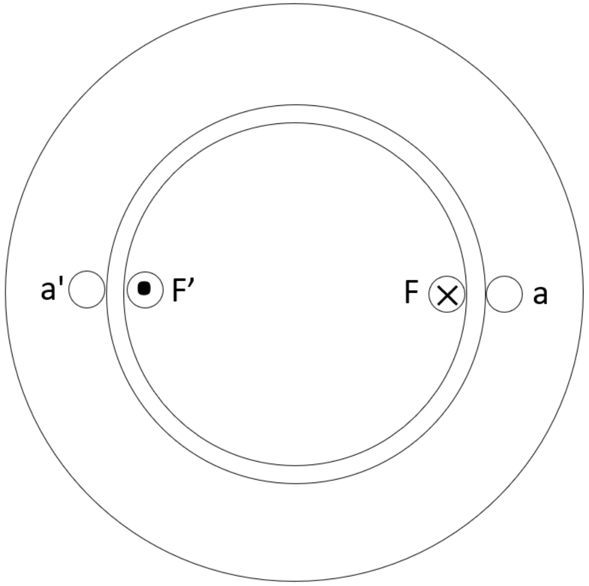

H
$\frac{N_f I_f}{2g}$
θ
$-\pi$
$-\pi/2$
$\pi/2$
π
H (B)
$\frac{N_f I_f}{2g}$
$(\mu_0 \frac{N_f I_f}{2g})$
θ
$-\pi$
$-\pi/2$
$\pi/2$
π

Generation of Sinusoidal Voltage in a Synchronous Generator



$$B= \frac{4}{\pi}\frac{N_f I_f}{2g}\mu_0\, cos\theta - \frac{4}{3\pi}\frac{N_f I_f}{2g}\mu_0\, cos3\theta + \frac{4}{5\pi}\frac{N_f I_f}{2g}\mu_0 cos5\theta - \cdots$$

Generation of Sinusoidal Voltage in a Synchronous Generator



$$B = B_1 \cos\theta + B_3 \cos 3\theta + B_5 \cos 5\theta + \cdots$$

$$e_{aa'} = e_1 \cos(\omega t - 90) + e_3 \cos 3(\omega t - 90) + e_5 \cos 5(\omega t - 90) + \cdots$$

$$e_i = 2lN_a r\omega B_i = \frac{4}{i\pi}\frac{N_f I_f}{2g}\mu_0 2lN_a r\omega$$

1- In the case of concentrated rotor winding, the i-th harmonic of the magnetic flux density is exactly 1/i of the fundamental harmonic.

2- In the case of concentrated stator winding and full-pitch winding, the generated ۲- voltage is exactly the same shape of Magnetic flux density, B.

Generation of Sinusoidal Voltage in a Synchronous Generator

$$B = B_1\, cos\theta + B_3\, cos3\theta + B_5\, cos5\theta + \cdots$$

$$e_{aa'} = e_1\ \cos(\omega t - 90) + e_3\, cos3(\omega t - 90) + e_5\, cos5(\omega t - 90) + \cdots$$

1- In the case of concentrated rotor winding, the i-th harmonic of the magnetic flux density is exactly 1/i of the fundamental harmonic.

2- In the case of concentrated stator winding and full-pitch winding, the generated voltage is exactly the same shape of Magnetic flux density, B. ۲-

Methods for Sine-Wave Shaping of Voltage

- Modifying windings to make magnetic flux density sine-shaped.
- Improving voltage shape relative to magnetic flux density B by modifying the stator winding.

Generation of Sinusoidal Voltage in a Synchronous Generator

Methods for Sine-Wave Shaping of Voltage

Modifying windings to make magnetic flux density sine-shaped

↓

Managing Rotor Windings

↓

Rotor Winding Distribution

Improving voltage shape relative to magnetic flux density B by modifying the stator winding

↓

Managing Stator Windings

- Stator Winding Distribution
- Stator Winding Pitch Fraction
- Stator Winding Connection

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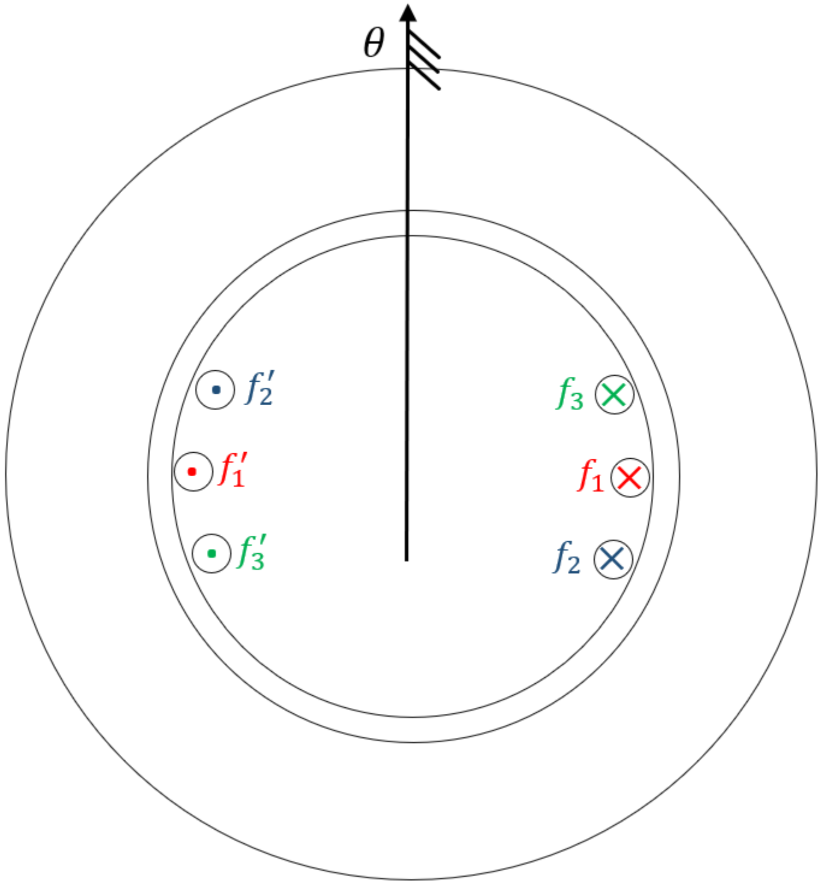
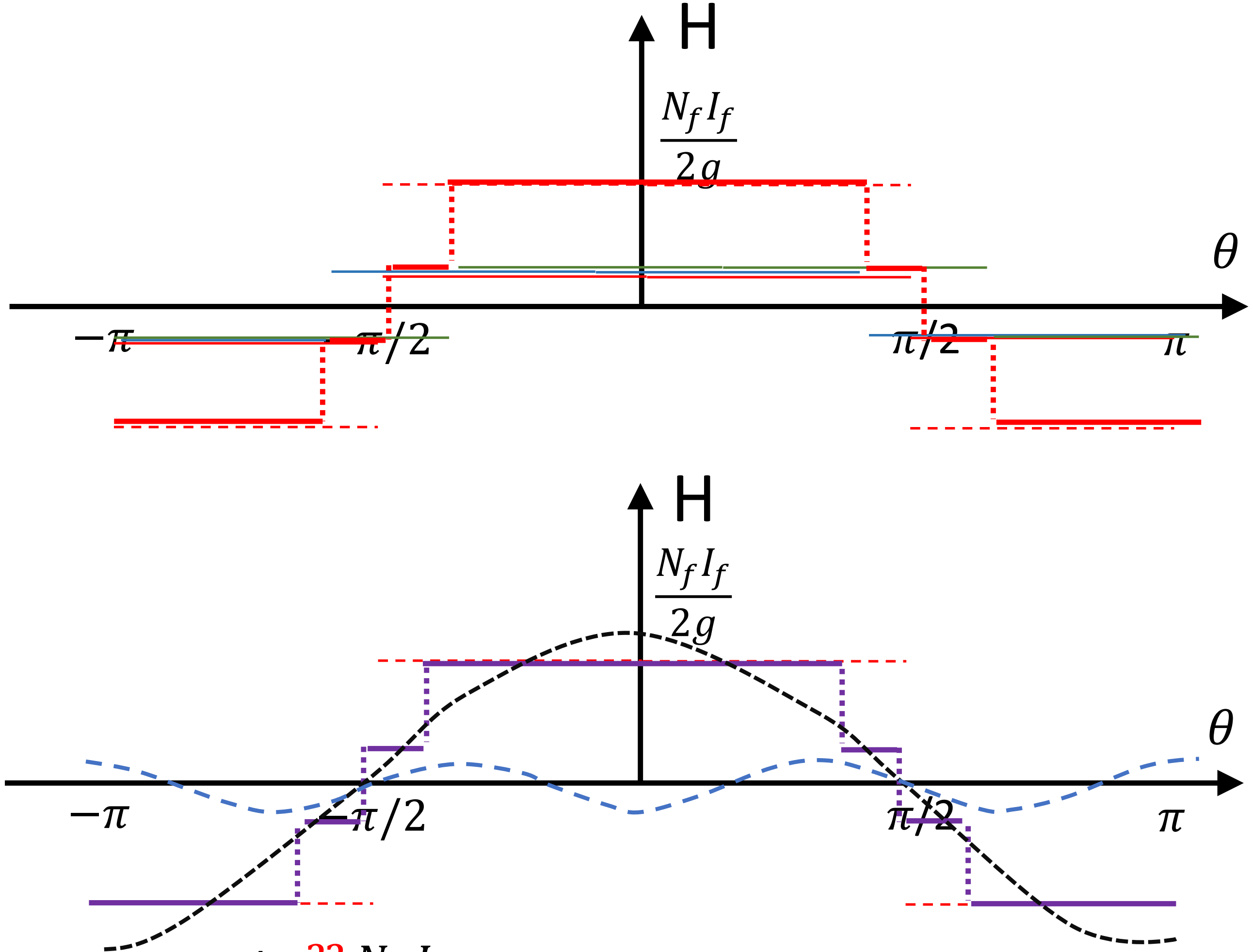
Rotor Winding Factors





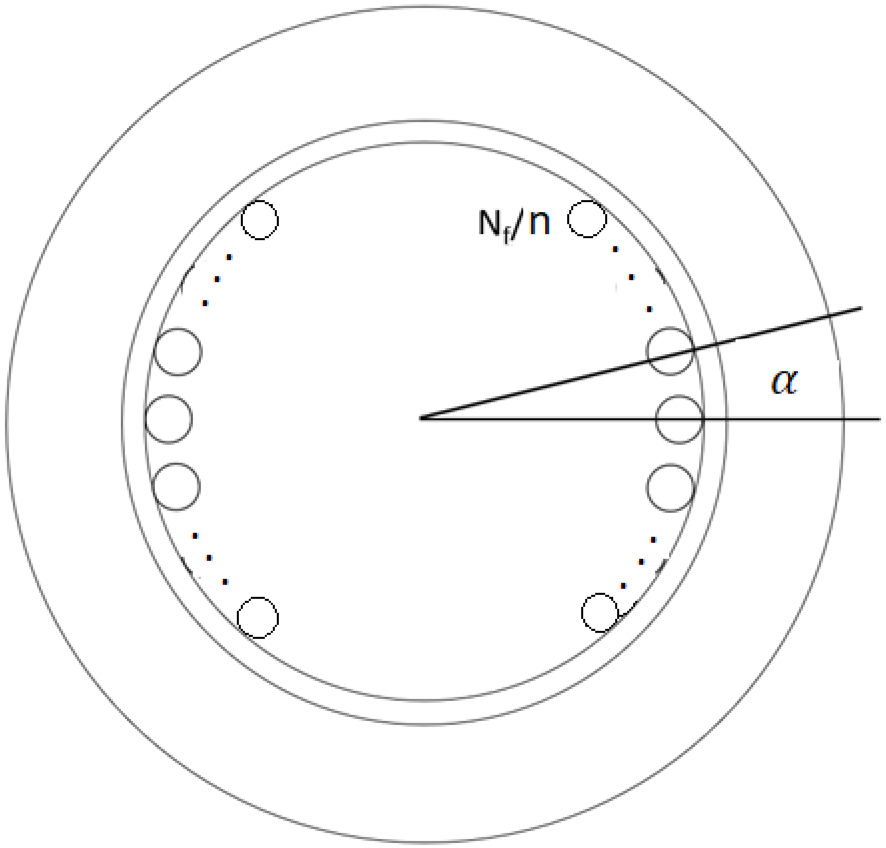
$$B = \frac{4}{\pi}\,\frac{??\ N_f I_f}{2g}\,\mu_0 \cos\theta - \frac{4}{3\pi}\,\frac{??\ N_f I_f}{2g}\,\mu_0 \cos 3\theta + \frac{4}{5\pi}\,\frac{??\ N_f I_f}{2g}\,\mu_0 \cos 5\theta - \cdots$$

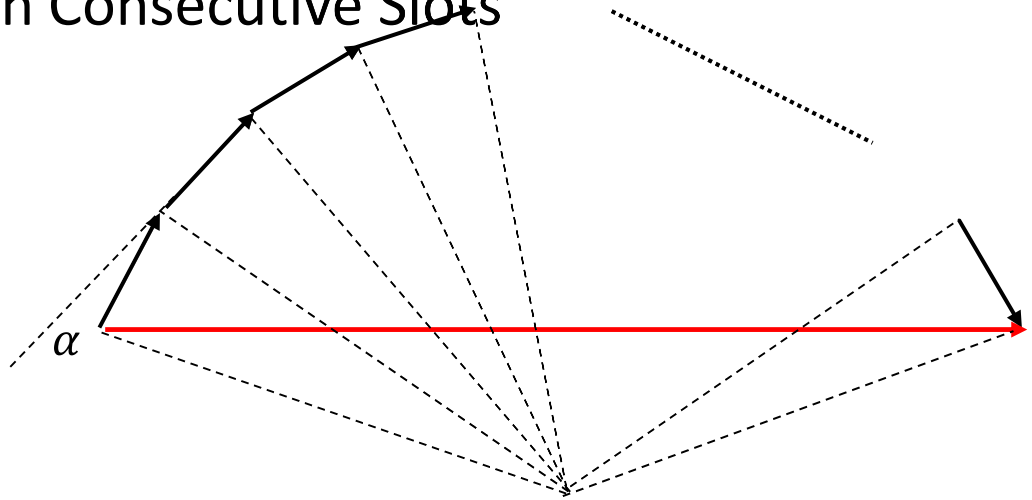
Rotor Winding Factor = ?

Effective Number of Rotor Winding Turns = ?

Rotor Winding Factors

Winding Factor for a Uniformly Distributed Rotor Winding with N_f Turns in *n* Slots and Angle α Between Consecutive Slots



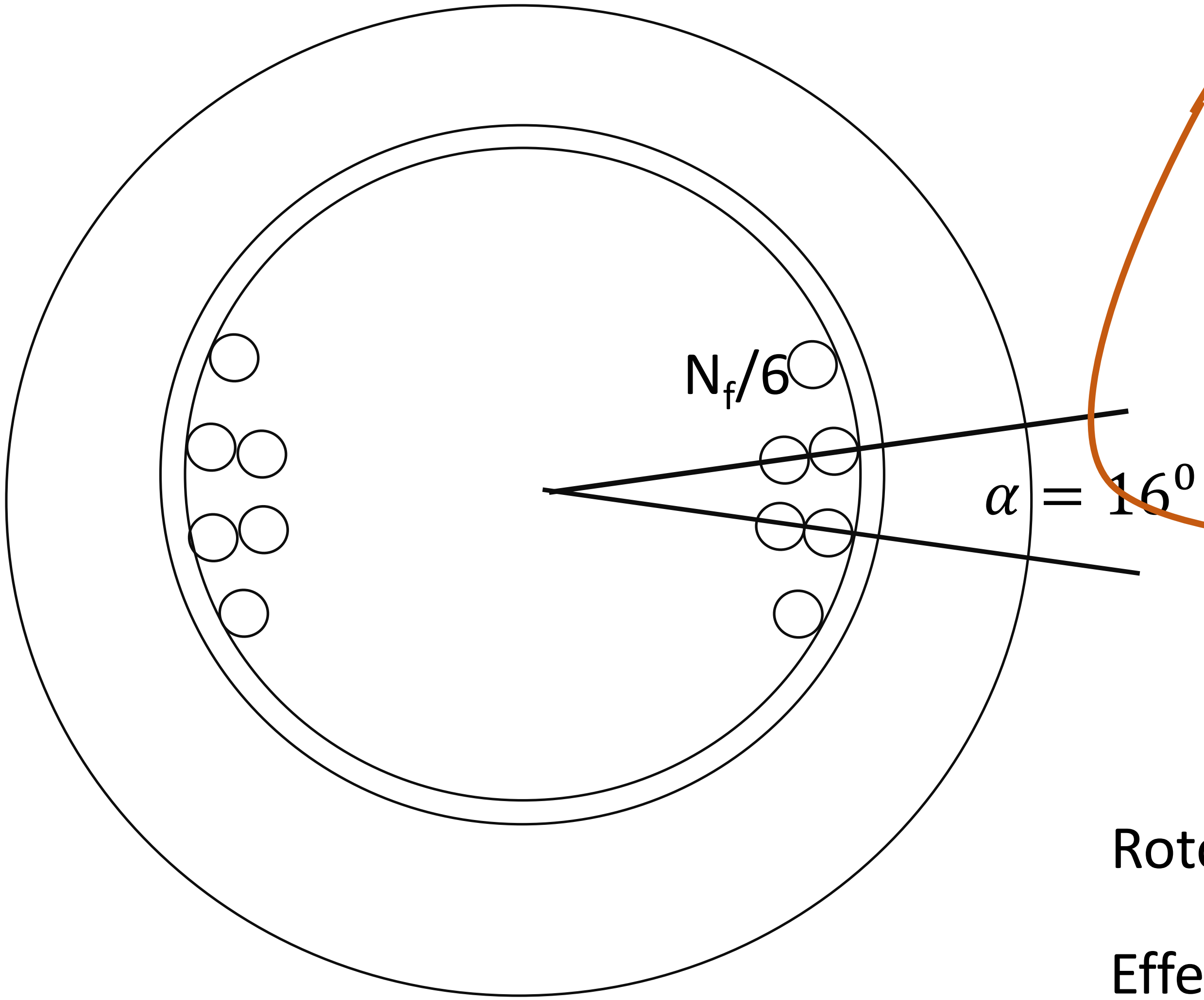


Distribution Factor of a Uniformly Distributed Winding in *n* Slots

$$k_{wh} = \frac{\sin(nh\frac{\alpha}{2})}{n\sin(h\frac{\alpha}{2})}$$

Rotor Winding Factors

Non-Uniform Distribution of N_f Turns of Rotor Winding in *n* Slots with Angle α



Distribution Factor of a Uniformly Distributed Winding in *n* Slots

$$k_{wh} = \frac{\sin(nh\frac{\alpha}{2})}{n\sin(h\frac{\alpha}{2})}$$

$B_{centralized}$=?? $B_{distributed}$=??

Rotor Winding Factor = ?

Effective Number of Rotor Winding Turns = ?

Generation of Sinusoidal Voltage in a Synchronous Generator

Methods for Sine-Wave Shaping of Voltage

Modifying windings to make magnetic flux density sine-shaped

→ Managing Rotor Windings

→ Rotor Winding Distribution

Improving voltage shape relative to magnetic flux density B by modifying the stator winding

→ Managing Stator Windings

- Stator Winding Distribution
- Stator Winding Pitch Fraction
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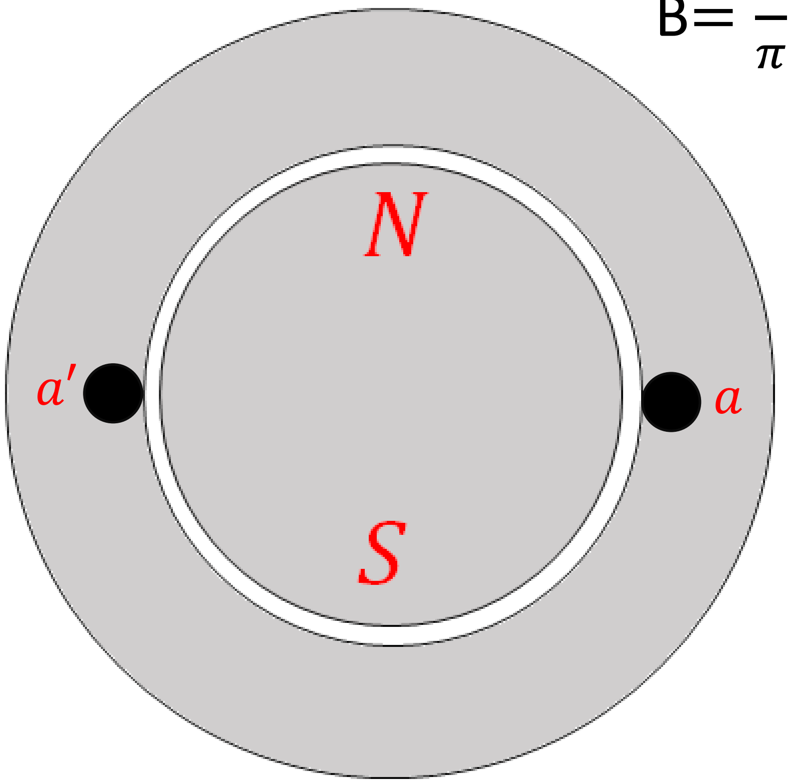
Stator Winding Factors-Stator Distribution Winding Factor

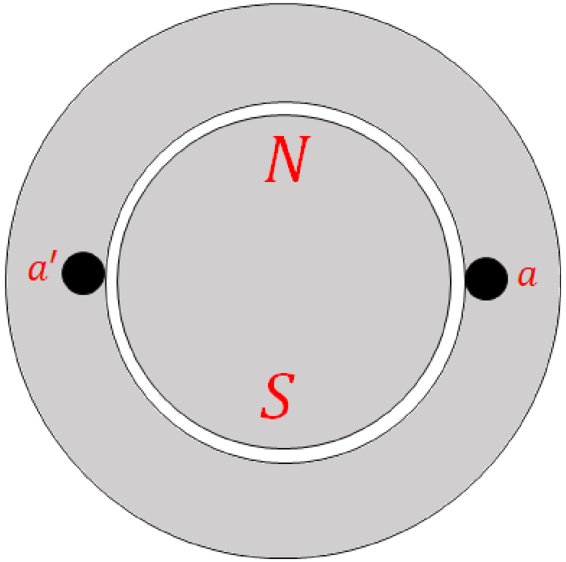


$$B = \frac{4}{\pi}\frac{k_{w1}N_fI_f}{2g}\mu_0\cos\theta - \frac{4}{3\pi}\frac{k_{w3}N_fI_f}{2g}\mu_0\cos3\theta + \frac{4}{5\pi}\frac{k_{w5}N_fI_f}{2g}\mu_0\cos5\theta - \cdots$$

$$B = B_1\cos\theta + B_3\cos3\theta + B_5\cos5\theta + \cdots$$

$$e_{aa'} = 2lN_ar\omega B_1\cos\omega t + 2lN_ar\omega B_3\cos3\omega t + 2lN_ar\omega B_5\cos5\omega t + \cdots$$

Stator Winding Factors-Stator Distribution Winding Factor



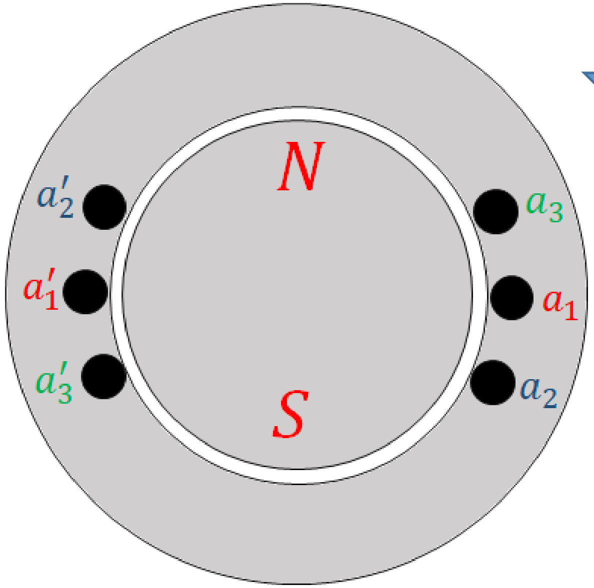
$$e_{aa'} = 2lN_a r\omega B_1 \cos\omega t + 2lN_a r\omega B_3\, cos3\omega t + 2lN_a r\omega B_5\, cos5\omega t - \cdots$$

Distributed winding(Why?)

$$e_{a1a1'} = 2l\frac{N_a}{3} r\omega B_1 \cos\omega t + 2l\frac{N_a}{3} r\omega B_3\, cos3\omega t + 2l\frac{N_a}{3} r\omega B_5\, cos5\omega t - \cdots$$

$$e_{a2a2'} = ???$$

$$e_{a3a3'} = ???$$

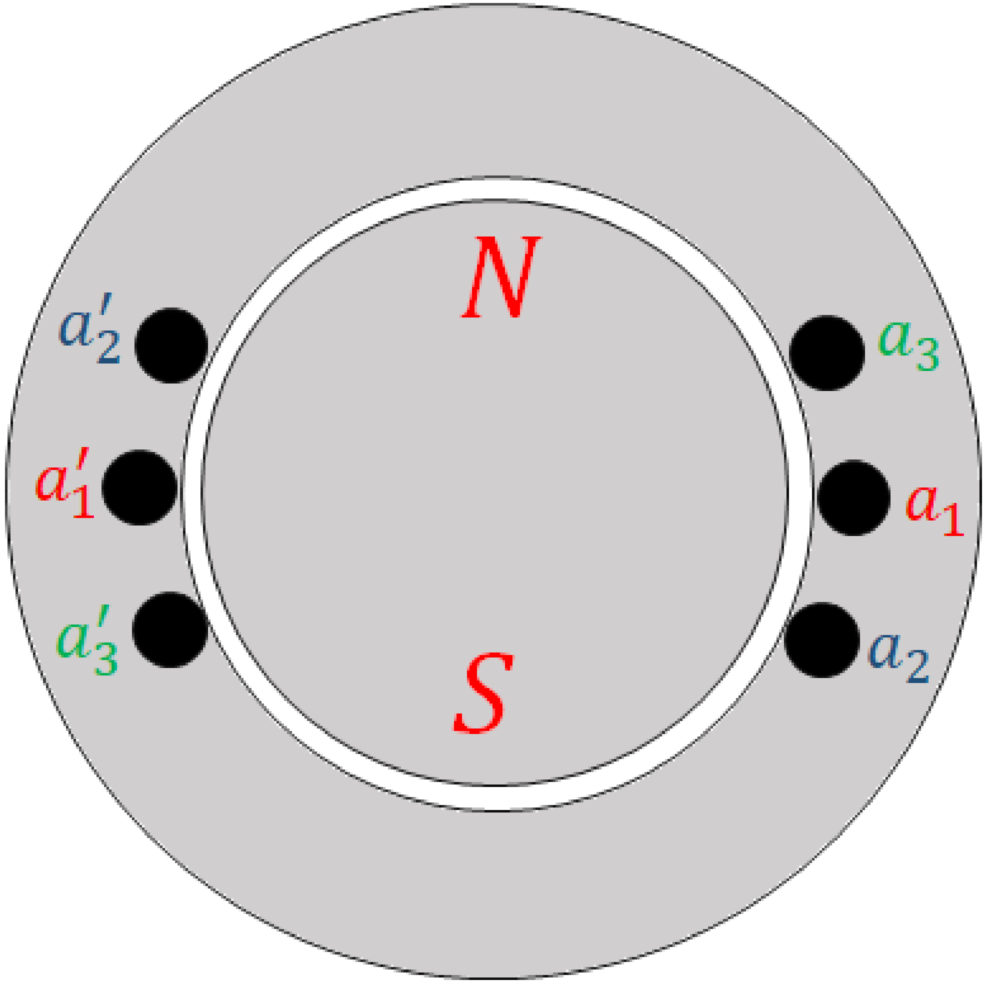


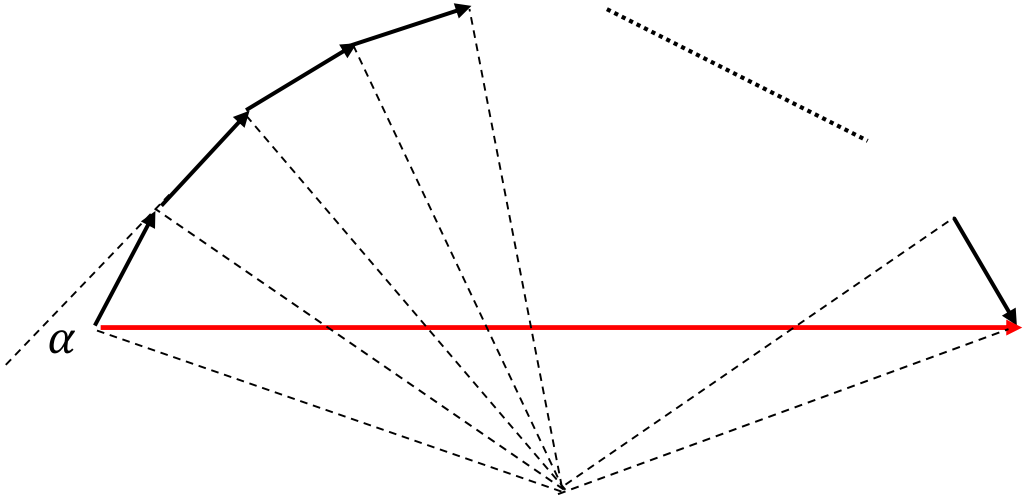
$$e_{aa'} = 2lN_a ??\, r\omega B_1 \cos\omega t + 2lN_a ??\, r\omega B_3\, cos3\omega t + 2lN_a ??\, r\omega B_5\, cos5\omega t - \cdots$$

Distribution Winding Factor = ?

Stator Winding Factors-Stator Distribution Winding Factor

Uniform Distribution of N_a Turns of stator Winding in *n* Slots with Angle α





Distribution Factor of the h-th Harmonic for Uniform Distribution in *n* Slots with Angle α

$$k_{dh} = \frac{\sin(nh\frac{\alpha}{2})}{n\sin(h\frac{\alpha}{2})}$$

Generation of Sinusoidal Voltage in a Synchronous Generator

Methods for Sine-Wave Shaping of Voltage

Modifying windings to make magnetic flux density sine-shaped

→ Managing Rotor Windings

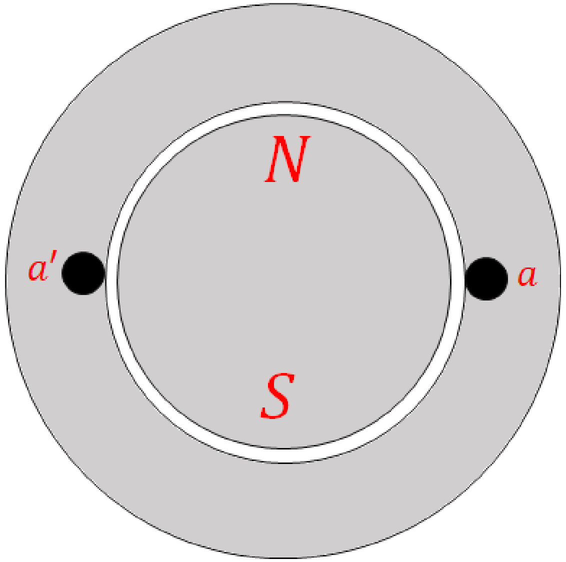
→ ✓ Rotor Winding Distribution

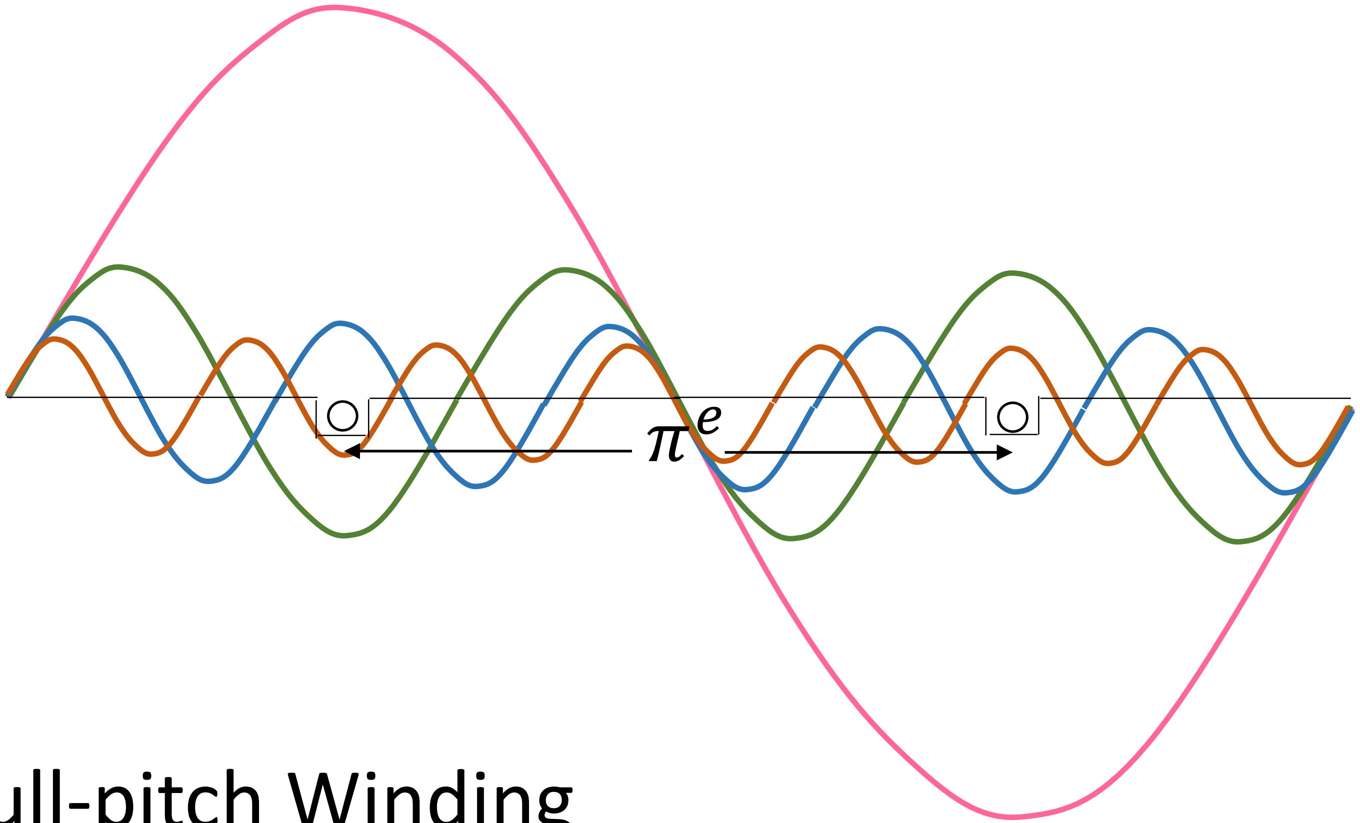
Improving voltage shape relative to magnetic flux density B by modifying the stator winding

→ Managing Stator Windings

- ✓ Stator Winding Distribution
- Stator Winding Pitch Fraction
- Stator Winding Connection

Stator Winding Factors-Stator Pitch Winding Factor

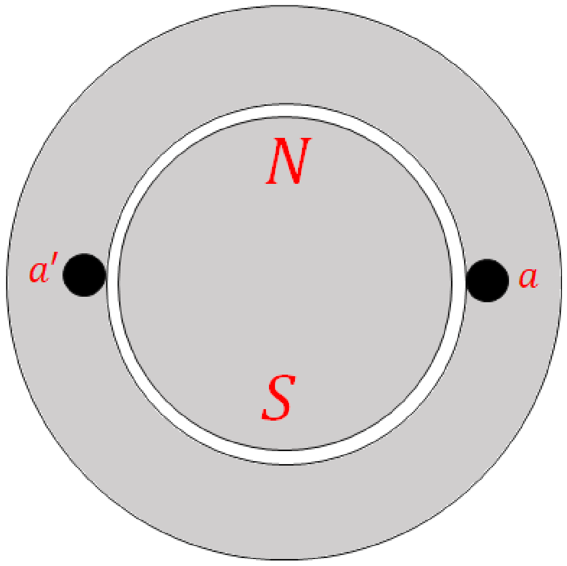


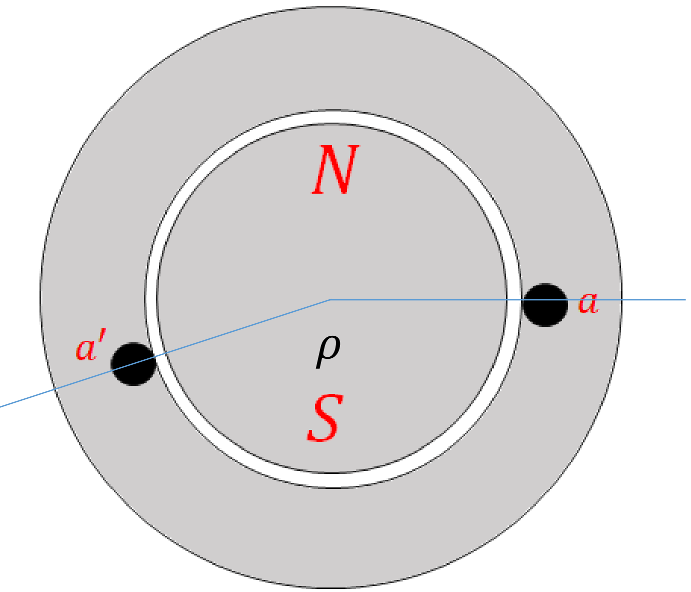


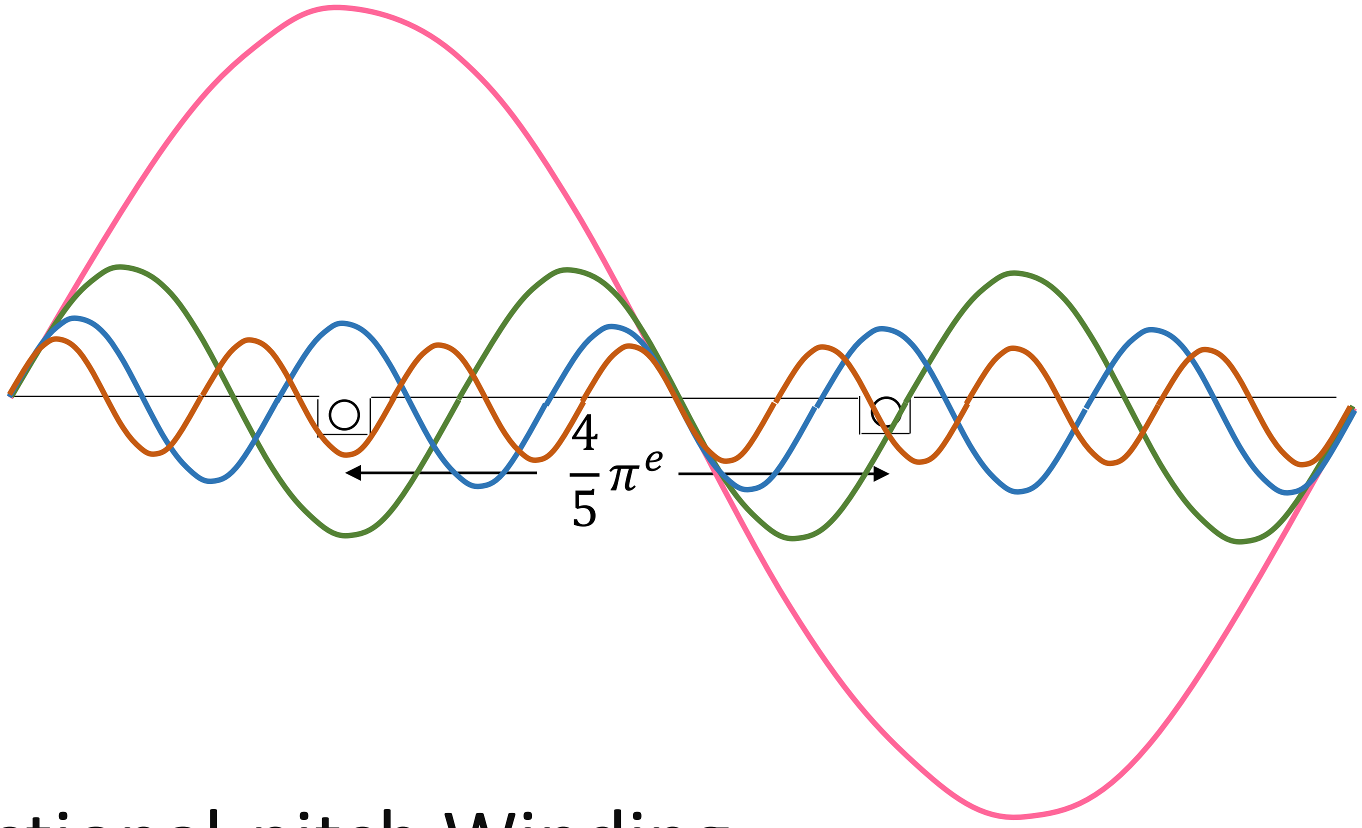
Full-pitch Winding

Fractional-pitch Winding ??

Stator Winding Factors-Stator Pitch Winding Factor



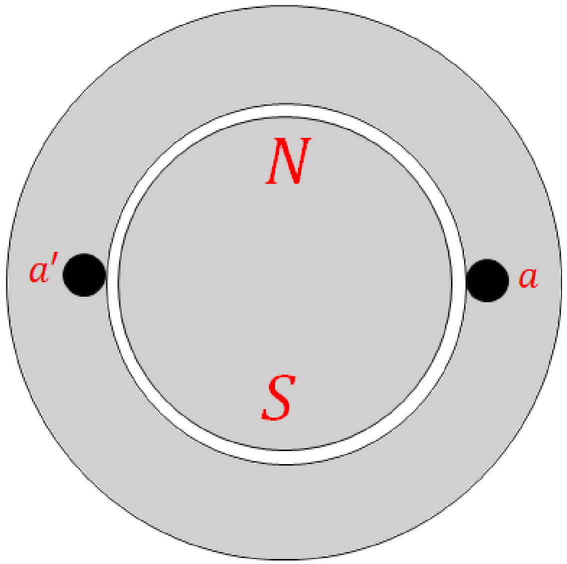




Fractional-pitch Winding

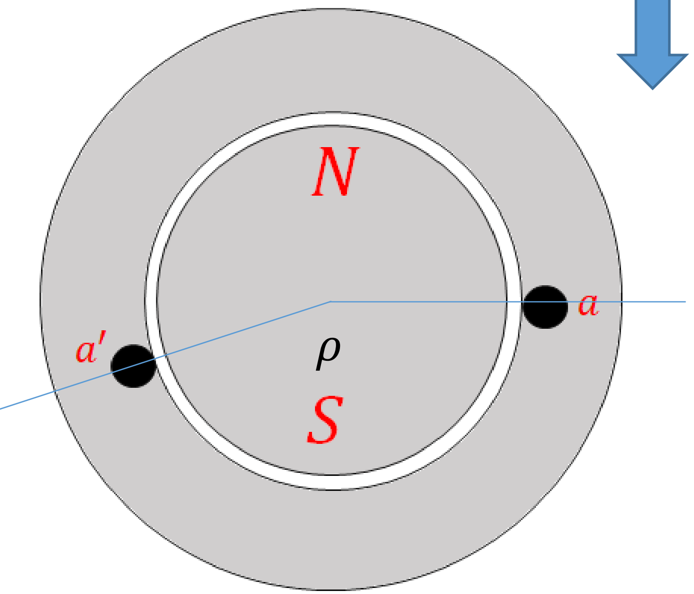
What happen to 5th harmonic ??

Stator Winding Factors-Stator Pitch Winding Factor



$$e_{aa'} = 2lN_a r\omega B_1 \cos\omega t + 2lN_a r\omega B_3\, cos3\omega t + 2lN_a r\omega B_5\, cos5\omega t - \cdots$$

Fractional-pitch winding



$$e_a = lN_a r\omega B_1 \cos\omega t + lN_a r\omega B_3\, cos3\omega t + lN_a r\omega B_5\, cos5\omega t - \cdots$$

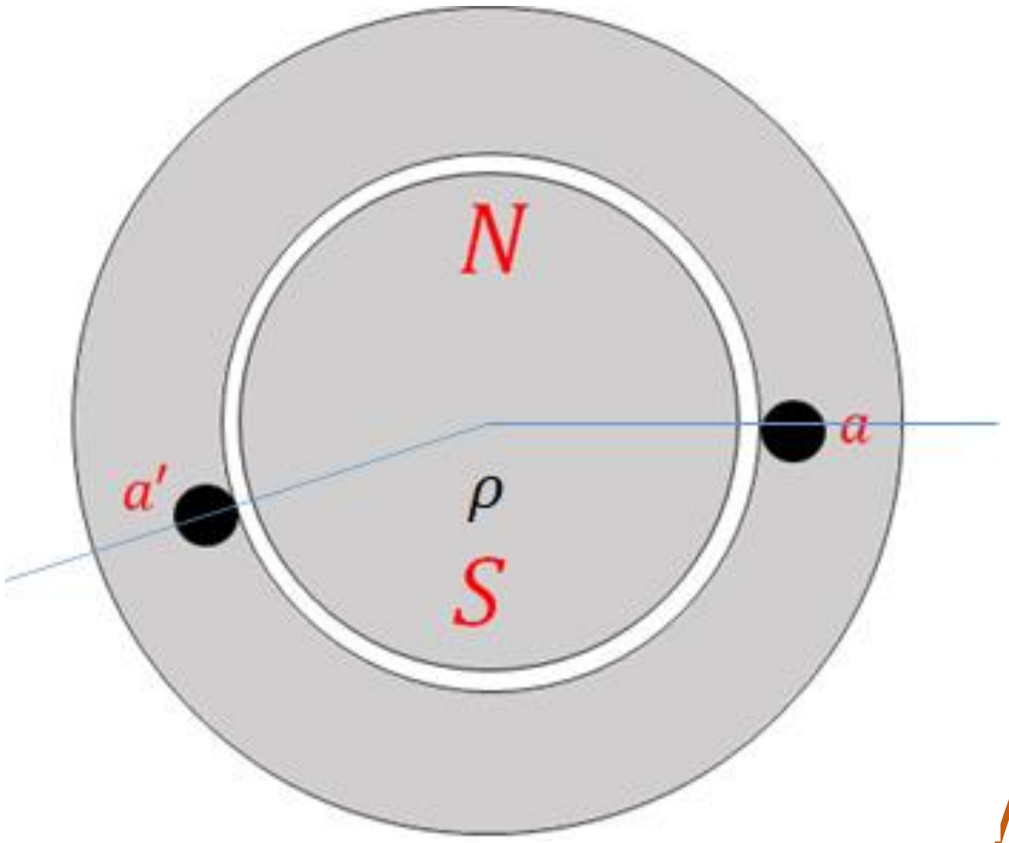
$$e_{a'} = ???$$

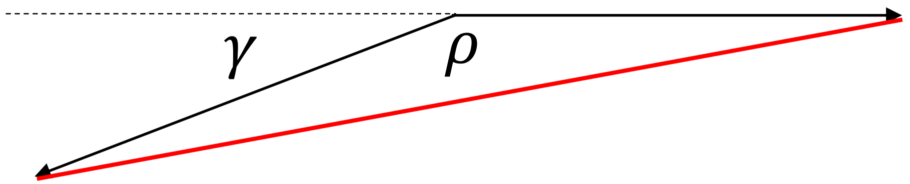
$$e_{ea'} = e_a - e_{a'}$$

$$e_{aa'} = 2lN_a ?? r\omega B_1 \cos\omega t + 2lN_a ?? r\omega B_3\, cos3\omega t + 2lN_a ?? r\omega B_5\, cos5\omega t -$$

Pitch factor ??

Stator Winding Factors-Stator Pitch Winding Factor





Pitch Factor of the h^th Harmonic of Stator Winding in Fractional Pitch with γ

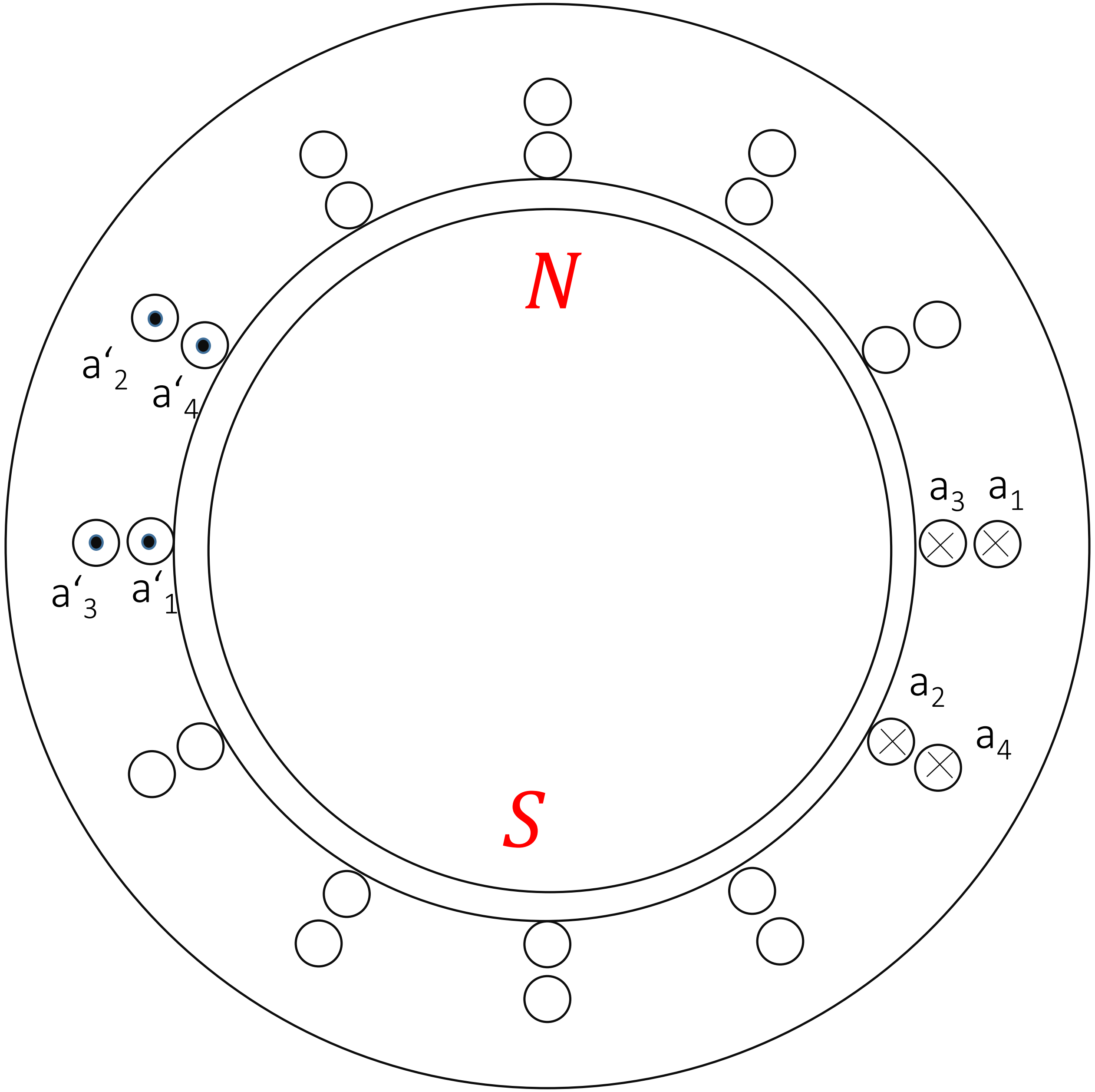
$$k_{ph} = \cos(h\frac{\gamma}{2})$$

Stator Winding Factors-Stator Pitch Winding Factor

Winding Factor of the hth Harmonic of Stator Winding

$$k_{wh} = k_{dh}\, k_{ph}$$

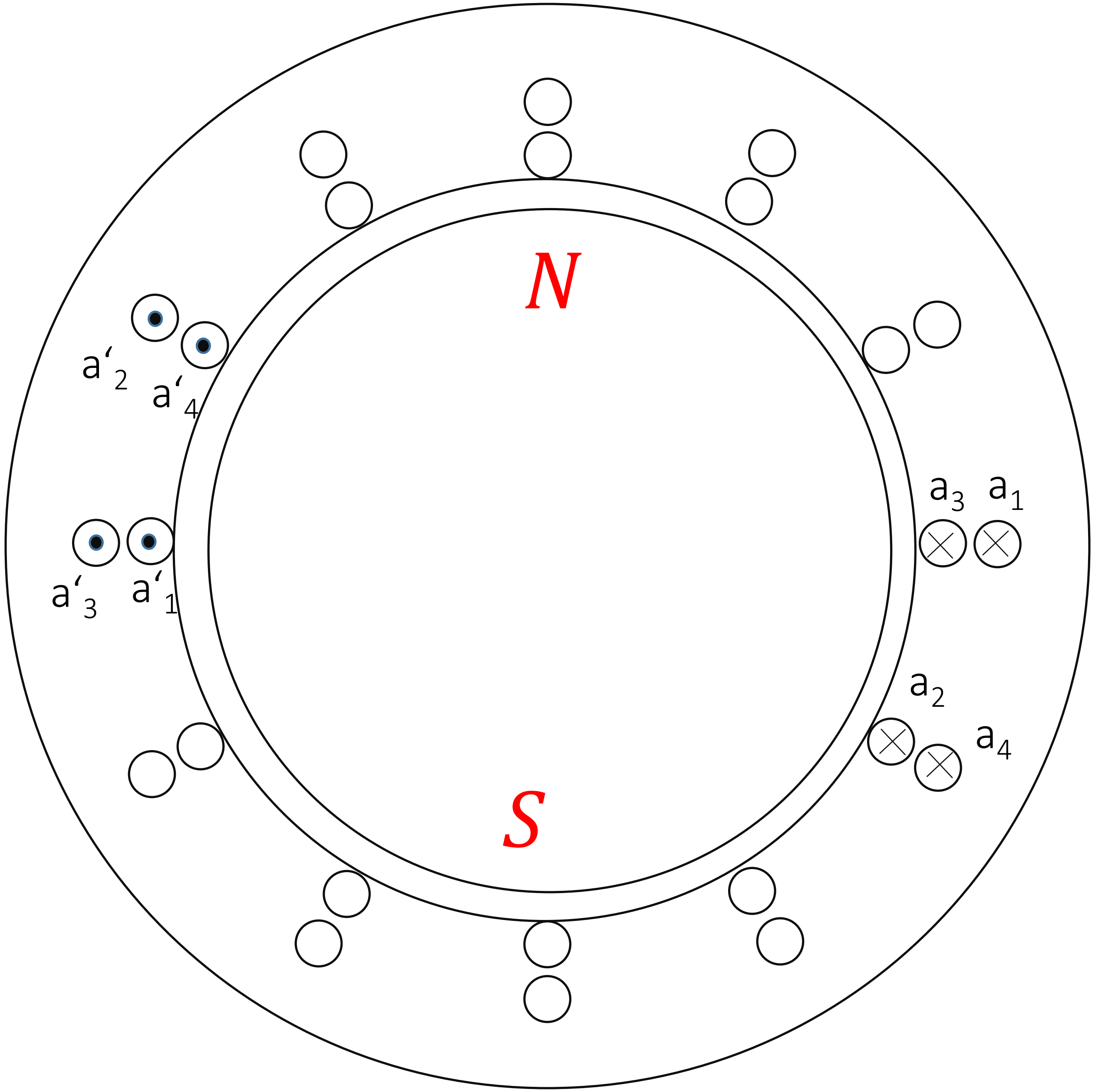
Stator Winding Factors-Stator Pitch Winding Factor



Double-layer winding

Two other phases ??

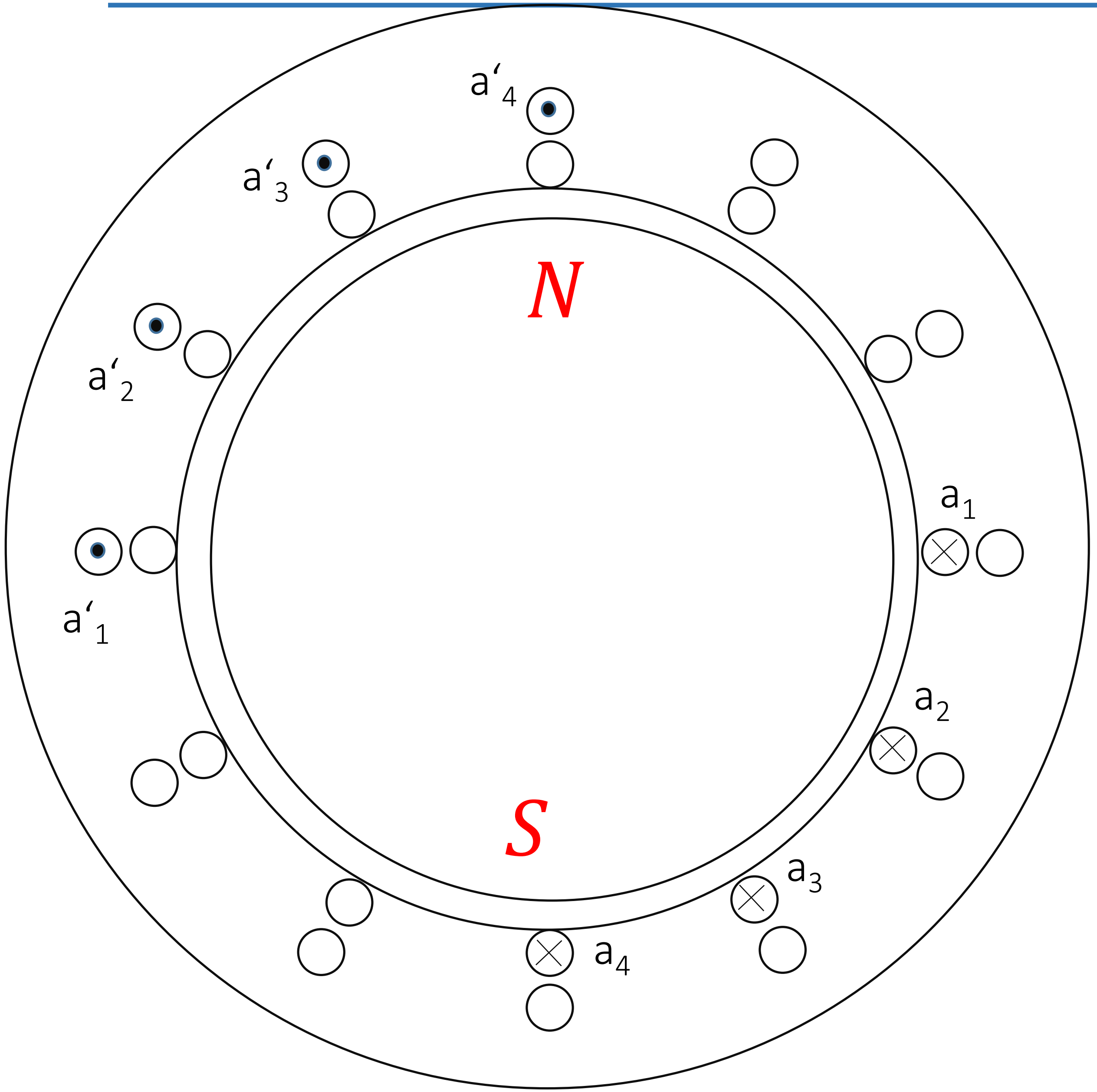
Stator Winding Factors-Stator Pitch Winding Factor



Double-layer winding

Two other phases ??

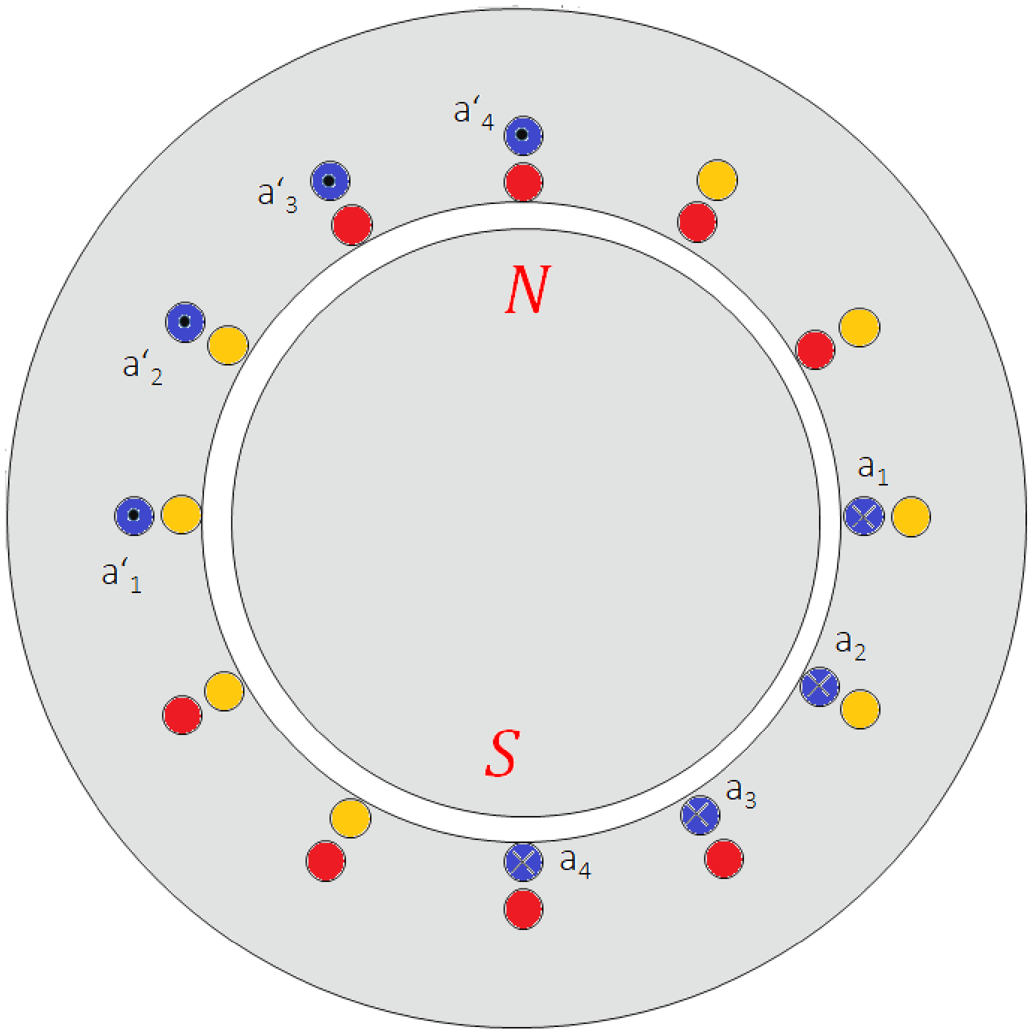
Stator Winding Factors-Stator Pitch Winding Factor



Double-layer winding

Two other phases ??

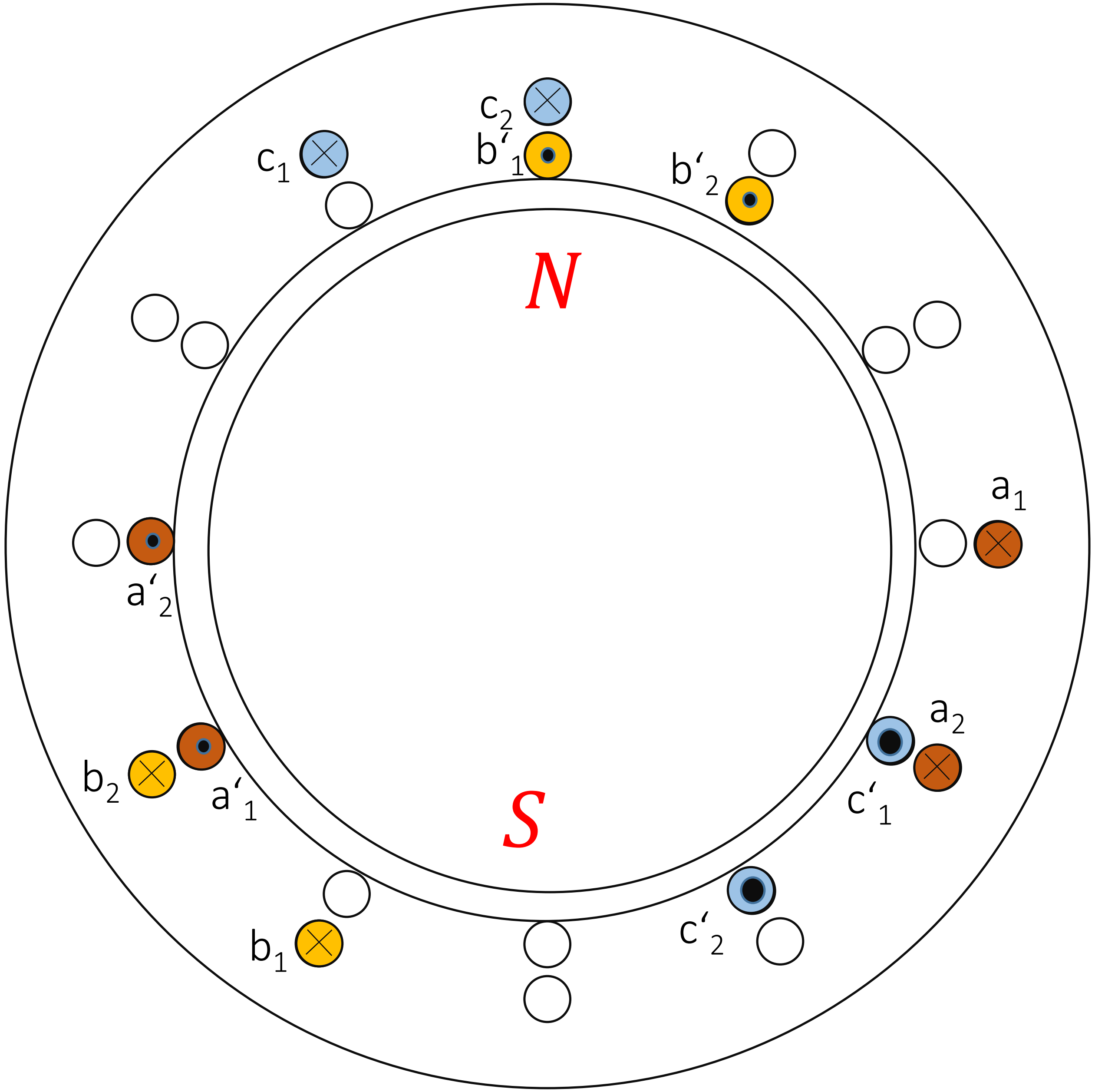
Stator Winding Factors-Stator Pitch Winding Factor



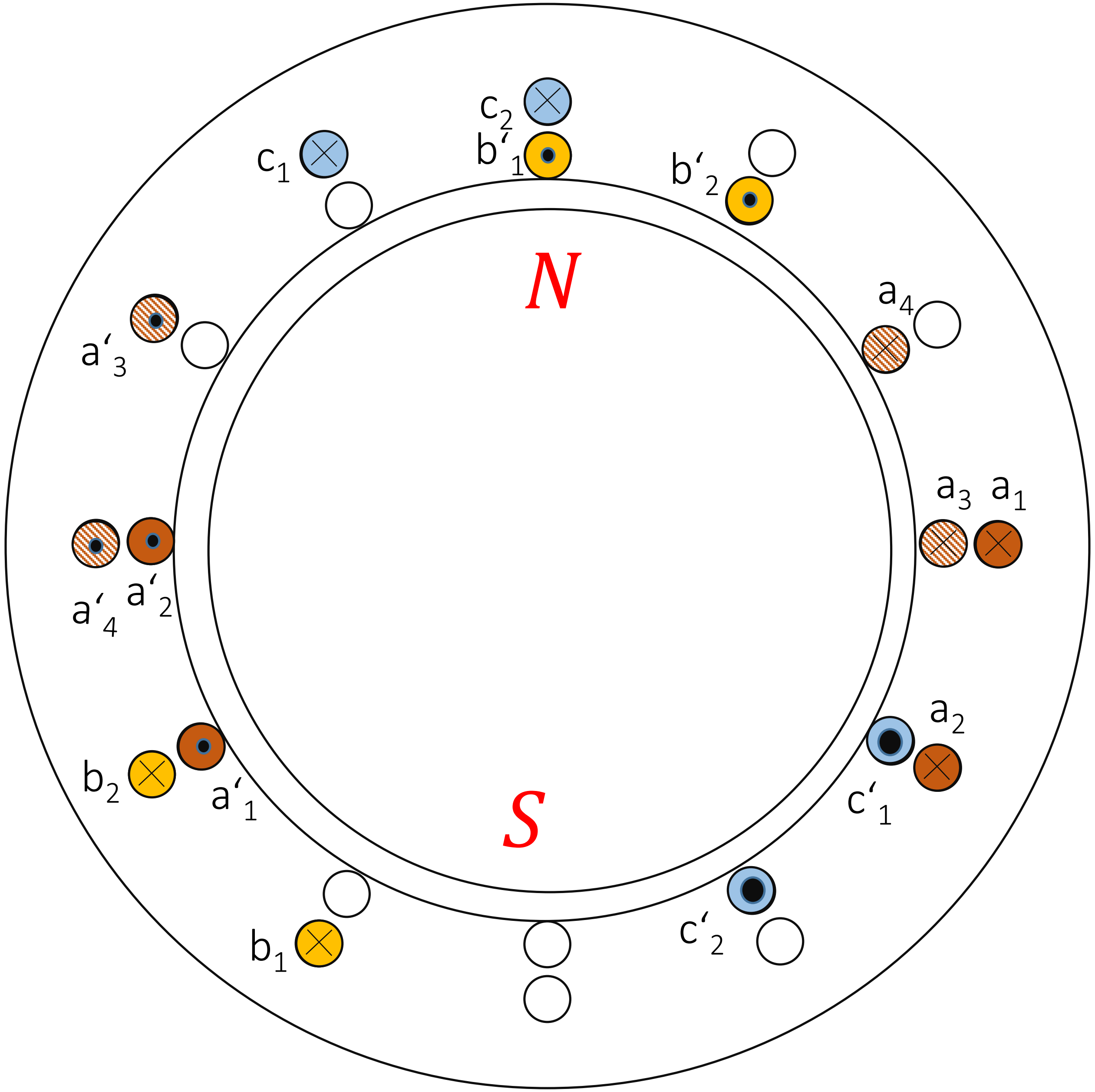
Double-layer winding

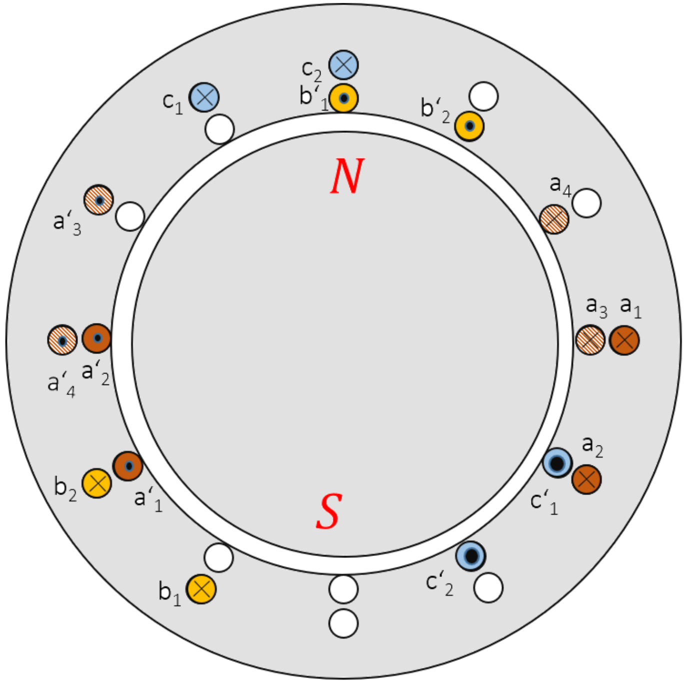
Why it is not ok ??

Stator Winding Factors-Stator Pitch Winding Factor



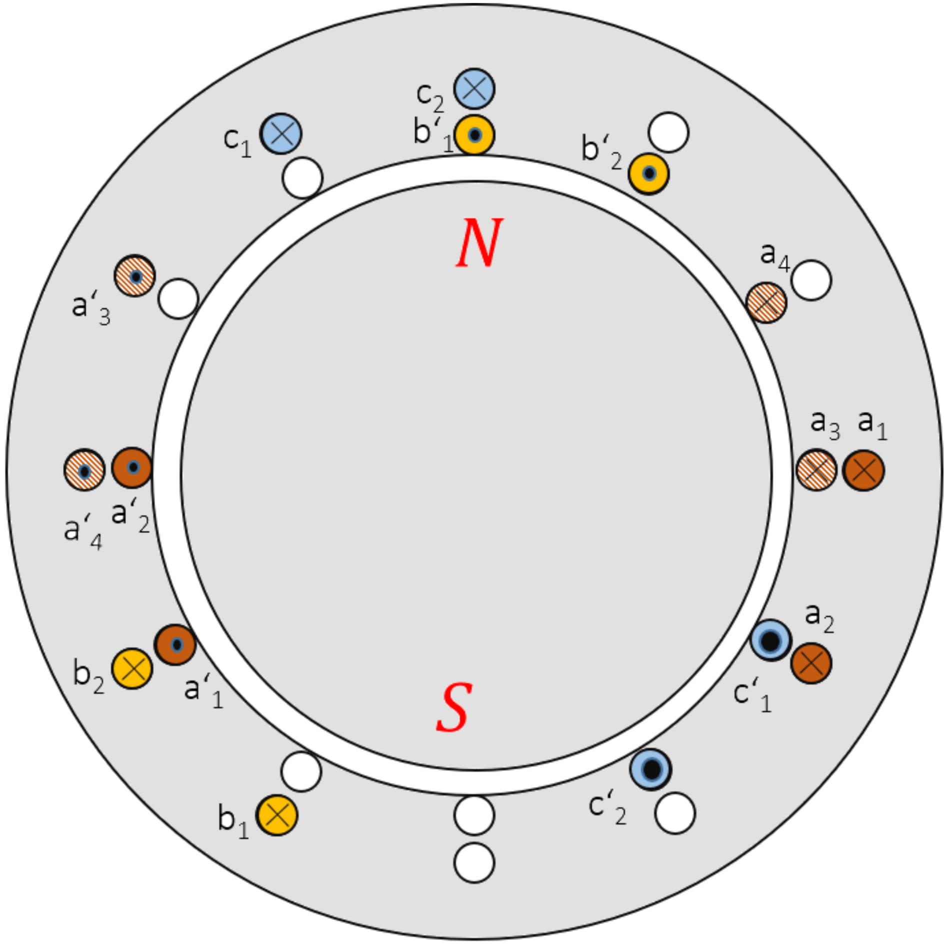
Stator Winding Factors-Stator Pitch Winding Factor



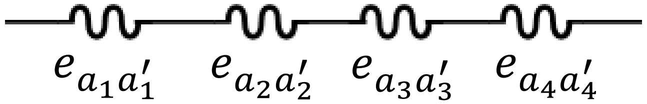


Two other phases ??

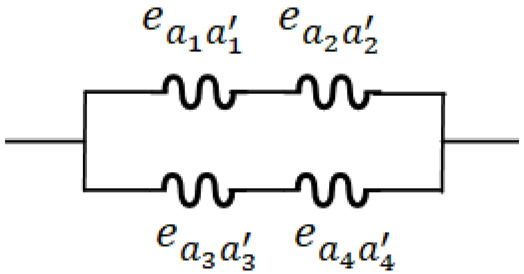
Stator Winding Factors-Stator Pitch Winding Factor



Coil connections?



Is it possible to connect as:



Bonus (1)

$$k_{d1} = \frac{\sin(2\frac{30}{2})}{2sin(\frac{30}{2})} = 0.9659$$

$$k_{p1} = \cos\left(\frac{30}{2}\right) = 0.9659$$

$$k_{w1} = 0.9659 * 0.9659 = 0.933$$

Stator Winding Factors-Stator Pitch Winding Factor

Example 1: The stator of a 3ϕ , 2-poles machine has 18 slots and a double-layer winding. The coils are short-pitched by 7/9. Determine winding factor for first and 3rd and 5th harmonies.

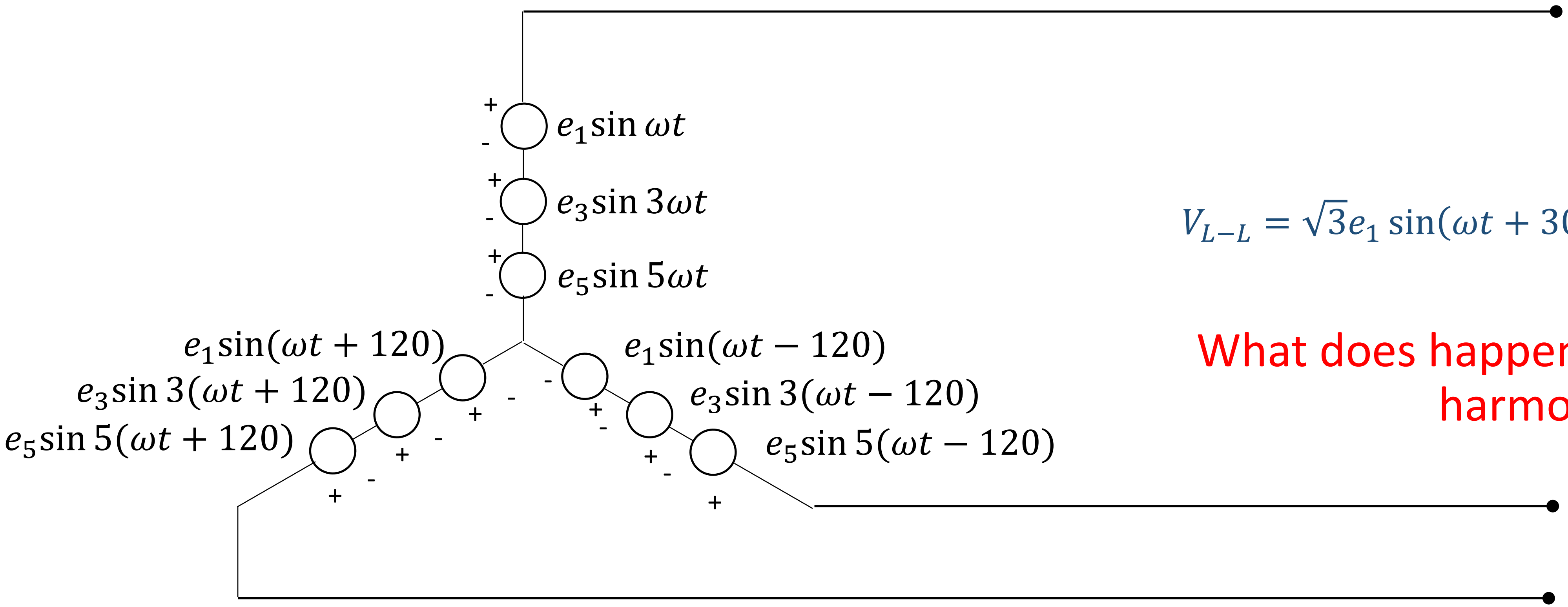
ans: $k_{w1} = 0.9598 * 0.9397 = 0.9019,\ \ k_{w3} = 0.6667 * 0.5 = 0.3333,\ \ k_{w5} = 0.2176 * (-0.1736) = -0.0378$

Generation of Sinusoidal Voltage in a Synchronous Generator

Methods for Sine-Wave Shaping of Voltage

- Modifying windings to make magnetic flux density sine-shaped
  - ↓ Managing Rotor Windings
    - ↓ ✓ Rotor Winding Distribution
- Improving voltage shape relative to magnetic flux density B by modifying the stator winding
  - ↓ Managing Stator Windings
    - ✓ Stator Winding Distribution
    - ✓ Stator Winding Pitch Fraction
    - Stator Winding Connection

Stator Winding Factors-Generator Connection



$$V_{L-L} = \sqrt{3}e_1 \sin(\omega t + 30) + \sqrt{3}e_5 \sin(5t - 30)$$

What does happen to 3rd , 9th , ….. harmonic?

Double layer winding(Distributed and short pitch winding)

Example 2: The stator of a 3ϕ , 8-poles machine has 96 stator slots and short-pitched by 9/12. The airgap flux density shows that third and fifth harmonics are present and are of amplitude 30 and 15 percent of the fundamental. Determine the ratio of the line-to-line voltage and line-natural voltage.

$\frac{96}{4} = 24$ Number of Slots per Pole Pair

$\frac{24}{3} = 8$ Number of Slots per Phase (Number of Coils)

$\frac{360}{24} = 15$ Electrical Angle Between Each Two Slots

$\frac{9}{12} 180 = 135$ Electrical Angle Between the Two Ends of a Coil

$$K_{d1} = \frac{\sin(4 \times 1 \times \frac{15}{2})}{4\sin(1 \times \frac{15}{2})} = 0.9577 \qquad K_{d3} = \frac{\sin(4 \times 3 \times \frac{15}{2})}{4\sin(3 \times \frac{15}{2})} = 0.6533 \qquad K_{d5} = \frac{\sin(4 \times 5 \times \frac{15}{2})}{4\sin(5 \times \frac{15}{2})} = 0.2053$$

$$K_{p1} = \cos\left(1 \times \frac{45}{2}\right) = 0.9239 \qquad K_{p3} = \cos\left(3 \times \frac{45}{2}\right) = 0.3827 \qquad K_{p5} = \cos\left(5 \times \frac{45}{2}\right) = -0.3827$$

$$K_{w1} = K_{d1}.K_{p1} = 0.8848 \qquad K_{w3} = K_{d3}.K_{p3} = 0.25 \qquad K_{w5} = K_{d5}.K_{p5} = -0.0786$$

Double layer winding(Distributed and short pitch winding)

Example 2: The stator of a 3ϕ , 8-poles machine has 96 stator slots and short-pitched by 9/12. The airgap flux density shows that third and fifth harmonics are present and are of amplitude 30 and 15 percent of the fundamental. Determine the ratio of the line-to-line voltage and line-natural voltage.

$K_{w1} = K_{d1}.K_{p1} = 0.8848$ $K_{w3} = K_{d3}.K_{p3} = 0.25$ $K_{w5} = K_{d5}.K_{p5} = -0.0786$

$E_1 \propto K_{w1}.B_1 = 0.8848k$ $E_3 \propto K_{w3}.B_3 = 0.25 \times 0.3k = 0.075k$ $E_5 \propto K_{w5}.B_5 = -0.0786 \times 0.15k = 0.0118k$

$E_{LN} = \sqrt{E_1^2 + E_3^2 + E_3^2} = 0.8881k$ $E_{LL} = \sqrt{(\sqrt{3}E_1)^2+(\sqrt{3}E_5)^2}= 1.5327k$ $E_{LL}/E_{LN} \neq \sqrt{3}$

Plot the winding of this machine for a pair of poles:

Bonus (1)

FROM 3 POINTS

Generation of Sinusoidal Voltage in a Synchronous Generator

Methods for Sine-Wave Shaping of Voltage

Modifying windings to make magnetic flux density sine-shaped

↓

Managing Rotor Windings

↓

√ Rotor Winding Distribution

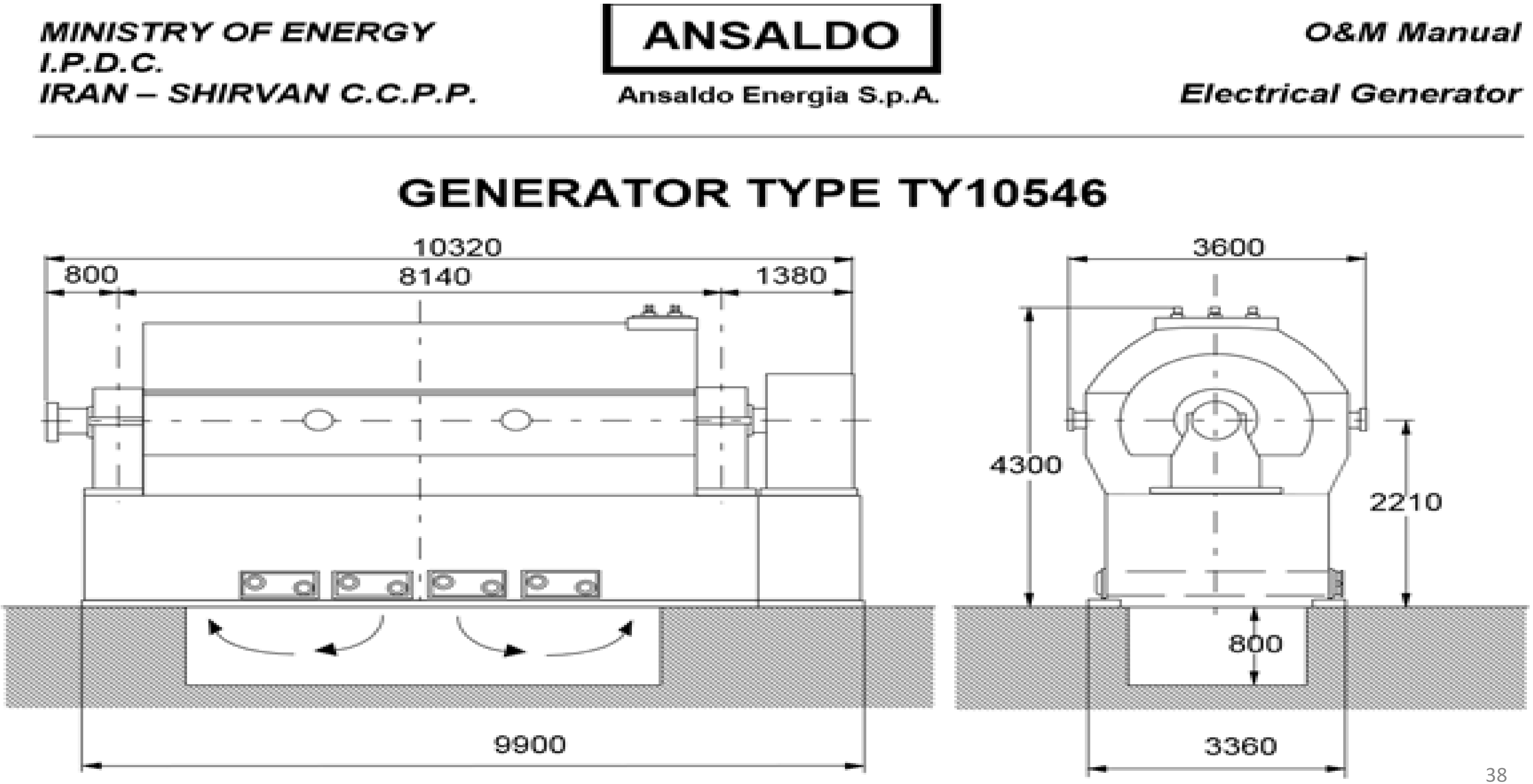
Improving voltage shape relative to magnetic flux density B by modifying the stator winding

↓

Managing Stator Windings

- √ Stator Winding Distribution
- √ Stator Winding Pitch Fraction
- √ Stator Winding Connection

View of a 200 MVA 2-Pole Generator at Shirvan Power Plant, Shirvan, Iran



Specifications of the 200 MVA 2-Pole Generator at Shirvan Power Plant, Shivan, Iran

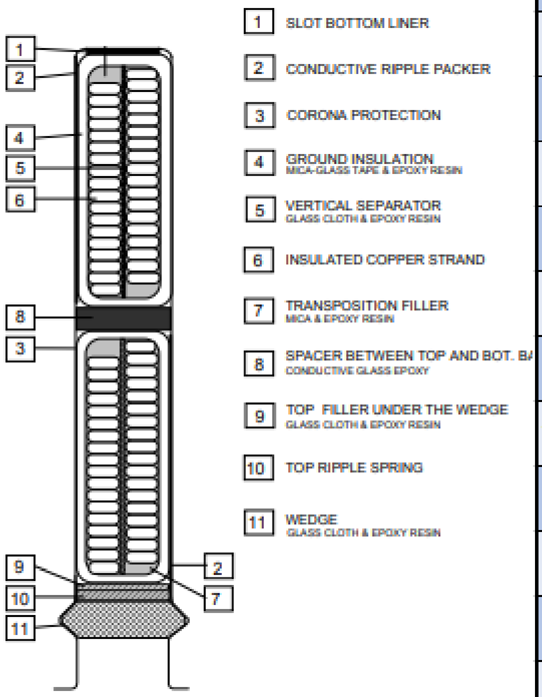
WEIGHTS and Dimensions FOR TRANSPORTATION AND LIFTING			
DESCRIPTION	**Unit**	**Value**	
Generator height	m	4.3	
Generatorm width	m	3.8	
Generatorm length	m	10.3	Around 14 (Shahid Salimi, Neka)
Stator core weight	ton	110	
Stator winding weight	ton	15	
Stator frame weight	ton	37	
Slip rings housing	ton	2.5	
Rotor winding weight	ton	5.9	
Rotor complete weight	ton	41	61 (Shahid Salimi, Neka)
Stator complete without bearings and coolers weight	ton	168	260 (Shahid Salimi, Neka)
Generator complete weight	ton	224	325 (Shahid Salimi, Neka)

Specifications of the 200 MVA 2-Pole Generator at Shirvan Power Plant, Shivan, Iran

Shivan Generator Specification

DESCRIPTION	Unit	Value	
Generator type	-	Air cooled	
Rated output at 40 °C	mVA	200	518 (Shahid Salimi, Neka)
Rated power factor	-	0.8	0.85 (Shahid Salimi, Neka)
Rated voltage	V	15750	21000 (Shahid Salimi, Neka)
Rated frequency	Hz	50	
Rated current	A	7331	14232 (Shahid Salimi, Neka)
Rated speed	rpm	3000	
Excitation system type	-	static type	
Excitation current at rated load	A	1417	4050 (Shahid Salimi, Neka)
Excitation voltage at rated load	V	296	
Excitation current at no-load rated terminal voltage	A	459	1290 (Shahid Salimi, Neka)
Short circuit ratio (Calculated values)	-	0.47	0.5 (Shahid Salimi, Neka)
Synchronous direct axis reactance (Calculated values)	%	238	
Transient direct axis reactance unsaturated (Calculated values)	%	23.4	
Subtransient direct axis reactance unsaturated (Calculated values)	%	17.9	
Conventional efficiencies according to IEC 34 Std. at rated load	%	98.54	
Conventional efficiencies according to IEC 34 Std. at 25% rated load	%	96.25	

Specifications of the 200 MVA 2-Pole Generator at Shirvan Power Plant, Shivan, Iran



Stator slot cross section

Shivan Generator Specification (stator & rotor)

DESCRIPTION	Unit	Value
Core length	cm	462
Inside core diameter(stator)	cm	115
Outside core diameter(stator)	cm	251
Number of stator slots	-	60
Height of the stator slot	cm	26
Width of the stator slot	cm	2.6
Lamination thickness	mm	0.5
Stator coil pitch in terms of slot pitch	-	25
Turn per phase in series(stator)	-	10
Number of parallel circuits per each phase(stator)	-	2
Number of conductors per slot(stator)	-	2
Winding connection(stator)	-	Y
Cross section of the stator bar	mm2	1375
Outer diameter(rotor)	cm	105
Number of wound slots	-	36
Effective turns per pole	-	96
Cross section of rotor conductor	mm2	265
Resistance at 75 °C	ohm	0.188

530 (Shahid Salimi, Neka)

134 (Shahid Salimi, Neka)

54 (Shahid Salimi, Neka)

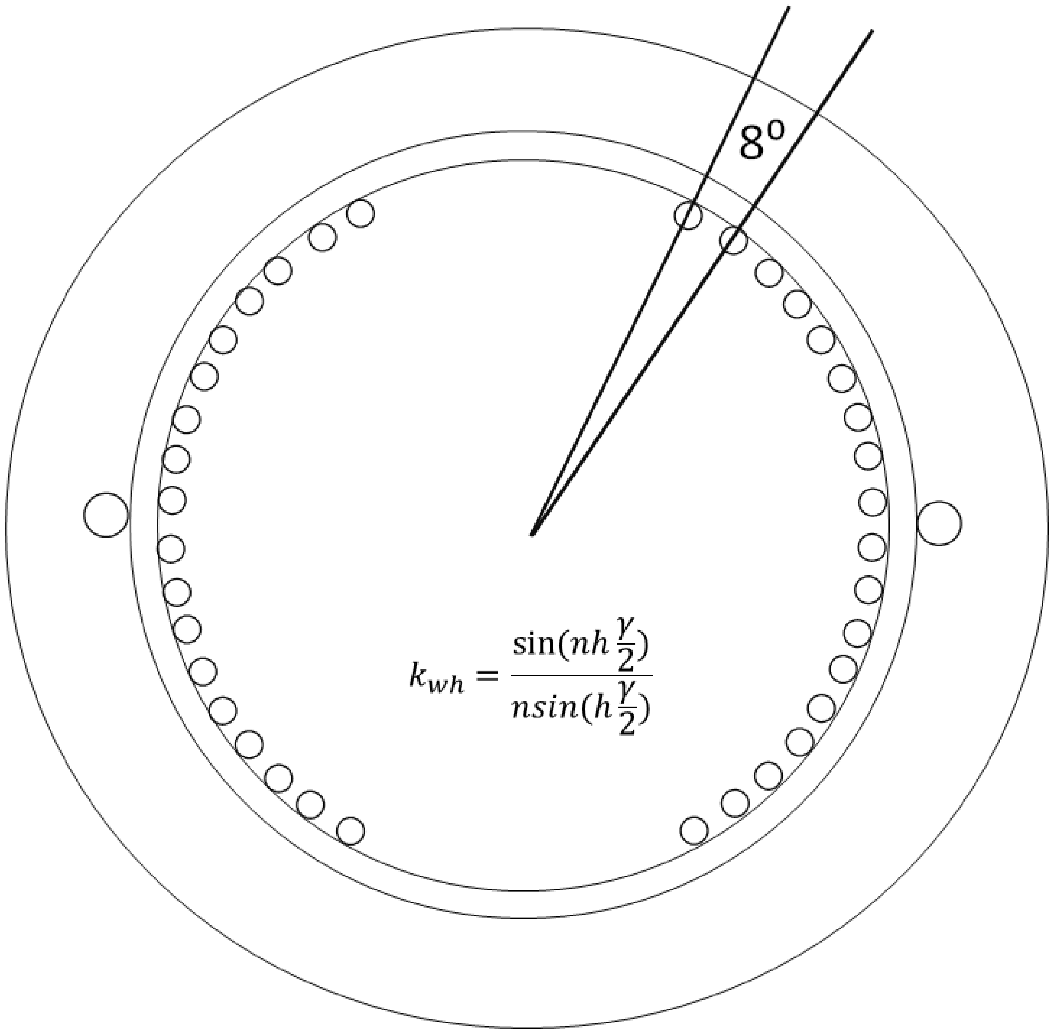
115 (Shahid Salimi, Neka)

28 (Shahid Salimi, Neka)

0.001267 at 20˚C (Shahid Salimi, Neka)

Rotor Winding of Ansaldo Generator

Given the rotor winding configuration as follows, the desired winding factors are:



$$k_{wh} = \frac{\sin(nh\frac{\gamma}{2})}{n\sin(h\frac{\gamma}{2})}$$

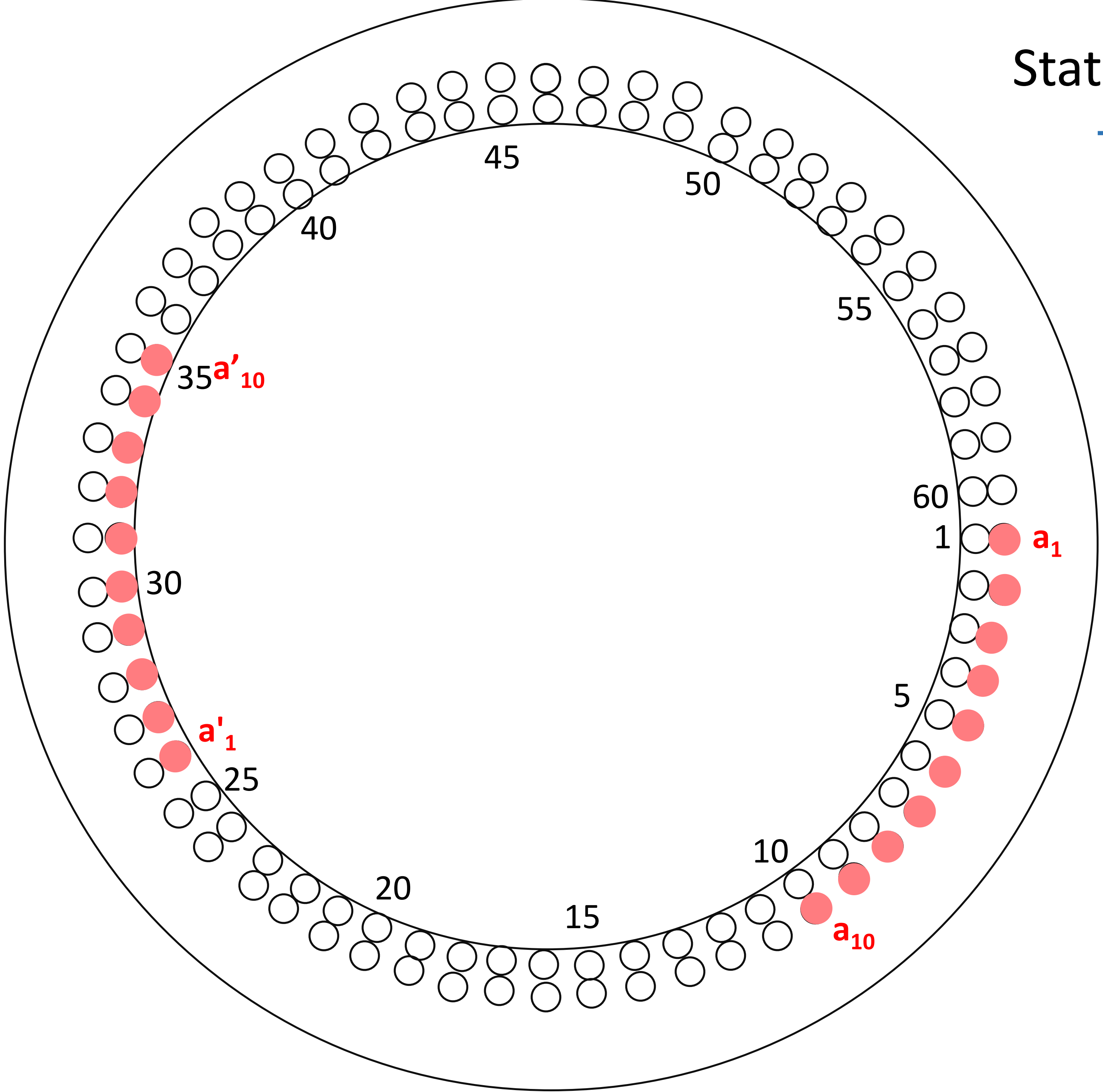
$$k_{w1} = \frac{\sin(18\frac{8}{2})}{n sin(\frac{8}{2})} = 0.7574$$

$$k_{w3} = \frac{\sin(18 \times 3 \times \frac{8}{2})}{n sin(3 \times \frac{8}{2})} = -0.1571$$

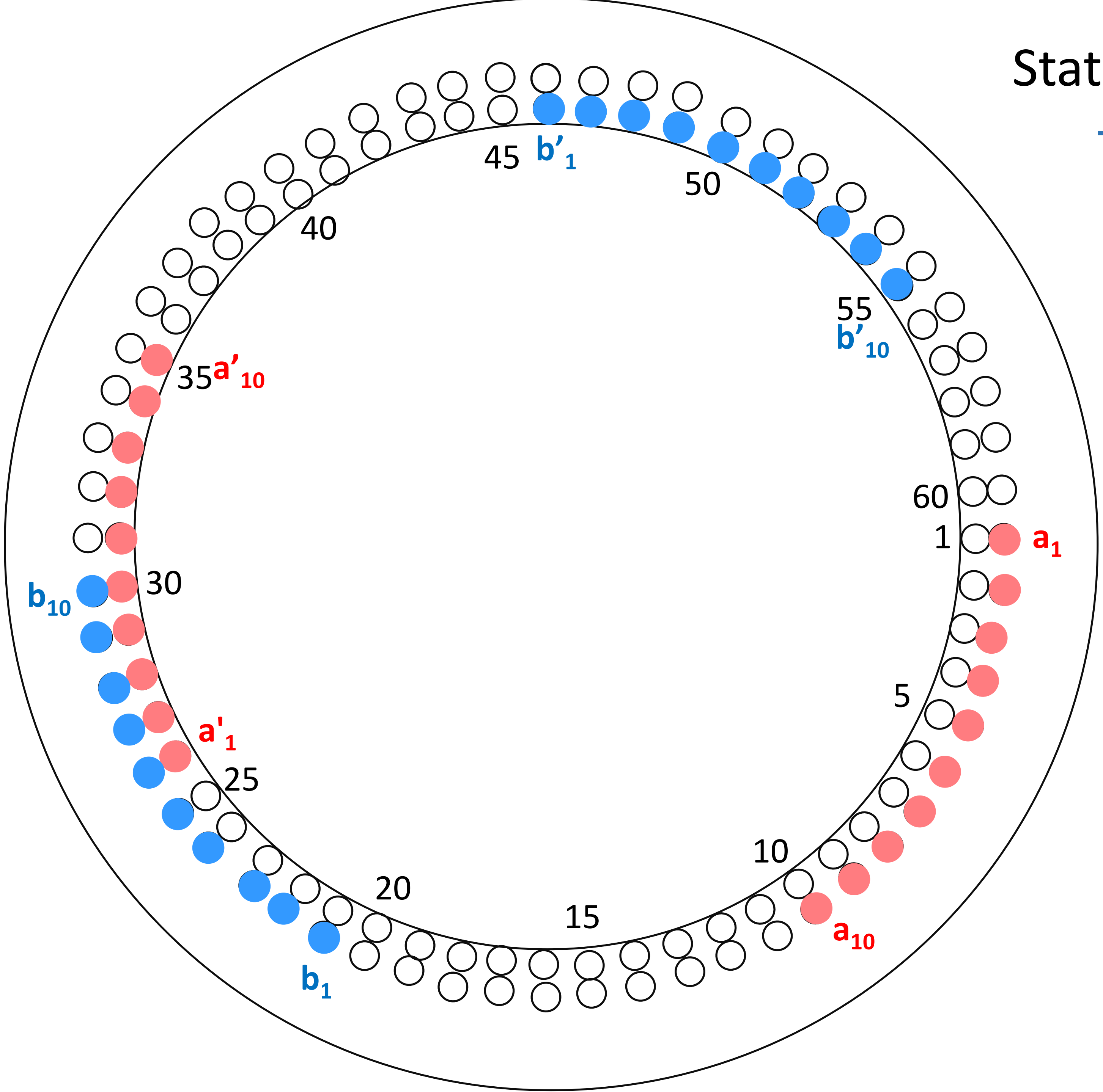
$$k_{w5} = \frac{\sin(18 \times 5 \times \frac{8}{2})}{n sin(5 \times \frac{8}{2})} = 0$$

$$k_{w7} = \frac{\sin(18 \times 7 \times \frac{8}{2})}{n sin(7 \times \frac{8}{2})} = 0.0696$$

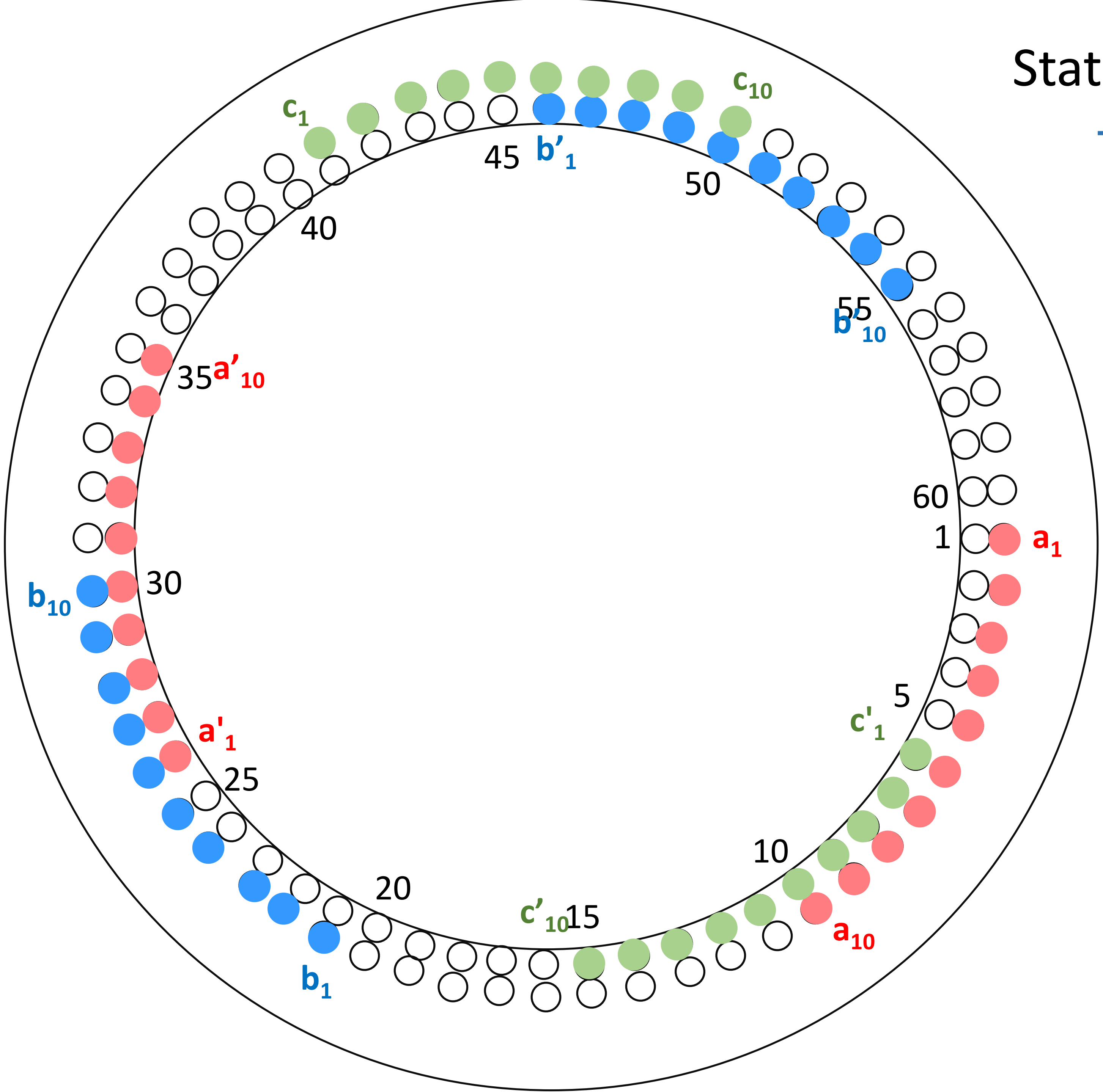
Stator Winding of Ansaldo Generator



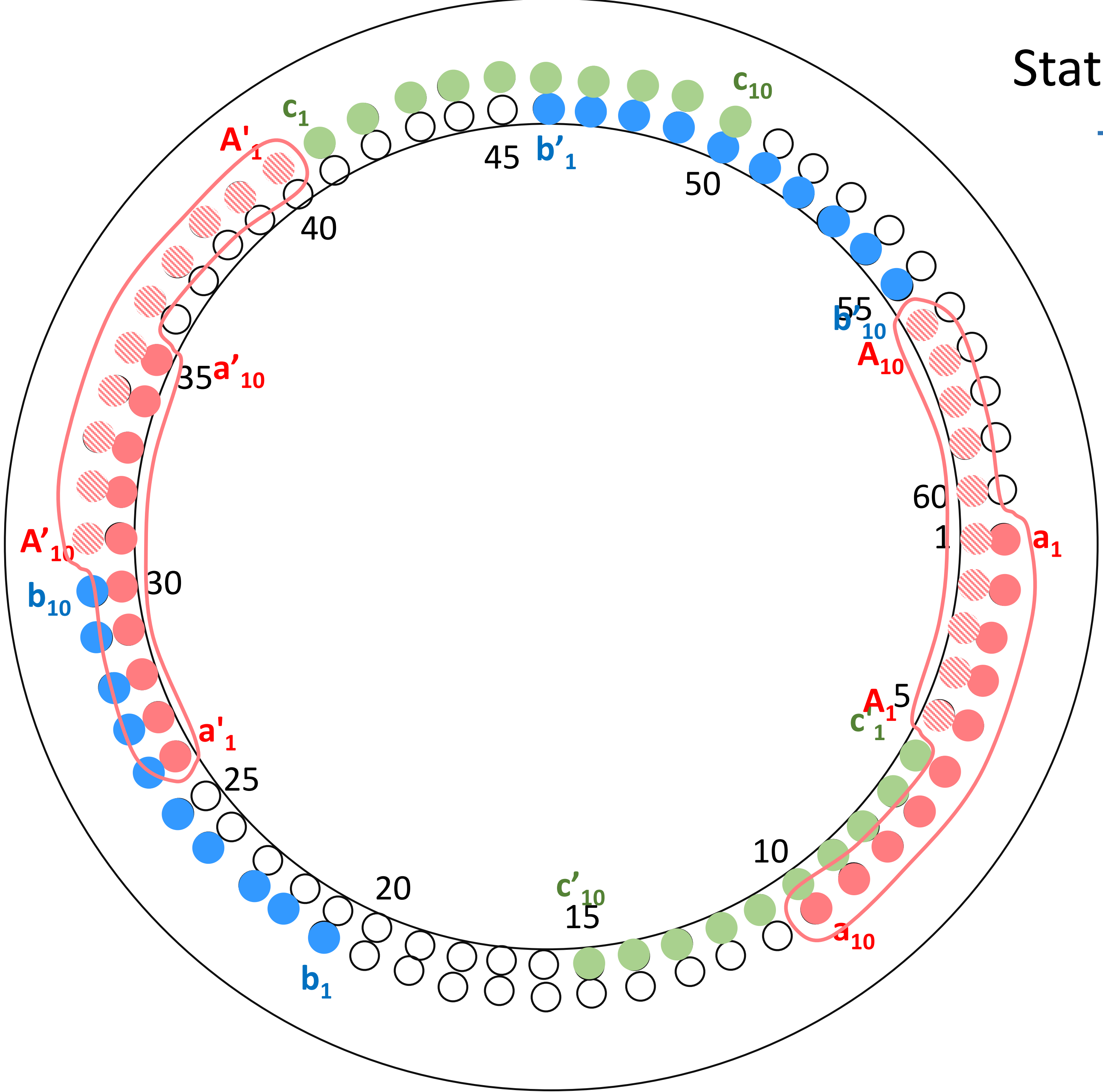
Stator Winding of Ansaldo Generator



Stator Winding of Ansaldo Generator

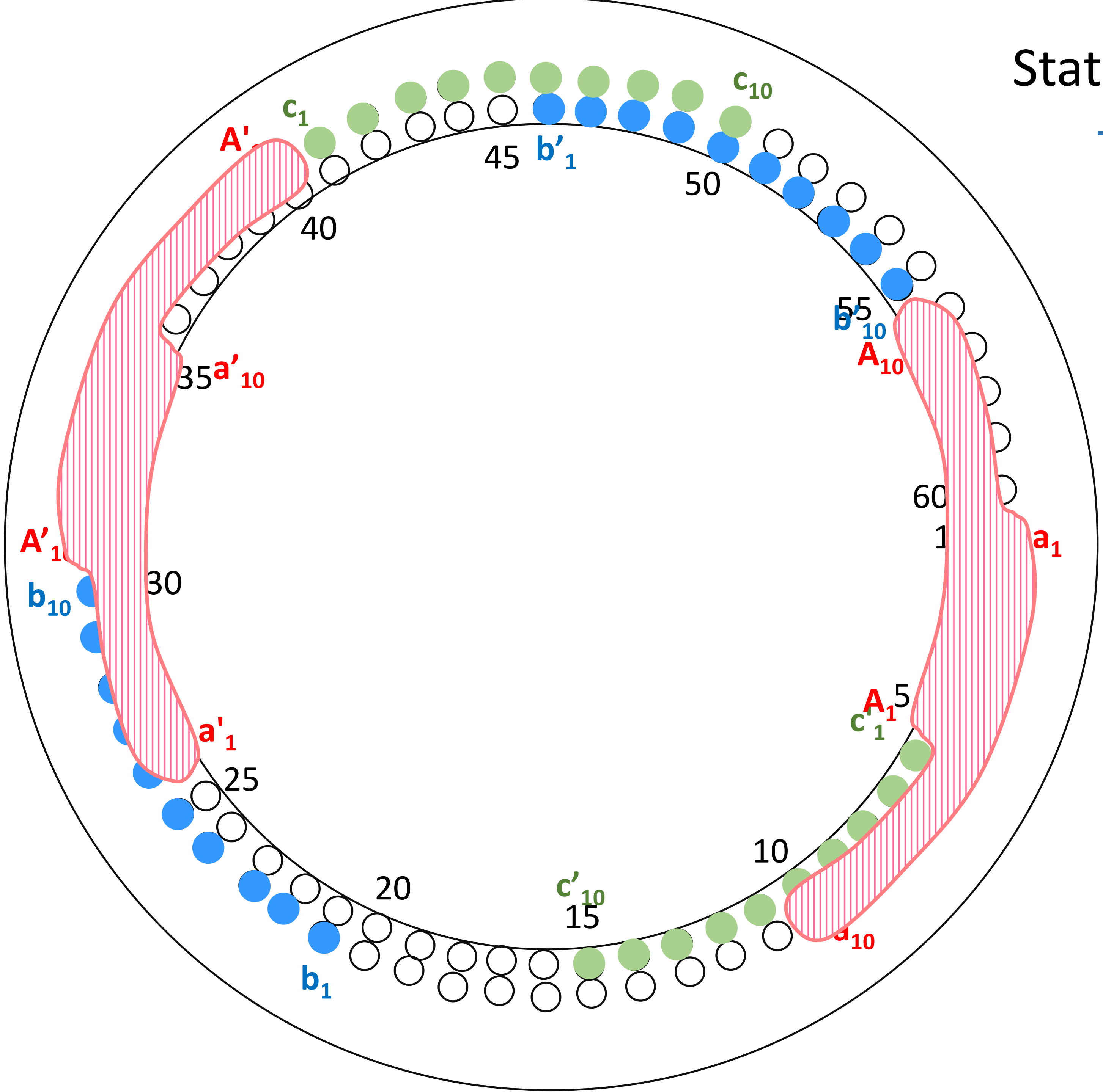


Stator Winding of Ansaldo Generator



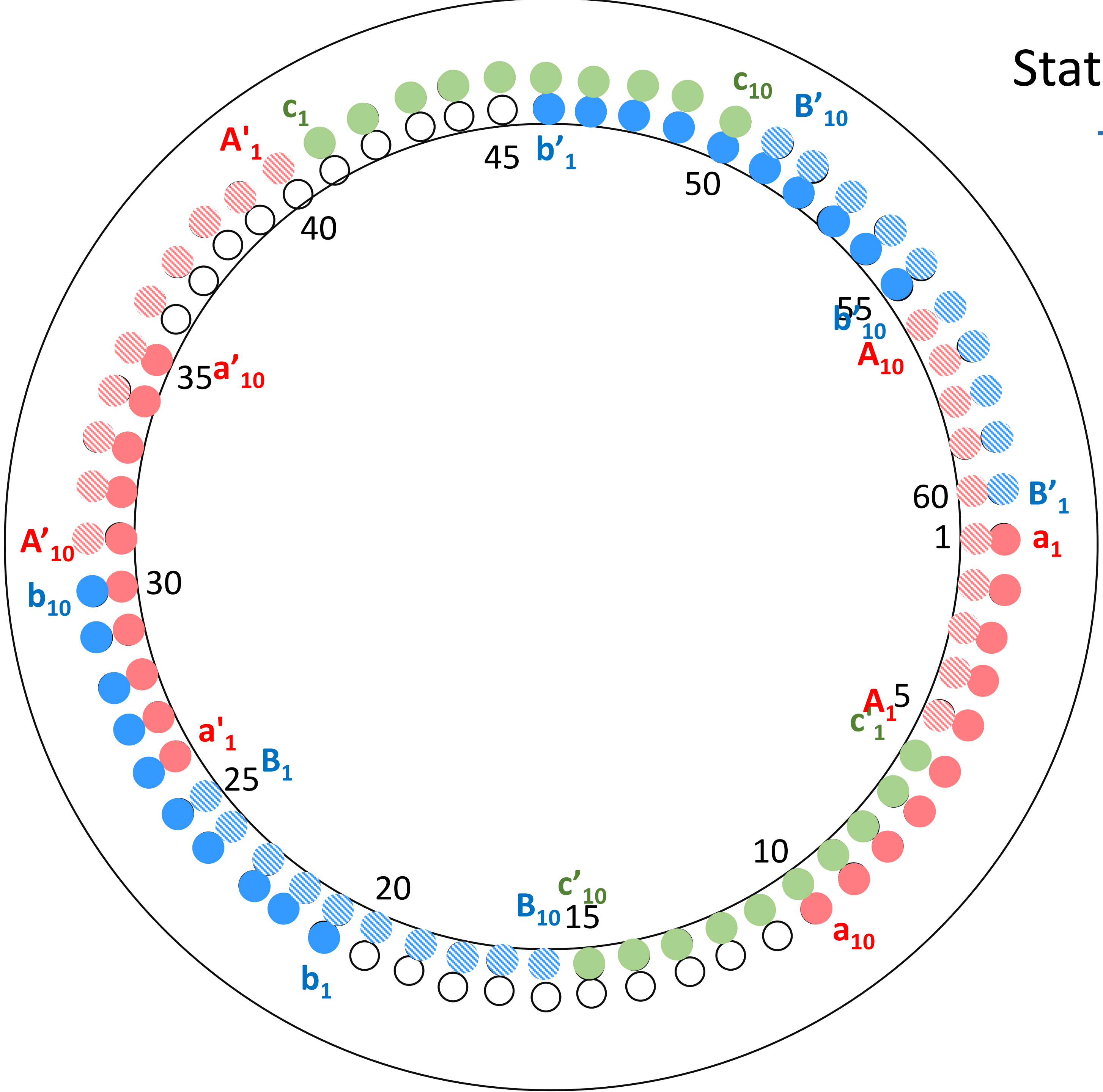
Show that: $e_{a_1 a_{10}'} = e_{A_1 A_{10}'}$

Stator Winding of Ansaldo Generator



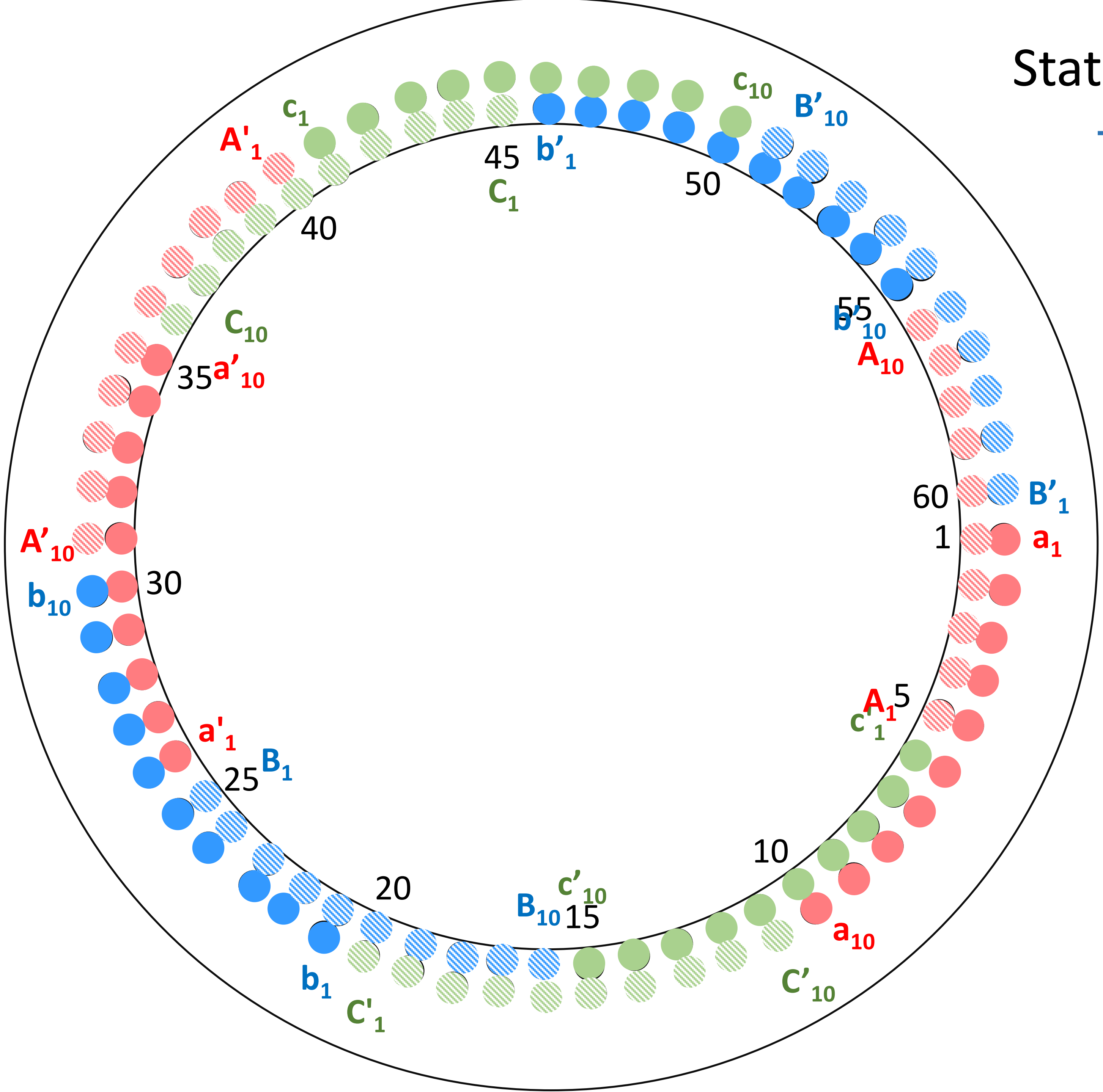
$Show\ that$: $e_{a_1 a_{10}'} = e_{A_1 A_{10}'}$

Stator Winding of Ansaldo Generator



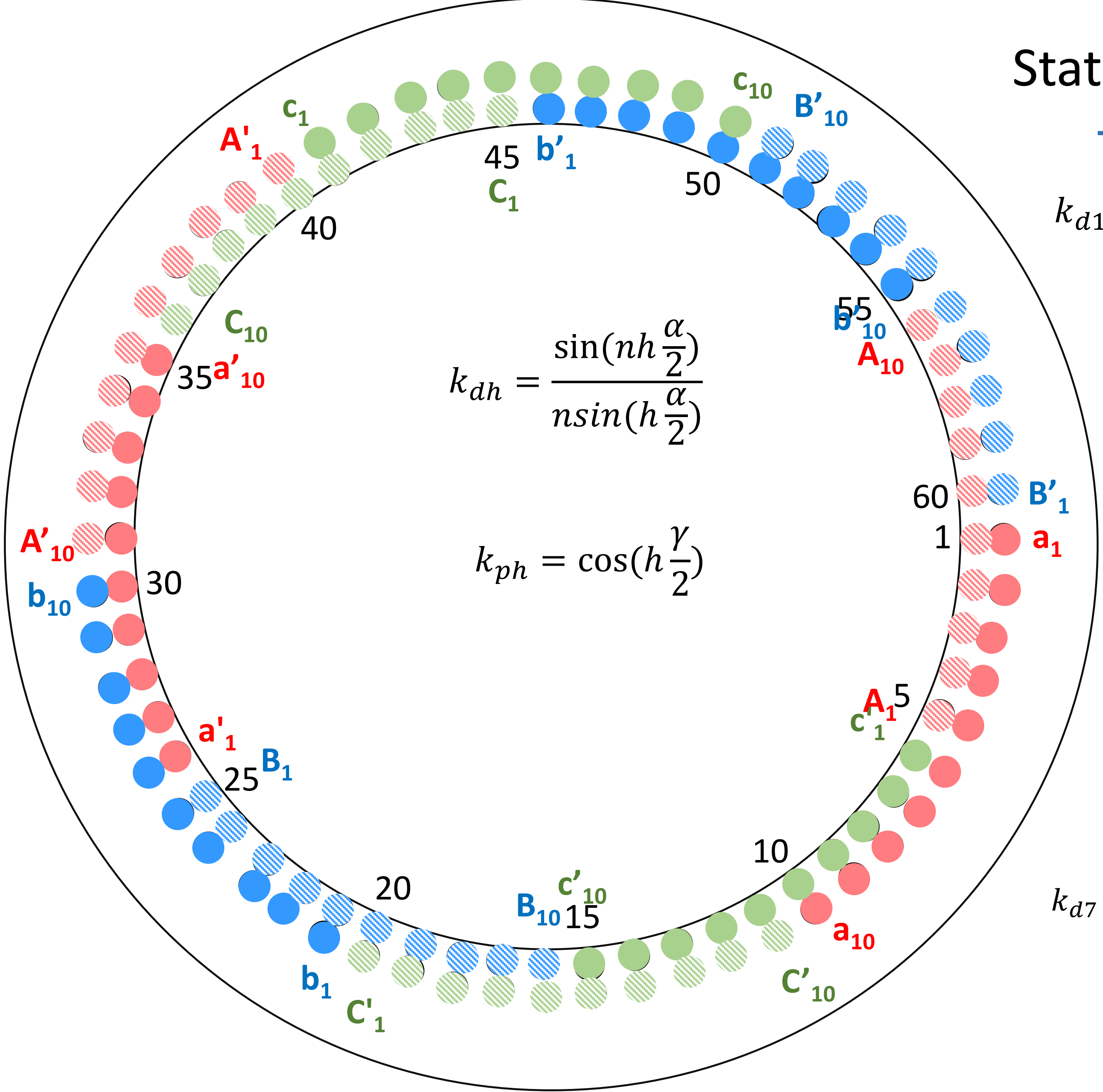
$Clearly\text{: } e_{b_1 b_{10}'} = e_{B_1 B_{10}'}$

Stator Winding of Ansaldo Generator



$$\mathit{Clearly}\colon\ e_{c_1c_{10}'} = e_{C_1C_{10}'}$$

Stator Winding of Ansaldo Generator



$$k_{dh} = \frac{\sin(nh\frac{\alpha}{2})}{n\sin(h\frac{\alpha}{2})}$$

$$k_{ph} = \cos(h\frac{\gamma}{2})$$

$$k_{d1} = \frac{\sin(10\frac{6}{2})}{10\sin(\frac{6}{2})} = 0.9554, k_{p1} = \cos\left(1\frac{30}{2}\right) = 0.9659$$

$$k_{w1} = k_{d1}\,k_{p1} = 0.9228$$

$$k_{d3} = \frac{\sin(3\times 10\frac{6}{2})}{10\sin(3\frac{6}{2})} = 0.6392, k_{p3} = \cos\left(3\frac{30}{2}\right) = 0.7071$$

$$k_{w3} = k_{d3}\,k_{p3} = 0.452$$

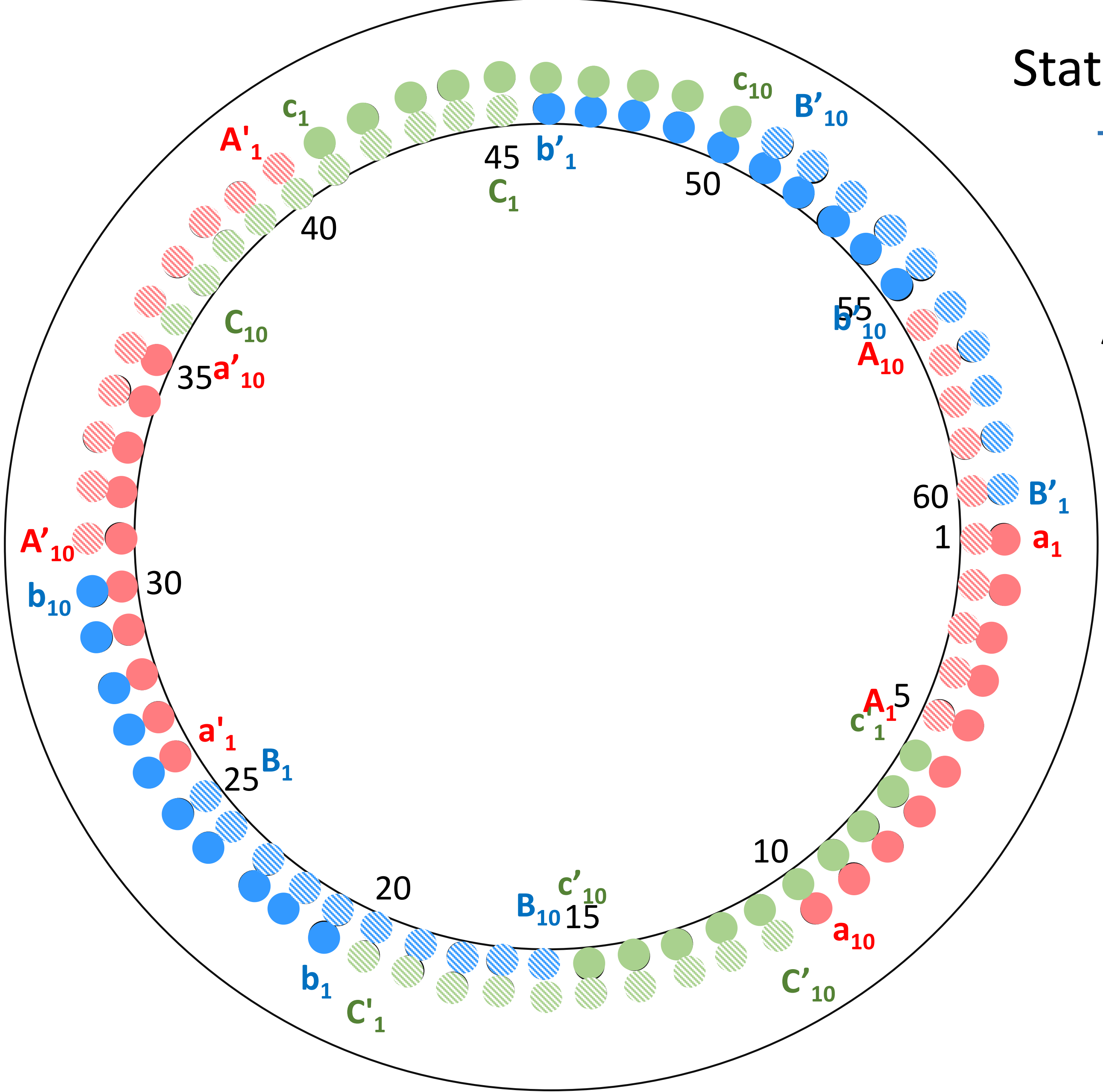
$$k_{d5} = \frac{\sin(5\times 10\frac{6}{2})}{10\sin(5\frac{6}{2})} = 0.1932, k_{p5} = \cos\left(5\frac{30}{2}\right) = 0.2588$$

$$k_{w5} = k_{d5}\,k_{p5} = 0.05$$

$$k_{d7} = \frac{\sin(7\times 10\frac{6}{2})}{10\sin(7\frac{6}{2})} = -0.1395, k_{p7} = \cos\left(7\frac{30}{2}\right) = -0.2588$$

$$k_{w7} = k_{d7}\,k_{p7} = 0.0361$$

Stator Winding of Ansaldo Generator



$k_{w1} = 0.9228 \qquad k_{w3} = 0.452 \qquad k_{w5} = 0.05$

$k_{w7} = 0.0361$

Assuming the amplitude of different harmonics of flux density as follows:

$B_1 = 0.705 \quad B_3 = 0.049 \quad B_5 = 0 \quad B_7 = 0.009$

Determine the effective line-to-neutral and line-to-line voltages.

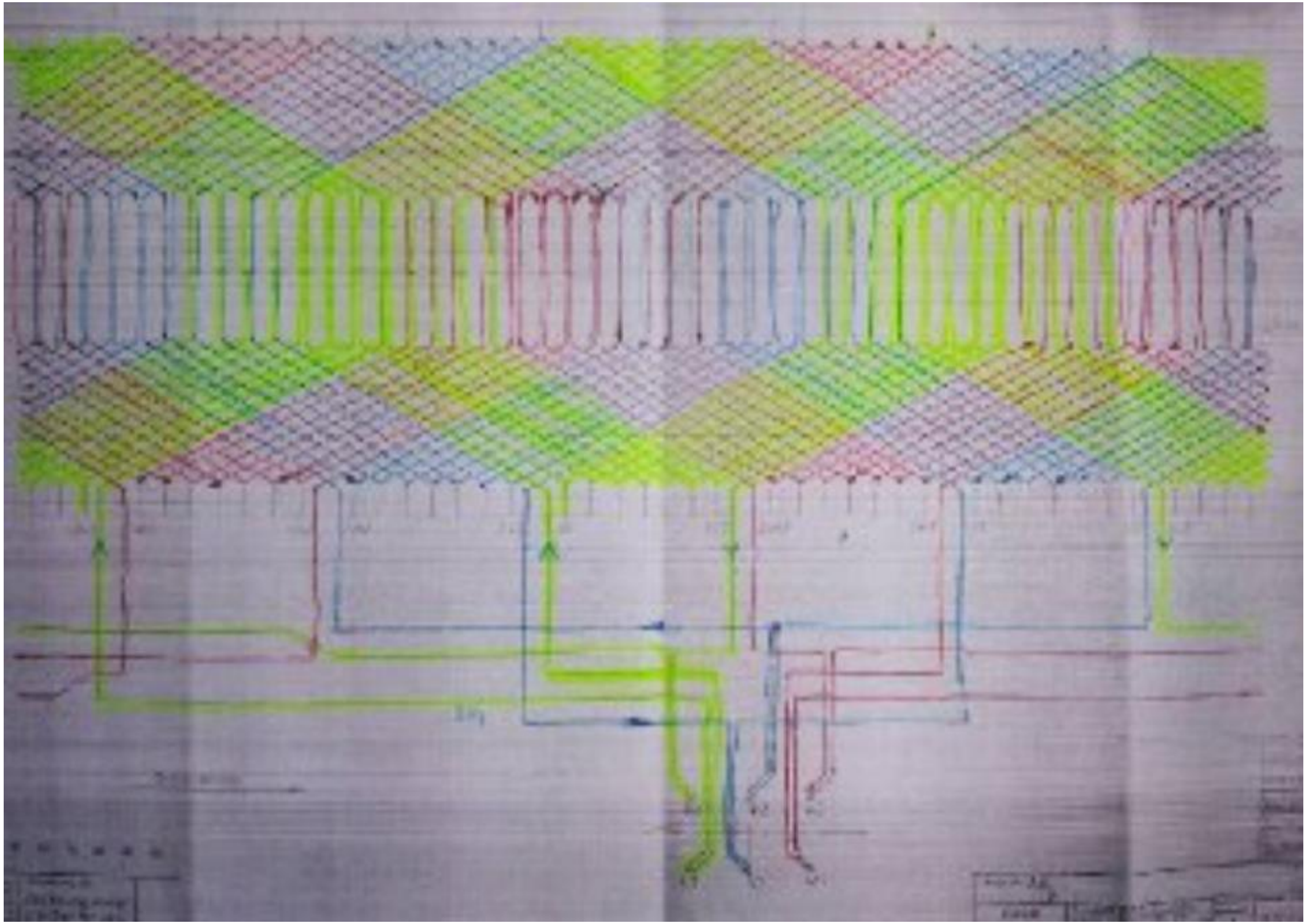
Stator Winding of Ansaldo Generator

Competition between students who are specializing in power or other areas and hav
Machine III and want to challenge themselves:
The next slide diagram shows the stator winding of a 48-slot, 2-pole generator (150 MW). Each stator phase consists of two parallel paths. Note that the voltages of the two paths must be exactly equal.

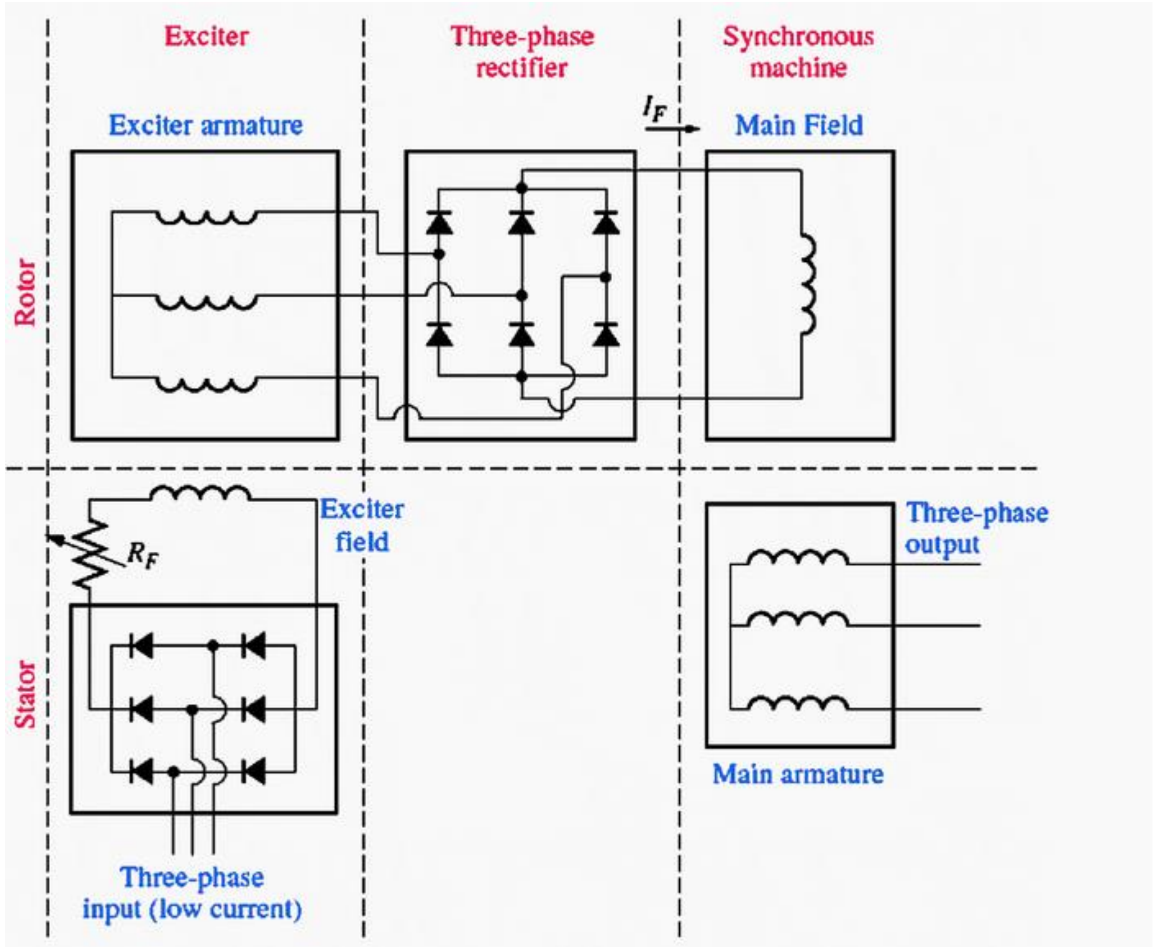
(a) First, draw the stator as a cylinder and show only the winding of one phase on it. Mark one path of the winding in blue and the other path in red.

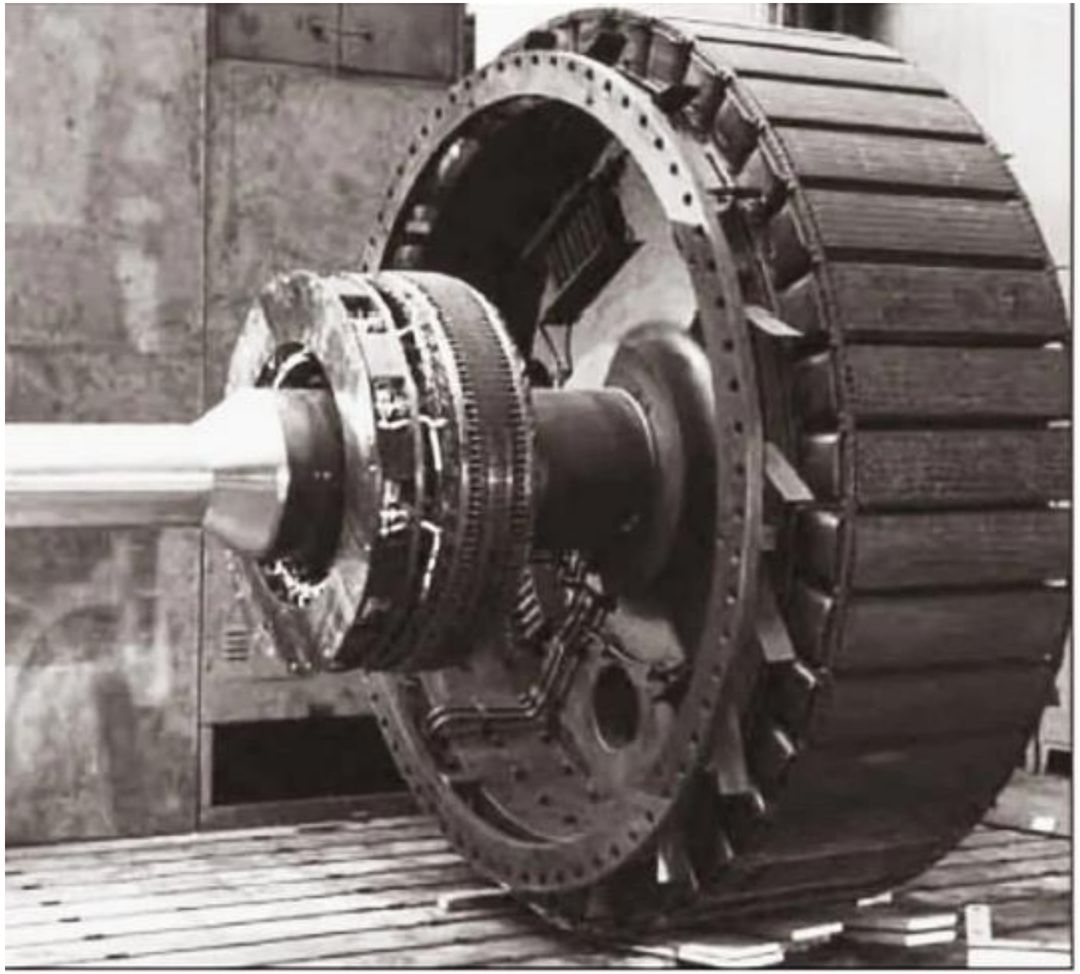
(b) Show that the voltages of the two paths are exactly equal.

Stator Winding of Ansaldo Generator



Extra work from 3 points





Good figures for exams