Armature windings

EE6303 Electric Machines II

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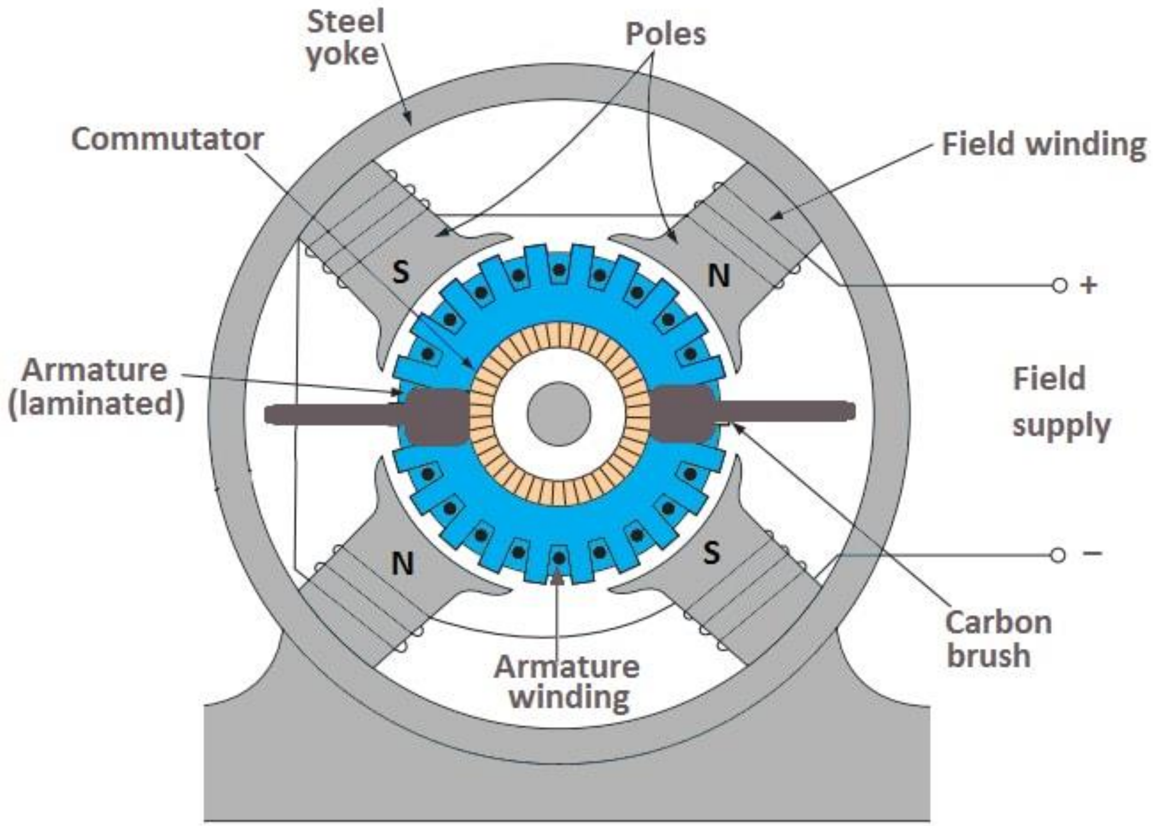
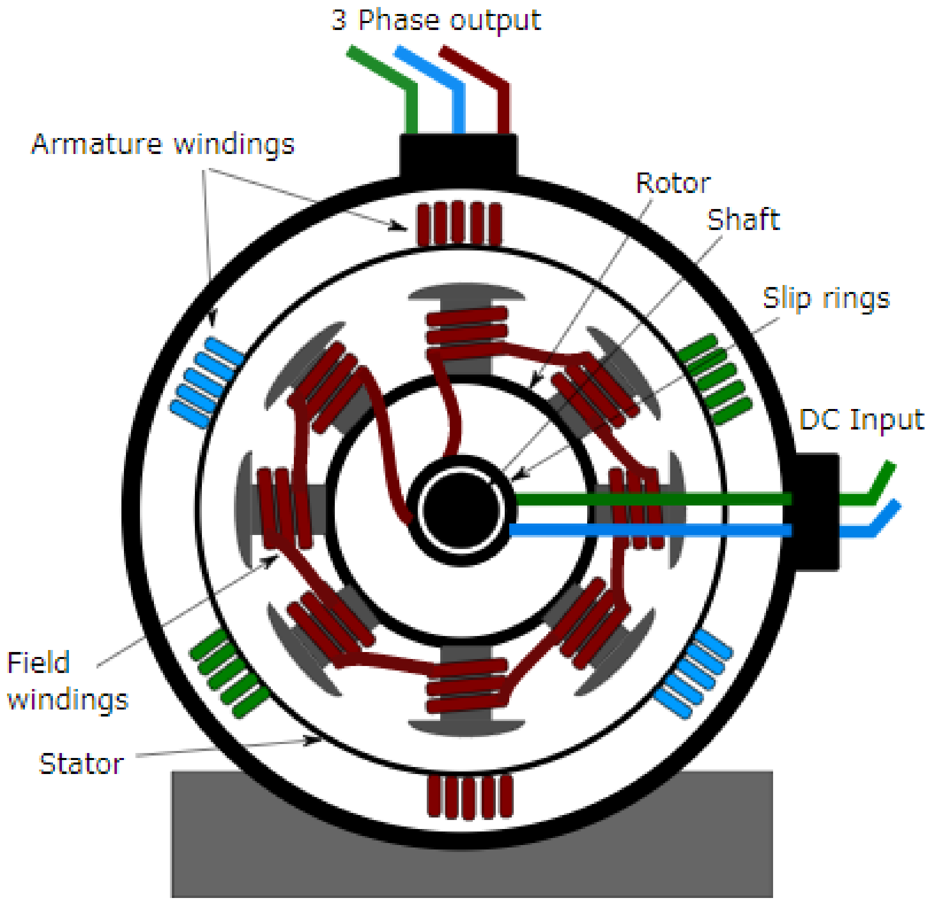
Electrical machine windings

- Field and armature windings are the essential features of electric machines (both DC and AC).



Construction of a DC machine.



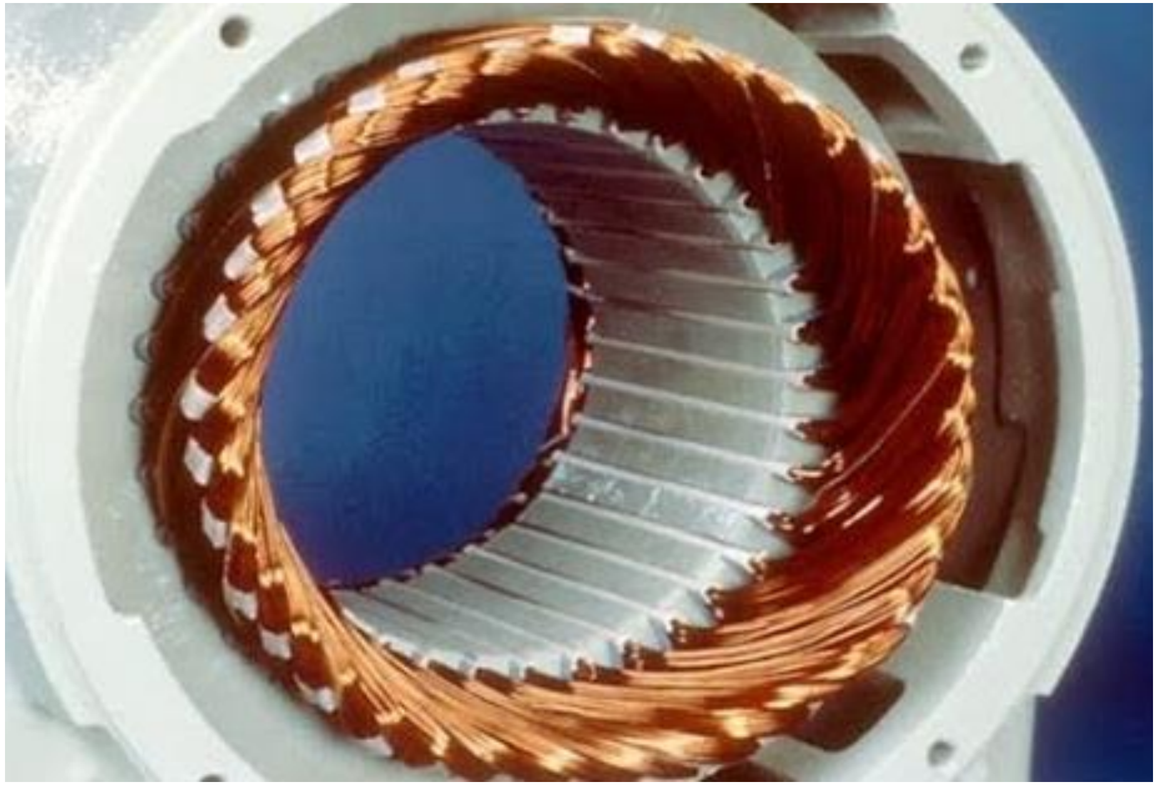
Construction of a salient pole type AC generator.

Electrical machine windings

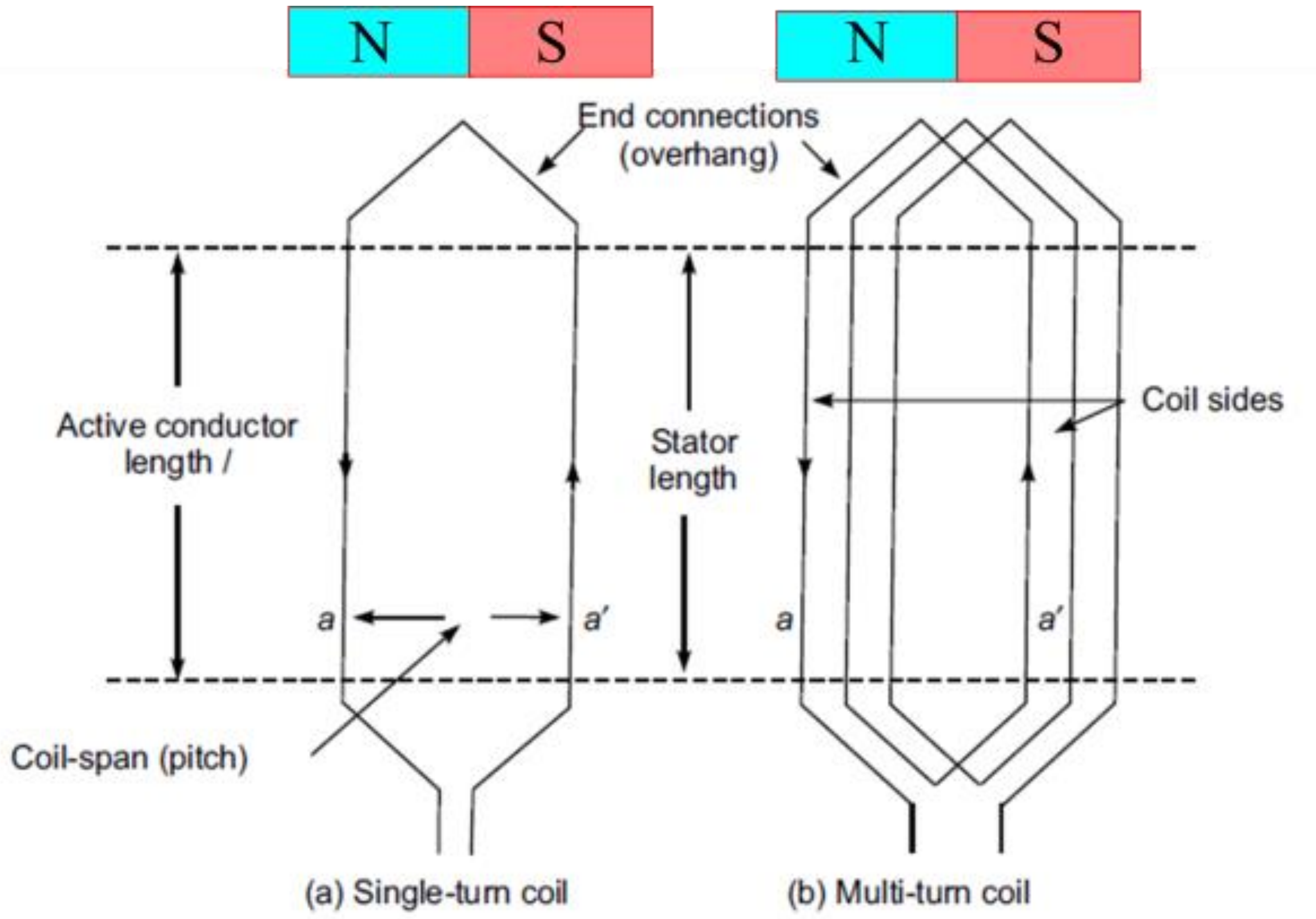
- The field windings are simple arrangements with concentrated coils.
- Concentrated coils: Coils in which all the turns have the same magnetic axis

Electrical machine windings

- Armature windings comprise a set of coils embedded in the slots, uniformly spaced round the armature periphery.



Common terminologies associated with armature windings



Coils.

Common terminologies associated with armature windings

- <u>Conductor</u>:

  An individual piece of wire (active length) placed in the slots in the machine in the magnetic field.

- <u>Turn</u>:

  A turn consists of two conductors separated from each other by a coil pitch and connected in series so that the emf induced will be additive.

- <u>Coil</u>:

  A coil is formed by connecting number of turns together. A coil may consist of a single turn or may consist of many turns. Each turn is insulated from the other turns and from the rotor slot.

- <u>Coil side</u>:

  A coil consists of two coil sides, which are placed in two different slots. The group of conductors on one side of the coil form one coil side while the conductors on the other side of the coil forms the second coil side.

Common terminologies associated with armature windings

- Coil throw:

  The location in an armature core of the sides of a coil starting in slot number one.

  Example 1:The coil throw 1 to 9 meaning that one side of the coil is inserted in slot number 1, and the other side in slot number 9.

- Slots per pole:

  The number of slots in the armature core divided by the number of poles constituting the field.

  Example 2: In a 4 pole three phase generator having 48 slots on the armature, the number of slots per pole is 48/4 = 12 slots.

Common terminologies associated with armature windings

- Pole pitch:

The distance between the central line of one pole to the central line of the next pole. The coil pitch could be expressed in terms of its angular span or in terms of slots.

Pole pitch is always 180 electrical degrees regardless of the number of poles on the machine.

$$\theta_e = \frac{P}{2}\theta_m$$

where θ_e is the electrical angle, θ_m is the mechanical angle, and P is the number of poles.

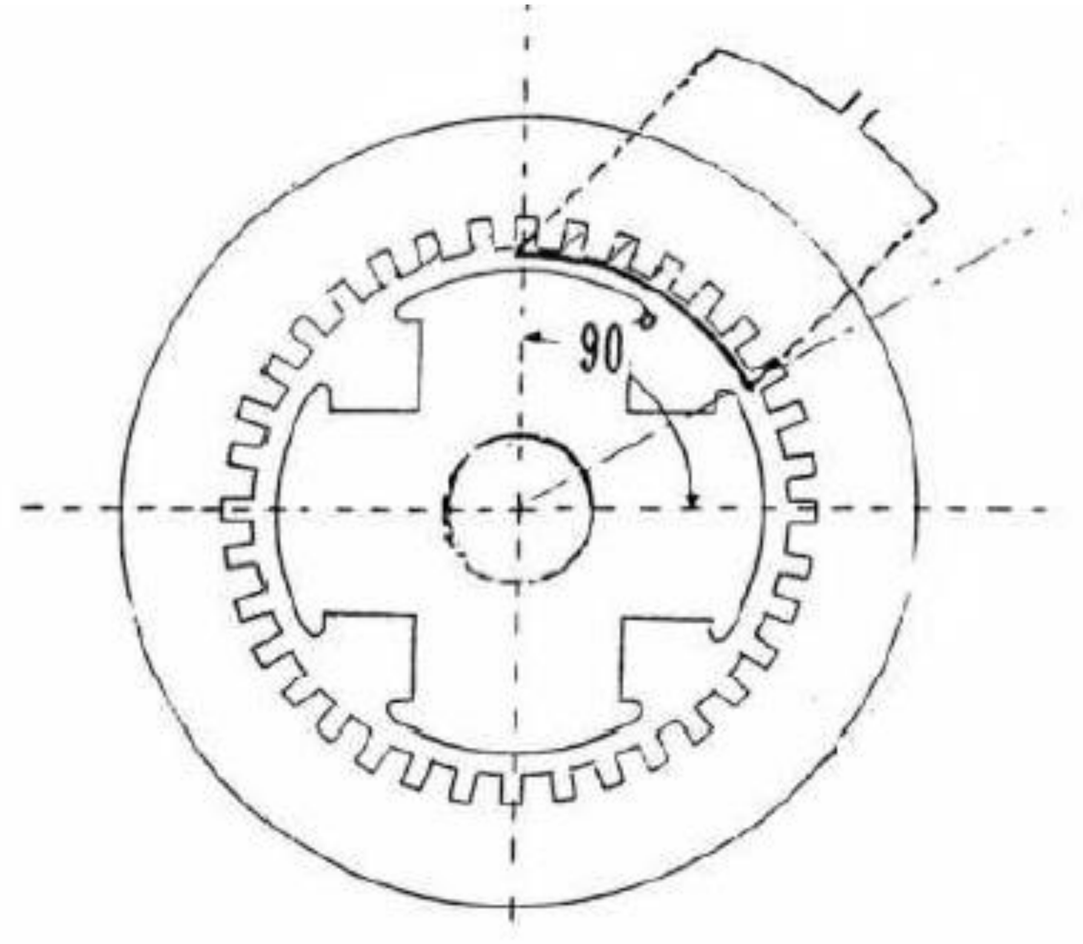
- Coil pitch or coil span:

The distance between the two coil sides of a coil is called coil span or coil pitch. The coil pitch could be expressed in terms of its angular span or in terms of slots.

Example 2: In example 1 mentioned in slide 11, the coil pitch is 8 slots (9 - 1).

Questions

Example: Find the slots per pole, coil pitch, and the pole pitch of the following machine.



Number of slots = 36
Number of poles = 4
Slots per pole = 9 slots
Coil Pitch = 6 slots,
Pole pitch = 9 slots.

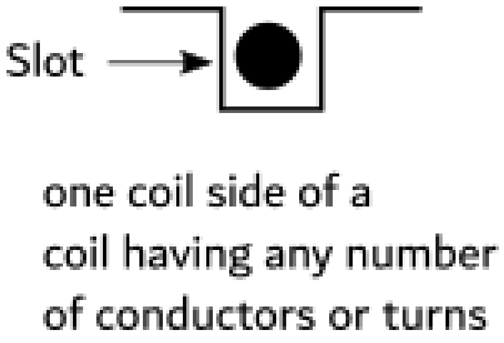
Common terminologies associated with armature windings

- <u>Single-layer winding and Double-layer windings</u>

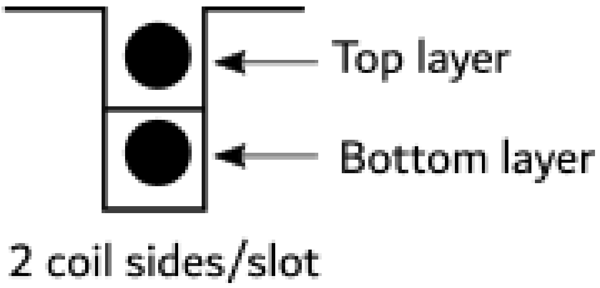
  In a single-layer winding, only one coil side is placed in one slot.

  In a double-layer winding, two coil sides are placed in a single slot and arranged in two layers.

  In a double-layer winding, all the coils are identical in shape and size with two coil-sides lying in two different planes. Each slot has one coil-side entering its bottom half from one side and the other coil-side leaving its top half on the other side.



Single-layer windings.



Double-layer windings.

Common terminologies associated with armature windings

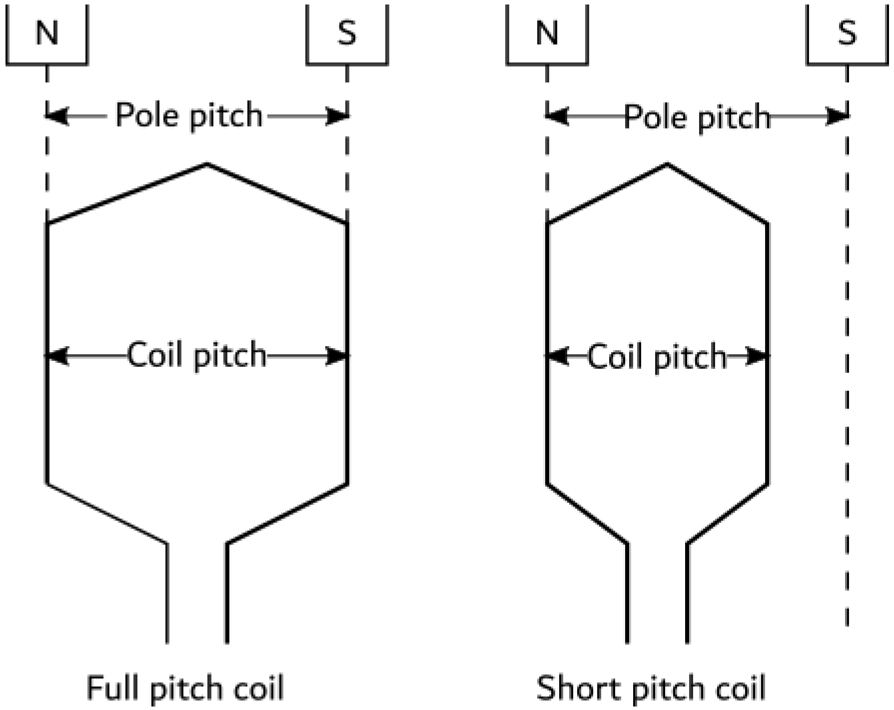
Full pitch coil and short pitch (chorded) coil

- Full pitch coil

  When the angular distance between the sides of a coil is exactly equal to the angular distance between the centers of adjacent field poles (coil pitch is equal to the pole pitch), the coil is termed to be a full pitch coil.

- Short pitch (chorded) coil

  When the angular distance between the sides of a coil is less than the angular distance between the centers of adjacent field poles (coil pitch is less than pole pitch), the coil is termed to be a short pitch coil.



Full pitch and short pitch coils.

Classification of windings

The windings (field and armature windings) used in rotating electrical machines (DC and AC) can be classified as:

- Concentrated windings
- Distributed Windings

Armature windings (both in DC and AC machines) in general can be classified as

- Closed Windings
- Open Windings

Concentrated and Distributed windings

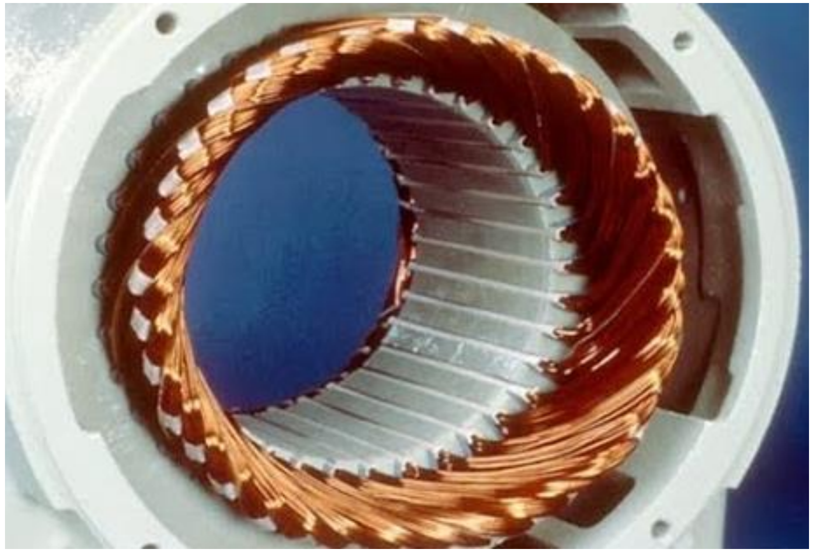
Concentrated windings

- In concentrated windings, all the winding turns are wound together in series to form one multi-turn coil and all the turns have the same magnetic axis.
- Examples of concentrated winding are:
  - Field windings of salient-pole synchronous machines.
  - Field windings of DC machines

Concentrated and Distributed windings

<u>Distributed Windings</u>

- All the winding turns are arranged in several full-pitch or fractional-pitch coils.
- These coils are then housed in the slots spread around the armature periphery.
- Examples of distributed winding are
  - Stator and rotor of induction machines
  - The armatures of both synchronous and DC machines



Closed and Open windings

<u>Closed Windings</u>

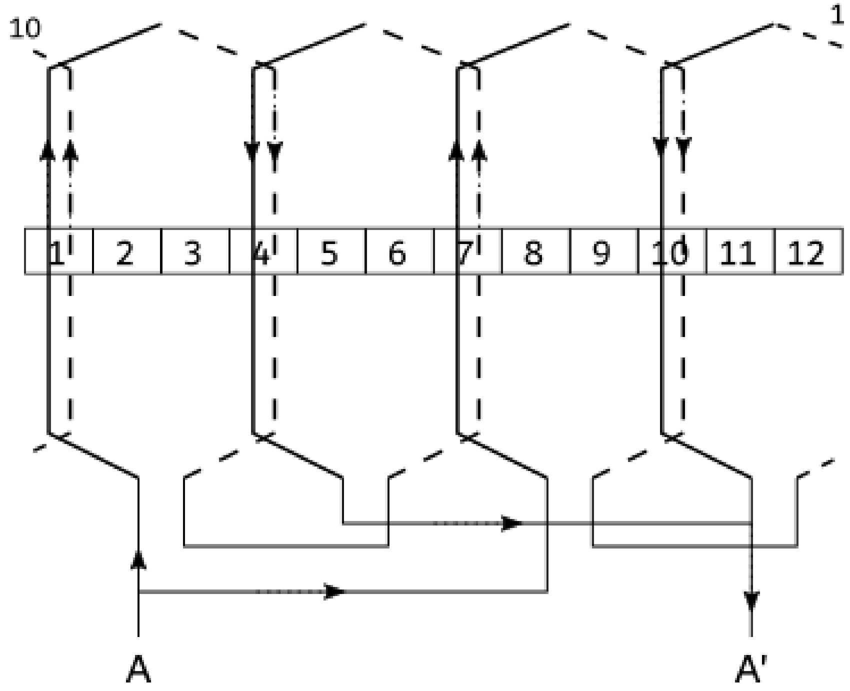
- There is a closed path in the sense that if one starts from any point on the winding and traverses it, one again reaches the starting point from where one had started.
- Used only in DC machines and AC commutator machines.

<u>Open Windings</u>

- There is no closed path in the windings.
- Used only for AC machines.

Developed winding diagram

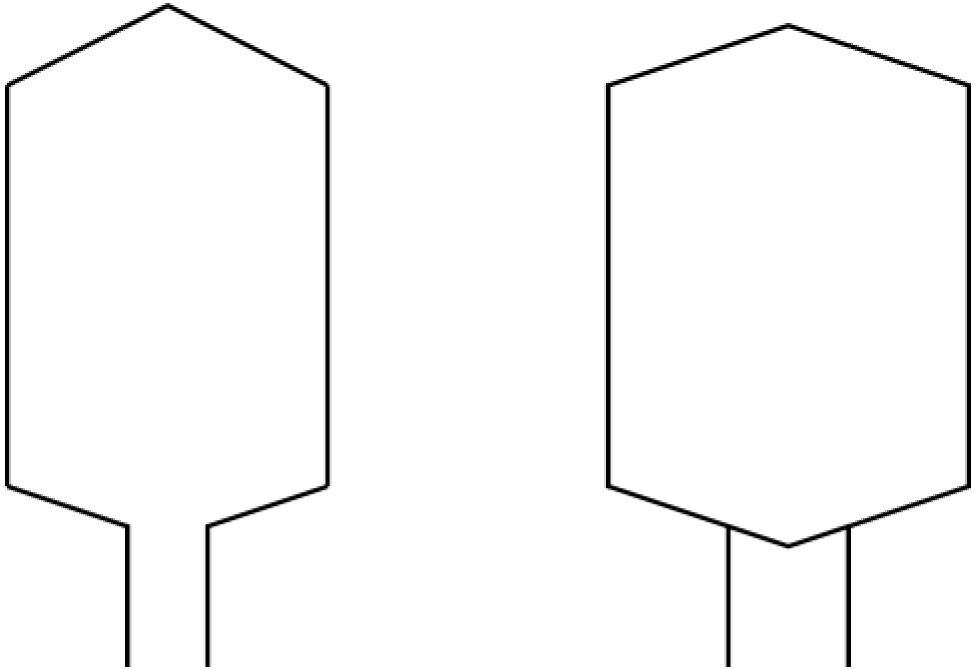
- The arrangement of coils round the armature periphery and their interconnections is best illustrated in form of a *developed winding diagram*.
- For the purpose of drawing a winding diagram, it is convenient to imagine the armature to be laid out flat in a developed form with slots parallel to each other.



Developed winding diagram.

Representation of a single turn coil and a multi turn coil

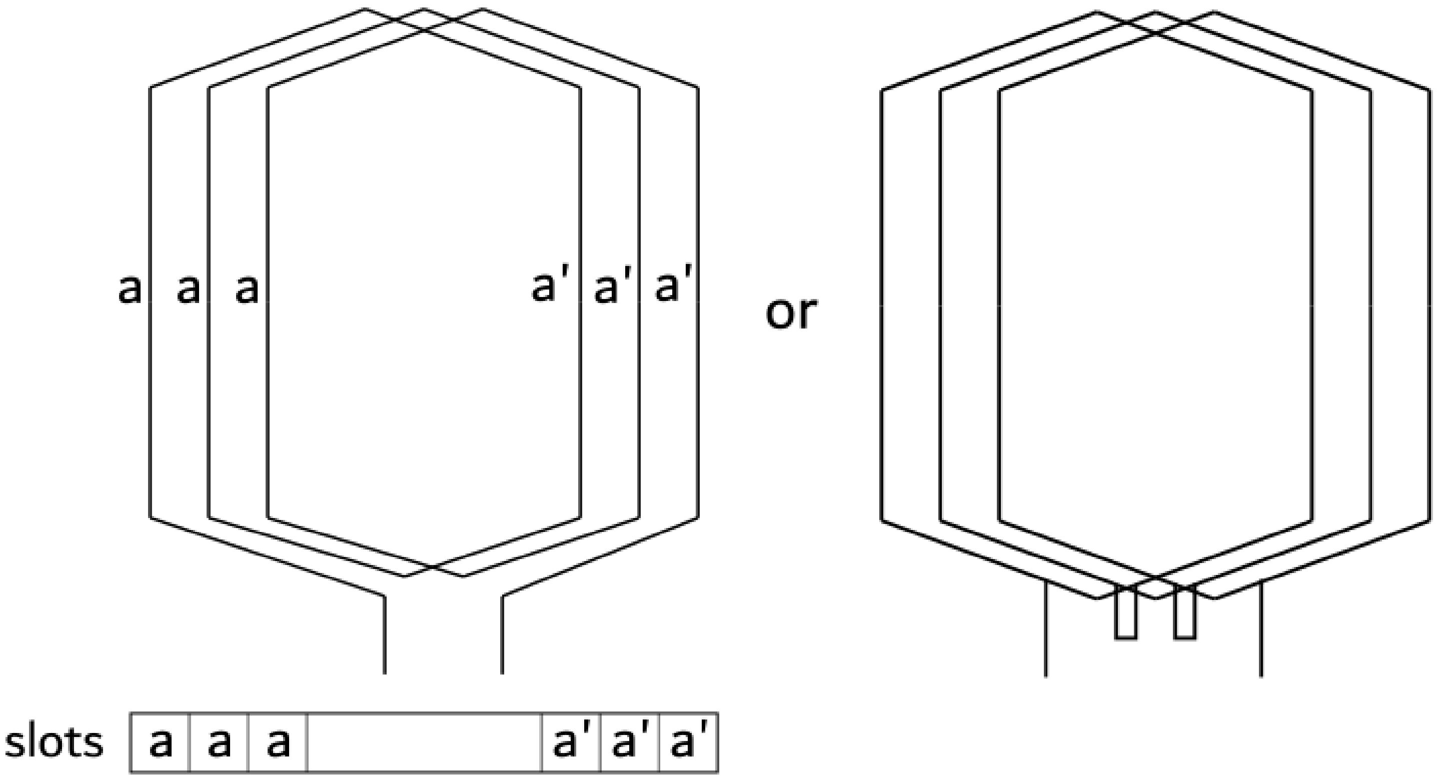
- In a developed winding diagram, single turn coils and multi-turn coils are represented as follows.



Single turn coil   Multi turn coil

Representation of Single-layer winding

Example: Single-layer representation of a winding with three series connected coils distributed in three consecutive slots.

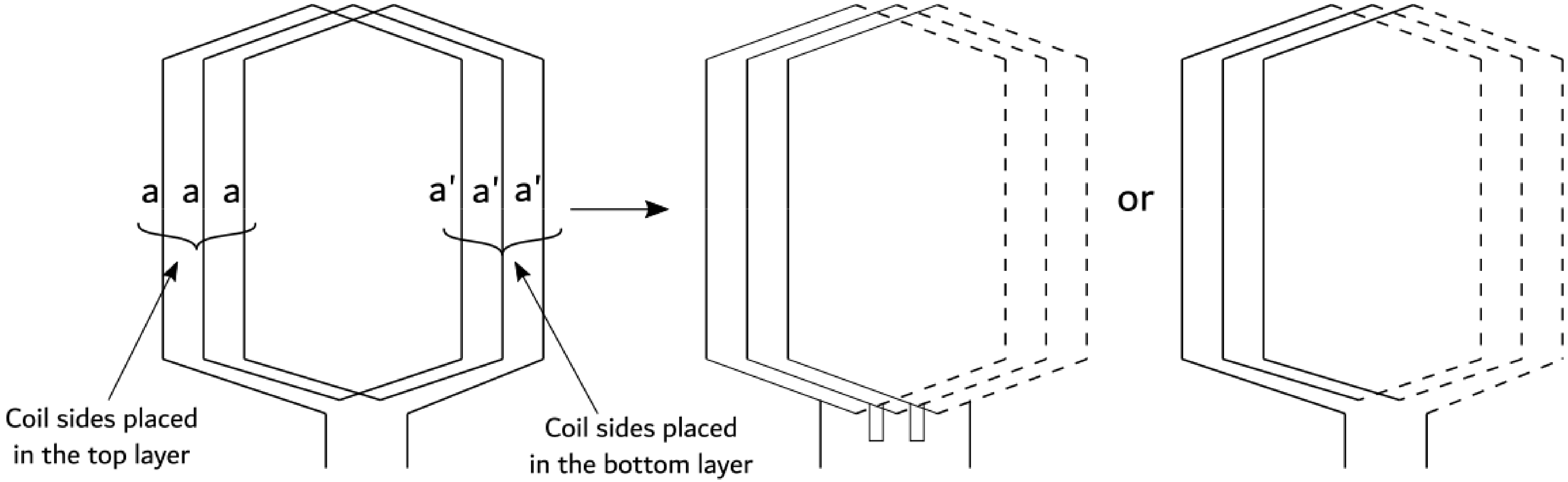


Single-layer winding representation in a winding diagram.

Representation of Double-layer winding

Example: Double-layer representation of a winding with three coils distributed in three consecutive slots.

The top layer coil sides are indicated by continuous lines and the bottom layer coil sides are indicated by dotted lines.



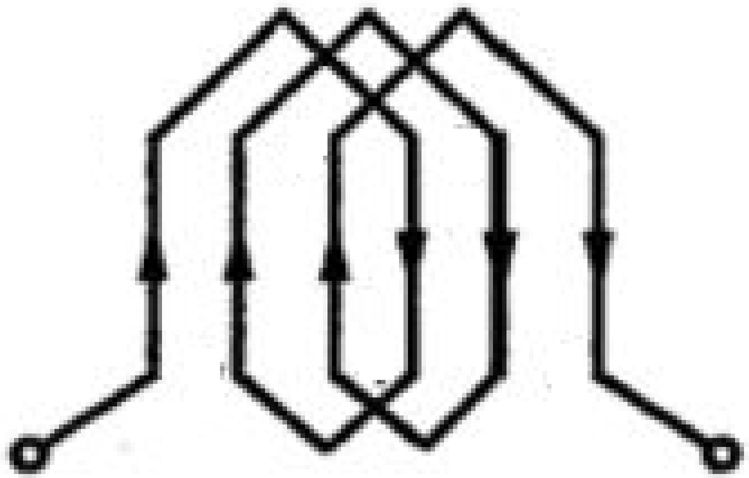
Top layer	a	a	a				
Bottom layer					a'	a'	a'

Double-layer winding representation in a winding diagram.

DC machine armature windings

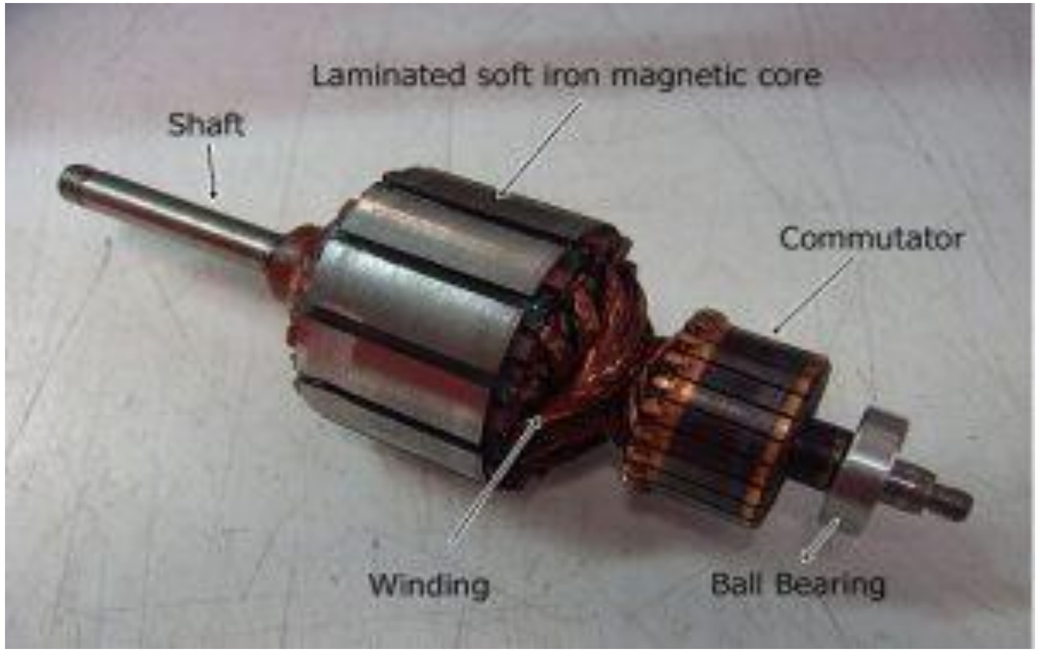
DC machine armature windings

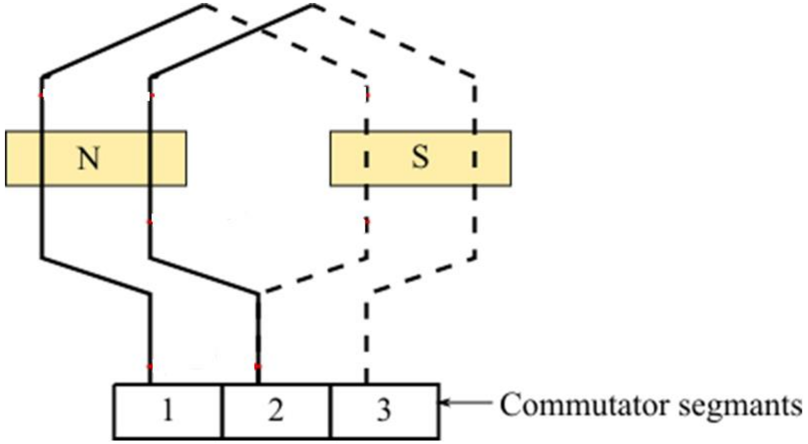
- Armature winding of a DC machine is always *closed and of double layer type*.
- Closed winding essentially means that all the coils are connected in series forming a closed circuit.



DC machine armature windings

- The junctions of the consecutive coils are terminated on copper bars called commutator segments.
- Each commutator segment is insulated from the adjacent segments by mica insulation.
- On a commutator segment, two coil sides (belonging to two different coils) terminate.
- Number of commutator segments must be equal to the number of slots.





Common terminologies

- *Commutator pitch* (y_c)

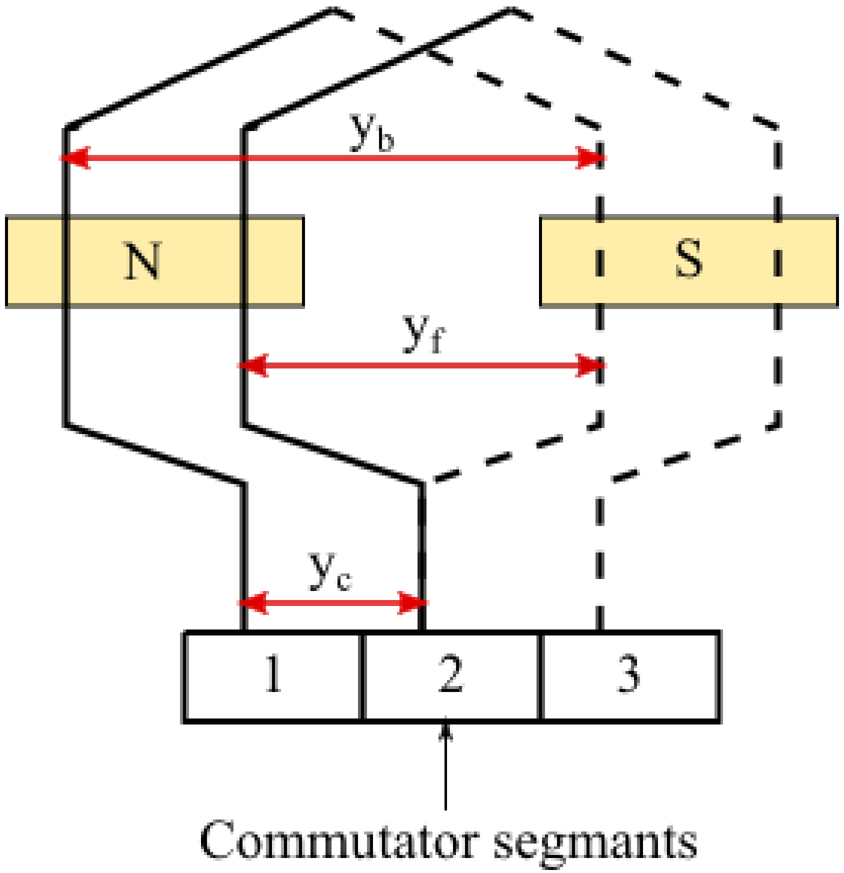
  The separation of coil sides of a coil in terms of number of commutator segments.

- *Back pitch* (y_b)

  The back pitch is similar to that of coil pitch i.e., the distance between the two coil sides of a coil. It is the distance between the armature conductors, which a coil advance on the back of the armature.

- *Front pitch* (y_f)

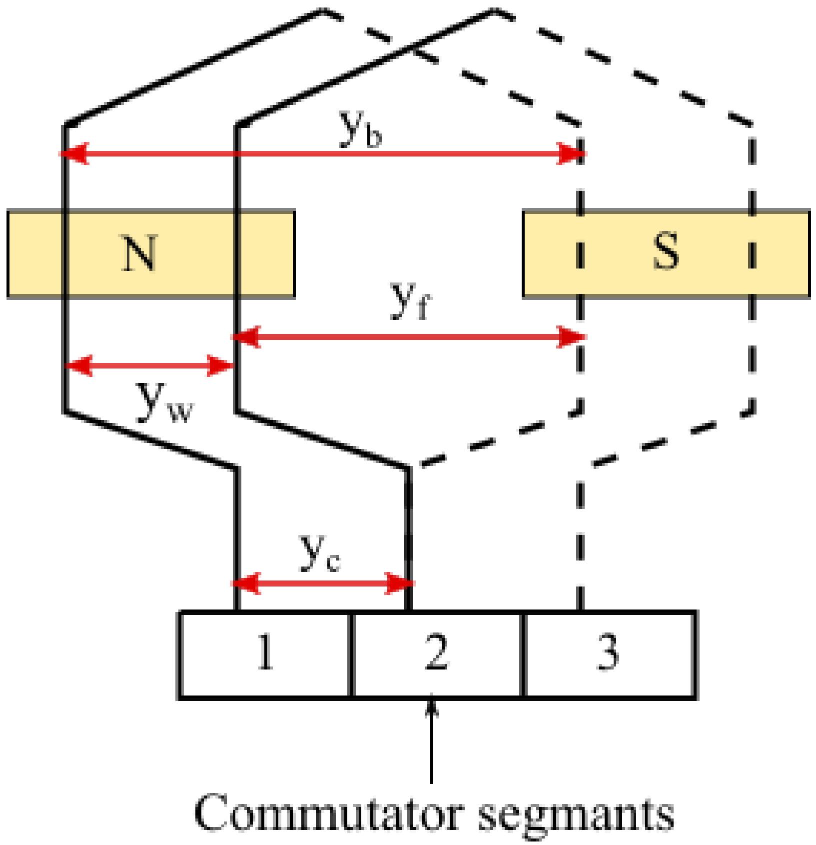
  The distance between the two coil sides connected to the same commutator segment.



Common terminologies

- *Winding pitch* (y_w)

The distance between the two consecutive and similar coil sides as the winding progresses.



DC machine armature windings types

- The different armature coils in a DC machine armature winding must be connected in series with each other by means of end connections in a manner so that the generated voltages of the respective coils will aid other in the production of the terminal emf of the winding.
- Two basic methods of making these end connections are;
  - Simplex Lap winding
  - Simplex Wave winding
- In each type, there are two modes:
  - Progressive
  - Retrogressive

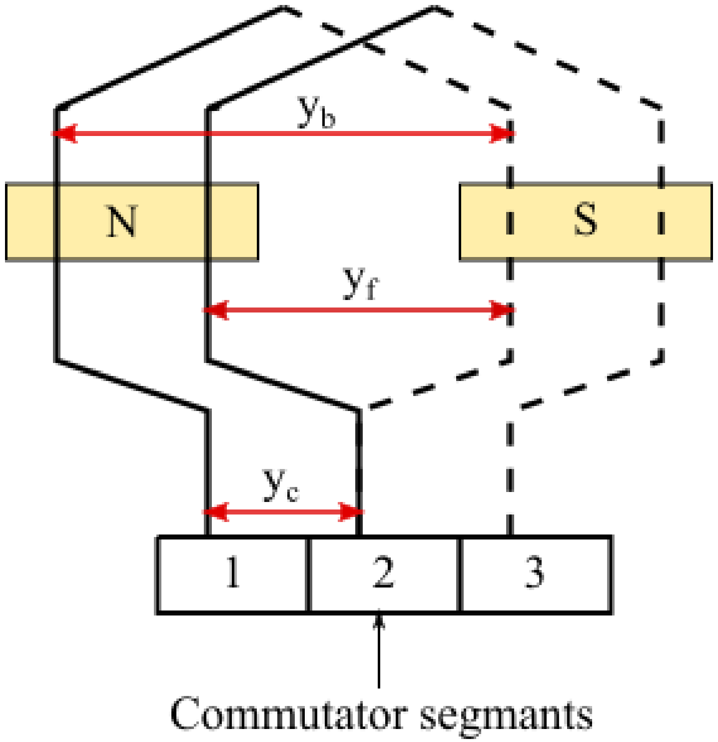
Design procedure

- Type of winding (lap or wave), total number of slots (S), and total number of poles (P) will be given.
- Calculate the front (y_f) and back pitches (y_b).
- Calculate the commutator pitch (y_c).
- Draw the developed view of the winding diagram showing
  - the positions of the coil sides in slots,
  - interconnection of the coils through commutator segments
- Place the stationary brushes on the correct commutator segment.
  - The function of brushes in the DC machine is to collet current from commutator segments.
  - The number of brushes in the DC machine equal to the number of parallel paths.

Simplex Lap winding

- In lap winding, the end of one coil is connected to the beginning of the next coil with the two ends of each coil coming out at adjacent commutator segments.

- Commutator pitch (y_c) for a lap winding is ± 1.
  - Progressive lap winding: $y_c = +1$,
  - Retrogressive lap winding: $y_c = -1$



- In simplex lap winding;

$$y_b \approx \frac{S}{P}$$

$$y_f = y_b - y_c$$

$$y_w = y_b - y_f$$

- For Lap winding, the numbers of parallel path are equal to the total number of poles.

  Therefore, the number of brushes is equal to the total number of poles.

Simplex Lap winding

- This winding is used in large current applications, because it has more parallel paths.
- It is suitable for low voltage and high current applications.
- This winding required a greater number of conductors for generating certain emf, hence the winding cost is high.

Example 1

Draw the developed armature winding diagram of a DC machine with 8 slots, four-pole, two-layer, progressive simplex lap winding. The number of turns per coil is one.

Slots per pole $= \frac{S}{P} = 2$ slots

Back pitch: $y_b \approx \frac{S}{P} = 2$ slots

Front pitch: $y_f = y_b - y_c = 2 - 1 = 1$ slots

The commutator pitch, $y_c = +1$

Example 1: Solution

- Winding table

Slot numbers where the coils sides are placed $[x, (x + y_b)']$	Commutator segments where the coil ends terminate $[x, x + y_c]$
1,1+2 = 1,3’	1,1+1=1,2
2,4’	2,3
3,5’	3,4
4,6’	4,5
5,7’	5,6
6,8’	6,7
7,1’	7,8
8,2’	8,1

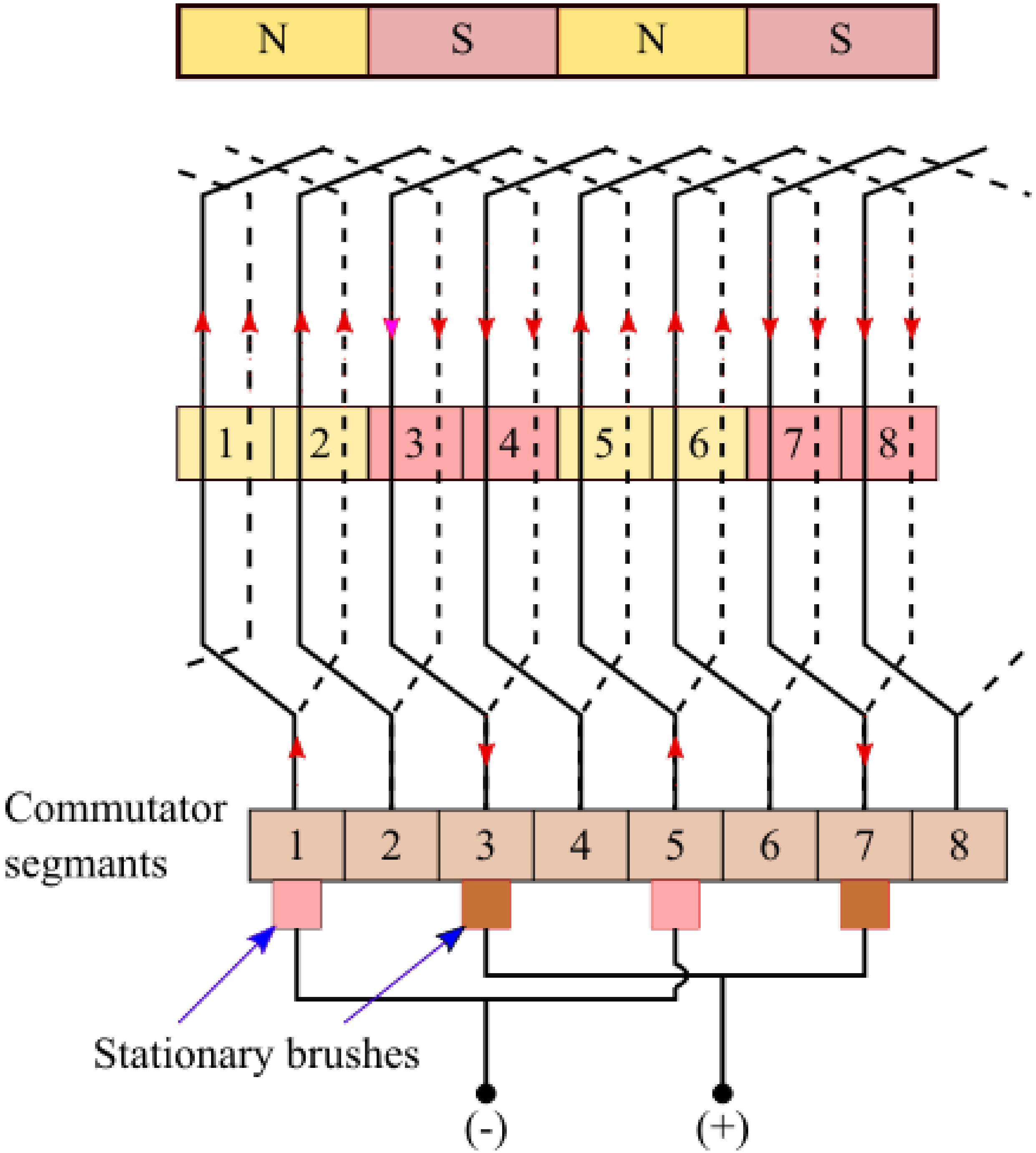
1,3’

Slot # 1, top layer

Slot # 3, bottom layer

Number of brushes = 4

Figure shows the winding connection where the two ends of a coil are connected to adjacent commutator segments. The coils in each path are connected in series and the winding close upon itself.



Example 2

Draw the developed armature winding diagram of a DC Machine with 4 poles, 16 slots, progressive, double layer simplex lap winding. Show the position of brushes and direction of induced emf. The number of turns per coil is one.

The commutator pitch, $y_c = +1$

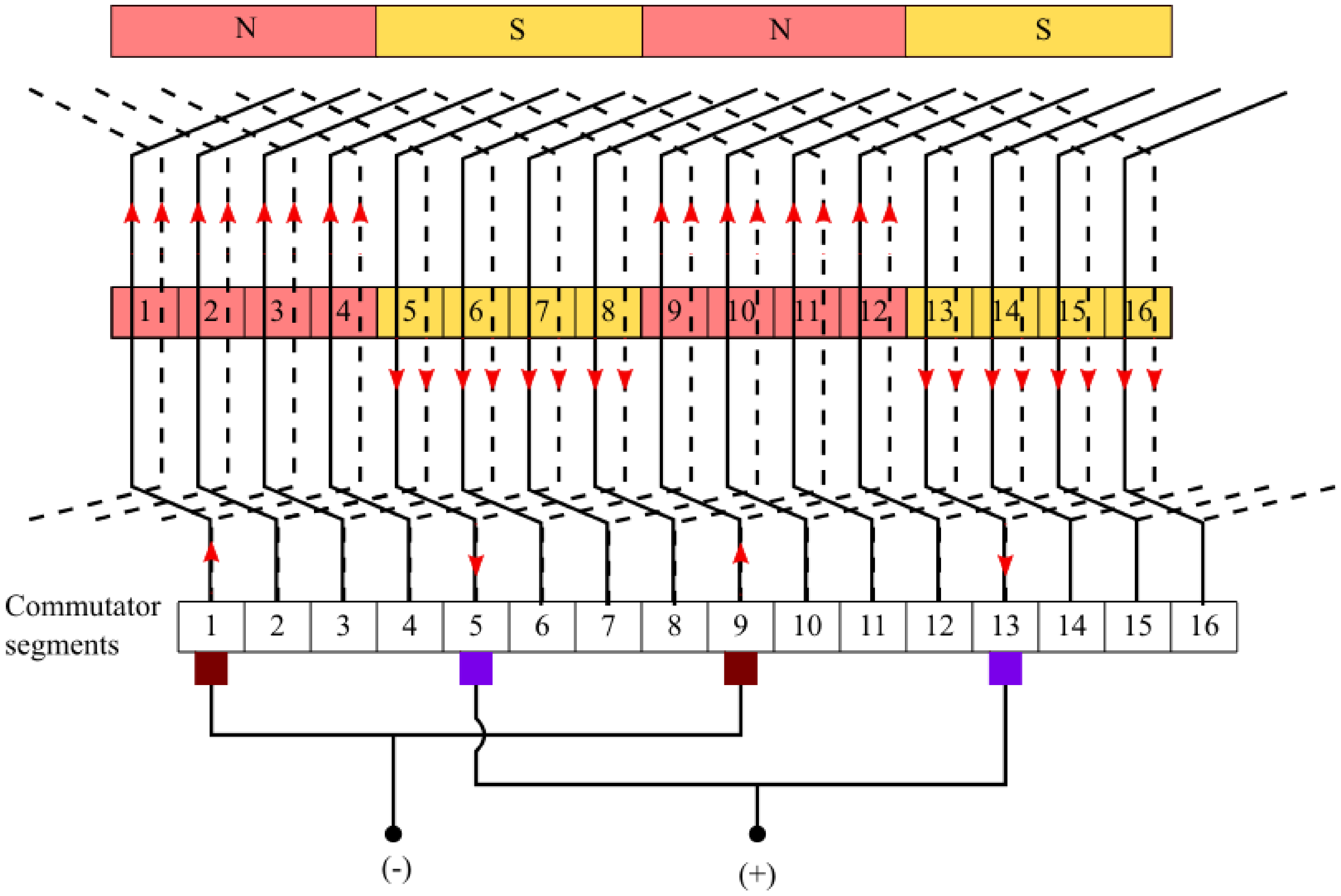
Back pitch: $y_b \approx \frac{S}{P} = 4$

Front pitch: $y_f = y_b - y_c = 4 - 1 = 3$

Number of brushes = 4

Winding table

Slot numbers where the coils sides are placed $[x, (x + y_b)']$	Commutator segments where the coil ends terminated $[x, x + y_c]$
1,1+4=1,5’	1,1+1=1,2
2,6’	2,3
3,7’	3,4
4,8’	4,5
5,9’	5,6
6,10’	6,7
7,11’	7,8
8,12’	8,9
9,13’	9,10
10,14’	10,11
11,15’	11,12
12,16’	12,13
13,1’	13,14
14,2’	14,15
15,3’	15,16
16,4’	16,1


N
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16
Commutator segments
1
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16
(-)
(+)

Simplex wave winding

- In wave winding, commutator pitch is selected to be closely equal to two pole pitch in terms of commutator segments (approximately 360 electrical degrees apart).

- Commutator pitch (y_c) for a wave winding is

$$y_c = \frac{2(S \pm 1)}{P}$$

  - Progressive wave winding: $y_c = \frac{2(S+1)}{P}$,
  - Retrogressive wave winding, $y_c = \frac{2(S-1)}{P}$

- For wave windings, number of parallel paths are always equal to two. Therefore, the number of brushes is always equal to two.

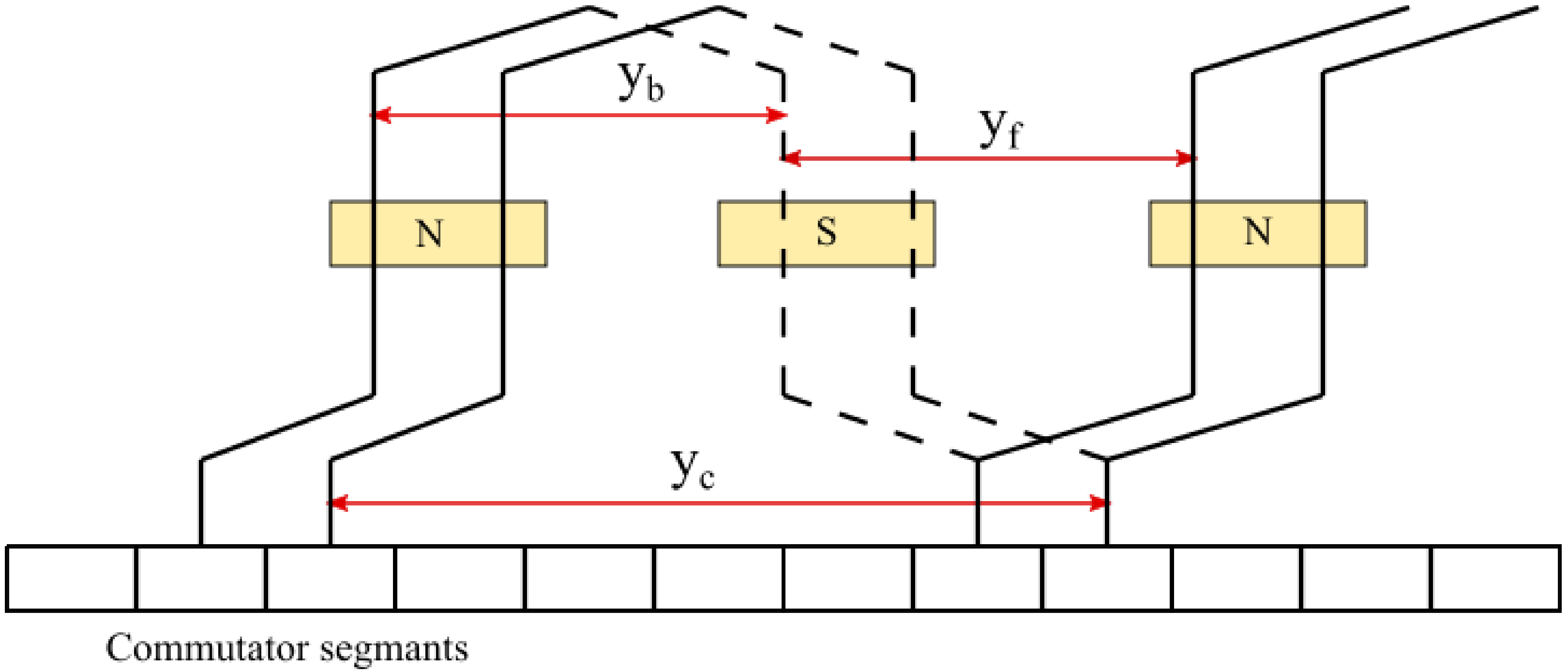
Simplex wave winding

- In simplex wave winding;

$$y_b \approx \frac{S}{P}$$

$$y_f = y_c - y_b$$

- The following diagram shows a part of simplex wave winding.



Example

Draw the developed armature winding diagram of a DC generator with 4 poles, 17 slots, progressive, double layer simplex wave winding.

Number of poles, $P = 4$

Number of slots, $S = 17$

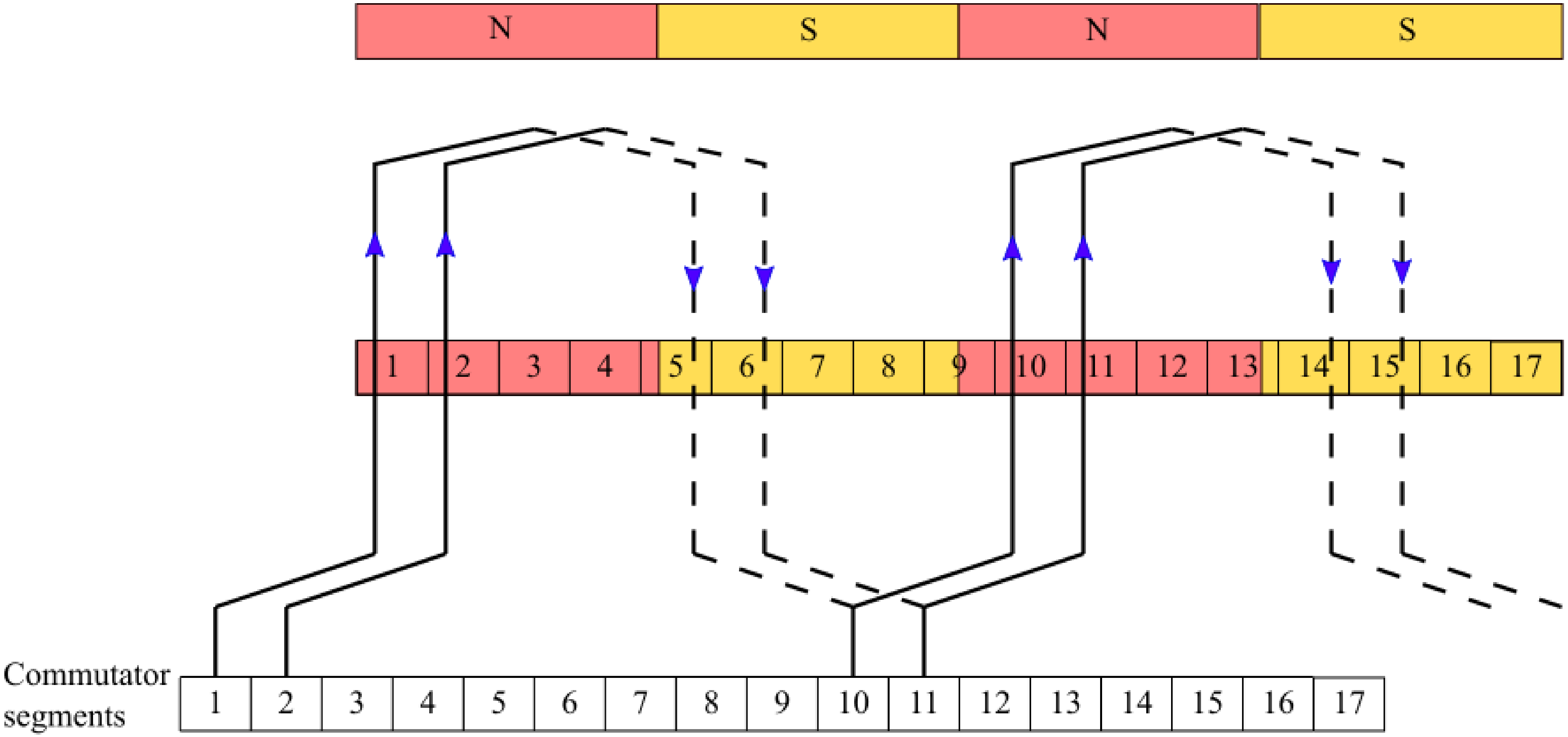
Commutator pitch, $y_c = \frac{2(S+1)}{P} = \frac{2(17+1)}{4} = 9$

Back pitch: $y_b \approx \frac{S}{P} = 4$

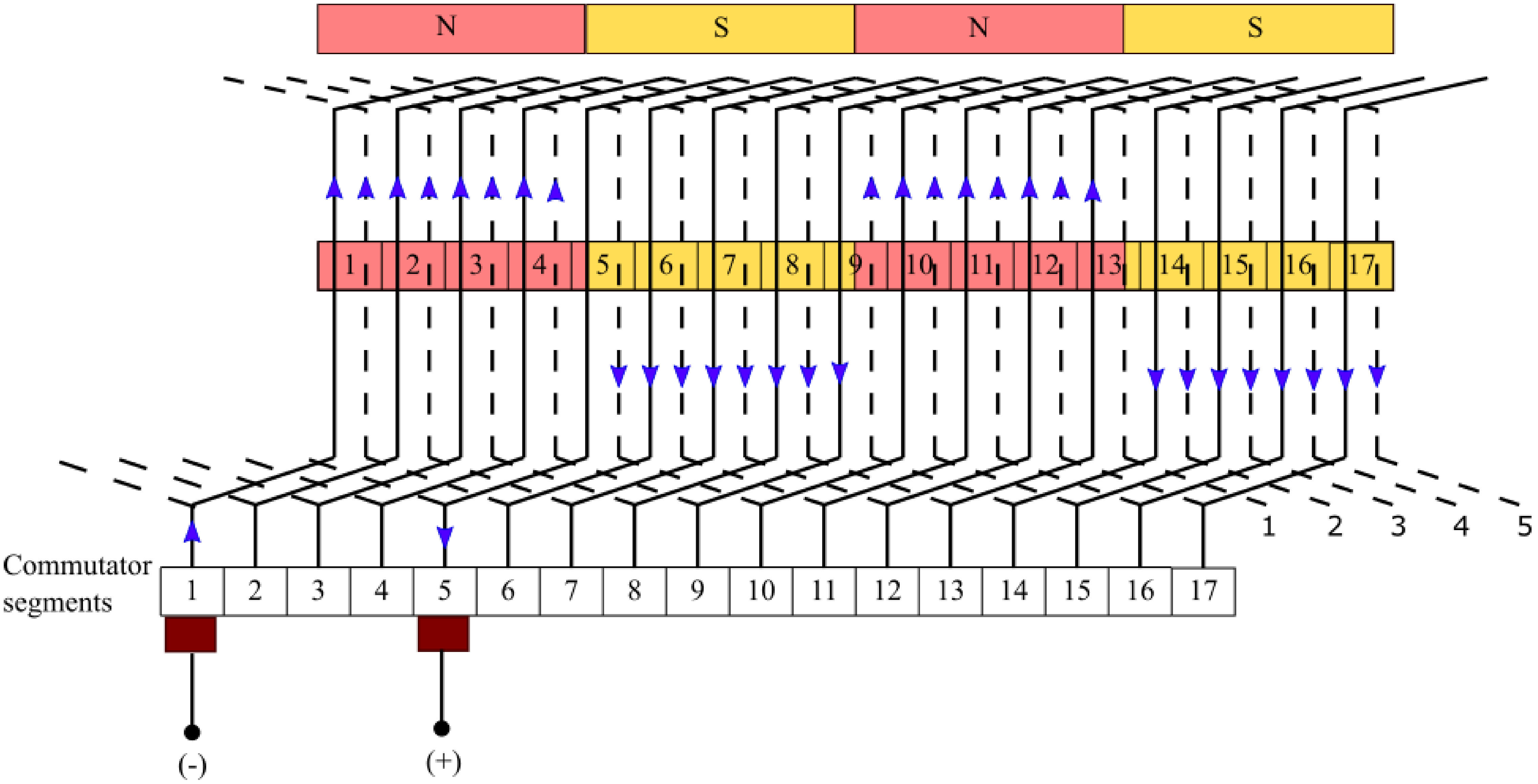
Front pitch: $y_f = y_c - y_b = 9 - 1 = 8$

Winding table

Slot numbers where the coils sides are placed $[x, (x + y_b)']$	Commutator segments where the coil ends terminated $[x, x + y_c]$
1,1+4= 1,5’	1, 1+9 = 1,10
10, 14’	10,2
2,6’	2,11
11,15’	11,3
3,7’	3,12
12,16’	12,4
4,8’	4,13
13,17’	13,5
5,9’	5,14
14,1’	14,6
6,10’	6,15
15,2’	15,7
7,11’	7,16
16,3’	16,8
8,12’	8,17
17,4’	17,9
9,13’	9,1



Starting a simplex progressive wave winding.



Complete simplex progressive wave winding.

AC machine armature windings

AC machine armature windings

- AC armature winding can be either single-phase or 3-phase.
- AC windings are generally of a 3-phase kind because of the inherent advantages of a 3-phase machine.
- In 3-phase windings it is essential that:
  - The generated emfs of all the phases are of equal magnitude.
  - The waveforms of the phase emfs are identical.
  - The frequency of the phase emfs are equal.
  - The phase emfs have mutual time-phase displacement of 120 electrical degrees.

Terminologies associated with AC machine armature windings

The following terminologies are associated only with AC armature windings.

- Slots per pole per phase (SPP): The number of slots in the armature core divided by the number of poles constituting the field times the number of phases.

  Example: In a 4 pole three phase generator having 48 slots on the armature, the number of slots per pole per phase is 48/(4x3) = 4.

- Slot angle pitch (γ): The phase difference contributed by one slot in electrical degrees is called slot angle pitch.

$$\gamma = \frac{180^\circ}{\text{Slots per pole}}$$

Phase belt and phase spread

Phase belt

A group of adjacent slots belonging to one phase under one pole pair is known as *phase belt.*

Phase spread

The angle (electrical) subtended by a phase belt is known as *phase spread.*

Phase spread = Phase belt x Slot angle pitch

3-phase armature winding

- In a three phase machine, armature consists of three windings, i.e. phase A winding, phase B winding, and phase C winding.
- The phase emfs of a 3-phase winding should have mutual time-phase displacement of 120° electrical radians.
- In order to achieve 120° phase displacement, the placement of coil sides of windings A, B, and C should be as follows.

Phase A: slot #1

Phase B: slot # $\left(1 + \frac{120^o}{\gamma}\right)$

Phase C: slot # $\left(1 + \frac{240^o}{\gamma}\right)$

where $\gamma = \dfrac{180^o}{\text{Slots per pole}}$

Examples: Phase belt and phase spread

1) Field winding on the rotor produce 2 poles and the stator carries 12 conductors housed in 12 slots as shown in the Figure.

$$\gamma = \frac{180^\circ}{\text{Slots per pole}} = \frac{180^\circ}{6} = 30^\circ$$

Phase A: slot #1

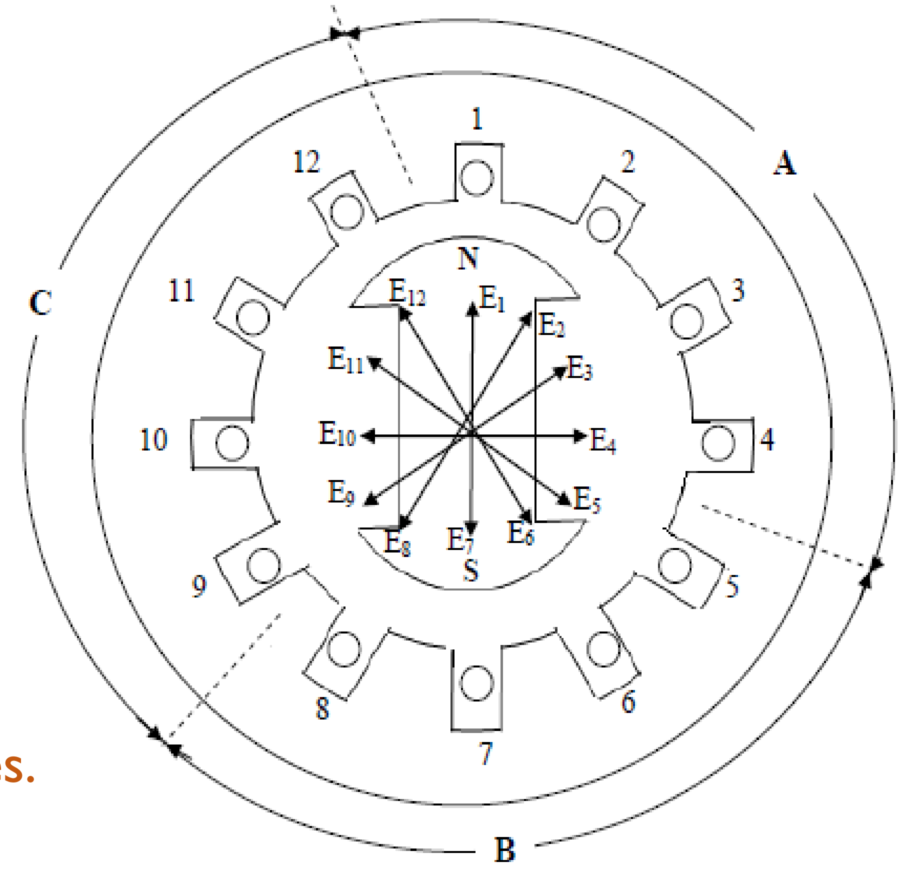
Phase B: slot # $\left(1 + \frac{120^o}{\gamma}\right) = \left(1 + \frac{120^o}{30^o}\right)$ = slot # 5

Phase C: slot # $\left(1 + \frac{240^o}{\gamma}\right) = \left(1 + \frac{240^o}{30^o}\right)$ = slot # 9

Phase belt = 4

Phase spread = $4 \times 30^o = 120^\circ$

Note: Phase spread of 120° is rarely adopted in AC machines.



Three phase winding with phase spread 120°.

Examples: Phase belt and phase spread

2) Field winding on the rotor produce 2 poles and the stator carries 12 conductors housed in 12 slots as shown in the Figure.

$$\gamma = \frac{180^o}{\text{Slots per pole}} = \frac{180^o}{6} = 30^o$$

Phase A: slot #1

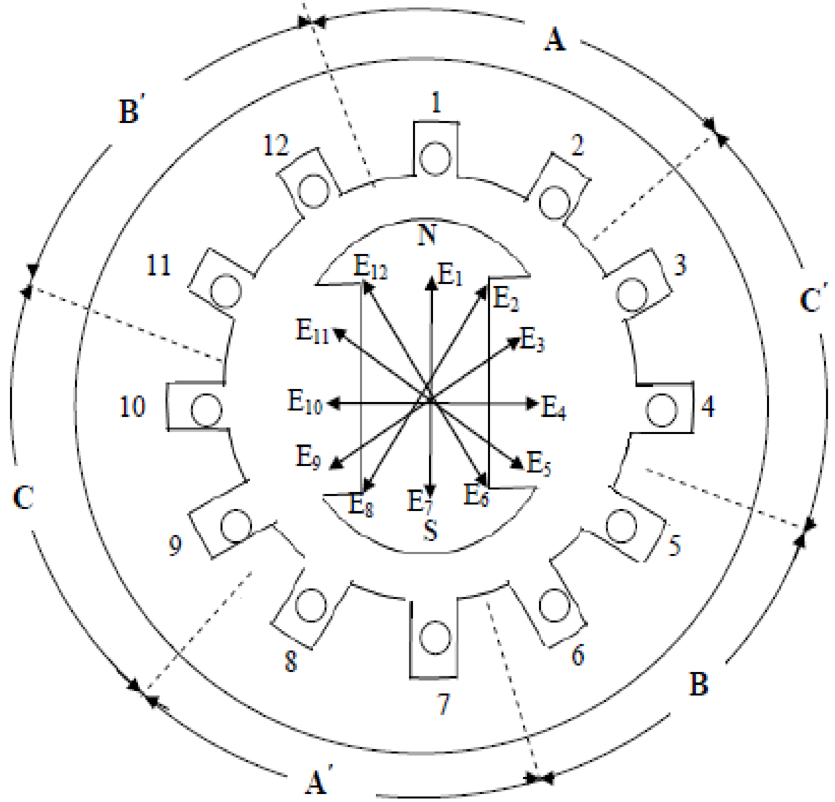
Phase B: slot # $\left(1 + \frac{120^o}{\gamma}\right) = \left(1 + \frac{120^o}{30^o}\right)$ = slot # 5

Phase C: slot # $\left(1 + \frac{240^o}{\gamma}\right) = \left(1 + \frac{240^o}{30^o}\right)$ = slot # 9

Phase belt = 2

Phase spread = 2×30^o = 60°

Note: Phase spread of 60° is commonly used in AC machines.



Three phase winding with phase spread 60°.

Types of AC armature windings

AC armature windings can be classified based on the distribution of coil sides in the armature slots as follows.

- Double layer windings
  - Integral slot winding
  - Integral slot chorded winding
  - Fractional slot winding
- Single layer windings
  - Concentric winding
  - Mush winding

End connections of coils

- Coil ends could be connected in series or various series-parallel connections could be employed.
- The most common connection methods are:
  - Lap
  - Wave
  - Concentric

Double layer winding

- Double-layer windings are the most widely used class of windings.
- Though both lap and wave types are possible for connecting coil ends, because of inherent problems of wave windings, lap type is commonly used.
- Double layer winding types:
  - Integral slot winding
  - Integral slot chorded winding
  - Fractional slot winding

Integral slot winding

- When the number of slots per pole per phase (SPP) is an integer, then the winding is called integral-slot winding.
- Example:

  Armature winding of a 3-phase machine with total number of slots = 24 and number of poles = 4.

  Slots per pole per phase = 24/(4x3) = 2 ⇒ An integer, therefore winding type is integral slot winding.

Example 1: Integral slot winding

Draw the armature winding diagram of a 3-phase machine with total number of slots = 12; number of poles = 4, phase spread = 60°, double-layer, full-pitch winding.

SPP = 12/(4x3) = 1 slot.

Pole pitch = $\frac{12}{4} = 3$ slots.

Full-pitch winding: coil pitch = pole pitch = 3 slots.

Slot angle pitch $\gamma = \dfrac{180^{\circ}}{\text{Slots per pole}} = \dfrac{180^{\circ}}{12/4} = 60^{\circ}$

Phase spread = 60°

Phase belt = Phase spread/Slot angle pitch = 60°/60° = 1 slot.

Example 1: Integral slot winding

Winding placement:

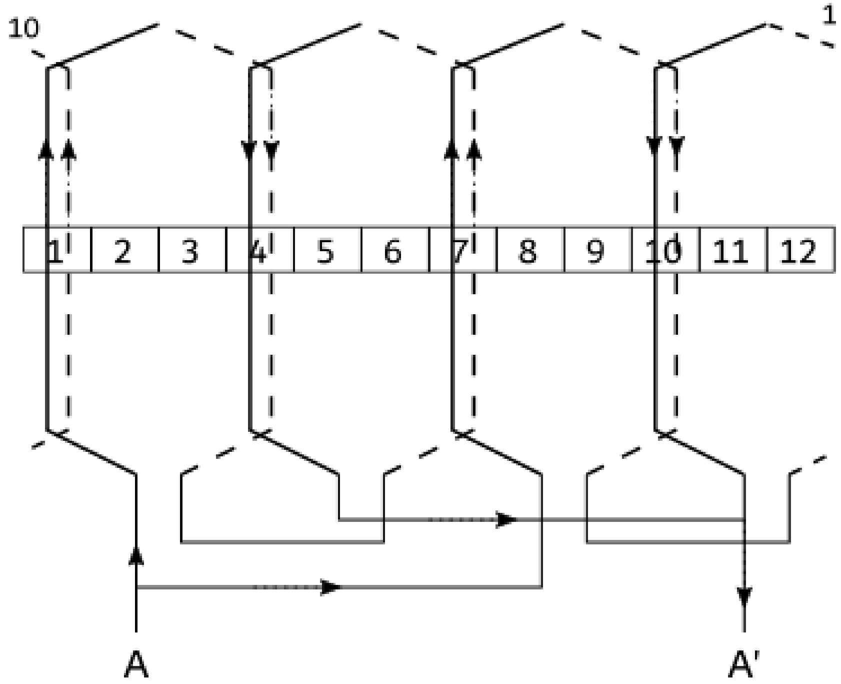
Phase A	One side of the first coil is placed at slot #1 in the top layer; other coil side should be placed at 1+coil pitch = 1+3 = slot #4 in the bottom layer.
Phase B	Starts at slot # $\left(1+\frac{120^o}{\gamma}\right)$ = slot $\left(1+\frac{120^o}{60^o}\right)$ = slot #3 in the top layer; other side of the coil should be placed at slot #6 in the bottom layer.
Phase C	Starts at slot # $\left(1+\frac{240^o}{\gamma}\right)$ = slot $\left(1+\frac{240^o}{60^o}\right)$= slot #5 in the top layer; other side of the coil should be placed at slot #8 in the bottom layer.

Example 1: Integral slot winding

- The four coils of one phase are connected in parallel in two series groups of two coils each.

Slot #	1	2	3	4	5	6	7	8	9	10	11	12
Top layer	a	c'	b	a'	c	b'	a	c'	b	a'	c	b'
Bottom layer	a	c'	b	a'	c	b'	a	c'	b	a'	c	b'

Coil placement in slots.

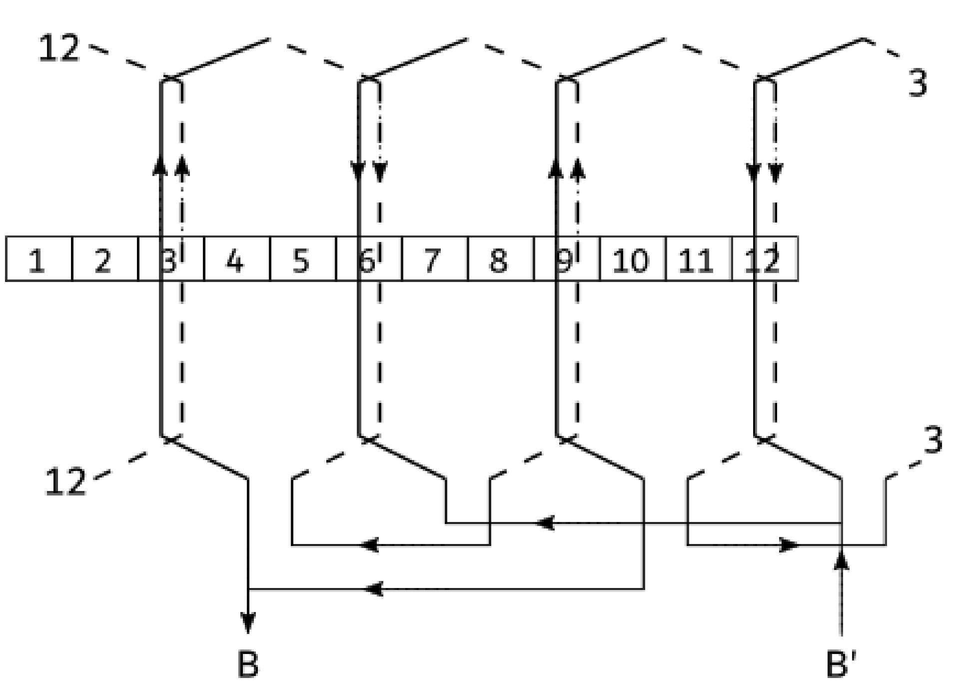


Winding diagram of phase A.

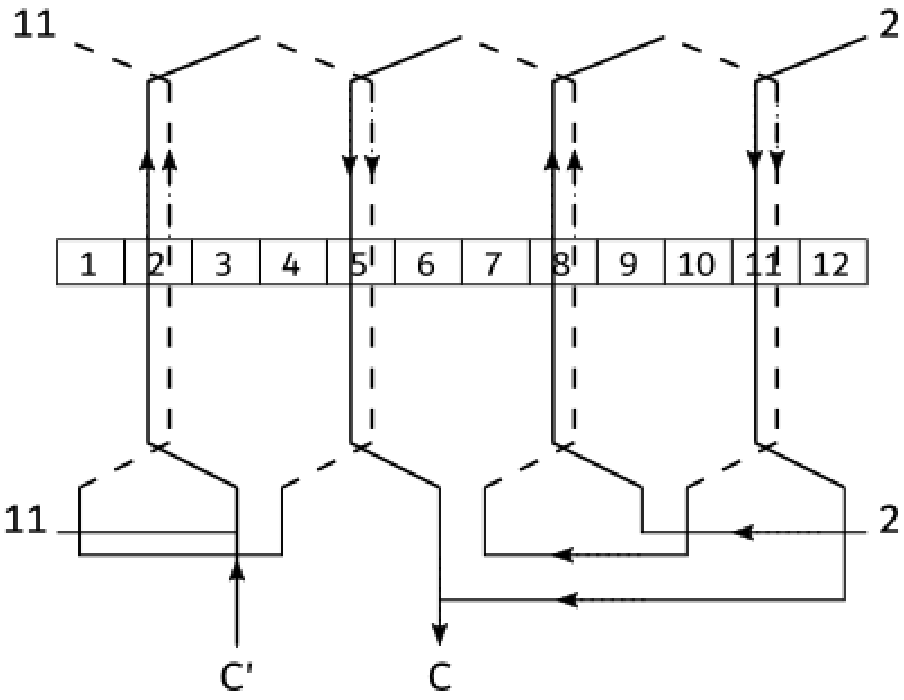
Example 1: Integral slot winding

Slot #	1	2	3	4	5	6	7	8	9	10	11	12
Top layer	a	c'	b	a'	c	b'	a	c'	b	a'	c	b'
Bottom layer	a	c'	b	a'	c	b'	a	c'	b	a'	c	b'

Coil placement in slots.



Winding diagram of phase B.



Winding diagram of phase C.

Example 2: Integral slot winding

Draw the armature winding diagram of a 3-phase machine with total number of slots = 24; number of poles = 4, phase spread = 60°, double-layer, full-pitch lap winding.

SPP = 24/(4x3) = 2 slots.

Pole pitch = $\frac{24}{4} = 6$ slots.

Full-pitch winding: coil pitch = pole pitch = 6 slots.

Slot angle pitch $\gamma = \frac{180^{o}}{\text{Slots per pole}} = \frac{180^{o}}{24/4} = 30^{o}$

Phase spread = 60°

Phase belt = Phase spread/Slot angle pitch = 60°/30° = 2 slots.

Example 2: Integral slot winding

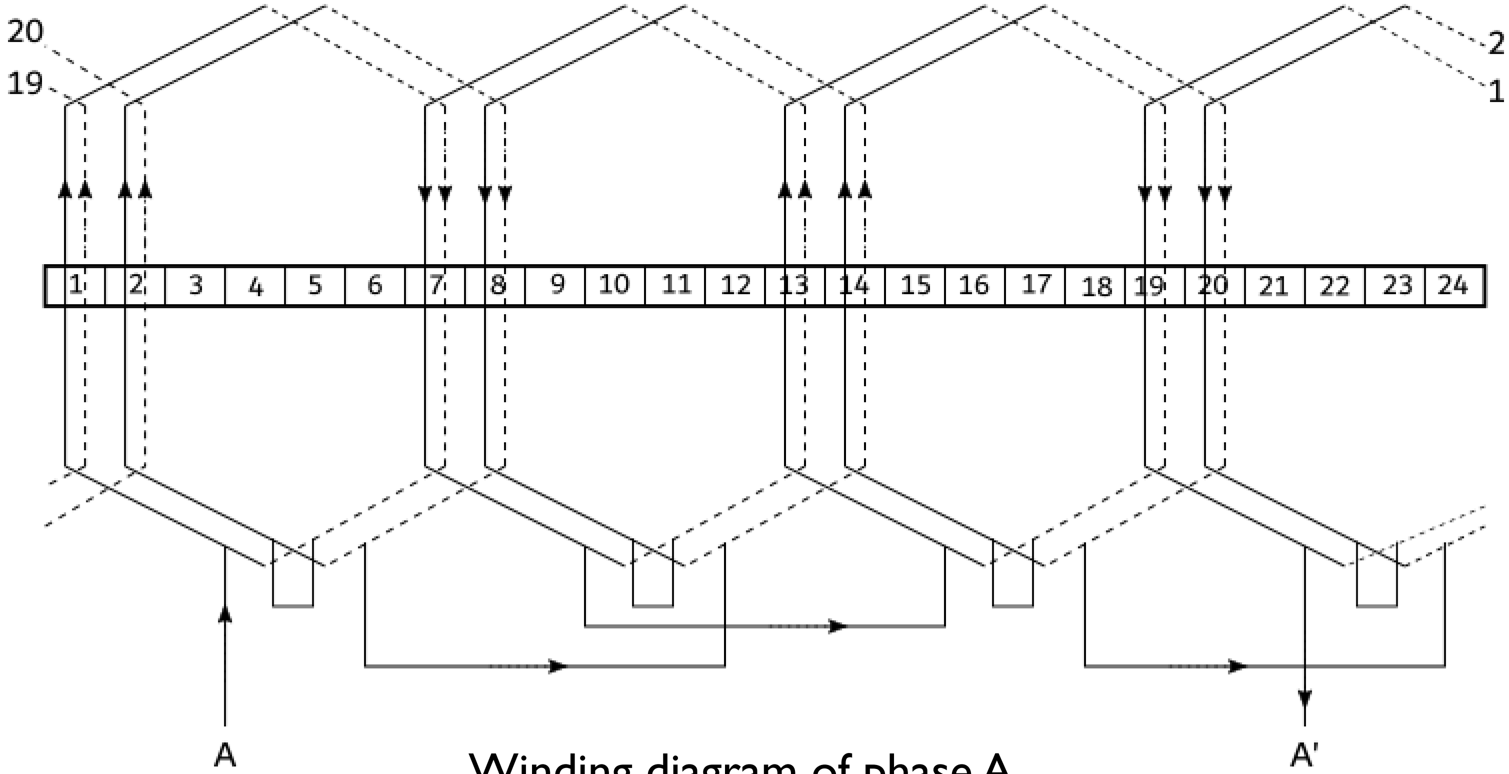
Winding placement:

Phase A	One side of the coil is placed at slot #1 in the top layer; other coil side should be placed at 1+coil pitch = 1+6 = slot #7 in the bottom layer.
Phase B	Starts at slot # $\left(1+\frac{120^o}{\gamma}\right)$ = slot $\left(1+\frac{120^o}{30^o}\right)$ = slot #5 in the top layer; other side of the coil should be placed at slot #11 in the bottom layer.
Phase C	Starts at slot # $\left(1+\frac{240^o}{\gamma}\right)$ = slot $\left(1+\frac{240^o}{30^o}\right)$= slot #9 in the top layer; other side of the coil should be placed at slot #15 in the bottom layer.

Example 2: Integral slot winding

Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Top layer	a	a	c'	c'	b	b	a'	a'	c	c	b'	b'	a	a	c'	c'	b	b	a'	a'	c	c	b'	b'
Bottom layer	a	a	c'	c'	b	b	a'	a'	c	c	b'	b'	a	a	c'	c'	b	b	a'	a'	c	c	b'	b'

Coil placement in slots.



Winding diagram of phase A.

- The four coils of one phase are connected in series.

Integral slot chorded winding

- When the number of slots per pole per phase (SPP) is an integer, and the coil pitch is less than the pole pitch, then the winding is called integral-slot chorded winding.
- The coil pitch generally varies from 2/3 pole pitch to full pole pitch.
- The advantages of using chorded coils are:
  - To reduce the amount of copper required for the end-connections (or over hang).
  - To reduce the magnitude of certain harmonics in the waveform of phase emfs and mmfs.

Example: Integral slot chorded winding

Draw the armature winding diagram of a three-phase machine: double-layer lap winding with total number of slots = 36, Number of poles = 4, chorded coils with coil pitch = 7, and pole pitch = 9.

SPP = 36/(4x3) = 3 slots.

Pole pitch = 9 slots.

Coil pitch = 7 slots.

Coil pitch < Pole pitch and SPP is an integer, hence winding is integral slot chorded type.

Pole pitch – Coil pitch = 9 – 7 = 2 slots, hence the coils are chorded by 2 slots.

Phase spread = 60°

Slot angle pitch $\gamma = \dfrac{180^\circ}{\text{Slots per pole}} = \dfrac{180^\circ}{36/4} = 20^\circ$

Phase belt = Phase spread/Slot angle pitch = 60°/20° = 3 slots.

Example: Integral slot chorded winding

Winding placement:

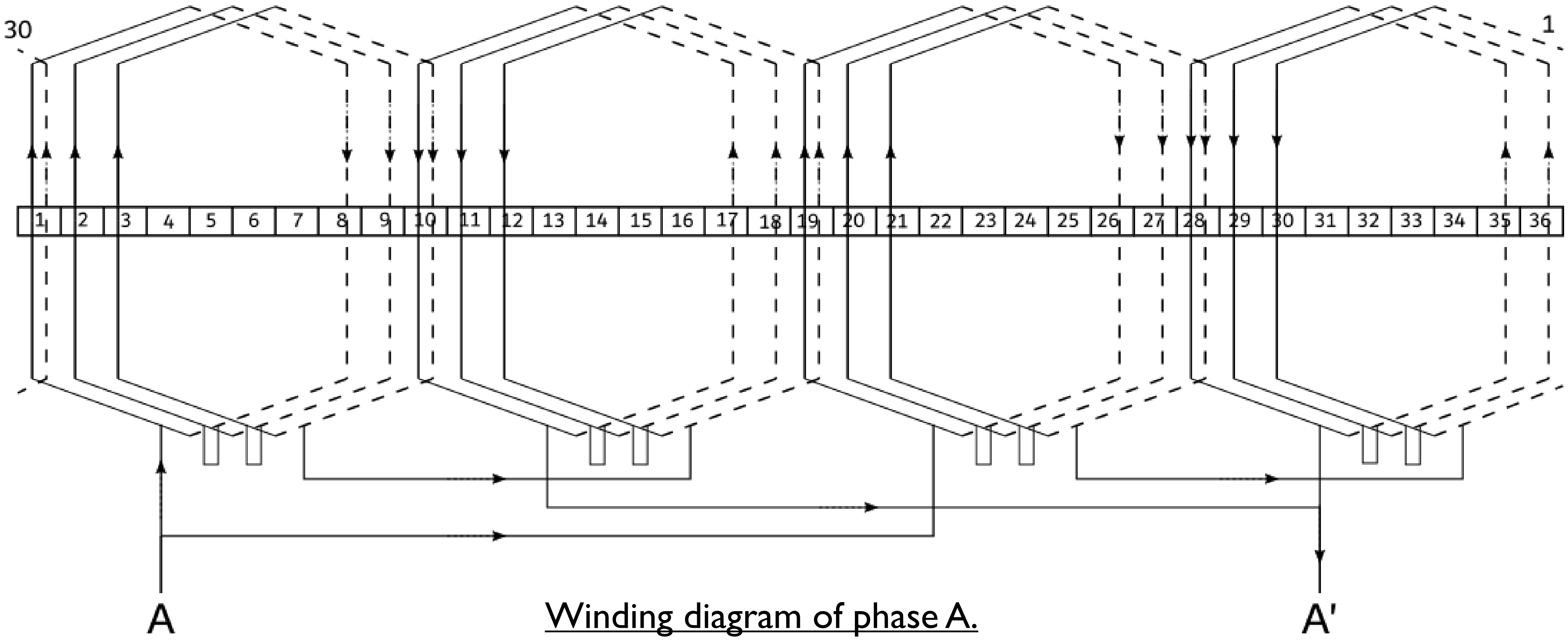
Phase A	One side of the coil is placed at slot #1 in the top layer; other coil side should be placed at 1+coil pitch = 1+7 = slot #8 in the bottom layer.
Phase B	Starts at slot # $\left(1+\frac{120^o}{\gamma}\right)$ = slot $\left(1+\frac{120^o}{20^o}\right)$ = slot #7 in the top layer; other side of the coil should be placed at slot #14 in the bottom layer.
Phase C	Starts at slot # $\left(1+\frac{240^o}{\gamma}\right)$ = slot $\left(1+\frac{240^o}{20^o}\right)$ = slot #13 in the top layer; other side of the coil should be placed at slot #20 in the bottom layer.

Example: Integral slot chorded winding

Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Top layer	a	a	a	c'	c'	c'	b	b	b	a'	a'	a'	c	c	c	b'	b'	b'	a	a	a	c'	c'	c'	b	b	b	a'	a'	a'	c	c	c	b'	b'	b'
Bottom layer	a	c'	c'	c'	b	b	b	a'	a'	a'	c	c	c	b'	b'	b'	a	a	a	c'	c'	c'	b	b	b	a'	a'	a'	c	c	c	b'	b'	b'	a	a

chorded by 2 slots

Coil placement in slots.



Winding diagram of phase A.

- The four coils of one phase are connected in parallel in two series groups of two coils each.

Fractional slot winding

- When the number of slots per pole per phase (SPP) of a winding is a fraction, then the winding is called a *fractional slot winding*.
- Advantages of fractional slot windings when compared with integral slot windings are:
  - a great freedom of choice with respect to the number of slots.
  - this winding allows more freedom in the choice of coil pitch.
  - the amount of copper used in the overhang is reduced and hence a saving on copper.
  - this winding reduces the high-frequency harmonics in the emf and mmf waveforms.

Fractional slot winding

- In fractional slot winding, SPP is a fraction.
- For symmetry, the total number of armature slots should be divisible by the number of phases, i.e. 3.
- Each phase should occupy the same number of slots otherwise the winding would be unbalanced.
- The slots per pole per phase is expressed as a whole number plus a fraction or as an improper fraction.

Example: A three phase ac machine armature with 36 slots constituting 8 field poles.

$$\text{SPP} = \frac{36}{8\times 3} = 1\frac{1}{2} \text{ or } \frac{3}{2}$$

Arranging fractional slot windings with the aid of tables

- The coil groups in a fractional-slot winding are easily arranged with the aid of a table.
- Taking a sheet paper, the table is drawn with as many horizontal lines as there are poles, and each line is divided into $3C$ boxes, where C is the numerator of the improper fraction representing the slots per pole per phase and 3 is no. of poles.
- The table is next divided by vertical lines forming three equal columns for the three phases with C boxes per phase.
- Following this, in ordinal succession, the boxes are filled in with the numbers of the slots at intervals of d boxes, where d is the denominator of the fraction expressing the number of slots per pole per phase.

Arranging fractional slot windings with the aid of tables

Example: Produce the winding table of a three-phase ac machine with armature slots of 27 and number of poles 6.

SPP = $\frac{27}{6\times3} = \frac{27}{18} = \frac{3}{2} = 1\,\frac{1}{2}$

Winding table:

Draw a table where no. rows = no. of poles= 6, and each column of three phases with C no. of sub columns, where, C is the numerator of the improper fraction, i.e. 3.

Fill the boxes starting from the extreme left top box with cross (representing adjacent slots). Proceed to the right marking crosses separated from each other by denominator of the improper fraction of no. of slots per phase per pole, i.e. 2.

Arranging fractional slot windings with the aid of tables

Winding table

No. Of Poles	Phase A			Phase C			Phase B		
N	X		X		X		X		X
S		X		X		X		X	
N	X		X		X		X		X
S		X		X		X		X	
N	X		X		X		X		X
S		X		X		X		X	

Arranging fractional slot windings with the aid of tables

Winding table Interpretation

- Reading the table horizontally line by line, write down the letter of the respective phase each time a cross appears in its column.
- This reveals the following sequence of the coils of each phase under consecutive poles.

aacbb, accb, aacbb,accb, aacbb, accb

- Each letter indicates the coils of each phase, and like letters succeeding one another indicate how many coils of the same phase the group will contain.

Coil groups: 2,1,2; 1,2,1; 2,1,2; 1,2,1; 2,1,2; 1,2,1.

- Thus, in our example, the sequence shows that it is necessary to prepare nine groups of two coils each and nine single coils.
- They will occupy (9x2)+9 = 27 slots.

Example

Design and draw the developed winding diagram of an AC motor with following details: No of poles= 6 no. of phases = 3, No. of slots = 27, coil pitch = 4, double layer lap winding.

SPP = $\frac{27}{6\times3} = \frac{27}{18} = \frac{3}{2} = 1\frac{1}{2}$

SPP is a fraction, therefore fractional slot winding is used.

Pole pitch = $\frac{27}{6} = 4.5$ slots

Coil pitch = 4.

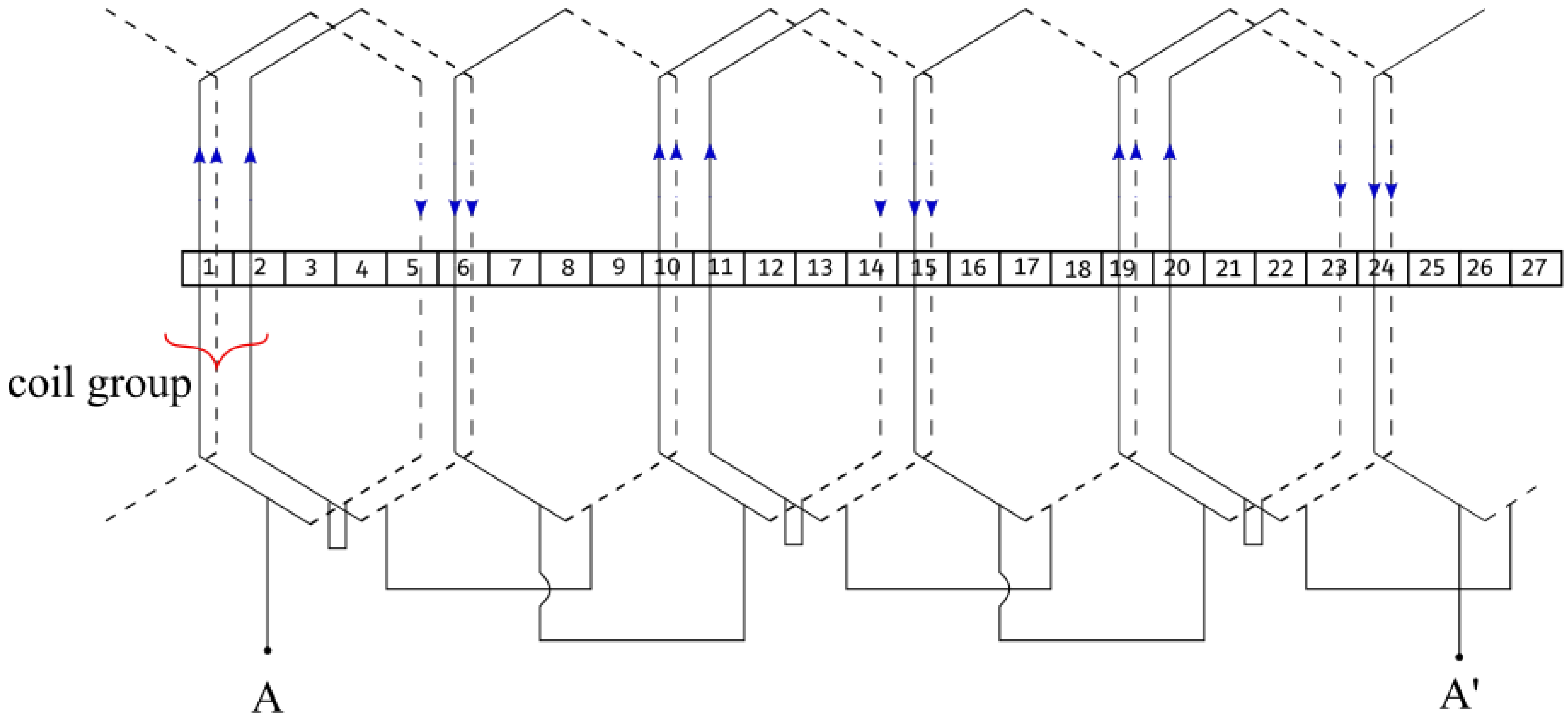
From the previous example, the sequence of coils of each phase under consecutive poles for the machine is

aacbb, accb, aacbb,accb, aacbb, accb.

Example: Solution

Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Top layer	a	a	c'	b	b	a'	c	c	b'	a	a	c'	b	b	a'	c	c	b'	a	a	c'	b	b	a'	c	c	b'
Bottom layer	a	c'	c'	b	a'	a'	c	b'	b'	a	c'	c'	b	a'	a'	c	b'	b'	a	c'	c'	b	a'	a'	c	b'	b'

Coil placement in slots.

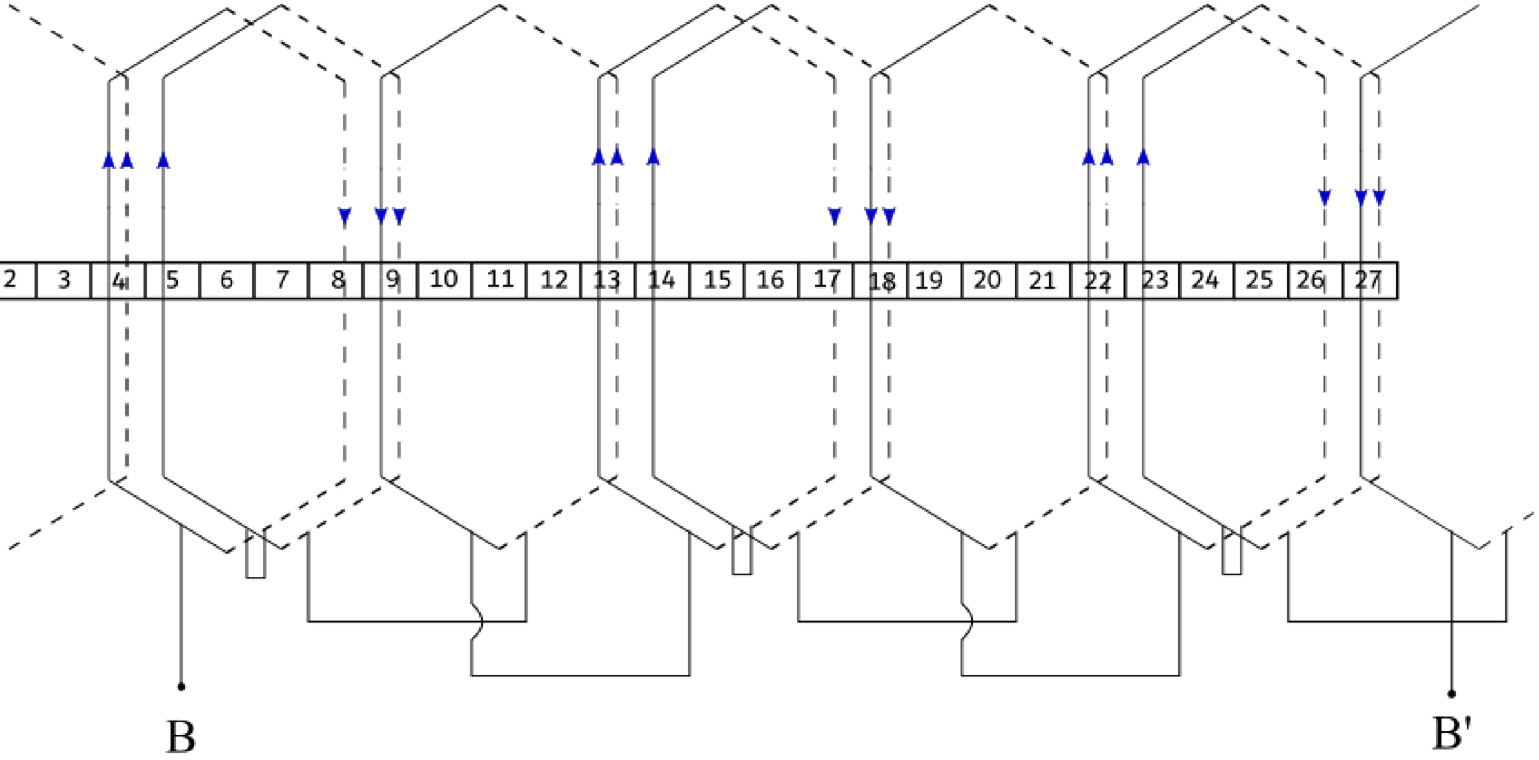


Winding diagram of phase A.

Example: Solution

Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Top layer	a	a	c'	b	b	a'	c	c	b'	a	a	c'	b	b	a'	c	c	b'	a	a	c'	b	b	a'	c	c	b'
Bottom layer	a	c'	c'	b	a'	a'	c	b'	b'	a	c'	c'	b	a'	a'	c	b'	b'	a	c'	c'	b	a'	a'	c	b'	b'

Coil placement in slots.

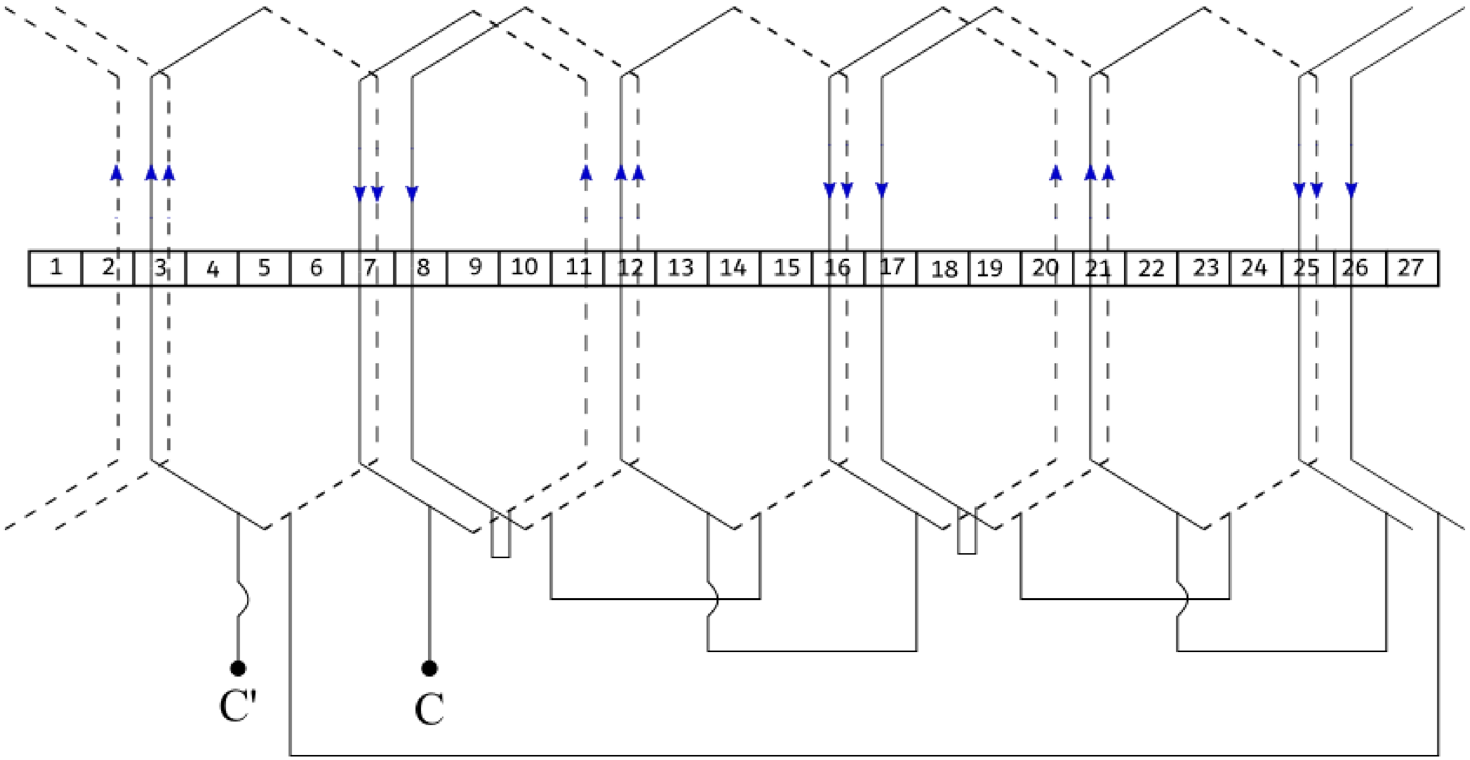


Winding diagram of phase B.

Example: Solution

Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Top layer	a	a	c'	b	b	a'	c	c	b'	a	a	c'	b	b	a'	c	c	b'	a	a	c'	b	b	a'	c	c	b'
Bottom layer	a	c'	c'	b	a'	a'	c	b'	b'	a	c'	c'	b	a'	a'	c	b'	b'	a	c'	c'	b	a'	a'	c	b'	b'

Coil placement in slots.



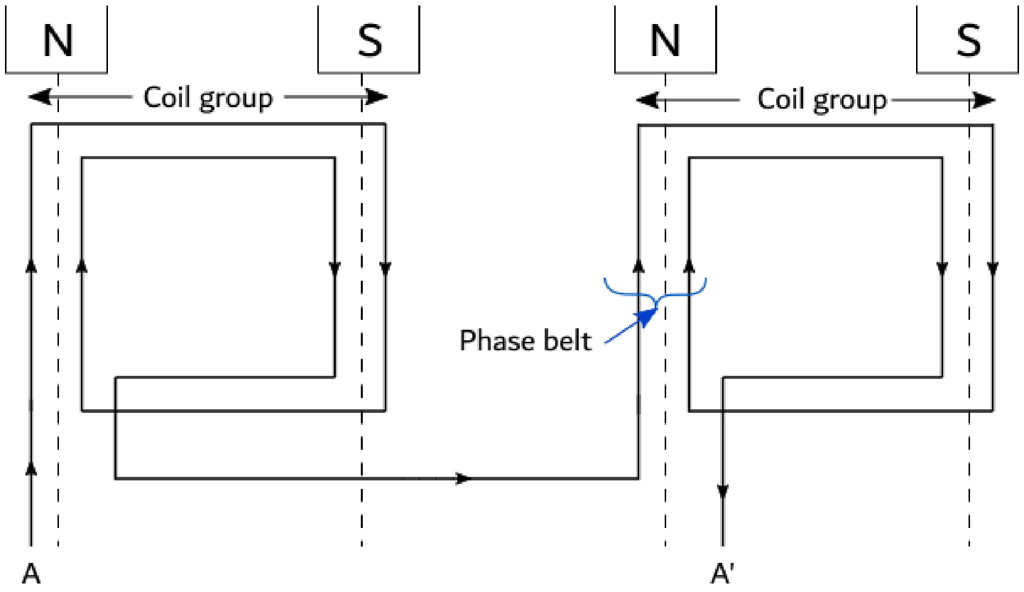
Winding diagram of phase C.

Single layer winding

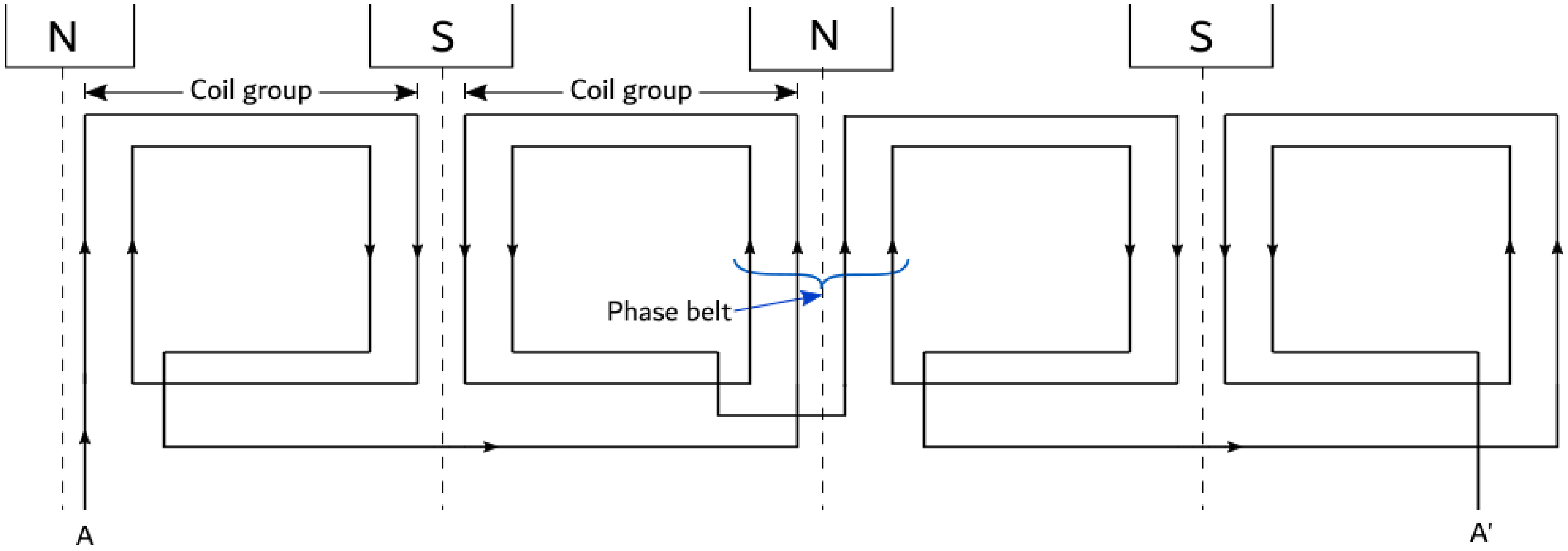
- Single-layer windings are not commonly used in practice except for machines of a few kW.
- One coil side occupies one slot completely, therefore number of coils is equal to half the number of slots.
- The 3-phase single-layer windings types:
  - Concentric winding
  - Mush winding
- In case of three phase machine, single layer winding must be designed to allow the end-connections to be accommodated in separate tiers or planes.

Concentric Windings

- The coils under one pole pair are wound such that the coils have one center.
- Coil Group: The group of coils having the same center is defined as *coil group*.
- The concentric winding can further be sub-divided into
  - half coil winding or unbifurcated winding
  - whole coil winding or bifurcated winding



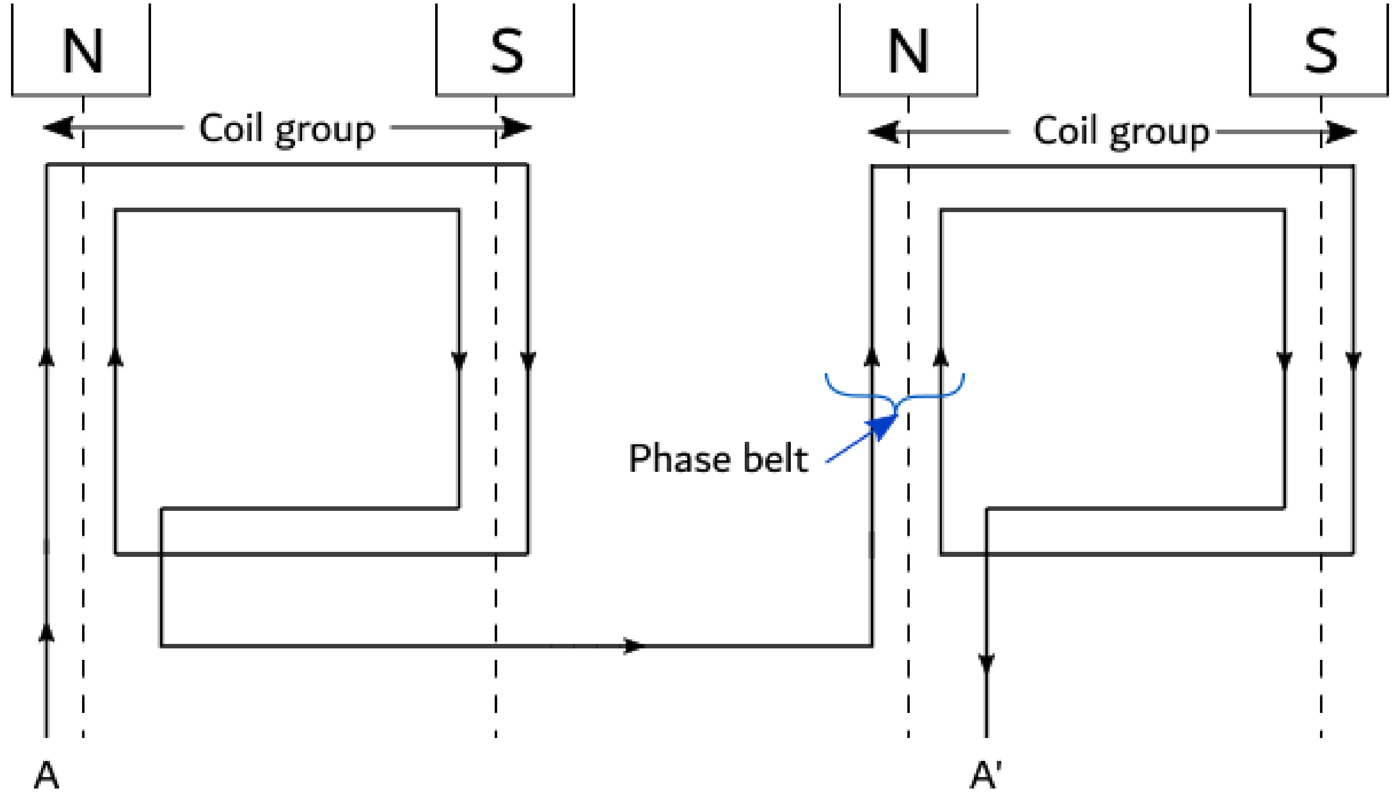
Half coil winding or unbifurcated winding



Whole coil winding
or bifurcated winding

Half coil winding or unbifurcated winding

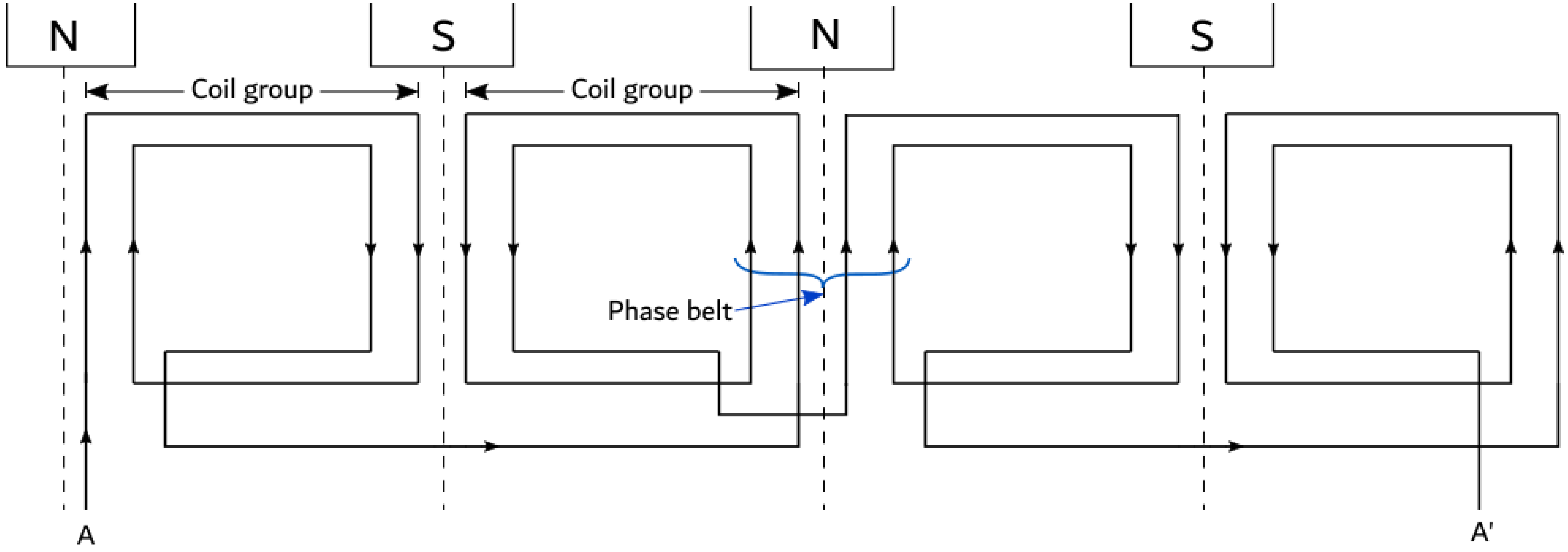
- The number of coils in each coil group = the number of coil sides in each phase belt.
- The direction of current in all coil groups are the same.



Half coil winding of phase A.

Whole coil winding or bifurcated winding

- In whole coil winding, the number of coil sides in each phase belt are double the number of coils in each coil group.
- The number of coil groups equals the number of poles.
- The adjacent coil groups carry currents in opposite directions.



Example: Half coil winding

Draw the half coil single layer concentric windings for a 3-phase machine with 24-slots, 4-poles for phase spread of 60°.

Total number of slots = 24

Pole pitch = 24/4 = 6 slots

SPP = 24/(3x4) = 2 slots

$$\gamma = \frac{180^{o}}{\text{Slots per pole}} = \frac{180^{o}}{24/4} = 30^{o}$$

Phase spread = 60°

Phase belt = Phase spread/Slot angle pitch = 60°/30° = 2 slots.

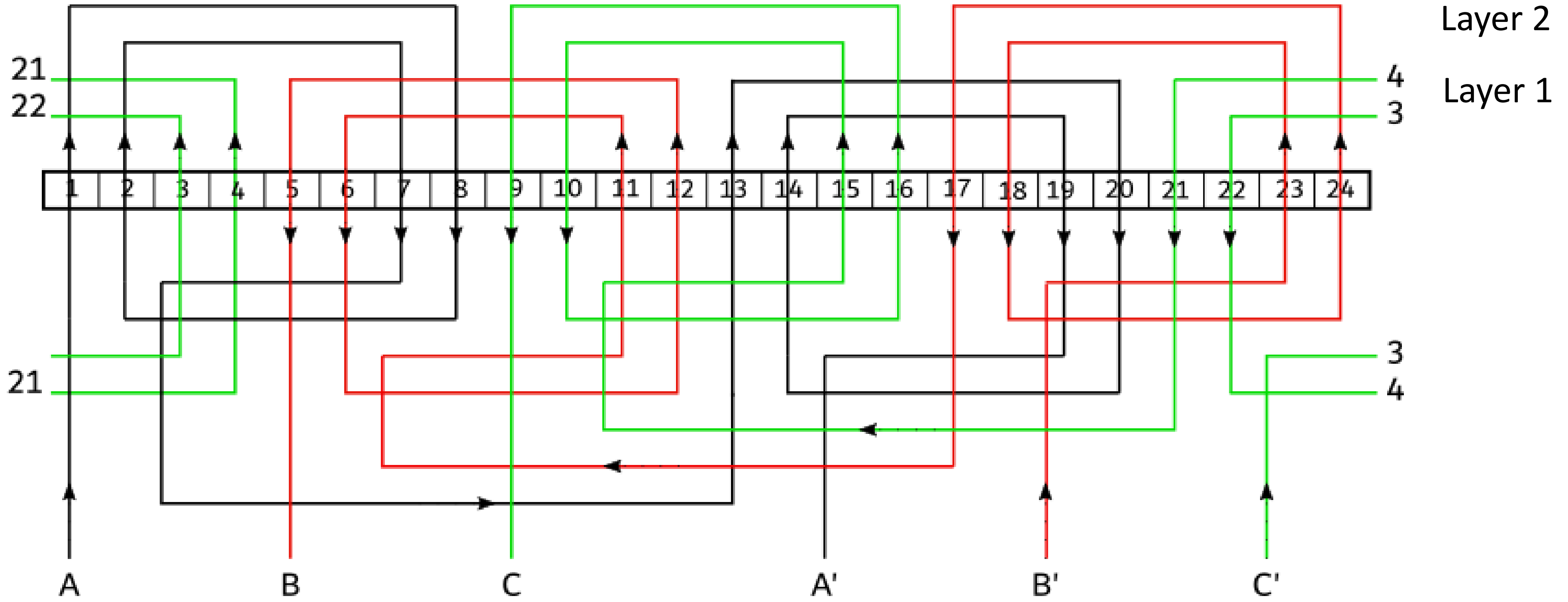
<u>Winding placement:</u>

Phase A	One side of the coil is placed at slot #1
Phase B	Starts at slot # $\left(1 + \frac{120^{o}}{\gamma}\right)$ = slot $\left(1 + \frac{120^{o}}{30^{o}}\right)$ = slot #5
Phase C	Starts at slot # $\left(1 + \frac{240^{o}}{\gamma}\right)$ = slot $\left(1 + \frac{240^{o}}{30^{o}}\right)$ = slot #9

Example: Half coil winding

Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	a	a	c'	c'	b	b	a'	a'	c	c	b'	b'	a	a	c'	c'	b	b	a'	a'	c	c	b'	b'

Coil placement in slots.



Example: Whole coil winding

Draw the whole coil single layer concentric windings for a 3-phase machine with 24-slots, 4-poles for phase spread of 60°.

SPP = 24/(3x4) = 2 slots

Pole pitch = 24/4 = 6 slots

$\gamma = 30^{o}$, Phase spread = 60°

The number of coils per phase belt = 2

The number of coils in each coil group = 1

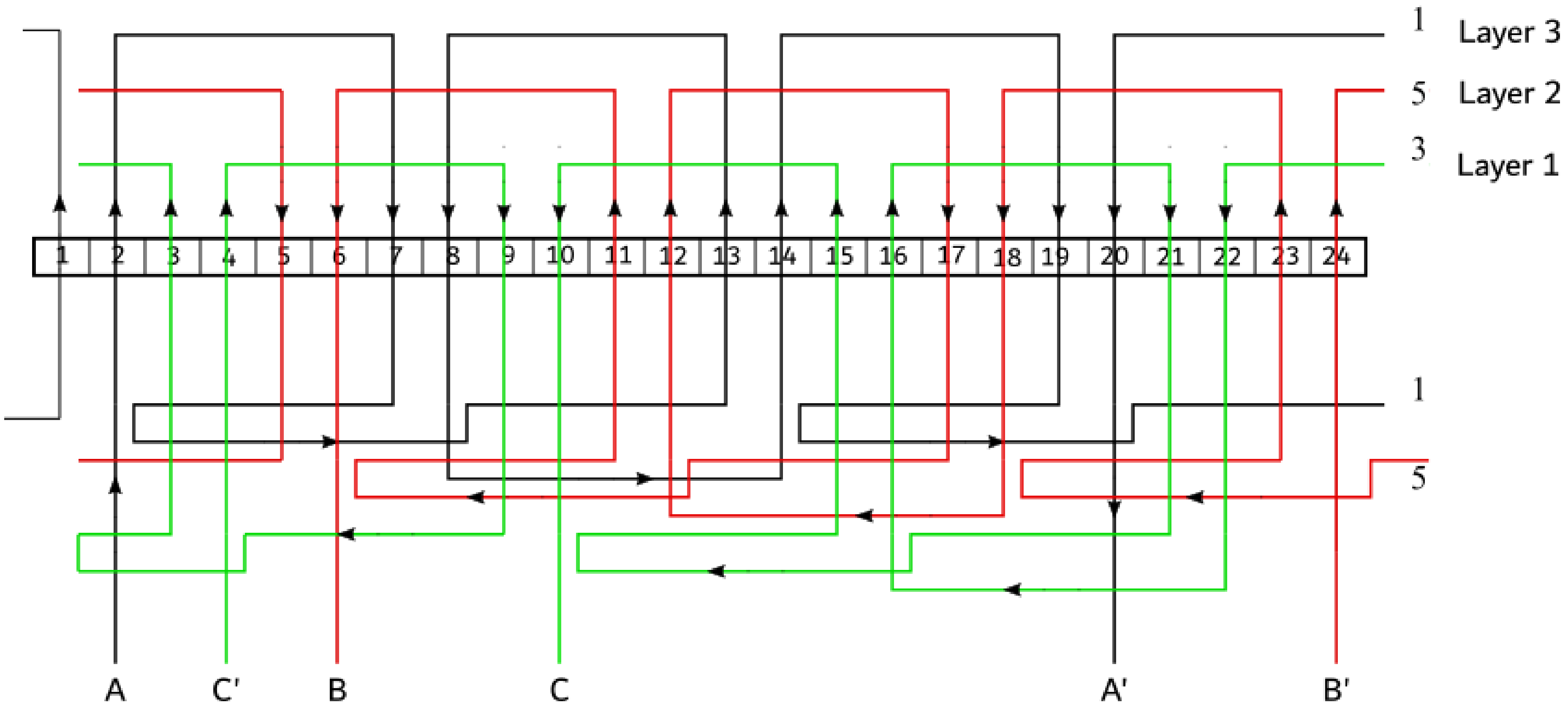
<u>Winding placement:</u>

Phase A	One side of the coil is placed at slot #1
Phase B	Starts at slot # $\left(1 + \frac{120^{o}}{\gamma}\right)$ = slot $\left(1 + \frac{120^{o}}{30^{o}}\right)$ = slot #5
Phase C	Starts at slot # $\left(1 + \frac{240^{o}}{\gamma}\right)$ = slot $\left(1 + \frac{240^{o}}{30^{o}}\right)$ = slot #9

Example: Whole coil winding

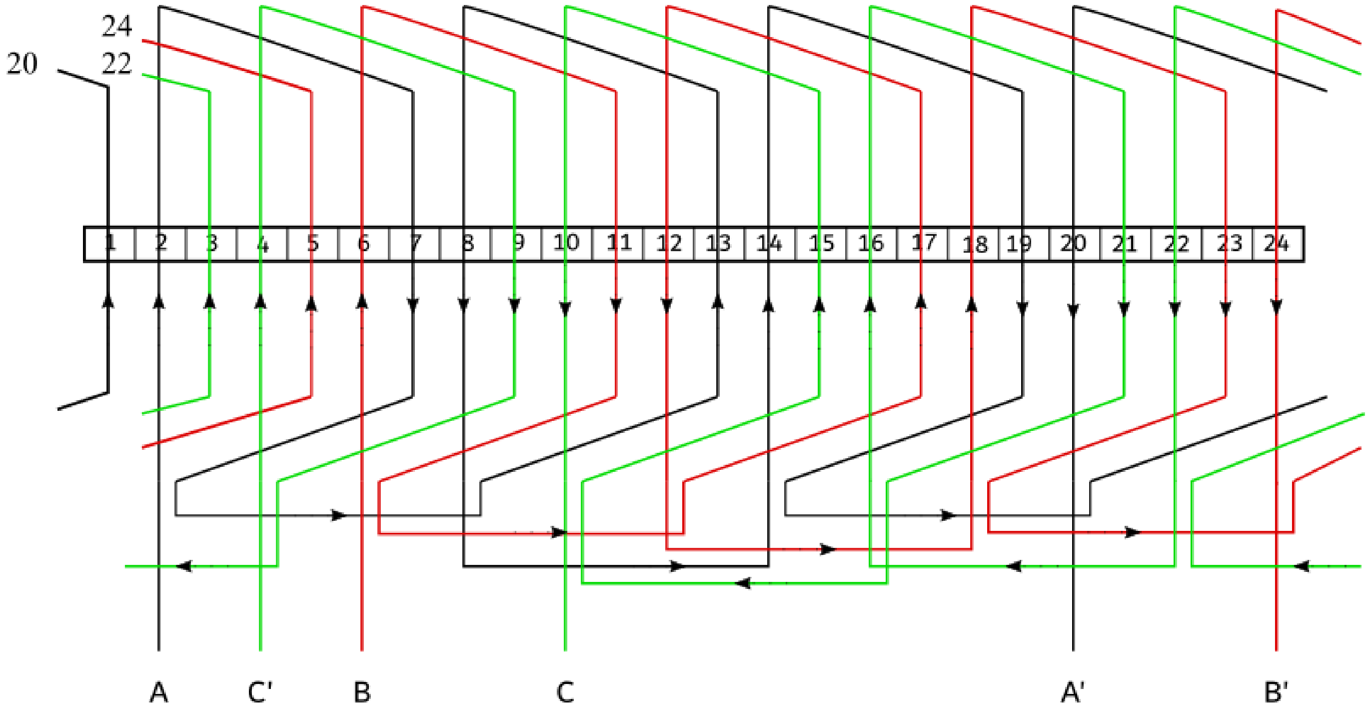
Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	a	a	c'	c'	b	b	a'	a'	c	c	b'	b'	a	a	c'	c'	b	b	a'	a'	c	c	b'	b'

<u>Coil placement in slots.</u>



Mush winding

- The coil pitch is the same for all the coils.
- Each coil is wound on a trapezoidal shaped.
- The number of slots per pole per phase must be a whole number.
- The coil pitch is always odd.



Example: Mush winding

Winding diagram of 24 slots, 4 poles, single-layer mush winding for a 3-phase machine.

SPP = 2 slots

Pole pitch = 24/4 = 6 slots

Winding placement:

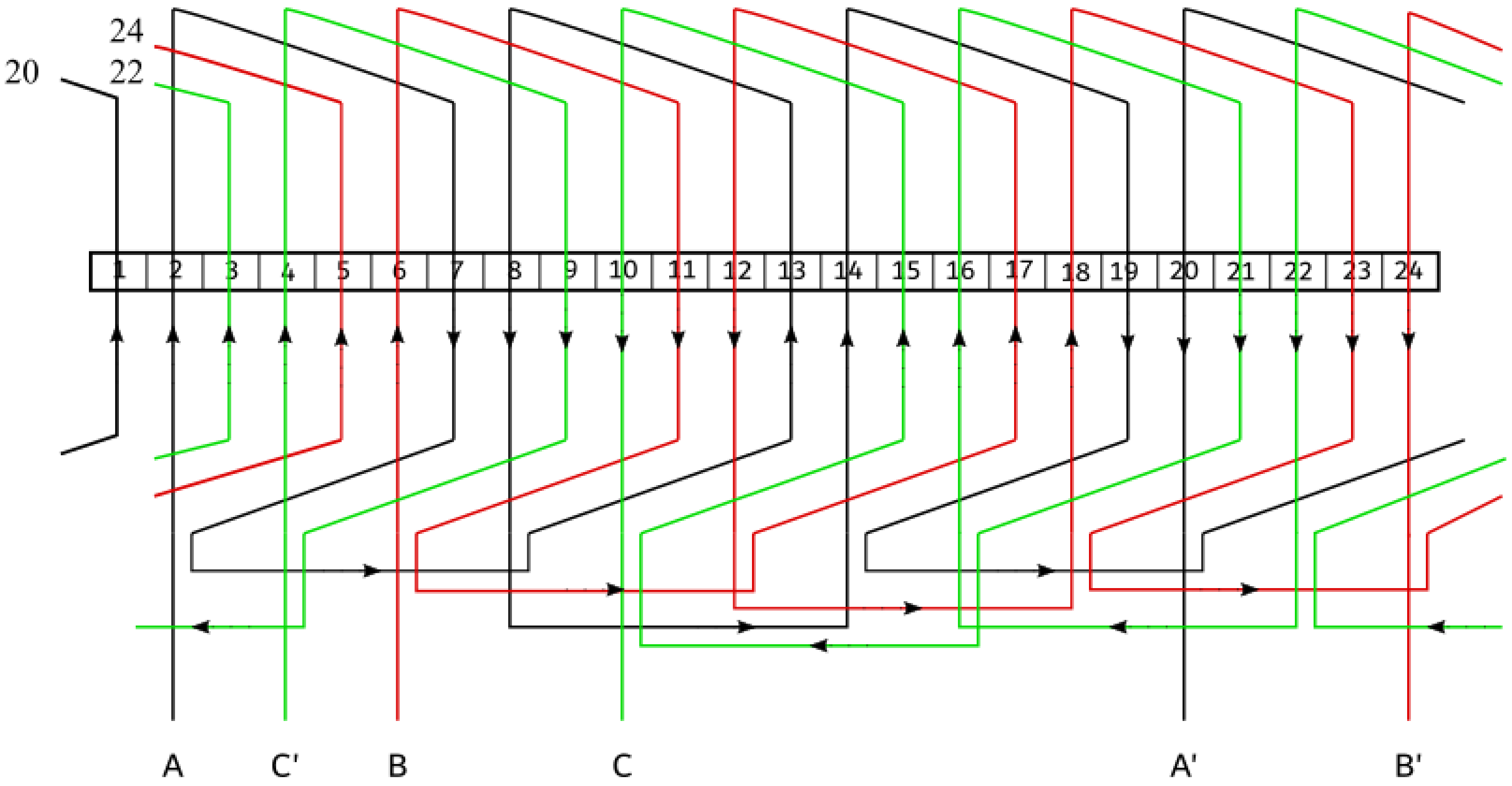
Phase A	One side of the coil is placed at slot #1
Phase B	Starts at slot # $\left(1+\frac{120^o}{\gamma}\right)$ = slot $\left(1+\frac{120^o}{30^o}\right)$ = slot #5
Phase C	Starts at slot # $\left(1+\frac{240^o}{\gamma}\right)$ = slot $\left(1+\frac{240^o}{30^o}\right)$= slot #9

Example: Mush winding

Slot #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	a	a	c'	c'	b	b	a'	a'	c	c	b'	b'	a	a	c'	c'	b	b	a'	a'	c	c	b'	b'

Coil placement in slots.

- Since the coil pitch must be odd, it can be taken as 5 or 7. Choosing here a coil pitch of 5 slot pitches.



Choice of winding

- *Type of coil:* lap, wave, concentric
- *Overhang:* diamond, multiplane, mush
- *Layers:* single, double
- *Phase spread:* 60°, 120°
- *Slotting:* integral, fractional
- *Coil-span:* full-pitched, chorded
- *Circuits:* series, parallel
- *Coils:* single-turn, multiturn