Synchronous Generators

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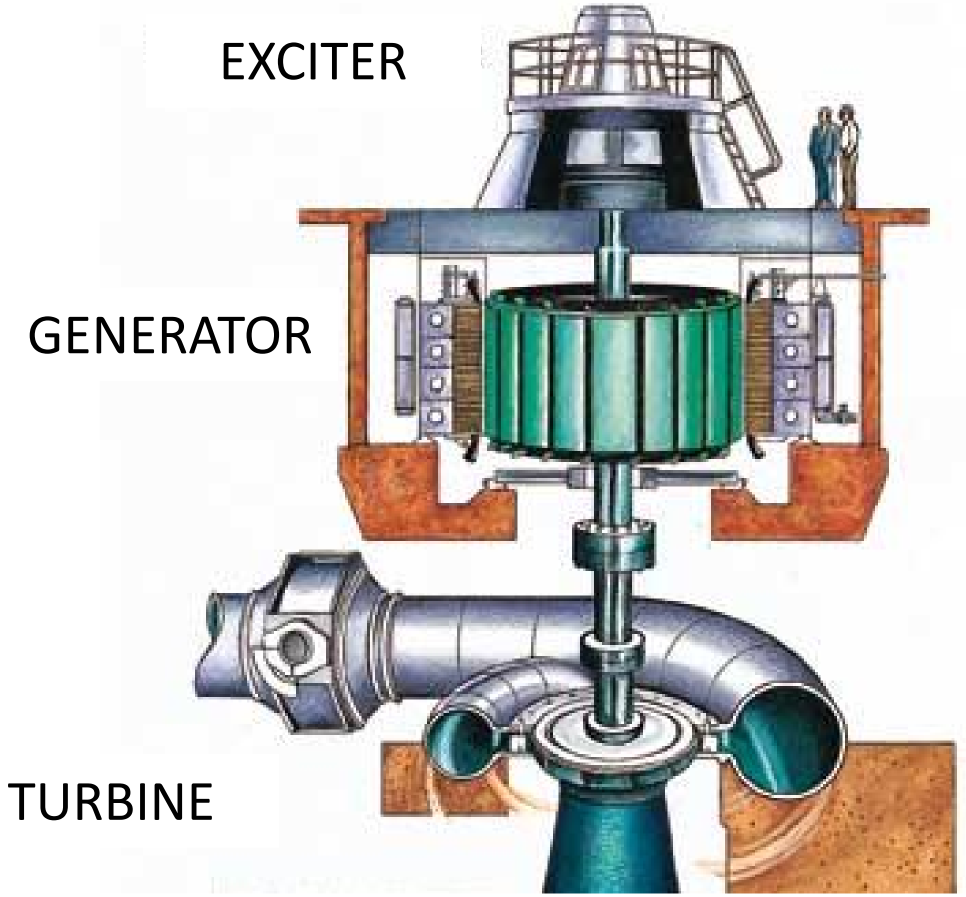
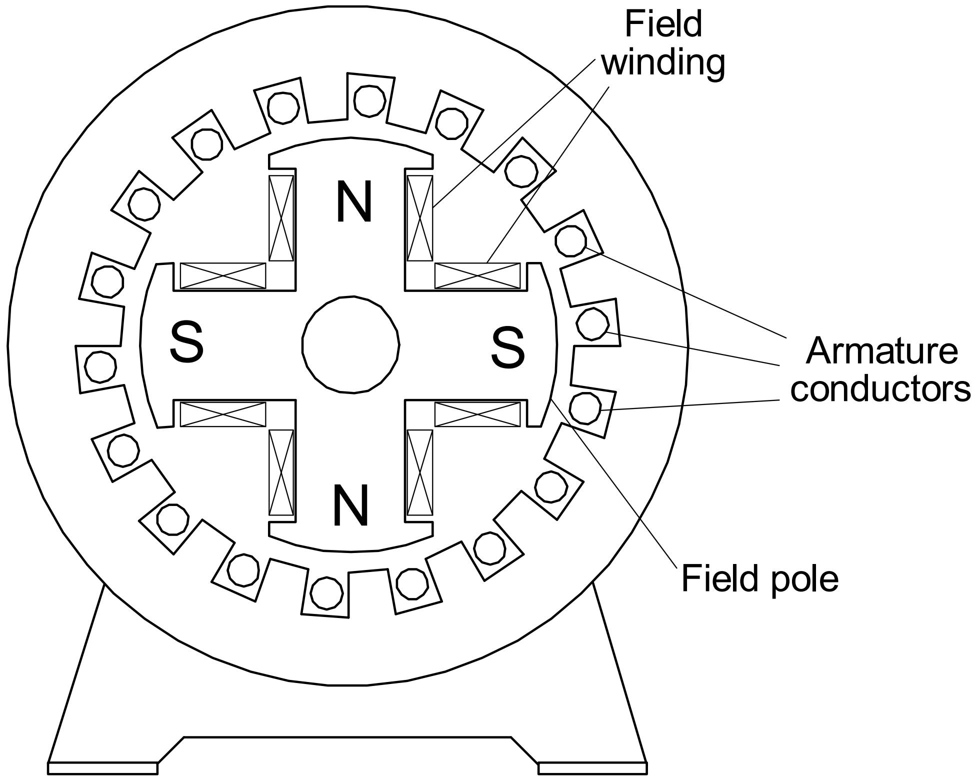


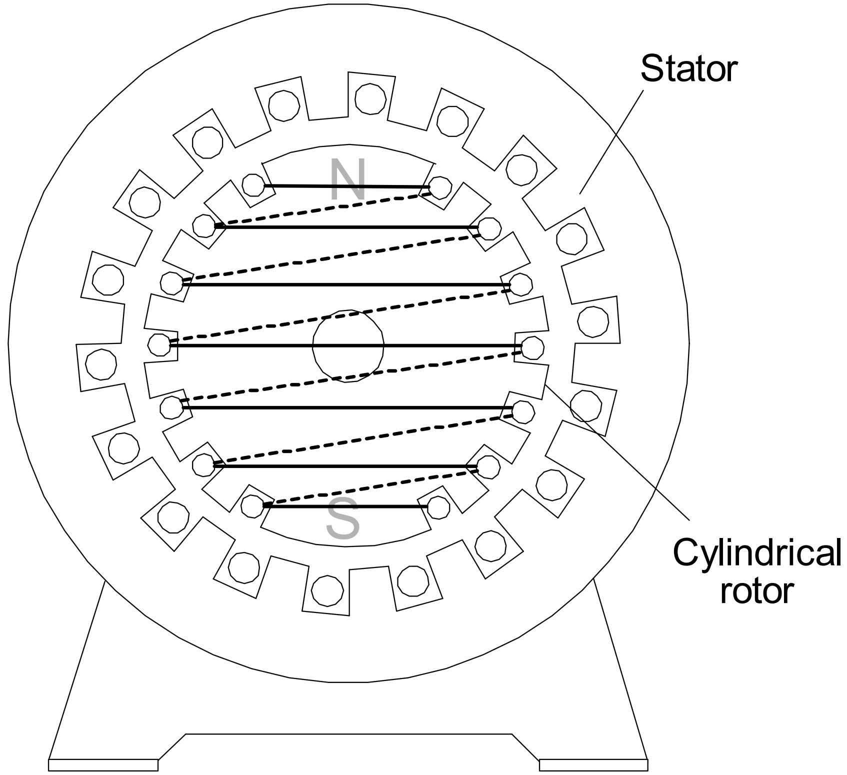
- Synchronous generator is the common type used in generating stations
- It runs at constant speed and generates constant frequency output
- The filed poles are on the rotor side and the armature is on stator side
- The armature winding is placed in the slots on stator core
- Field poles are excited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

Types of Construction

Salient Pole type

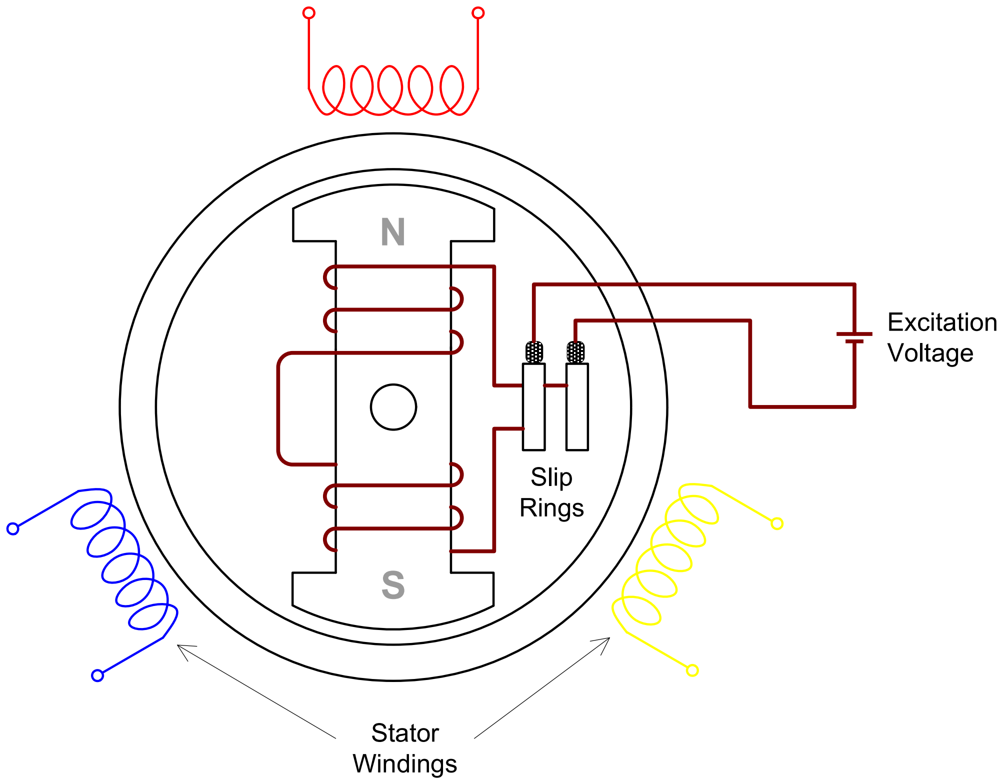


Cylindrical Rotor type



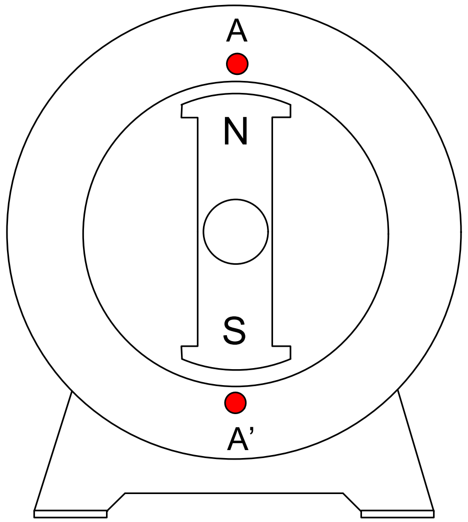
Why Armature on Stator?

- 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.



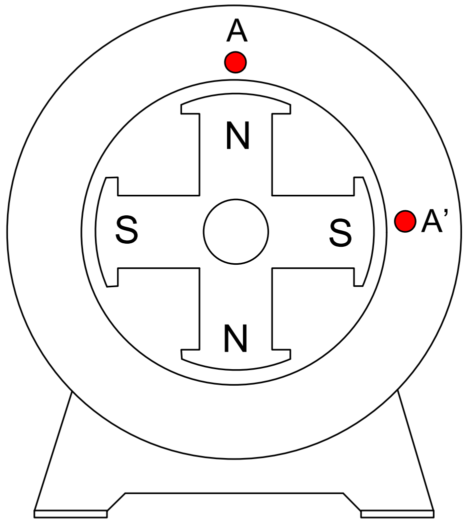
Relation between Speed and Frequency

2 Pole



1 revolution per second (*RPS*) makes 1 Hertz

4 Pole



1 revolution per second (*RPS*) makes 2 Hertz

General case

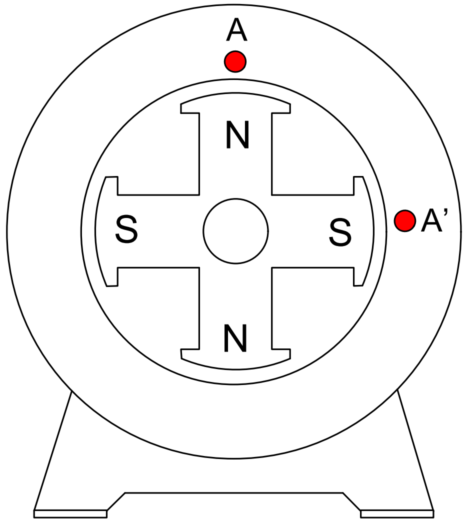
$$RPS = \frac{2f}{P}$$

where f is the freuency
and P is the number of poles

$$RPM, \ N = \frac{120f}{P}$$

Synchronous Speed

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



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

$$\text{Revolution per second} = \frac{N}{60}$$

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

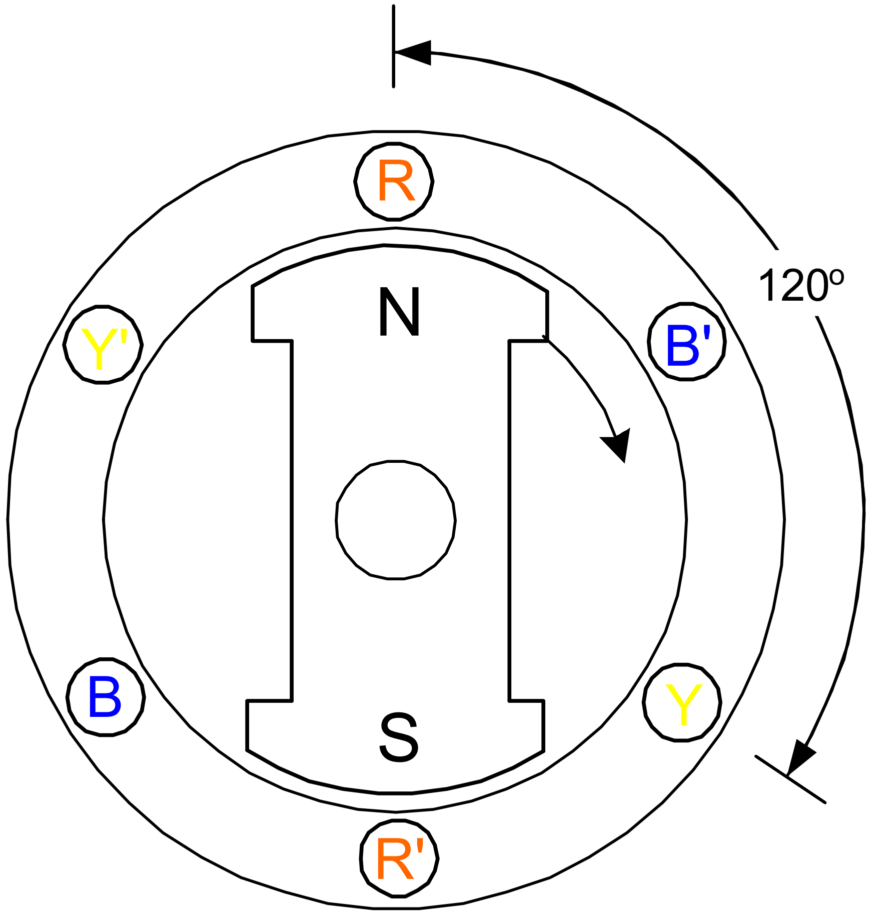
$$RPM, \; N = \frac{120 f}{P}$$

f - freuency

P - number of poles

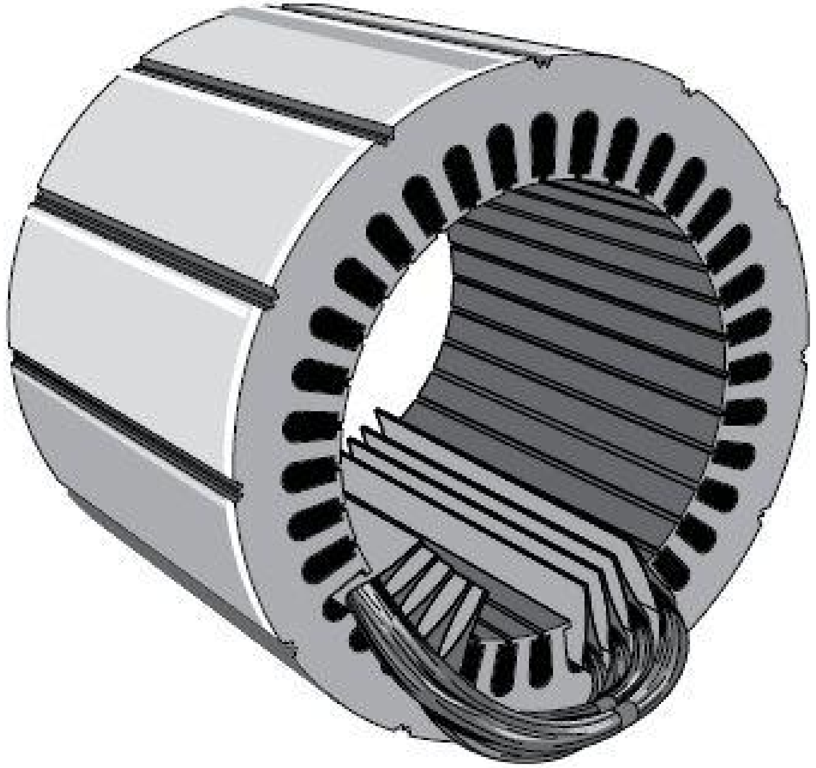
N - speed in RPM

Three Phase Generator

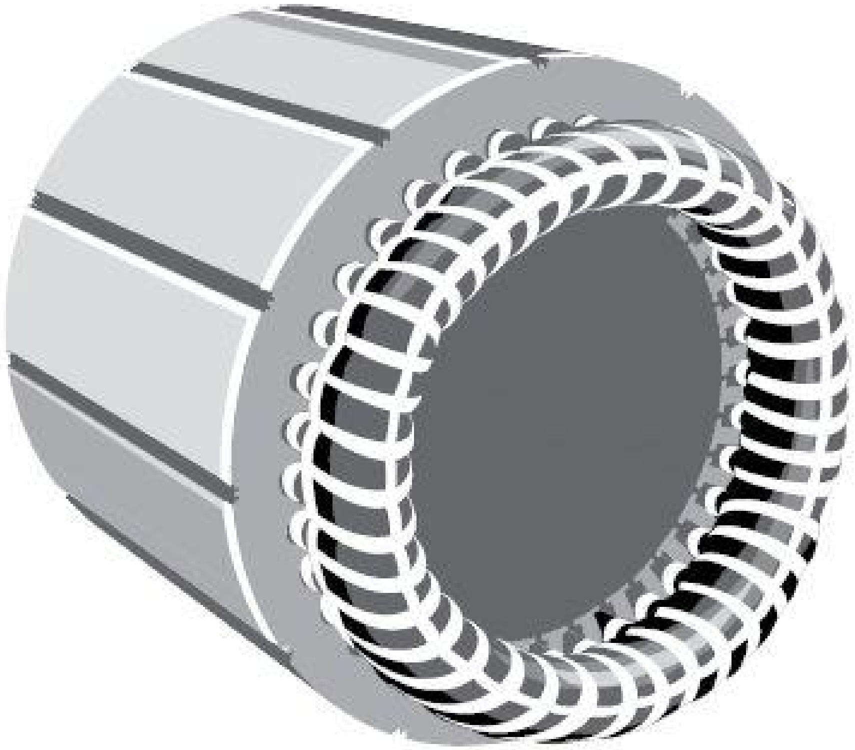


- There will be three sets of similar windings
- Windings are placed 120 degrees apart
- Practically each phase winding will be distributed across several slots

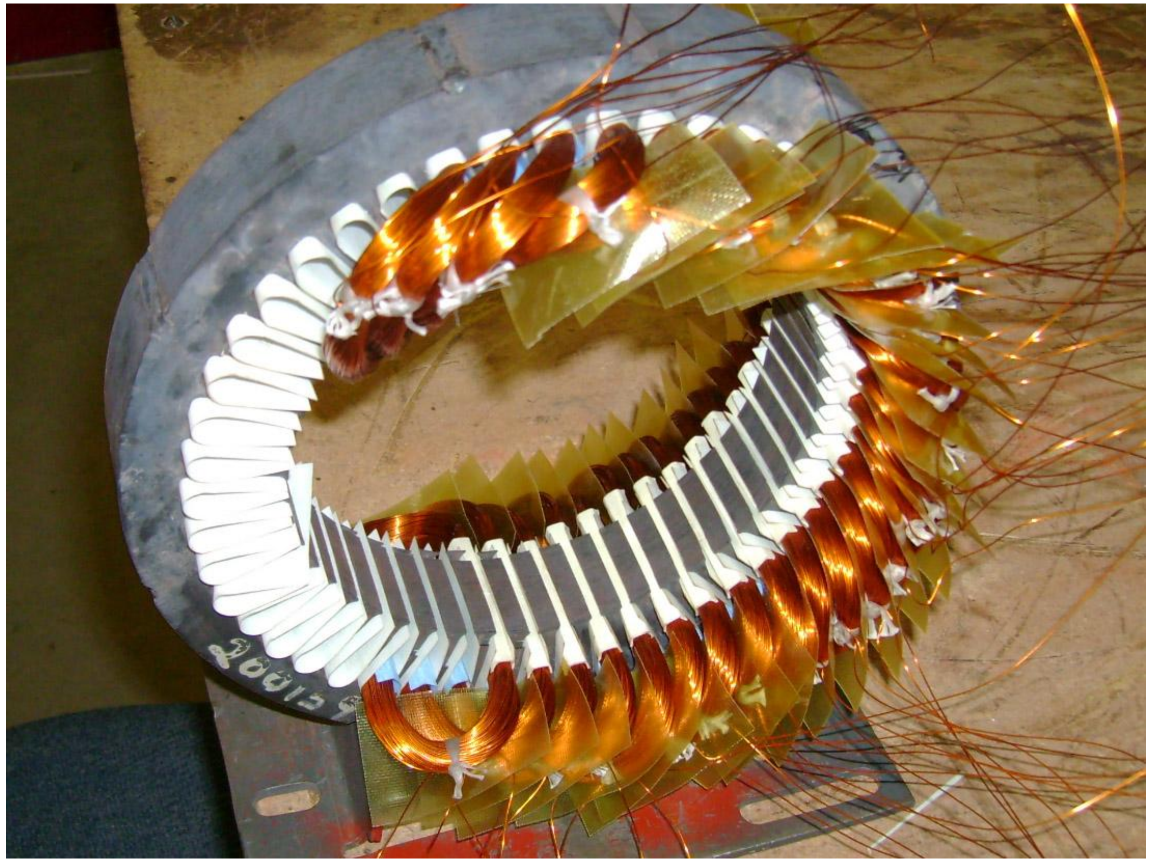
Practical Winding



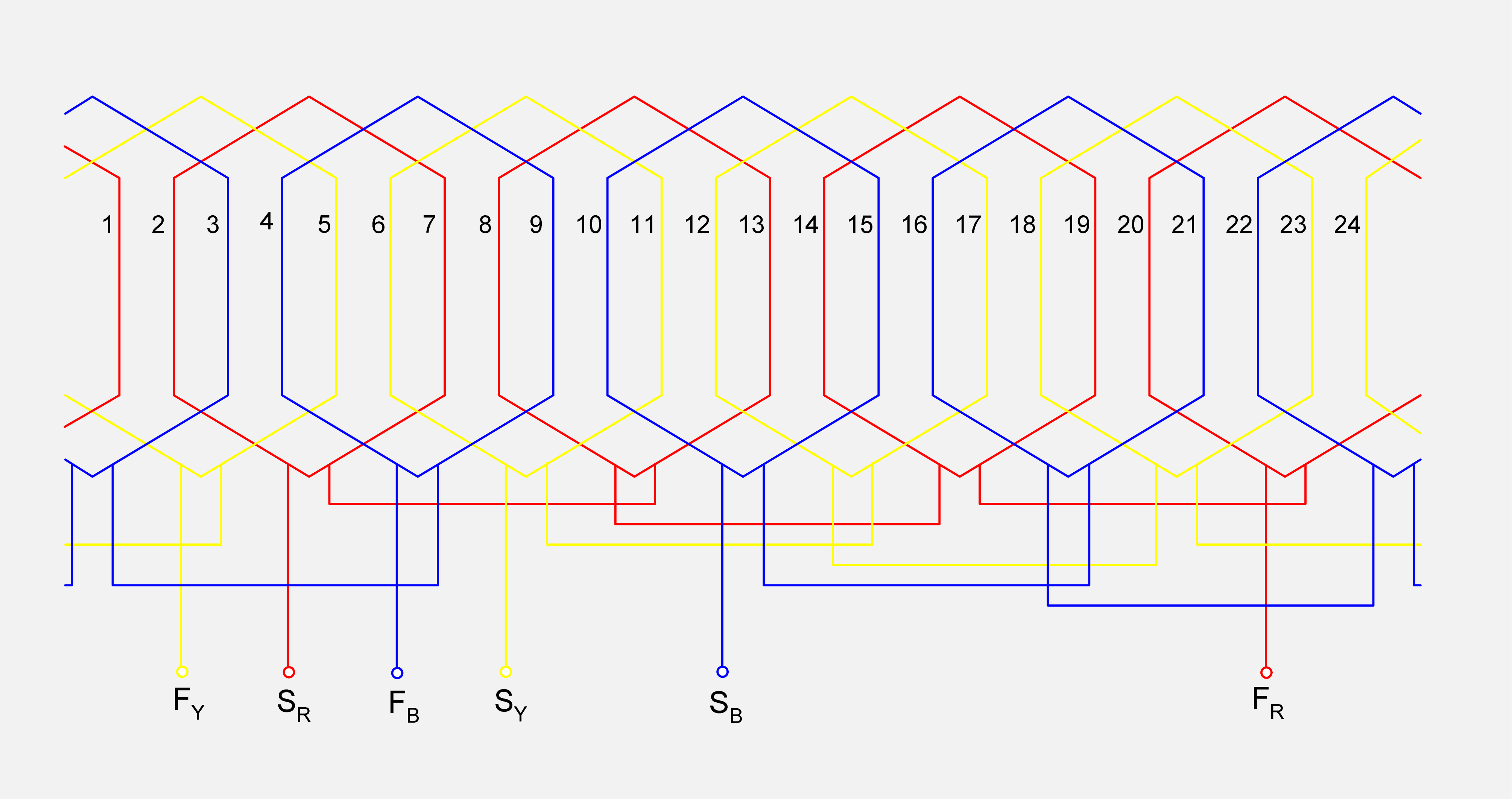
Stator Windings Partially Completed

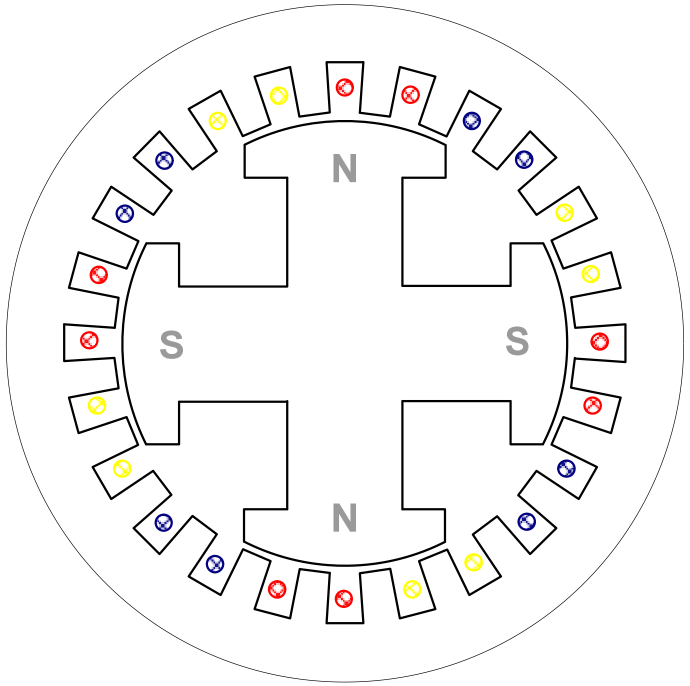


Stator Windings Completed



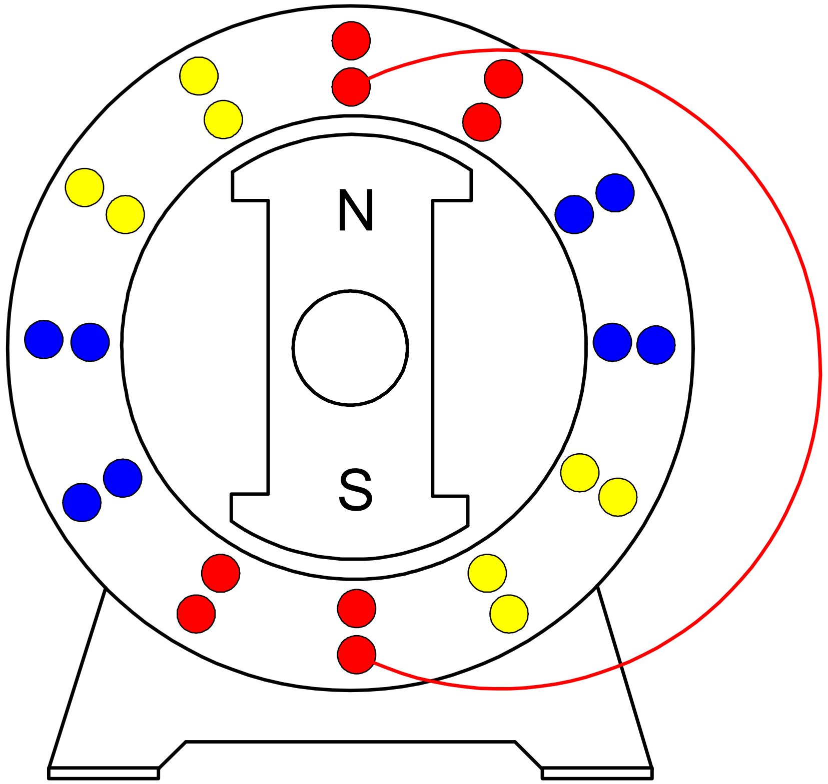
Single Layer Winding

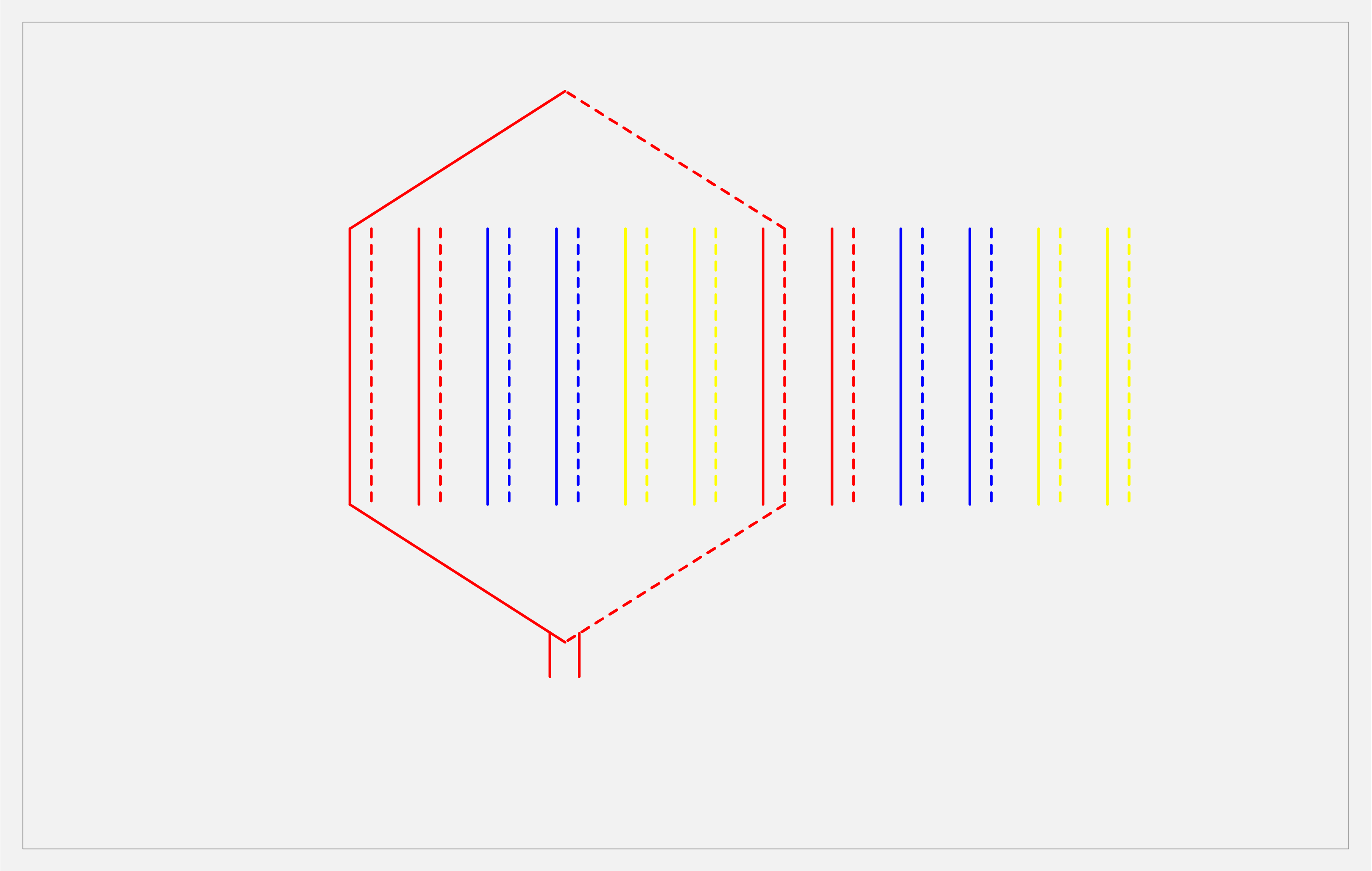




Winding example (Full pitch)

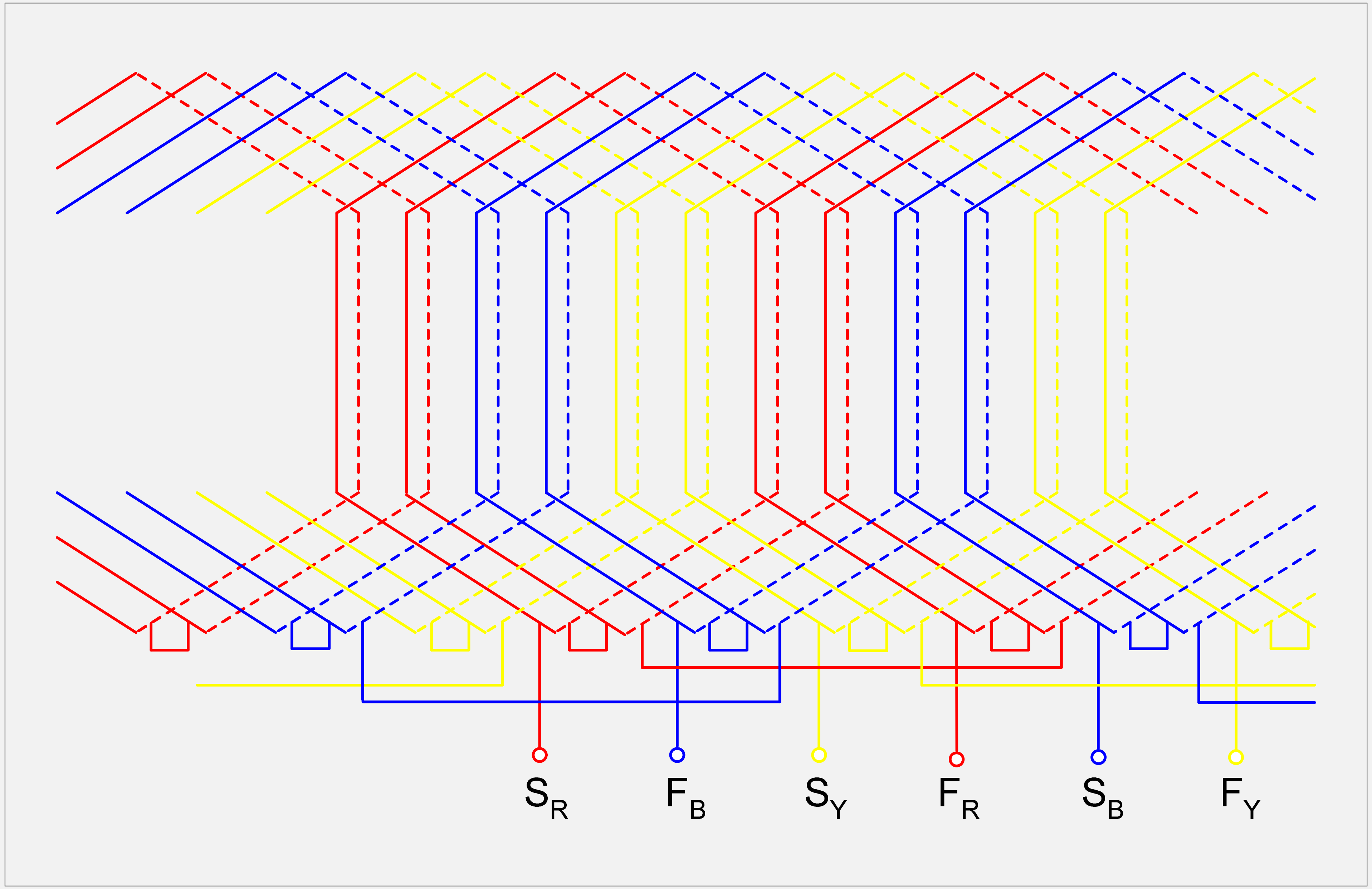
No of poles: 2, No of slots: 12, Double layer → Slots/pole/phase = 12/(2x3) = 2





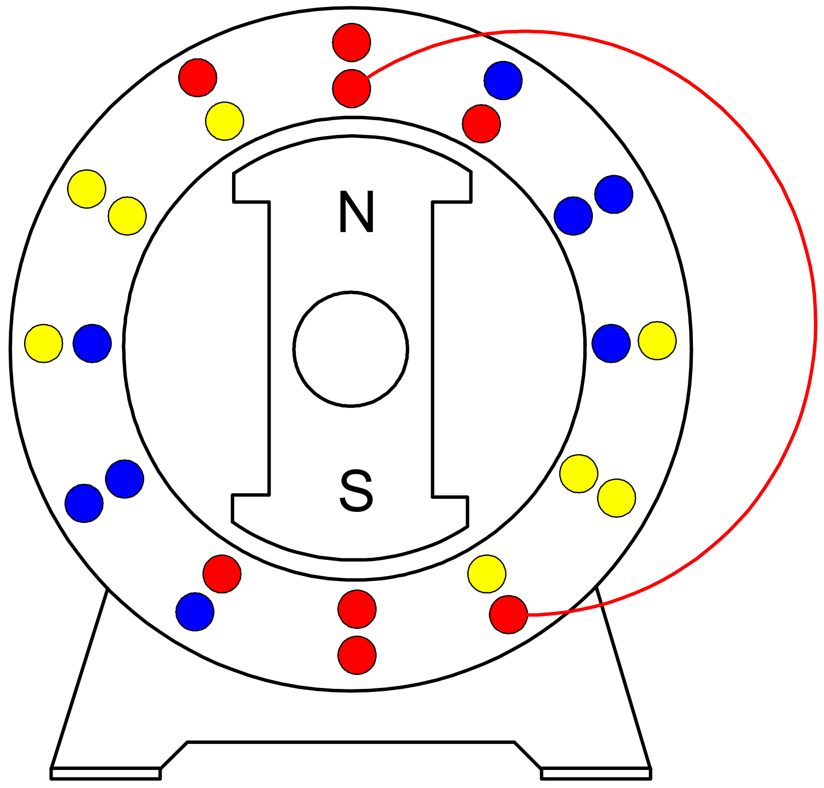
Winding example (Full pitch)

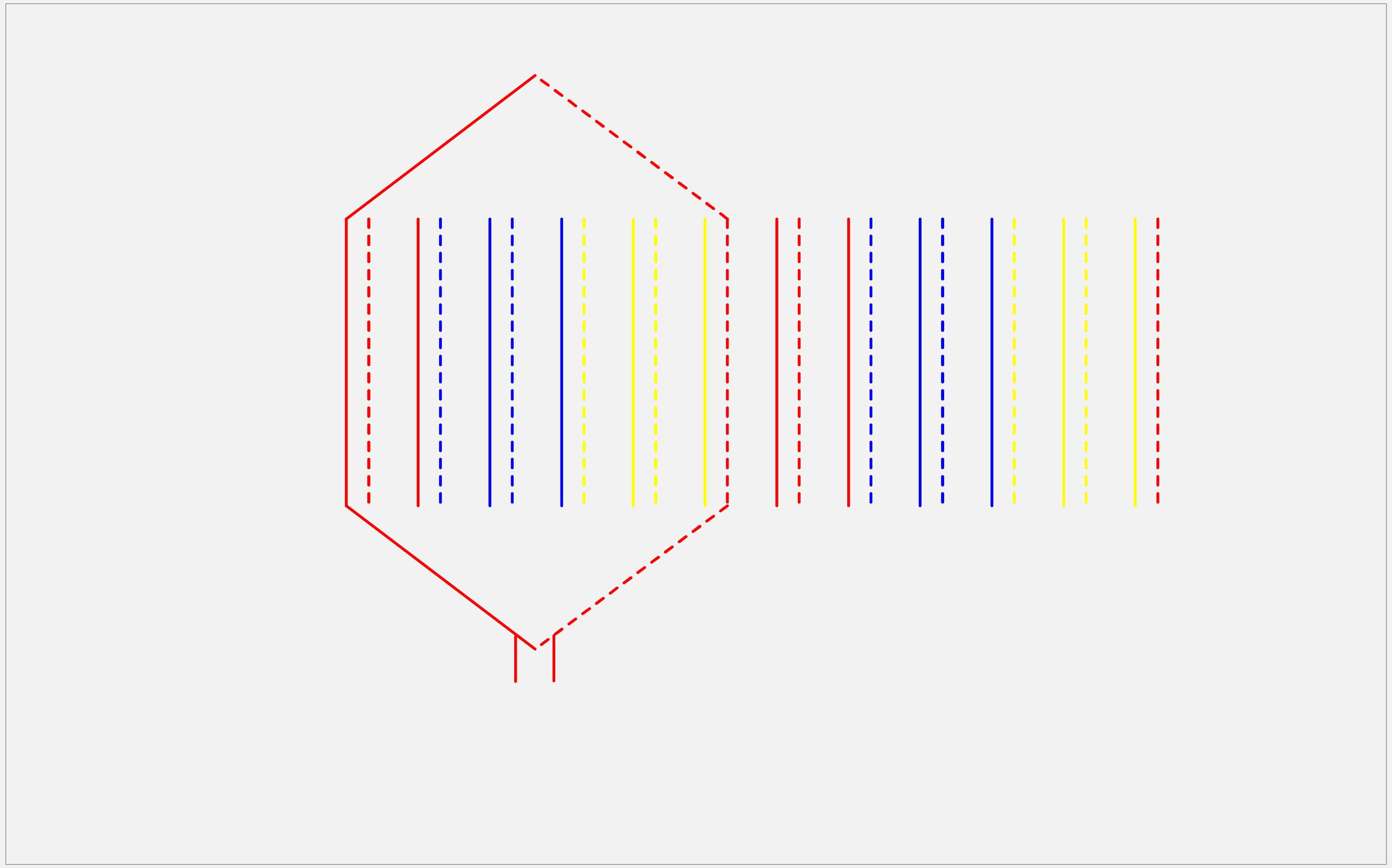
3 phase
2 pole
12 slot
Double layer winding



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
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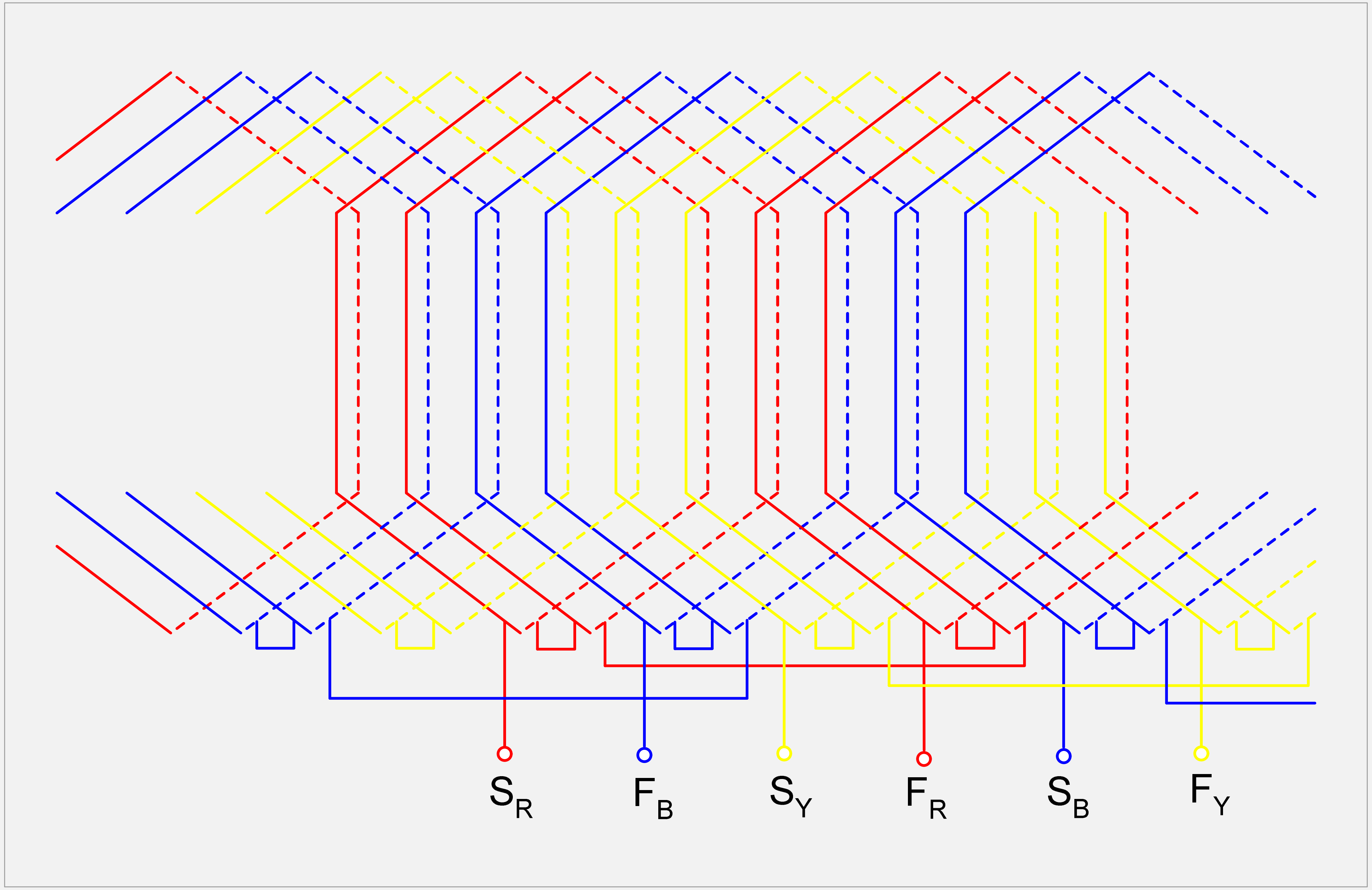
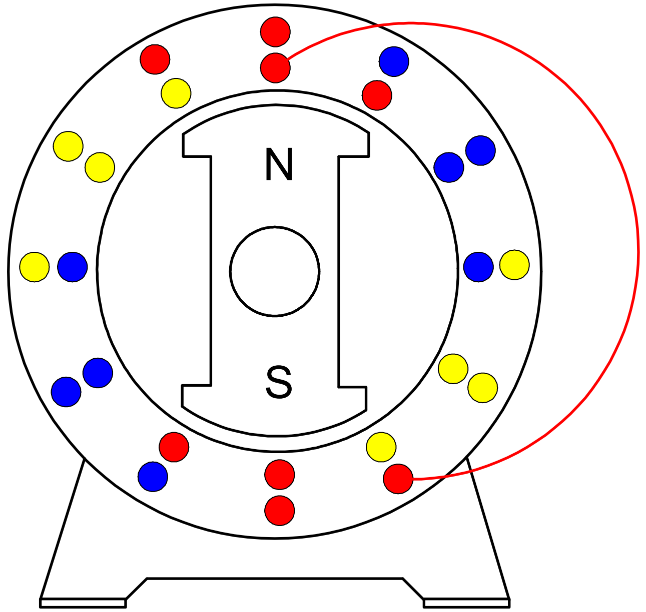
12 slot
Double layer winding



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

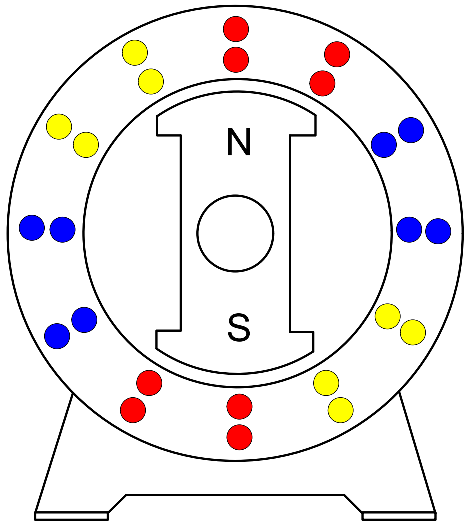
$$\text{Slot angle} = \frac{180}{\text{Slots/pole}}$$

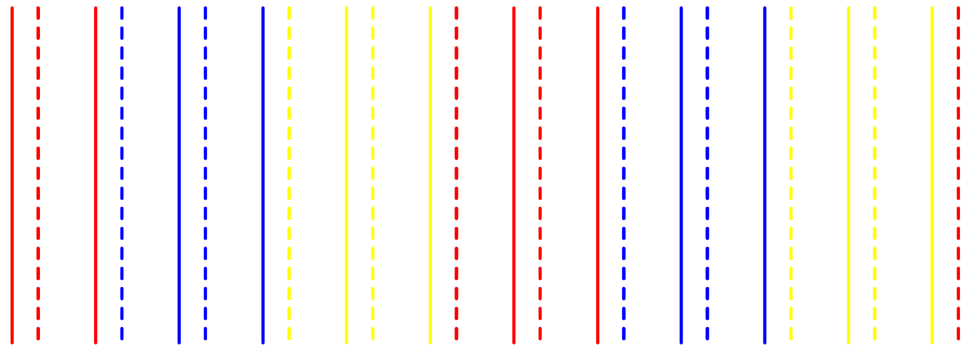
In this case (2 pole, 12 slot):

$$\text{Slot angle} = \frac{180}{6} = 30°$$

For a 4 pole 36 slot machine:

$$\text{Slot angle} = \frac{180}{9} = 20°$$



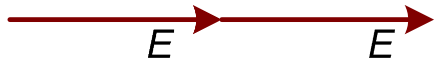


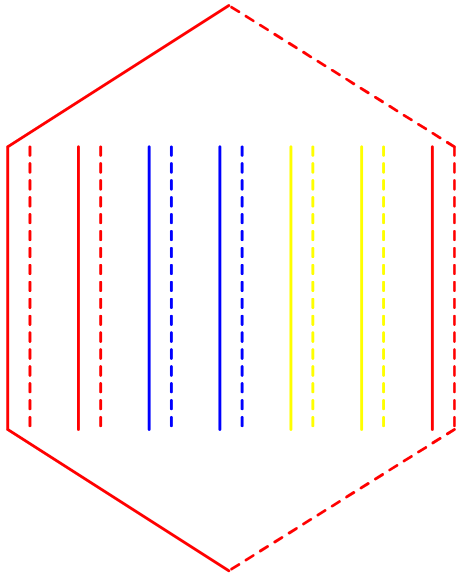
Pitch Factor

Let the voltage induced in a conductor is E

If the coil is full pitched,

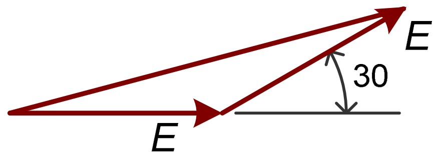
Total induced voltage in a coil $= 2E$

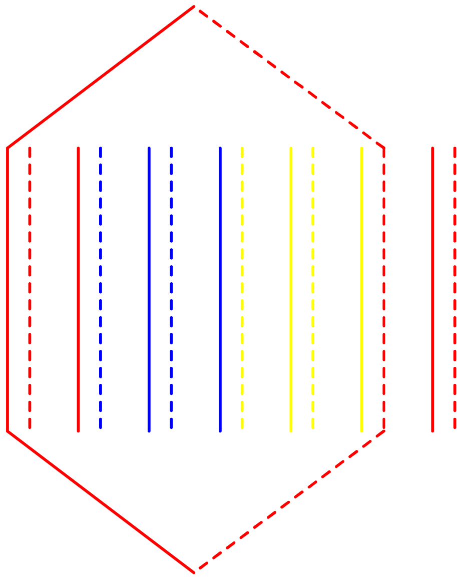




If the coil is short pitched by an angle α

$$\text{Total induced voltage} = 2\ \text{E} \cos\frac{\alpha}{2}$$





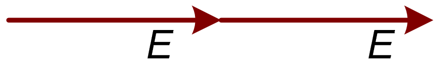
Pitch Factor

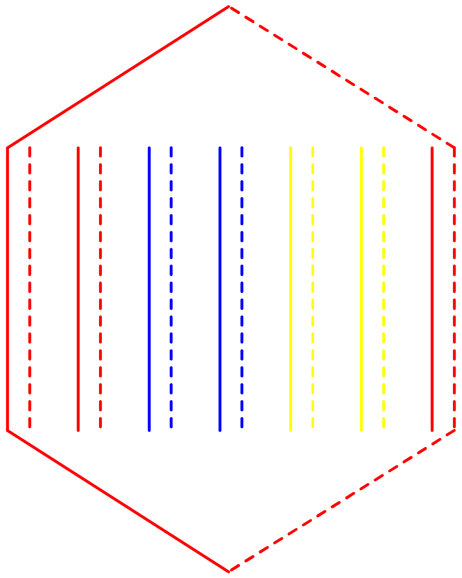
Also known as **coil span factor**

Let the voltage induced in a conductor is E

If the coil is full pitched,

Total induced voltage in a coil $= 2E$



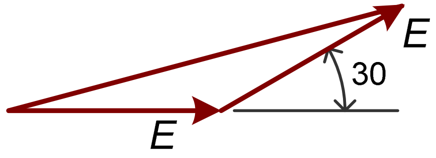


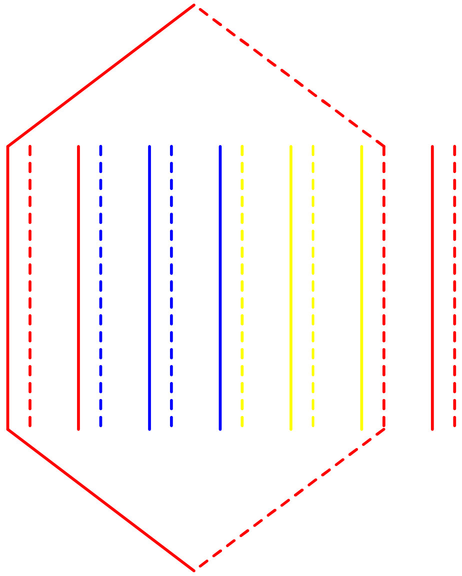
If the coil is short pitched by an angle α

Total induced voltage $= 2\ E\ \cos\dfrac{\alpha}{2}$

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

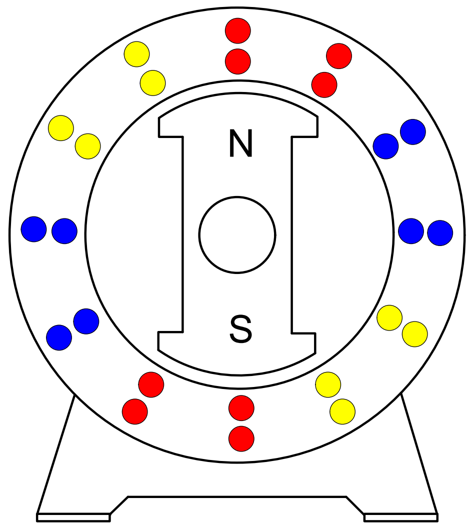
$$= \frac{2E\cos\dfrac{\alpha}{2}}{2E} = \cos\frac{\alpha}{2}$$





Distribution factor

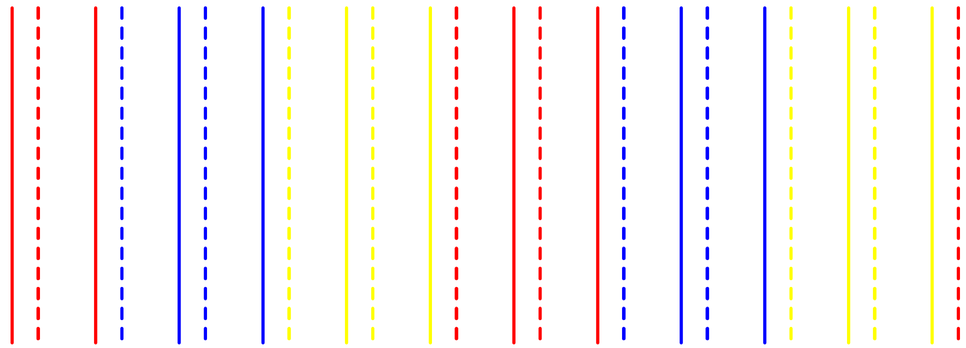
$$\text{Distribution facor, } K_d = \frac{\text{emf with distributed winding}}{\text{emf with concentrated winding}}$$



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

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

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



Distribution factor

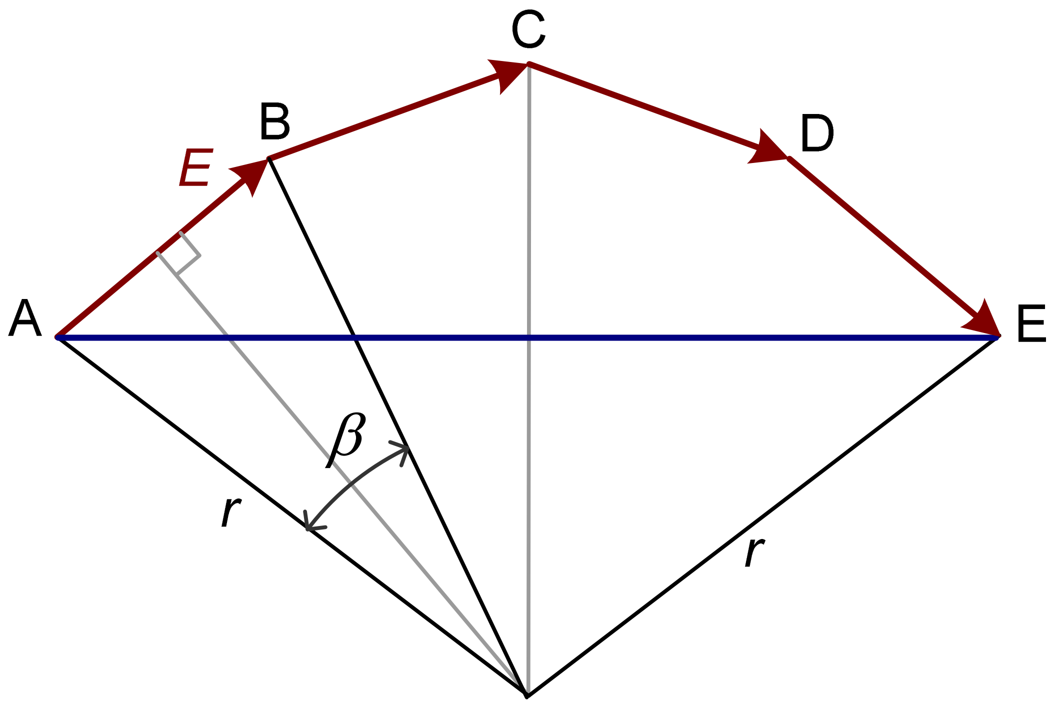
$$\text{Distribution facor, } K_{\mathrm{d}} = \frac{\text{emf with distributed winding}}{\text{emf with concentrated winding}}$$

$$\mathrm{AB} = 2r\sin\frac{\beta}{2}$$

$$\text{Arithematic sum} = m\,2r\sin\frac{\beta}{2}$$

$$\text{Vector sum} = 2r\sin\frac{m\beta}{2}$$

$$K_{\mathrm{d}} = \frac{2r\sin\frac{m\beta}{2}}{m\,2r\sin\frac{\beta}{2}} = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}}$$



Example

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

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

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

$$\text{Distribution factor, } K_\mathrm{d} = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}} = \frac{\sin \frac{3 \times 20}{2}}{3 \sin \frac{20}{2}} = 0.956$$

EMF Equation

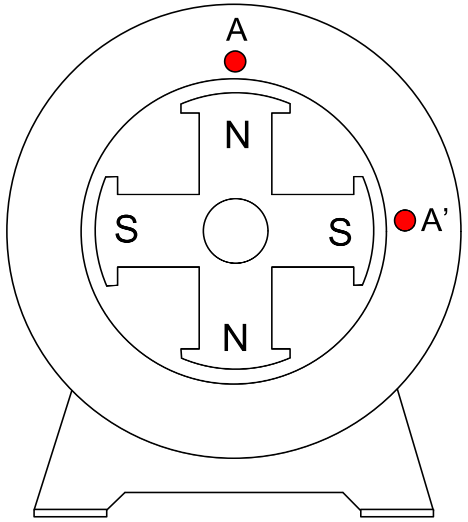
Z = Number of coil sides in series per phase

P = Number of poles

f = Frequency

N = Speed in RPM

Φ = Flux per pole



In one revolution each conductor is cut by ΦP webers

$$d\Phi = \Phi P \qquad dt = \frac{60}{N}$$

$$\text{Average emf induced} = \frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi N P}{60} \text{ volts}$$

Substituting for N

$$\text{Average emf induced} = \frac{\Phi P}{60} \times \frac{120 f}{P} = 2 f \Phi \text{ volts}$$

EMF Equation

For the total winding, average emf $= 2 f \Phi Z$

$$= 4 f \Phi T$$

RMS value $= 4.44 f \Phi T$

Considering pitch factor and distribution factor,

$$K_c = \cos\frac{\alpha}{2}$$

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

$$K_d = \frac{\sin\frac{m\beta}{2}}{m \sin\frac{\beta}{2}}$$

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.

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

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

$$\text{Coil pitch} = (15-3) \times 12 = 144^\circ \qquad \text{Short chording angle, } \alpha = (180-144) = 36^\circ$$

$$\text{Number of turns, } T = \frac{60 \times 4}{2 \times 3} = 40$$

$$K_c = \cos\frac{\alpha}{2} = \cos\frac{36}{2} = 0.951$$

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

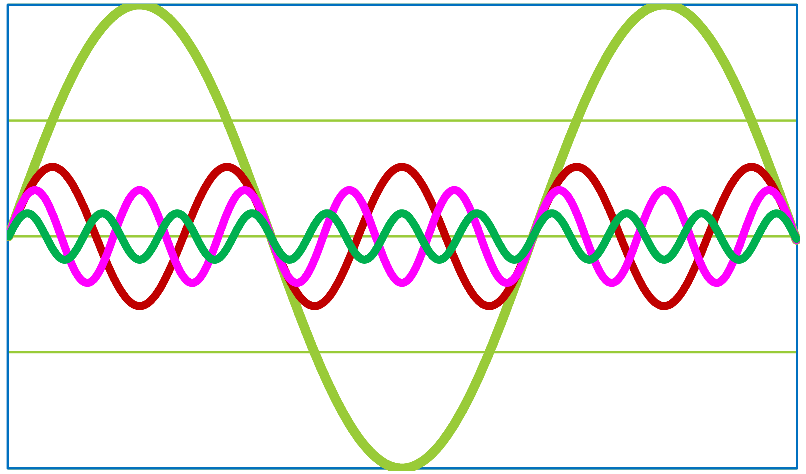
$$\text{Per phase voltage} = 4.44\, K_c\, K_d\, \Phi\, f\, T$$

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

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

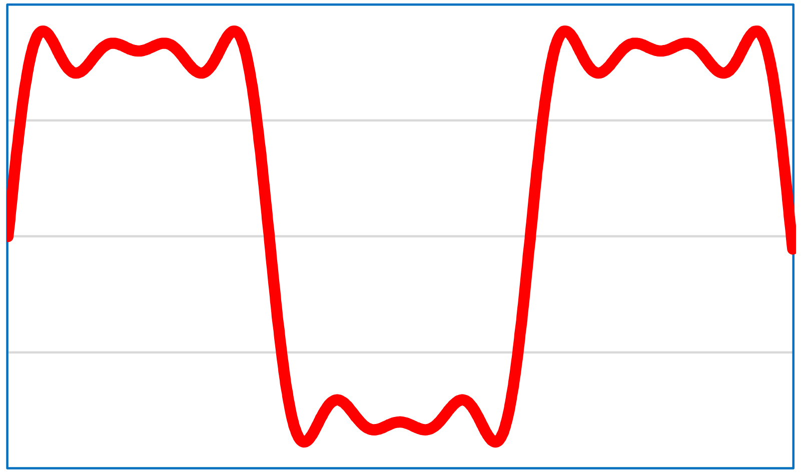
$$= \sqrt{3} \times 6061.3 = 10498.5 \text{ volts}$$

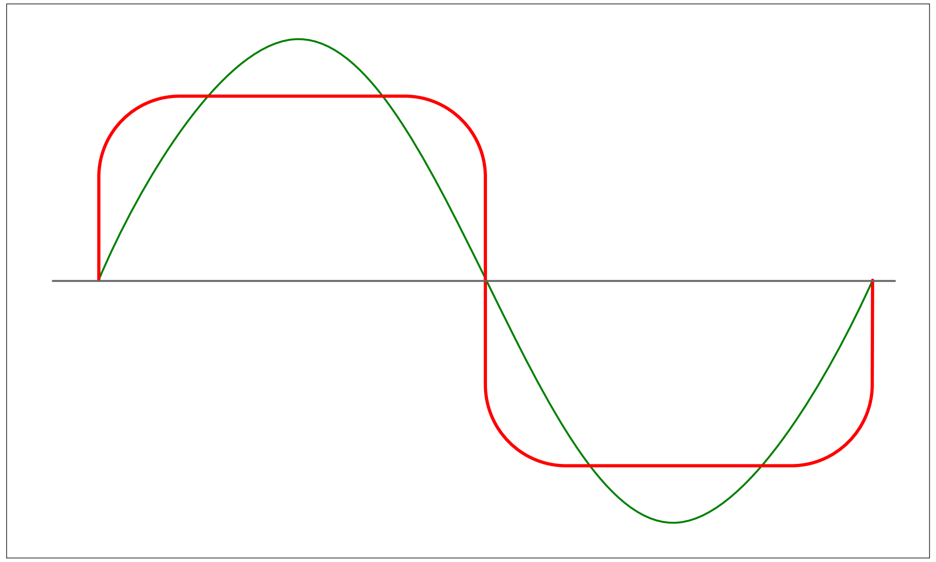
Harmonics



- 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

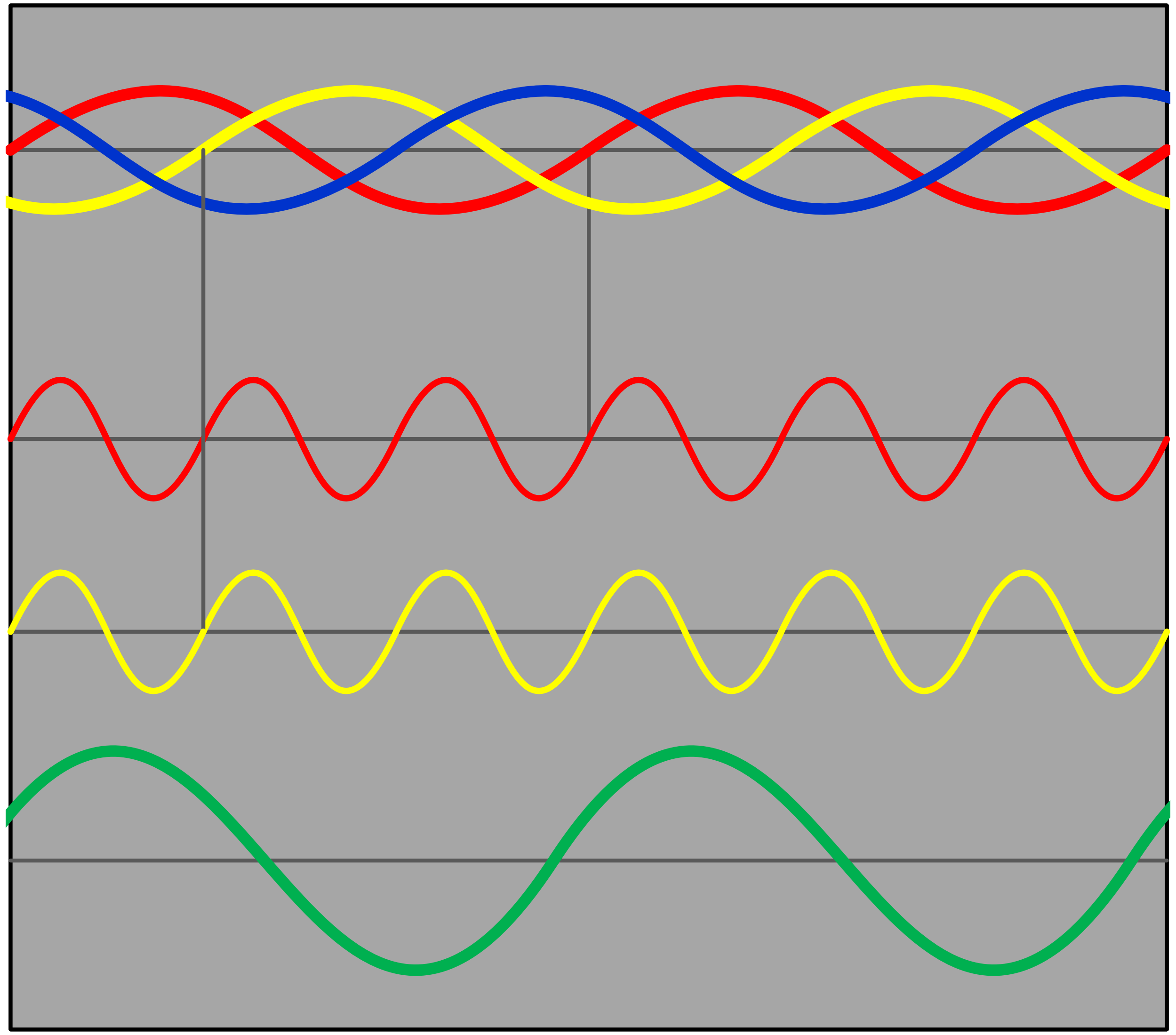
$$K_{\mathrm{cn}} = \cos\frac{n\alpha}{2} \qquad K_{\mathrm{dn}} = \frac{\sin\frac{mn\beta}{2}}{m\sin\frac{n\beta}{2}}$$

where n is the harmonic order

if $n = 5$ and $\alpha = 36°$ $\qquad K_{\mathrm{c5}} = \cos\frac{5\times 36}{2} = 0$

Short chording can help to eliminate harmonics

Line voltage with harmonics in generated emf



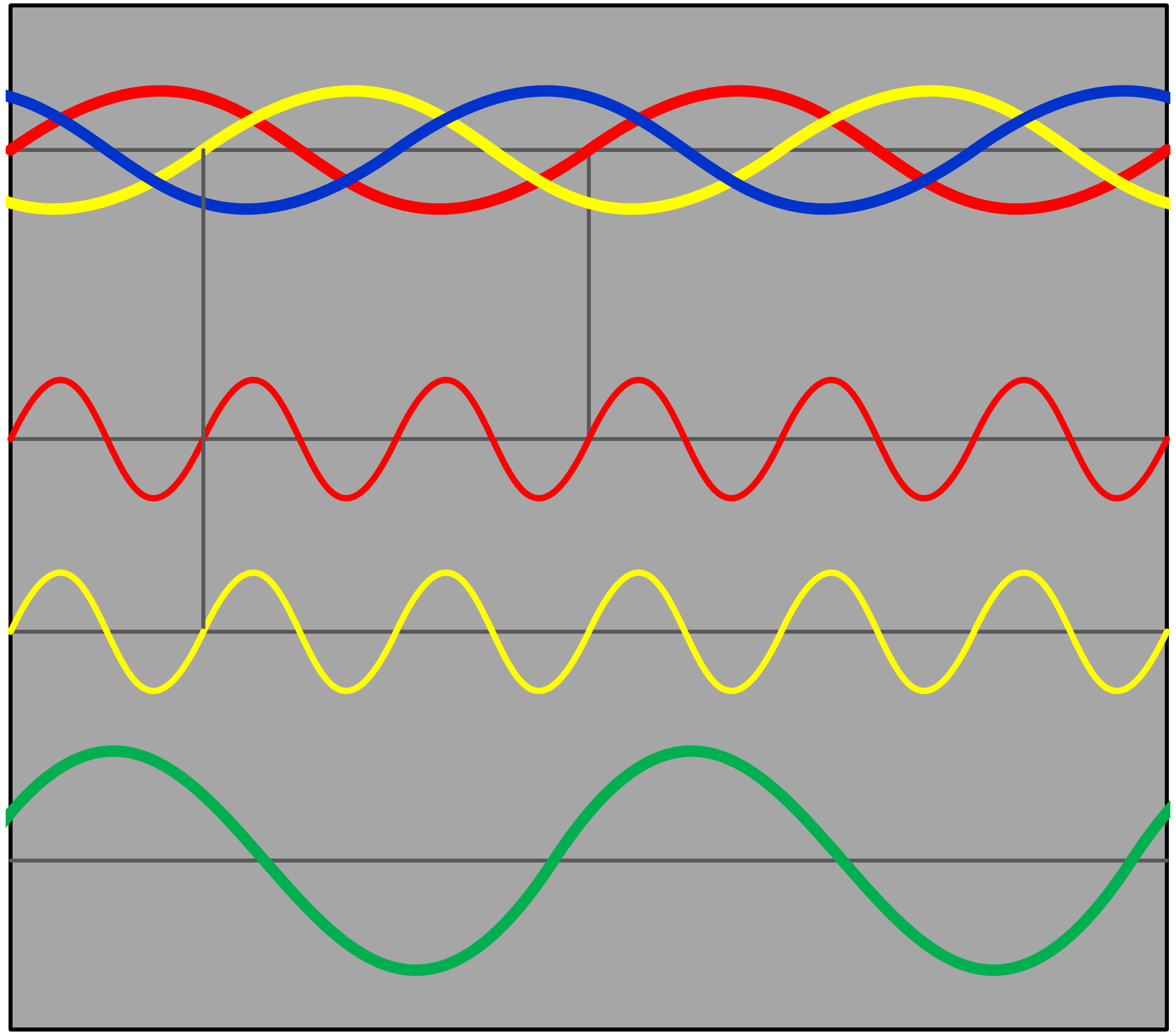
Phase voltage

Third Harmonic voltages

Line voltage

$$V_{RY} = V_R - V_Y$$

Line voltage with harmonics in generated emf



Phase voltage

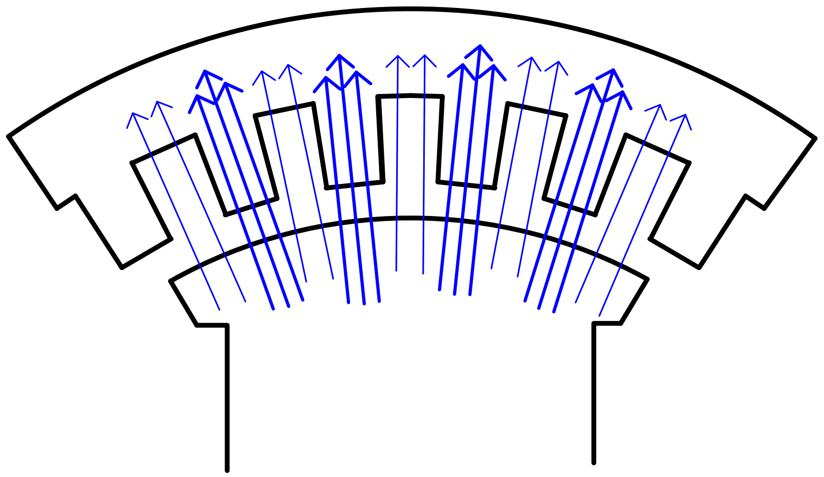
$$V_{RY} = V_R - V_Y$$

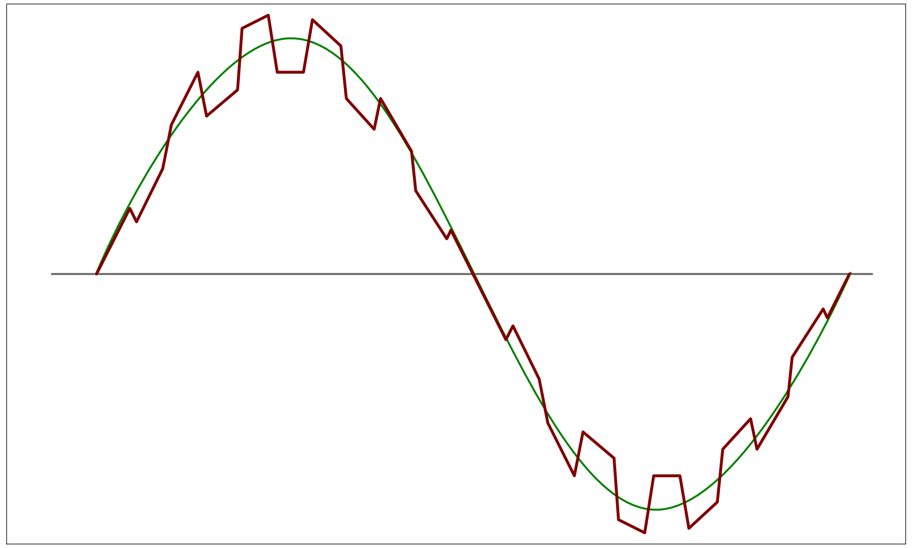
Third Harmonic voltages

Line voltage

Third harmonics cancel in line voltage

Slot Harmonics



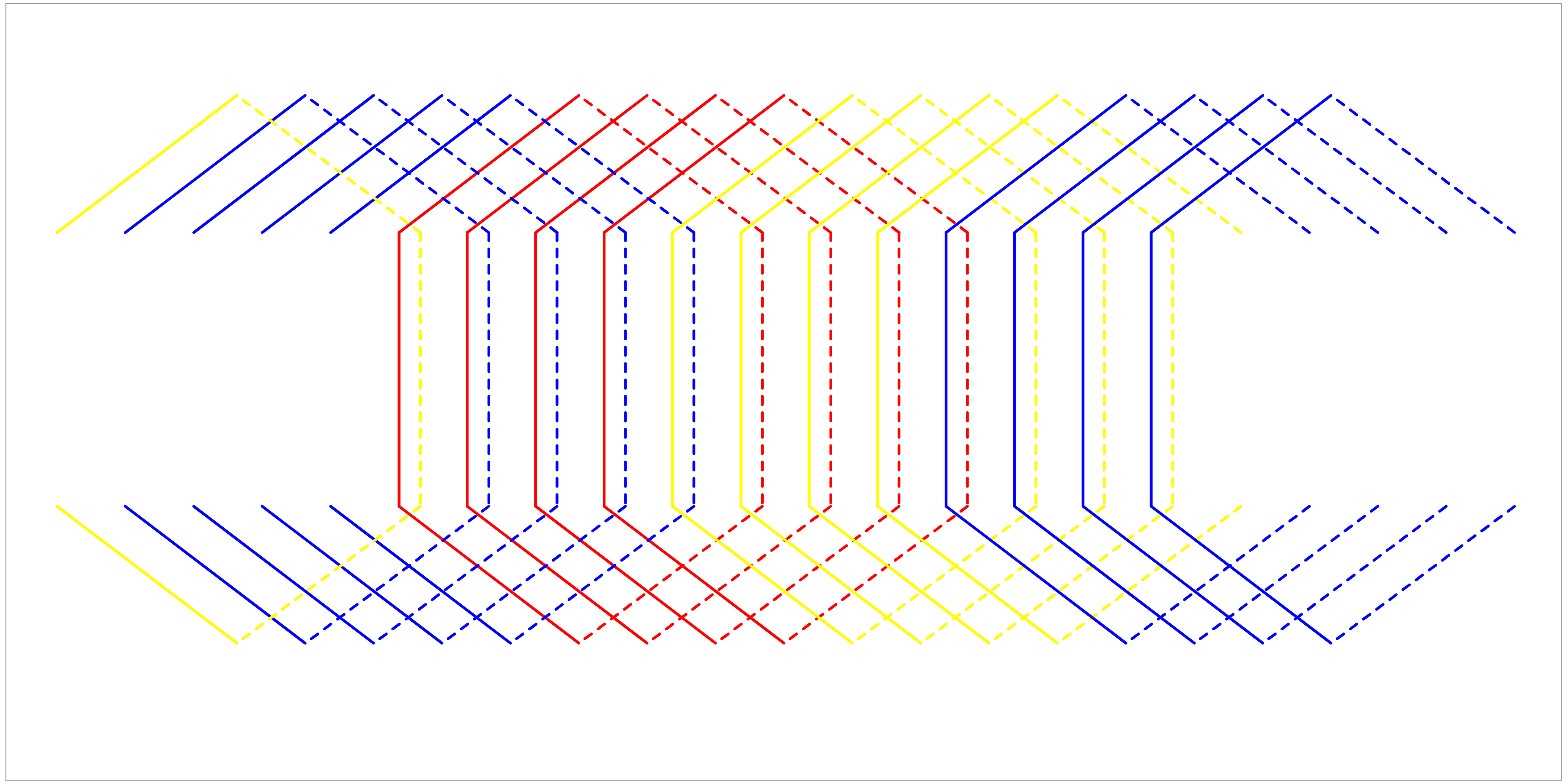


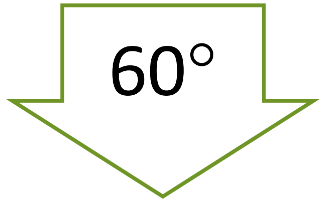
- Distortion of flux occur due to variation of reluctance between the slot area and tooth area
- Distortion of flux produce distortion in voltage waveform which is known as slot harmonics
- Slot harmonics is reduced either by skewing of field poles or by incorporating fractional slot winding

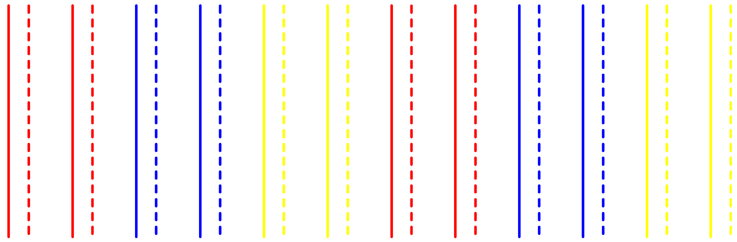
Methods for Elimination of Harmonics

- 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

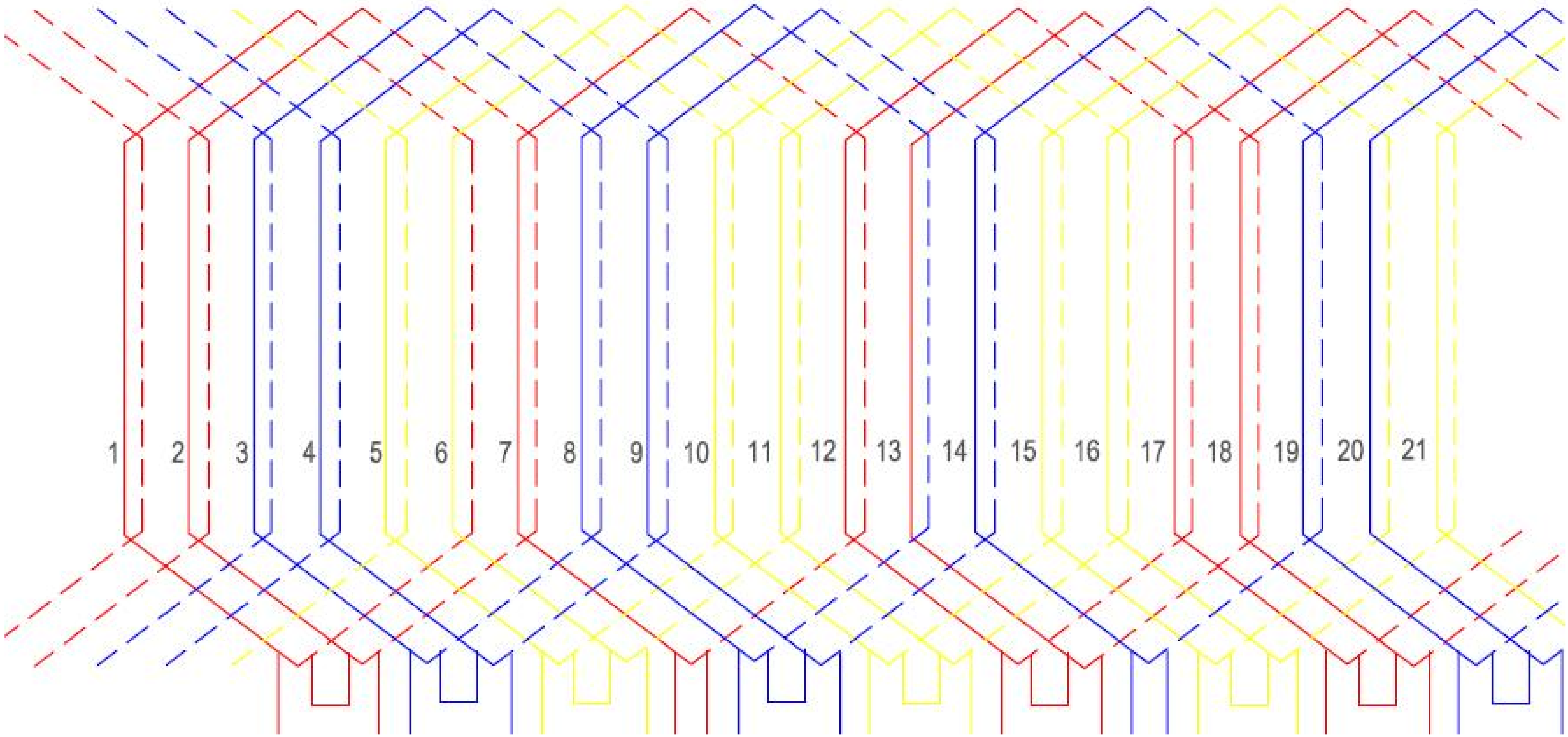
120 Degree Phase Spread Winding







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.

$$\text{Slots/pole/phase, } m = 2 \qquad \text{Slots/pole} = 2 \times 3 = 6$$

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

$$\text{Short chording angle, } \alpha = (180 - 150) = 30^\circ$$

$$\text{Number of turns, } T = \frac{10 \times 2 \times 4}{2} = 40$$

$$K_c = \cos\frac{\alpha}{2} = \cos\frac{30}{2} = 0.966$$

$$K_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}} = \frac{\sin\frac{2\times 30}{2}}{2\times\sin\frac{30}{2}} = 0.966$$

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

$$K_{c3} = \cos\frac{3\alpha}{2} = \cos\frac{3\times 30}{2} = 0.707$$

$$K_{d3} = \frac{\sin\frac{mn\beta}{2}}{m\sin\frac{n\beta}{2}} = \frac{\sin\frac{2\times 3\times 30}{2}}{2\times\sin\frac{3\times 30}{2}} = 0.707$$

$$\Phi_3 = \frac{0.2 \times 0.12}{3} = 0.008 \text{ Wb} \qquad f_3 = 150 \text{ Hz}$$

$$\text{Per phase third harmonic voltage} = 4.44\, K_{c3}\, K_{d3}\, \Phi_3\, f_3\, T$$
$$= 4.44 \times 0.707 \times 0.707 \times 0.008 \times 150 \times 40 = 106 \text{ volts}$$

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

$$\text{Line voltage} = \sqrt{3} \times 995 = 1723.4 \text{ volts}$$

Thank You