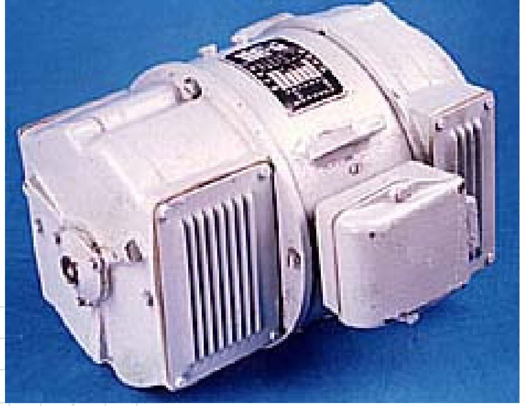
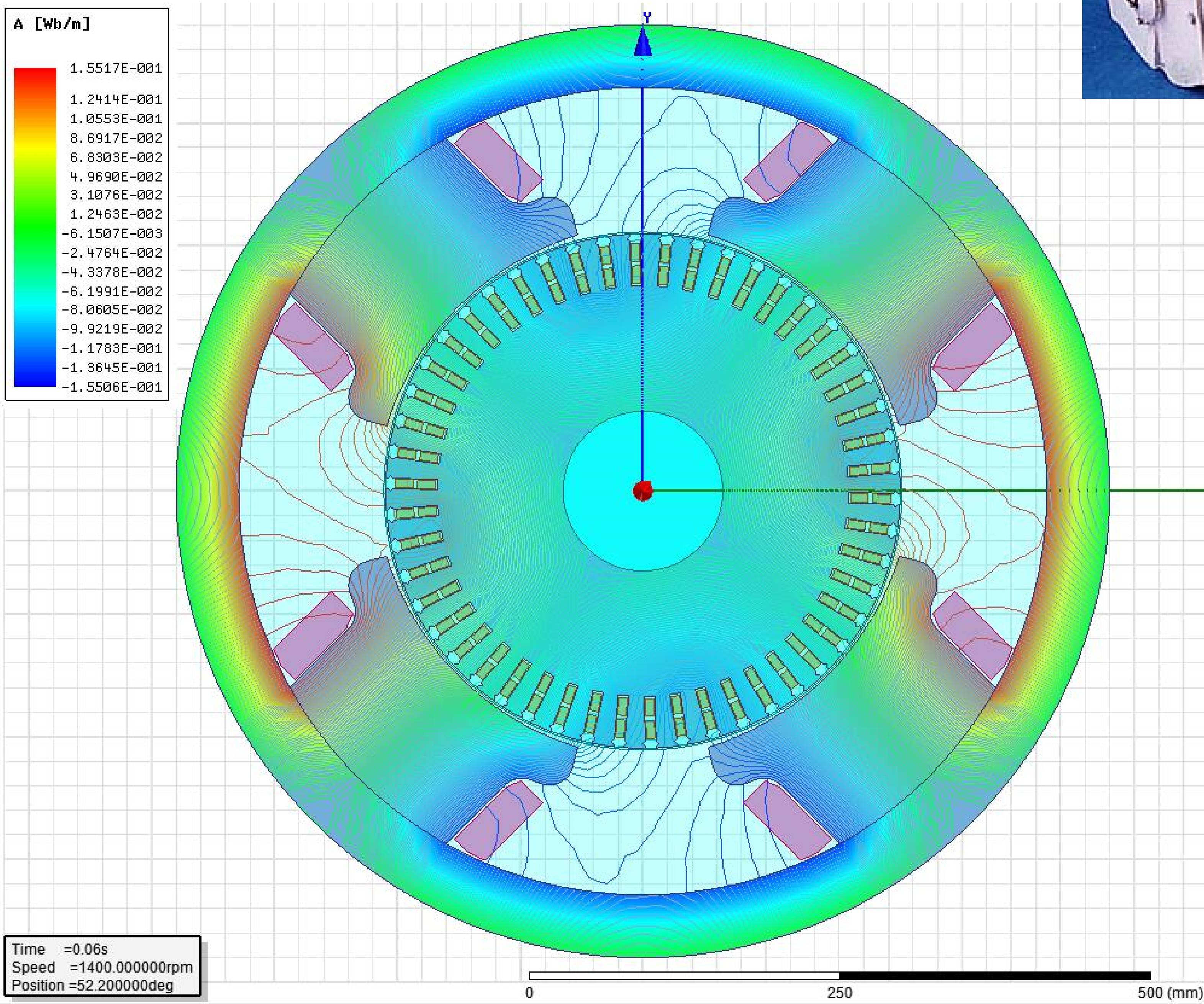
Chapter3
Basic principles of DC Motor

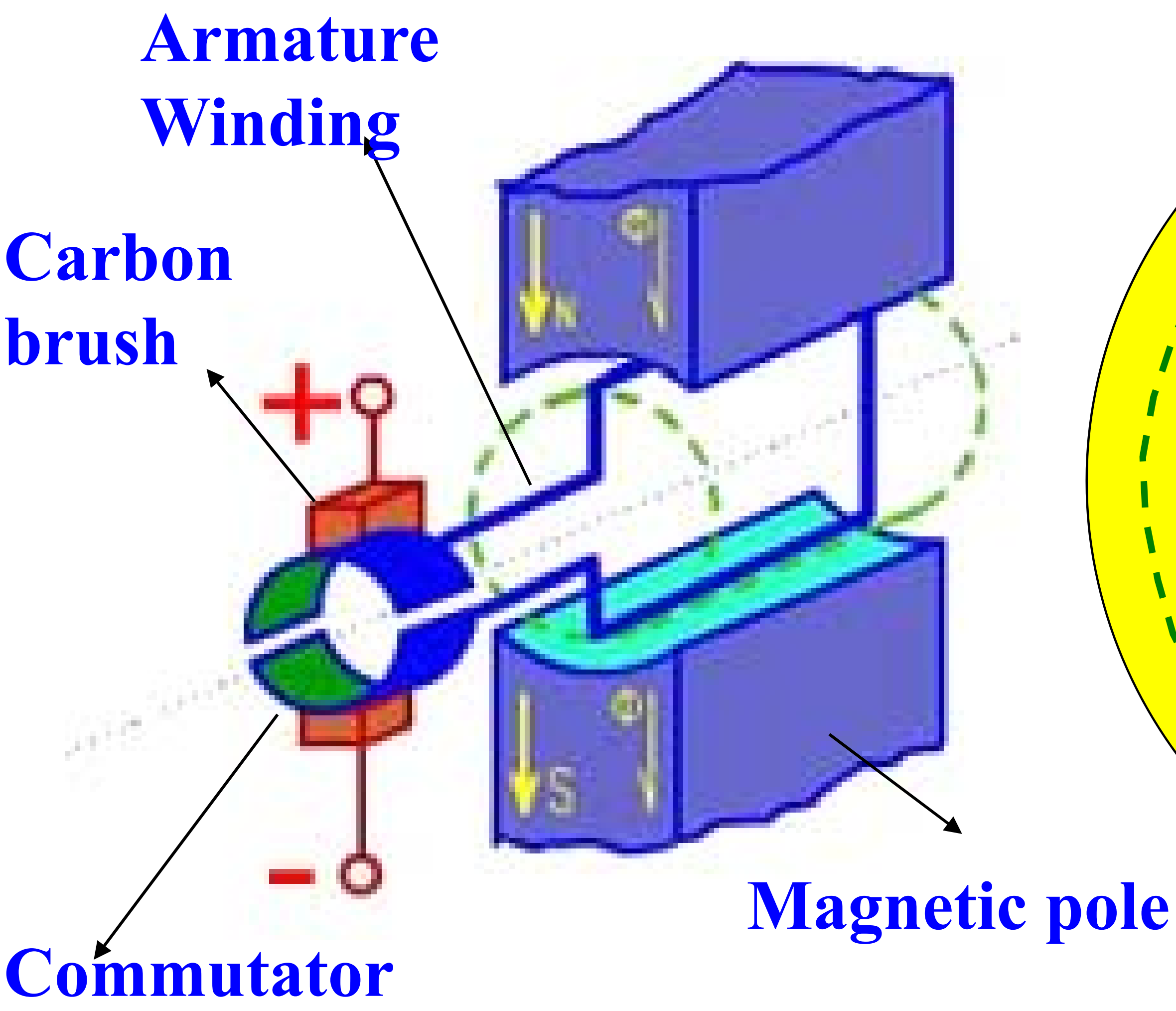


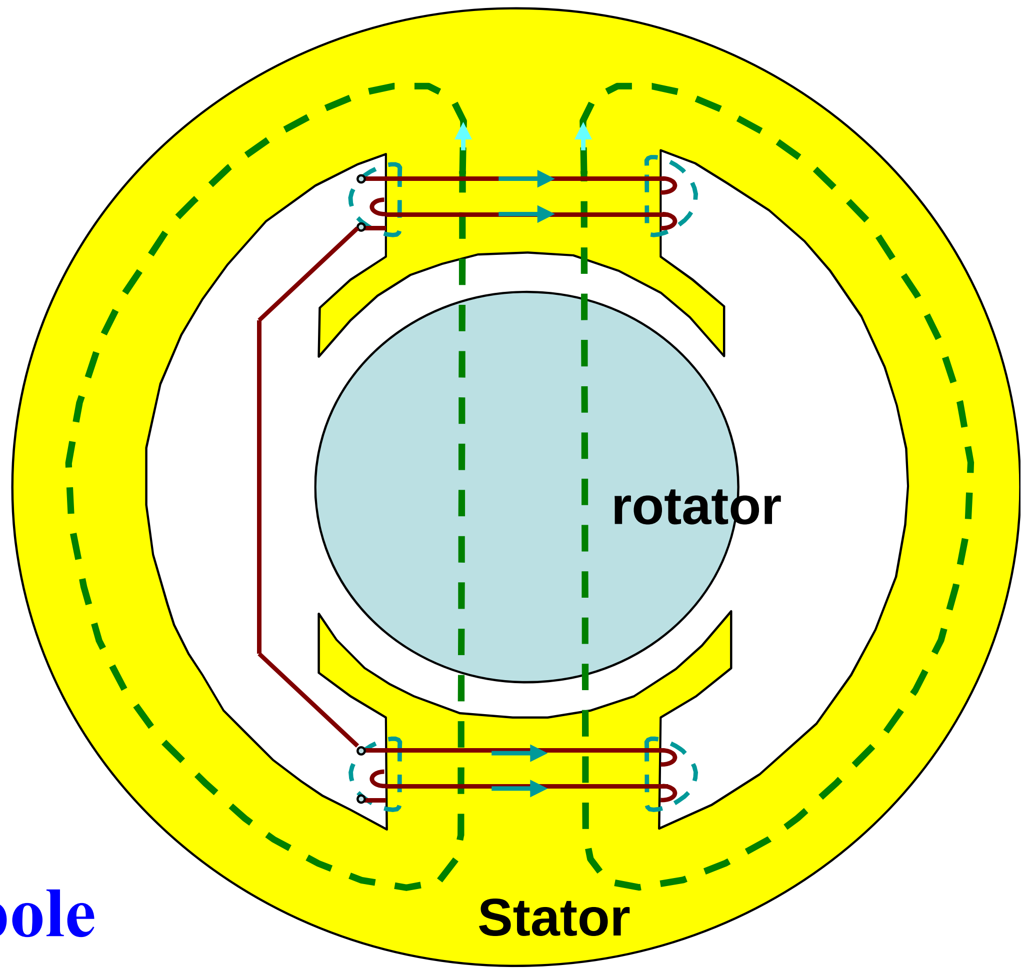


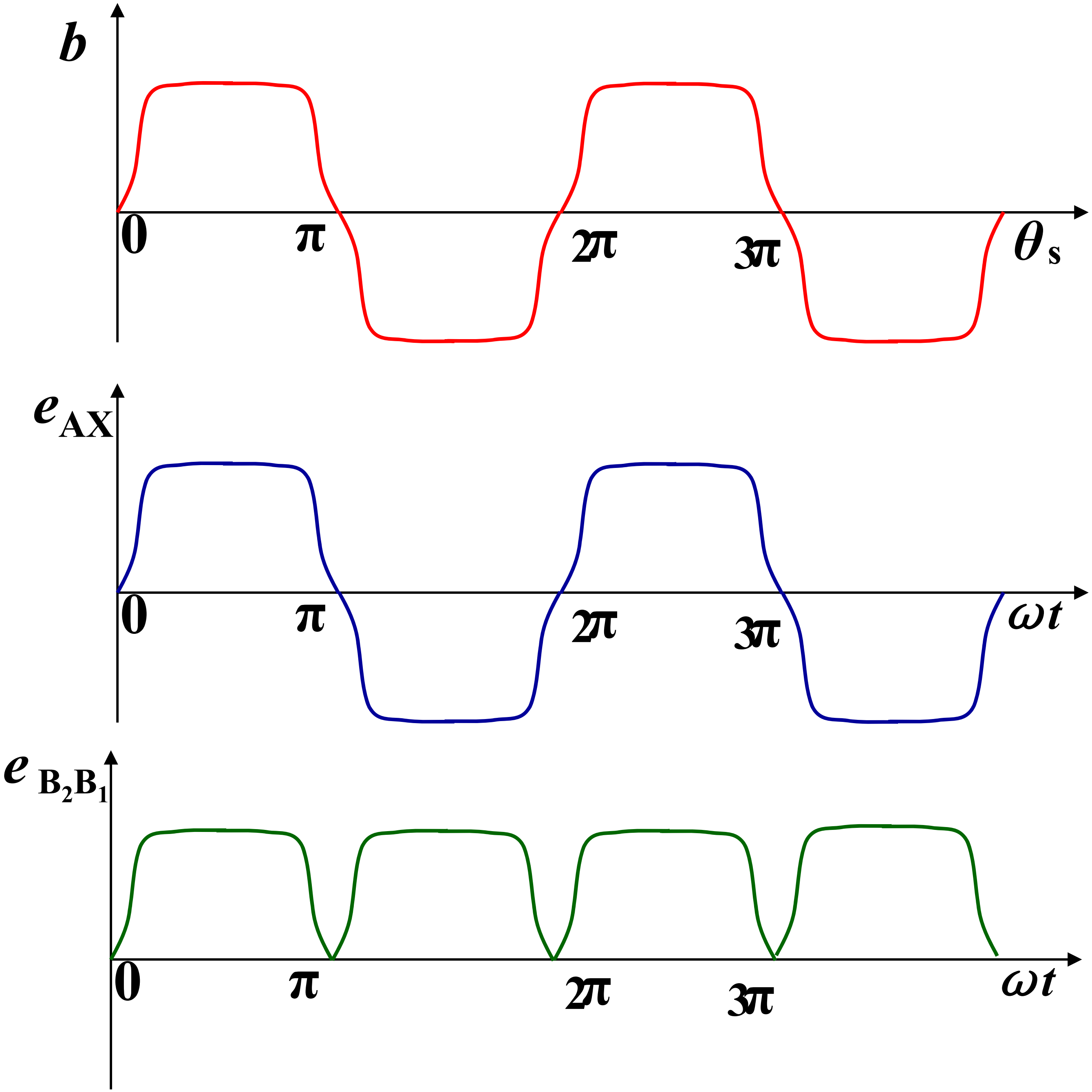
Outline

1. Basic Structure of DC machines
2. Basic Principles of DC machines
3. Magnetic field of DC machines with no loading
4. Magnetic field of DC machines with loading
5. Electromotive Force (EMF) and Electromagnetic Torque
6. Conclusion and discussion

3.1 Basic Structure of DC machines







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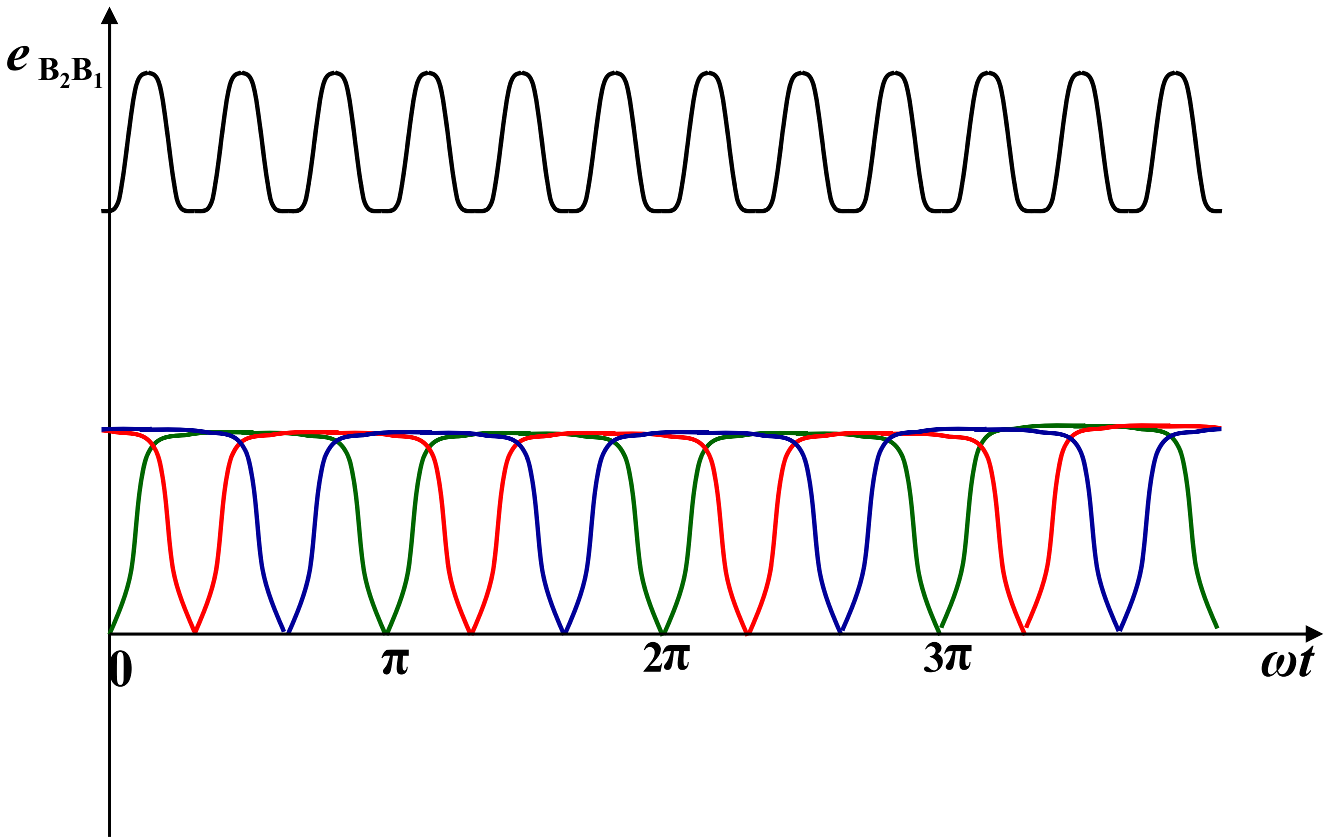

$e_{B_2B_1}$
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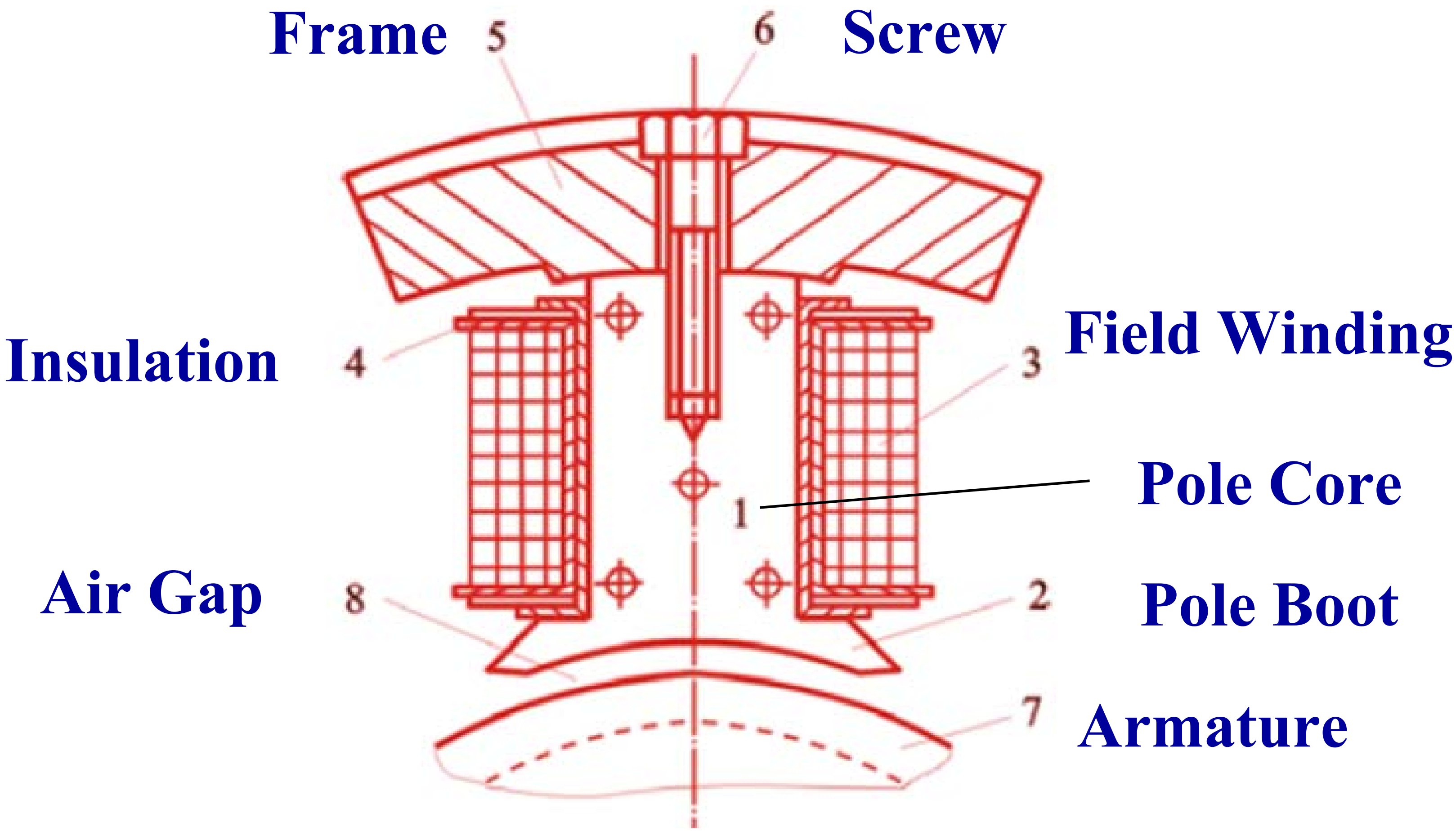
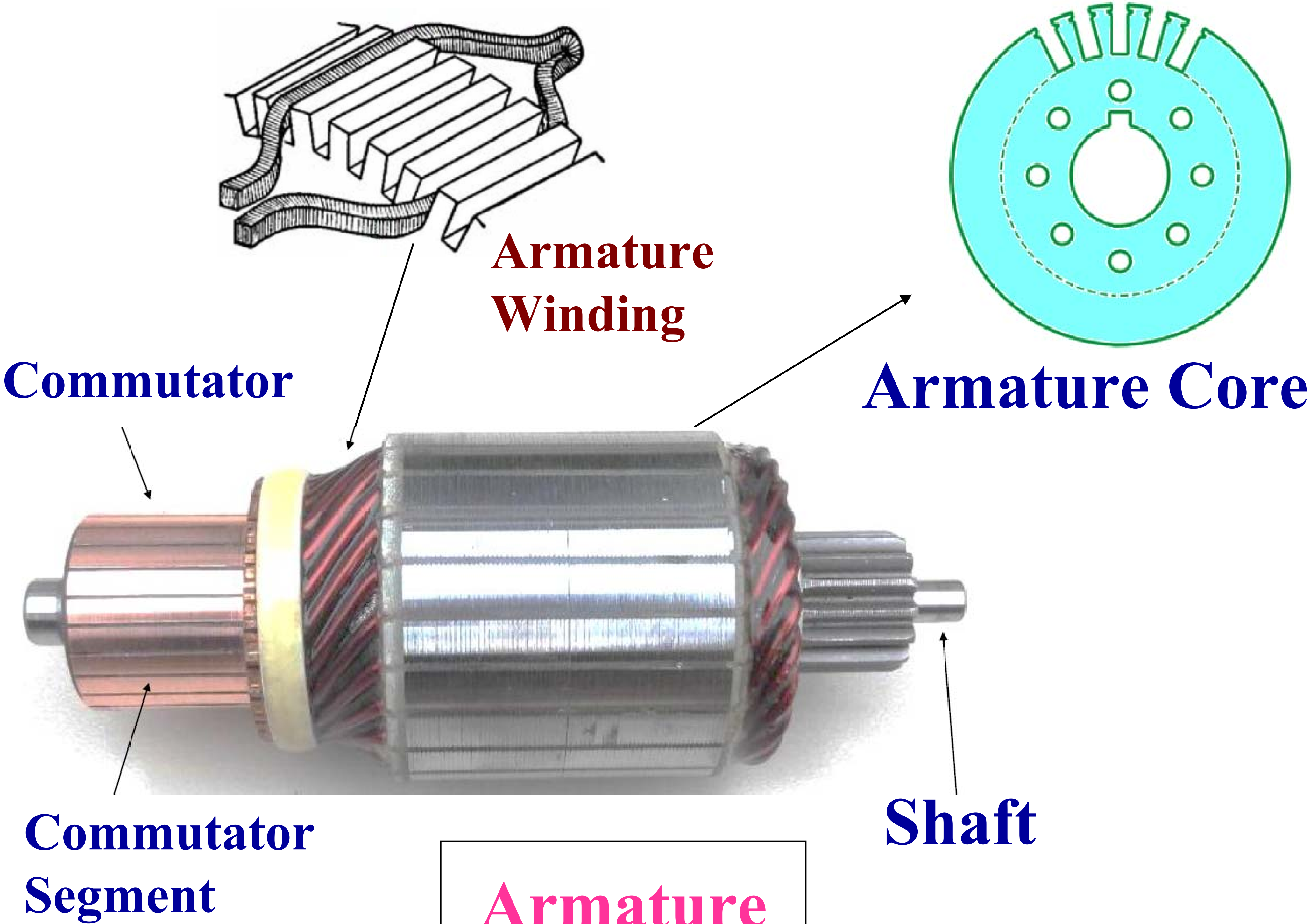
3.1 Basic Structure of DC machines

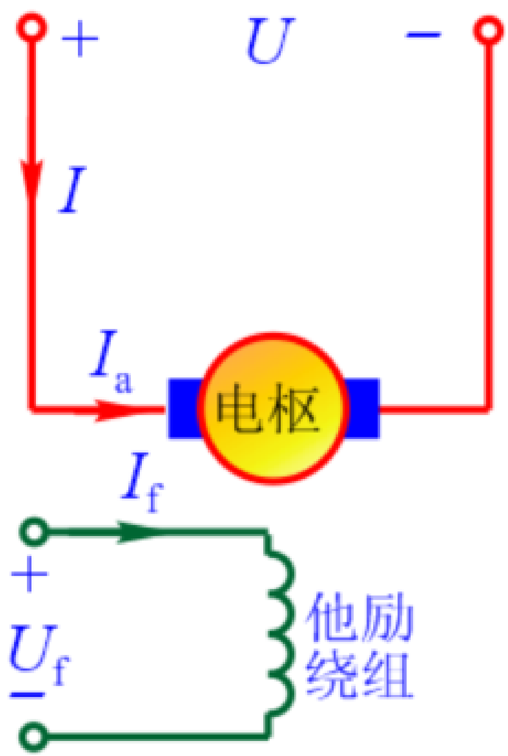


Main pole

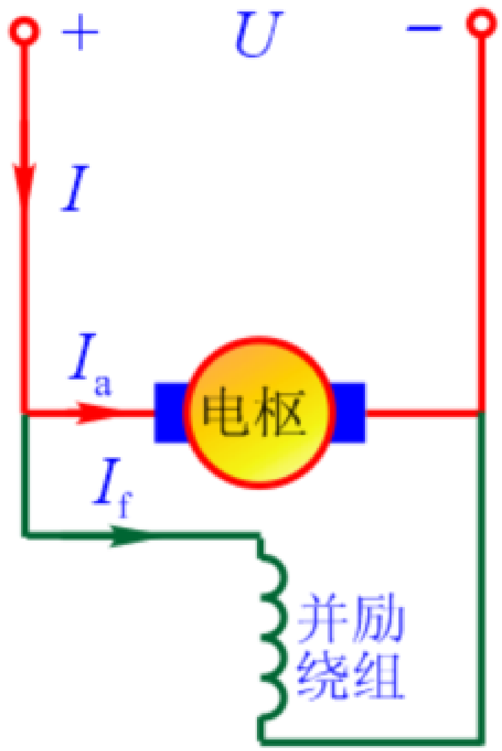

Armature
Winding
Armature Core
Commutator
Commutator
Segment
Shaft

Armature

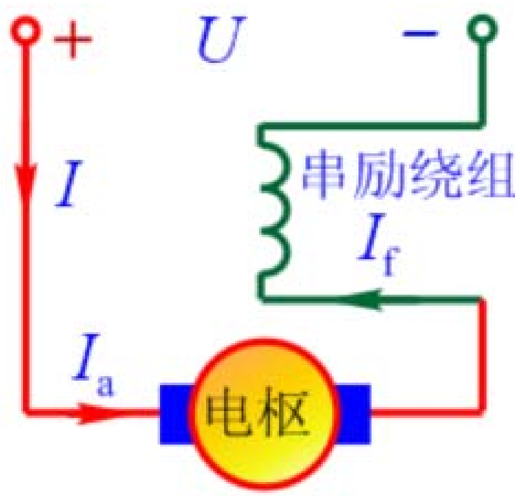
Field winding connections



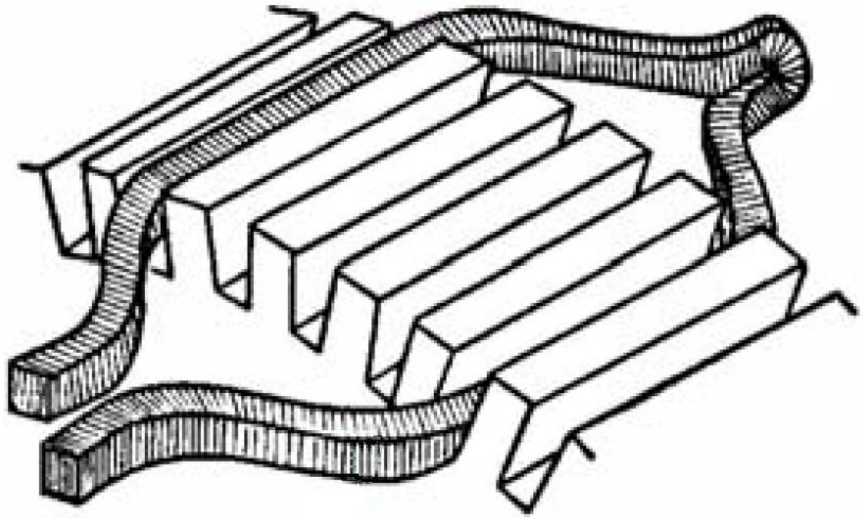
Separate excitation

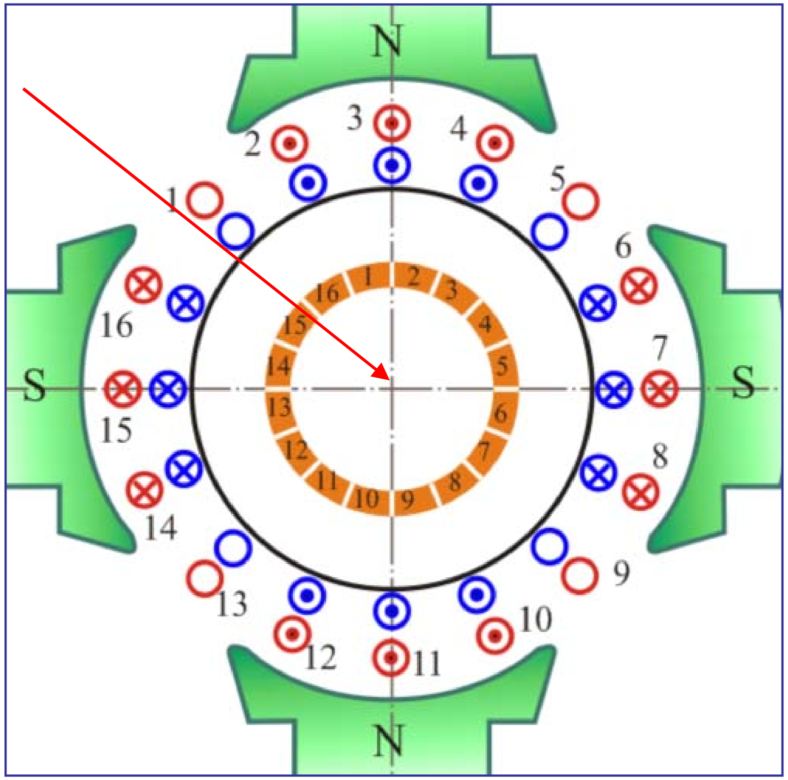


Shunt excitation



Series excitation

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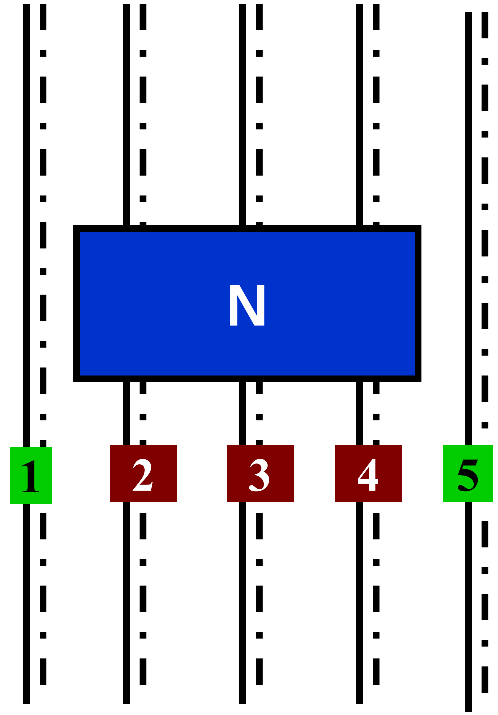
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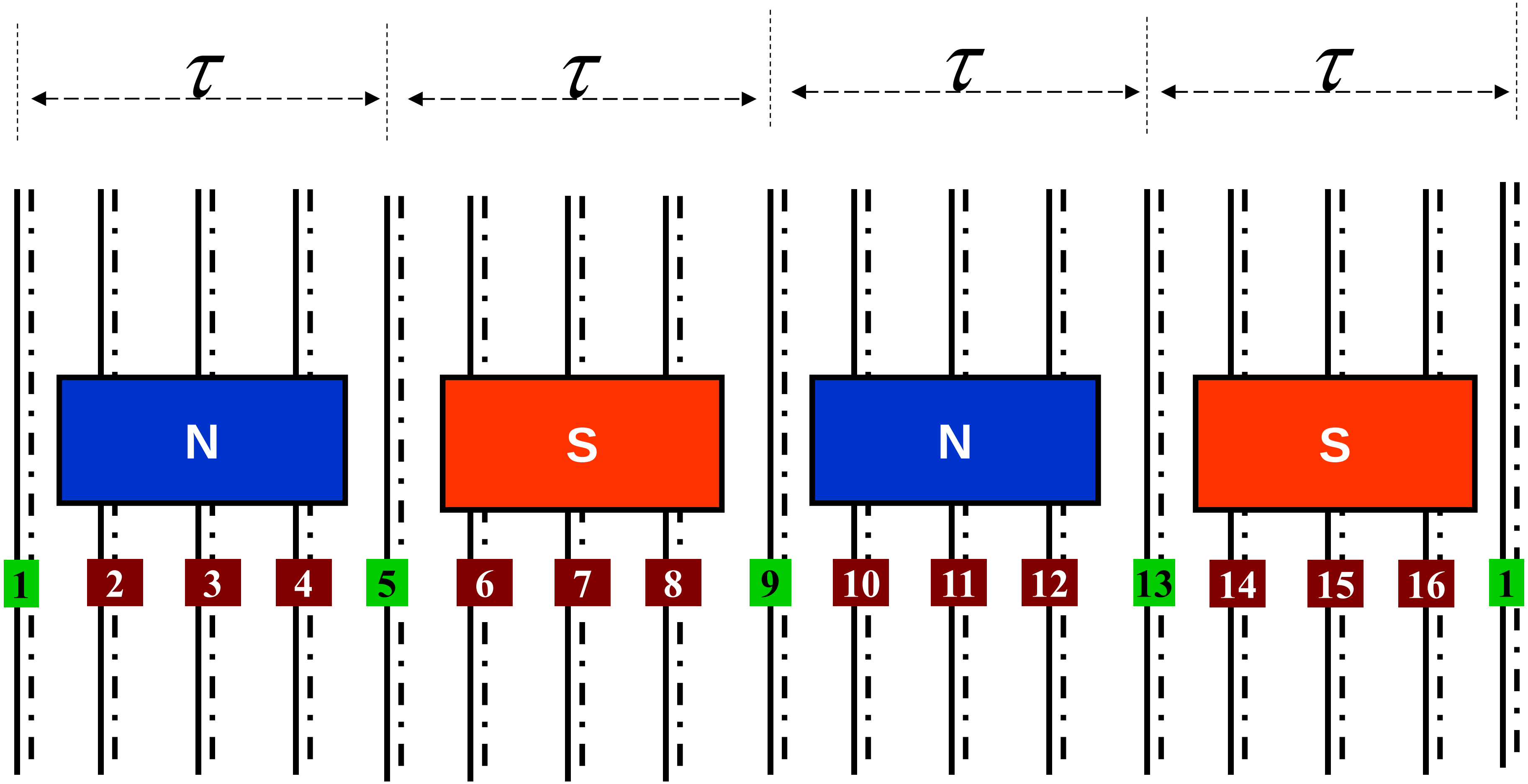

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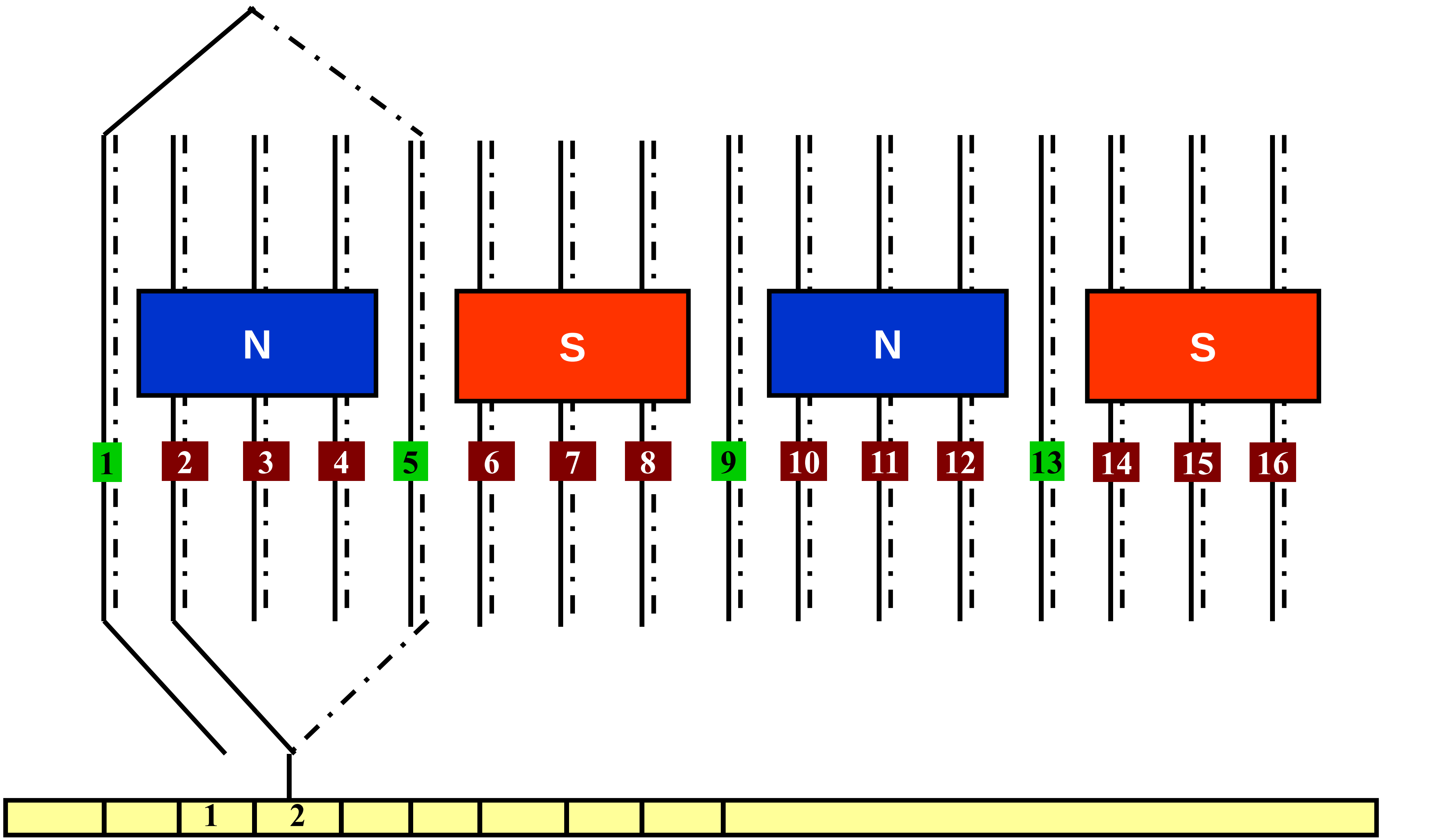
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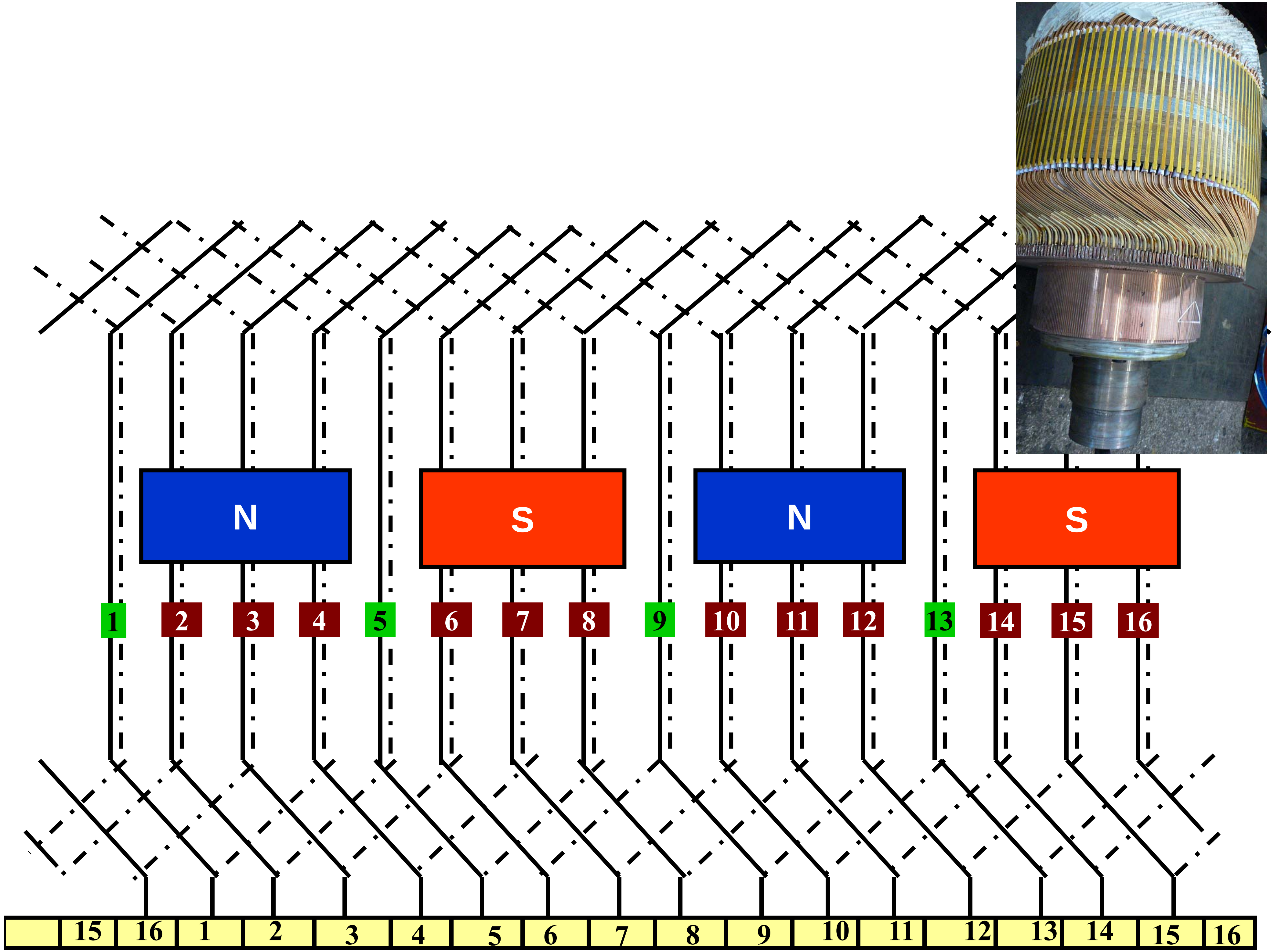
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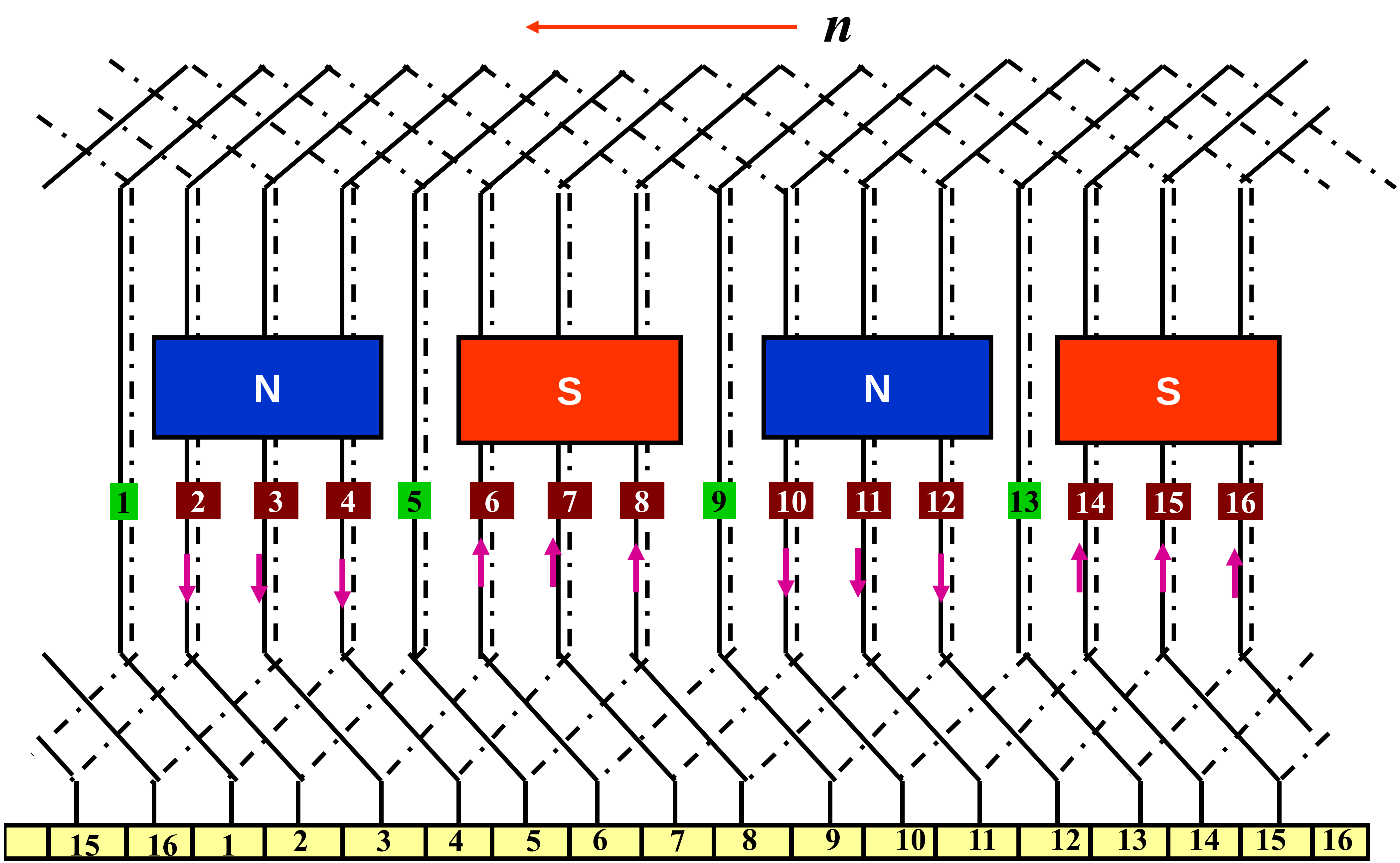

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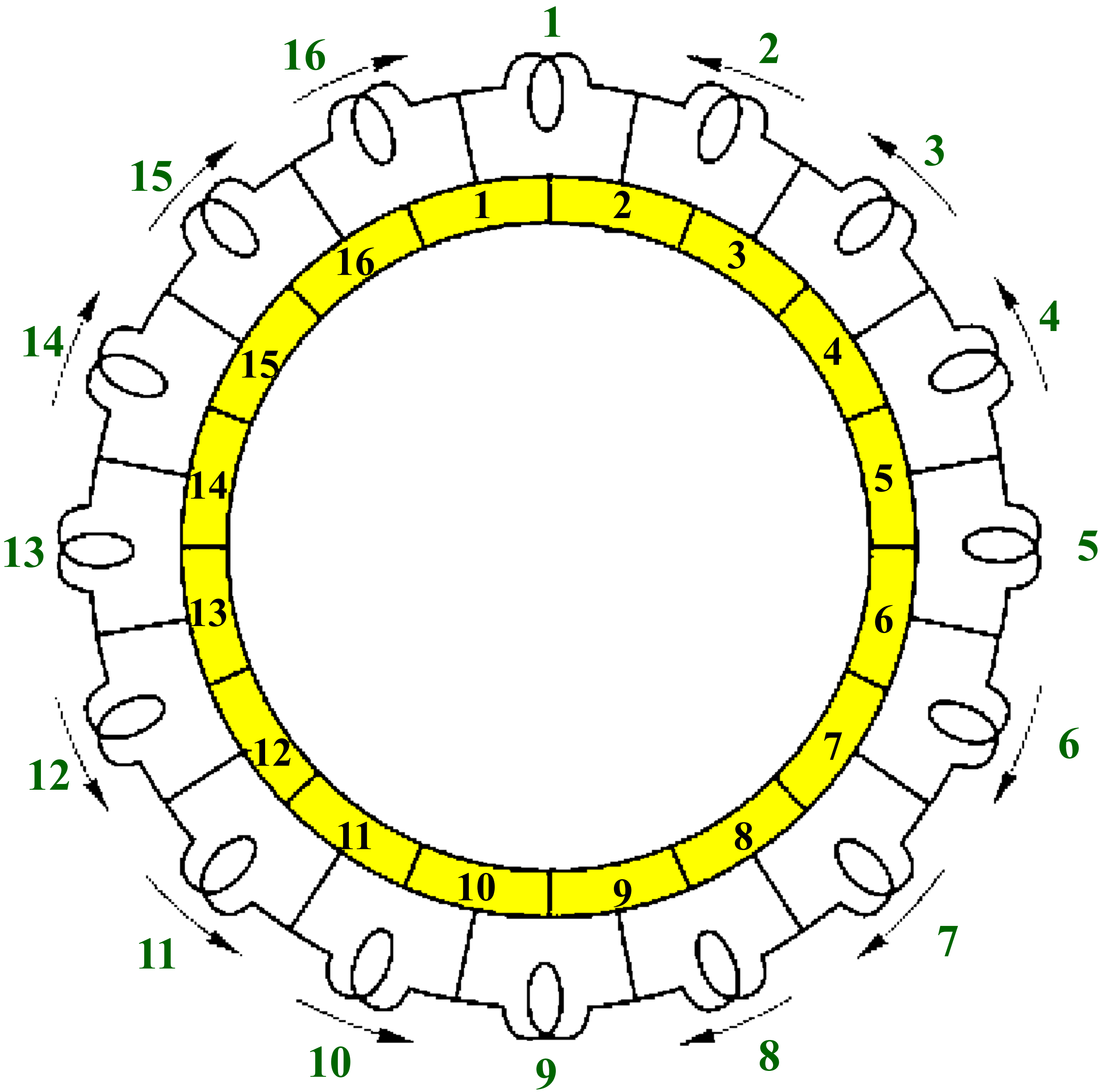

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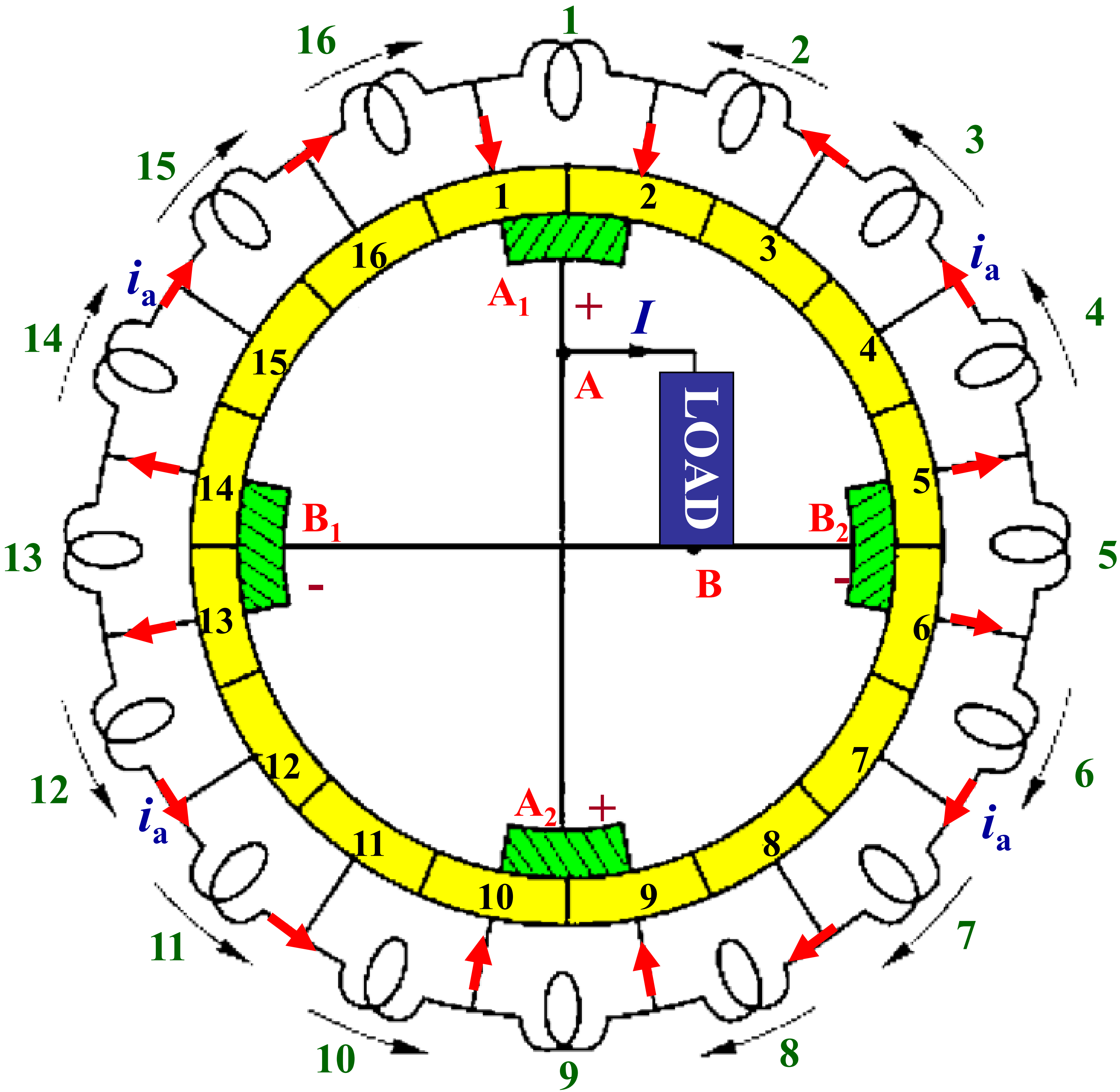
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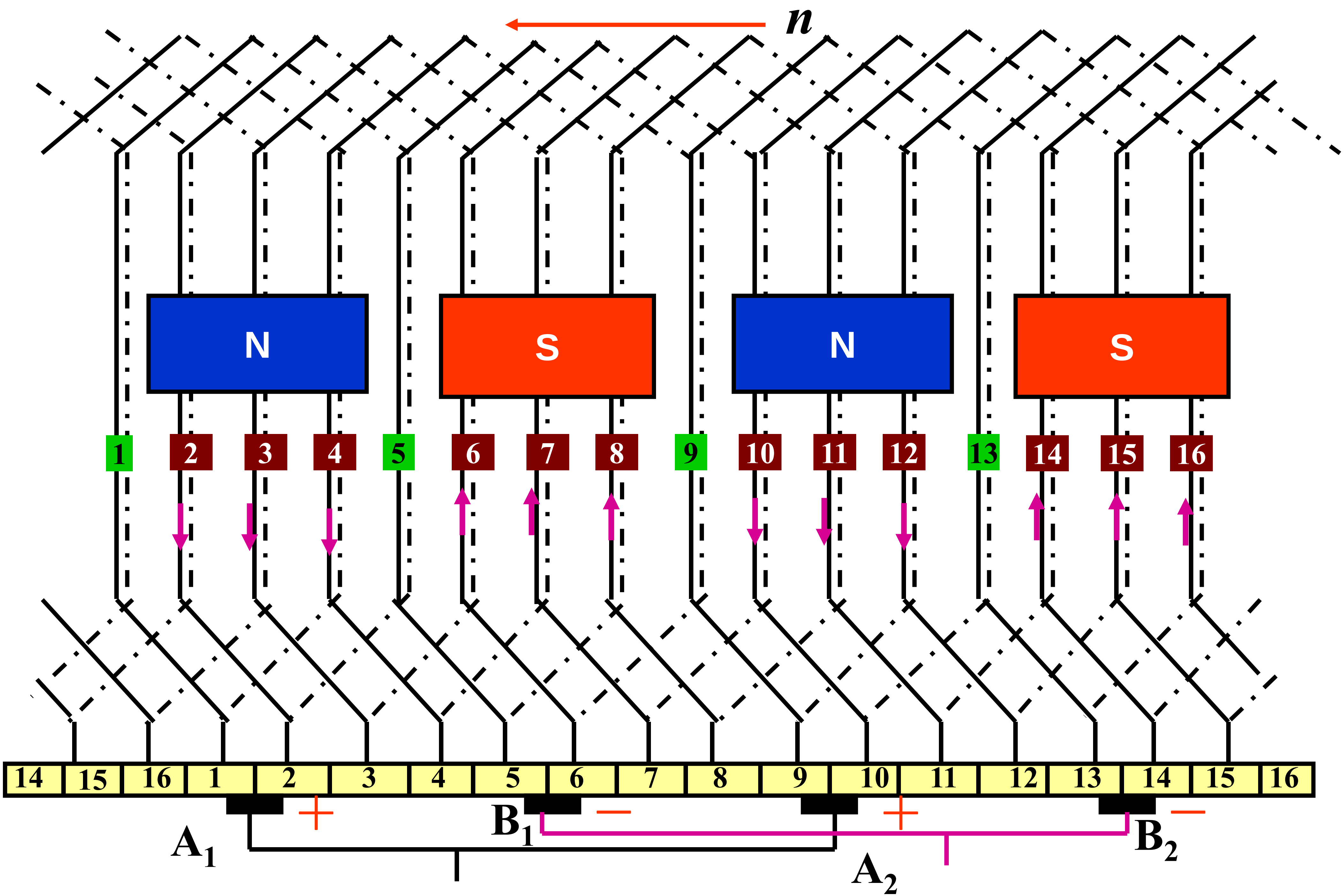

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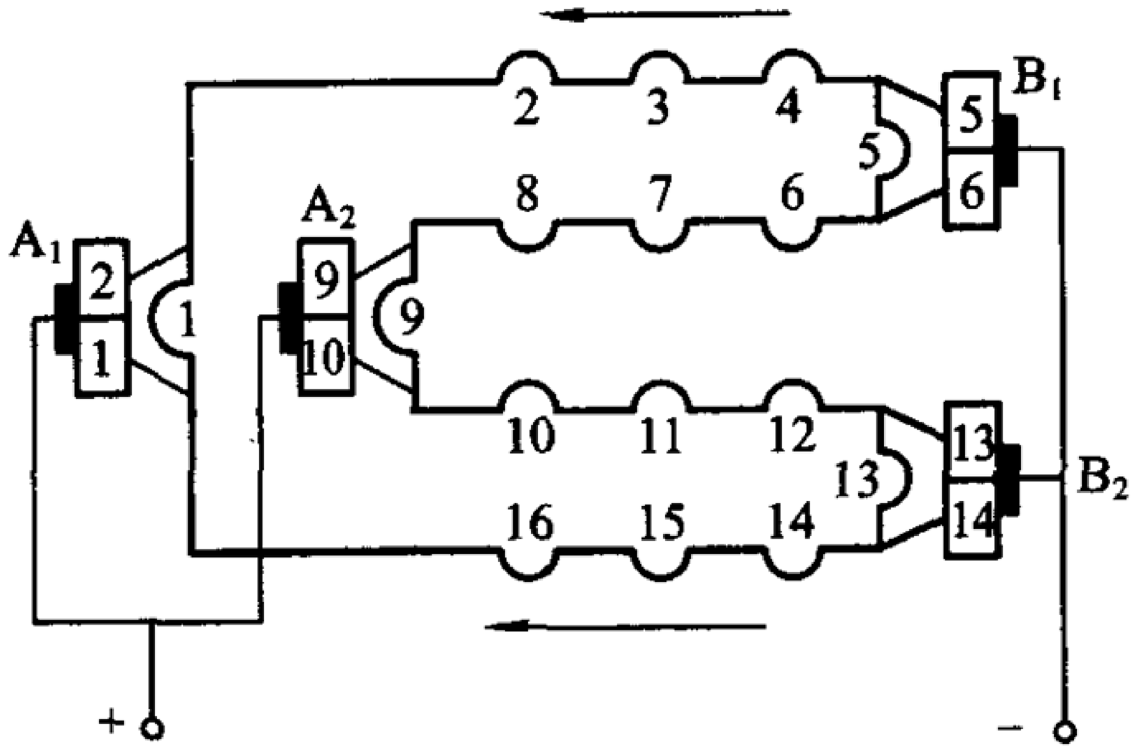


1. Armature winding is closed by many same coils.
2. One coil is connected to two commutator segments, and one commutator segment is connected to two coils.
3. Branch numbers are equal to brush numbers, which are equal to pole

Features:

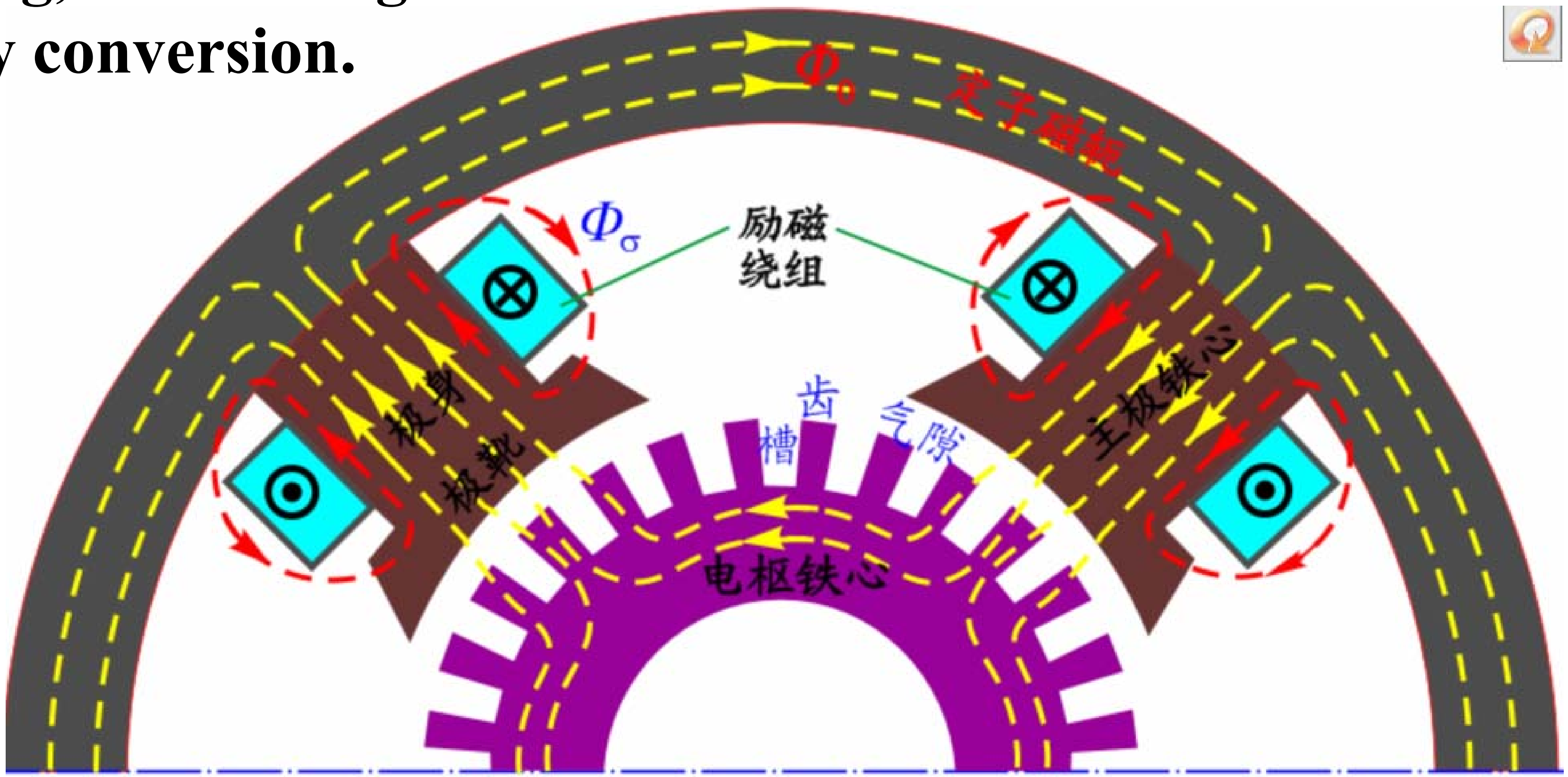
1. The EMF in each coil is alternative.
2. The alternating current of coil can be "rectified" to pulsing direct current of branch by the mechanical interaction of commutator and brushes.
3. To reduce the influence of pulsing dc, the real armature winding are constituted by many coils.

3.3 Magnetic field with no loading

Magnetic Field at no-loadis built up only by the field current because the armature current is zero or ignorable.

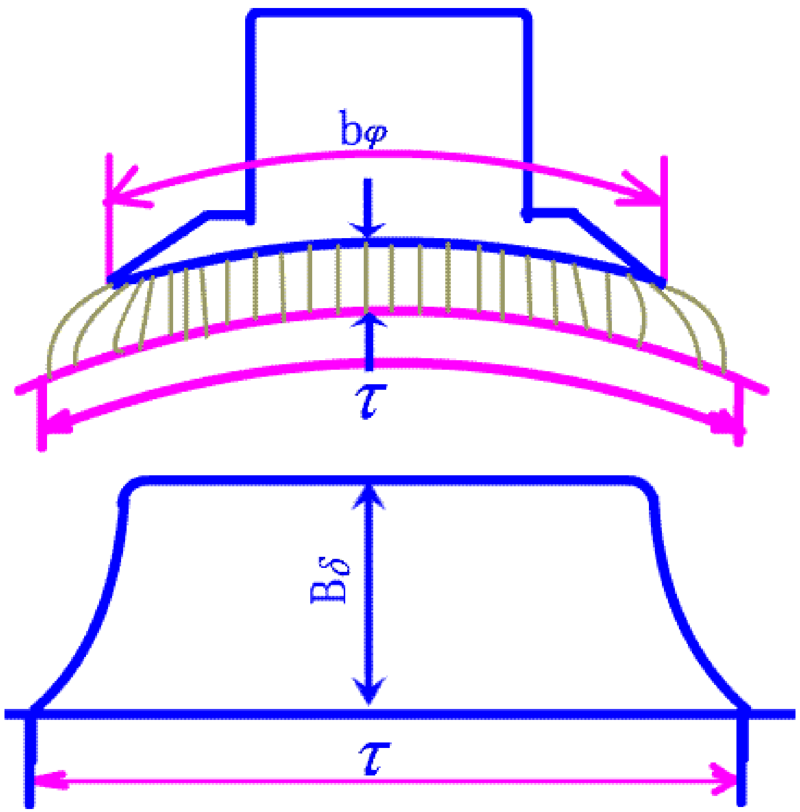
(a)Main flux
Φ_0 couples with both field winding and armature winding, is the bridge of energy conversion.

(b) Leakage flux $\Phi_{f\sigma}$ is no linkage with armature winding, no function of energy conversion



3.3 Magnetic field with no loading

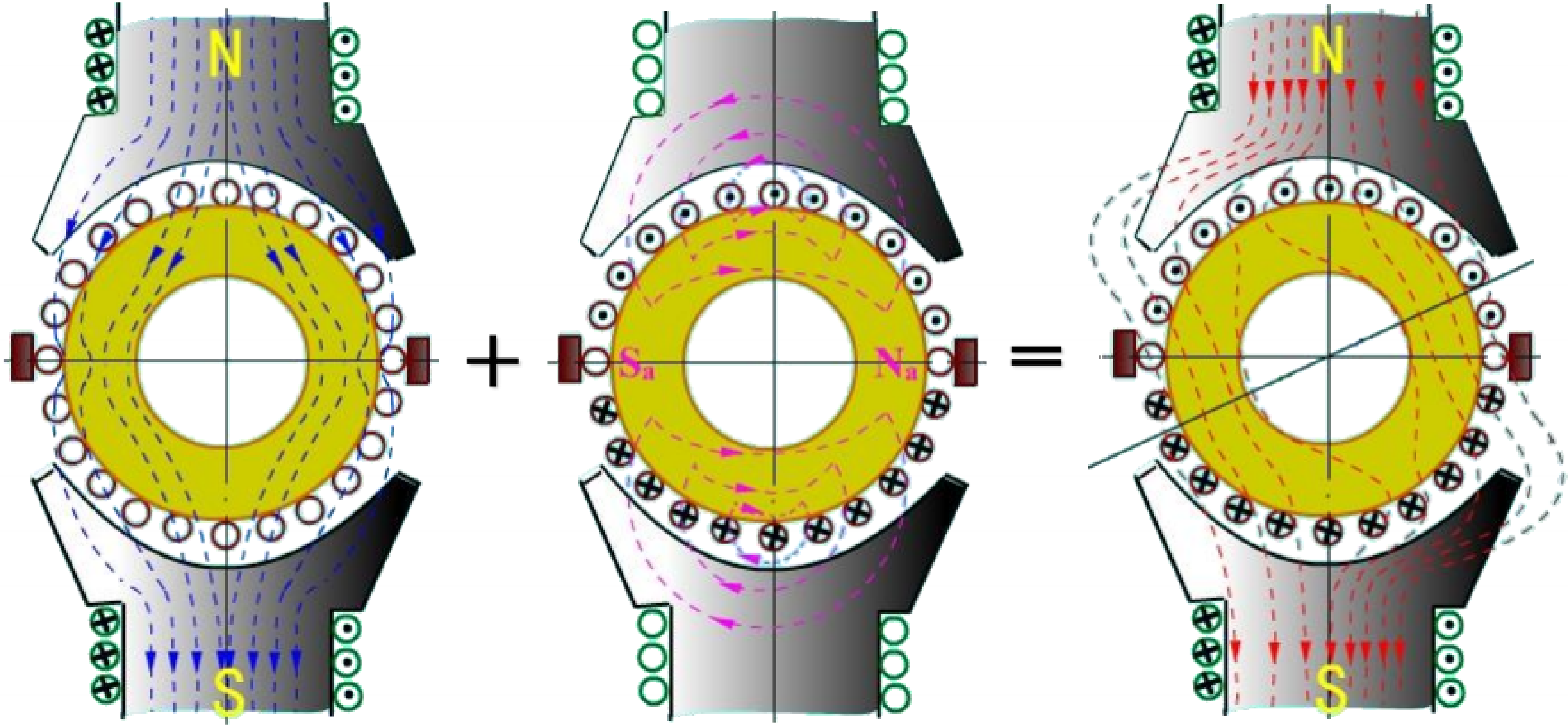
Flux density of Air gap



Flux density is decreased with the increase of length of Air gap, the waveform of the flux density is almost flat wave.

3.3 Magnetic field with loading

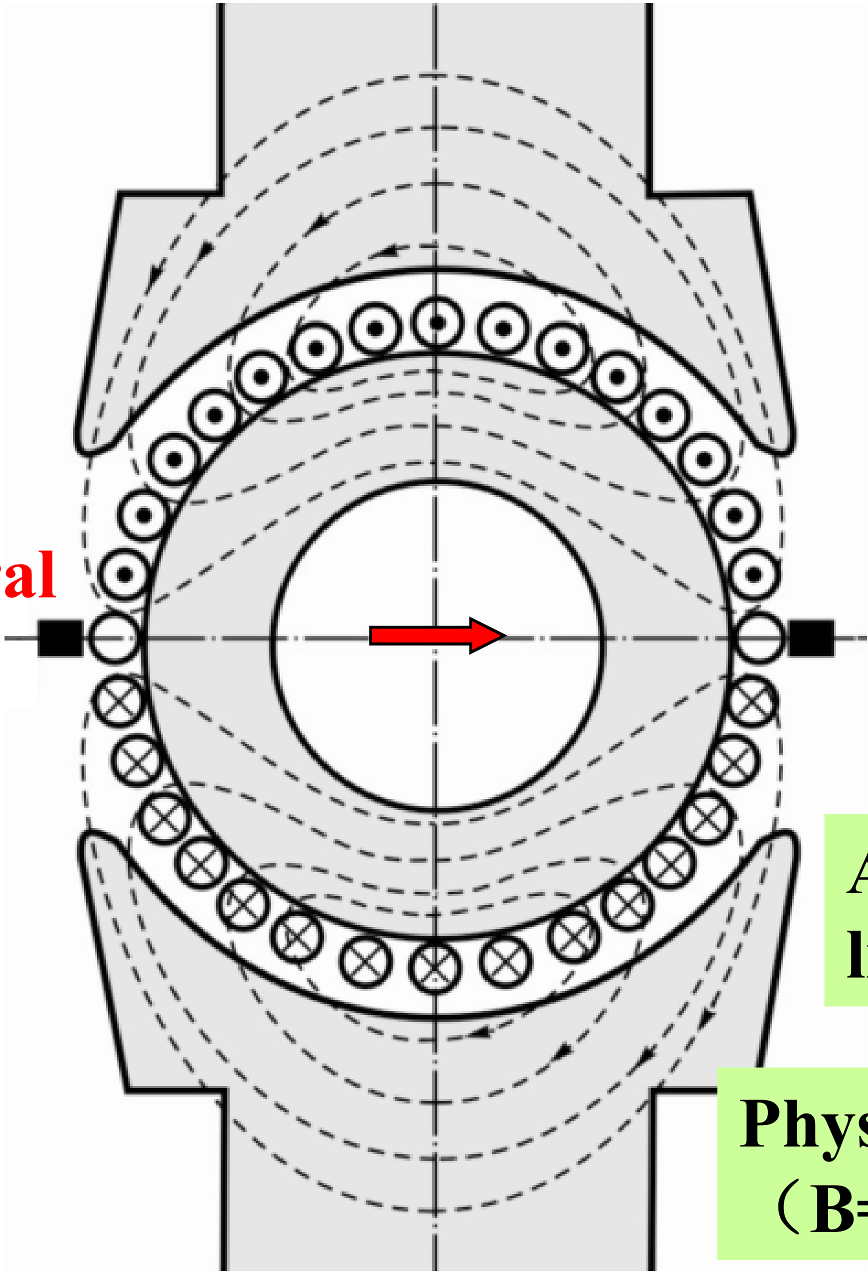
Solution



Magnetic field of excited current + Magnetic field of armature current = Integrated magnetic field

Armature MMF and Armature effect

Neutral line



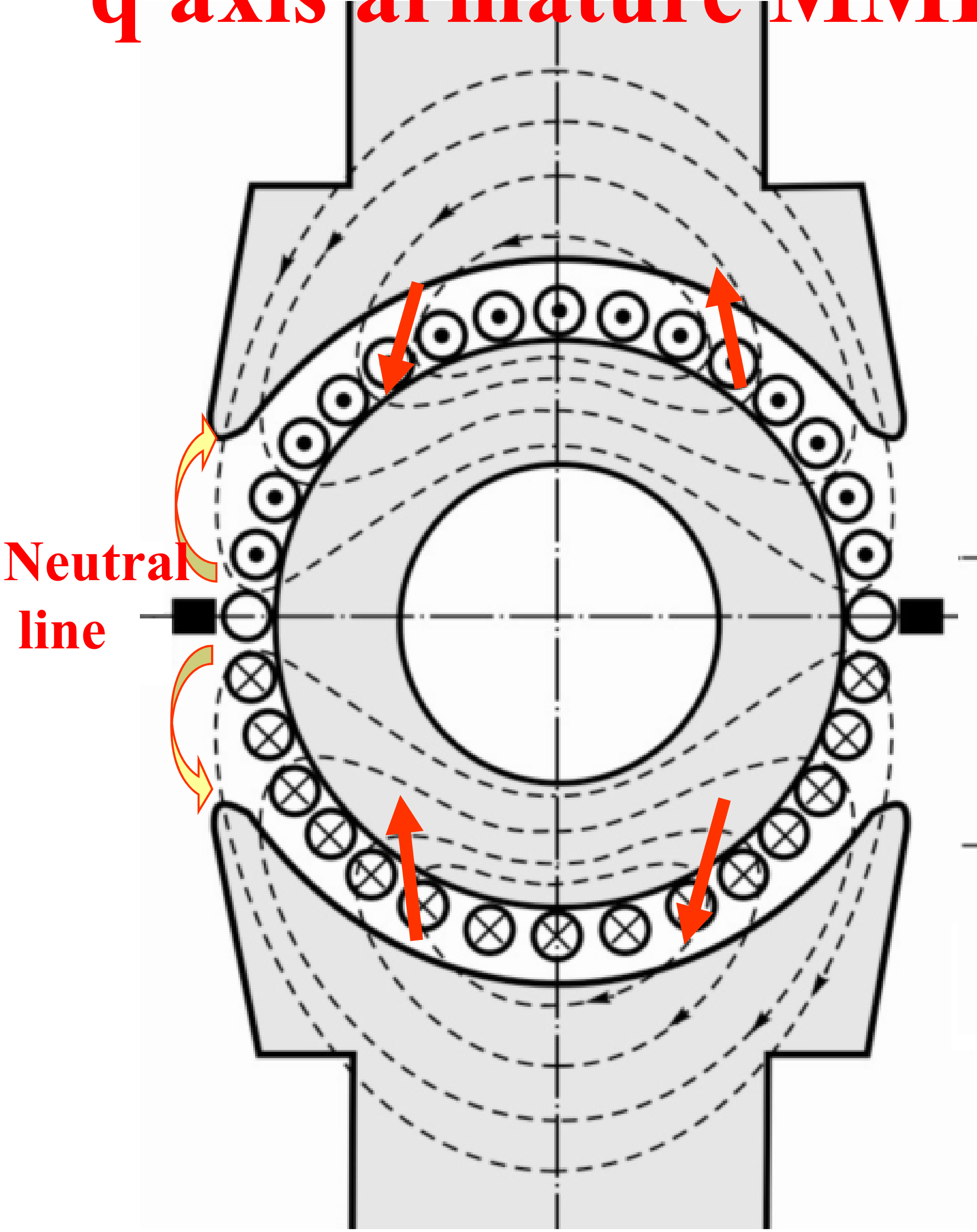
Direct axis (d axis)

Quadrature axis(q axis)

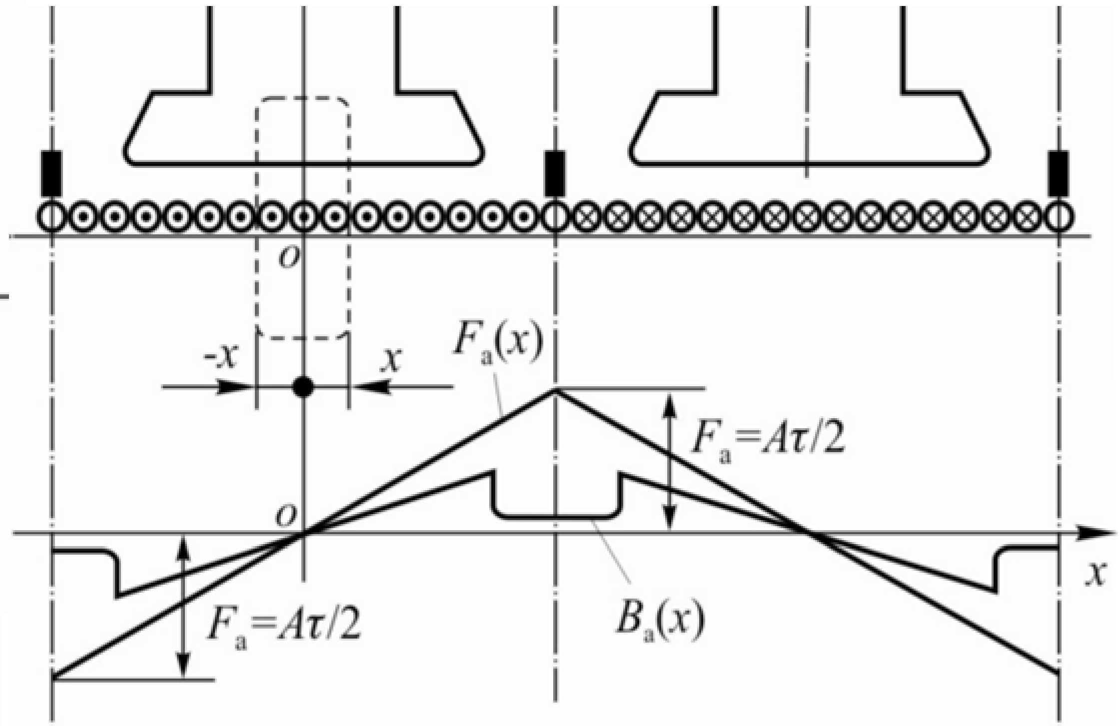
Armature geometric center line(q axis)

Physical geometric centerline （B=0）

q axis armature MMF and Armature effect

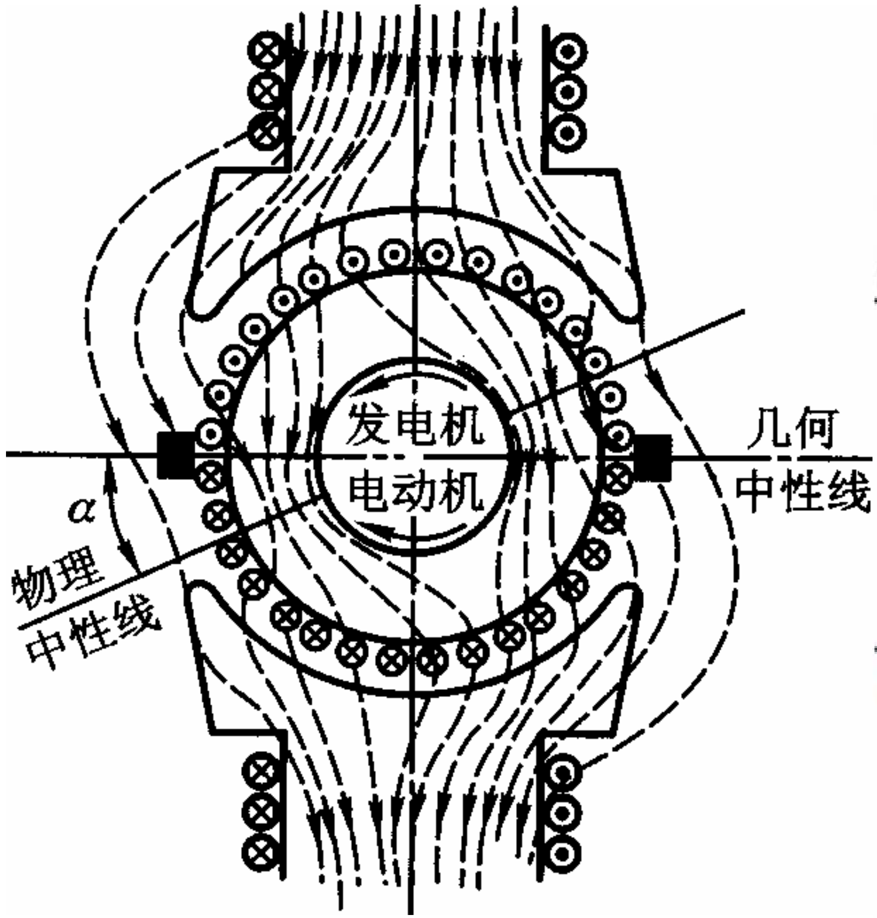


$$A = \frac{Z_a i_a}{\pi D}$$



Armature MMF

Armature Effect


发电机
电动机
几何
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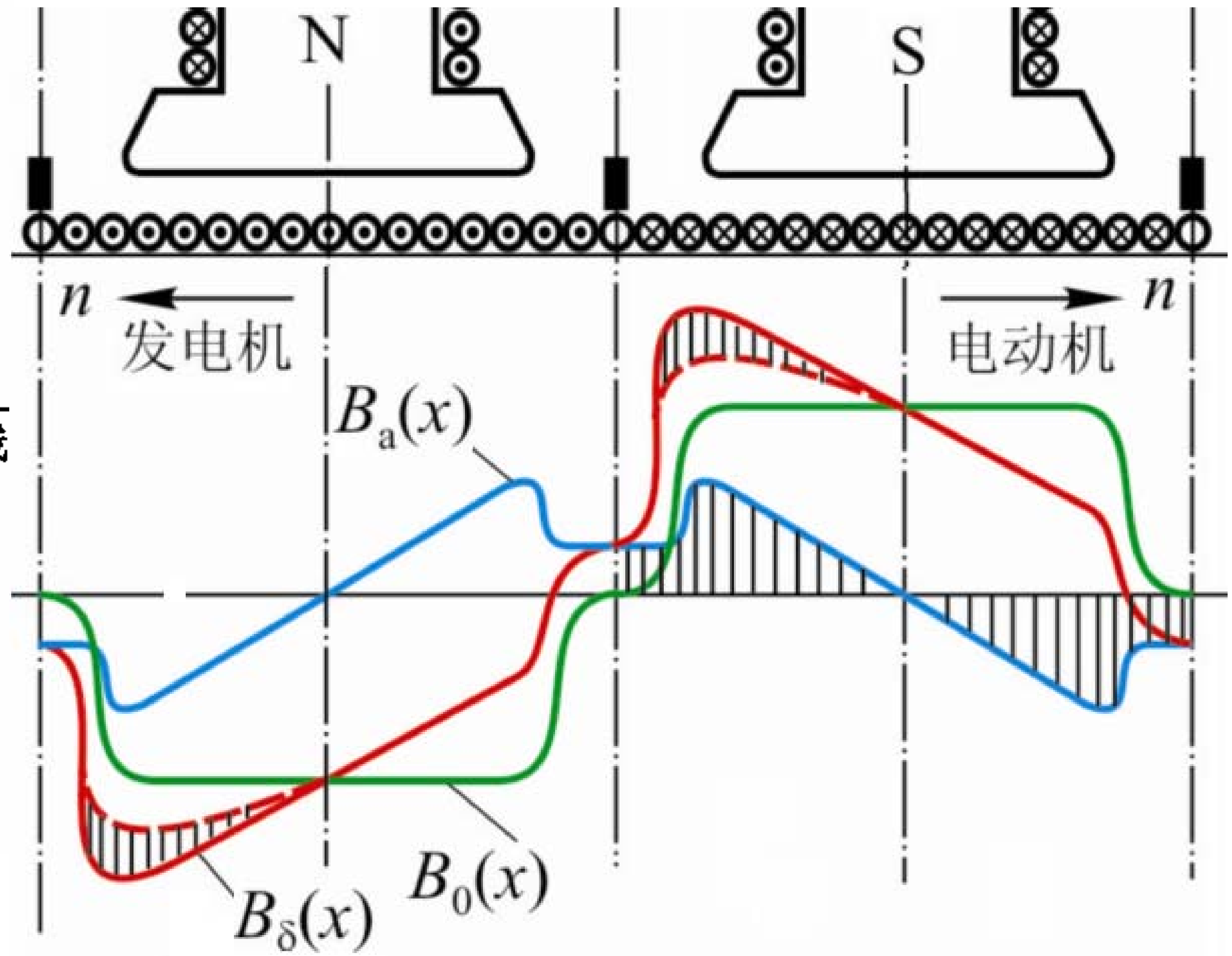
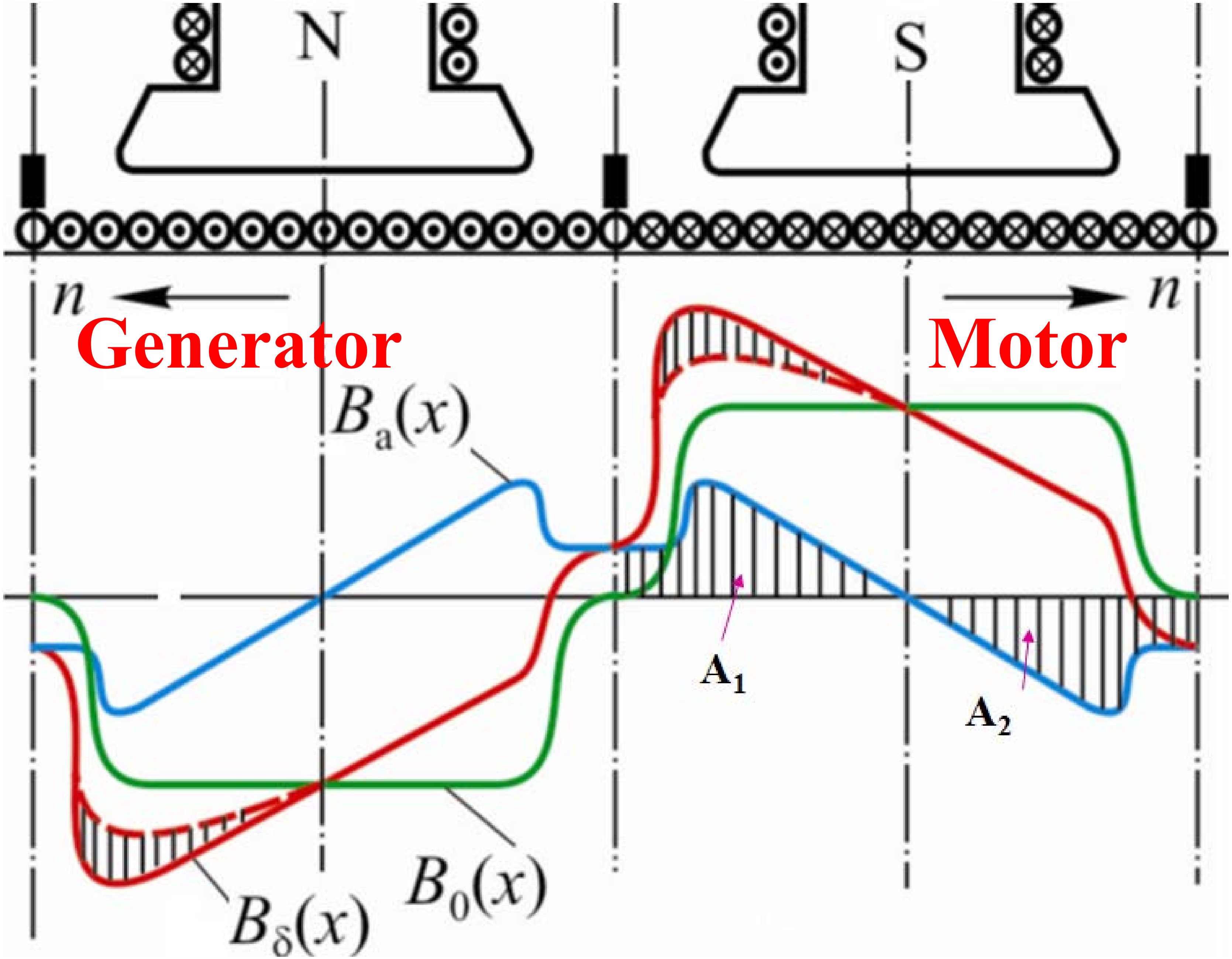
中性线


N
S
n
发电机
n
电动机
$B_a(x)$
$B_0(x)$
$B_\delta(x)$



N
S
n
n
Generator
Motor
$B_a(x)$
$B_0(x)$
$B_\delta(x)$
A_1
A_2

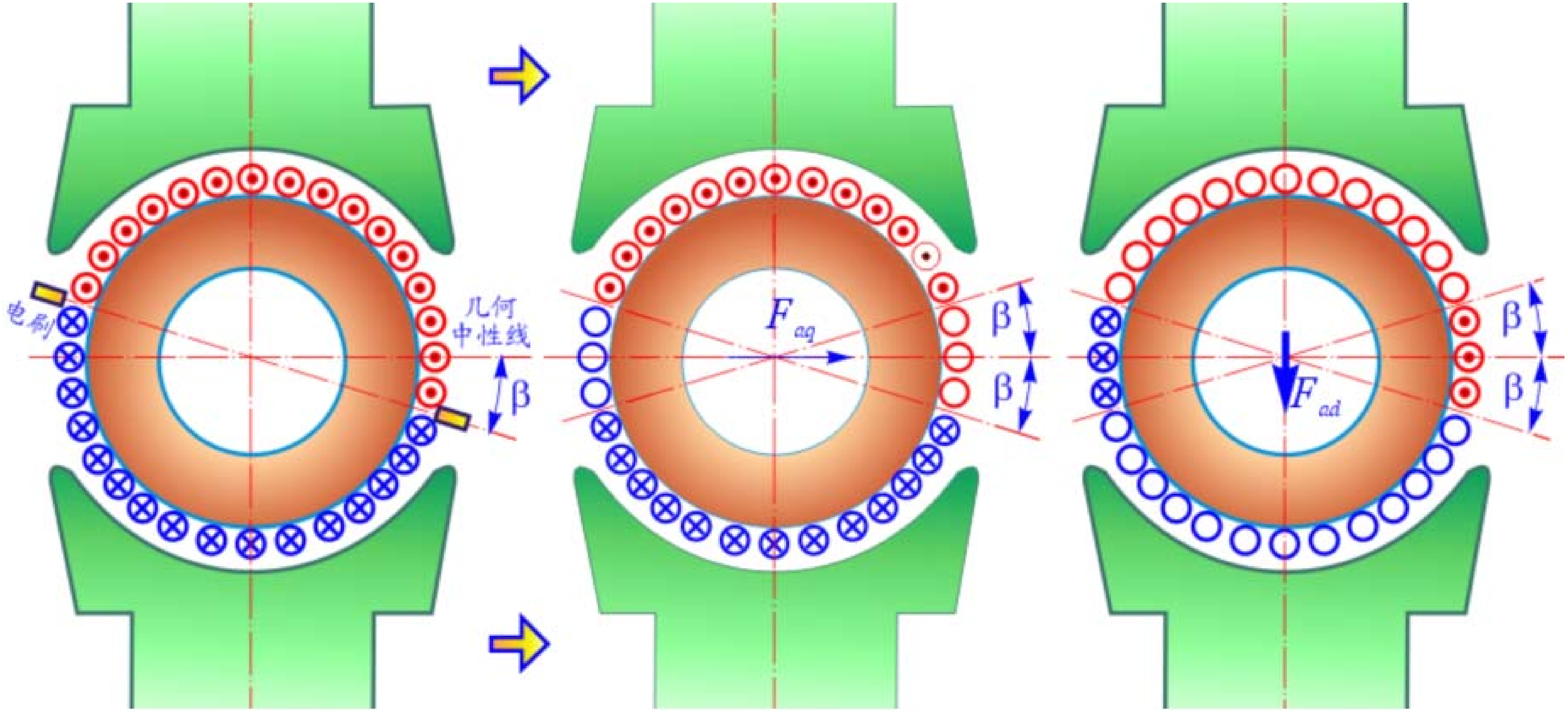
1.Quadrature axis armature reaction leads to the distortion of air gap magnetic field.

2.The physical centerline of generator shifts α angle along the direction of rotation, but the physical centerline of motor shifts α angle along the opposite direction of rotation.

3. If the core saturation is ignored, the effects of both magnetization and demagnetization of quadrature axis armature reaction are same, which lead to the magnetic flux per pole keeps constant from no-load to load operation. ($\Phi_\delta=\Phi_0$).

4.If the core saturation is considered, the demagnetization effect is larger than the magnetization effect about quadrature axis armature reaction, which leads to the magnetic flux per pole decrease from no-load to load operation. ($\Phi_\delta<\Phi_0$).

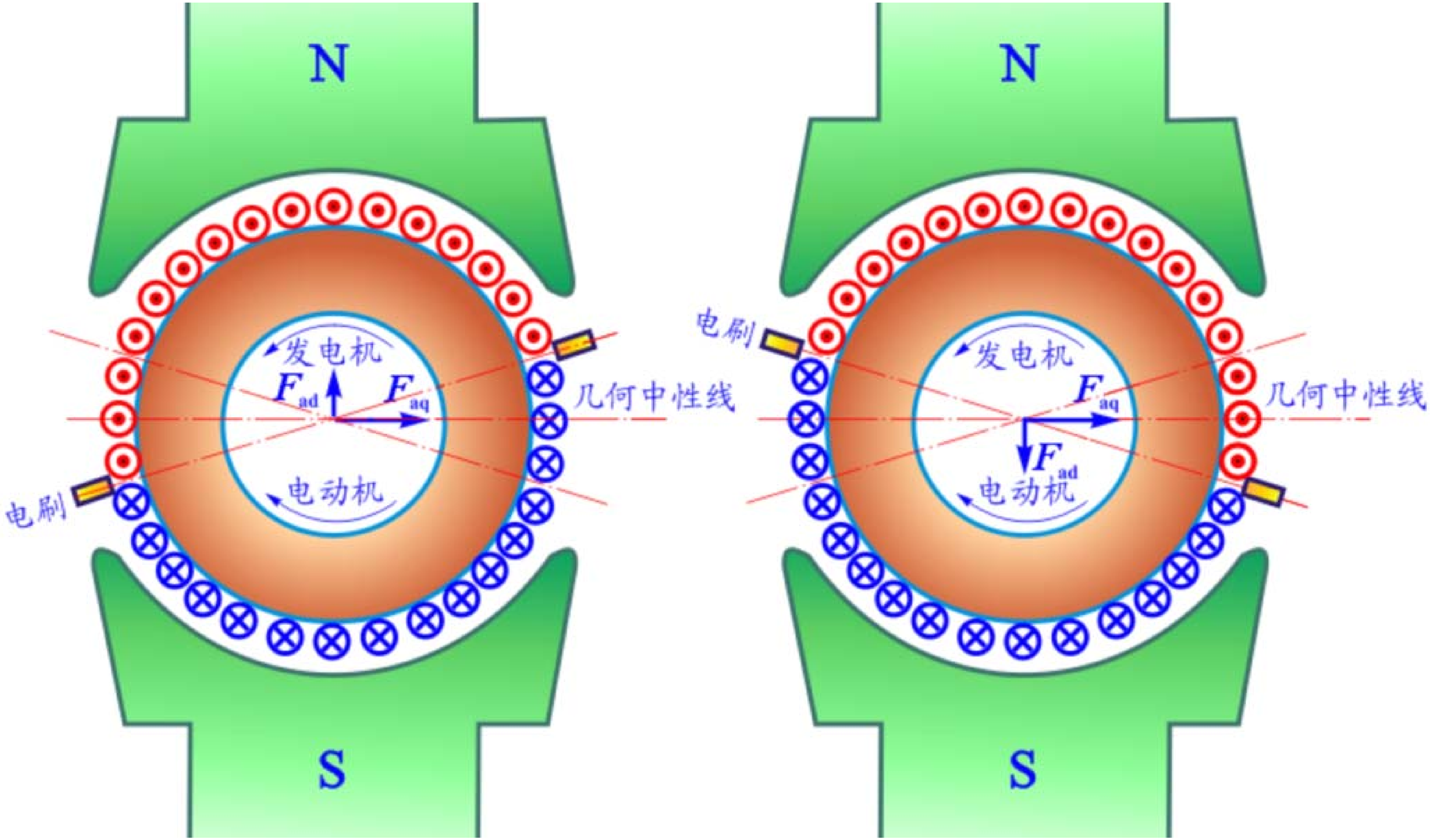
d q axis armature MMF and effect

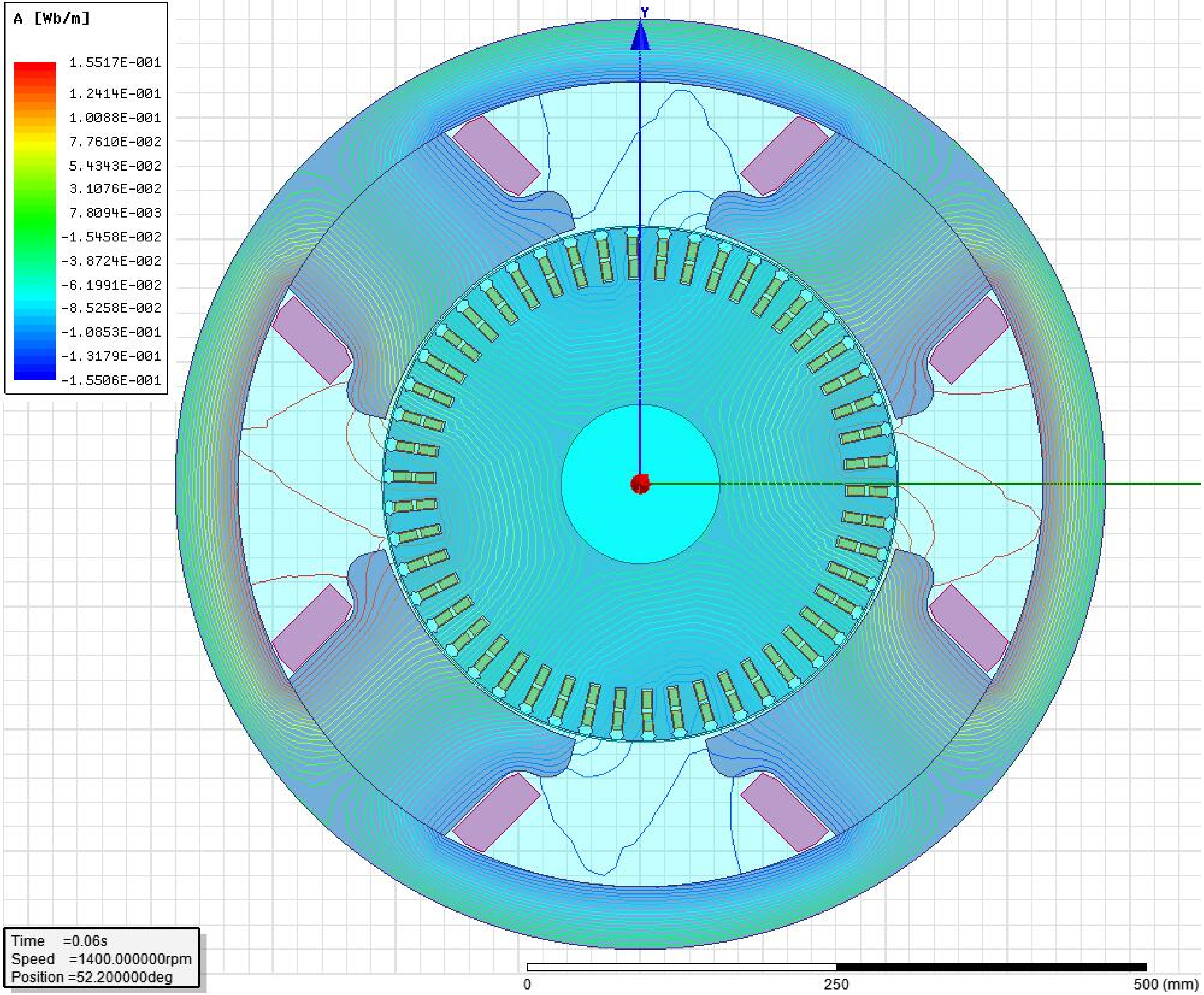


$$F_{\mathrm{aq}} = A\left(\frac{\tau}{2} - b_{\beta}\right)$$

$$F_{\mathrm{ad}} = Ab_{\beta}$$

d q axis armature MMF and effect




A [Wb/m]
1.5517E-001
1.2414E-001
1.0088E-001
7.7610E-002
5.4343E-002
3.1076E-002
7.8094E-003
-1.5458E-002
-3.8724E-002
-6.1991E-002
-8.5258E-002
-1.0853E-001
-1.3179E-001
-1.5506E-001
Y
Time =0.06s
Speed =1400.000000rpm
Position =52.200000deg
0
250
500 (mm)

3.4 EMF and Electromagnetic Torque

Armature EMF

Point 1: $e=B_\delta lv$

Point 2: Armature EMF E_a

= EMF between two brushes

= EMF of one branch

Point 3: Magnetic flux density B_δ in air gap is uneven, which can be replaced by the average magnetic flux density B_{av}.

$$E_a = \frac{pZ_a}{60a_=}\Phi n = C_e \Phi n$$

3.4 EMF and Electromagnetic Torque

(1) Torque per conductor : $T_c = f_e \times r = b_\delta l i_a \times D/2$

(2) Torque per pole: $T_p = \sum_{c=1}^{Z_a/2p} T_c$

(3) *Torque* : $T_e = 2p \times T_p$

$$\boxed{T_e = C_T \Phi I_a}$$

$$\boxed{C_e = \frac{pZ_a}{60a_=}}$$

Torque Coefficient ：

$$\boxed{C_T = \frac{pZ_a}{2\pi a_=}}$$

$$\boxed{C_e / Ct = \frac{\pi}{30}}$$

3.4 EMF and Electromagnetic Torque

$$\boxed{E_a = C_e n\Phi, \quad T_e = C_T \Phi I_a}$$

(1)Can be used in Generator and motor mode

(2)Main Flux Φ is base condition

(3)No-loading: $\Phi = \Phi_0$;

(4)Loading: $\Phi = \Phi_\delta$ Saturated: Less than Φ_0

Conclusion

(1)Main components in DC machines can be introduced.

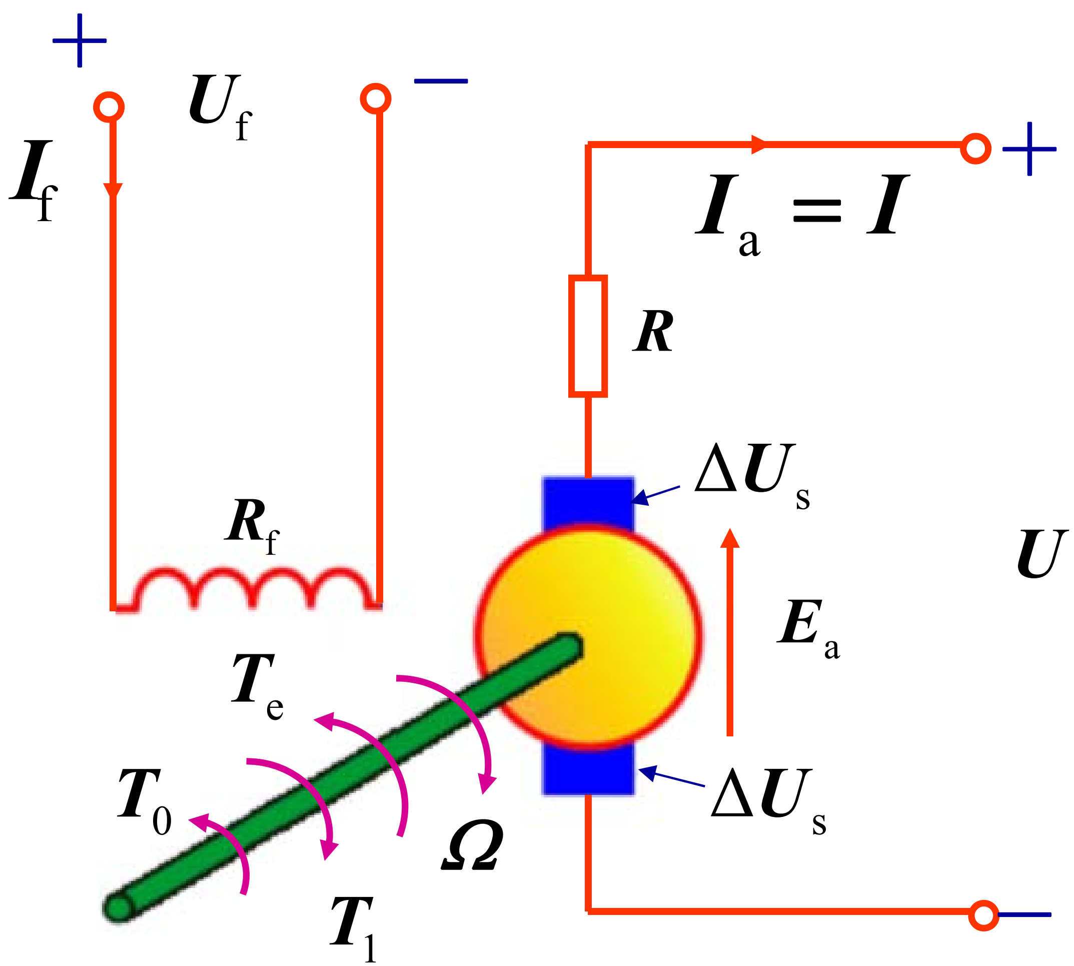
(2)AC EMF and current in the armature coil, and DC EMF can be got by the brush and commutator.

(3)The gap magnetic filed is from the excited current When DC machines with no-loading.

(4)The gap magnetic filed is changed due to the armature current When DC machines with loading, need to consider the effect of armature MMF.

(5)The EMF and Electromagnetic Torque can be got

3.5 Steady state equations of DC machines



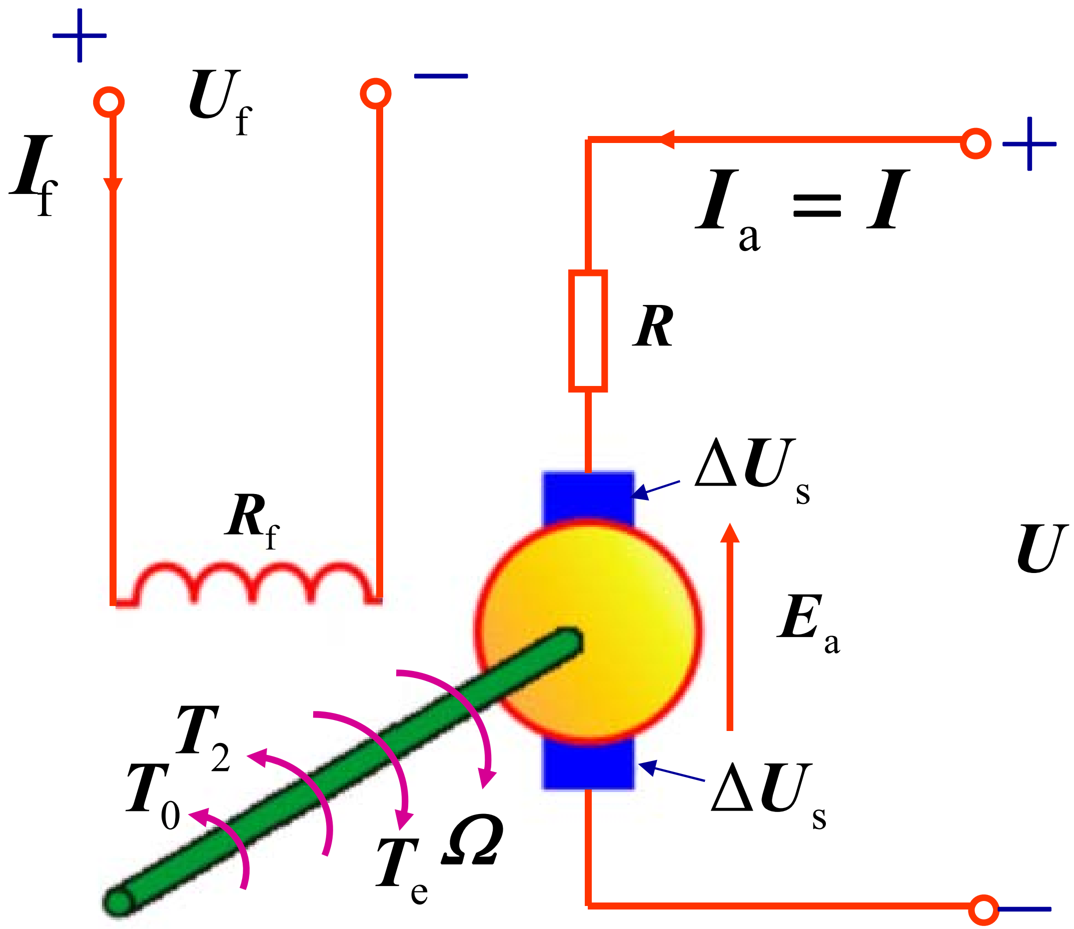
Generator mode

$$E_a = U + I_a R + 2\Delta U_s$$
$$= U + I_a R_a$$

$$R_a = R + \frac{2\Delta U_s}{I_a}$$

$$U_f = I_f R_f \qquad I_a = I$$

3.5 Steady state equations of DC machines



Motor mode

$$U = E_a + I_a R + 2\Delta U_s$$
$$= E_a + I_a R_a$$

$$R_a = R + \frac{2\Delta U_s}{I_a}$$

3.5 Steady state equations of DC machines

Generator mode

- ✓ $E_a = U + I_a R + 2\Delta U_s = U + I_a R_a$
- ✓ $I_a = I + I_f$ (shunt) , $I_a = I$ (separate/series)

Motor mode

R_a: Total resistance of armature loop

- ✓ $U = E_a + I_a R + 2\Delta U_s = E_a + I_a R_a$
- ✓ $I_a = I - I_f$ (shunt) , $I_a = I$ (separate/series)

Operational State :

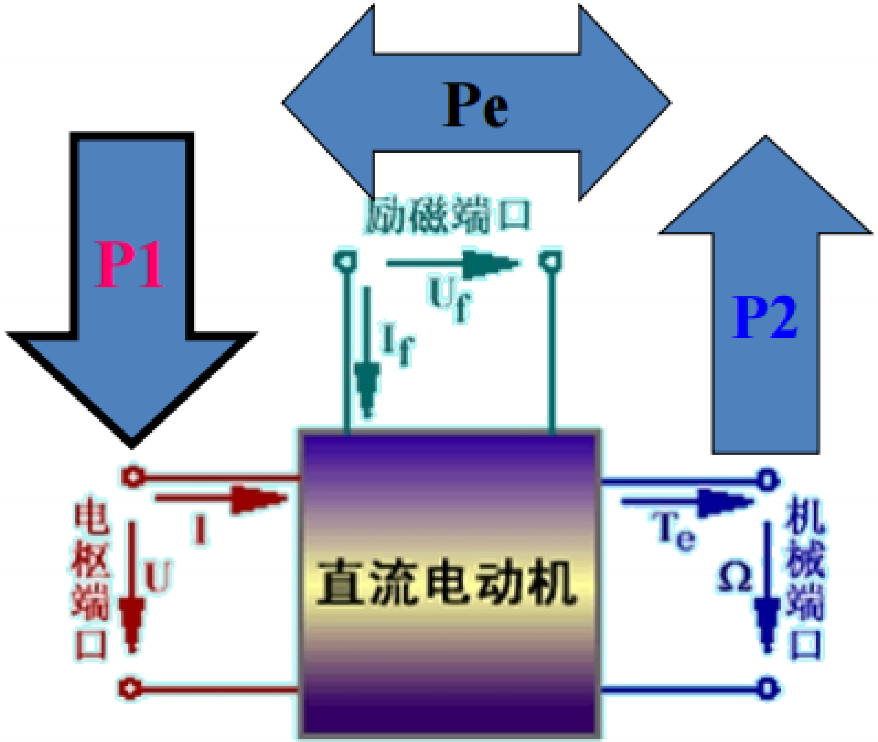
- ✓ Generator : $E_a > U$; Motor : $E_a < U$

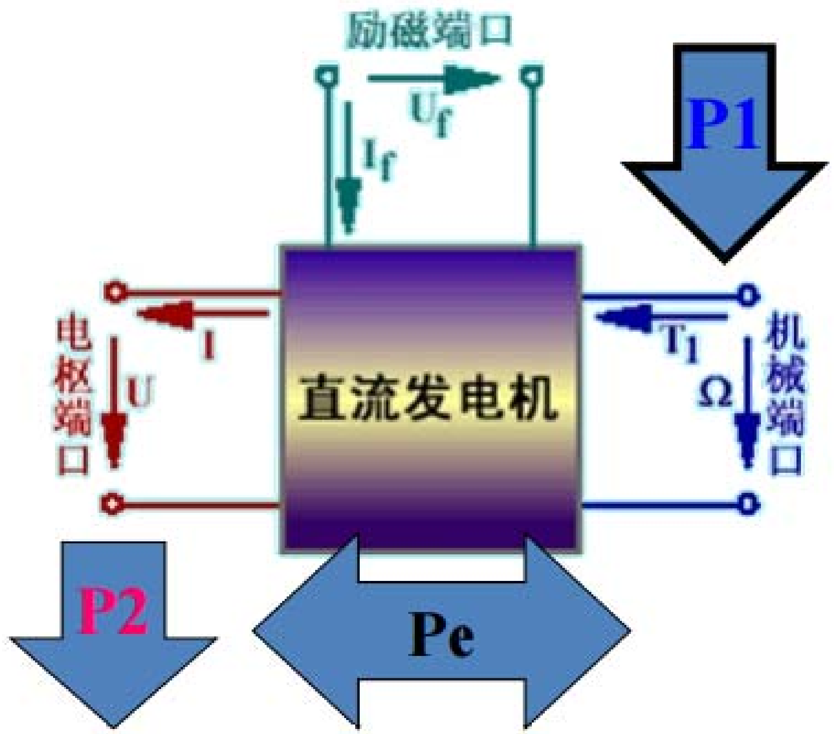
Electromagnetic Power

$$P_e = E_a I_a = T_e \Omega$$

Mechanical angular speed:

$$\Omega = 2\pi n/60 \quad \text{(rad/s)}$$





Power equations and power flow

Generator mode

$P_1 = P_e + p_\Omega + p_{Fe} + p_\Delta$

$P_e = P_2 + p_{Cua} + p_s + p_{Cuf}$

Copper loss: $p_{Cua} = I_a^2 R$

Brush loss: $p_s = 2\Delta U_s I_a$

Excitation loss: $p_{Cuf} = U_f I_f$

$T_1 = T_e + T_0$

$T_1 = P_1 / \Omega$

$T_e = P_e / \Omega$

$T_0 = (p_\Omega + p_{Fe} + p_\Delta) / \Omega$

$P_0 = p_\Omega + p_{Fe} + p_\Delta$ is called as **the rotational losses**.

Power equations and power flow

Motor mode

$$T_e = T_2 + T_0$$

$$T_e = P_e / \Omega$$

$$T_2 = P_2 / \Omega$$

$$T_0 = (p_\Omega + p_{Fe} + p_\Delta) / \Omega$$

$P_0 = p_\Omega + p_{Fe} + p_\Delta$ **is called as the rotational losses.**

$$P_1 = P_e + p_{Cua} + p_s + p_{Cuf}$$

$$P_e = P_2 + p_\Omega + p_{Fe} + p_\Delta$$

Copper loss: $p_{Cua} = I_a^2 R$

Brush loss: $p_s = 2\Delta U_s I_a$

Excitation loss: $p_{Cuf} = U_f I_f$

3.6 Performances of DC generator

1. No-loading

$n = n_N, \quad I = 0: \quad U_0 = f(I_f)$

2. External characteristic (V-A)

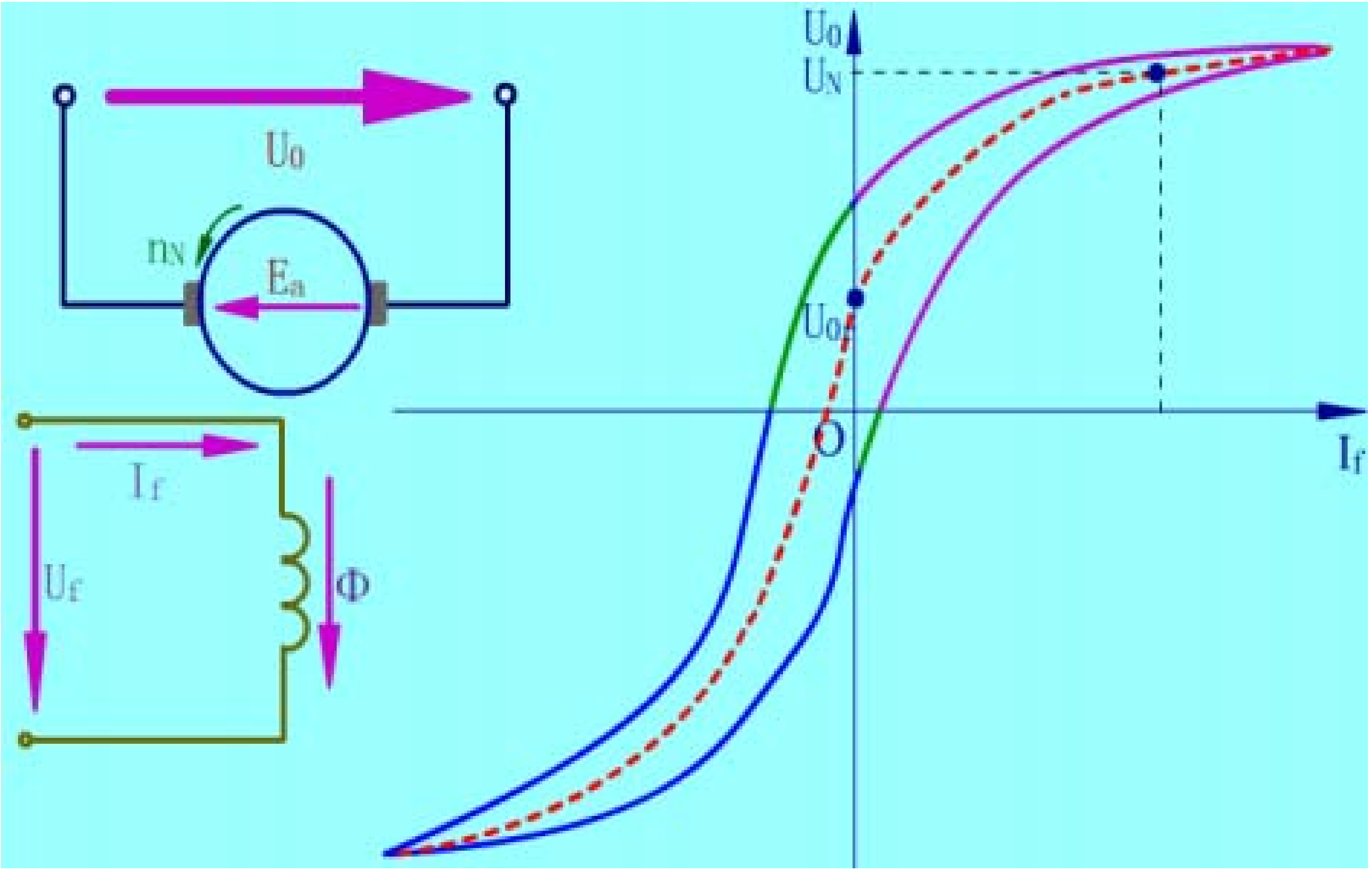
$n = n_N, \quad I_f = C \;\text{ or }\; R_f = C: \quad U = f(I)$

3. Regulation characteristic

$n = n_N, \quad U = U_N: \quad I_f = f(I)$

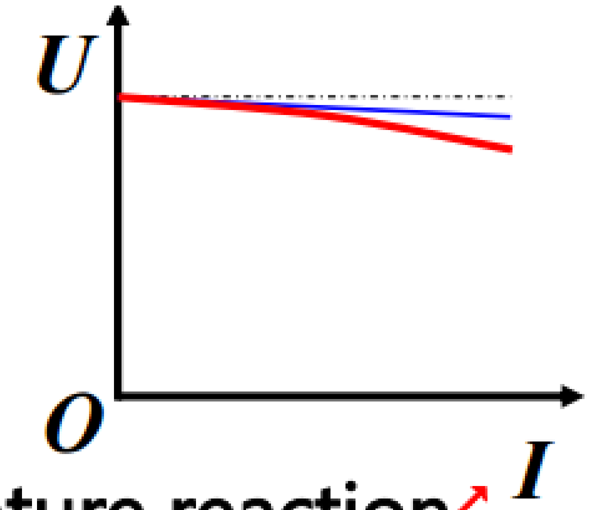
Dependent on the different Excited types of DC machines

No-loading of separately DC generator



External performances-Separate excitation

$n = n_N$, $I_f = C$: $U = f(I)$



$U = E_a - I_a R_a = C_e n_N \Phi - I_a R_a$

(1) $I\nearrow \rightarrow I_a R_a \nearrow \rightarrow U\searrow$

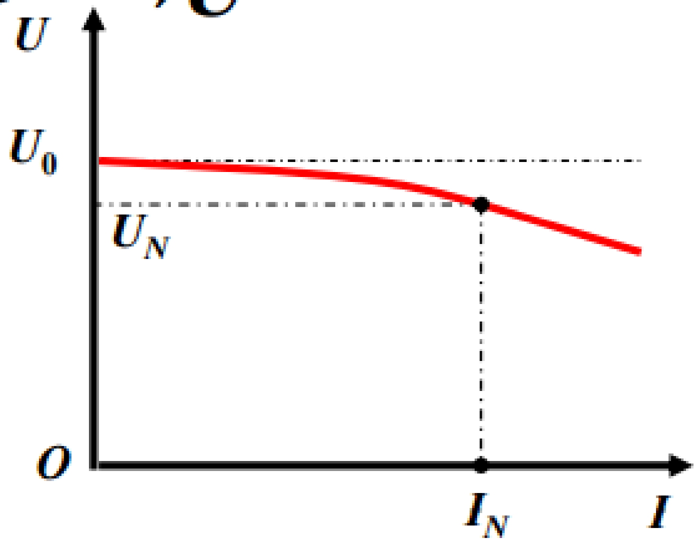
(2) $I\nearrow \rightarrow I_a\nearrow \rightarrow F_a\nearrow \rightarrow$ Armature reaction$\nearrow$

$\rightarrow$de-magnetic effect $\Phi\searrow \rightarrow U\searrow$

rate of change for the voltage

$$\boxed{\Delta u_N = \frac{U_0 - U_N}{U_N} \times 100\%}$$

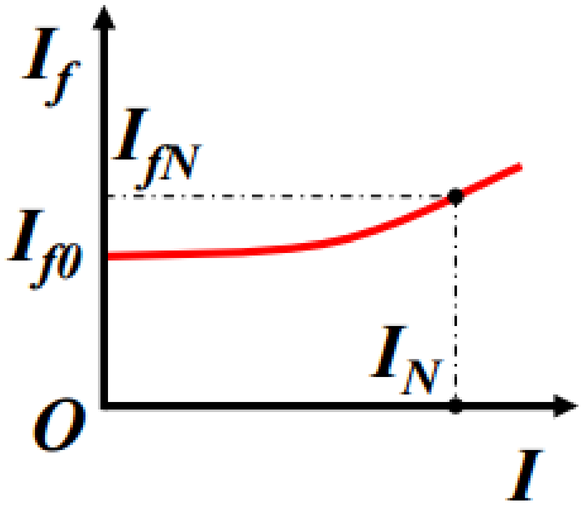
$$\Delta u_N \approx 5\%\sim 10\%$$



Regulation performances performances-Separate excitation

$n = n_N$, $U = U_N$: $I_f = f(I)$

$U = E_a - I_a R_a = C_e n_N \Phi - I_a R_a$



Keep $U = U_N$,

$I_f \nearrow \rightarrow \Phi \nearrow \rightarrow E_a \nearrow$

External performances of shunt Excitation

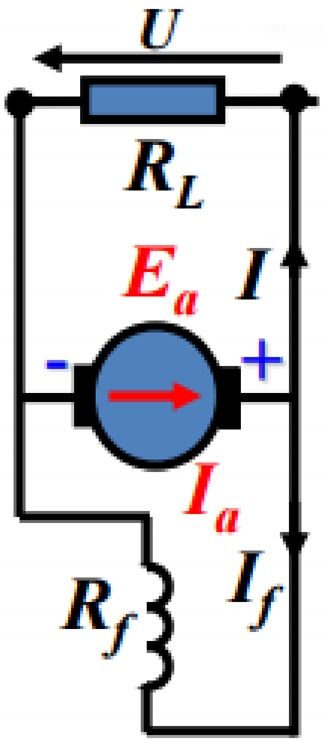
$n=n_N$, $R_f=C$: $U=f(I)$

$U=E_a-I_aR_a=C_en_N\Phi-I_aR_a$

Comparing with separately DC generator

$U\searrow \rightarrow I_f\searrow \rightarrow \Phi\searrow \rightarrow E_a\searrow \rightarrow U\searrow\searrow$

Shunt DC generator: $\Delta u_N \approx 20\%$

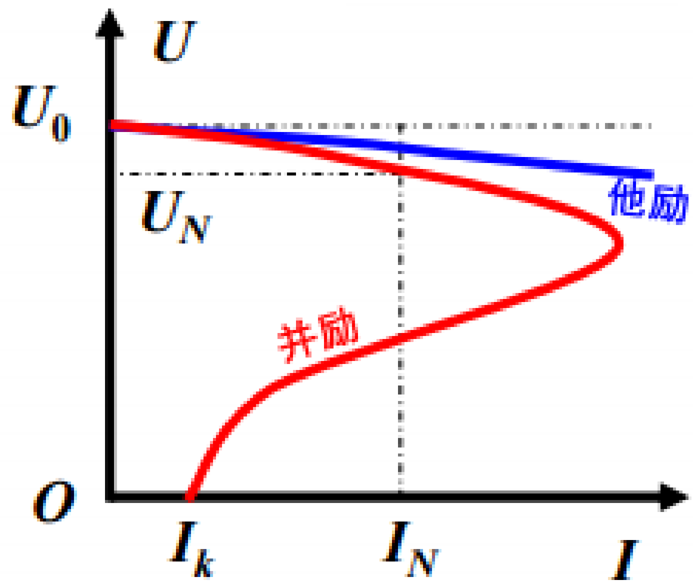


Separately DC generator: $\Delta u_N \approx 5\% \sim 10\%$

For the Shunt DC generator

How to get the no-load voltage?

Why the short-circuit current is small?



Example: The rated values of a shunt DC generator are known as P_N=107.8kW, U_N=440V, I_{fN}=5A, R_a=0.078Ω, T_1=2250N.m, n_N=500 r/min. When the armature reaction is ignored, find: Ω_N, I_{aN},E_{aN}, P_{eN}, T_{eN}, T_0, P_1 and η_N.

Solution:

$$\Omega_N=2\pi n_N/ 60= 2\pi*500/ 60=52.36(\text{rad/ s})$$

$$I_{aN}=I_N+I_{fN}=P_N/U_N+I_{fN}=107.8*10^3/440+5=250(\text{A})$$

$$E_{aN}=U_N+I_{aN}R_a=440+250*0.078=459.5(\text{V})$$

$$P_{eN}=E_{aN}/I_{aN}=459.5*250=114.88(\text{kW})$$

$$T_{eN}=P_{eN}/ \Omega_N=114.88*10^3/52.36=2194(\text{N.m})$$

$$T_0=T_1-T_{eN}=2250-2194=56(\text{N.m})$$

$$P_1=T_1\Omega_N=2250*52.36=117.8(\text{kW})$$

$$\eta_N=P_N/P_1=107.8/117.8=91.5\%$$

Discussion: When the rotating speed increases 20%, please analyze the changes of no-load voltage of a separate excitation and a shunt excitation DC generator respectively .

Separate Excitation

I_f=C→Φ=C.

$n\nearrow$20%→U_0=E_a=$C_e n\Phi\nearrow$20%

Shunt Excitation

I_f changes with U_0.

$n\nearrow$20%→$U_0\nearrow$20%→$I_f\nearrow$20%→$\Phi\nearrow$→U_0=$C_e n\Phi\nearrow$ more than 20%

3.7 Performances of DC Motor

1. Operational performances

Keep $U=U_N$, $I_f=I_{fN}(R_f=C)$

- Rotational speed : $n=f(P_2)$
- Electromagnetic torque : $T_e=f(P_2)$
- Efficiency : $\eta=f(P_2)$

2. Mechanical performances

- $n=f(T_e)$

Dependent on the different excited types of DC motor .

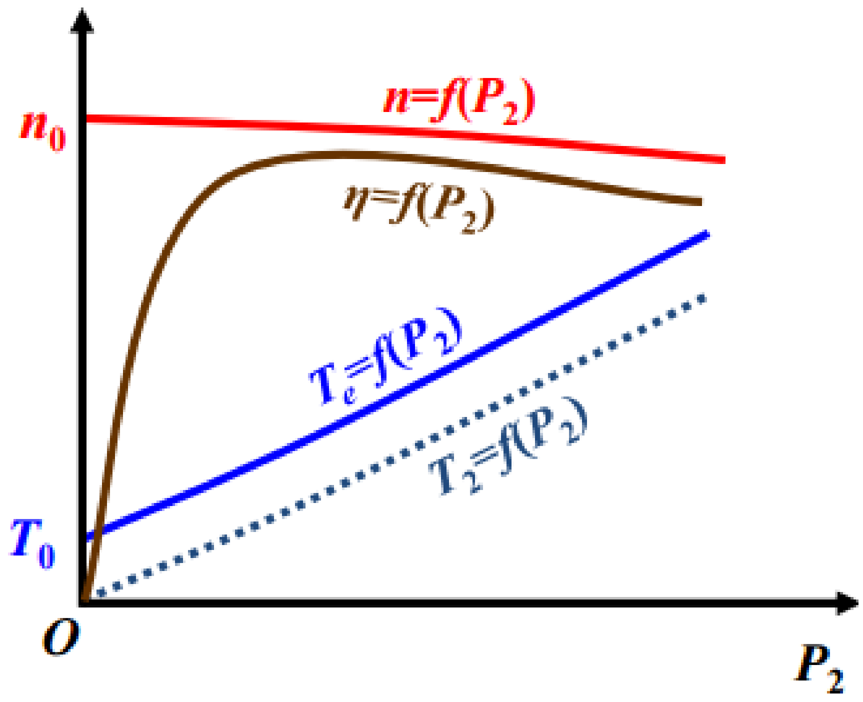
Operational performances of DC Motor

$U=U_N$, $I_f=I_{fN}(R_f=C)$--------$n, T_e, \eta=f(P_2)$

$$\boxed{n=\frac{E_a}{C_e\Phi}=\frac{U}{C_e\Phi}-\frac{R_a}{C_e\Phi}I_a}$$

$$\boxed{\Delta n=\frac{n_0-n_N}{n_N}\times 100\%}=(3\sim 8)\%$$

$$\boxed{T_e=T_0+T_2=T_0+\frac{P_2}{\Omega}}$$



Mechanical performances of DC Motor

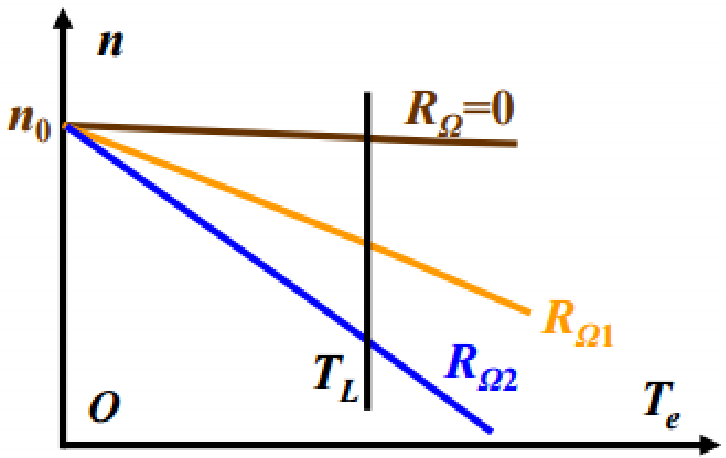
1. Separately /Shunt excited DC motor

$U = U_N$, $R_f = C$-------$n = f(T_e)$

$$\begin{cases} n = \dfrac{U}{C_e\Phi} - \dfrac{R_a}{C_e\Phi} I_a \\ T_e = C_T \Phi I_a \end{cases}$$

$$\boxed{n = \frac{U}{C_e\Phi} - \frac{R_a}{C_T C_e \Phi^2} T_e}$$

$$\boxed{n = n_0 - kT_e}$$



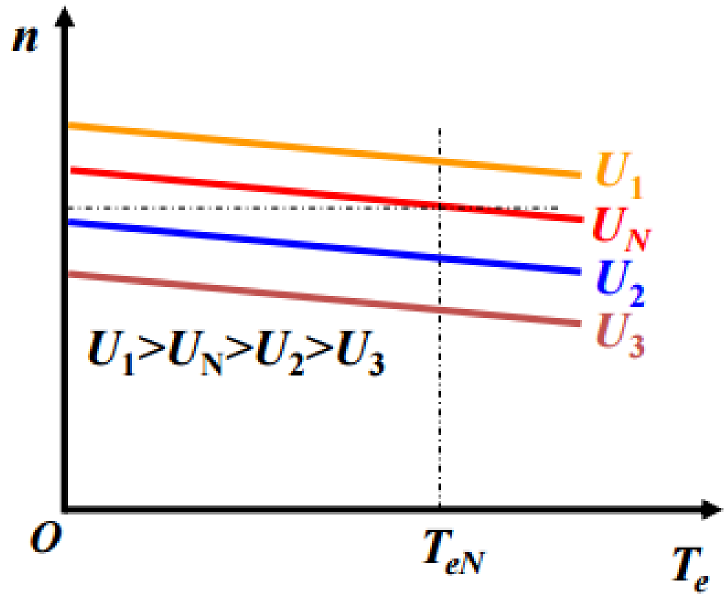
Mechanical performances of DC Motor

2. Separately excited DC motor

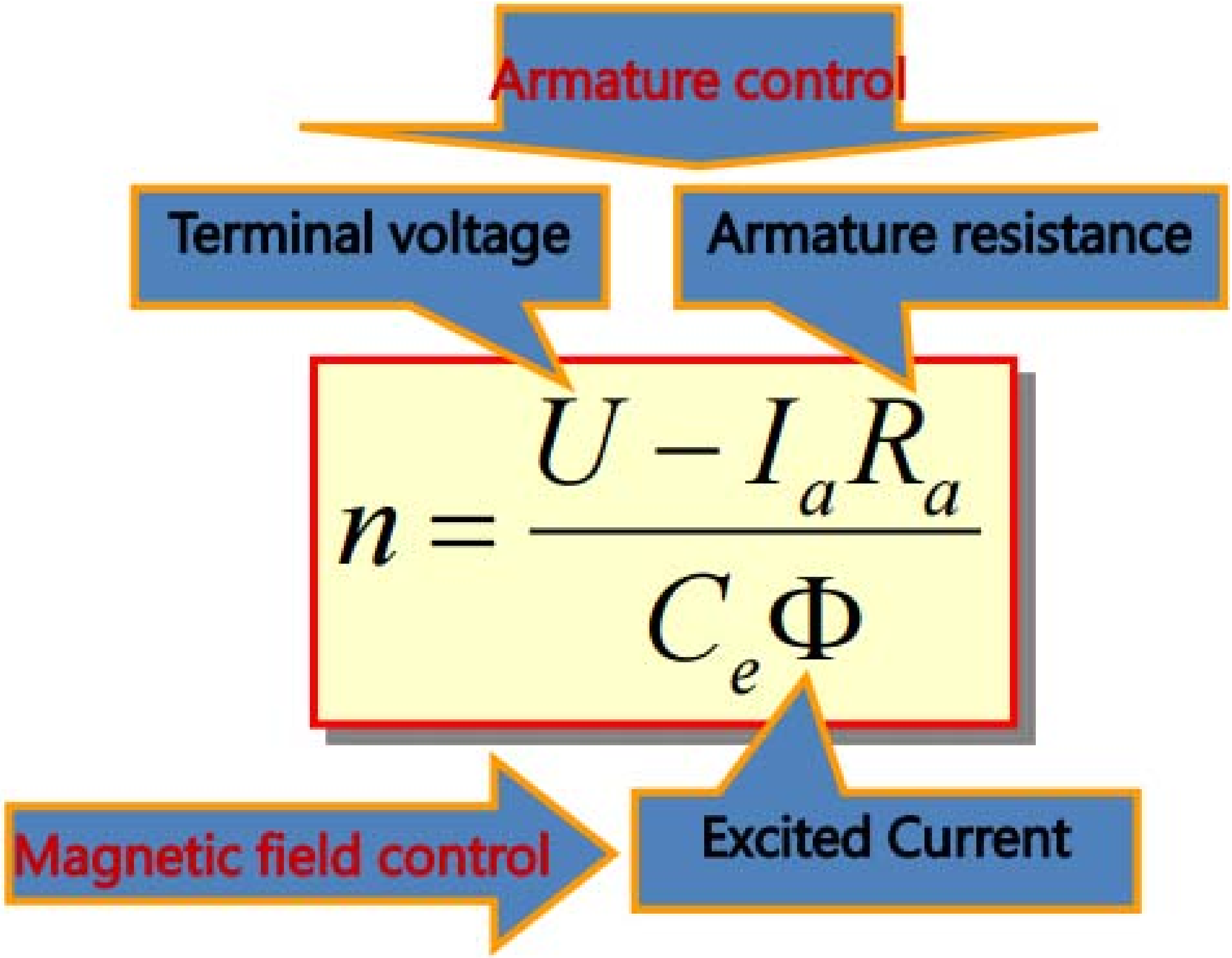
$I_f = C$ -------- $n = f(T_e)$

$$\boxed{n = \frac{U}{C_e\Phi} - \frac{R_a}{C_T C_e \Phi^2} T_e}$$

$$\boxed{n = n_0 - kT_e}$$



Regulation speed of DC Motor

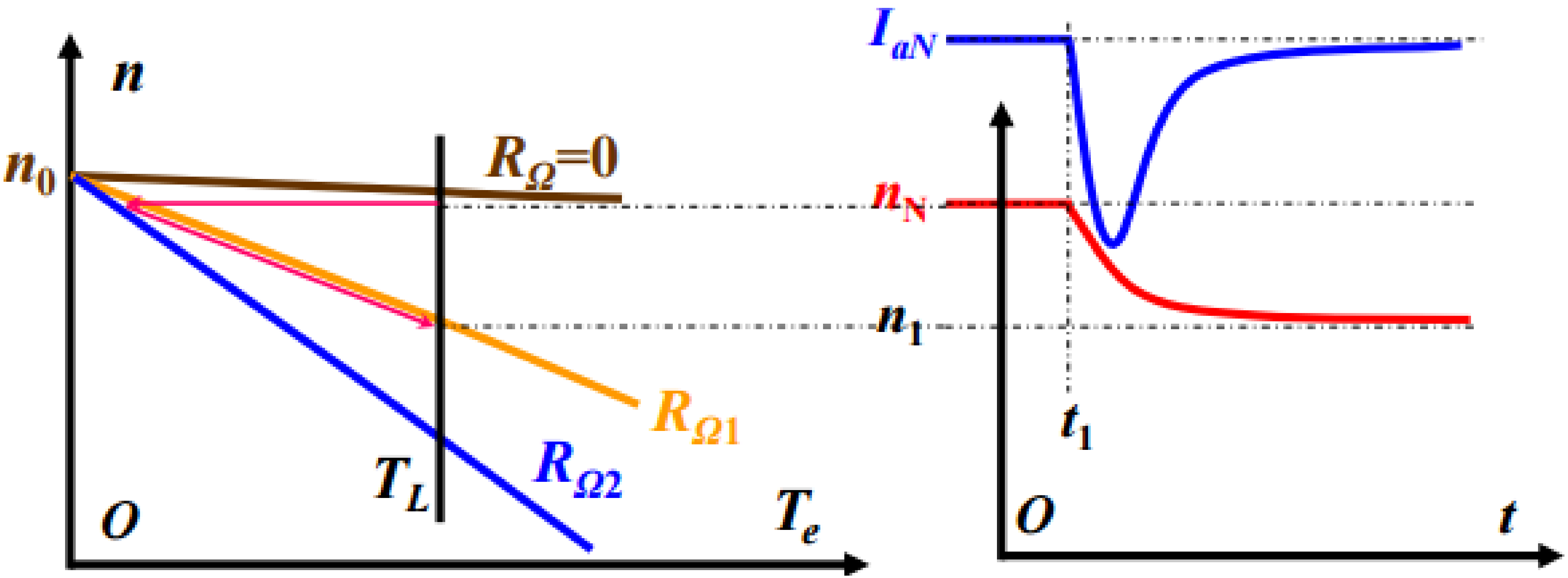


$$n = \frac{U - I_a R_a}{C_e \Phi}$$

Regulation speed of DC Motor

For separately /shunt excited DC motor

▲Increased armature resistance

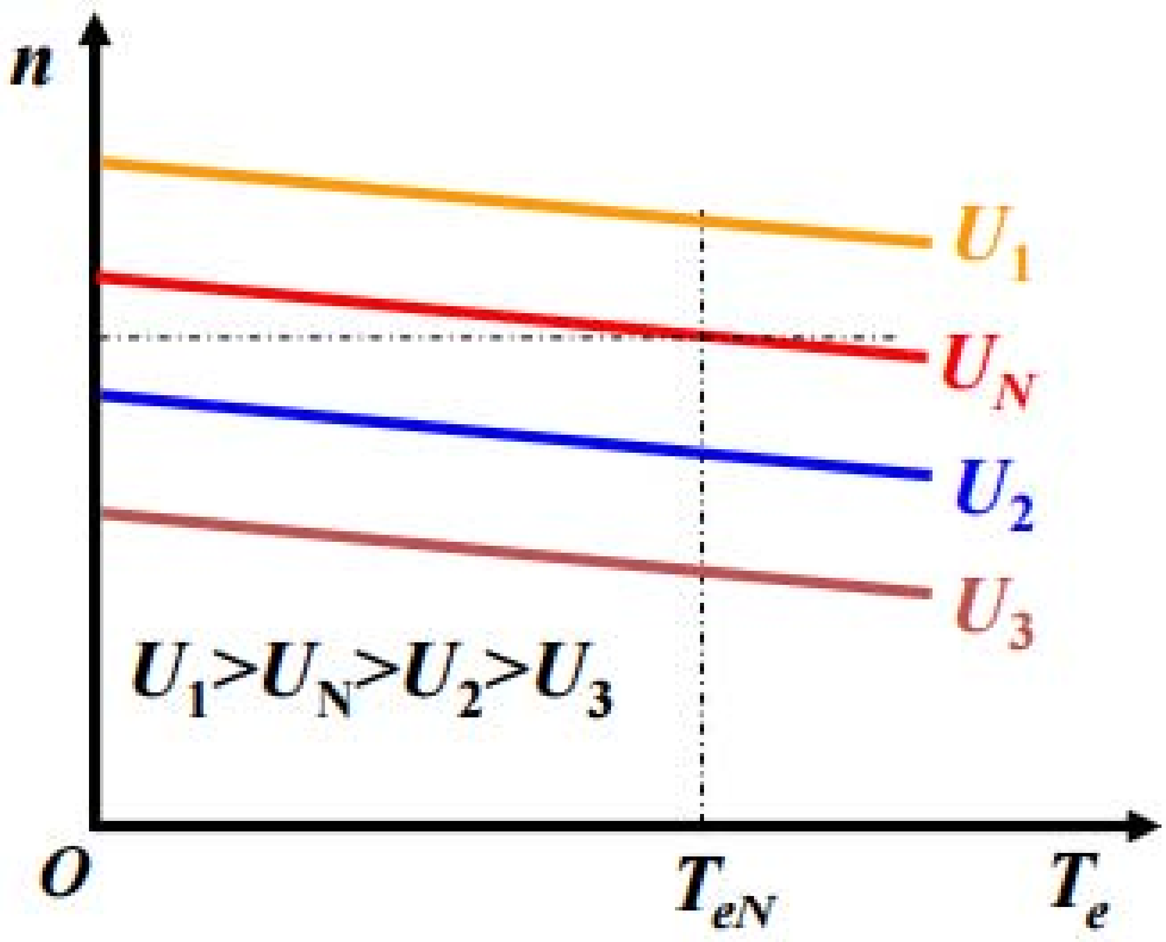


$$T_e=C_T\Phi I_a$$

Regulation speed of DC Motor

For separately excited DC motor

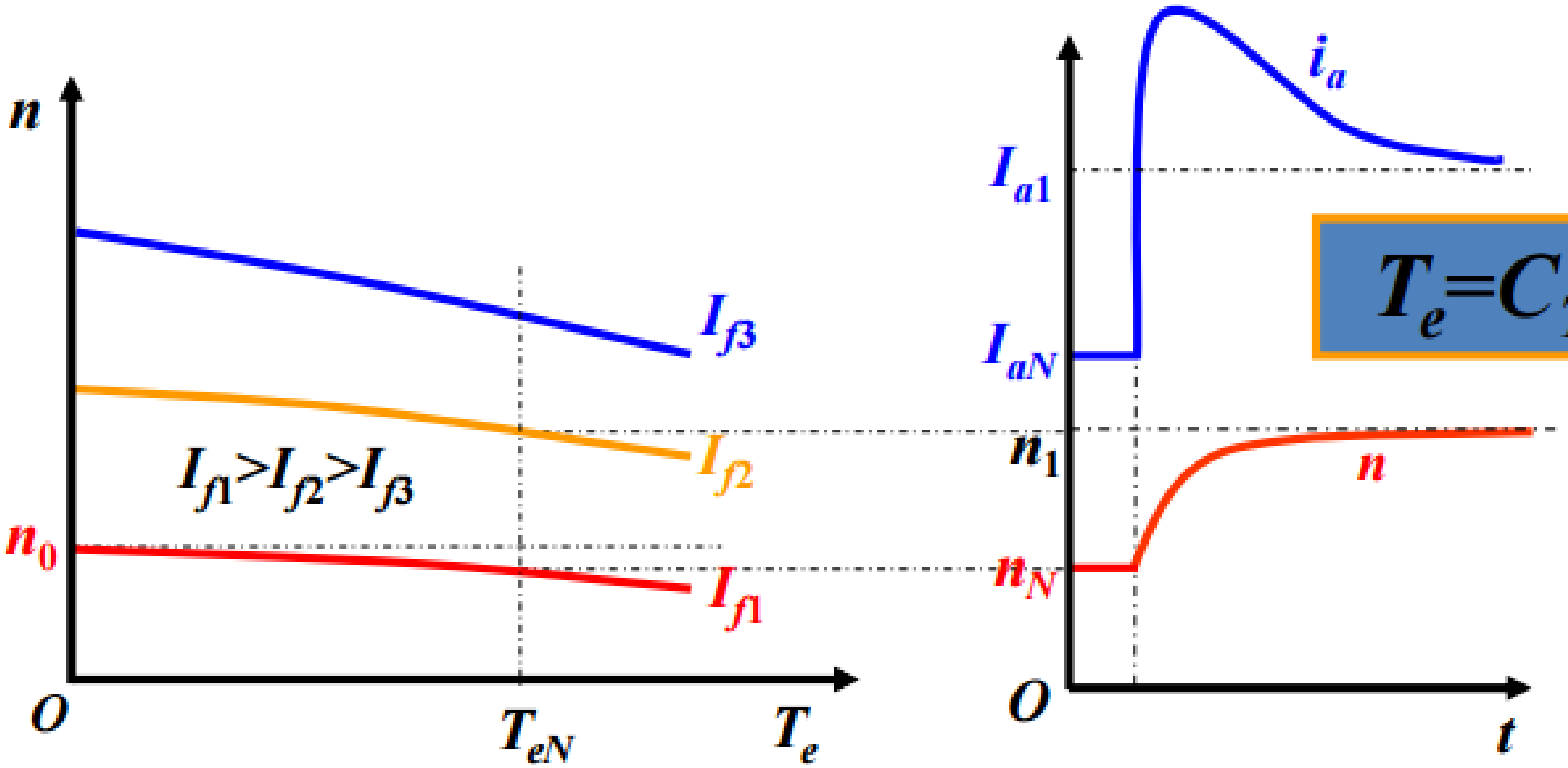
▲Changed terminal voltage



Regulation speed of DC Motor

For separately /shunt excited DC motor

▲Increased excitation resistance



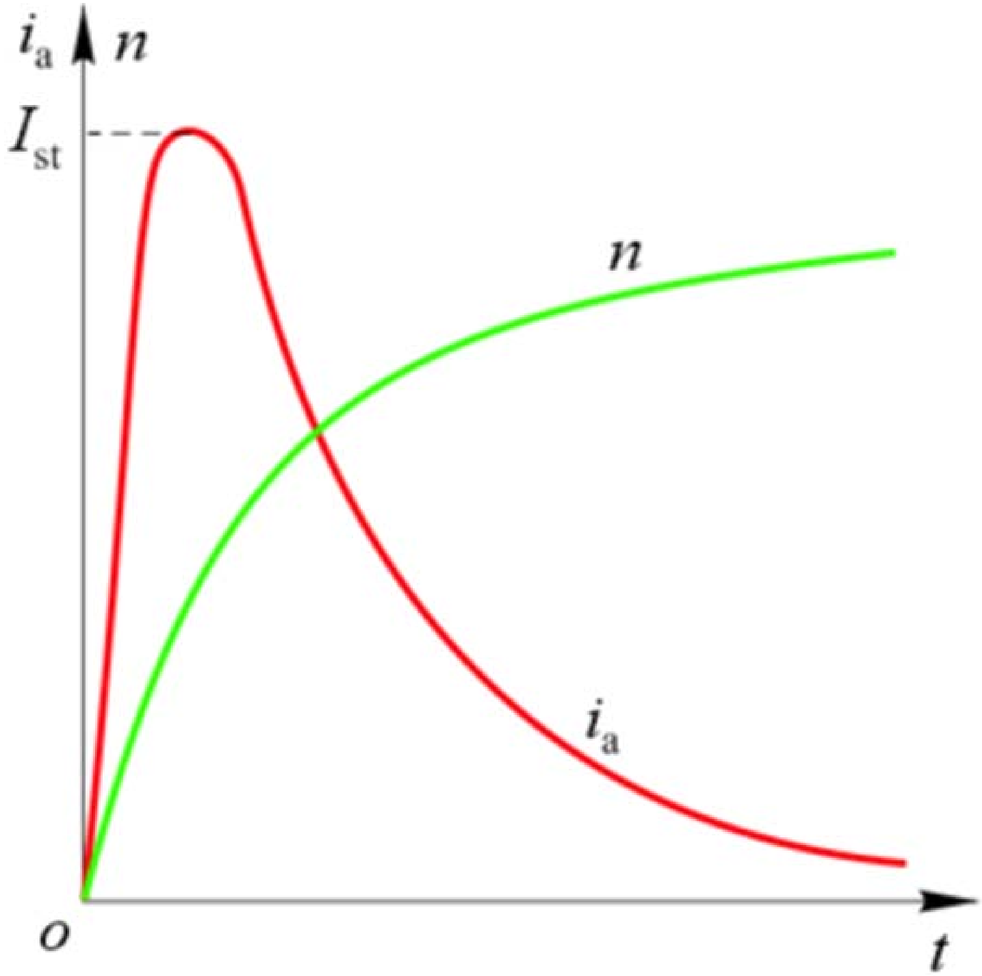
$$T_e = C_T \Phi I_a$$

Speed Control of DC Motor

SeparateExcitation (Change *U*)	Shunt Excitation (Change *R*ator R_f)	Series Excitation (Change R_s)
Advantages: 1. Mechanical characteristics are parallel curves, their hardness are same. 2. The speed can be either increased or decreased easily. **Disadvantages**: Adjustable DC source is necessary and costly.	**Advantages**: Speed control is simple and easy. **Disadvantages**: 1. Additional copper loss occurs. 2. Speed can be only unidirectionally controlled and mechanical characteristics are softened with the increase of R_a or R_f alone.	**Advantages**: Starting torque and overload ability are large. **Disadvantages**: 1. Mechanical characteristics are soft. 2. No-load operation is forbidden.

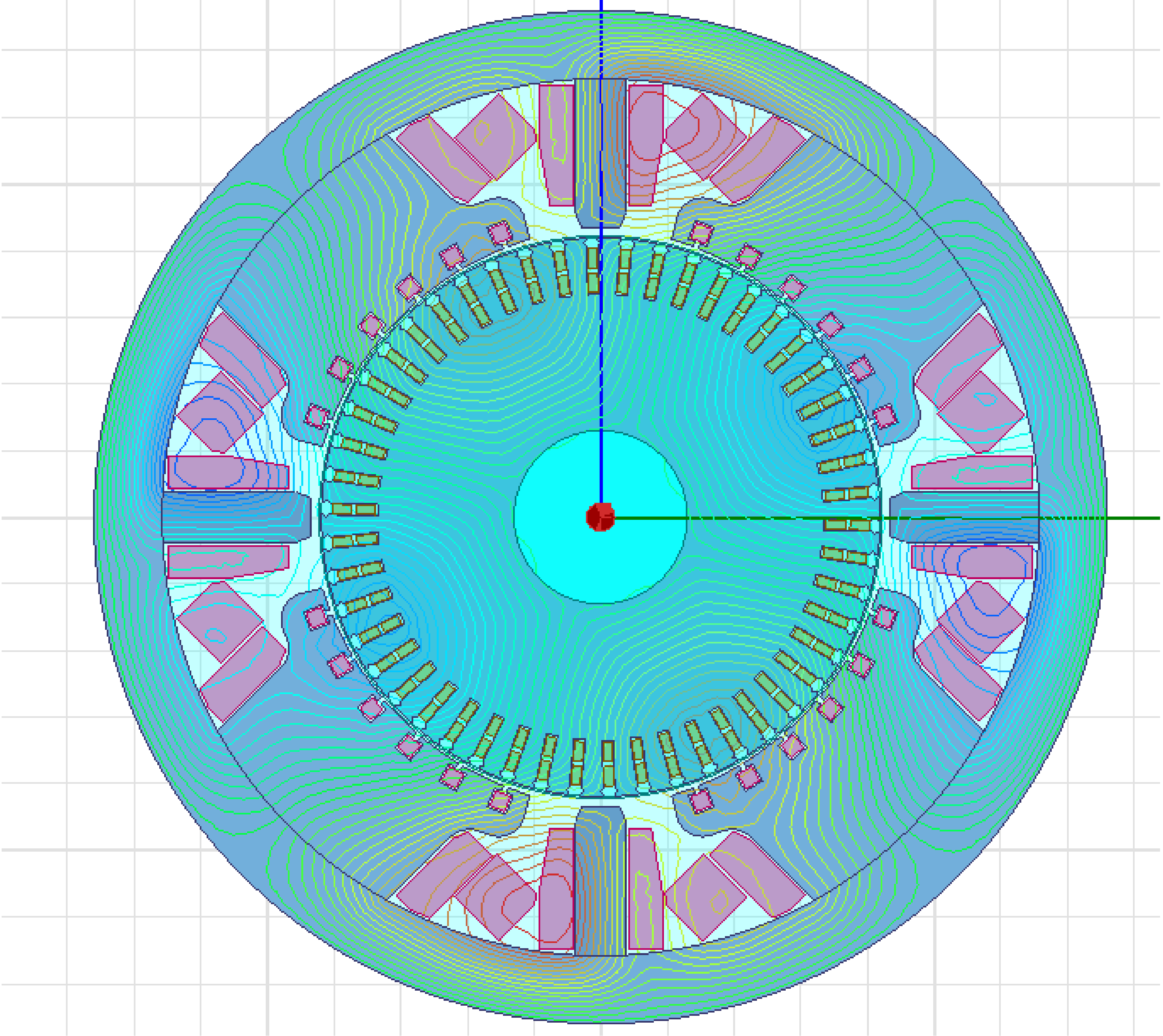
Starting performances of DC motor

- **Direct Starting**



Starting of Series resistance in the armature loop

Starting of decreased terminal voltage



Example: A shunt excitation DC motor operates at the rated speed 1000r/min and the rated input power is 10kW. When the voltage and the load torque keep constant, R_a is increased to decrease the speed to 800r/min. Please find the input power at this time.

Solution:

$$U=C \rightarrow I_f=C \rightarrow \Phi=C$$

$$T_2=C \rightarrow T_e=C \rightarrow I_a=C$$

$$\rightarrow I=I_a+I_f=C \rightarrow P_1=UI=C=10\text{kW}$$

Discussion: **A shunt excitation DC motor operates at the rated speed 1000r/min and the rated input power is 10kW. When the voltage and the load torque keep constant, R_a is increased to decrease the speed to 800r/min. Please analyze the changes of output power and efficiency.**

P_1=C, $n \searrow 20\% \rightarrow \Omega \searrow 20\%$

T_2=C $\rightarrow P_2 = T_2 \Omega \searrow 20\%$

$\eta = P_2 / P_1 \searrow 20\%$

Conclusion

(1)Basic voltage equations and electromagnetic power expressions can be introduced.

(2)Basic performances of DC generator need to be analyzed, no-loading, external and regulation performances for different excited types.

(3)Basic performances of DC Motor need to be analyzed, operational performances and mechanical performances, as well as the regulated speed, and the starting performances. Also need to consider the different excited types for DC motor.