Chapter 3

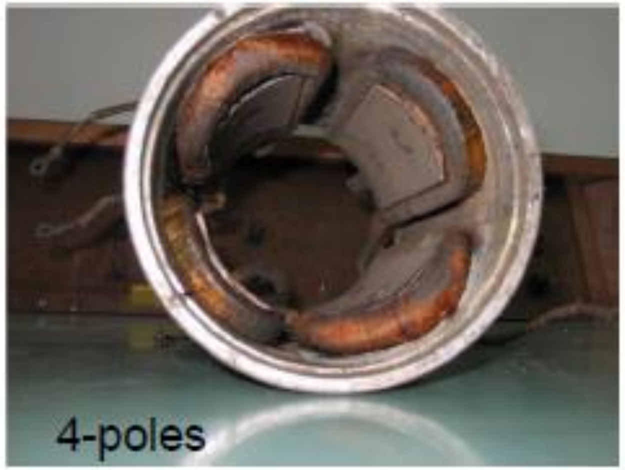
Brushless DC motor Drives

Why Brushless DC motor?

- The maximum speed and torque of the Brushed DC Motor is limited by the carbon brush-commutator.
- However, the control of speed and torque of a DC motor is the simplest, because the torque characteristic is linear with i_a and i_f.
- The brushless structure has all the linear characteristics of the brushed DC motor but without the complexity and maintenance requirement of the brush-commutator.

Construction of brushed and brushless DC machines

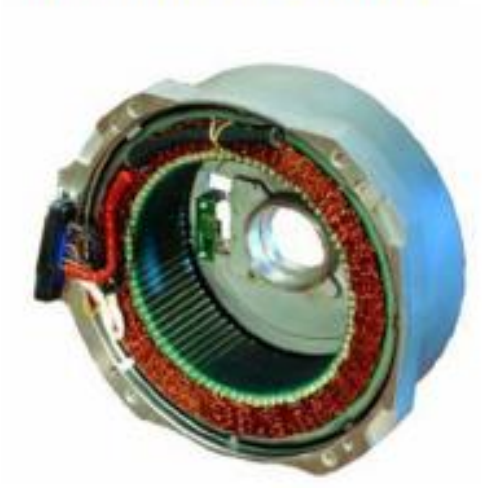
Brushed DC Motor



Stator - Field

Rotor- Armature

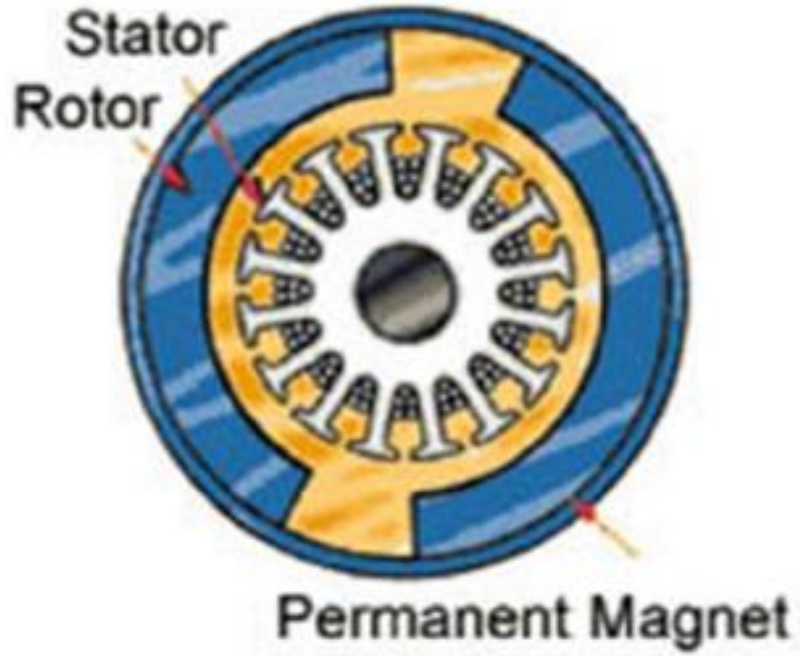
Brushless DC Motor

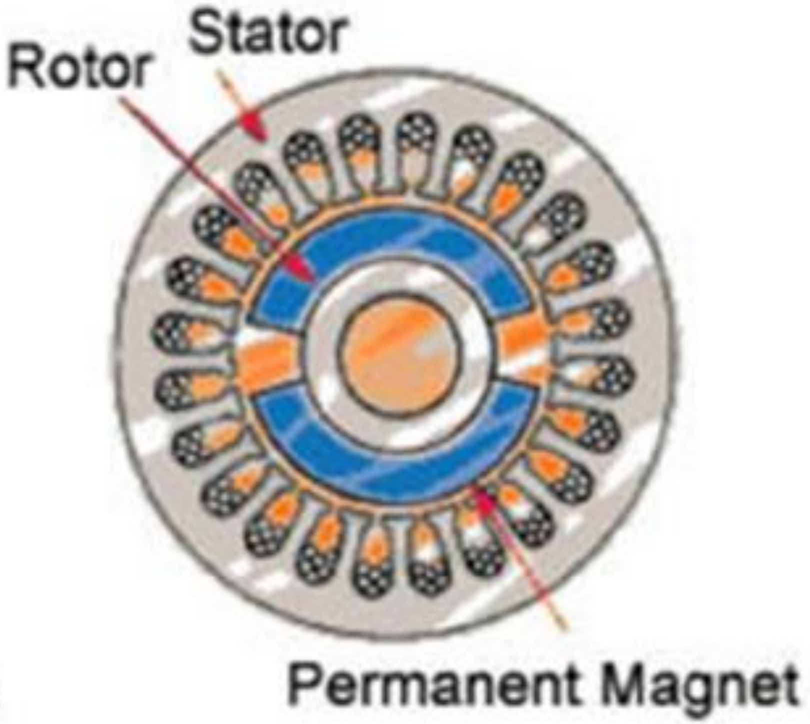


Stator- Armature

Rotor- Field

Permanent magnet Brushed and Brushless DC motor



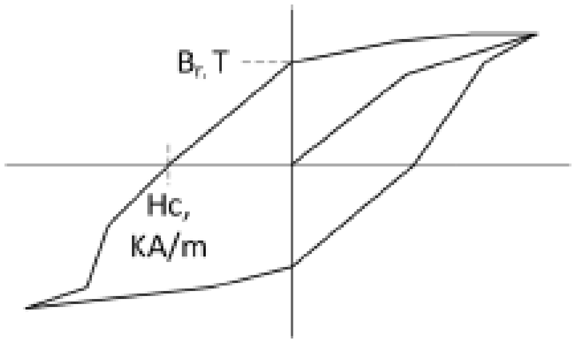


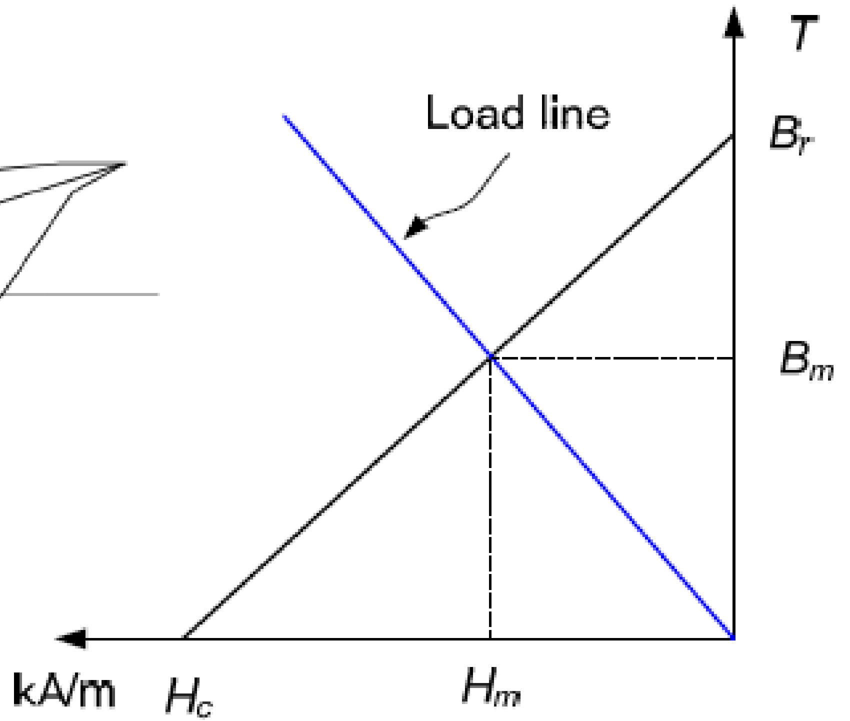
The brush-commutator is replaced by a 3-phase *electronic commutator*, consisting of three Hall sensors for rotor position and a 3-phase inverter.

Permanent magnets for BLDC motor

Neodymium Iron Boron (NdFeB) and Samarium Cobalt

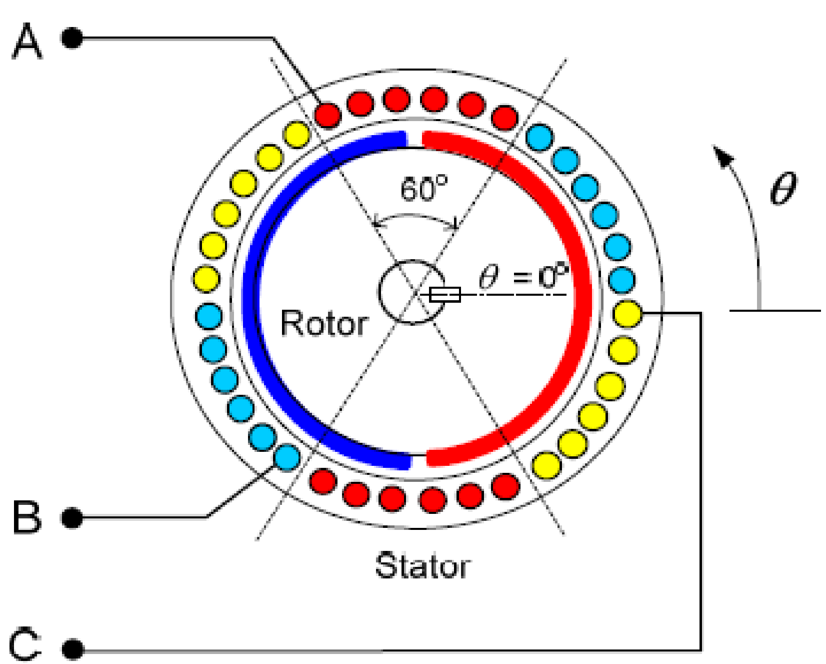
NdFeB: $B_r = 0.8 - 1.4$ T; $H_c > 1$MA/m; $\mu_{recoil} \approx 1$; $T_{Curie} = 120\ ^{\circ}C$



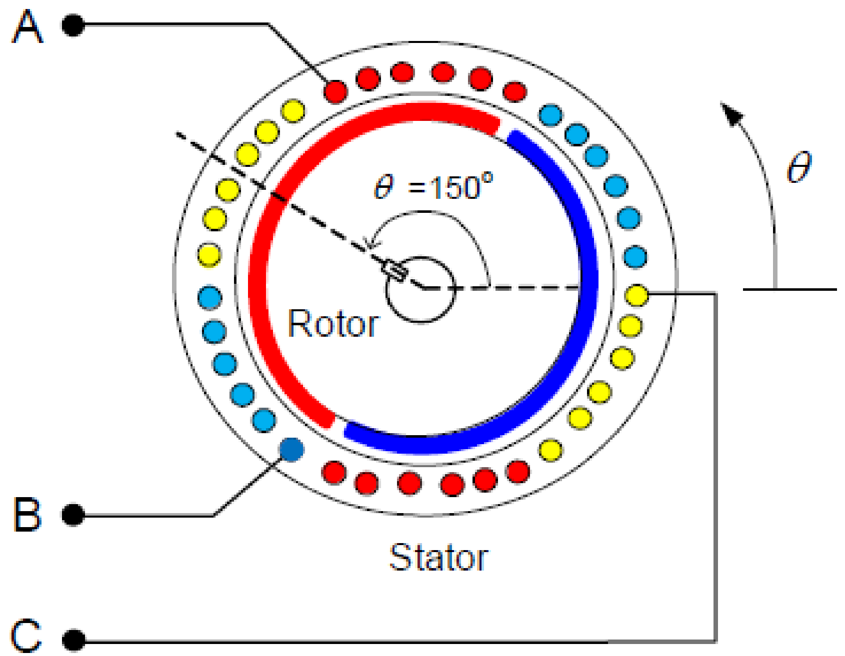


Remanent flux density or Remanence (*Br*) and Coercivity (*Hc*) field intensity

Three Phase Stator



(a) $\theta = 0°$



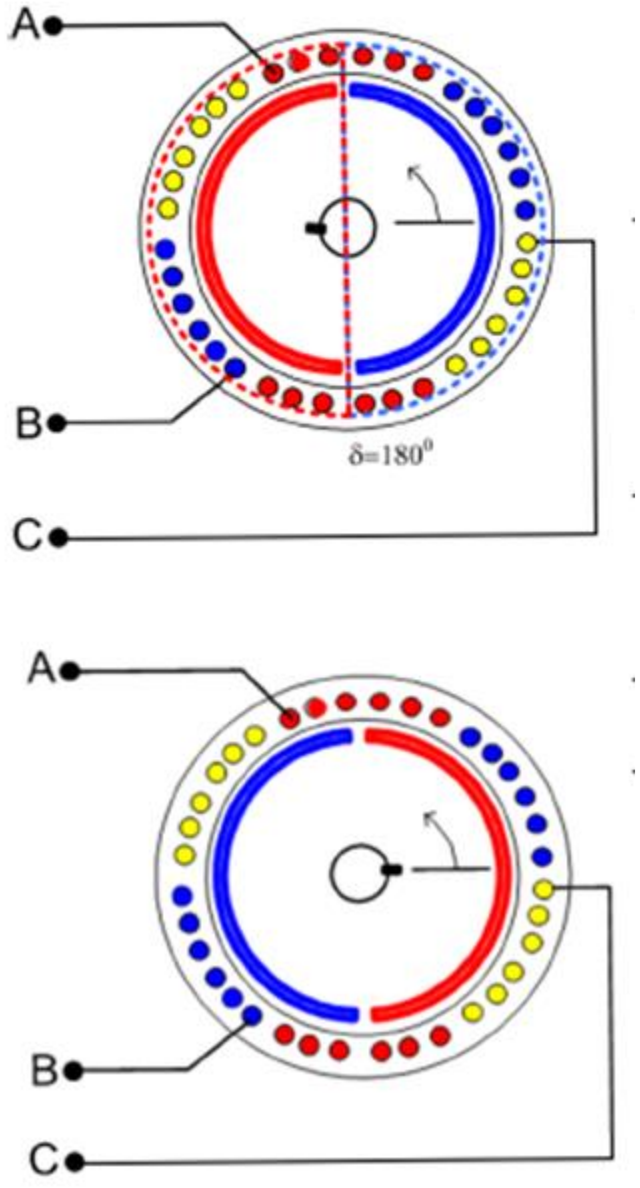
(b) $\theta = 150°$

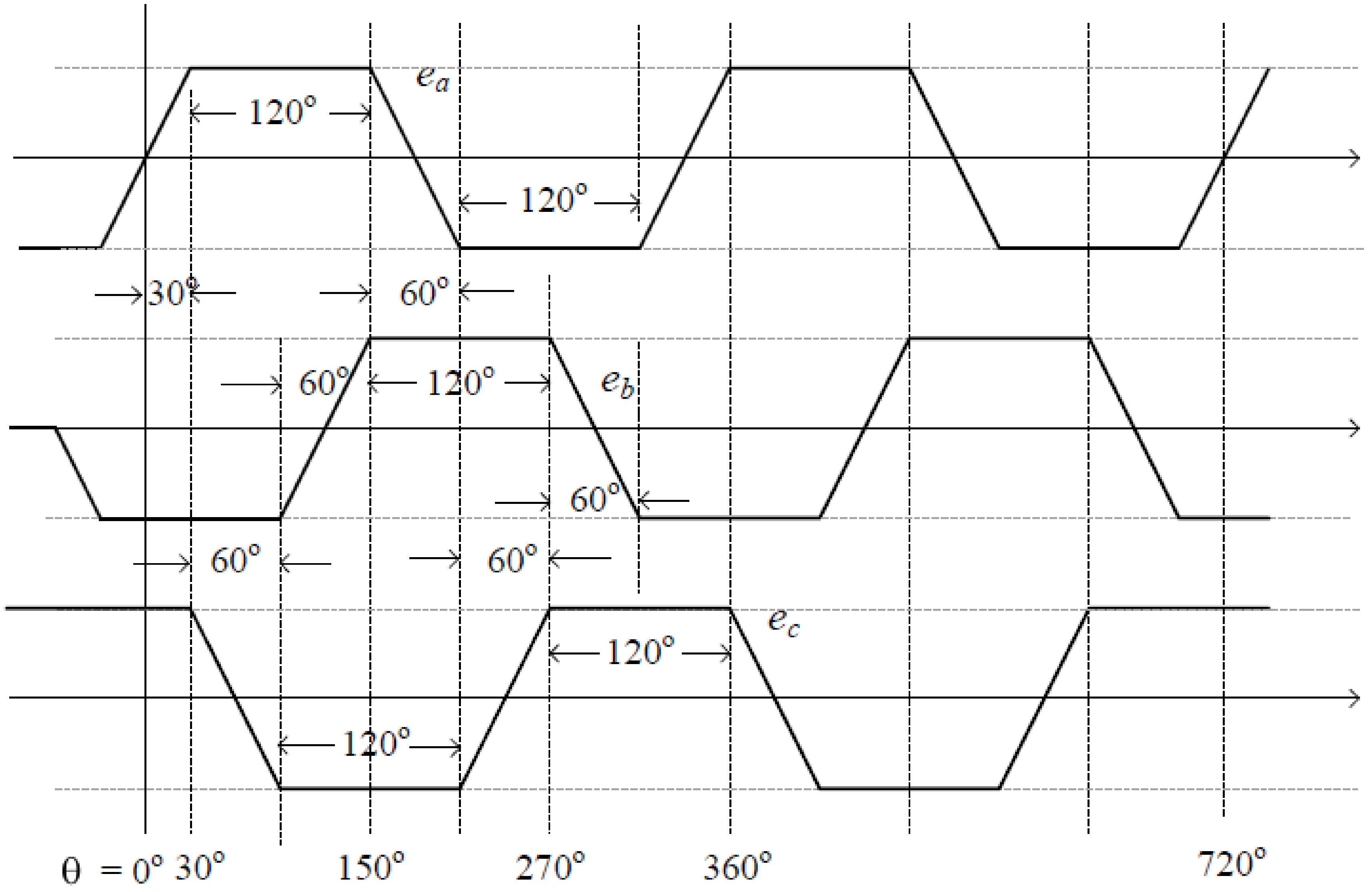
$$\theta = \int_0^t \omega_m dt + \theta_o$$

The three-phase stator winding is normally star-connected.

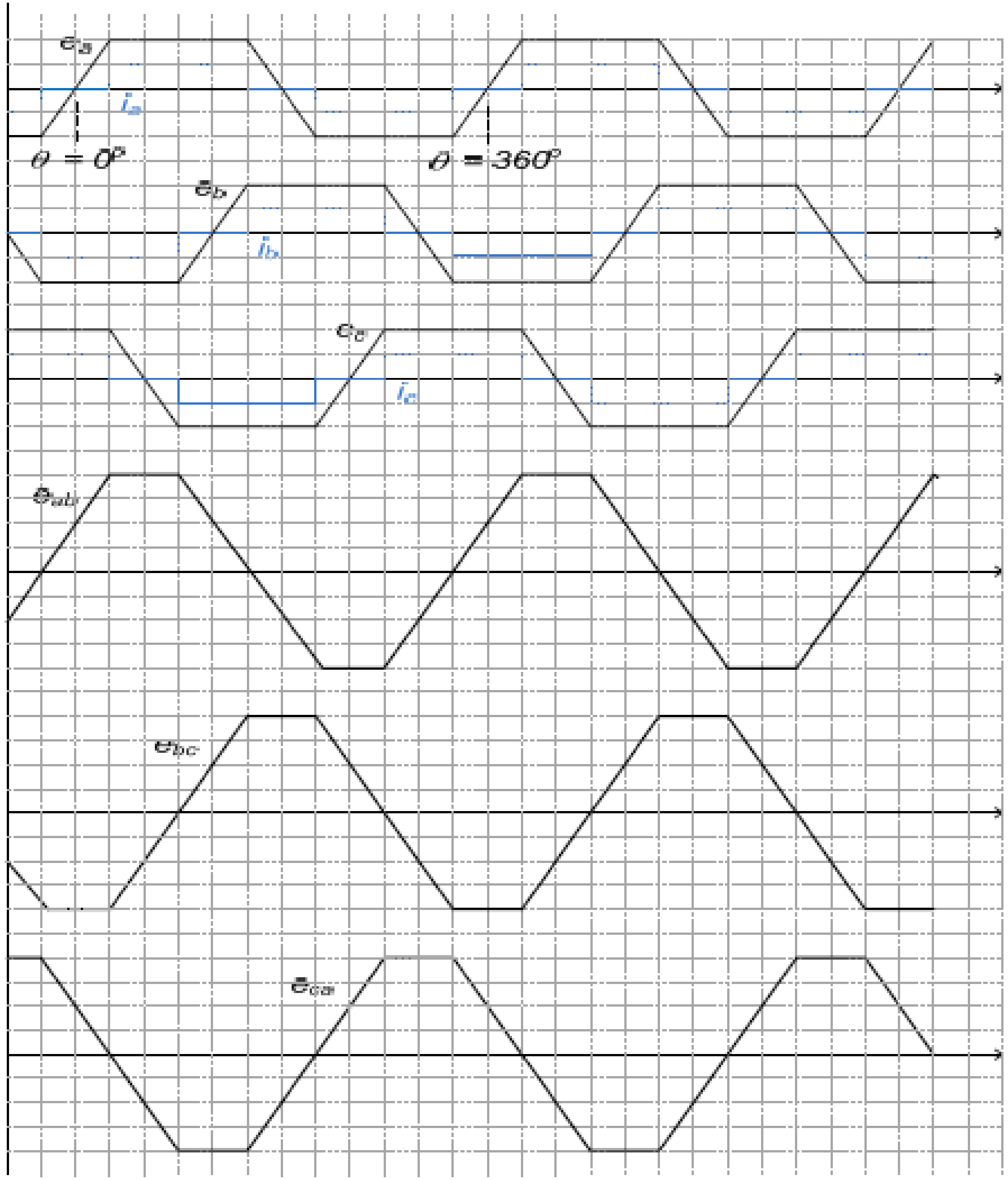
Each phase winding spans 60°(electrical) on each side (i.e., per pole), so the total span for each phase winding is 120°. There are six conductors per pole (i.e., $N_S = 6$) of each winding in 60° spans. The stator windings of each phase are displaced by 120° from its adjacent phase winding.

The Back EMF Waveform





Phase & line-line voltages



Machine back emf

For the two-pole ($p = 1$) machine, $e = -N_s \dfrac{d\varphi}{dt} = Blv = Blr\omega_m$

$$e_{max} = 2N_s Blv = 2N_s lrB\omega_m \quad \text{V}$$

where l is the active length of the conductors in meters

r is the radius of the stator in meters

ω_m is the rotational speed of the rotor in rad/sec.

B is the air-gap field in Tesla

N_s is the number of conductors per pole

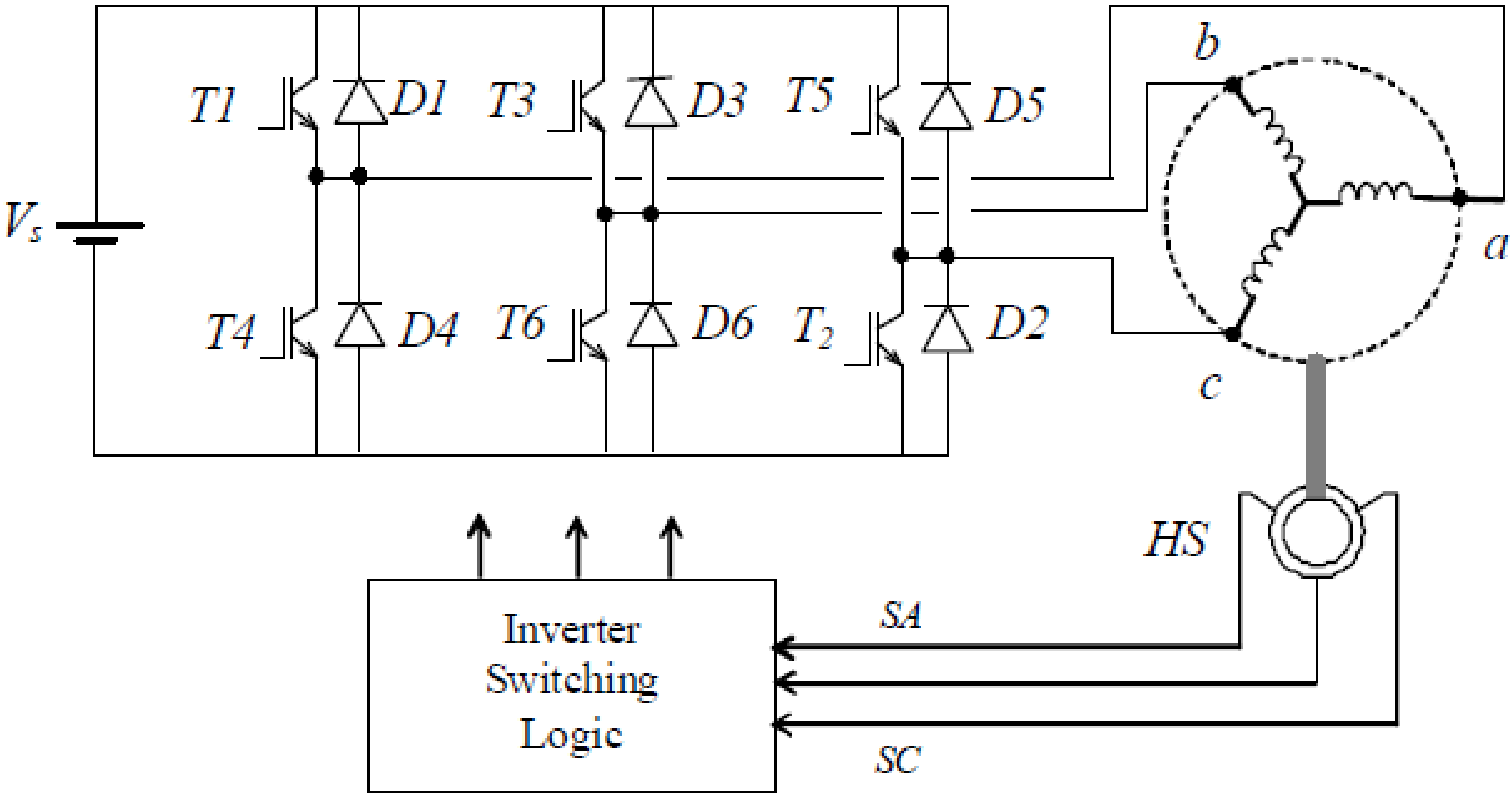
For a star-connected machine with p pole-pairs (i.e., $2p$ poles),

$$e_{max} = 2N_s plrB\omega_m = k_e'\varphi_f\omega_m \quad \text{V/phase}$$

$$e_{abmax} = max(e_a - e_b) = 4N_s plrB\omega_m = k_E'\varphi_f\omega_m \quad \text{V}_{\text{line-line}}$$

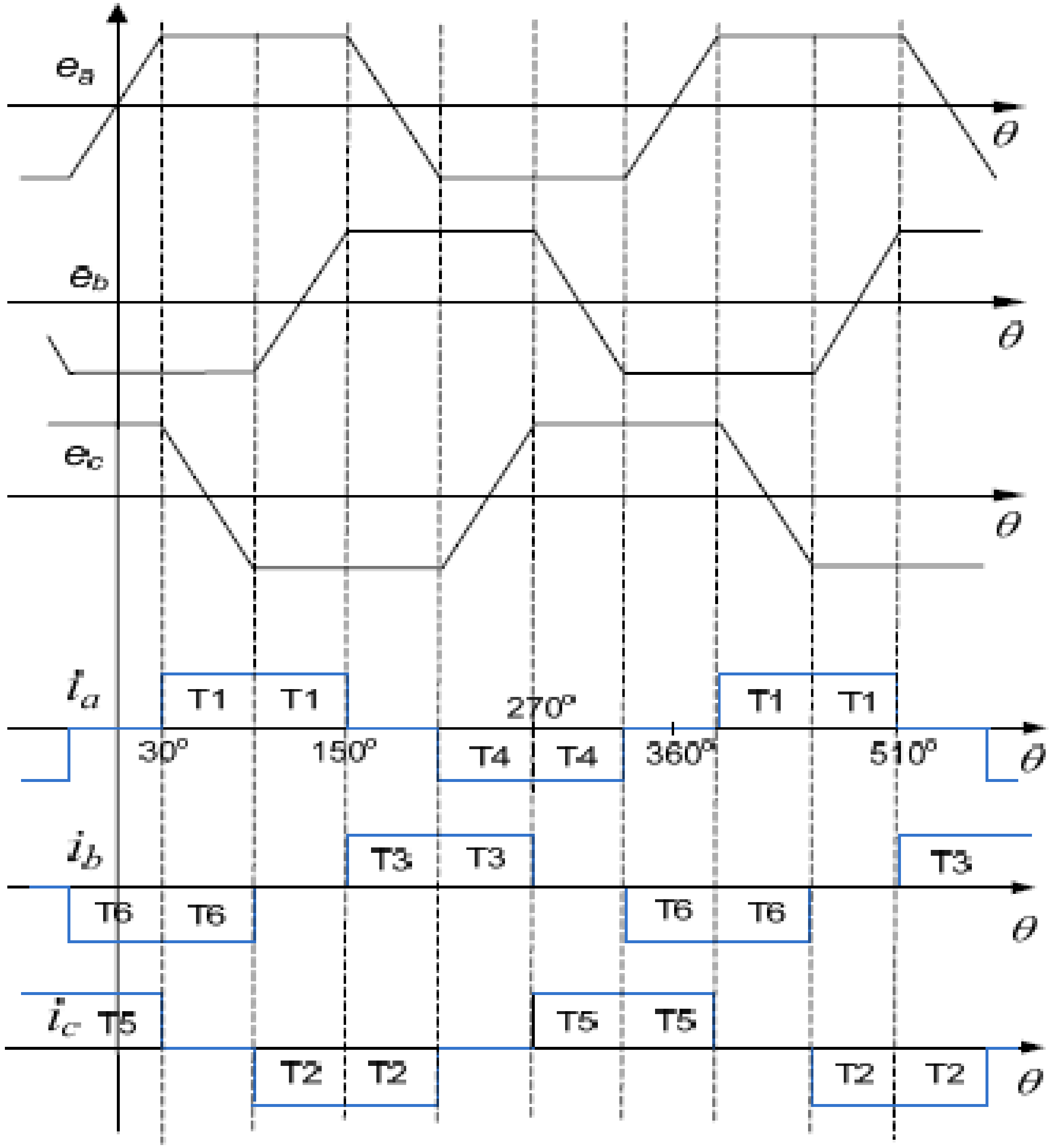
Inverter drive BLDC machine

The quasi-square three-phase current waveforms can be supplied from the three phase inverter. The three Hall sensor outputs SA - SC are converted into the six switching signals T1 - T6, by the inverter switching logic block.

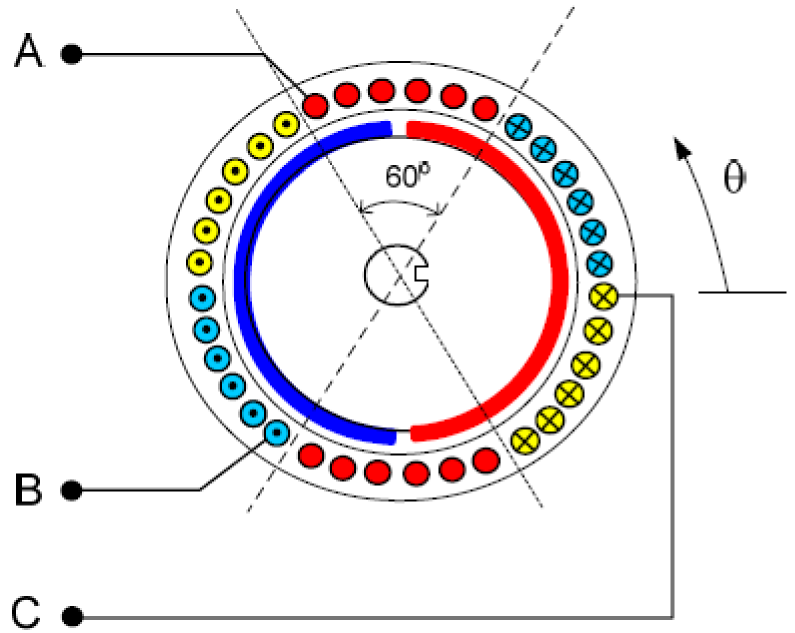


Ideal motor current waveforms

$$T = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m}$$



Inverter switching table



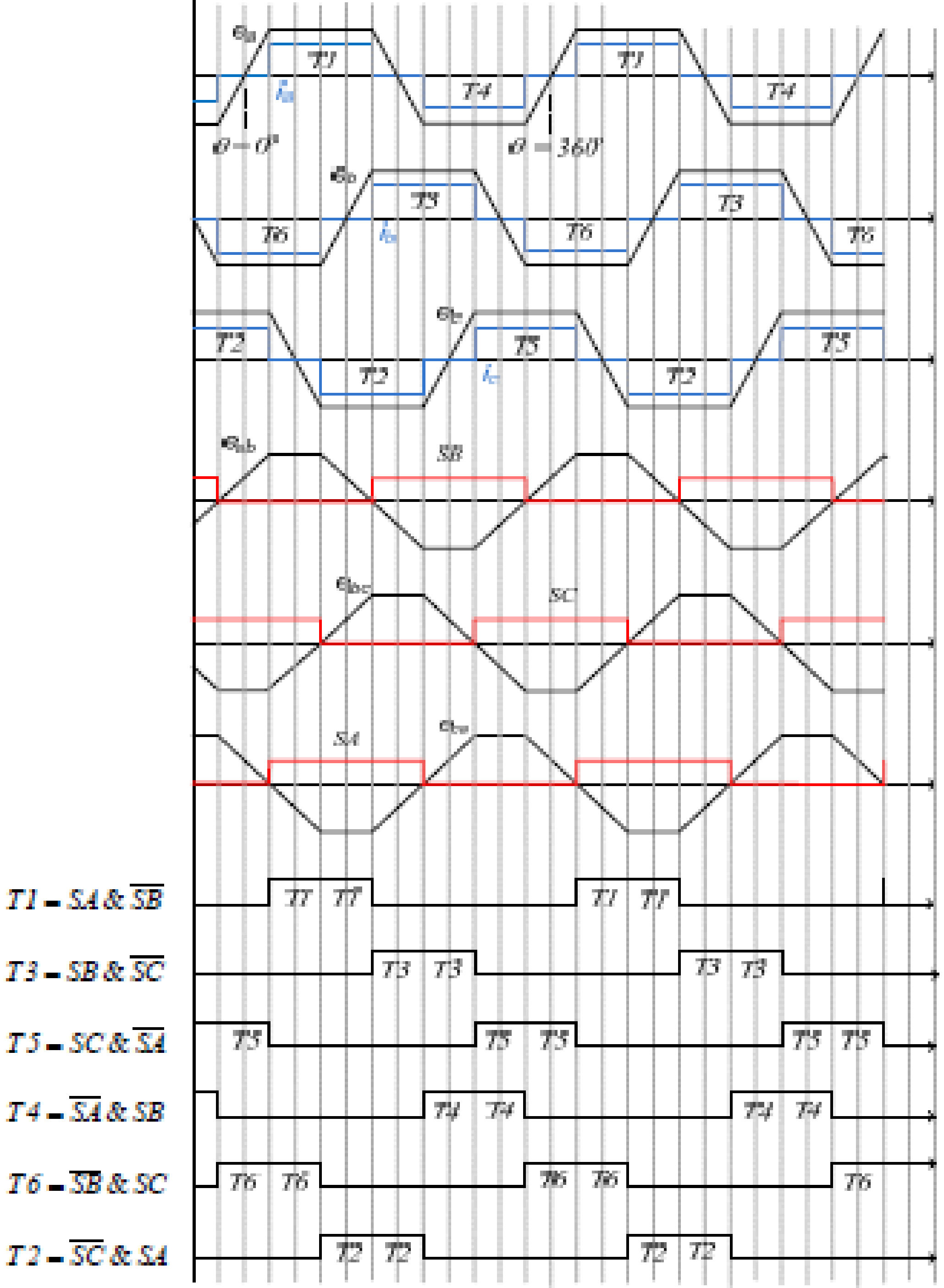
Inverter switching table for $\omega > 0$, or CCW motion

δ	Switches ON	Current flow
-30º - 30º	T5, T6	$C+$ and $B-$
30º - 90º	T6, T1	$B-$ and $A+$
90º - 150º	T1, T2	$A+$ and $C-$
150º - 210º	T2, T3	$C-$ and $B+$
210º - 270º	T3, T4	$B+$ and $A-$
270º - 330º	T4, T5	$A-$ and $C+$

Inverter switching table

Inverter switching table for $\omega < 0$, or CW motion

δ	**Switches ON**	**Current flow**
-30º - 30º	T5, T6	$C+$ and $B-$
30º - 90º	T6, T1	$B-$ and $A+$
90º - 150º	T1, T2	$A+$ and $C-$
150º - 210º	T2, T3	$C-$ and $B+$
210º - 270º	T3, T4	$B+$ and $A-$
270º - 330º	T4, T5	$A-$ and $C+$


e_a
T1
i_a
T4
$\theta = 0^\circ$
$\theta = 360^\circ$
e_b
T3
T6
i_b
e_c
T2
T5
i_c
e_{ab}
SB
e_{bc}
SC
SA
e_{ca}
$T1 = SA \,\&\, \overline{SB}$
$T3 = SB \,\&\, \overline{SC}$
$T5 = SC \,\&\, \overline{SA}$
$T4 = \overline{SA} \,\&\, SB$
$T6 = \overline{SB} \,\&\, SC$
$T2 = \overline{SC} \,\&\, SA$

The developed torque

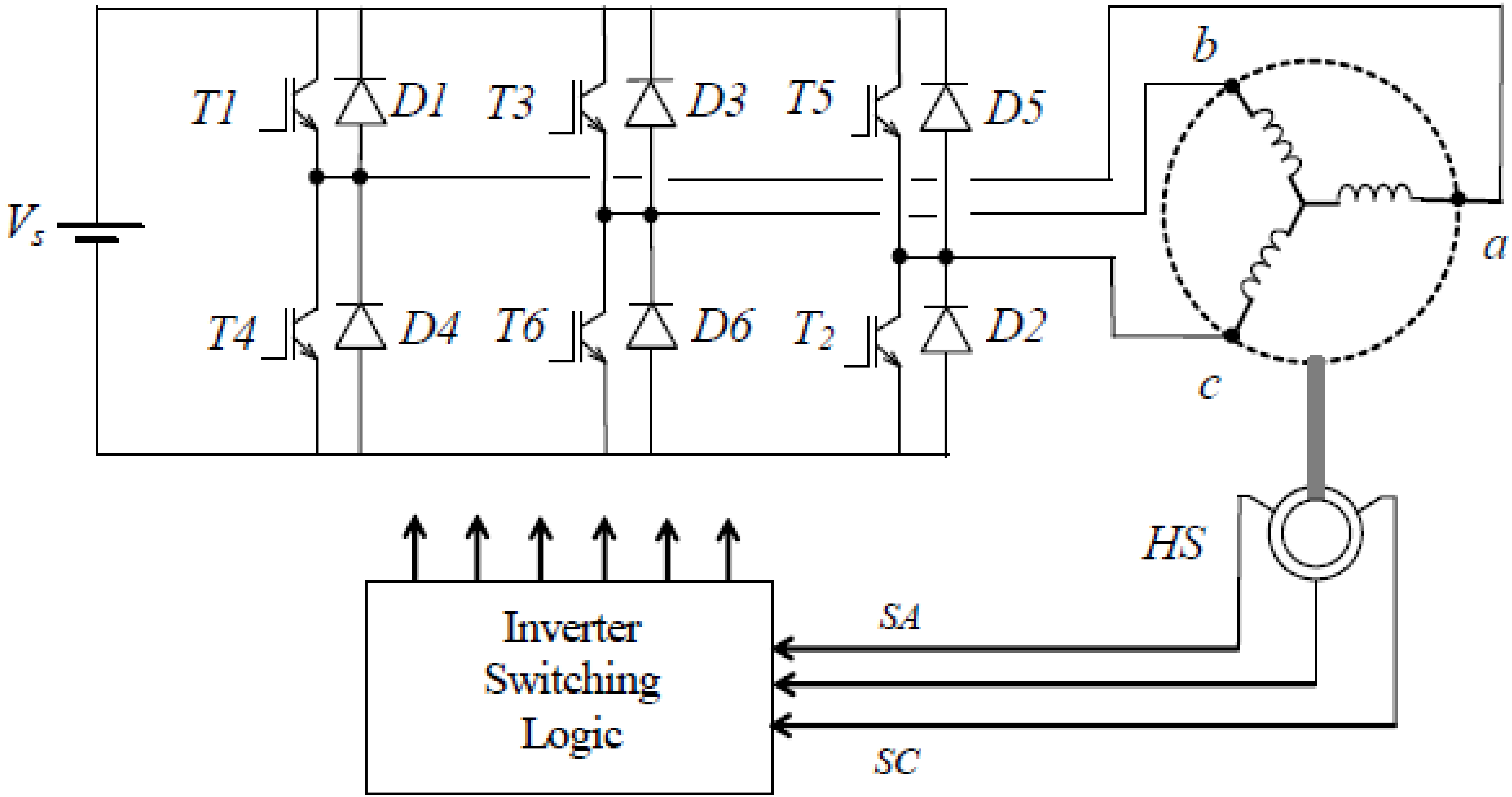
For a 2-pole machine ($p = 1$)

$$T = 2N_s rlBI \qquad \text{Nm/phase}$$
$$= 4N_s rlBI \qquad \text{Nm}$$

For a machine with p pole-pairs (i.e., 2p poles)

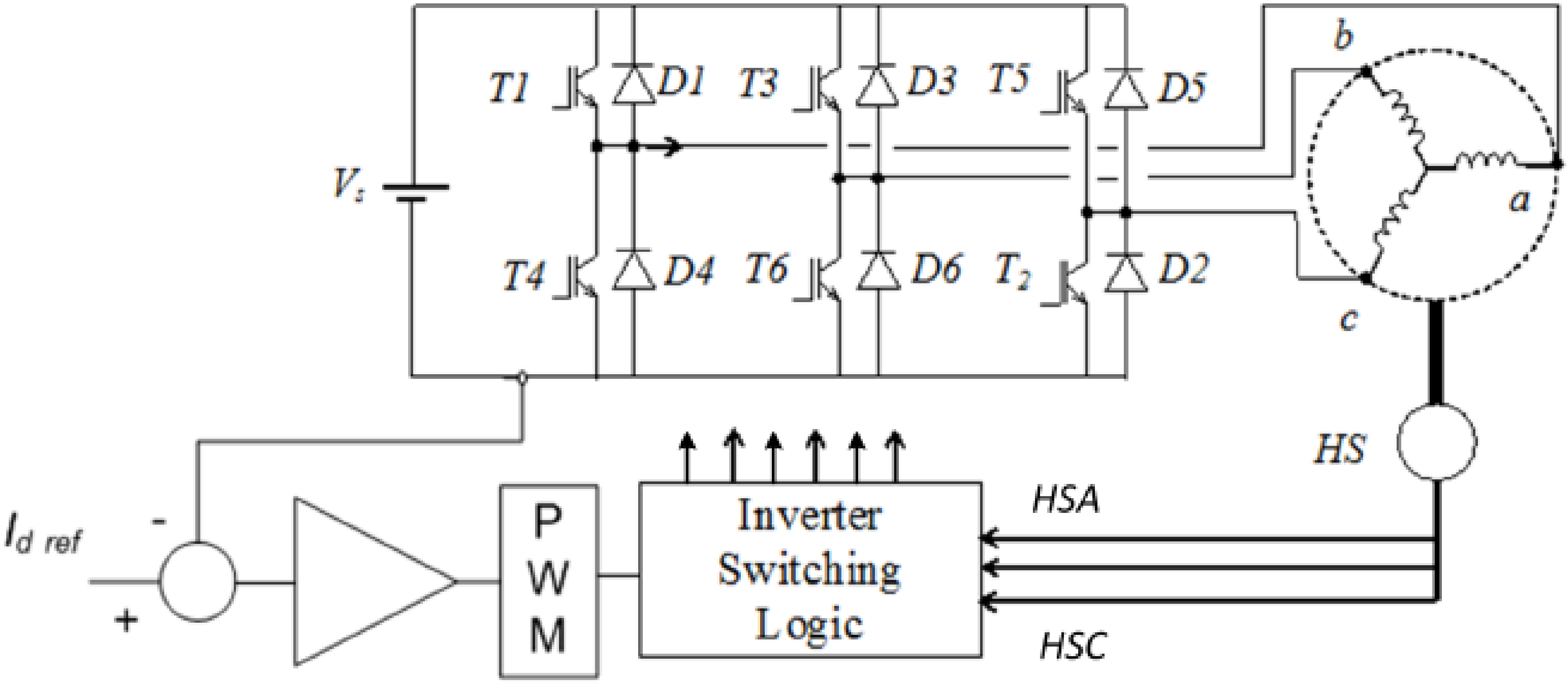
$$T = 4N_s prlBI = k_T' \varphi_f I \qquad \text{Nm}$$

Note that the back emf and torque equations of this AC machine are exactly the same as for the brushed DC machine. There are no brushes or commutator. Hence the *name Brushless DC Machine*.



T1
D1
T3
D3
T5
D5
b
V_s
a
T4
D4
T6
D6
T_2
D2
c
HS
Inverter
Switching
Logic
SA
SC

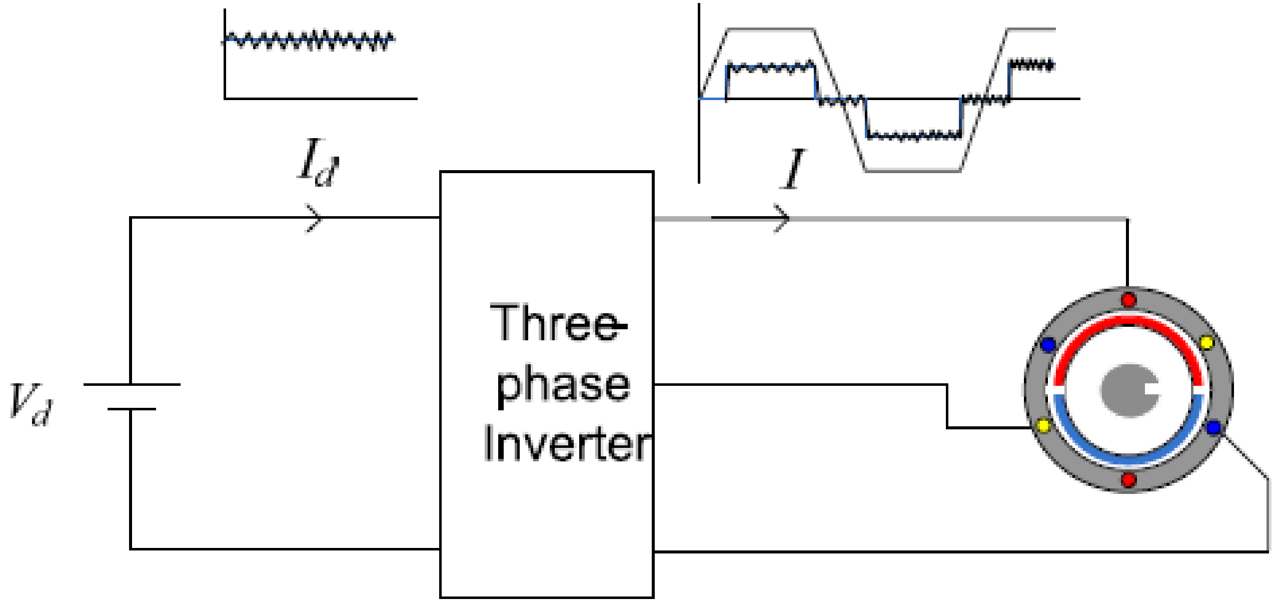
Torque control via DC link current control



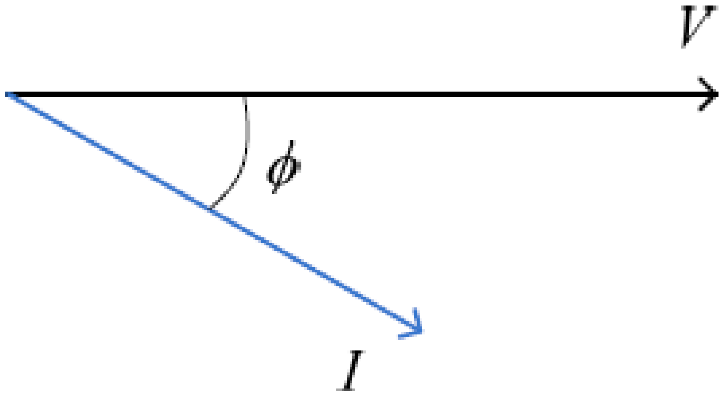
Ideally, the DC-link currents (+ve and –ve) should remain constant, at all times. This can be achieved by one DC current regulator, or three separate phase current regulators.

DC link voltage versus speed

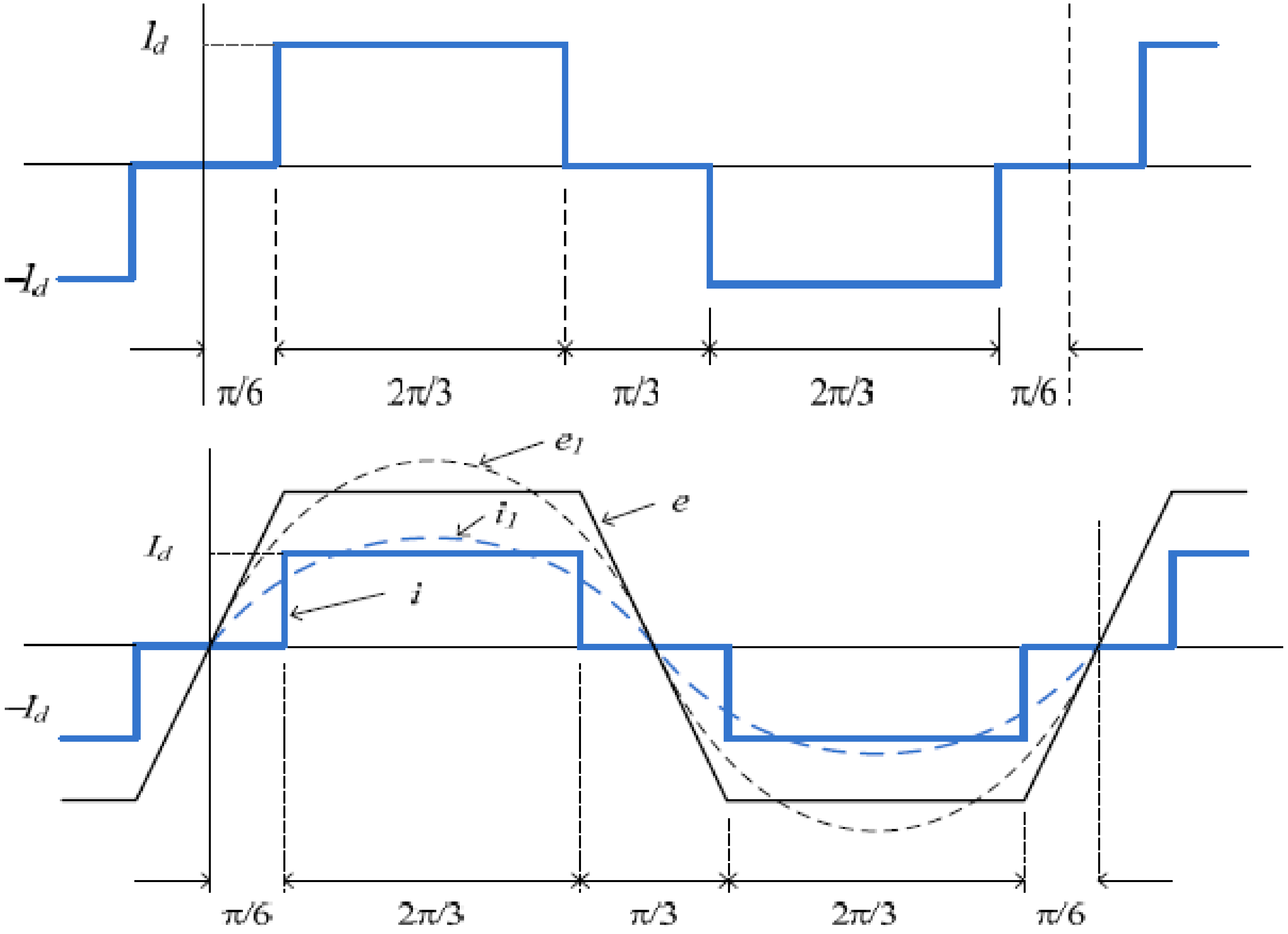
Assuming quasi-square phase currents in each winding, via DC-link or phase current controls



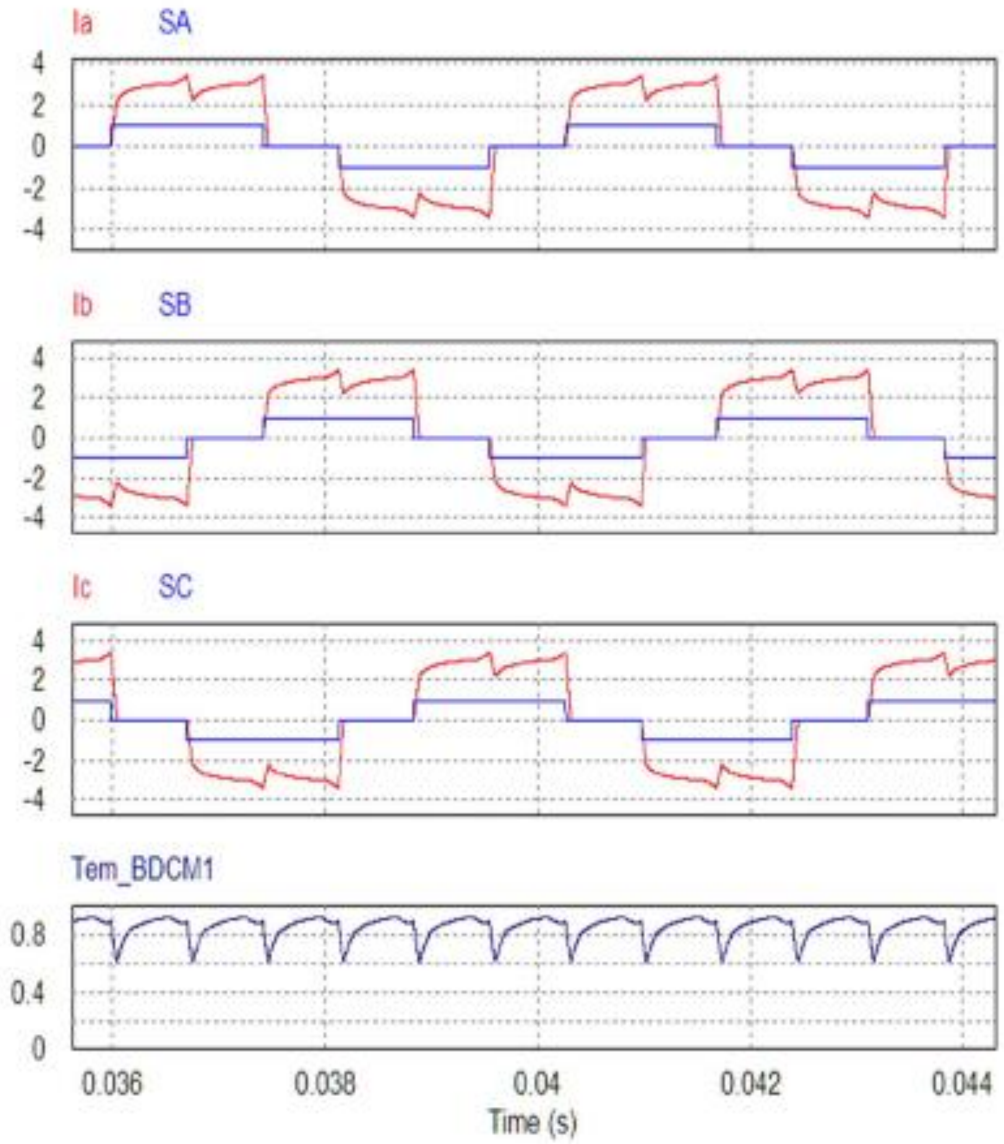
$$V_d I_d = 3VI\cos\phi$$



Fourier analysis of phase current



Phase and DC-link current waveforms



Phase current harmonics

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} i\cos(n\omega t)\,d\omega t$$

$$= \frac{1}{\pi}\int_{-\pi/3}^{\pi/3} I_d\cos(n\omega t)\,d\omega t + \frac{1}{\pi}\int_{-\pi}^{-2\pi/3} -I_d\cos(n\omega t)\,d\omega t + \frac{1}{\pi}\int_{2\pi/3}^{\pi} -I_d\cos(n\omega t)\,d\omega t$$

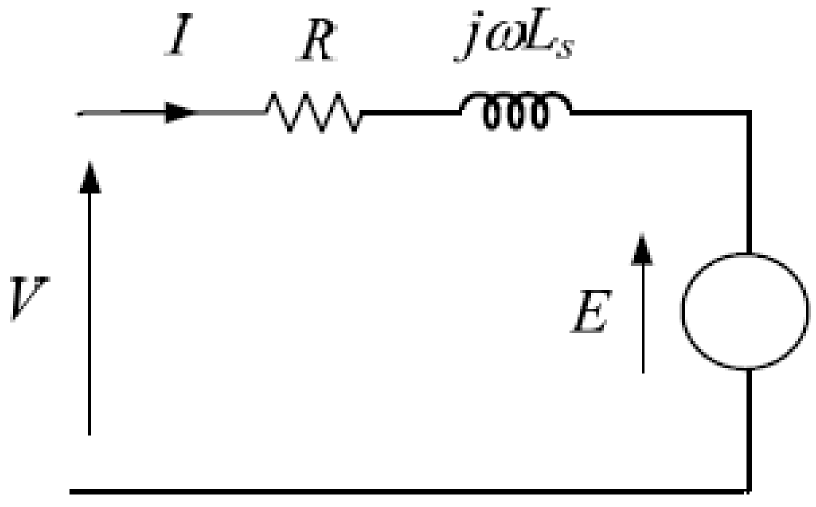
$$= \frac{2I_d}{n\pi}\left[\sin\left(\frac{n\pi}{3}\right) + \sin\left(\frac{2n\pi}{3}\right)\right]$$

$$= \frac{4I_d}{n\pi}\cos\left(\frac{n\pi}{6}\right) \qquad (n=1,3,5)$$

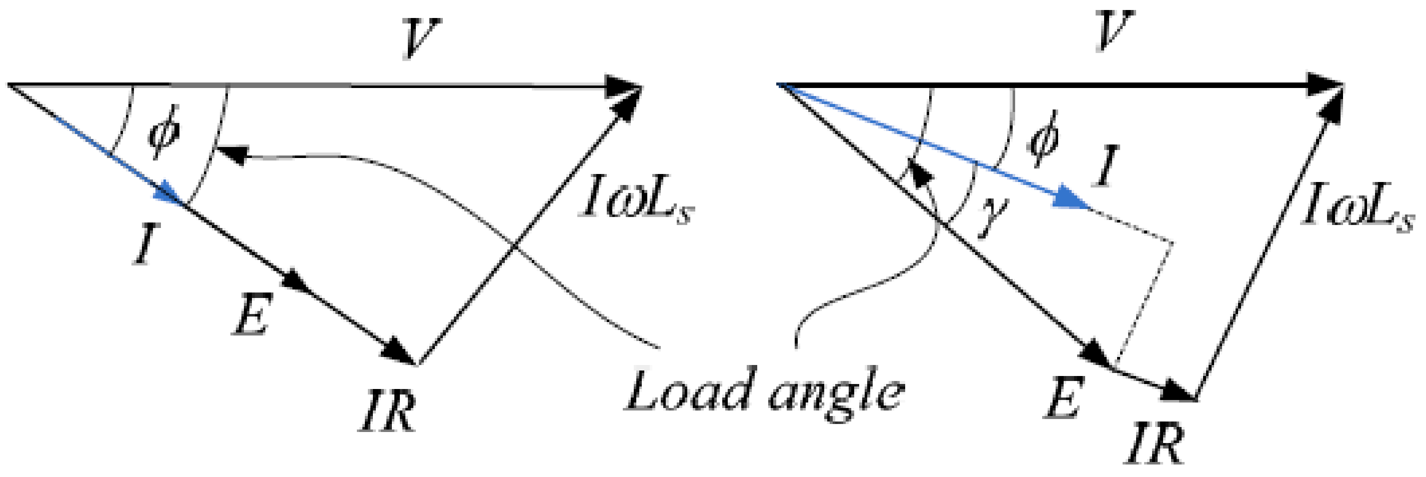
$$I_1 = a_1/\sqrt{2} = \frac{4I_d}{\sqrt{2}\pi}\cos\left(\frac{\pi}{6}\right) = \frac{\sqrt{6}I_d}{\pi}$$

$\therefore\ I_d = \frac{\pi}{\sqrt{6}}I$ where I is the RMS value of the fundamental phase current. Note, I is also the peak value.

Per-phase Phasor diagram



(a)



(b) (c)

Relationship between V_d and ω_m

$V\cos\phi = E_f \cos\gamma + IR$; $V_d I_d = 3VI\cos\phi = 3IE\cos\gamma + 3I^2R$

Noting that $I_d = \frac{\pi}{\sqrt{6}} I$ and cancelling I, $0.427V_d = E\cos\gamma + IR$

When $\gamma = 0°$; $0.427V_d = E + IR = V_d'$ Thus, for small IR, $\omega_m \propto V_d$

V_d' is the per phase RMS voltage supplied to the motor by the inverter.