SERVO MOTORS AND MOTION CONTROL SYSTEMS

(Servo Motors, Drives, and Control Methods: Part II- Lecture 6)

Dr. Caglar UYULAN

Permanent Magnet Synchronous AC Machines (PMSM) & Permanent Magnet Brushless Machines (BLDCM)

1. Construction and Operation Principle:

- In brushless DC motors with permanent magnets, the rotor (the rotating part) contains the permanent magnets, while the stator (the stationary part) holds the main windings, which carry the current. This is a key difference compared to traditional brushed DC motors.
- The absence of brushes and a commutator (the collector-brush assembly) in these motors is a direct result of this design. Unlike brushed motors, where the commutator mechanically switches the direction of the current in the rotor's windings, brushless motors use electronic commutation.

2. Advantages of Brushless Design:

- **Safety in Hazardous Environments:** Since there are no brushes and commutators, brushless DC motors do not produce sparks. This makes them safer for use in explosive or dusty environments, where brushed DC motors would pose a significant risk.
- **Maintenance and Reliability:** The brushless configuration significantly reduces maintenance needs. In brushed motors, brushes are a wear-and-tear component, requiring regular replacement. The brushless design enhances the motor's lifespan and reliability.
- **Reduced Inertia:** The rotor in a brushless DC motor does not carry windings, contributing to lower inertia. This feature is beneficial in applications where rapid acceleration and deceleration are required.

3. Typical Configuration:

- Brushless DC motors are commonly three-phase. This means they require a three-phase power supply and a more complex control strategy compared to single-phase motors. The three-phase design allows for smoother operation and better control over motor speed and torque.

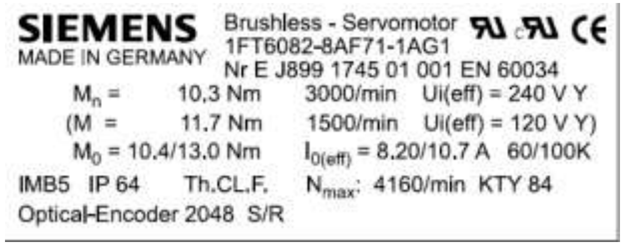
4. Classification:

- These motors are generally classified into two main types based on the arrangement of magnets and windings. The two types are: a. **Outer Rotor Design:** In this design, the rotor is outside the stator. This configuration is often used in applications where low speed but high torque is required. b. **Inner Rotor Design:** Here, the rotor is inside the stator. This design is more common and is used in a variety of applications, offering a good balance of speed and torque.

Implications and Applications

The unique characteristics of brushless DC motors with permanent magnets make them ideal for various applications. They are widely used in aerospace, automotive, robotics, and consumer electronics, where efficiency, reliability, and compact design are critical. The advancements in electronic control systems have further enhanced the capabilities of these motors, enabling precise control and integration into complex systems.

PMSM



SIEMENS Brushless - Servomotor
MADE IN GERMANY 1FT6082-8AF71-1AG1
Nr E J899 1745 01 001 EN 60034
M_n = 10,3 Nm 3000/min Ui(eff) = 240 V Y
(M = 11.7 Nm 1500/min Ui(eff) = 120 V Y)
M_0 = 10.4/13.0 Nm $I_{0(eff)}$ = 8.20/10.7 A 60/100K
IMB5 IP 64 Th.CL.F. N_{max}: 4160/min KTY 84
Optical-Encoder 2048 S/R

Electromagnetic Characteristics

1. Air Gap Flux and Induced Voltage:

In these motors, the air gap flux is crucial for inducing voltage in the stator windings. Due to the nature of the magnetic field generated by the permanent magnets and the motor's geometry, the induced voltage typically has a sinusoidal waveform.

This sinusoidal nature is significant because it leads to more efficient and smoother operation of the motor compared to non-sinusoidal (e.g., trapezoidal) waveforms.

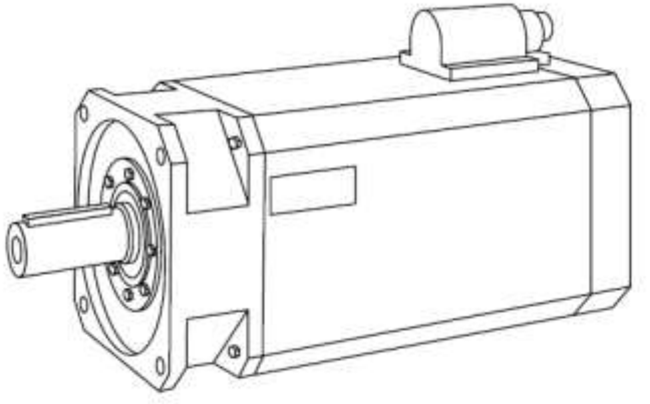
2. Three-Phase Configuration:

As mentioned earlier, these motors are predominantly three-phase. This setup involves arranging the phase windings at 120-degree electrical phase shifts from each other. Such an arrangement ensures a balanced and continuous magnetic field, crucial for smooth rotation and torque generation.

3. Role of Electronic Commutation:

Electronic commutation in brushless DC motors replaces the mechanical switching mechanism found in brushed motors. It involves precisely controlling the timing of current flow through the motor's windings.

The sinusoidal induced voltage requires sinusoidal currents for optimal performance. When the motor is powered by sinusoidal currents, it avoids torque ripples or fluctuations, ensuring a more uniform torque output and efficient energy conversion.



Position Sensing and Control

1. Importance of Precise Position Sensing:

Accurate determination of the motor's rotor position is essential for effective electronic commutation. It enables the control system to synchronize the current supply with the rotor's position.

Simple and inexpensive solutions like Hall effect sensors are often inadequate for this purpose due to their limited precision.

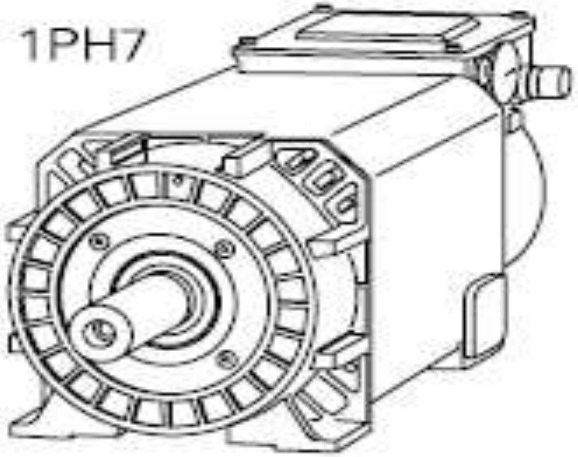
2. Advanced Sensing Solutions:

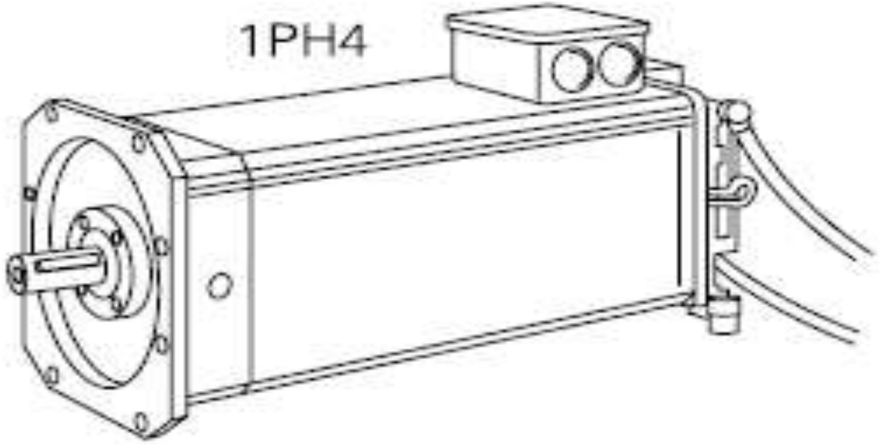
More sophisticated position sensors, such as incremental encoders or resolvers, are typically required. These devices provide higher accuracy and resolution in determining the rotor's position.

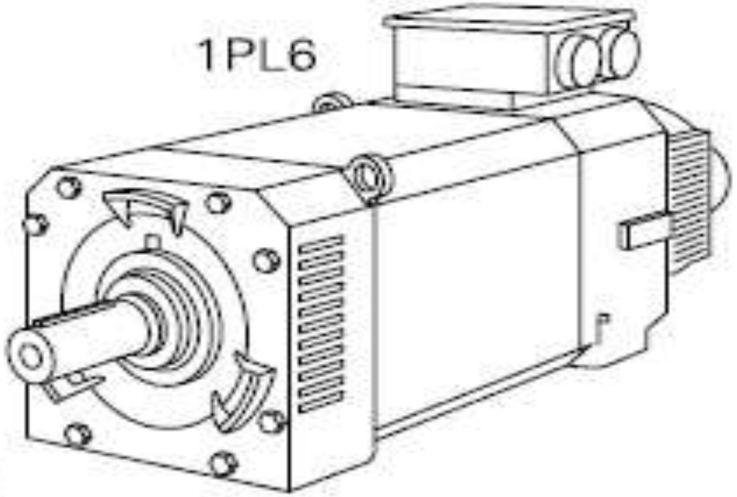
While these advanced sensors may seem like an initial disadvantage due to their complexity and cost, they offer dual benefits. Not only do they facilitate precise commutation, but they also provide necessary feedback for position control. This dual functionality makes them an integral part of the motor's control system.

Integrated Measurement System

The incorporation of an advanced measurement system in brushless DC motors is not just for commutation. It also plays a crucial role in feedback control for precise position and speed regulation. This integrated approach is particularly advantageous in applications requiring high precision and reliability, such as robotics, aerospace, and high-performance industrial machinery.







Motor	Protection	Cooling	Power Range kW (HP)	Rated Torque Nm (lb-ft)
1PH7	IP 55	Blower Vent Surface	3.7 - 215 (5 - 288)	22 - 1145 (16 - 844)
1PL6	IP23	Blower Vent	24.5 - 300 (32.8 - 400)	370 - 1720 (273 - 1268)
1PH4	IP65	Water	7.5 - 61 (10 - 81)	48 - 330 (35 - 243)

Mathematical Model of the PMSM

It is a brushless alternating current machine whose induced voltage varies sinusoidally due to the air gap flux.

$$v_{as} = R_s i_{as} + \frac{d}{dt}\left[\lambda_{as}(\theta_s) i_{as}\right]$$

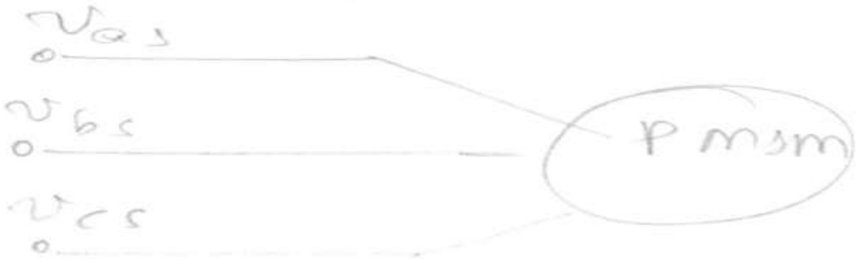
$$v_{bs} = R_s i_{bs} + \frac{d}{dt}\left[\lambda_{bs}(\theta_s) i_{bs}\right]$$

$$v_{cs} = R_s i_{cs} + \frac{d}{dt}\left[\lambda_{cs}(\theta_s) i_{cs}\right]$$

$$\lambda_{as}(\theta, i_{as}) = L_s(\theta) i_{as} \rightarrow \frac{d\lambda_{as}}{dt} = \frac{dL_s(\theta)}{d\theta}\frac{d\theta}{dt} i_{as} + L_s(\theta)\frac{di_{as}}{dt}$$

$$\lambda_{bs}(\theta, i_{bs}) = L_s(\theta) i_{bs} \rightarrow \frac{d\lambda_{bs}}{dt} = \frac{dL_s(\theta)}{d\theta}\frac{d\theta}{dt} i_{bs} + L_s(\theta)\frac{di_{bs}}{dt}$$

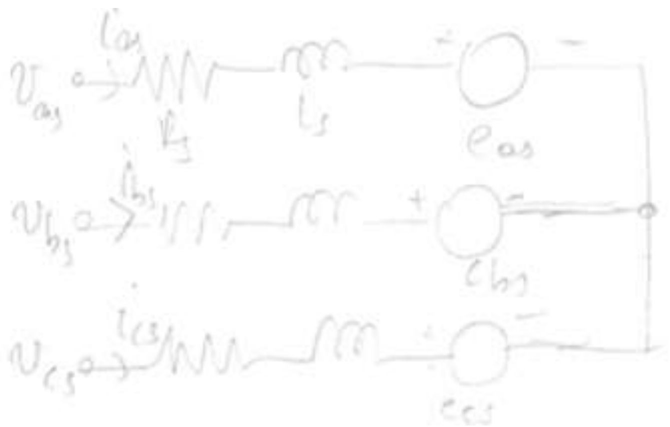
$$\lambda_{cs}(\theta, i_{cs}) = L_s(\theta) i_{cs} \rightarrow \frac{d\lambda_{cs}}{dt} = \frac{dL_s(\theta)}{d\theta}\frac{d\theta}{dt} i_{cs} + L_s(\theta)\frac{di_{cs}}{dt}$$

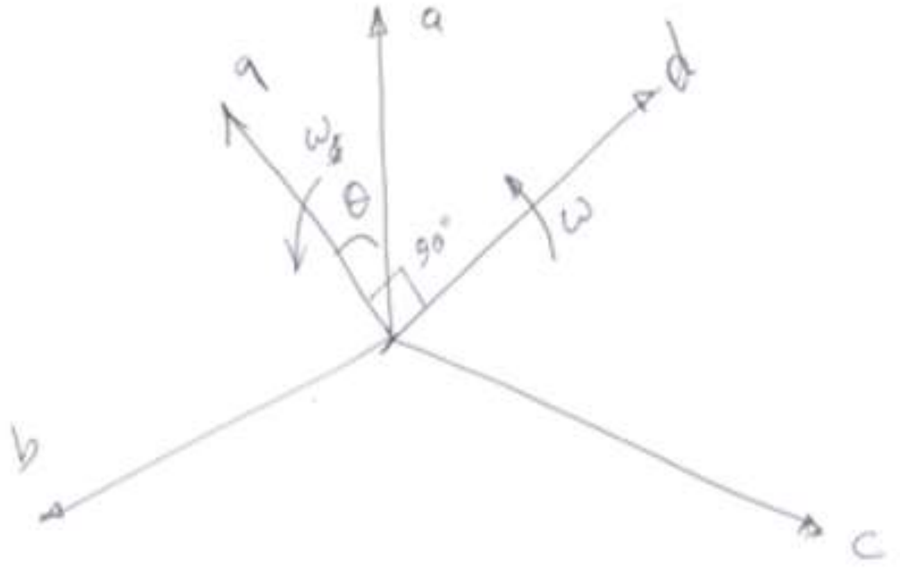


$$\frac{\partial L_s(\theta)}{\partial \theta} i_{as} \frac{d\theta}{dt} = \lambda_{fd}\omega \sin(\theta) = e_{as}$$

$$\frac{\partial L_s(\theta)}{\partial \theta} i_{bs} \frac{d\theta}{dt} = \lambda_{fd}\omega \sin\left(\theta - \frac{2\pi}{3}\right) = e_{bs}$$

$$\frac{\partial L_s(\theta)}{\partial \theta} i_{cs} \frac{d\theta}{dt} = \lambda_{fd}\omega \sin\left(\theta + \frac{2\pi}{3}\right) = e_{cs}$$





$$\begin{bmatrix} X_q \\ X_d \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix}$$

When switching from A-B-C to D-Q axis set, all variables defined in A-B-C axis set become defined in D-Q axis set.

$$i_{a,b,c} \rightarrow i_{d,q}$$

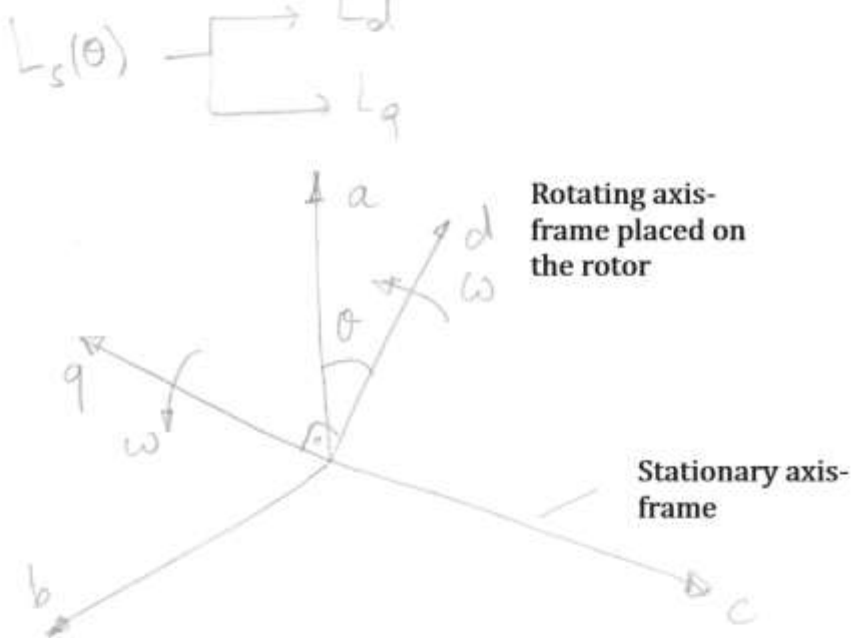
$$v_{a,b,c} \rightarrow v_{d,q}$$

$$e_{a,b,c} \rightarrow e_{d,q}$$

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} - \omega L_d i_d + \omega \lambda_{fd}$$

$$T_m = \frac{3}{2} p\left[\lambda_{fd} i_q + \left(L_d - L_q\right) i_d i_q\right] = J\frac{d\omega_m}{dt} + B\omega_m + T_L$$



Rotating axis-frame placed on the rotor

Stationary axis-frame

Permanent Magnet Synchronous Motors are widely used in various applications due to their high efficiency, high power density, and robust performance. These motors use permanent magnets embedded in the rotor, producing a constant magnetic field. The interaction of this field with the stator winding creates rotation.

Control Techniques for PMSM

Constant Torque Angle Control or Zero d-axis Current Control

Principle: This method is based on maintaining a constant angle between the stator current vector and the rotor magnetic field vector. Ideally, this angle is 90 degrees to ensure maximum torque per ampere.

Application: It's used in applications requiring constant torque and precise control, such as robotics and CNC machines.

Advantages & Challenges: It offers excellent torque control but requires accurate rotor position information, which can be a challenge in sensorless systems.

Field Weakening Control (For High-Speed Operations)

Principle: Field weakening allows the motor to operate beyond its nominal speed by reducing the magnetic field strength. This is achieved by injecting a d-axis current component that opposes the rotor's magnetic field.

Application: Used in applications needing a wide speed range, such as electric vehicles or high-speed machinery.

Advantages & Challenges: It extends the motor's speed range but can lead to increased losses and heating, necessitating careful thermal management.

Field-Oriented Control (FOC)

Principle: FOC, also known as vector control, involves controlling the stator currents represented in a rotating reference frame aligned with the rotor's magnetic field. This method decouples the control of torque and flux.

Application: Widely applicable in various sectors, including automotive, aerospace, and industrial automation.

Advantages & Challenges: Provides precise control of both torque and speed, adapting well to dynamic load changes. The complexity of implementation and the need for accurate rotor position information are its main challenges.

Advanced Topics in PMSM Control

Sensorless Control: Innovations in sensorless control, where rotor position is estimated rather than measured, are crucial for reducing cost and increasing reliability.

Adaptive and Predictive Control Strategies: These involve adjusting control parameters in real-time based on changing load conditions or predicting future states for more efficient operation.

Integration with Power Electronics: The synergy between motor control and advances in power electronics, like wide bandgap semiconductors, opens up new frontiers in efficiency and performance.

$$\underline{i_d \to 0}$$

$\lambda_{fd} \simeq$ **constant**

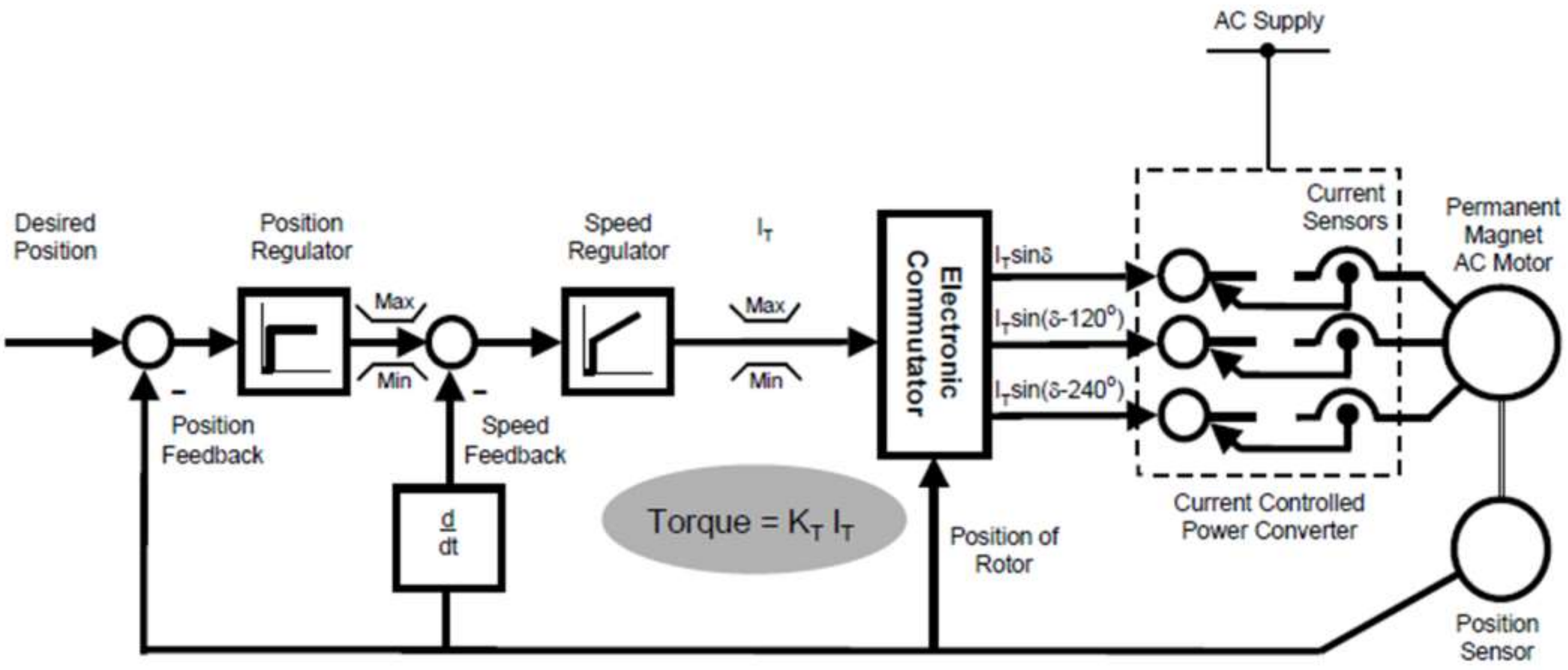
$$v_q = R_s i_q + L_q \frac{di_q}{dt} + p\omega_m \cancelto{0}{L_d i_d} + \underbrace{p\omega_m \lambda_{fd}}_{\textbf{induced voltage}}$$

$$v_d = R_s \cancelto{0}{i_d} + L_d \cancelto{0}{\frac{di_d}{dt}} - p\omega_m L_q i_q$$

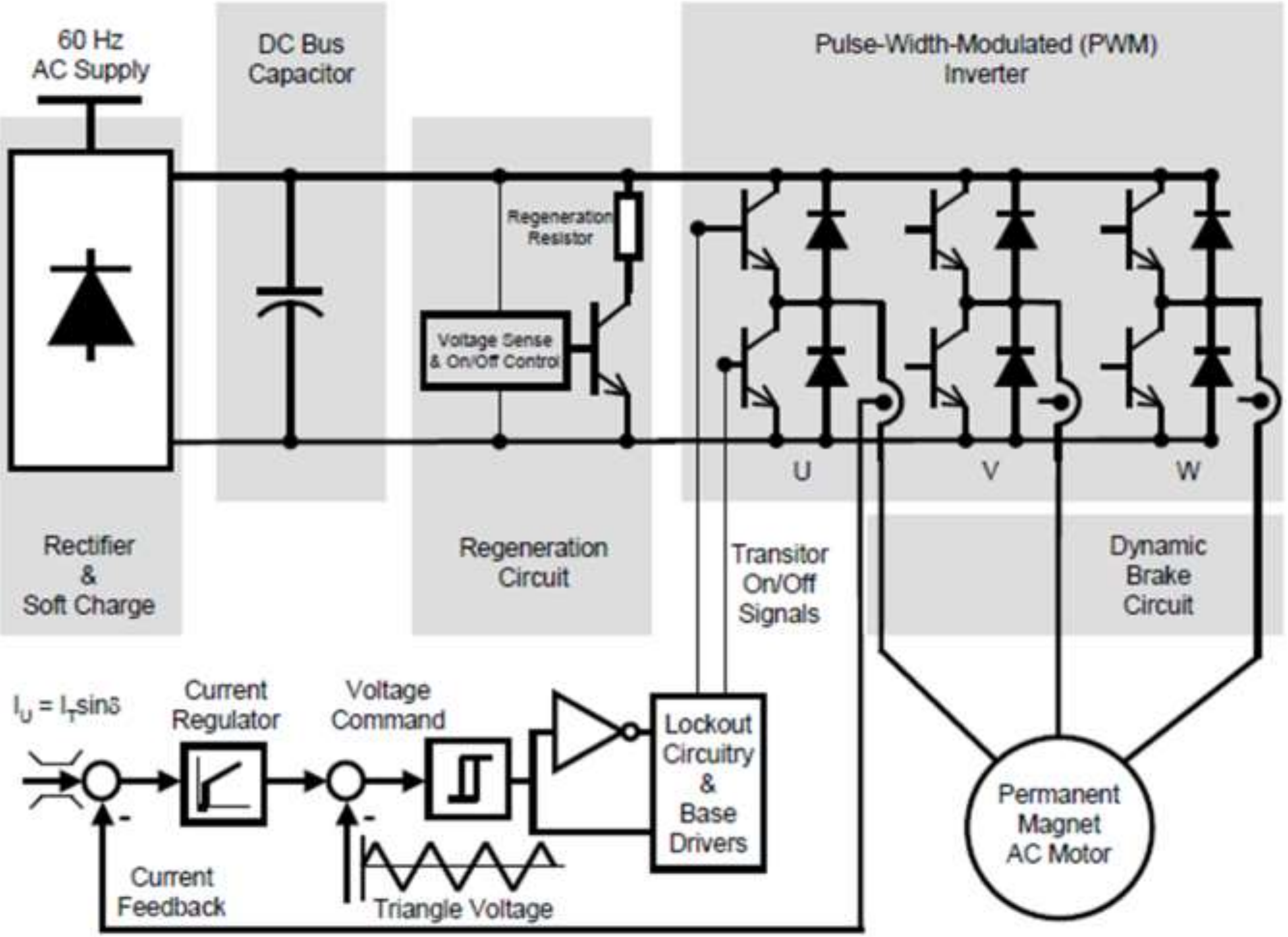
$v_d = -p\omega_m L_q i_q$ olarak oluşturulur.

$$T_m = \frac{3}{2} p \left[\lambda_{fd} i_q\right] = k_t i_q$$

Turned into Brushed DC Motor

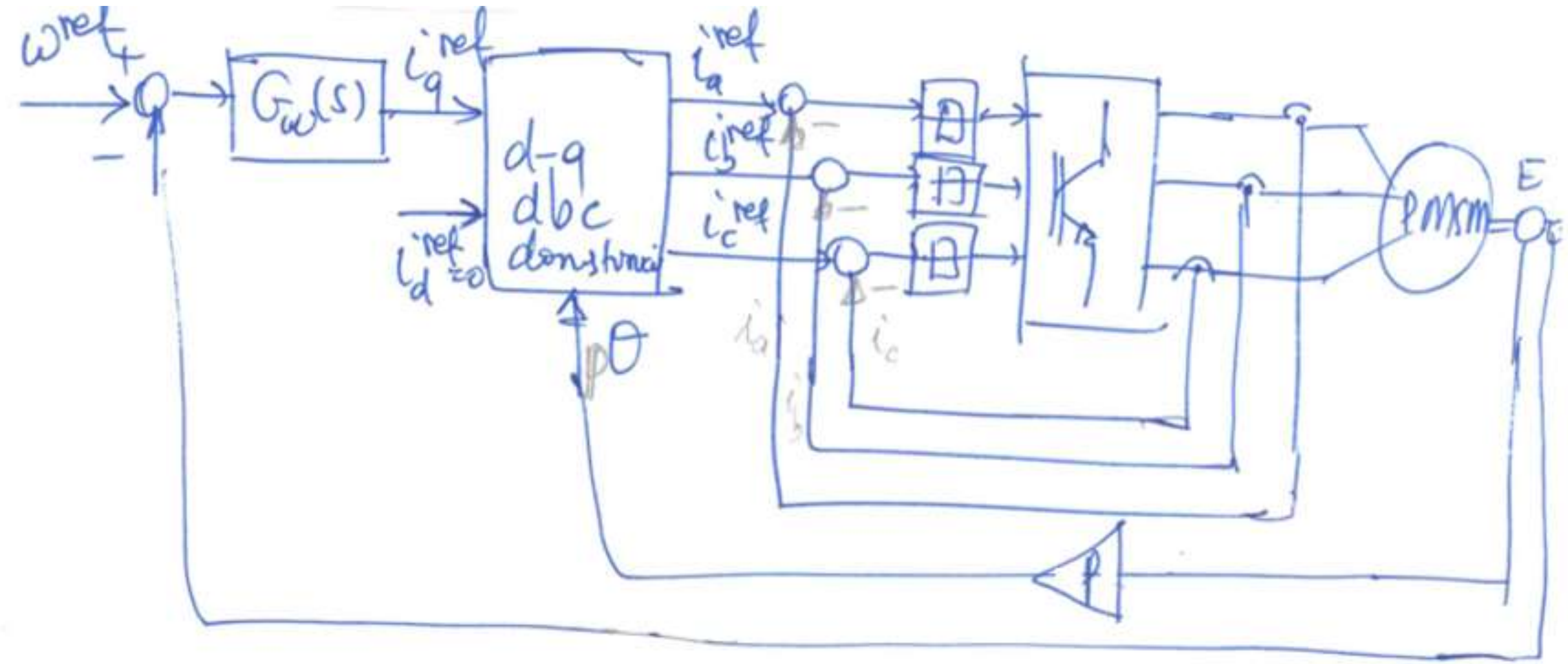


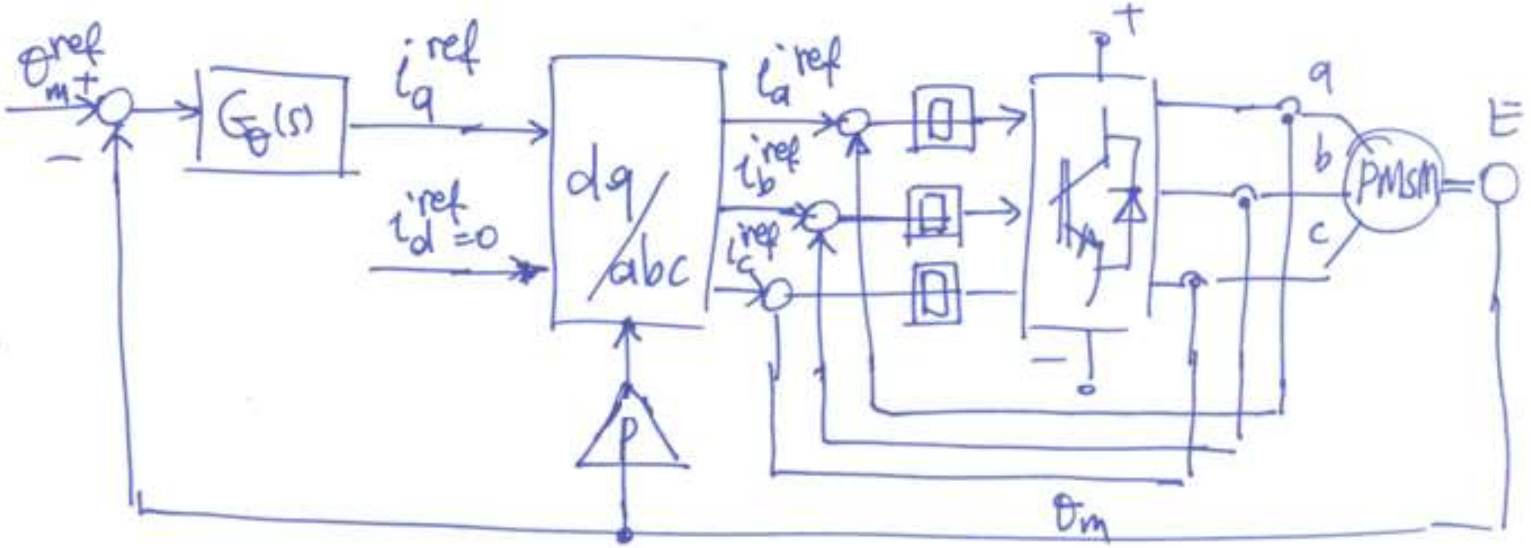
Cascade Control Structure of the High Performance AC Servo System with Field-Oriented Control



Block Diagram of the Current Controlled Power Converter

Hysteresis-PWM Control





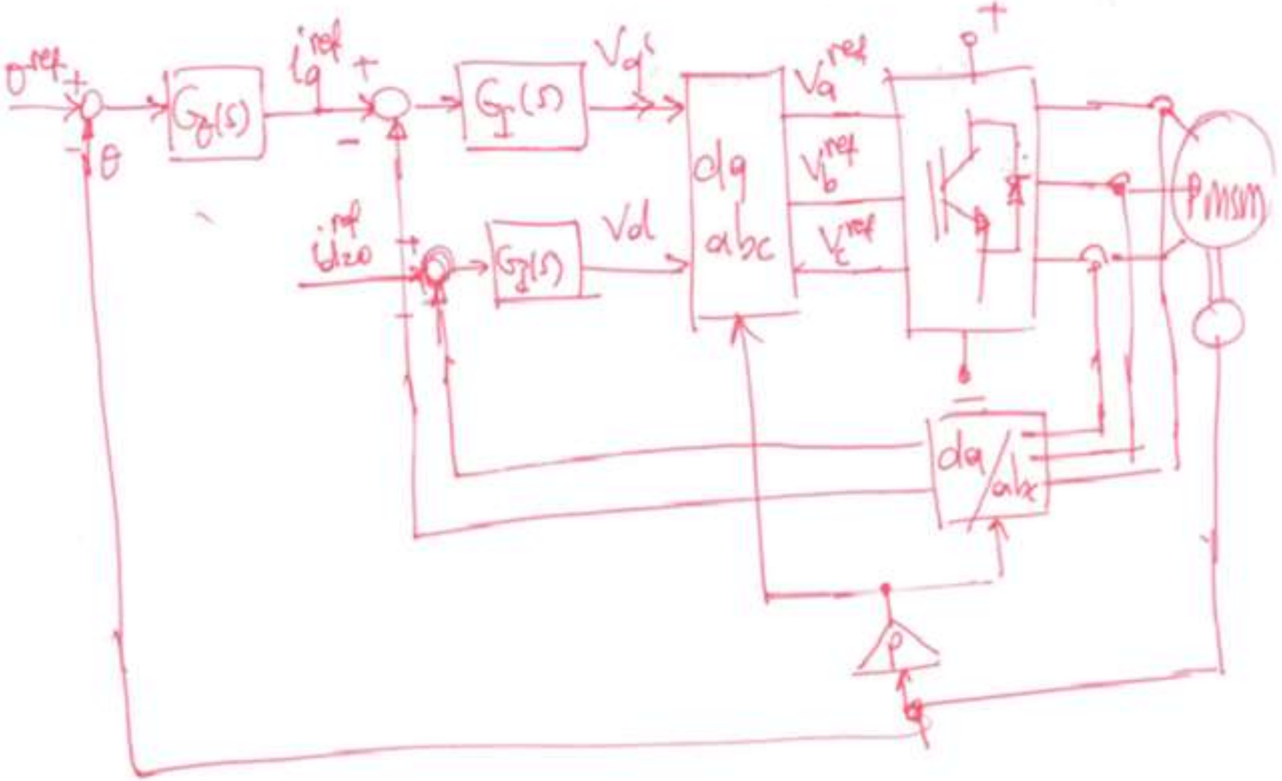
$$i_a^{ref} = I_q^{ref}\cos(p\theta_m) + i_d^{ref}\sin(p\theta_m)$$

$$i_b^{ref} = I_q^{ref}\cos\left(p\theta_m - \frac{2\pi}{3}\right) + i_d^{ref}\sin\left(p\theta_m - \frac{2\pi}{3}\right)$$

$$i_c^{ref} = I_q^{ref}\cos\left(p\theta_m - \frac{4\pi}{3}\right) + i_d^{ref}\sin\left(p\theta_m - \frac{4\pi}{3}\right)$$

$i_a^{ref}, i_b^{ref}, i_c^{ref}, \quad i_q^{ref}$

PWM **Current Control**



Example

$R_s = 4.765\,\Omega$

$L_d - L_q = 14 \cdot 10^{-3}$ H

$\lambda_{fd} = 0.1848$ Wb

$V_{dc} = 300$ V

$n_{mn} = 3750$ rpm

pmsm

$J_m = 1.05 \cdot 10^{-4}$ kgm^2

$B_m = 4.05 \cdot 10^{-4}$ Nm s/rad

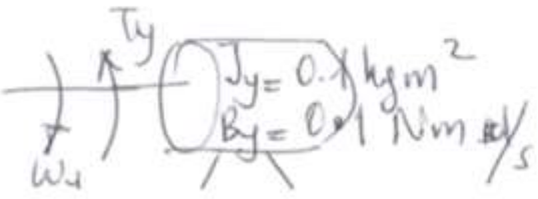
$p = 2$

$T_{mn} = 2.1$ Nm

$n_m = 2000$ rpm

$\ddot{u} = 10$ **Transmission Ratio (Mechanical)**

Constant Torque $(i_d^{ref} = 0)$ **Control Method**



$T_y = 15$ Nm

constant

a) Calculate the maximum value of the current passing through the windings of the star-connected motor in steady state.

b) Calculate the values of the voltages vd and vq applied to the motor in steady state.

$$\omega_y = \frac{\omega_m}{ü} = \frac{2\pi n_m}{60 * ü} = \frac{2\pi \cdot 2000}{600} = 20.94 \text{ rad/s}$$

$$T_m = \frac{1}{10}\left(15 + 0.1405 * 20.94\right)$$

$$= 1.794 \text{ Nm}$$

$$T_m = k_t \cdot i_q = \frac{3}{2} p \lambda_{fd} \cdot i_q$$

$$= 1.5 * 2 * 0.1848 * i_q$$

$$i_q = \frac{1.794}{3 * 0.1848} = \underline{\underline{3.236 \text{ A}}}$$ bulunur.

$$i_q = I_m = 3.236 \text{ A}$$

$$i_q^{ref} \simeq i_q$$

$$T_m = \frac{1}{ü}\left(T_y + B \cdot \omega_y\right) + \frac{1}{ü}\left(J_m ü^2 + J_y\right)\alpha$$

$$B = B_m ü^2 + B_y = 4.05 \cdot 10^{-4} * 100 + 0.1$$

$$= 0.1405 \text{ Nms/rad}$$

$$v_q = R_s\, i_q + p\,\omega_m \lambda_{fd}$$

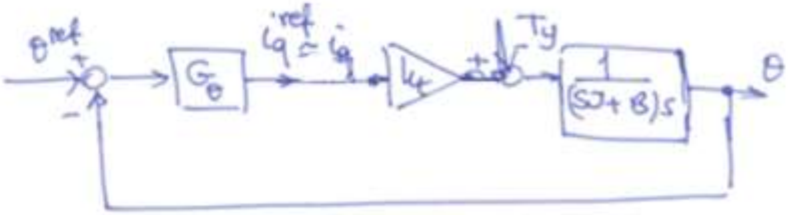
$$= 4.765 * 3.236 + 2 * \frac{2\pi\, 2000}{60} \cdot 0,1848$$

$$= 92,83 \text{ V}$$

$$v_d = -2 * \frac{2000 * 2\pi}{60} * 14 \cdot 10^{-3} * 3,236$$

$$= -18.977 \text{ V}$$

Position control with zero steady-state error



a) $T_y = 0$
b) T_y [illegible] T_y

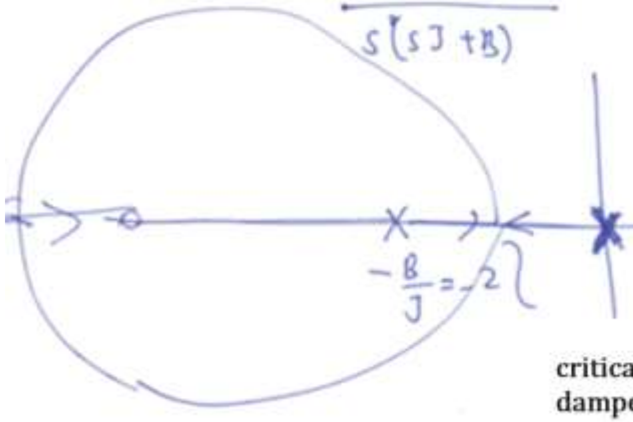
G_θ

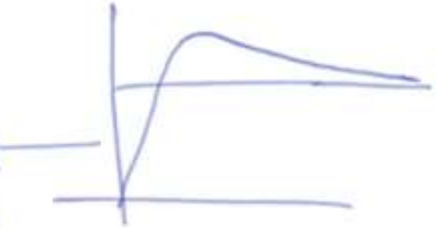
$J = 0.01\ kgm^2$
$B = 0.02\ Nms/rad$

$T_y = 15\ Nm$
$k_t = 1$

$T_y = 0$

$$\frac{G_\theta \cdot k_t}{s(sJ+B)}$$





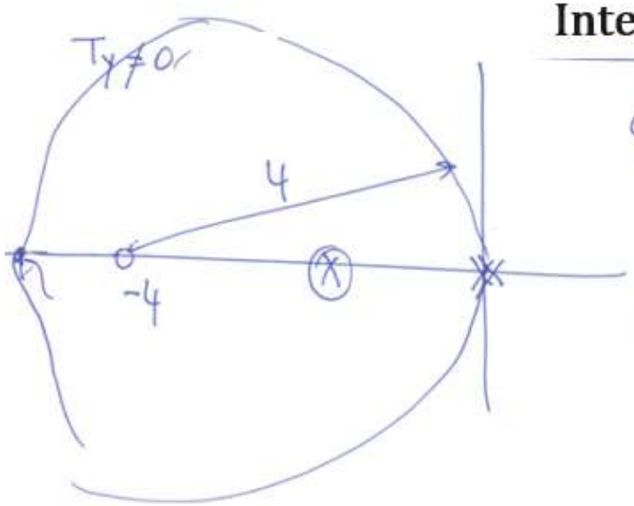
critically
damped

$$\frac{G_\theta(s)\quad 100}{s(s+2)}$$

PD

$$G_\sigma(s) = K(s+a)$$

$a = 10$



Internal mode control

$$G_\theta = \frac{(s+a)(s+b)K}{s}$$

$a = 2$

$b = \underline{\underline{4}}$

$(s+8)^2$

breaking point

$\boxed{s=-8}$

$$\frac{(s\overset{2}{\cancel{+a}})(s+\overset{4}{b})\overset{K_1}{K{*}100}}{s^2(s\cancel{+2})}$$

characteristic equation:

$$s^2 + K_1 s + 4K_1 = 0$$

$$s^2 + 16s + 64 = 0$$

$$\boxed{K_1 = 4}$$

$$\overset{K}{\frac{4}{100}}\left[s^2 + (a+b)s + a.b\right]$$

$$\underset{\underset{K_d}{\uparrow}}{\frac{4}{100}s^2} + \underset{\underset{K_p}{\uparrow}}{\frac{24}{100}}s + \underset{\underset{K_I}{\uparrow}}{\frac{32}{100}}$$

$$G_\theta(s) = K_p + \frac{K_I}{s} + K_d s$$

$K_p = 0.24$

$K_I = 0.32$

$K_D = 0.04$

Field weakening is employed when operation above the nominal speed is required. In PMSMs, the speed of the motor is directly related to the frequency of the stator voltage and inversely related to the number of pole pairs. However, beyond a certain speed (the base speed), increasing the frequency further becomes impractical due to voltage limits imposed by the inverter and the motor's insulation.

Key Concepts in Field Weakening:

1. **Torque-Speed Characteristics**:
    1. At high speeds, due to power limitations, the motor operates with high angular speed but low torque.
    2. Meaning: At higher speeds, the motor should be loaded with lower torque. This is a fundamental limitation due to the constant power operation range.
2. **Control of d-axis Current (id) and Flux (λd)**:
    1. Decreasing d-axis flux (λd) is necessary for acceleration beyond the base speed.
    2. This is achieved by introducing a negative d-axis current (id), which reduces the d-axis flux.
    3. Significance: Reducing λd allows the voltage to be used more for speed than for flux, thus facilitating higher speeds.

$\omega_m \nearrow \quad T_m \downarrow$ **Power Limitation**

$$T_m = k \cdot \lambda_{fd} \cdot i_q$$

$$\lambda_d = \lambda_{fd} + L_d \underbrace{i_d}_{<0}$$

$$V_q = R_q i_q + L_q \frac{di_q}{dt} + \underbrace{\left(L_d i_d + \lambda_{fd}\right)}_{\lambda_d} p \omega_m \qquad \text{e.m.k.}$$

Steady-State

$$V_q = R_q i_q + \left(L_d i_d + \lambda_{fd}\right) \omega_m$$

$$\Uparrow \omega_m = \frac{\Uparrow V_q - R_q i_q}{\left(L_d i_d + \lambda_{fd}\right) p}$$

Constraints and Limitations

q-axis voltage (Vq) can be increased up to its nominal value, but not beyond due to insulation constraints.

For higher speeds, reduction of d-axis flux is necessary, which requires negative id.

Regarding torque production at speeds above nominal:

The q-axis current (iq) can be increased up to its nominal value.

Temporarily, iq can reach up to 1.5 times its nominal value, but this is not sustainable due to overheating and insulation damage risks.

Continuous operation at this level will lead to motor overheating and potential damage to the insulation, thus iq must be limited.

Practical Implications and Considerations

Motor Efficiency: Operating in the field-weakening region can lead to reduced efficiency due to increased current and hence increased losses.

Thermal Management: Adequate cooling and thermal management are essential, especially when operating with increased iq for extended periods.

Control Challenges: Precise control of id and iq is crucial, often requiring advanced control algorithms and real-time adjustments based on motor and load characteristics.

$$0 \le V_q \le V_{q_n}$$

$$0 \le \omega_m \le \omega_{m_n}$$

$$V_q = V_{q_n}$$

$$\lambda_d \downarrow \qquad \omega_m \nearrow$$

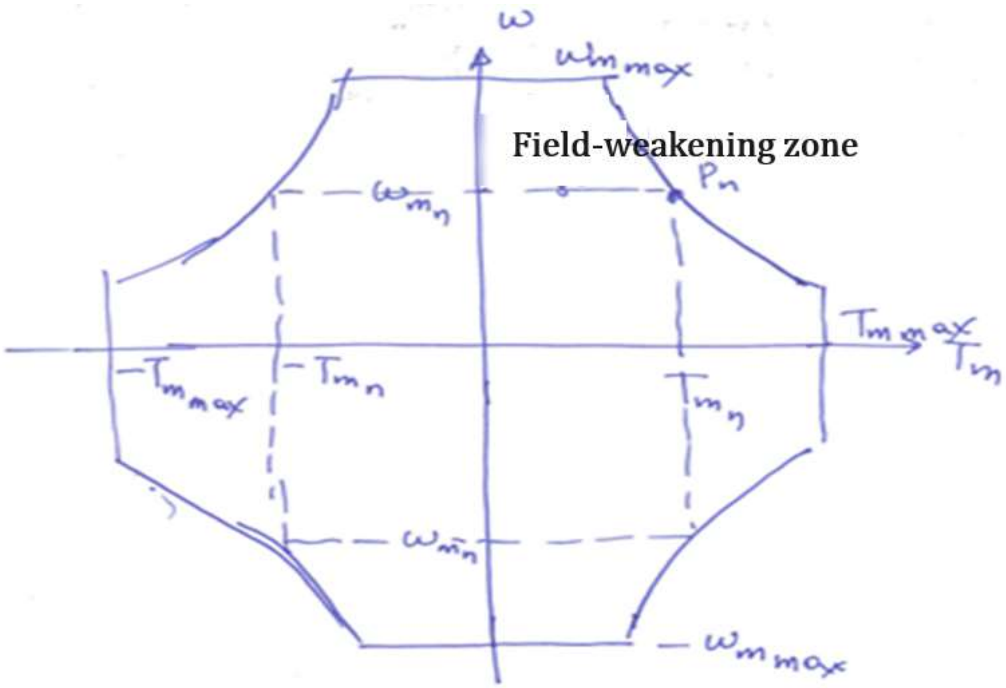
$$T_m = \frac{3}{2} p \lambda_d i_q$$

$$i_q \Rightarrow i_{q_n}$$

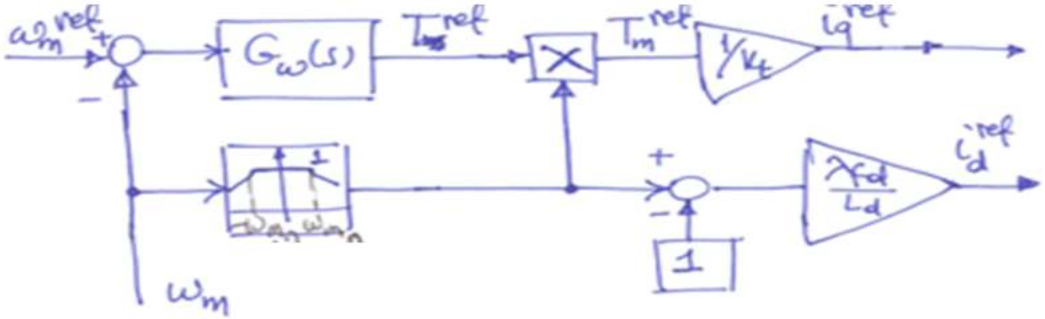
$$i_q \leq i_{q_n}$$

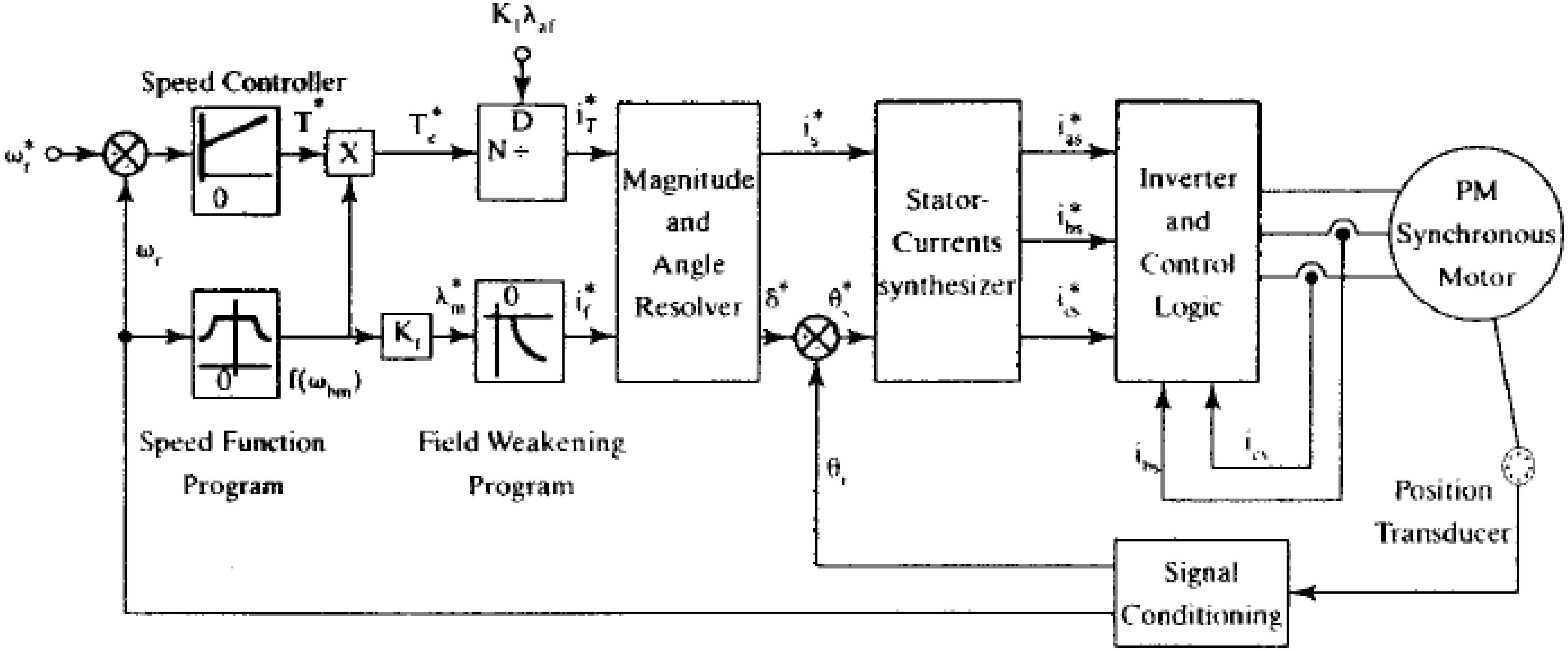
$$i_q = 1.5\, i_{q_n}$$

$$T_{m_n} \cdot \omega_n = P_n = \overset{\cup}{\cancelto{}{\omega}}_m \cancel{T}_m$$


Field-weakening zone

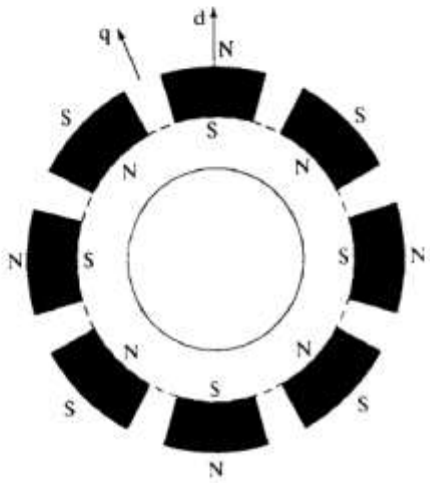
Field-Weakening Control Scheme



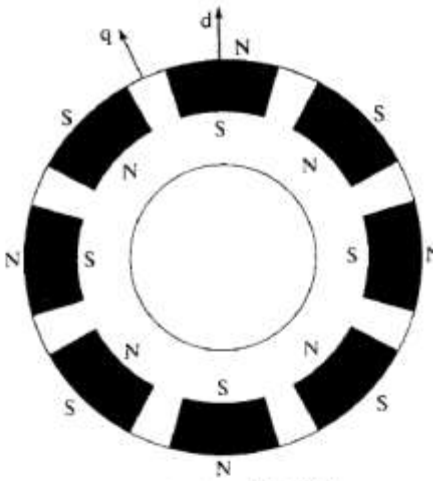


Note : N — Numerator

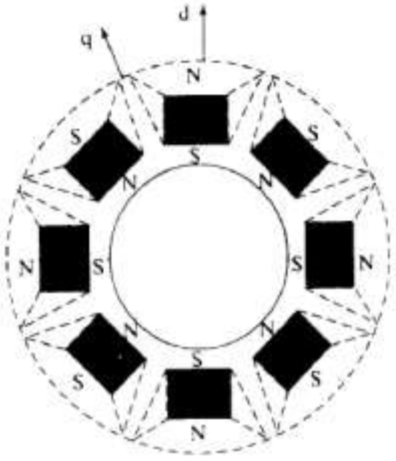
D — Denominator



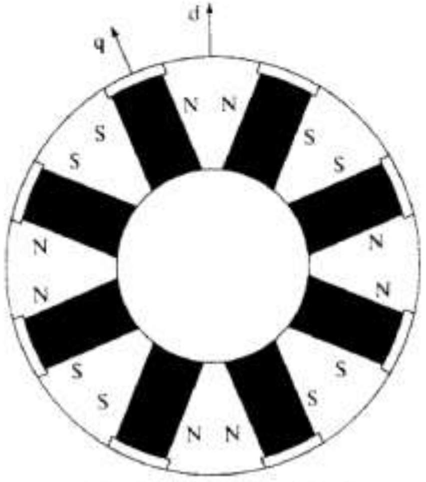
(i) Surface PM (SPM) synchronous machine



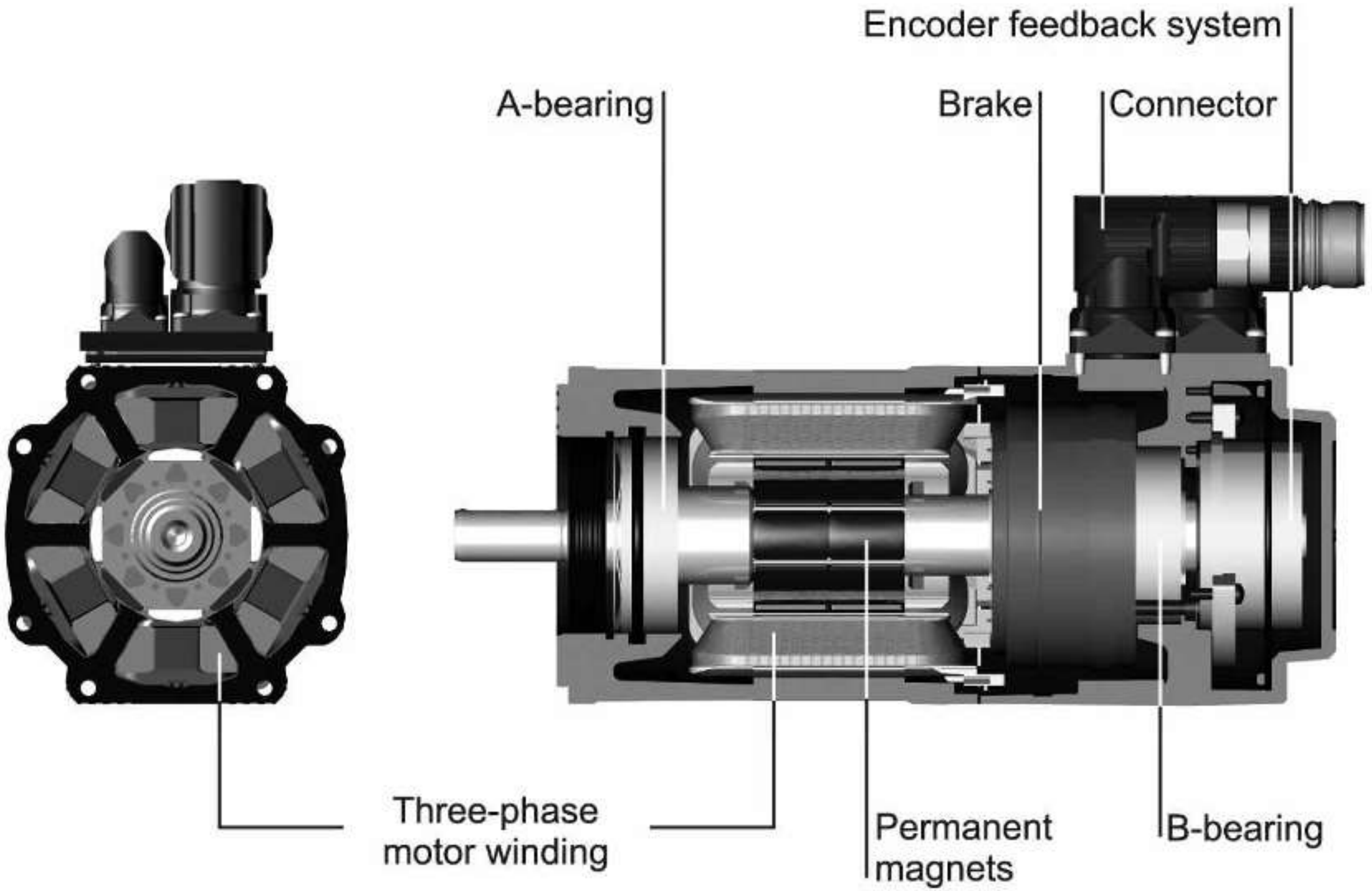
(ii) Surface inset PM (SIPM) synchronous machine

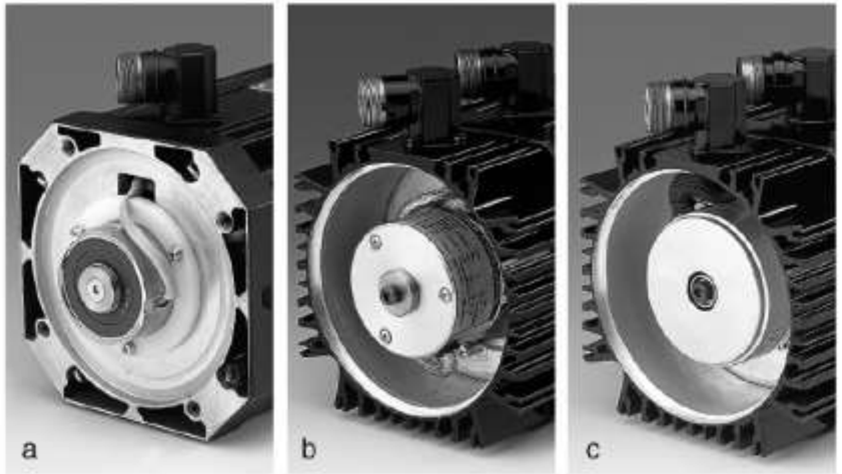


(iii) Interior PM (IPM) synchronous machine

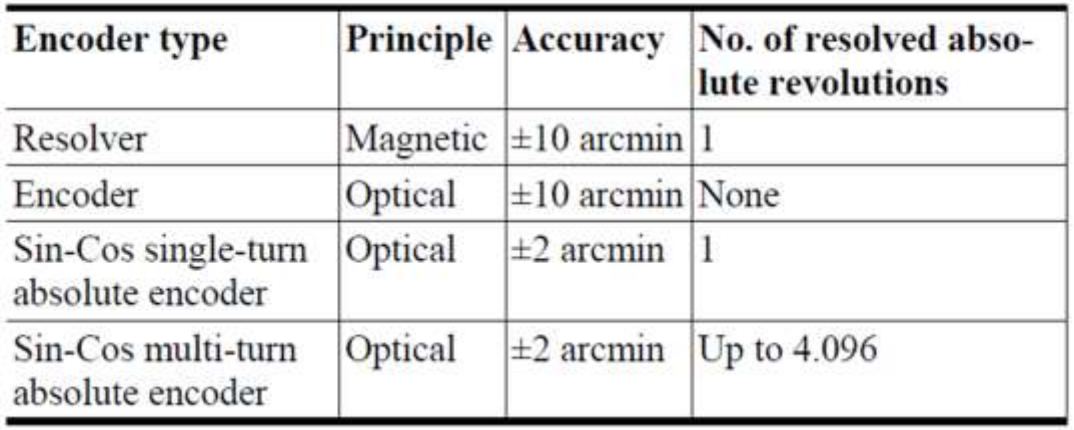


(iv) Interior PM with circumferential orientation synchronous machine

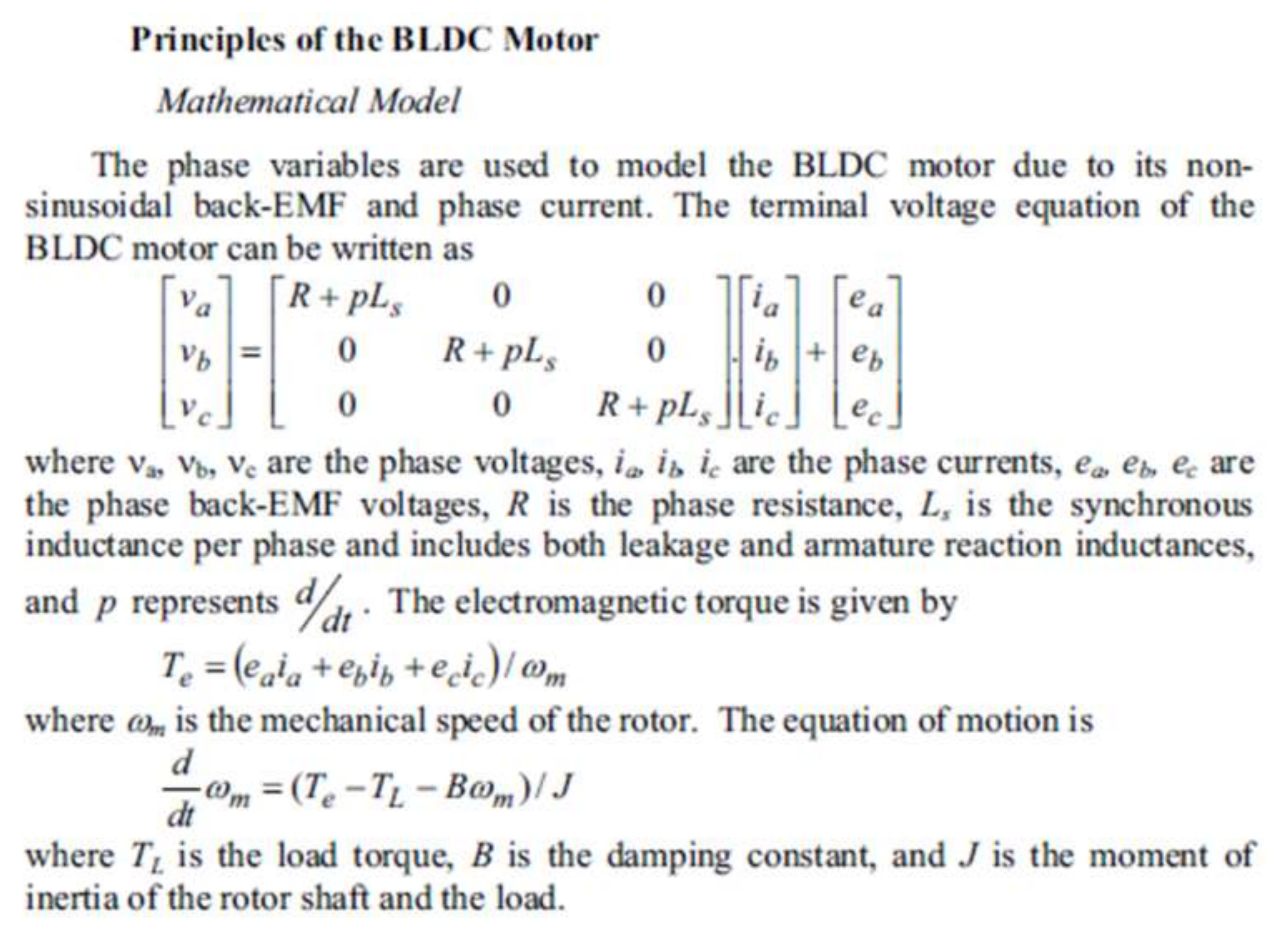

Encoder feedback system
A-bearing
Brake
Connector
Three-phase motor winding
Permanent magnets
B-bearing



Encoder installed in a servo motor: a: Resolver, b: Incremental encoder, c: Sin-Cos absolute encoder



Encoder type	**Principle**	**Accuracy**	**No. of resolved absolute revolutions**
Resolver	Magnetic	±10 arcmin	1
Encoder	Optical	±10 arcmin	None
Sin-Cos single-turn absolute encoder	Optical	±2 arcmin	1
Sin-Cos multi-turn absolute encoder	Optical	±2 arcmin	Up to 4.096



Principles of the BLDC Motor

Mathematical Model

The phase variables are used to model the BLDC motor due to its non-sinusoidal back-EMF and phase current. The terminal voltage equation of the BLDC motor can be written as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R + pL_s & 0 & 0 \\ 0 & R + pL_s & 0 \\ 0 & 0 & R + pL_s \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

where v_a, v_b, v_c are the phase voltages, i_a, i_b, i_c are the phase currents, e_a, e_b, e_c are the phase back-EMF voltages, R is the phase resistance, L_s is the synchronous inductance per phase and includes both leakage and armature reaction inductances, and p represents d/dt. The electromagnetic torque is given by

$$T_e = \left(e_a i_a + e_b i_b + e_c i_c\right) / \omega_m$$

where ω_m is the mechanical speed of the rotor. The equation of motion is

$$\frac{d}{dt}\omega_m = (T_e - T_L - B\omega_m) / J$$

where T_L is the load torque, B is the damping constant, and J is the moment of inertia of the rotor shaft and the load.

Torque Generation

the electromagnetic torque of the BLDC motor is related to the product of the phase back-EMF and current. The back-EMFs in each phase are trapezoidal in shape and are displaced by 120 electrical degrees with respect to each other in a three-phase machine. A rectangular current pulse is injected into each phase so that current coincides with the crest of the back-EMF waveform, hence the motor develops an almost constant torque. This strategy, commonly called six-step current control, The amplitude of each phase's back-EMF is proportional to the rotor speed, and is given by

$$E = k\phi\omega_m$$

where k is a constant and depends on the number of turns in each phase, ϕ is the permanent magnet flux, and ω_m is the mechanical speed. during any 120^0 interval, the instantaneous power converted from electrical to mechanical is the sum of the contributions from two phases in series, and is given by

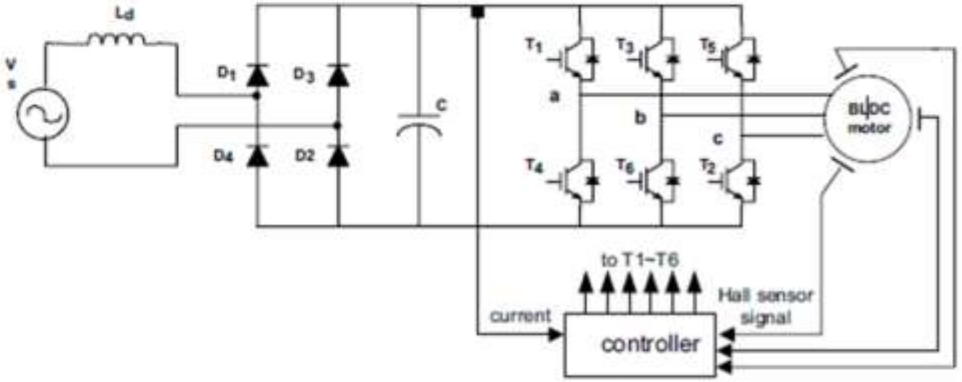
$$P_o = \omega_m T_e = 2EI$$

where T_e is the output torque and I is the amplitude of the phase current.

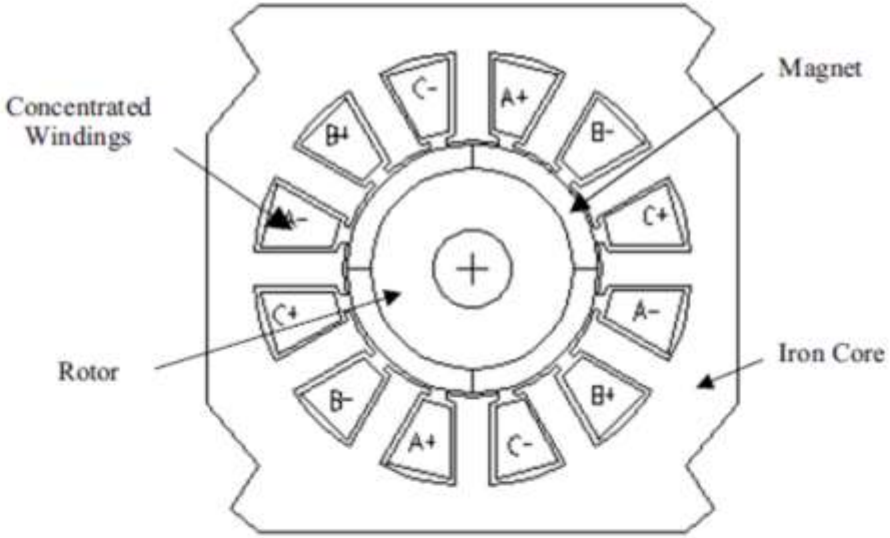
, the expression for output torque can be written as

$$T_e = 2k\phi I = k_t I$$

where k_t is the torque constant. Since the electromagnetic torque is only proportional to the amplitude of the phase current , torque control of the BLDC motor is essentially accomplished by phase current control.



BLDC motor control system.



The 4-pole 12-slot BLDC motor.

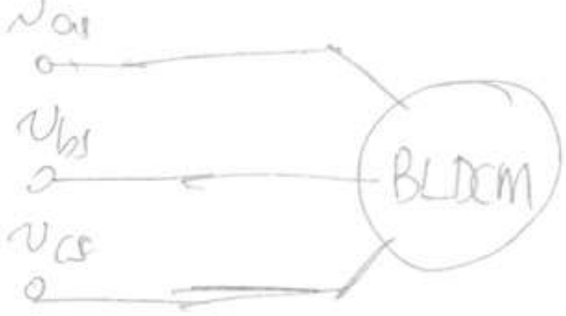
$$E_p = K_p \lambda_p \omega_m \qquad P = 2 K_p \lambda_p \omega_m I_p$$

$$P = T_m \cdot \omega_m \rightarrow T_m = \underbrace{2 K_p \lambda_p}_{k_t} I_p = k_t \cdot I_p$$

$$v_{as} = R_s i_{as} + \frac{d \lambda_{as}(\theta, i_{as})}{dt}$$

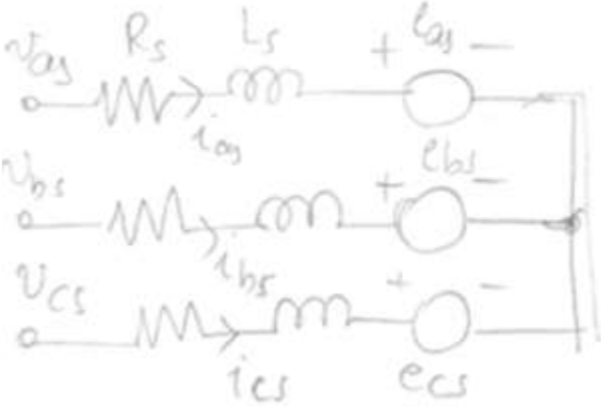
$$v_{bs} = R_s i_{ab} + \frac{d \lambda_{bs}(\theta, i_{bs})}{dt}$$

$$v_{cs} = R_s i_{cs} + \frac{d \lambda_{cs}(\theta, i_{cs})}{dt}$$



If saturation effect is neglected

$$\frac{d\lambda_{as}(\theta, i_{as})}{dt} = \frac{d}{dt}\left[L_s(\theta)\, i_{as}\right] = \underbrace{\frac{\partial L_s(\theta)}{\partial \theta}}\cdot \underbrace{\frac{d\theta}{dt}}_{\omega} i_{as} + L_s(\theta)\cdot\frac{di_{as}}{dt}$$



$$\underbrace{\frac{\partial L_s(\theta)}{\partial \theta}}\cdot i_{as}\cdot\omega = \underbrace{\lambda_p\, f_{as}(\theta)}_{\text{trapezoidal}}\cdot\omega = e_{as}$$

$$\underbrace{\frac{\partial L_s(\theta)}{\partial \theta}}\, i_{bs}\cdot\omega = \underbrace{\lambda_p\, f_{bs}(\theta)}\cdot\omega = e_{bs}$$

$$\underbrace{\frac{\partial L_s(\theta)}{\partial \theta}}\, \underbrace{i_{cs}}\cdot\omega = \underbrace{\lambda_p\, f_{cs}(\theta)}\cdot\omega = e_{cs}$$

Trapezoidal Function

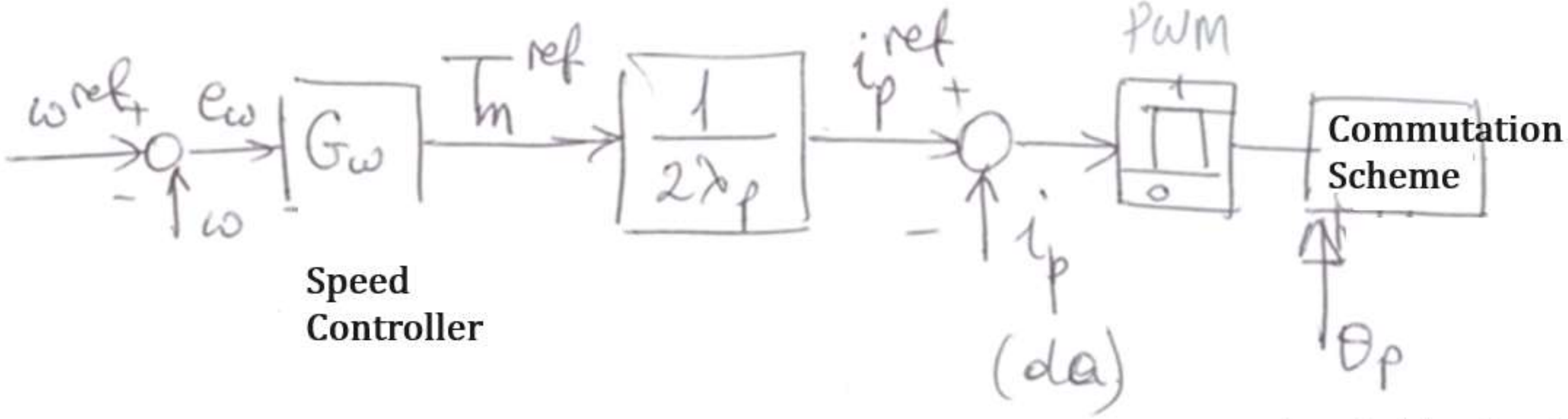
$f_{as}(\theta) \longrightarrow$

$$T_m = \lambda_p \left[\underbrace{f_{as}(\theta)\, i_{as} + f_{bs}(\theta)\, i_{bs} + f_{cs}(\theta)\, i_{cs}}_{2I_p} \right] = J\frac{d\omega_m}{dt} + B\omega_m + T_y$$

$$\theta = p\theta_m$$

$$\omega = p\omega_m$$

$$T_m = \frac{e_{as} i_{as} + e_{bs} i_{bs} + e_{cs} i_{cs}}{\omega}$$



Speed Controller

Commutation Scheme

6-switching level

Understanding Electrical Angle (θp) in BLDC Motors

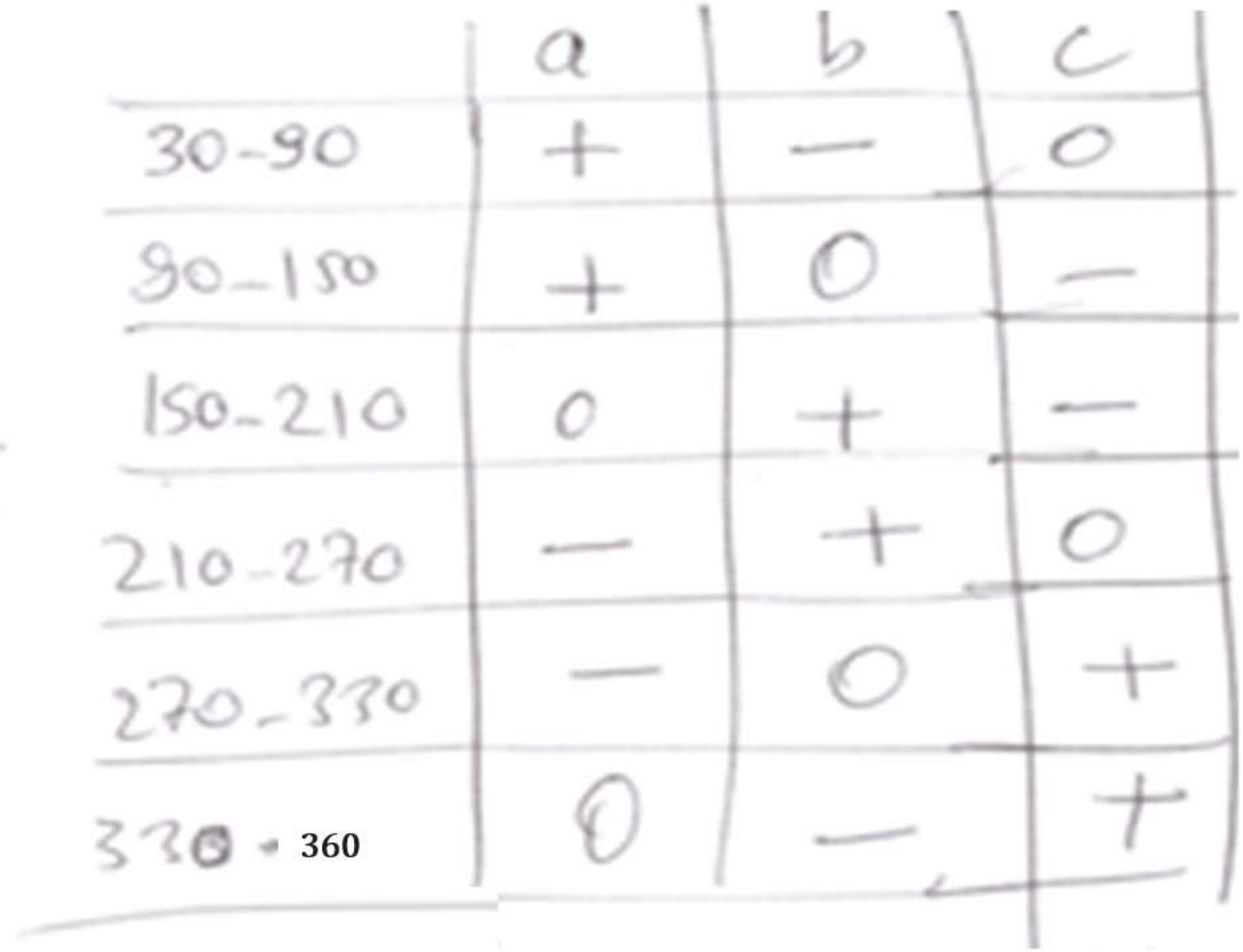
1. **Role of θp in Induced Voltages**:
    1. In BLDC motors, θp is crucial for identifying the start and end points of the induced voltages in the motor coils.
    2. These points are essential for accurate timing of the motor's commutation, which is the process of switching current in the motor windings to maintain rotation.
2. **Importance in Commutation**:
    1. Accurate commutation is vital for the efficient operation of BLDC motors. It ensures that the electromagnetic forces are applied at the right moments to produce smooth and efficient rotation.

Commutation in 3-Phase BLDC Motors

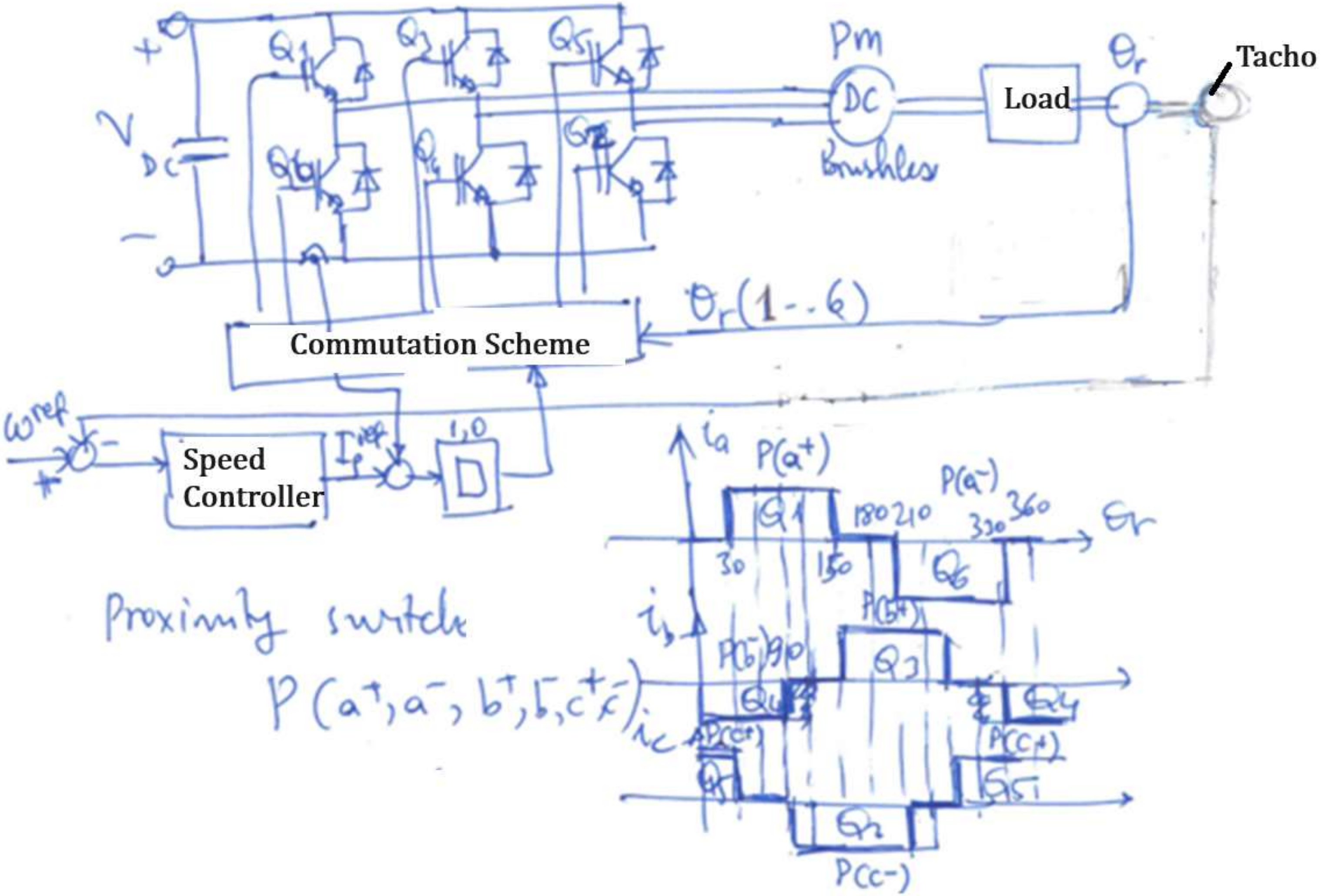
1. **Basic Commutation Principle**:
    1. In a 3-phase BLDC motor, only six distinct positions are needed for each electrical cycle for effective commutation.
    2. At any given time (t), only two of the three phases are conducting: one with positive and the other with negative current.
2. **Use of Hall Sensors**:
    1. BLDC motors often utilize Hall sensors for determining the rotor's position relative to the stator coils.
    2. These sensors provide the necessary signals for commutation, indicating which phases of the motor should be energized.
3. **Implementation of Hall Sensors**:
    1. Typically, three Hall sensors are used, each placed at a 120-degree electrical angle from each other.
    2. They are positioned on a rotating platform, oriented to face small magnets (usually on the rotor).
    3. As the rotor turns, the magnets pass by the Hall sensors, generating signals that correspond to the rotor's position.

Significance and Applications

- **Precision in Control**: The accurate positioning and use of Hall sensors enable precise control over the motor’s speed and torque, which is crucial in applications requiring high precision and efficiency.
- **Application Areas**: BLDC motors with such commutation strategies are widely used in applications ranging from electric vehicles to drones, household appliances, and industrial automation.

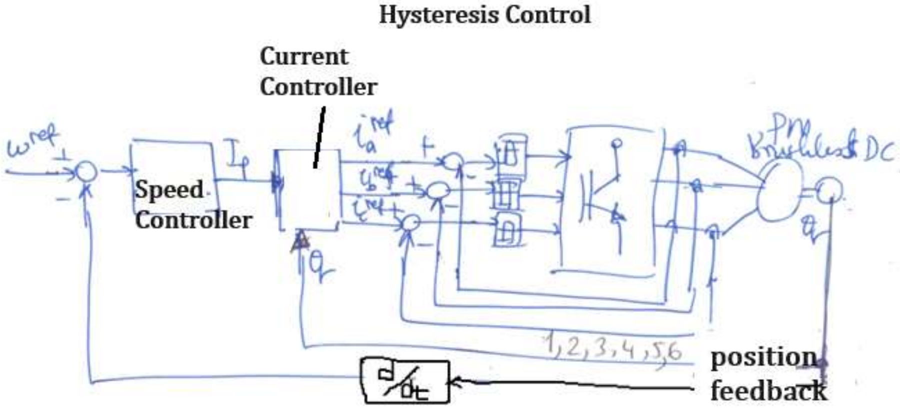


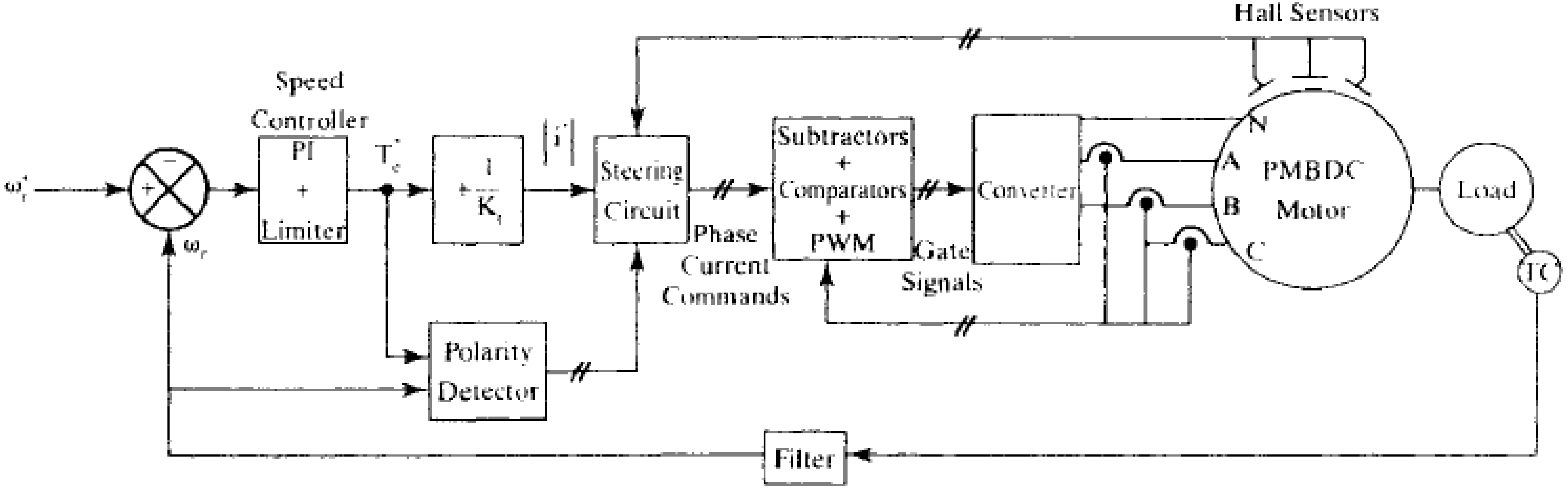
	a	b	c
30-90	+	–	0
90-150	+	0	–
150-210	0	+	–
210-270	–	+	0
270-330	–	0	+
330 - 360	0	–	+

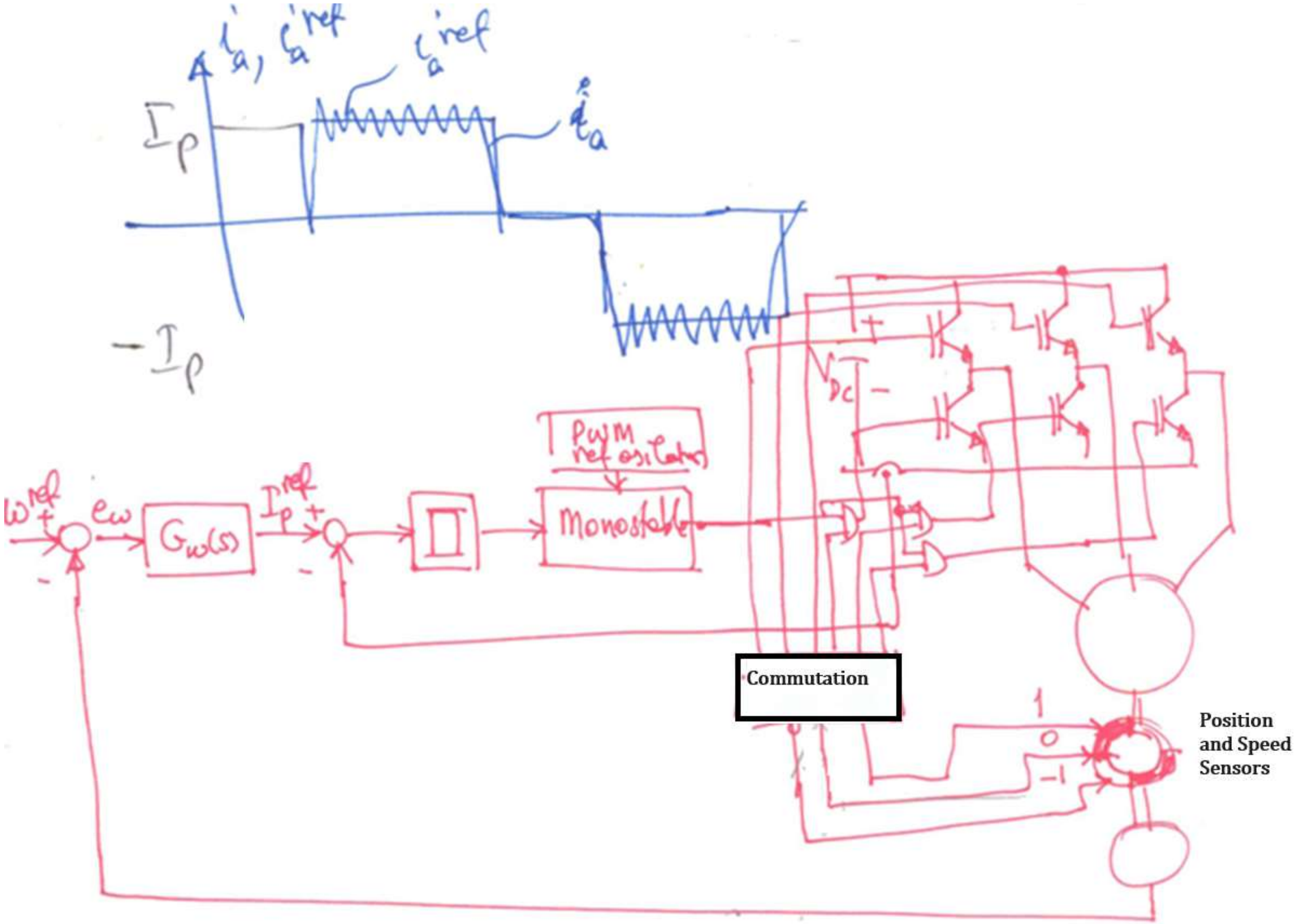

+
V_{DC}
−
Q_1
Q_3
Q_5
Q_6
Q_4
Q_2
PM
DC
Brushless
Load
θ_r
Tacho
$\theta_r(1..6)$
Commutation Scheme
ω_{ref}
−
+
Speed Controller
I_p^{ref}
1,0
D
i_a
$P(a^+)$
$P(a^-)$
Q_1
30
150
180
210
330
360
θ_r
Q_6
i_b
$P(b^-)$
90
$P(b^+)$
Q_3
Q_4
Q_4
i_c
$P(c^+)$
$P(c^+)$
Q_5
Q_5
Q_2
$P(c^-)$
Proximity switch
$P(a^+, a^-, b^+, b^-, c^+, c^-)$

0-30	**30-90**	**90-150**	**150-210**	**210-270**	**270-330**	**330-360**
T5-T6	T1-T6	T1-T2	T3-T2	T3-T4	T5-T4	T5-T6

$$\min\_sensor\_number = {}^{2\pi}\!\big/_{n_{phase}} * p$$

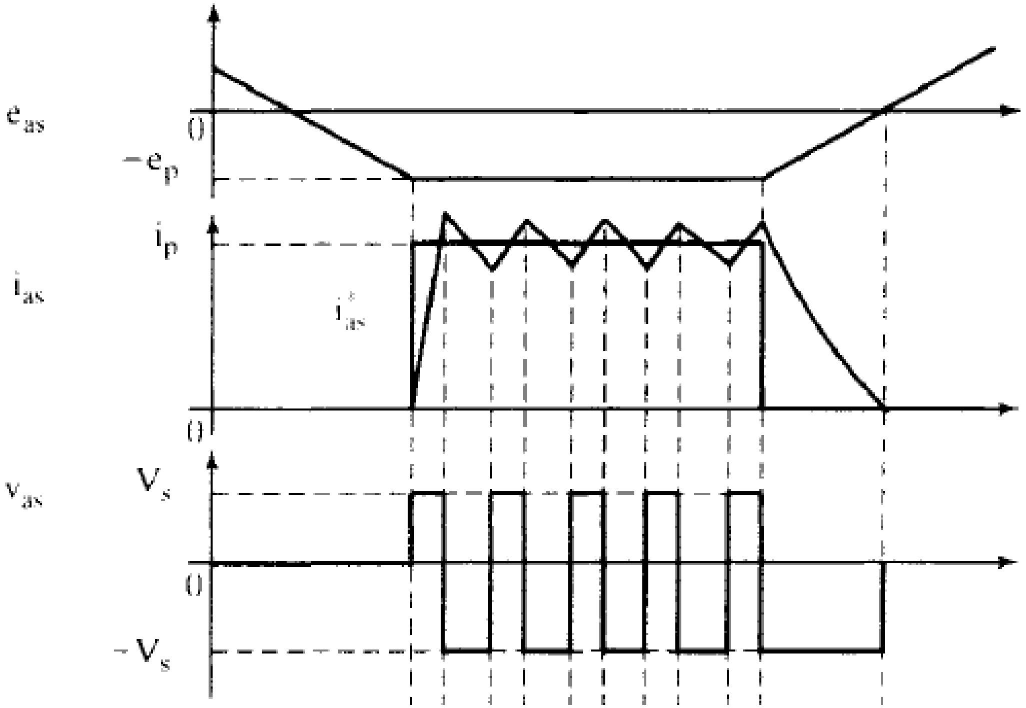


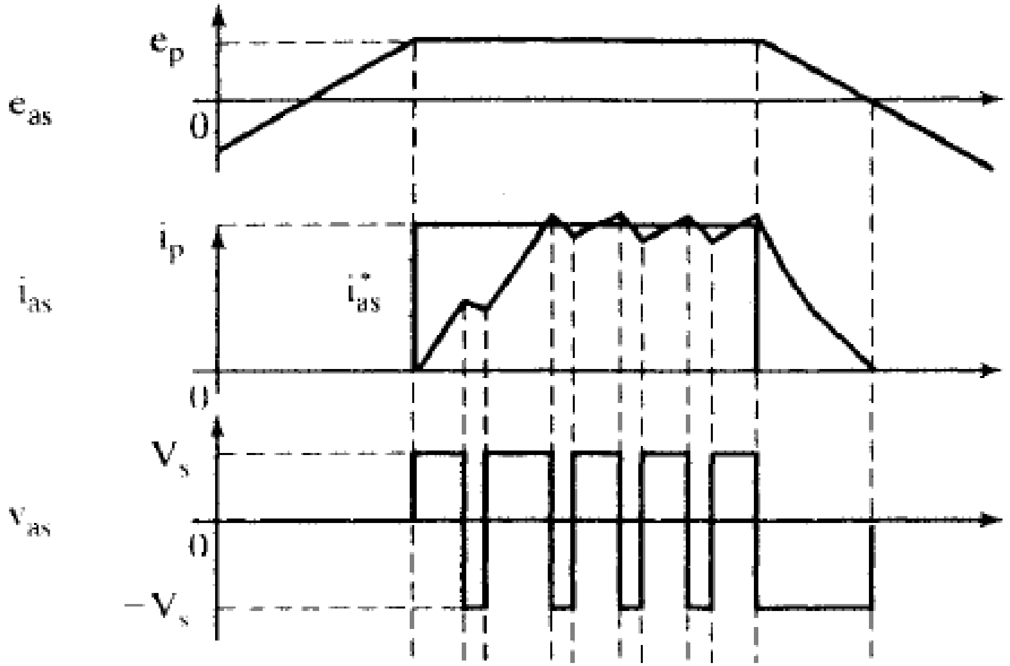

ω_r^*
+
−
ω_r
Speed Controller
PI + Limiter
T_e^*
$\frac{1}{K_t}$
$|i^*|$
Steering Circuit
Phase Current Commands
Subtractors + Comparators + PWM
Gate Signals
Converter
Hall Sensors
N
A
B
C
PMBDC Motor
Load
TC
Polarity Detector
Filter

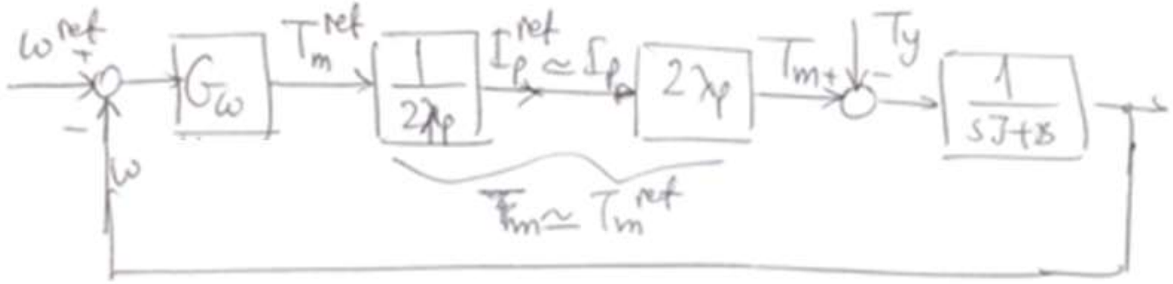


Commutation

Position and Speed Sensors


e_as
0
−e_p
i_p
i_as
i*_as
0
v_as
V_s
0
−V_s

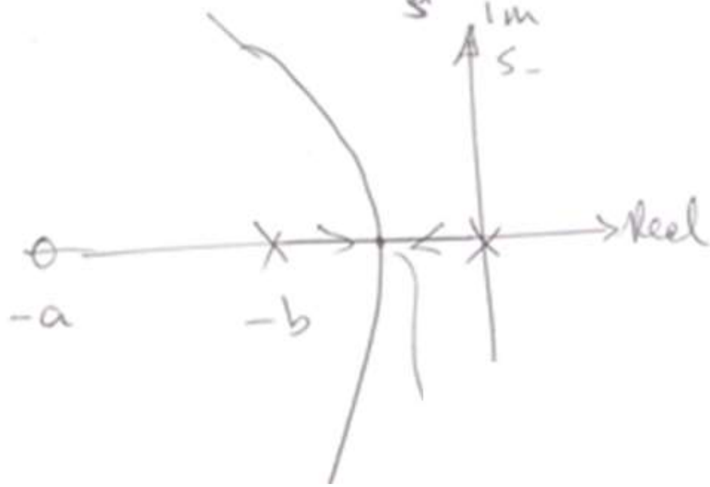

e_p
e_as
0
i_p
i_as
i*_as
0
V_s
v_as
0
−V_s



$$G_\omega(s) = k_p + \frac{k_I}{s} \quad \cdot PI \cdot$$

$$= \frac{K(s+a)}{s}$$

$$G_m = \frac{1/J}{s+b}$$



Hall Effect Sensors in BLDC Motors

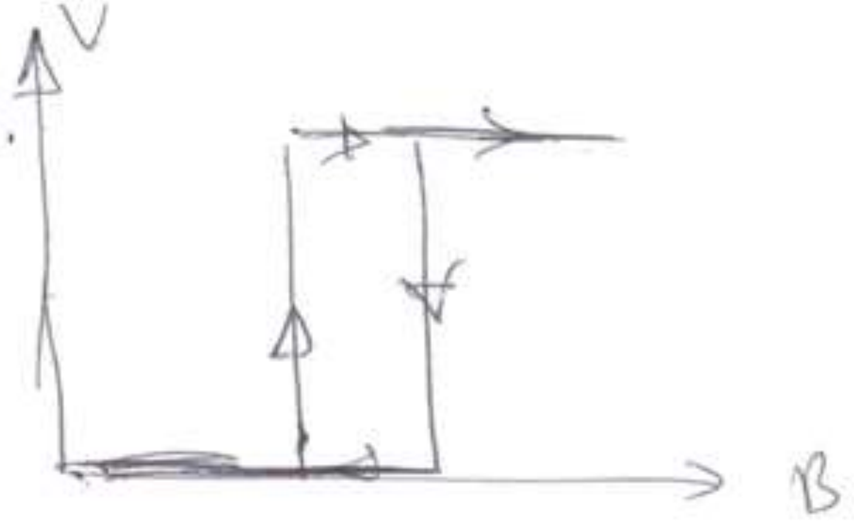
Functionality:

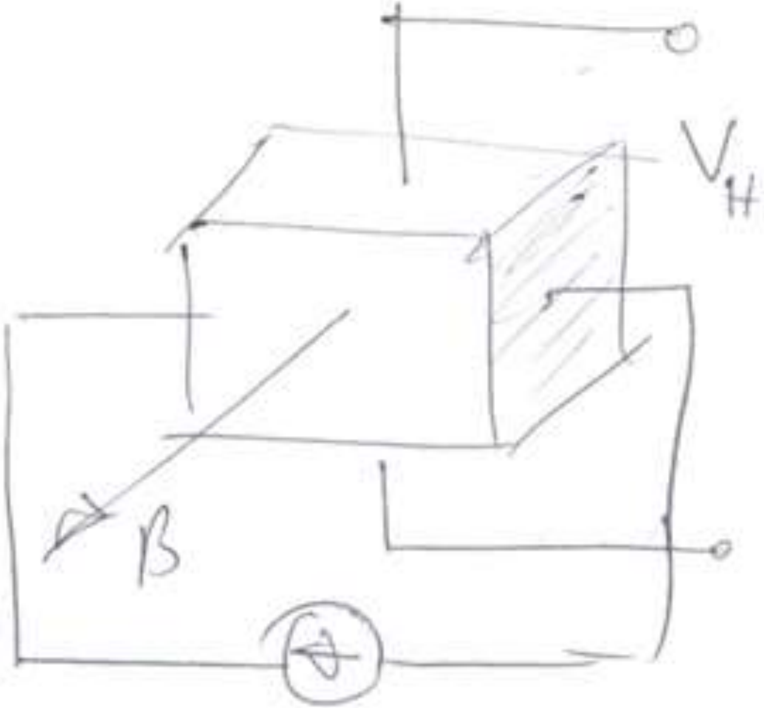
Hall effect sensors are semiconductor magnetic sensors used for measuring the rotor's position in BLDC motors.
They detect the magnetic field generated by magnets placed on the rotor.
The magnetic field is converted into a voltage by Hall effect elements located in the stator's circuitry.
Signal Processing:

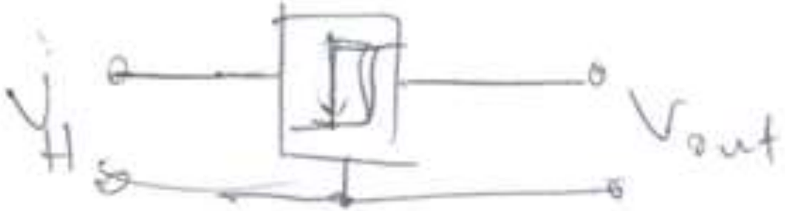
The voltage generated by the Hall effect element is processed through a Schmitt trigger to produce a square wave.
This wave effectively represents the direct sensing of the rotor's magnetic field.
Temperature Sensitivity:

Hall effect sensors are notably sensitive to temperature variations.
This sensitivity can affect their accuracy, necessitating careful design considerations and possibly temperature compensation mechanisms.
In some designs, permanent magnets may not be used due to their susceptibility to temperature changes.
Motor Configuration:

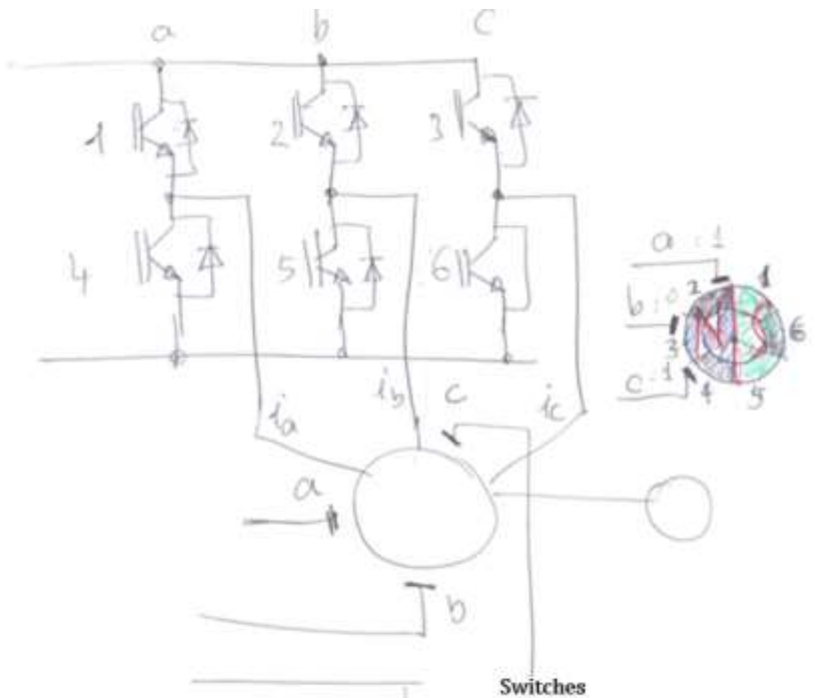
In a typical 3-phase, 2-pole BLDC motor, the Hall sensors are operated with a 120-degree phase difference to align with the motor's geometry.
This configuration ensures accurate commutation and efficient motor operation.



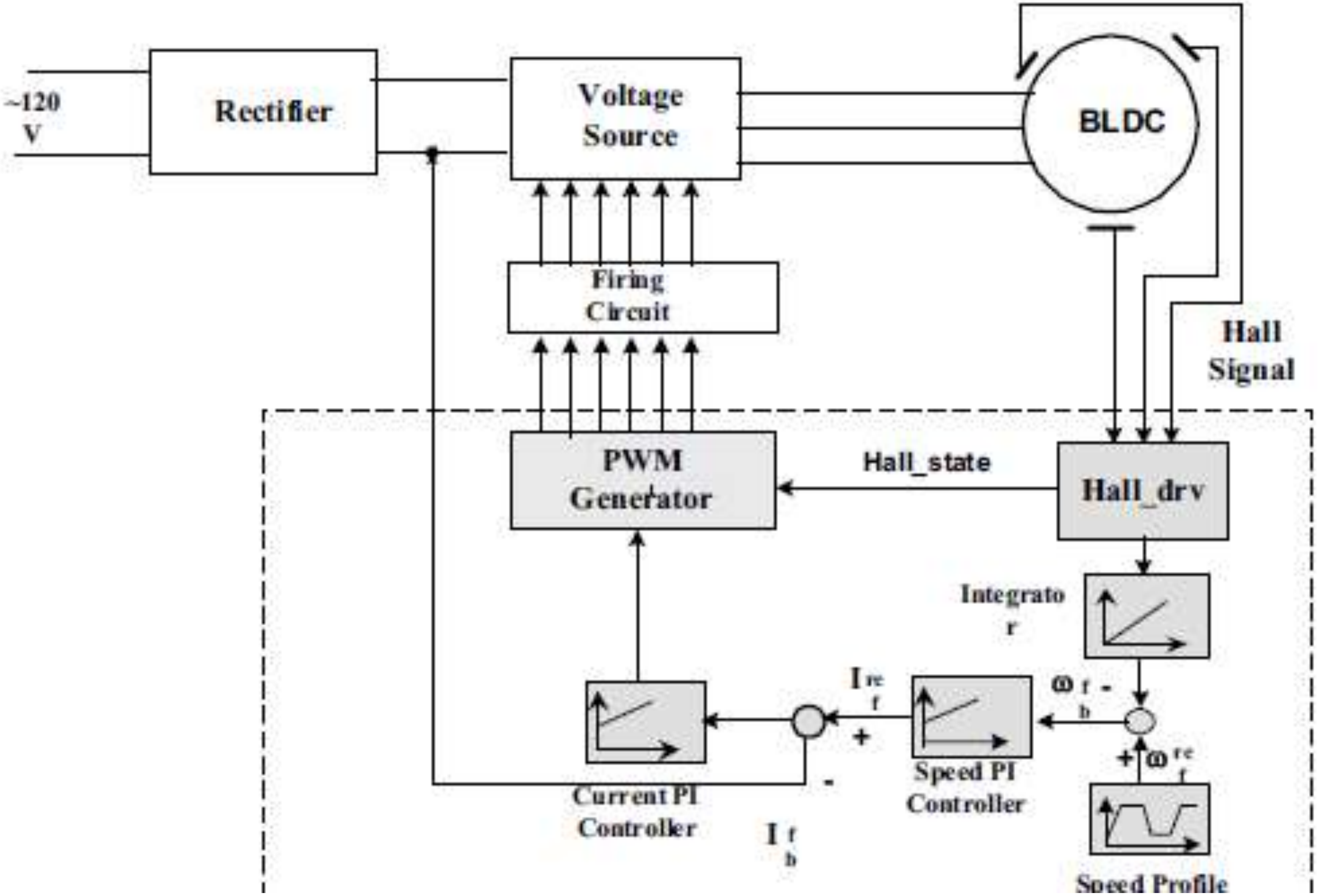


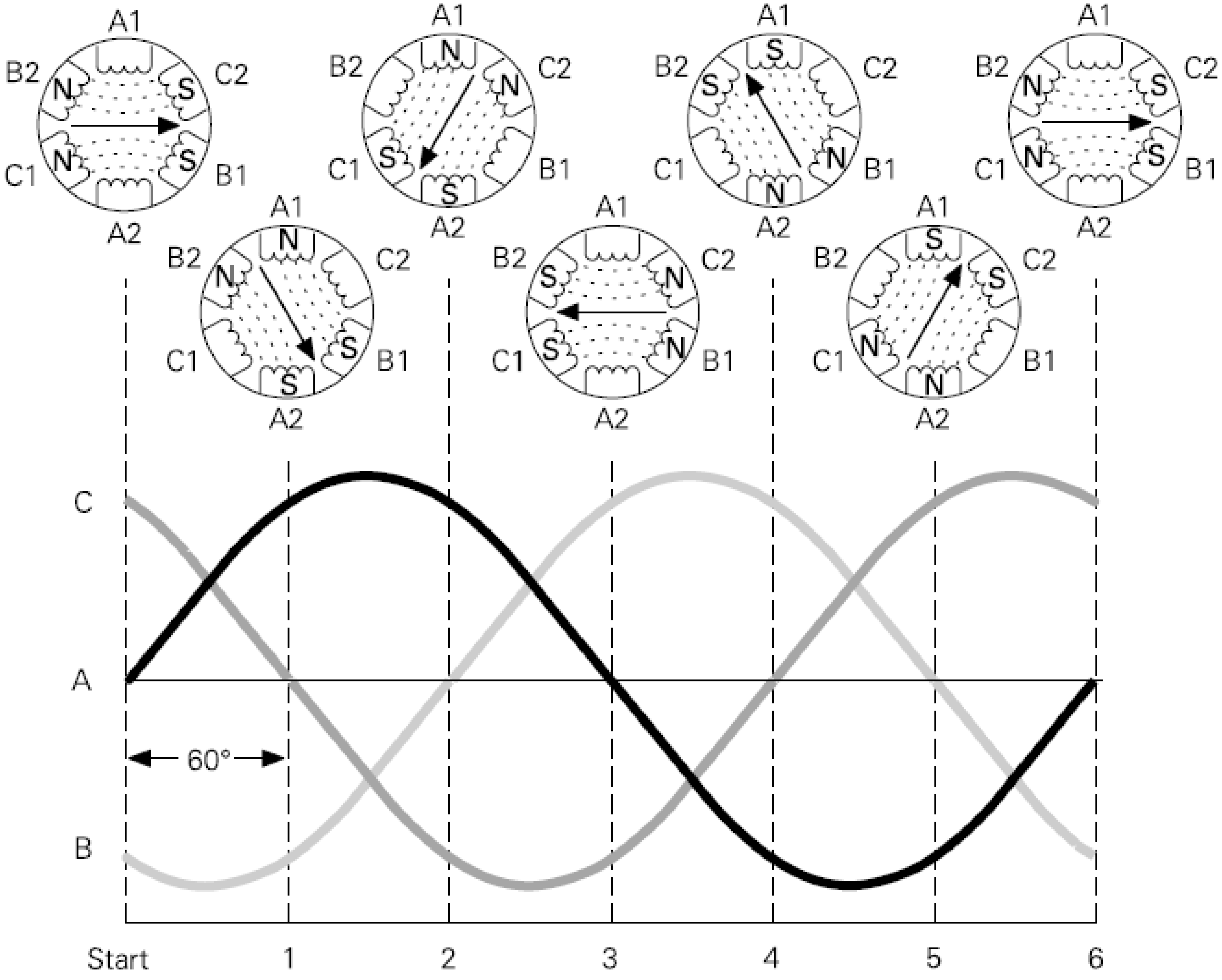


$V_H = h \cdot B I$



a	b	c	Switches Forward	 Backward
0	0	1	2 4	1 5
1	0	1	2 6	3 5
1	0	0	1 6	3 4
1	1	0	1 5	2 4
0	1	0	3 5	2 6
0	1	1	3 4	1 6


~120 V
Rectifier
Voltage Source
BLDC
Firing Circuit
Hall Signal
PWM Generator
Hall_state
Hall_drv
Integrator
ω fb
-
+
ω ref
I ref
+
-
I fb
Speed PI Controller
Current PI Controller
Speed Profile


A1
B2
C2
C1
B1
A2
N
S
C
A
B
60°
Start
1
2
3
4
5
6

Stator Winding DC Excited and Rotor Winding AC excited

A rotor winding supplied with a 1-ϕ AC through a commutator was shown to produce a flux alternating on a fixed axis.

$$\tau = k\, B_{loop} \times B_s = k\, B_{loop} \cdot B_s \cdot \sin\theta$$

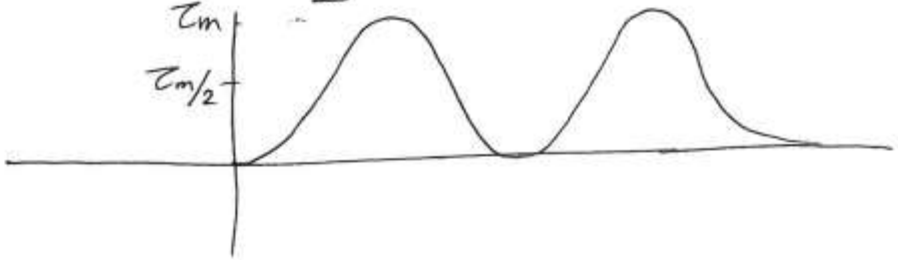
B_{loop} created by i, so if i is subsituted $i = I_m \sin\alpha$

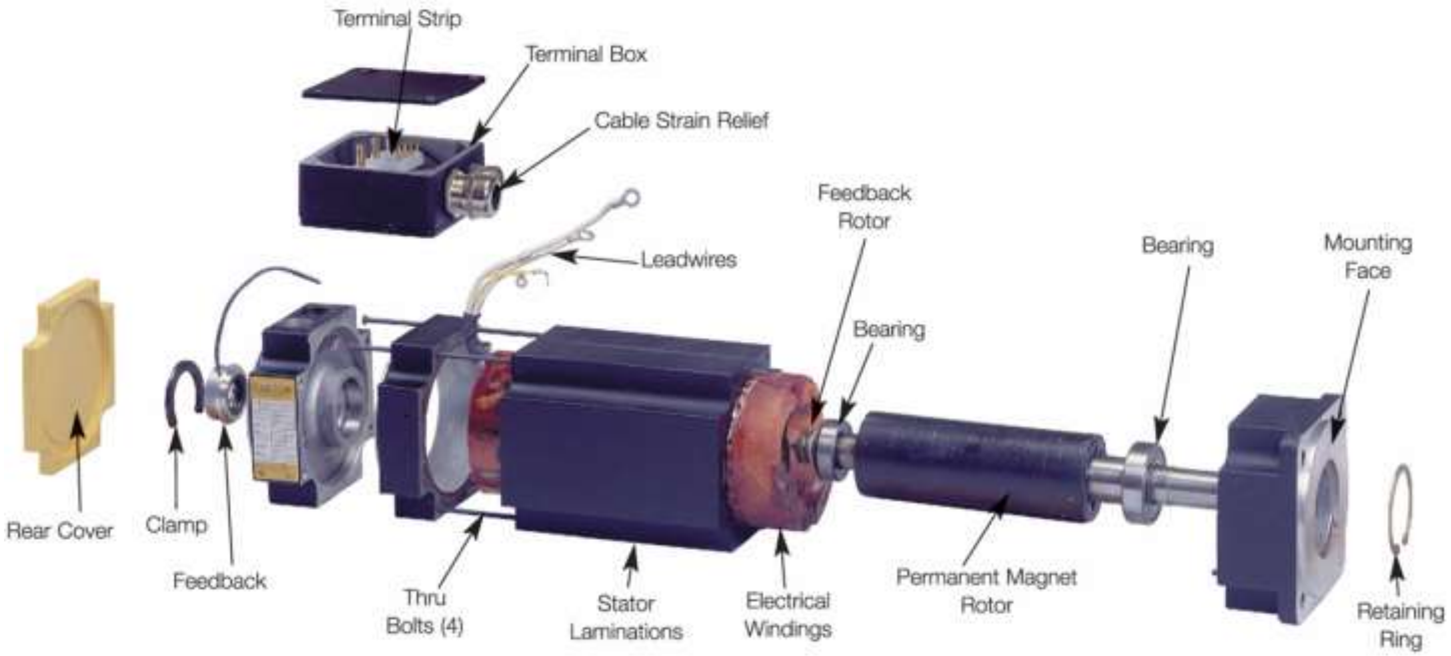
$$\tau = K I_m \cdot B_s \cdot \sin\alpha \, \sin\theta$$

$$= k\, I_m B_s \left[\frac{1}{2}\cos(\alpha - \theta) - \frac{1}{2}\cos(\alpha + \theta)\right]$$

So, only when $\alpha = \theta$, τ will have an average value.

$$\tau = \tau_m \frac{(1 - \cos 2\theta)}{2}$$





AC Brushless Motor Breakdown

Brushless Adjustable Speed Package

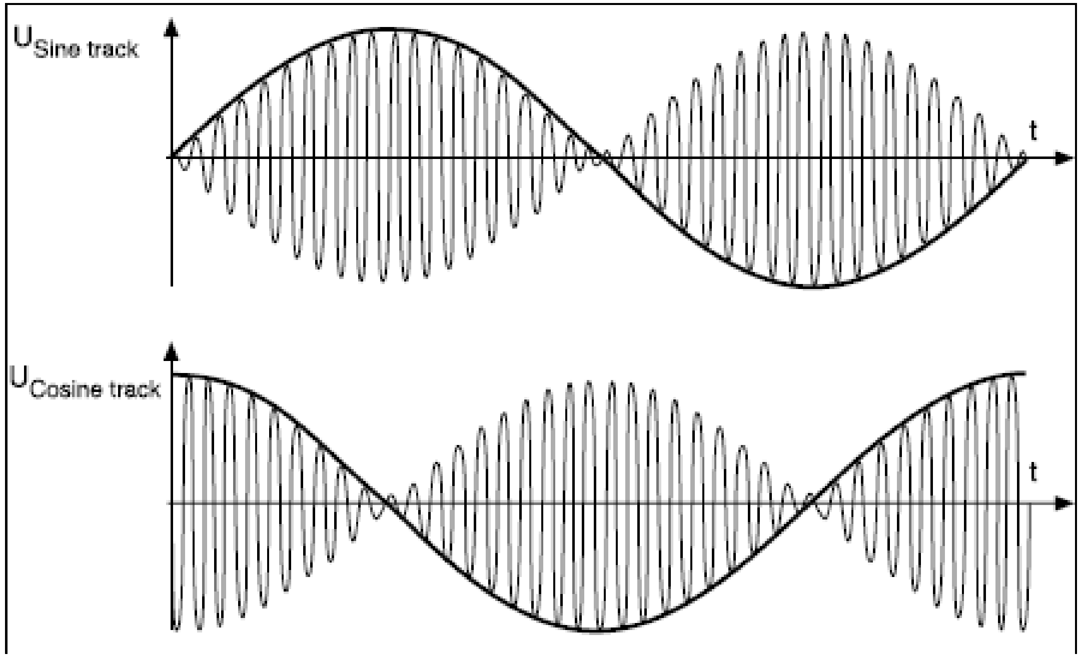
Drive

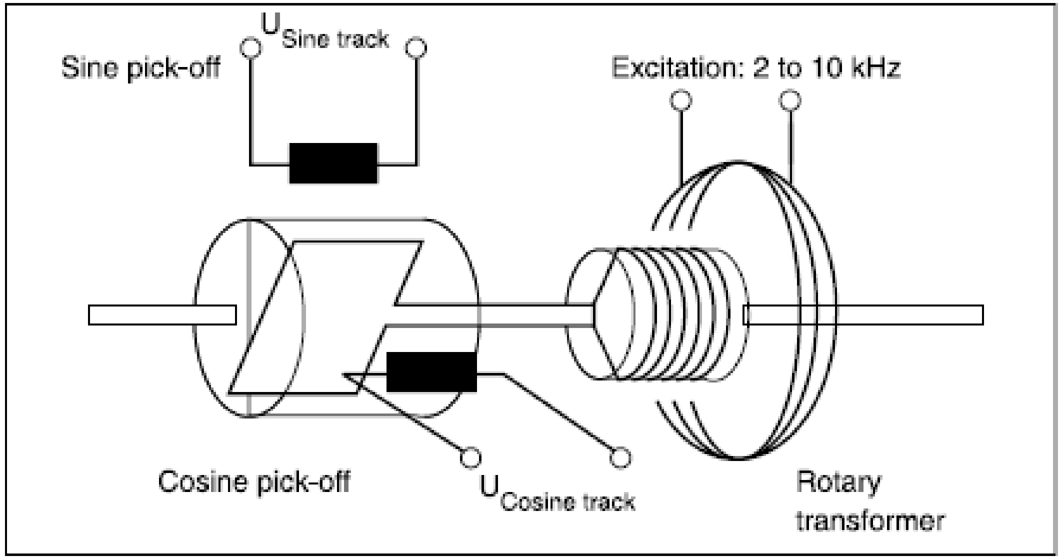
- 1.5 to 9 amps
- No programming necessary
- Potentiometer or +/- 10V control
- Hall sensor control
- Meant for speed applications
- Less than $500.00 NET for 1HP
- motor and drive package

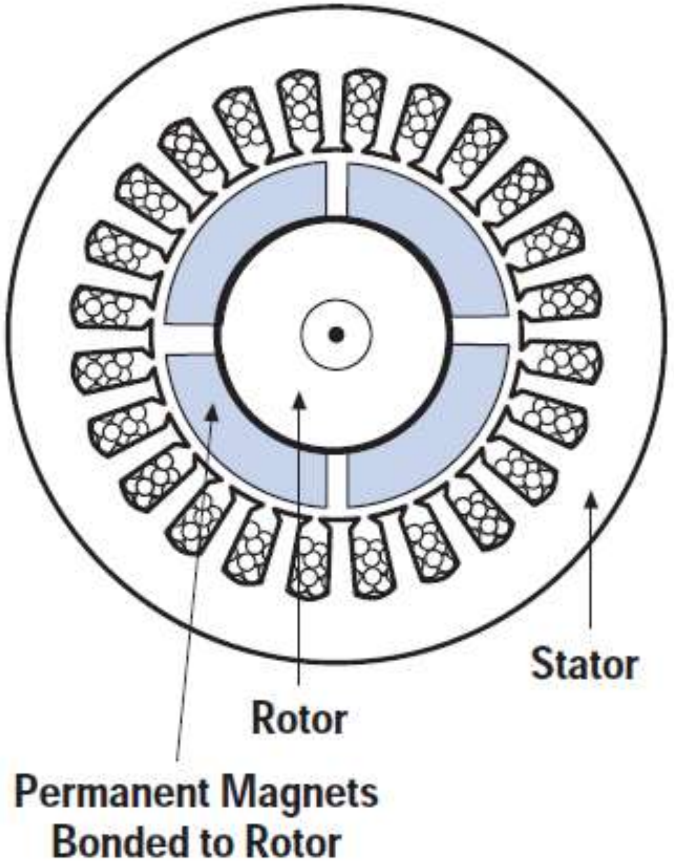
Motor

- 1/4 - 3 HP
- Hall sensor feedback
- Encoder or resolver optional
- Nema 42 & 56
- 1800 base speed

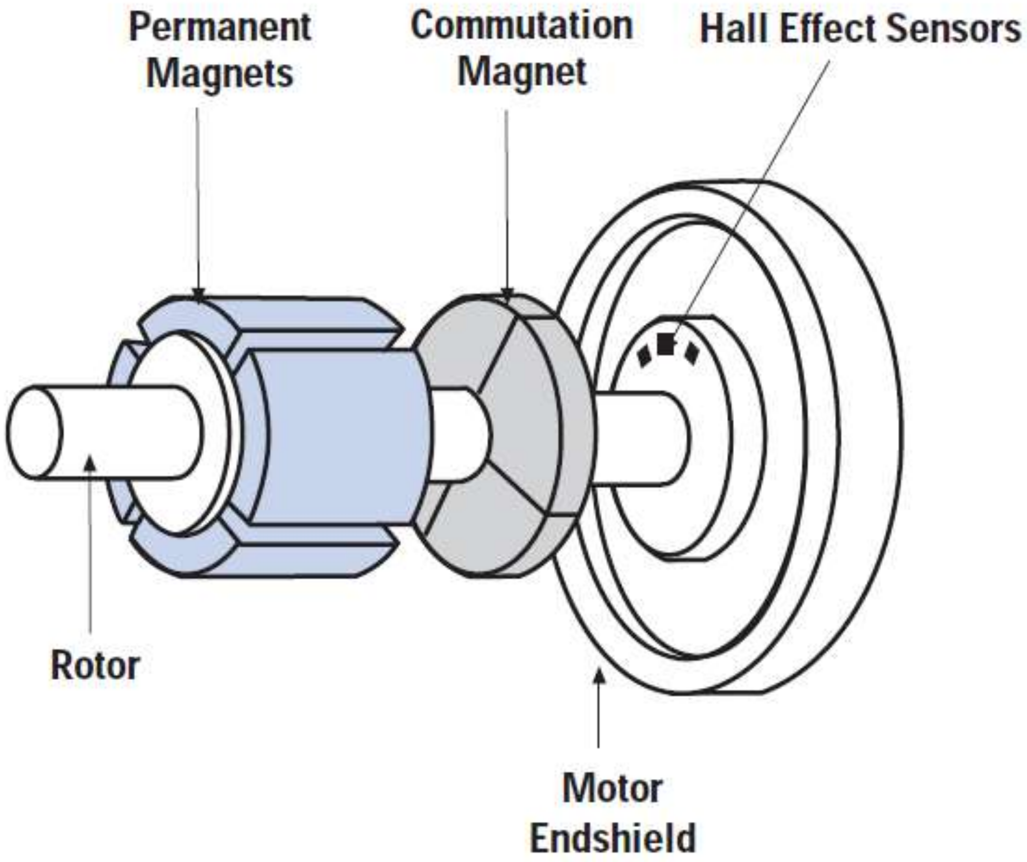
	Induction	**Brushless Servo**
1 Hp	40 lbs	12 lbs
2 Hp	65 lbs	35 lbs
5 Hp	100 lbs	62 lbs
10 Hp	150 lbs	80 lbs


$U_{\text{Sine track}}$
t
$U_{\text{Cosine track}}$
t


Sine pick-off
$U_{\text{Sine track}}$
Excitation: 2 to 10 kHz
Cosine pick-off
$U_{\text{Cosine track}}$
Rotary transformer



BRUSHLESS MOTOR



BRUSHLESS MOTOR

BALDOR

BALDOR · DODGE · RELIANCE

Brushless AC Servo Motors

BSM R-Series

- Compact rugged brushless motors
- 50, 100, 200, 400 watt output
- Torque sizes 0.16 to 1.27 Nm (1.4 - 11.2 lb-in)
- Resolver or Encoder feedback
- Optional 24 VDC brake
- UL/CE

Smaller Brushless Servomotors

Existing - BSM50

- 800 Watt
- Modifications
  - Custom windings
  - Custom shaft & mounting
- 50 & 100 Watt
- 200 & 400 Watt
- Choices
  - Encoder or encoder/brake
  - Stepper or Metric mount

BSM series motors

UL/CSA/CE

155 deg C continuous operation

IEC mountings standard

Custom designs

Two week lead-times

Optional holding brakes

Exxon PolyrexEM grease

Standard windings for 115, 230, or 460V input.

Blower optional for increase in torque

BSM N series motors

Lowest Inertia to attain

- Higher acceleration
- Faster positioning
- Higher machine throughput
- Max torque per package size

Five different sizes

- BSM50, 63, 80, 90, & 100

Neodymium Iron Bore Magnets

4 to 354 lb-in continuous

Larger Brushless Servomotors

Existing – BSM100

- 5 HP @ 1800 rpm

- BSM132
- 20 HP @ 1800 rpm
- 30 HP with additional cooling
- Up to IP65 sealing
- Custom capabilities

Stainless Steel BSM

Designed for food, liquid, pharmaceutical, washdown, and hygiene applications.

IP67

1500PSI

Low and Standard inertia designs (N & C series)

Approximately 15% de-rate below standard motors

4 to 283 lb–in continuous

Laser etched nameplate

304 SS housing - 416 SS shaft

FDA approved shaft seal

BISSC/UL/CSA/CE – agency approvals

GBSM Servo Gearheads

- **Five different sizes to fit all motors**
- **Standard backlash 10, 12, and 15 arc-min max**
- **Precision 5 to 10 arc-min available**
- **Up to 40NM input torque**
- **Single stage ratios from 3 to 10**
- **Double stage ratios from 16 to 100**
- **Stainless Steel version also available**

Applications of BLDC Motors

Transportation:

BLDC motors are extensively used in hybrid electric vehicles and electric scooters due to their efficiency, reliability, and power density.

Consumer Electronics:

They are a common choice in hard disk drives, CD/DVD players, and cooling fans due to their precise control and efficient operation.

HVAC Systems:

BLDC motors find applications in certain HVAC systems where efficiency and control are paramount.

Aerospace and Drones:

In quadcopters and similar applications, BLDC motors are favored for their balance of power, weight, and control.