Advanced Power Electronics

Electronically Commutated Motors

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Contents

Introduction

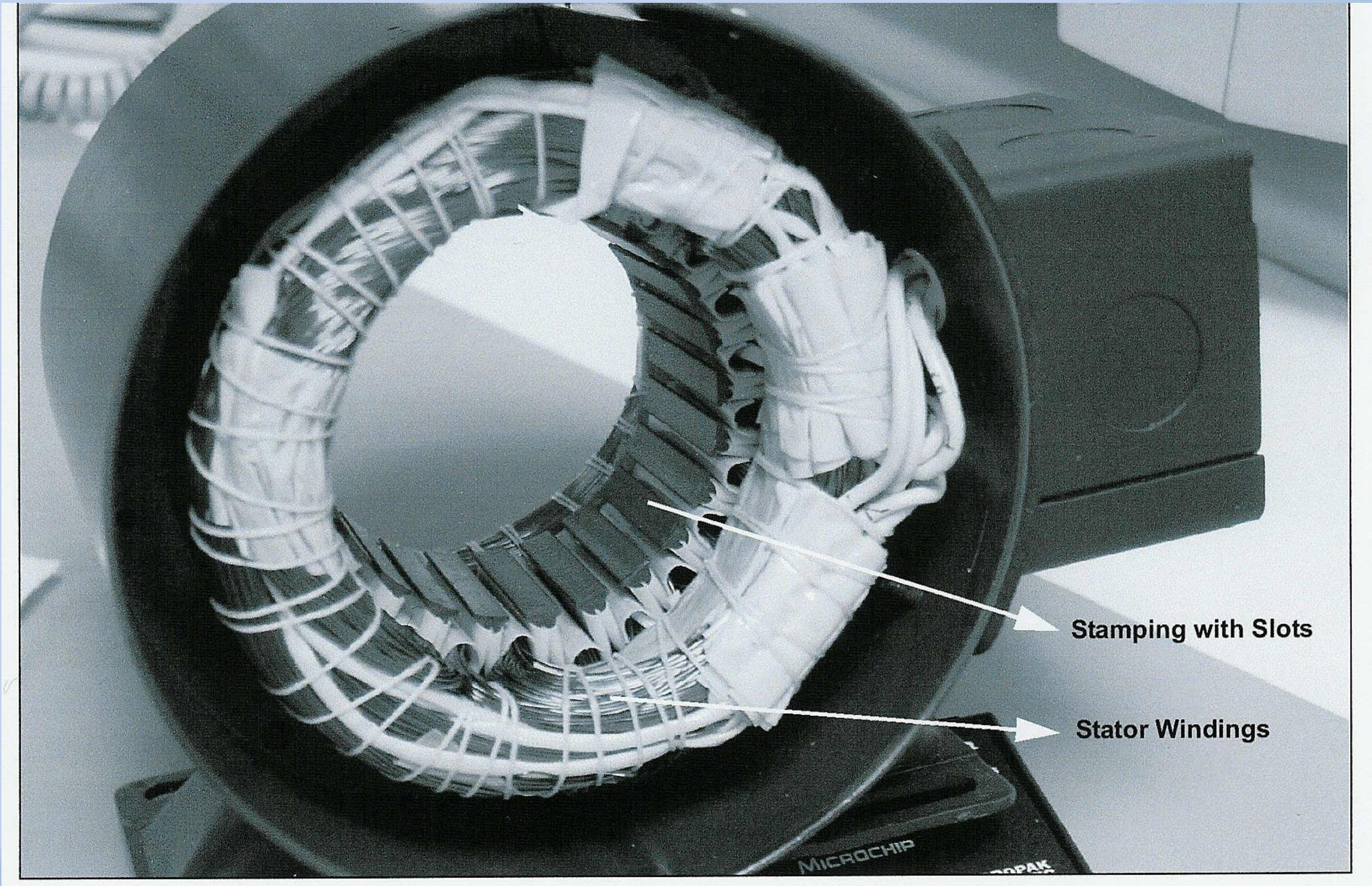
- Introduction to Permanent Magnet Motors

Click Here

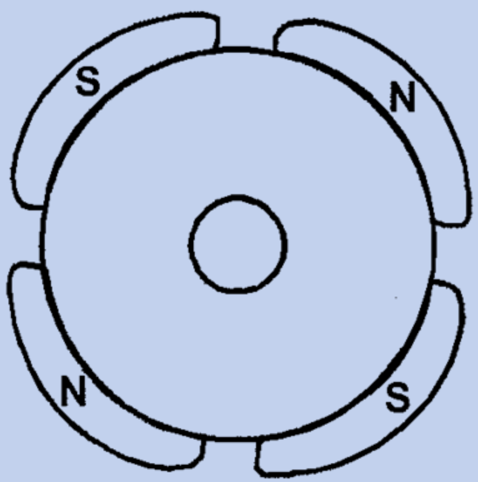
Brushless DC (BLDC) Motors

- Brushless DC Motors are a type of synchronous motor
  - magnetic fields generated by the stator and rotor rotate at the same frequency
  - no slip
- Available in single-phase, 2-phase, and 3-phase configurations

BLDC Motor Stator

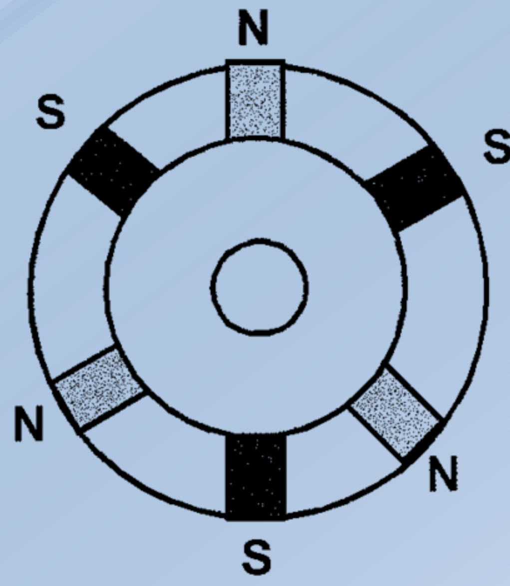


BLDC Motor Rotors



Circular core with magnets
on the periphery

Circular core with rectangular
magnets embedded in the rotor



Circular core with rectangular magnets
inserted into the rotor core

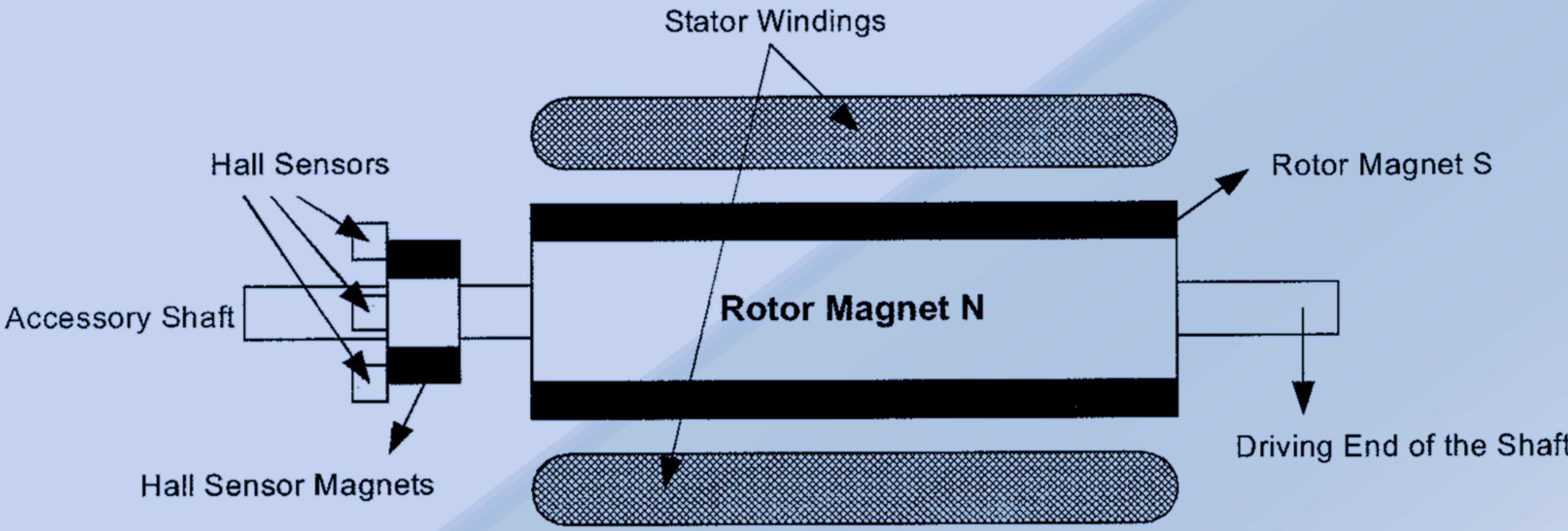
Hall-Effect

- If a current-carrying conductor is kept in a magnetic field, the magnetic field exerts a force on the moving charge carriers, tending to push them to one side of the conductor, producing a measurable voltage difference between the two sides of the conductor.

Hall-Effect Sensors

- Need 3 sensors to determine the position of the rotor
- When a rotor pole passes a Hall-Effect sensor, get a high or low signal, indicating that a North or South pole

Transverse Sectional View of Rotor



Commutation Sequence

- Each sequence has
  - one winding energized positive (current into the winding)
  - one winding energized negative (current out of the winding)
  - one winding non-energized

Torque-Speed Characteristic

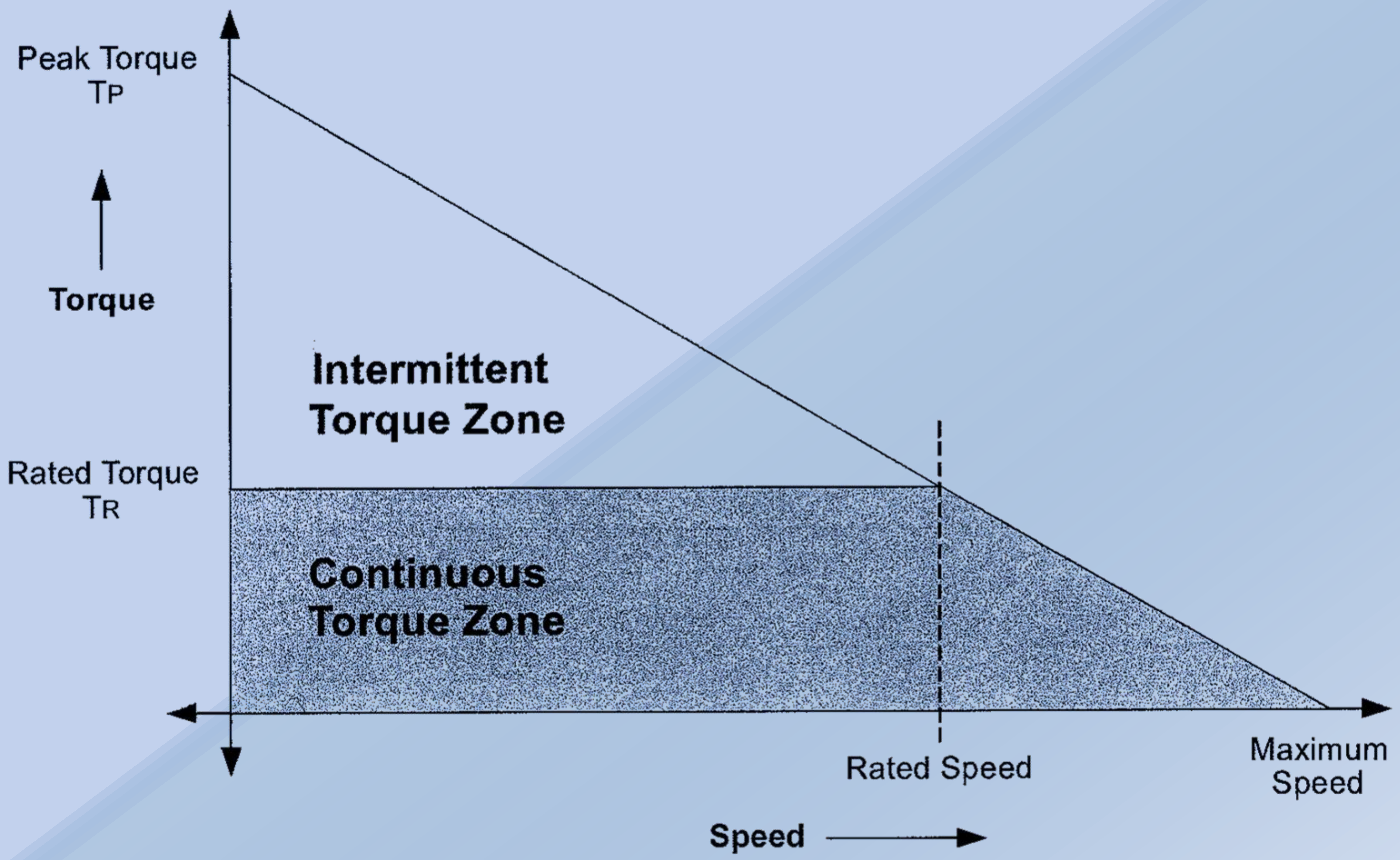


TABLE 1: COMPARING A BLDC MOTOR TO A BRUSHED DC MOTOR

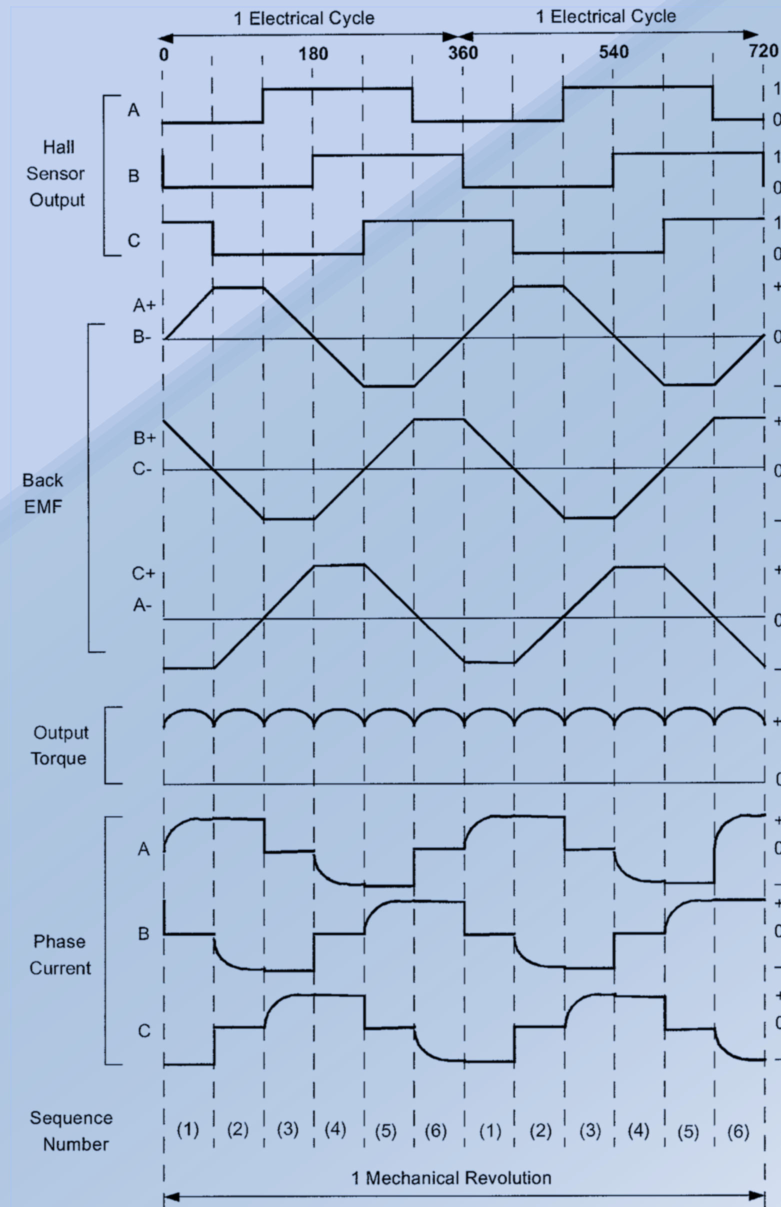
Feature	BLDC Motor	Brushed DC Motor
Commutation	Electronic commutation based on Hall position sensors.	Brushed commutation.
Maintenance	Less required due to absence of brushes.	Periodic maintenance is required.
Life	Longer.	Shorter.
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load.	Moderately flat – At higher speeds, brush friction increases, thus reducing useful torque.
Efficiency	High – No voltage drop across brushes.	Moderate.
Output Power/ Frame Size	High – Reduced size due to superior thermal characteristics. Because BLDC has the windings on the stator, which is connected to the case, the heat dissipation is better.	Moderate/Low – The heat produced by the armature is dissipated in the air gap, thus increasing the temperature in the air gap and limiting specs on the output power/frame size.
Rotor Inertia	Low, because it has permanent magnets on the rotor. This improves the dynamic response.	Higher rotor inertia which limits the dynamic characteristics.
Speed Range	Higher – No mechanical limitation imposed by brushes/commutator.	Lower – Mechanical limitations by the brushes.
Electric Noise Generation	Low.	Arcs in the brushes will generate noise causing EMI in the equipment nearby.
Cost of Building	Higher – Since it has permanent magnets, building costs are higher.	Low.
Control	Complex and expensive.	Simple and inexpensive.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is required only if variable speed is desired.

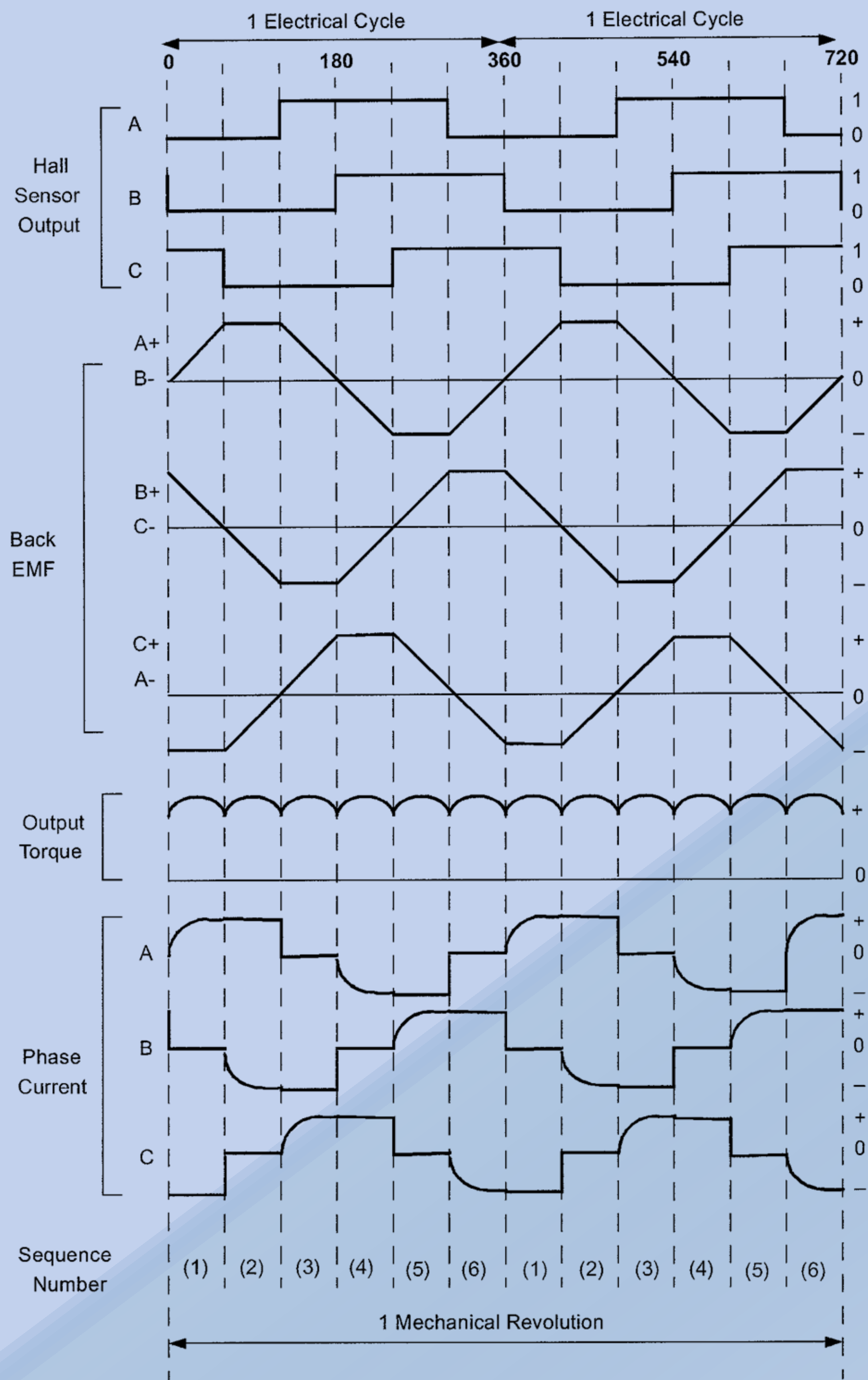
TABLE 2: COMPARING A BLDC MOTOR TO AN INDUCTION MOTOR

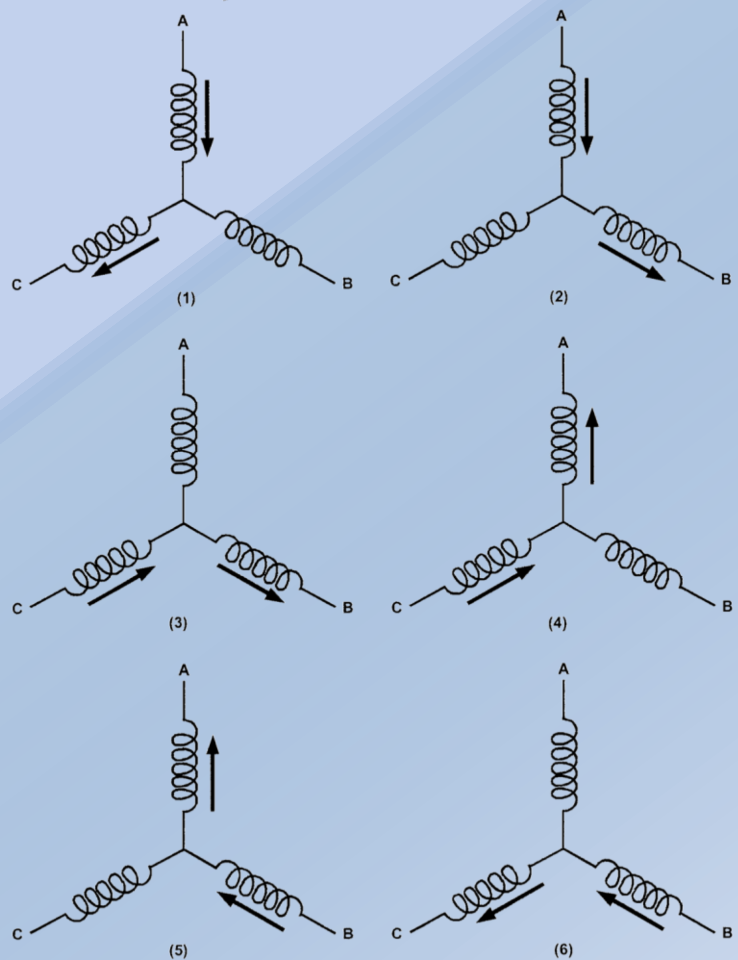
Features	BLDC Motors	AC Induction Motors
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load.	Nonlinear – Lower torque at lower speeds.
Output Power/ Frame Size	High – Since it has permanent magnets on the rotor, smaller size can be achieved for a given output power.	Moderate – Since both stator and rotor have windings, the output power to size is lower than BLDC.
Rotor Inertia	Low – Better dynamic characteristics.	High – Poor dynamic characteristics.
Starting Current	Rated – No special starter circuit required.	Approximately up to seven times of rated – Starter circuit rating should be carefully selected. Normally uses a Star-Delta starter.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is required only if variable speed is desired.
Slip	No slip is experienced between stator and rotor frequencies.	The rotor runs at a lower frequency than stator by slip frequency and slip increases with load on the motor.

Six-Step Commutation (4-pole)

- Hall-Effect Sensors spaced 60 electrical degrees apart
- 6 steps to complete one electrical cycle
- Phase current switching updated every 60 electrical degrees







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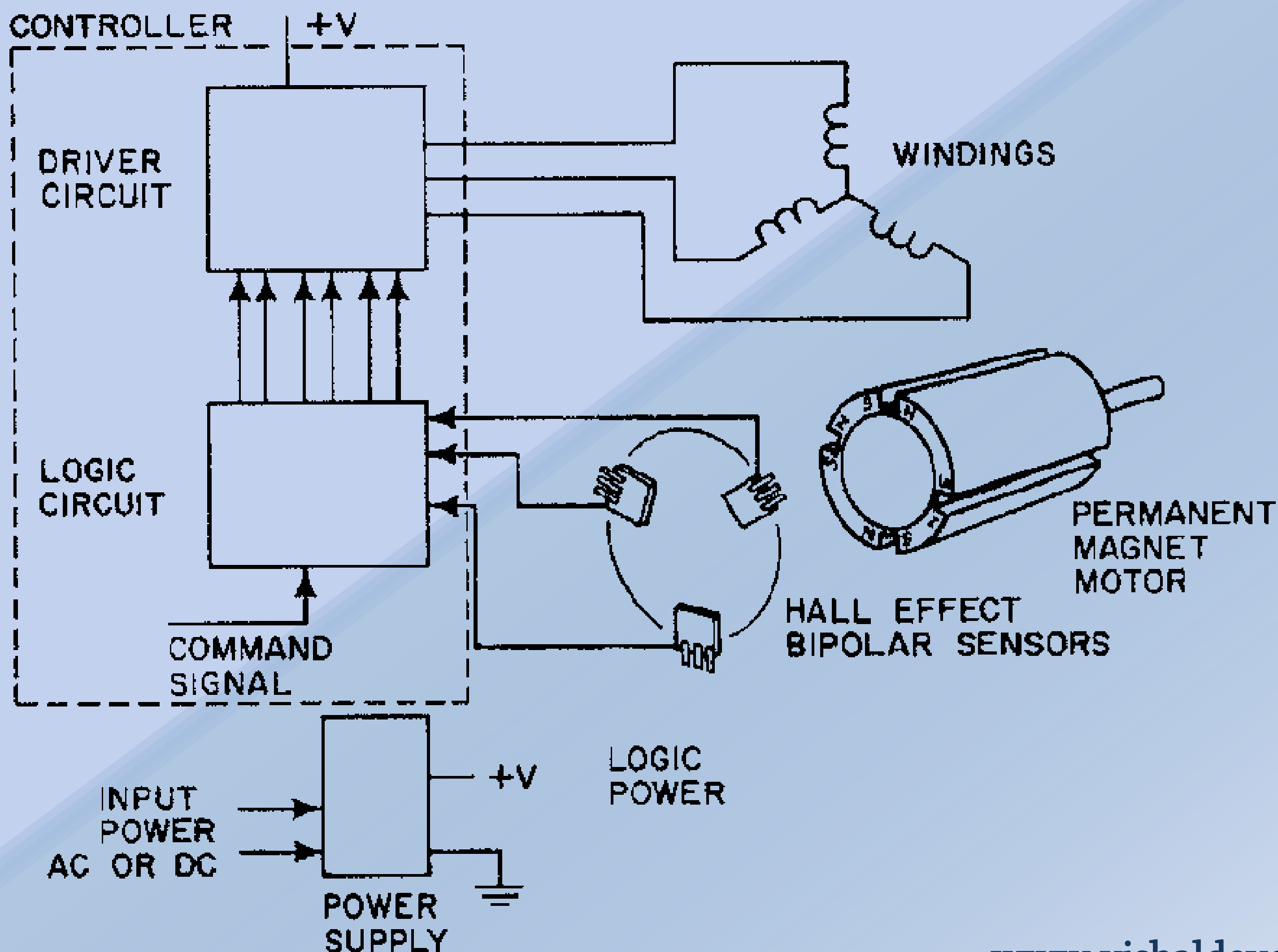
Essential Elements of a Typical BLDC Motor



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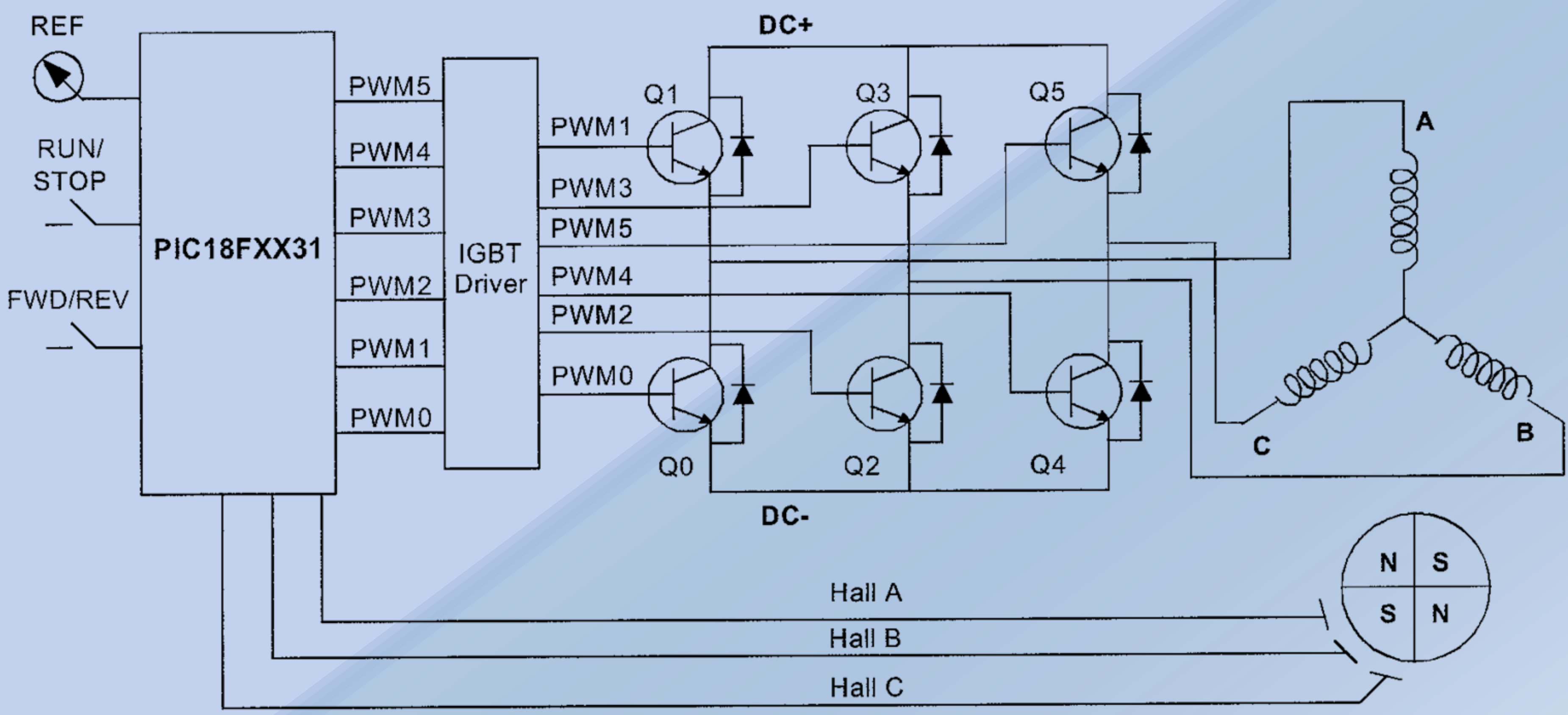
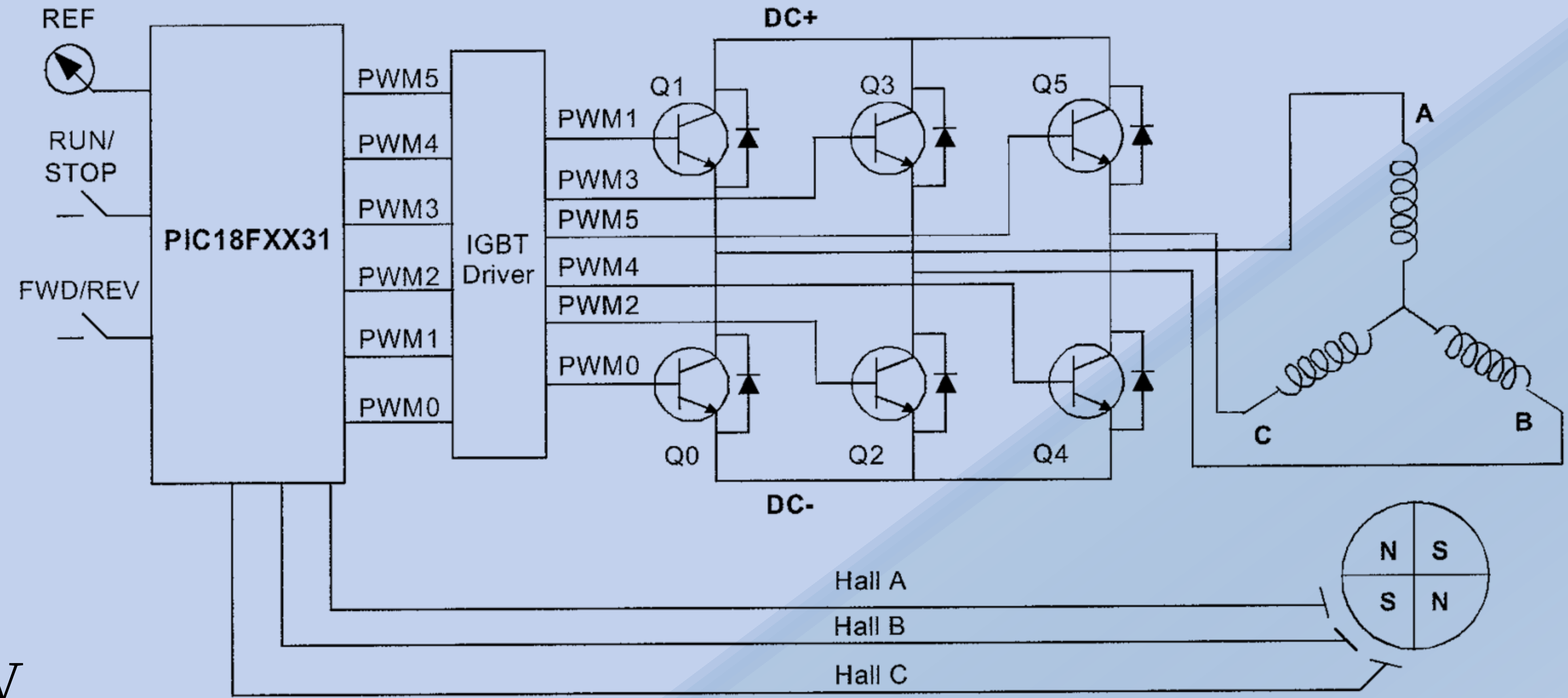
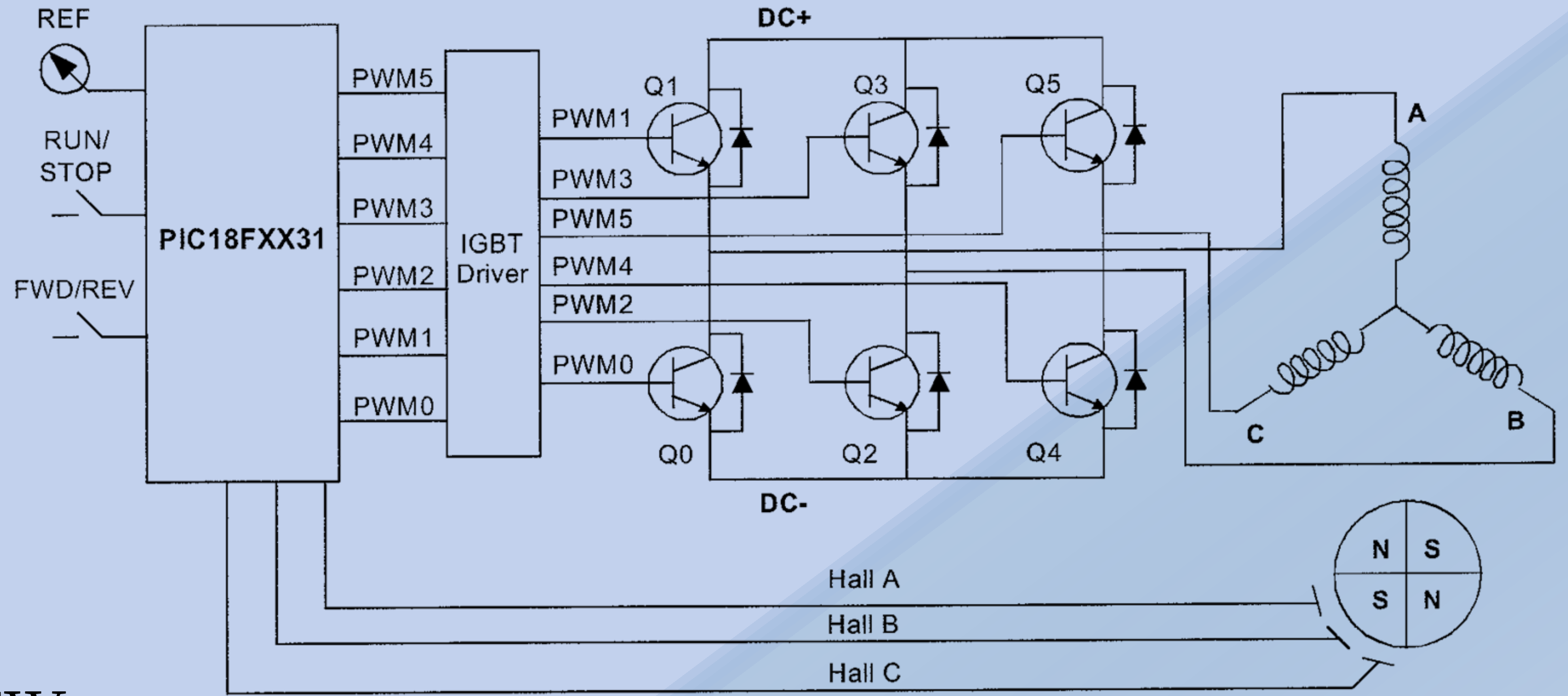
BLDC Control





CW

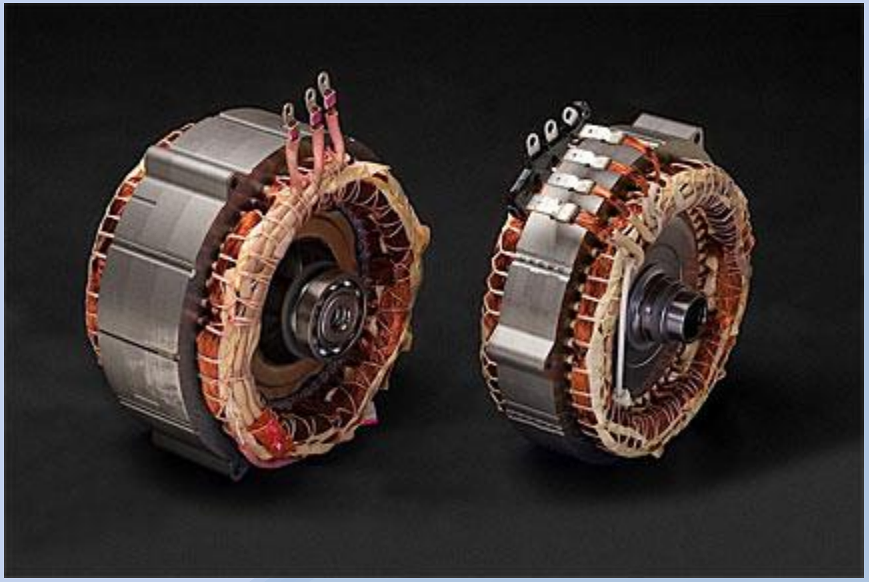
Sequence #	Hall Sensor Input			Active PWMs		Phase Current		
	A	B	C			A	B	C
1	0	0	1	PWM1(Q1)	PWM4(Q4)	DC+	Off	DC-
2	0	0	0	PWM1(Q1)	PWM2(Q2)	DC+	DC-	Off
3	1	0	0	PWM5(Q5)	PWM2(Q2)	Off	DC-	DC+
4	1	1	0	PWM5(Q5)	PWM0(Q0)	DC-	Off	DC+
5	1	1	1	PWM3(Q3)	PWM0(Q0)	DC-	DC+	Off
6	0	1	1	PWM3(Q3)	PWM4(Q4)	Off	DC+	DC-



CCW

Sequence #	Hall Sensor Input			Active PWMs		Phase Current		
	A	B	C			A	B	C
1	0	1	1	PWM5(Q5)	PWM2(Q2)	Off	DC-	DC+
2	1	1	1	PWM1(Q1)	PWM2(Q2)	DC+	DC-	Off
3	1	1	0	PWM1(Q1)	PWM4(Q4)	DC+	Off	DC-
4	1	0	0	PWM3(Q3)	PWM4(Q4)	Off	DC+	DC-
5	0	0	0	PWM3(Q3)	PWM0(Q0)	DC-	DC+	Off
6	0	0	1	PWM5(Q5)	PWM0(Q0)	DC-	Off	DC+

Permanent Magnet Synchronous Motors



Permanent Magnet Technology

The use of permanent magnets (PMs) in construction of electrical machines brings the following benefits:

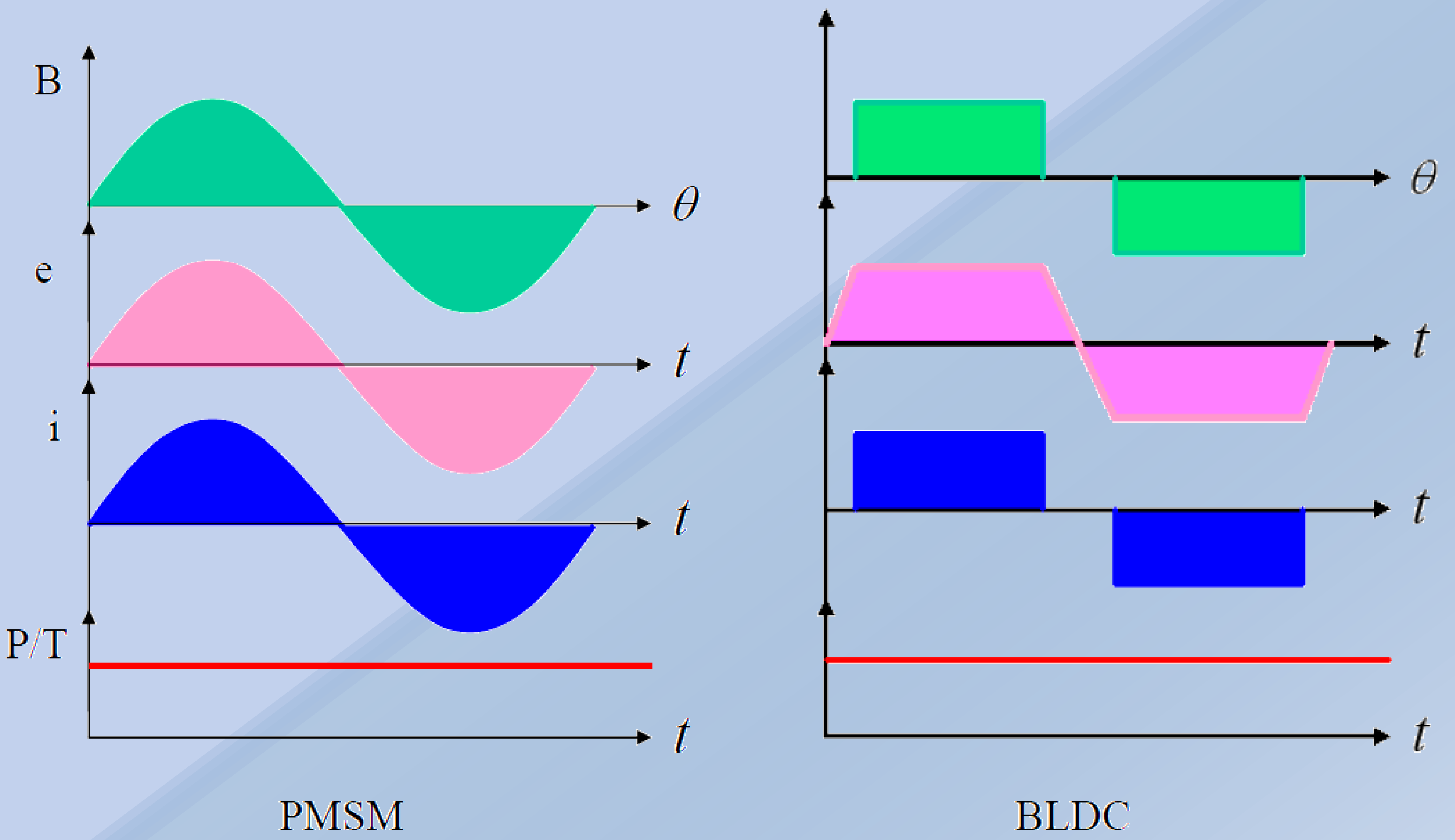
- no electrical energy is absorbed by the field excitation system and thus there are no excitation losses which means substantial increase in the efficiency,
- higher torque and/or output power per volume than when using electromagnetic excitation,
- better dynamic performance than motors with electromagnetic excitation (higher magnetic flux density in the air gap),
- simplification of construction and maintenance,
- reduction of prices for some types of machines.

Permanent Magnet Classification

PM Motor →
- PM Synchronous Motor (PMSM)
- PM Brushless Motor (BLDC)

	PMSM	BLDC
Flux Density (in space)	Sinusoidal Distribution	Square Distribution
Back-EMF	Sinusoidal Wave	Trapezoidal Wave
Stator Current	Sinusoidal Wave	Square Wave
Total Power	Constant	Constant
Electromagnetic Torque	Constant	Constant

Permanent Magnet Classification



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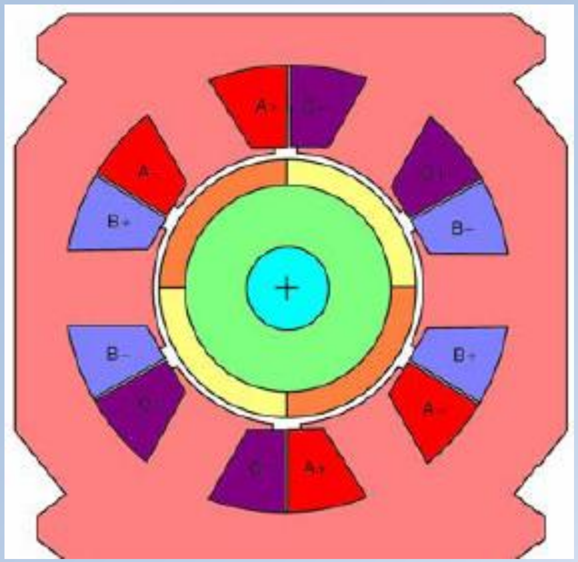
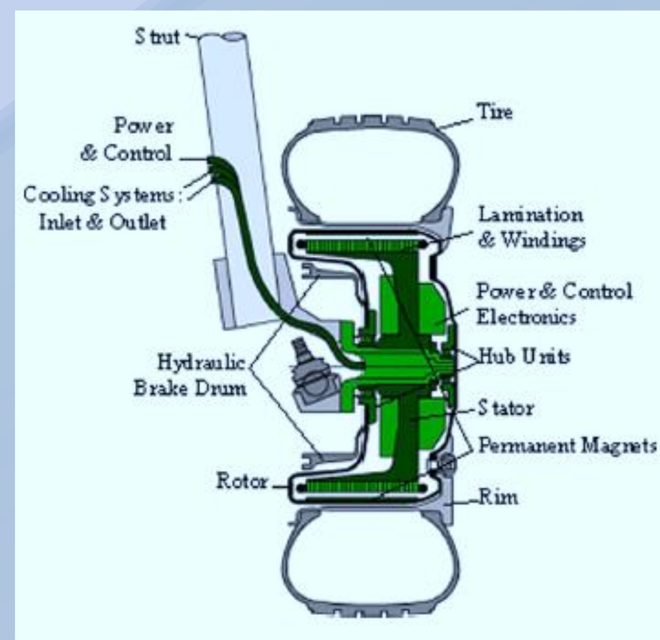
Introduction

- PM synchronous motors are widely used in industrial servo-applications due to its high-performance characteristics.
- PMSM Nick-name : Sine-wave brushless DC motor
- General characteristics
  - Compact
  - High efficiency (no excitation current)
  - Smooth torque
  - Low acoustic noise
  - Fast dynamic response (both torque and speed)
  - Expensive



Application

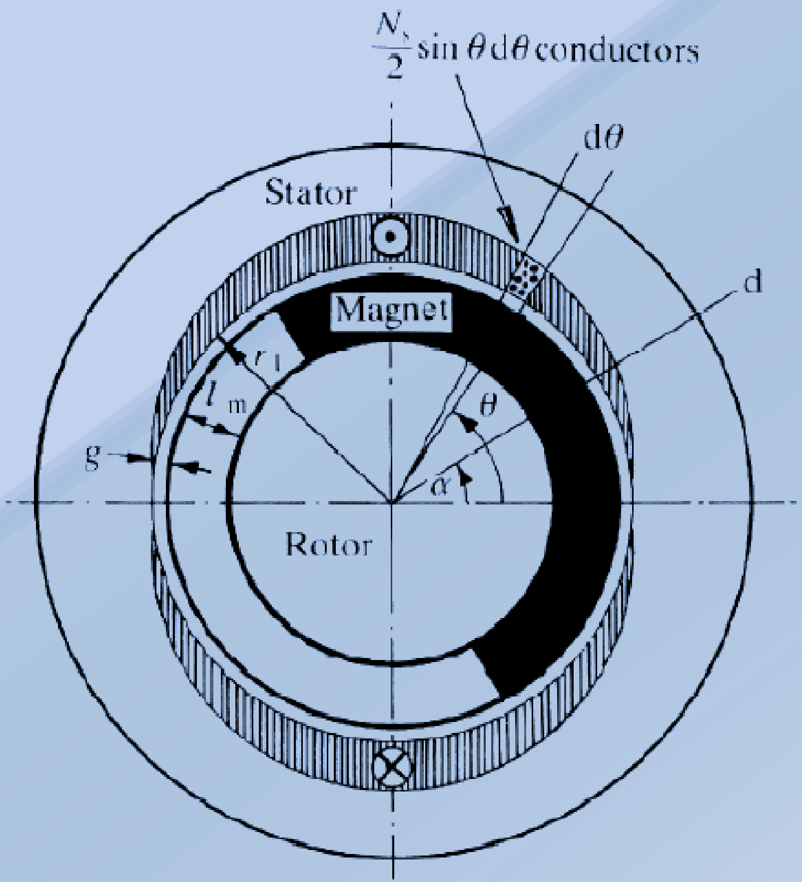
- industrial drives, e.g., pumps, fans, blowers, mills, hoists, handling systems
- elevators and escalators, people movers, light railways and streetcars (trams), electric road vehicles, aircraft flight control surface actuation



Construction

General features about the layout

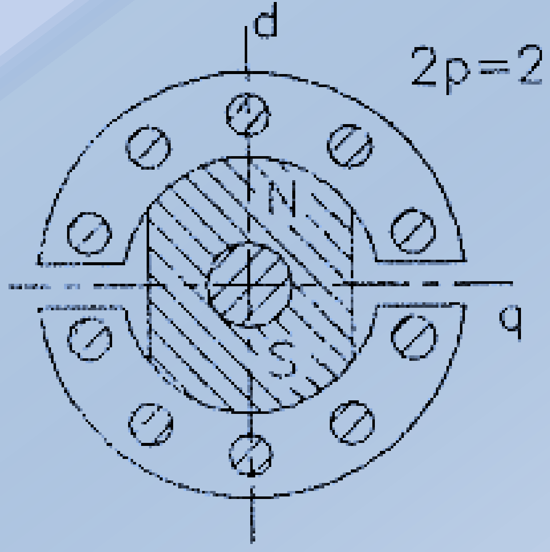
- Sinusoidal or quasi sinusoidal distribution of magnet flux in the air-gap
- Sinusoidal or quasi sinusoidal current waveforms
- Quasi sinusoidal distribution of stator conductors



Classification based on rotor technology

Merrill's rotor-Classical configuration

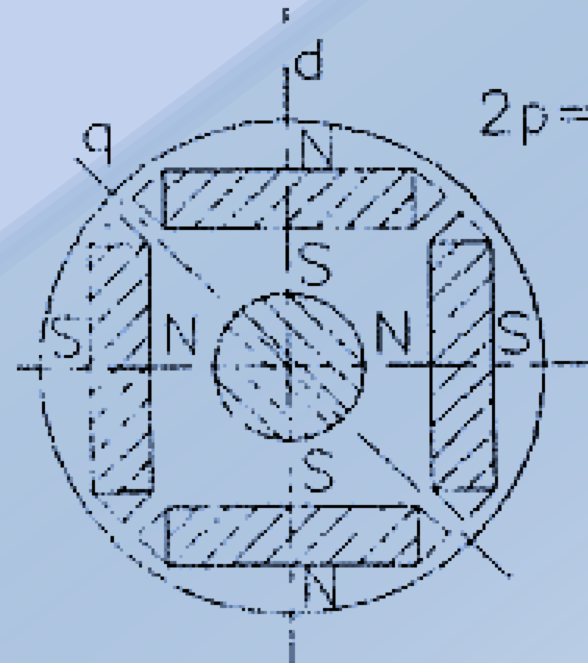
The laminated external ring has deep narrow slots between each of the PM poles. The leakage flux produced by the PM can be adjusted by changing the width of the narrow slots. The PM is mounted on the shaft with the aid of an aluminum or zinc alloy sleeve.



Classification based on rotor technology

Interior-Magnet

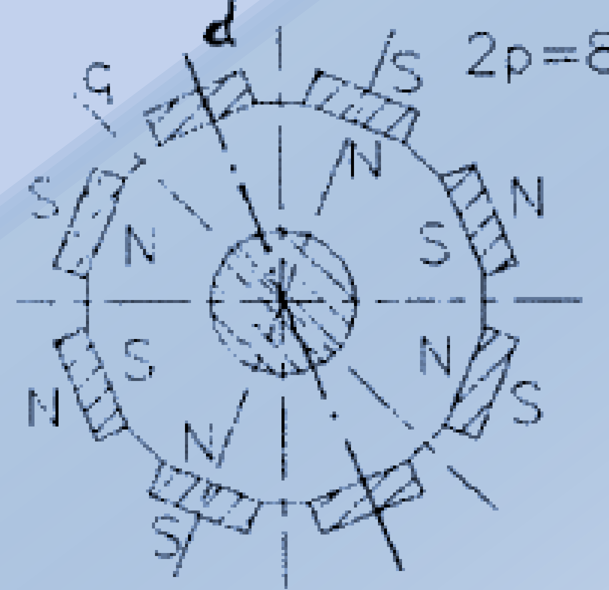
The interior-magnet rotor has radially magnetized and alternately poled magnets. Because the magnet pole area is smaller than the pole area at the rotor surface, the air gap flux density on open circuit is less than the flux density in the magnet. The magnet is very well protected against centrifugal forces. Such a design is recommended for high frequency high speed motors.



Classification based on rotor technology

Surface-Magnet Rotor

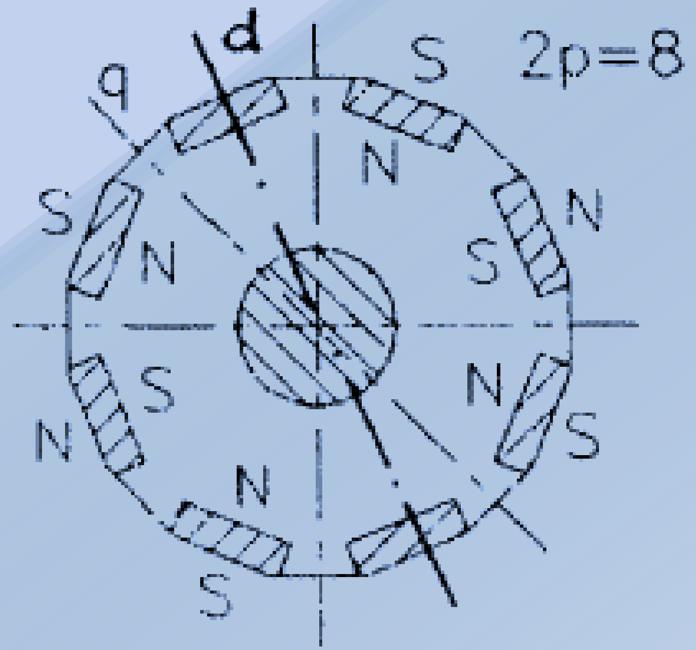
The surface magnet motor can have magnets magnetized radially or sometimes circumferentially. An external high conductivity non-ferromagnetic cylinder is sometimes used. It protects the PMs against the demagnetizing action of armature reaction and centrifugal forces, provides an asynchronous starting torque, and acts as a damper.



Classification based on rotor technology

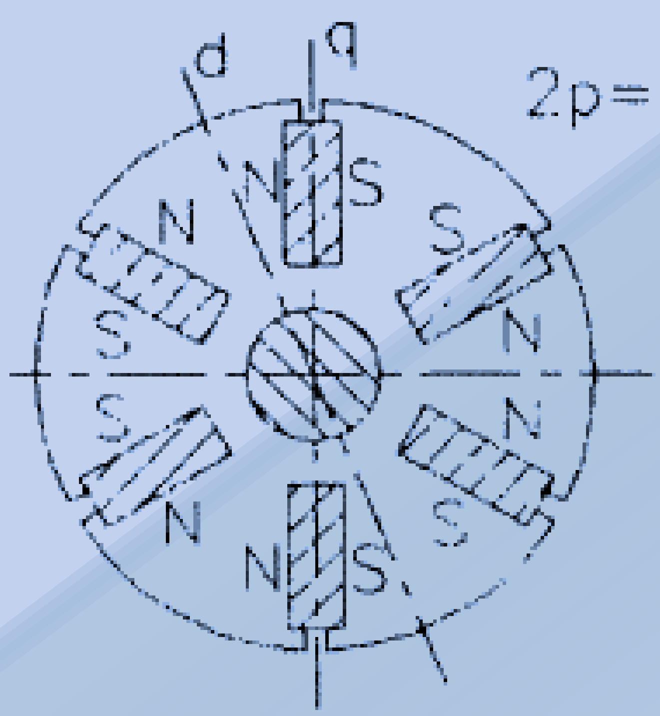
Inset-Magnet Rotor

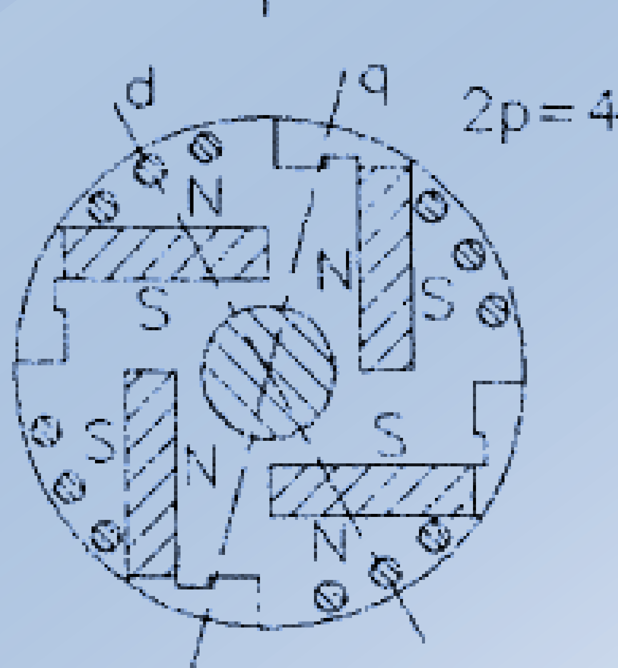
In the inset-type motors PMs are magnetized radially and embedded in shallow slots. The rotor magnetic circuit can be laminated or made of solid steel. In the first case a starting cage winding or external non-ferromagnetic cylinder is required. The q-axis synchronous reactance is greater than that in the d-axis.



Classification based on rotor technology

The synchronous reactance in q-axis is greater than that in d-axis. A starting asynchronous torque is produced with the aid of both a cage winding incorporated in slots in the rotor pole shoes (laminated core) or solid salient pole shoes made of mild steel sleeve.





Comparison between surface and buried magnet PMSM

Surface Magnets

- Simple motor construction
- Small armature reaction flux
- Permanent magnets not protected against armature fields
- Eddy-current losses in permanent magnets
- Expensive damper

Buried Magnets

- Relatively complicated motor construction
- High armature reaction flux
- Permanent magnets protected against armature fields
- No eddy-current losses in permanent magnets
- Less expensive damper

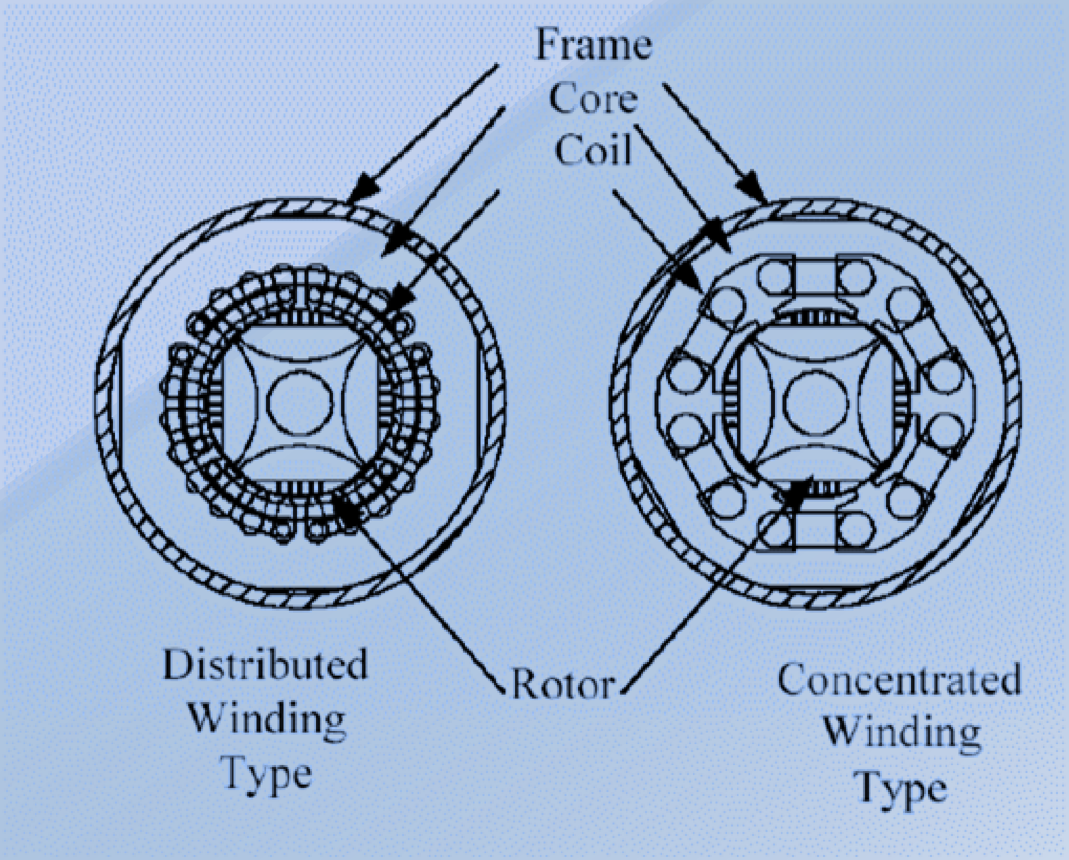
Comparison between surface and buried magnet PMSM

	Surface Mounted Magnet	Inset Magnet	Buried Magnet
Suitability	BLDC	BLDC/PMSM	PMSM
Rotor Complexity	Low	Medium	High
Flux Distribution	Square Wave	Square Wave or Sinusoidal	Sinusoidal
Speed Limit	1.2 X Rated speed	1.5 X Rated speed	(2~3) X Rated speed

New Trends in PMSM

Concentrated windings

- - Short end-turns
- - Compact winding
- - High inductance



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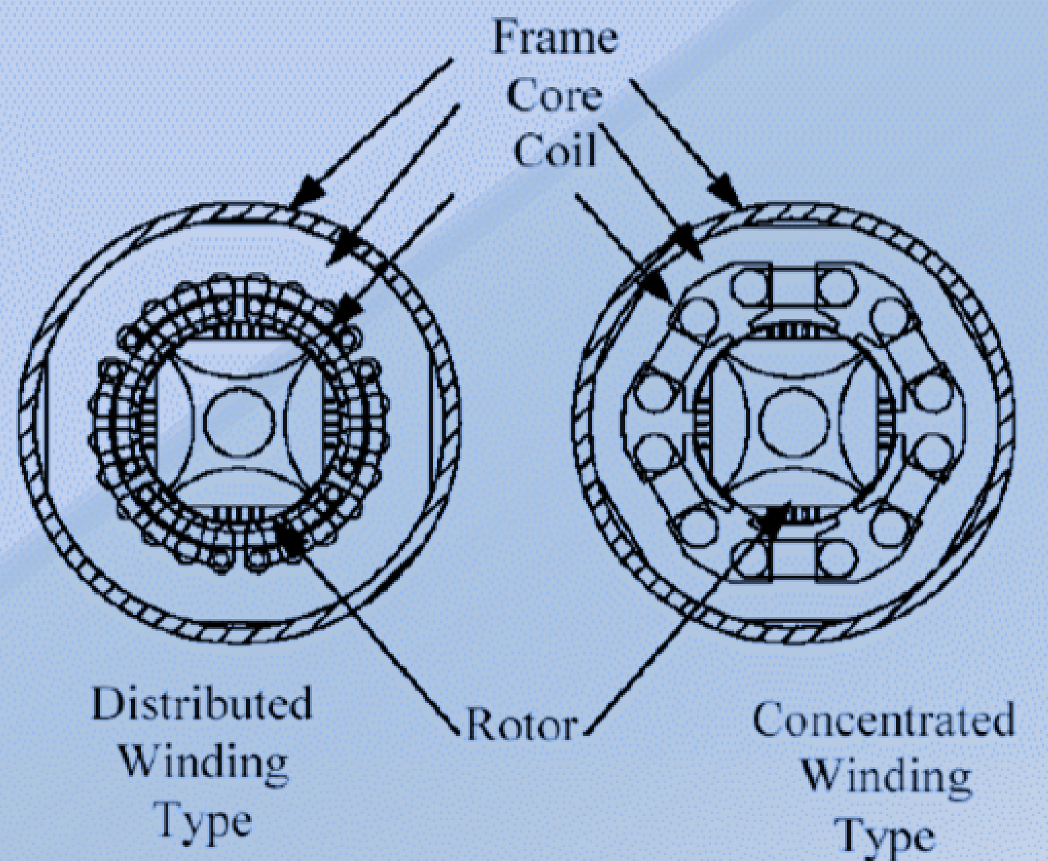
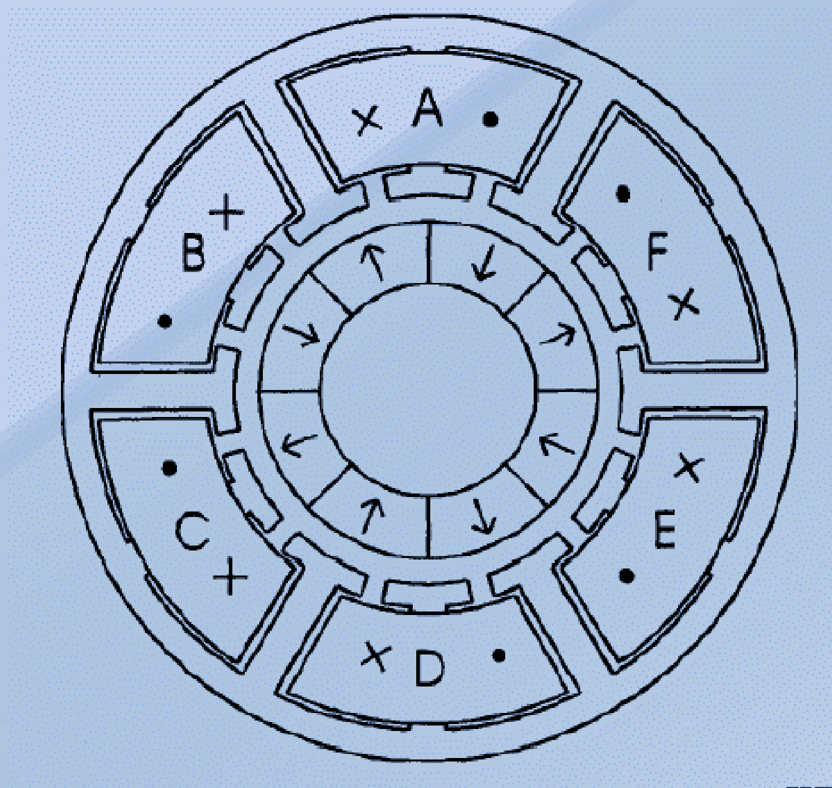


New Trends in PMSM

Special winding configuration for "fault tolerant" PM drives

Electric, magnetic and thermal decoupling of phases.

High inductance can be used to limit a short-circuit



Role of Magnet Thickness in PMSM

- Thicker magnets gives higher flux and thus more torque per amp.

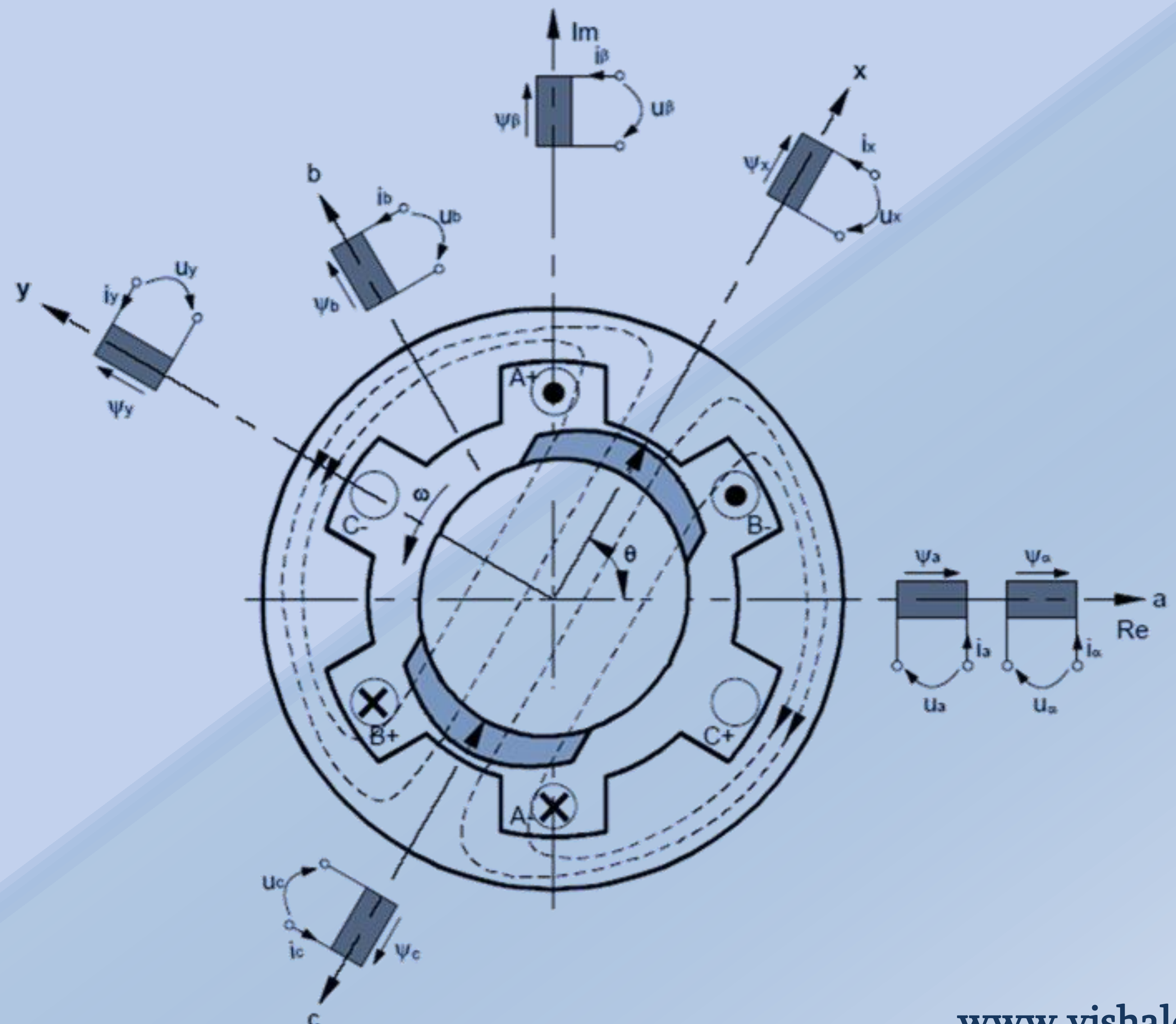
But higher flux also means higher core losses.

- Thicker magnets gives lower inductances

Faster respond, but higher PWM current ripple

- Thicker magnets makes the motor more resistant to demagnetization
- Thicker magnet also increases the cost significant.
- Doubling the thickness will typically only give 5-10% more flux

Operation Principle



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Theory

Phase Resistance R

The resistance in the copper used in the phase winding

Phase emf or peak flux-linkage from the PM

$$\psi_{pm} = \hat{\psi}_{pm} \cos(\theta) \qquad e = \frac{d\psi_{pm}}{dt} = \frac{d\psi_{pm}}{d\theta}\omega = \omega\hat{\psi}_{pm} \sin(\theta)$$

Phase inductance L_{ph}

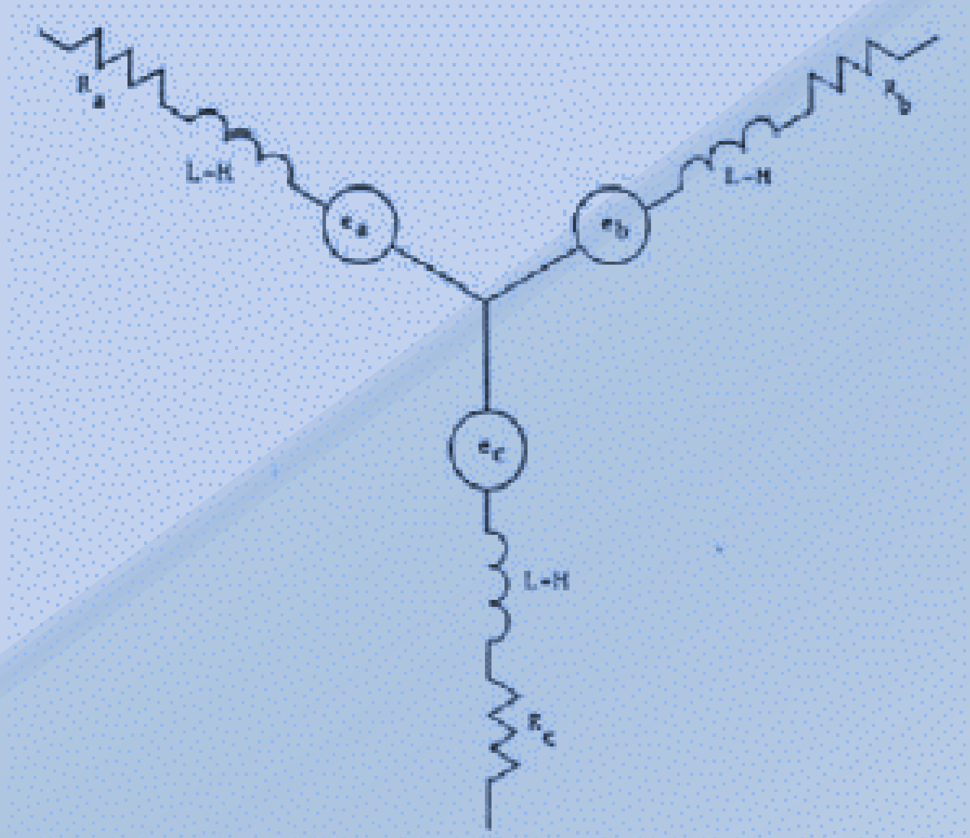
Typically the sum of air-gap, slot and end-turn inductance

Mutual inductance M

The flux linkage coupling from one phase to another with sinusoidal windings on a three phase machine 1/2 of the airgap flux will couple to the other phase.

Theory

A three phase PMSM can be modeled by the equivalent diagram shown in the figure



Theory

The voltage equation is easily derived as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + p \begin{bmatrix} L_a & L_{ba} & L_{ca} \\ L_{ba} & L_b & L_{cb} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

Assuming symmetry in all phases and surface mounted magnets i.e constant

inductances and mutual inductances) the voltage equation is simplified to

$$L_a = L_b = L_c = L$$

$$L_{ab} = L_{ca} = L_{bc} = M$$

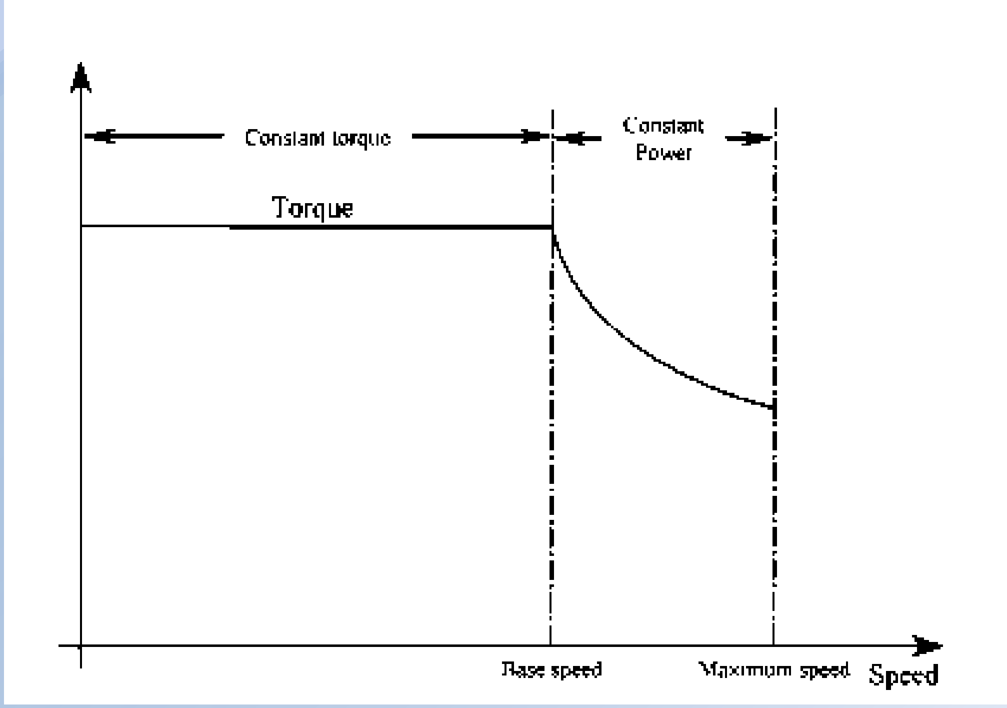
$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix}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

Theory

The voltage equation can be simplified as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

Torque $$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega_r.$$



Theory

PSMS in dq reference frame

$$v_d = Ri_d + p\lambda_d - \omega_r \lambda_q \qquad \lambda_q = L_q i_q$$

$$v_q = Ri_q + p\lambda_q - \omega_r \lambda_d \qquad \lambda_d = L_d i_d + \lambda_{af}$$

Torque

$$T_e = 3P[\lambda_{af} i_q + (L_d - L_q) i_d i_q]/2$$

Note for a PMSM with surface mounted magnets Ld ≈ Lq . i.e

$$T_e = 3\lambda_{af} i_q / 2 = K_t i_q$$

This means the torque simply is proportional to the q-axis current

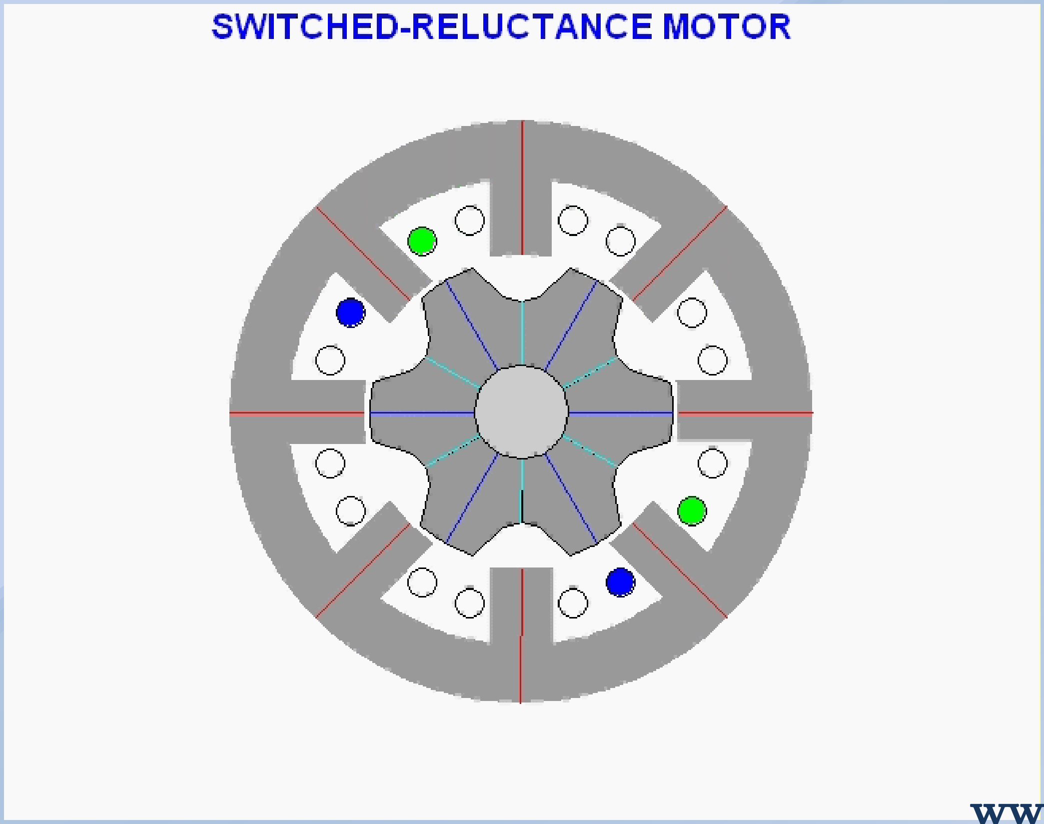
Disadvantages of PMSM

- Low speed range at high constant power but hybrid design with reluctance torque allows phase advance to extend speed range

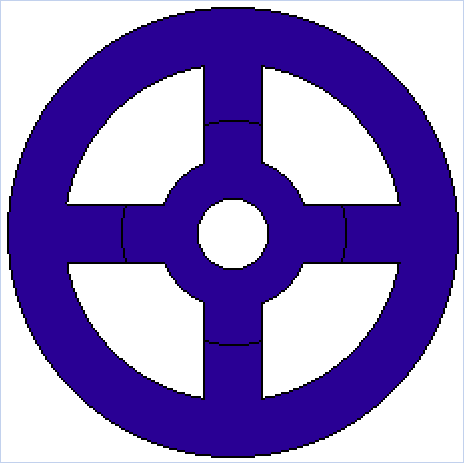
  With high energy permanent magnet can give 3:1 speed range and do not need any change of ratio
- High cost of permanent magnets
- Magnet corrosion and possible demagnetization
- Large air gap in surface mount PM machines

SRM

- [Switched Reluctance Motor (SRM)]



SRM Configurations



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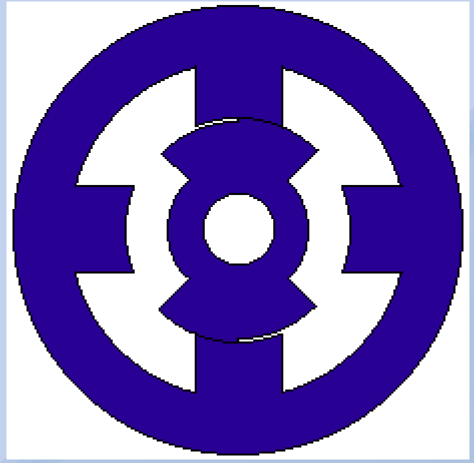

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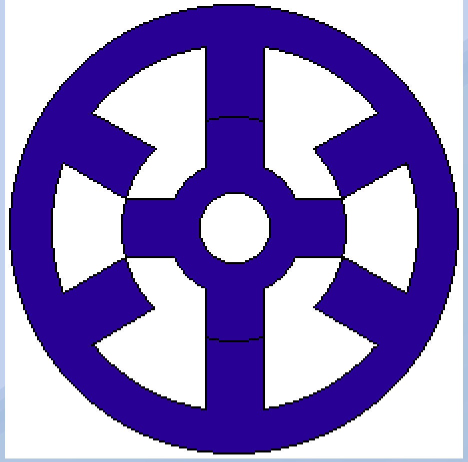

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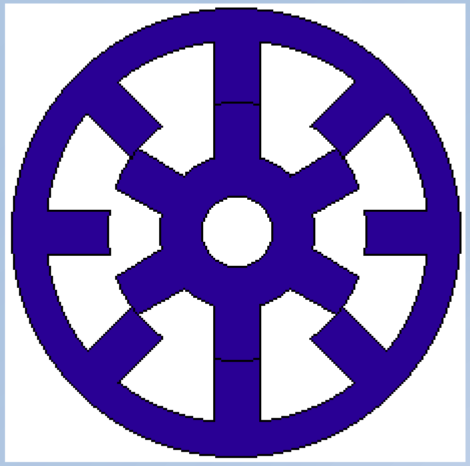

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Stepper Motors – An Overview

What's a Stepper Motor?

A stepper motor is a motor that, as the name suggests, moves in steps.

Compare With a Servo

- Stepper motors are similar to servo motors as we can perform position control with both.
- However, Servo motors require some form of analog feedback whereas stepper motors are often open loop.
- Stepping motors can be used in simple open-loop control systems; these are generally adequate for systems that operate at low accelerations with static loads, but closed loop control may be essential for high accelerations.

Compare With a Servo (Contd.)

- For high accelerations with variable loads, all rotor information is lost, and we require closed loop for accurate control

- Servo motors are not subject to this problem

Types of Stepper Motors

- Permanent Magnet
  - Employ permanent magnet
  - Low speed, relatively high torque
- Variable Reluctance
  - Does not have permanent magnet
  - Low torque

Types of Stepper Motors

- Hybrid
  - multi-toothed stator poles and a permanent magnet rotor
  - High static and dynamic torque

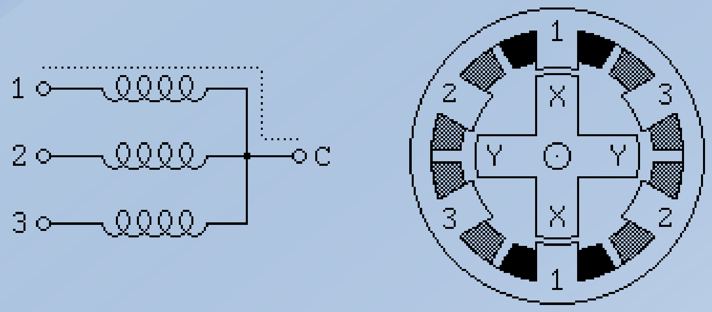
Variable Reluctance Motors

The variable reluctance motor in the illustration has four "stator pole sets" (A, B, C,), set 15 degrees apart.

Current applied to pole A through the motor winding causes a magnetic attraction that aligns the rotor (tooth) to pole A.

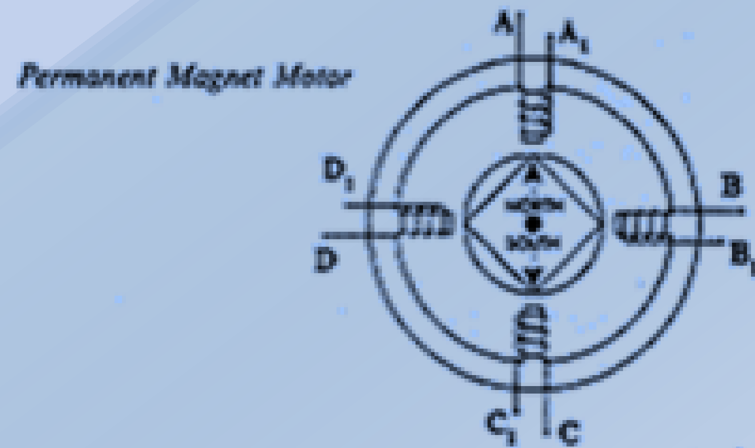
Energizing stator pole B causes the rotor to rotate 15 degrees in alignment with pole B.

This process will continue with pole C and back to A in a clockwise direction. Reversing the procedure (C to A) would result in a counterclockwise rotation.



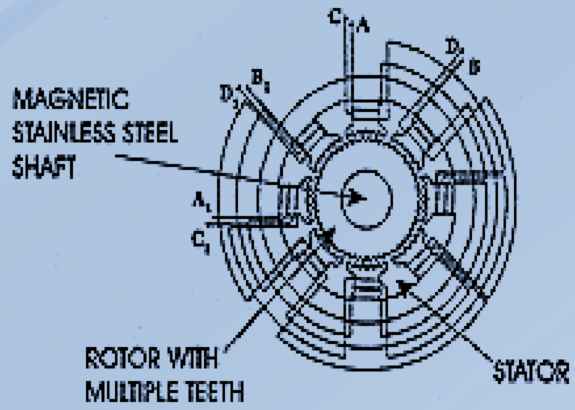
Permanent Magnet Motors

Unlike the other stepping motors, the PM motor rotor has no teeth and is designed to be magnetized at a right angle to it's axis. The above illustration shows a simple, 90 degree PM motor with four phases (A-D). Applying current to each phase in sequence will cause the rotor to rotate by adjusting to the changing magnetic fields. Although it operates at fairly low speed the PM motor has a relatively high torque characteristic.

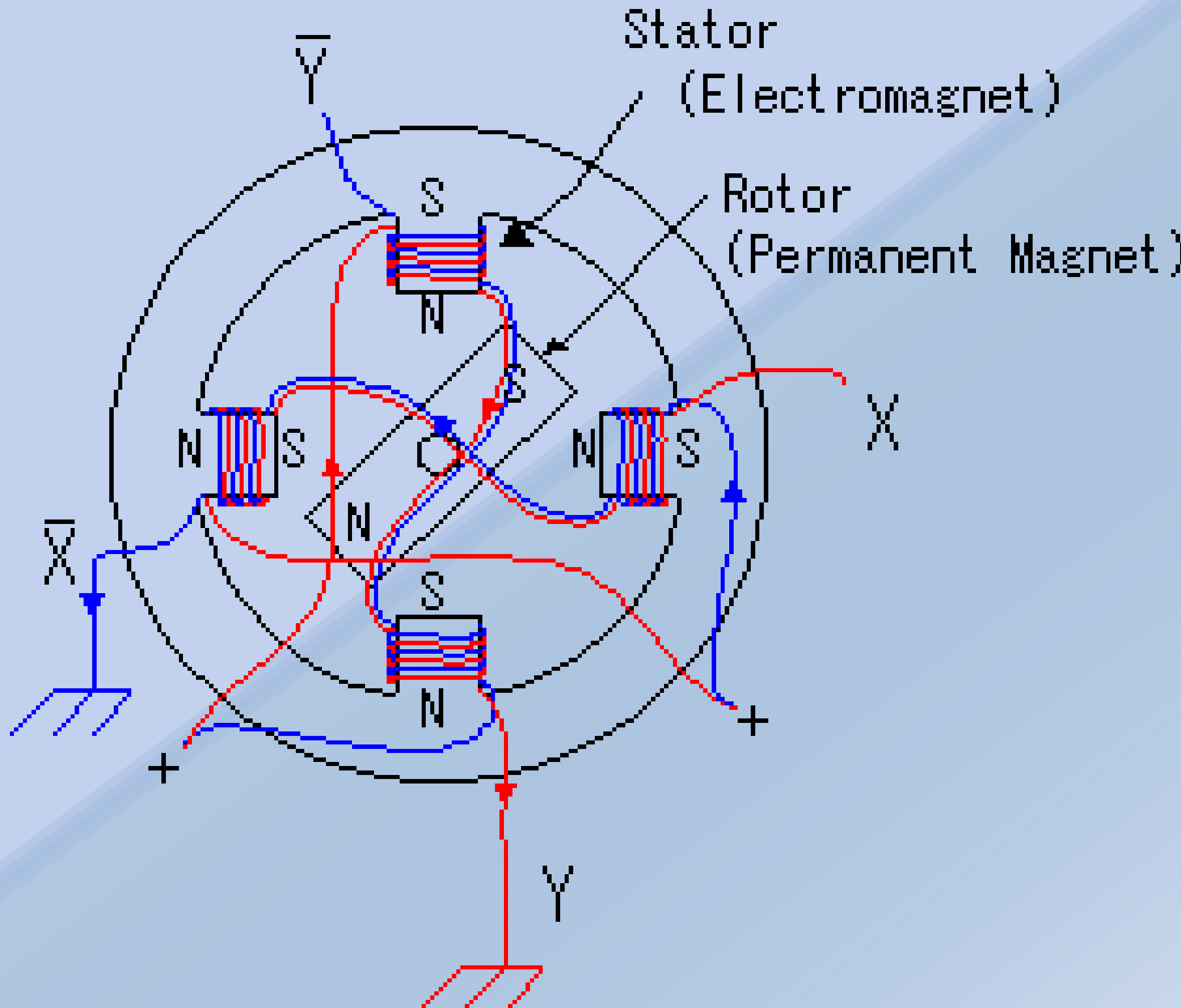


Hybrid Motors

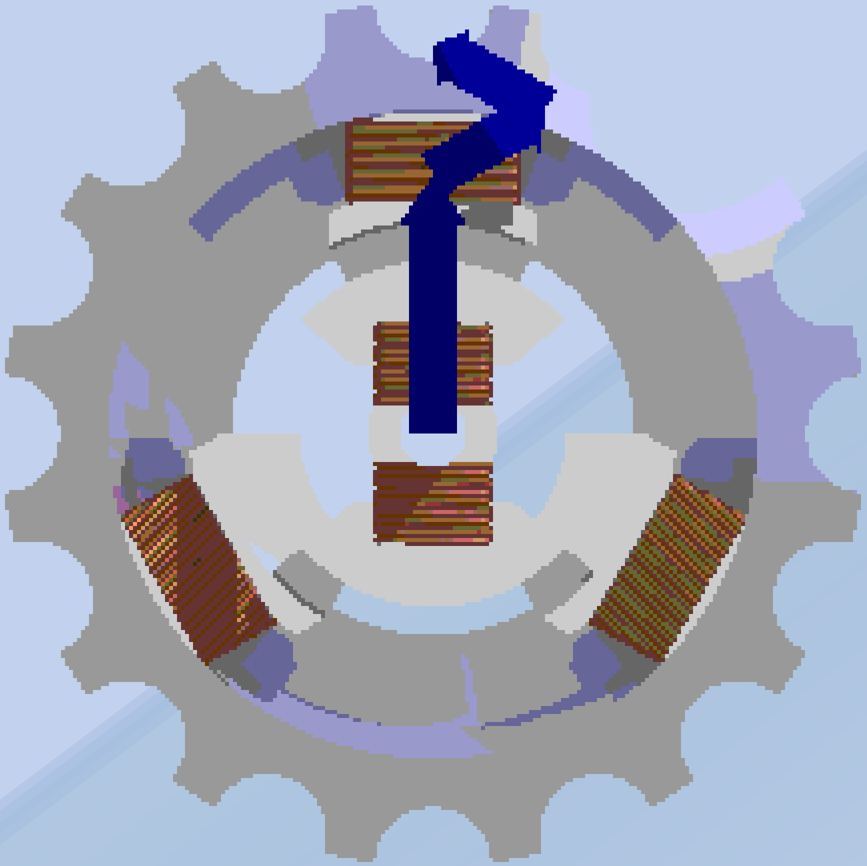
They are constructed with multi-toothed stator poles and a permanent magnet rotor. Standard hybrid motors have 200 rotor teeth and rotate at 1.80 step angles. Other hybrid motors are available in 0.9ºand 3.6º step angle configurations. Because they exhibit high static and dynamic torque and run at very high step rates, hybrid motors are used in a wide variety of industrial applications.



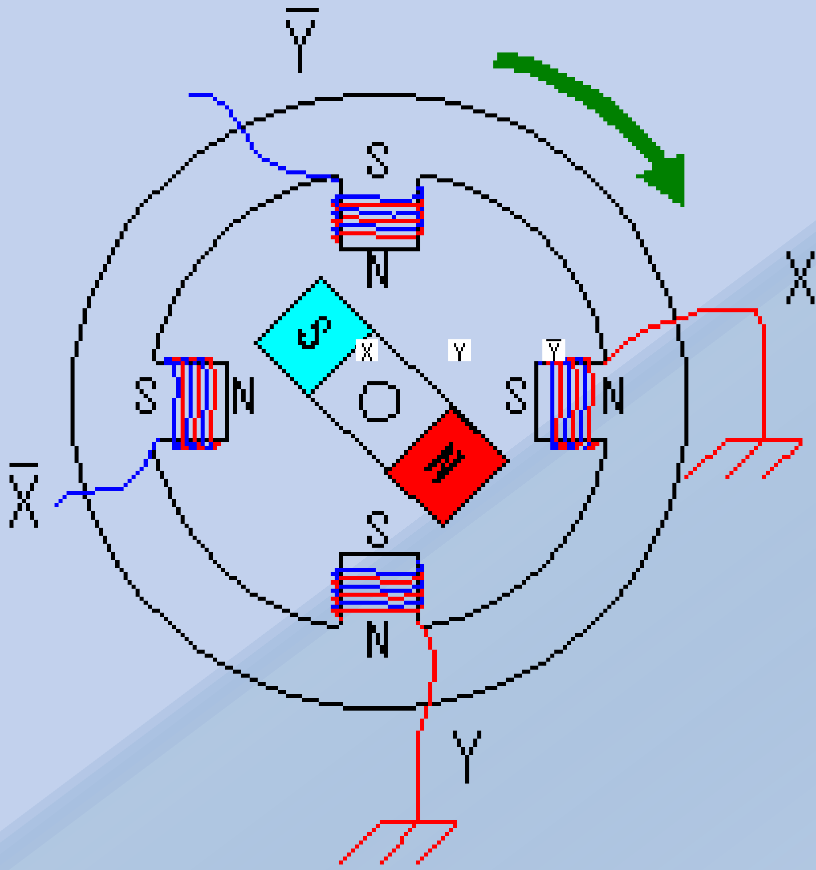
Hybrid Motor



Stator
(Electromagnet)
Rotor
(Permanent Magnet)
Y
X
S
N
N
S
N
S
S
N
S
N
X
Y
+
+

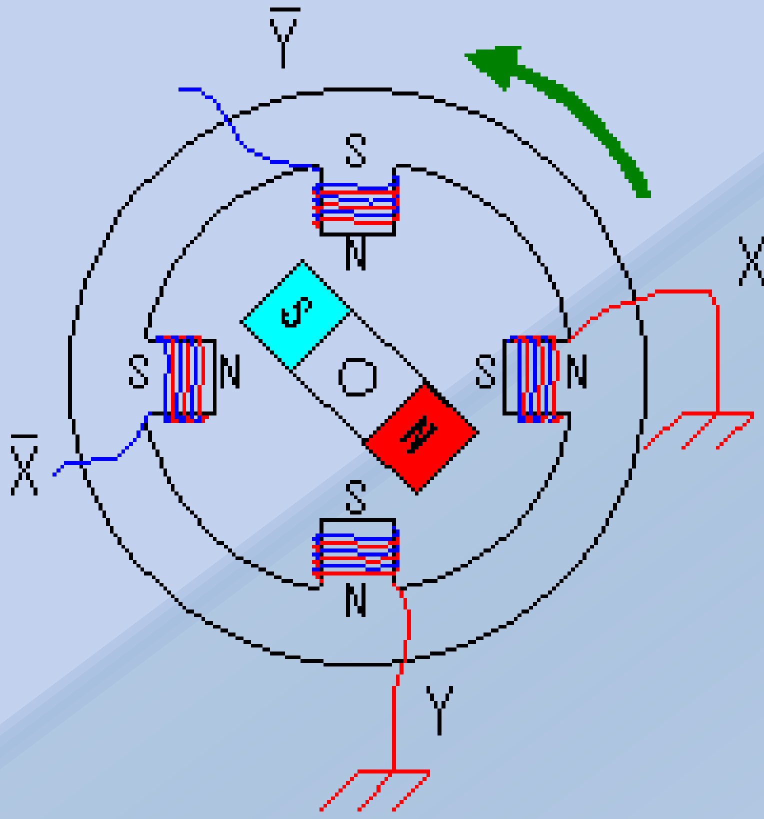


Clockwise Control

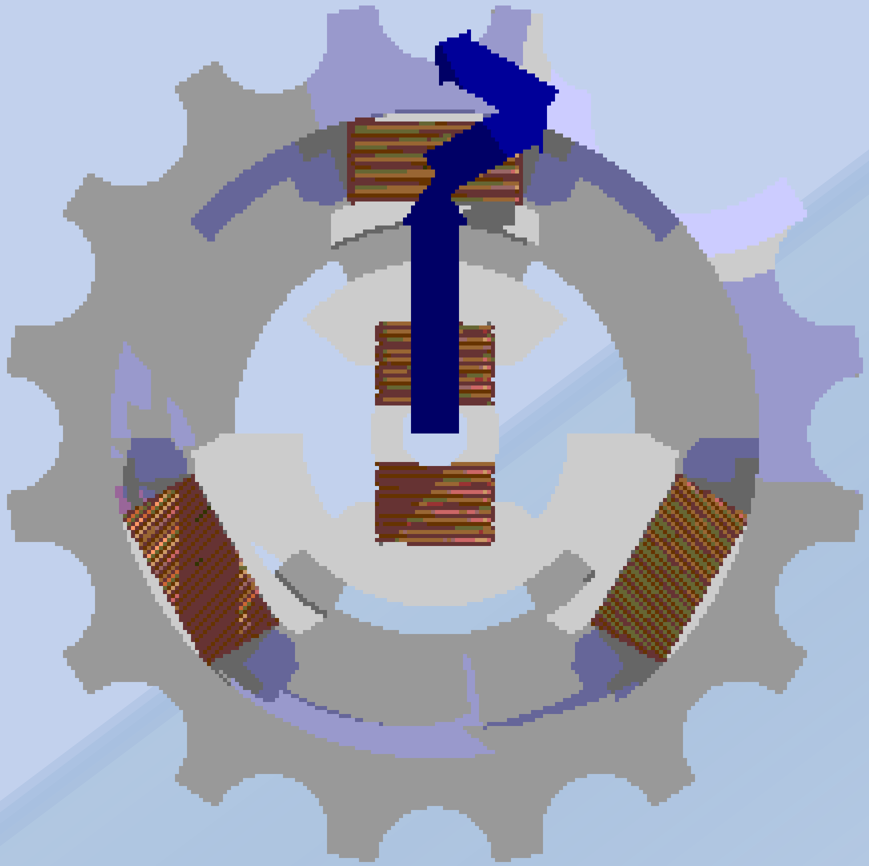


X	$\overline{X}$	Y	$\overline{Y}$
0	1	0	1
1	0	0	1
1	0	1	0
0	1	1	0

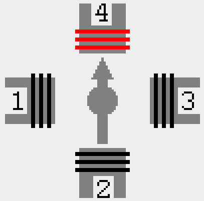
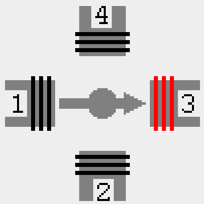
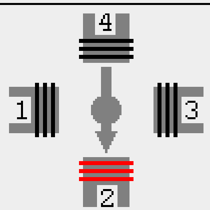
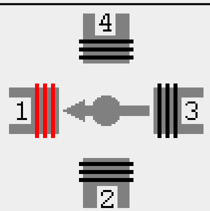
Counterclockwise control

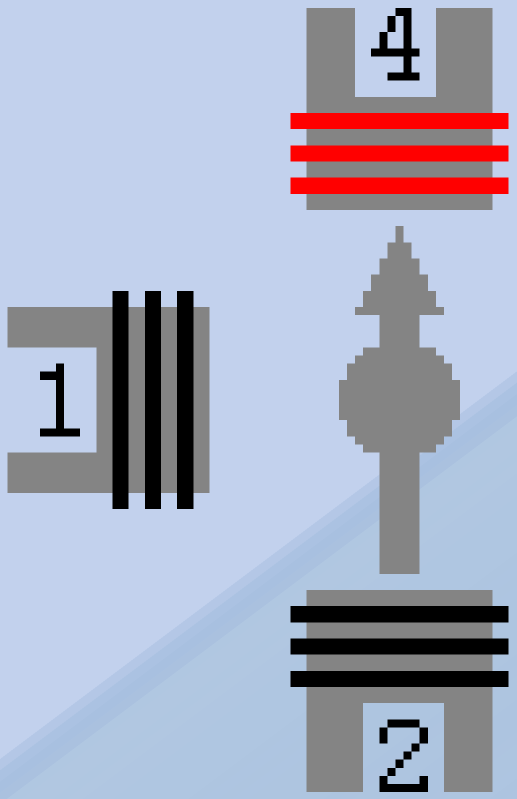


X	$\bar{X}$	Y	$\bar{Y}$
0	1	0	1
0	1	1	0
1	0	1	0
1	0	0	1



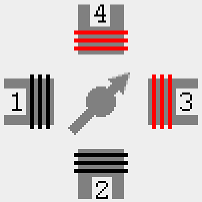
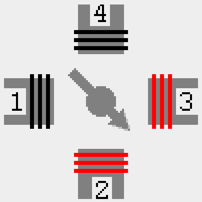
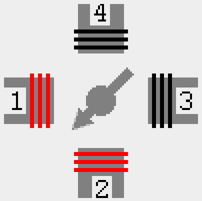
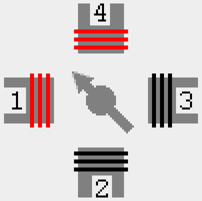
. **Single-Coil Excitation** - Each successive coil is energized in turn.

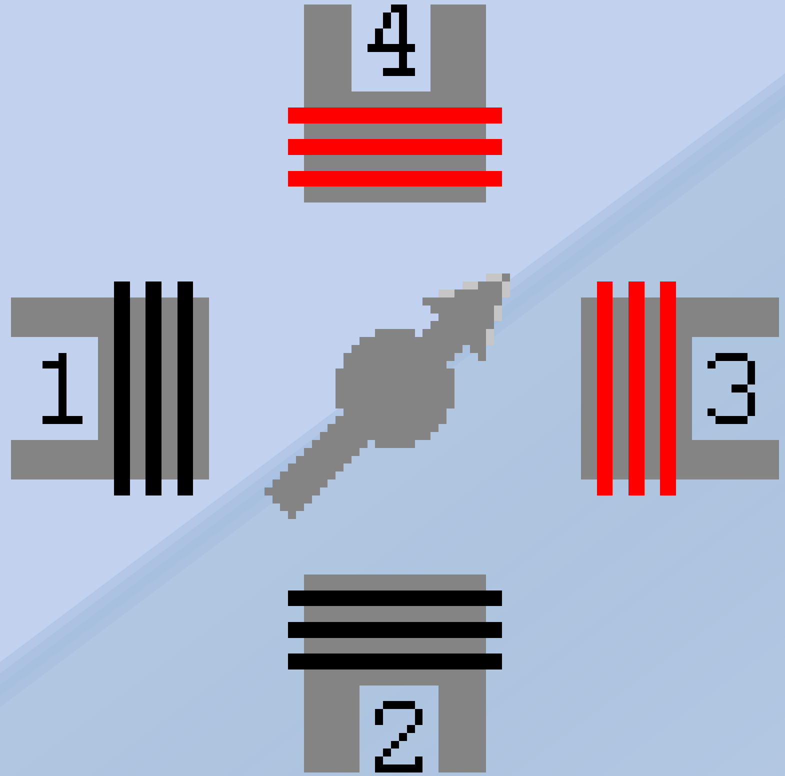
Step	Coil 4	Coil 3	Coil 2	Coil 1	
a.1	**on**	off	off	off	
a.2	off	**on**	off	off	
a.3	off	off	**on**	off	
a.4	off	off	off	**on**	



4
1
3
2

Two-Coil Excitation - Each successive pair of adjacent coils is energised in turn.

Step	Coil 4	Coil 3	Coil 2	Coil 1	
b.1	on	on	off	off	
b.2	off	on	on	off	
b.3	off	off	on	on	
b.4	on	off	off	on	


4
1
3
2

Thank You

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