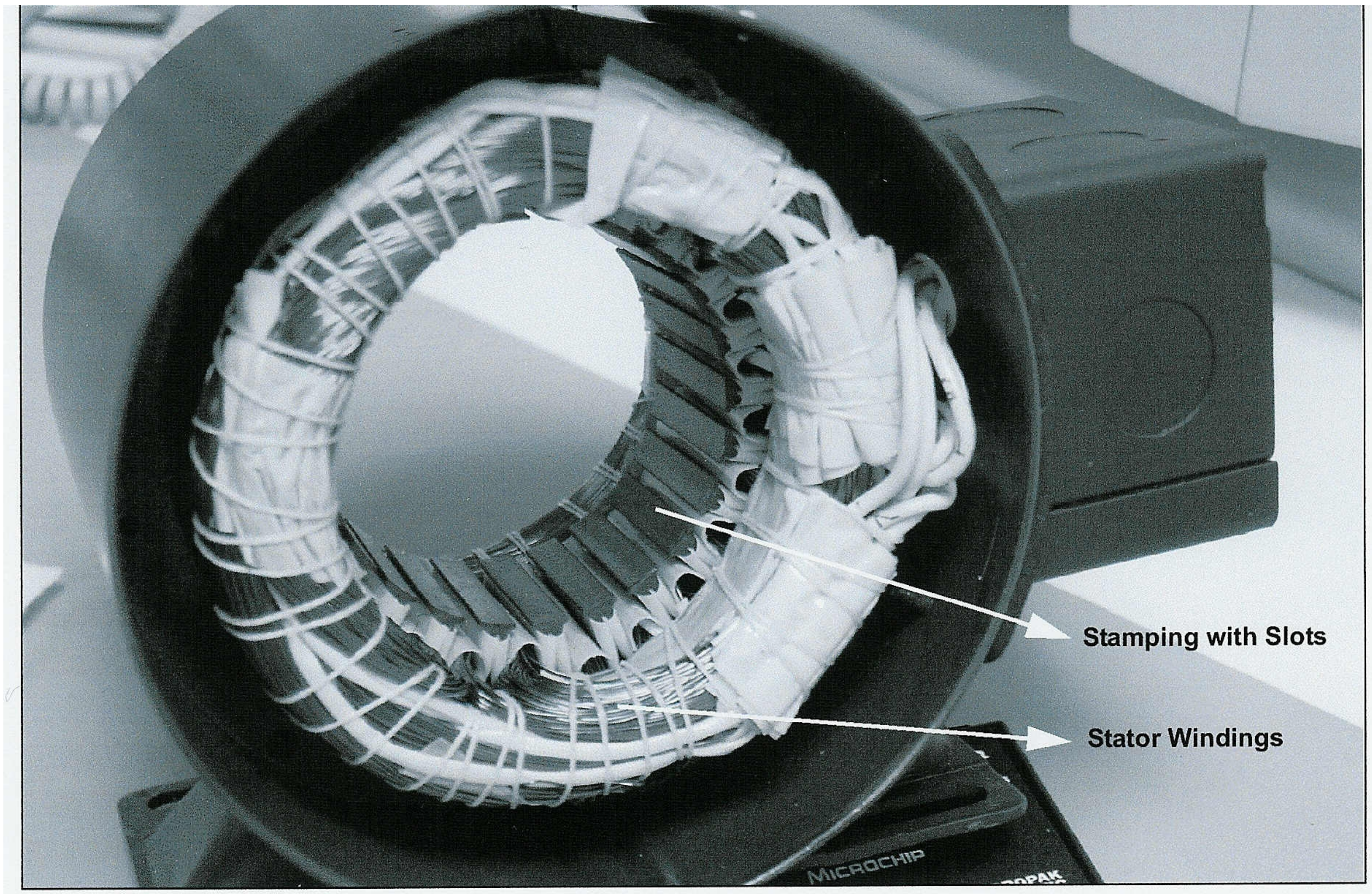
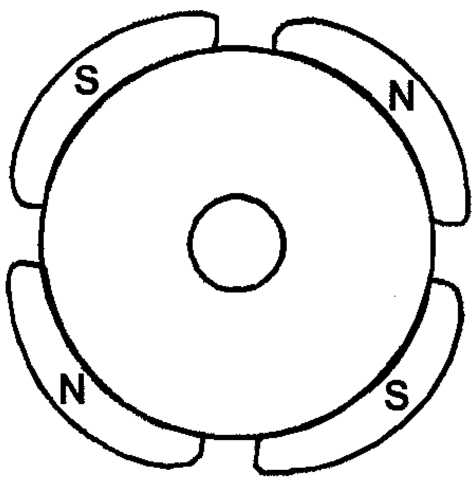
Brushless DC (BLDC) Motors

- 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

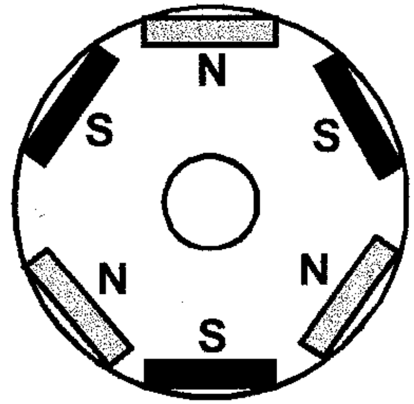
BLDC Motor Stator



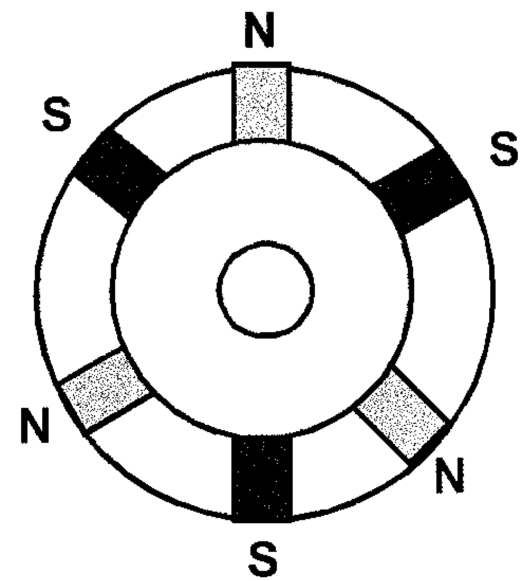
BLDC Motor Rotors



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

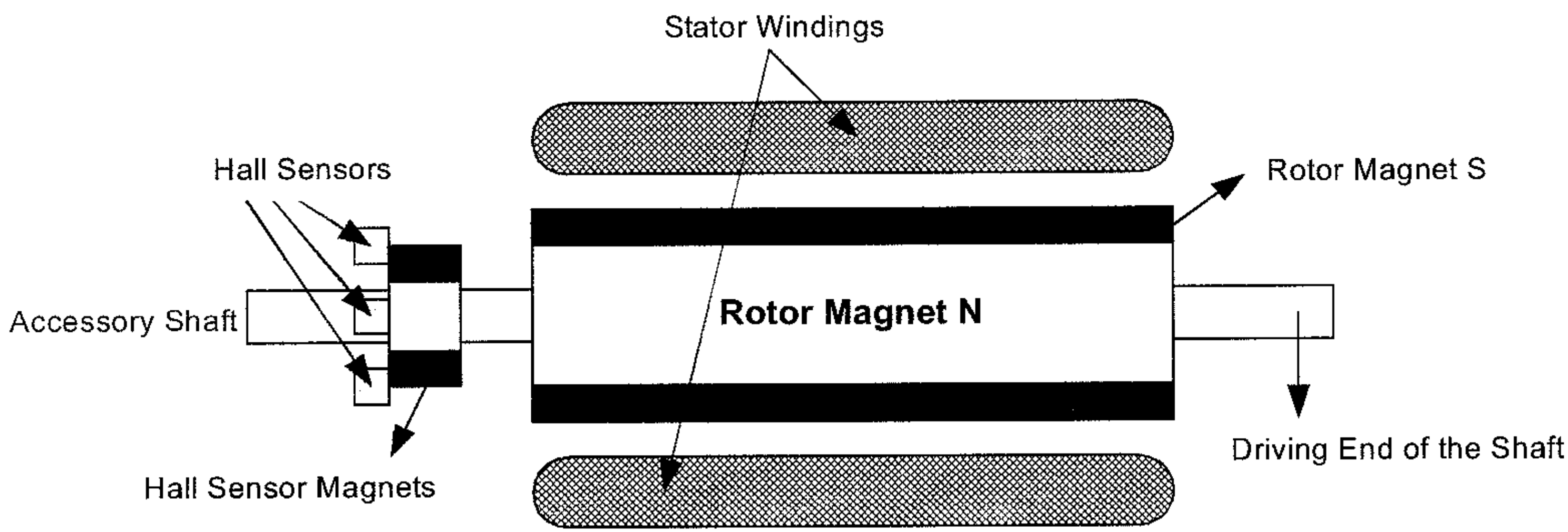
Hall-Effect

- 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

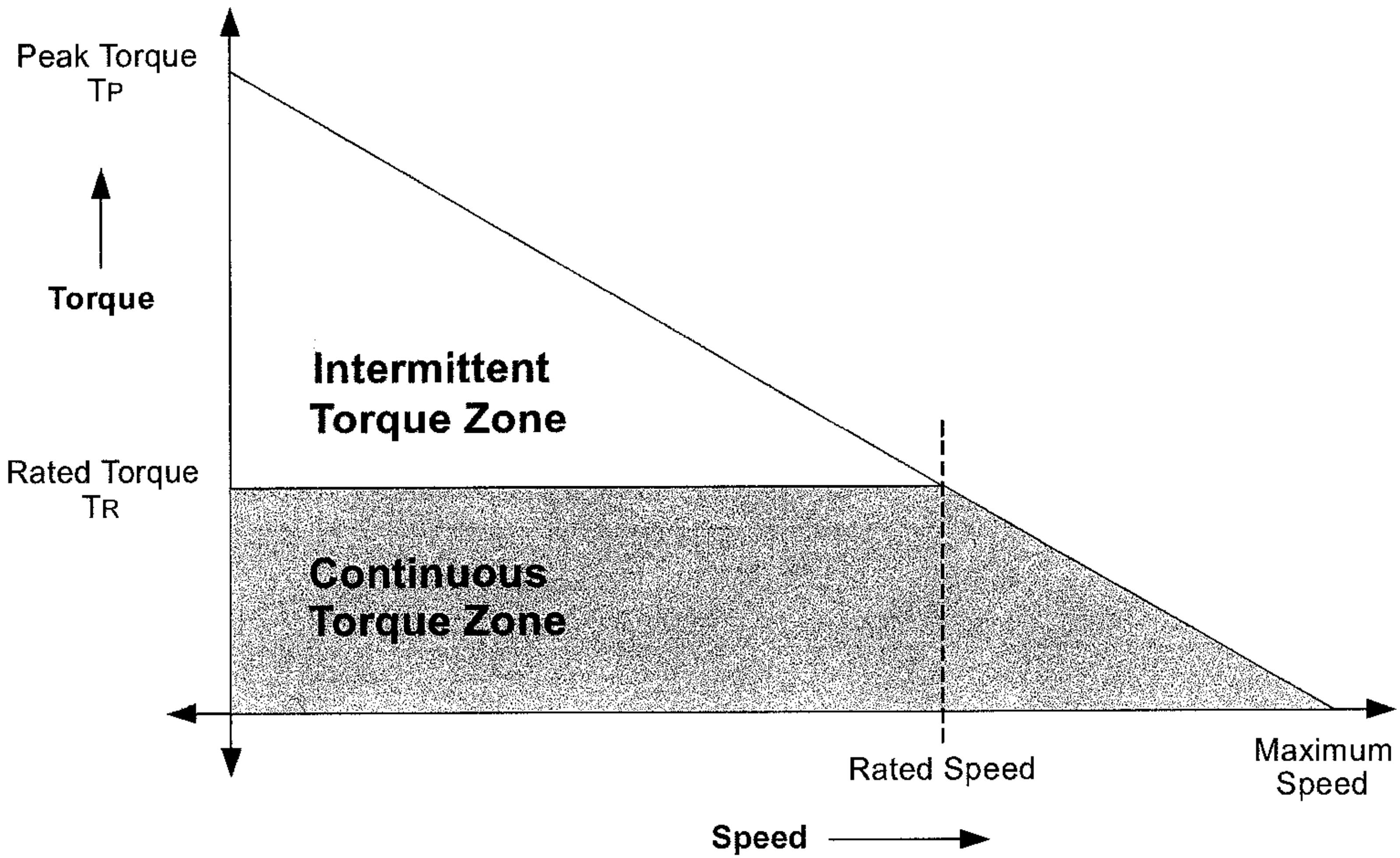


TABLE 1: COMPARING A BLDC MOTOR TO A BRUSHED DC MOTOR

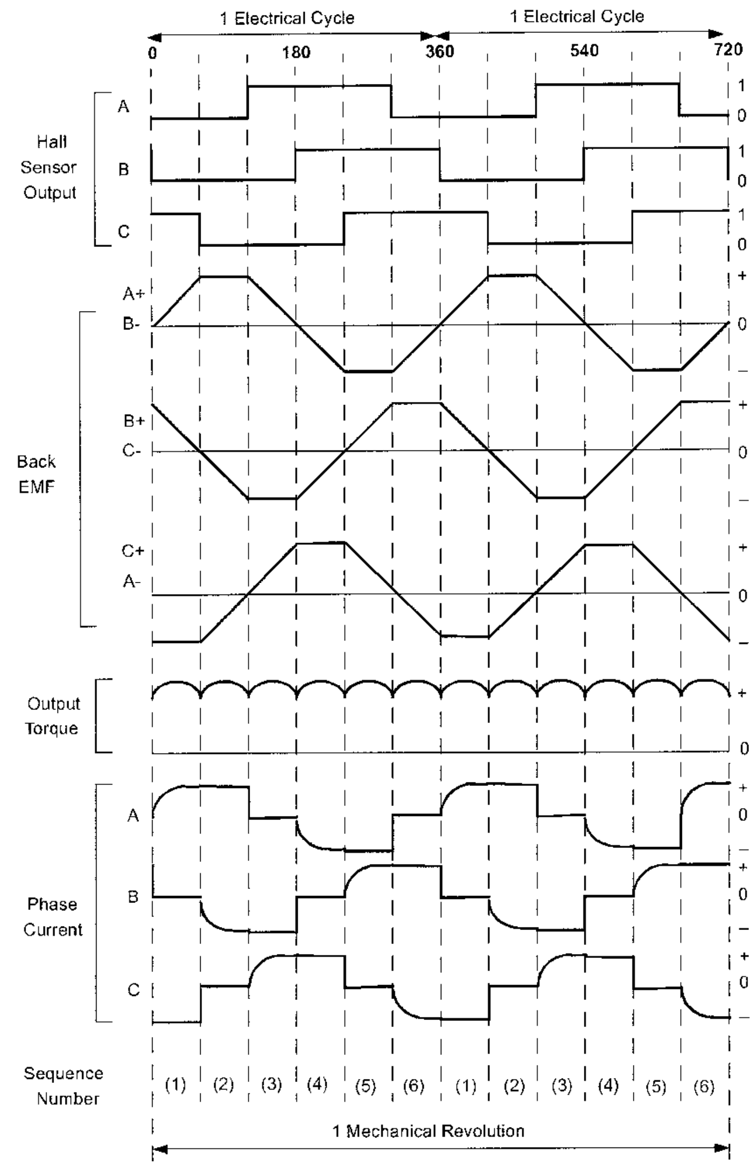
Feature	BLDC Motor	Brushed DC Motor
Commutation	Electronic commutation based on Hall position sensors.	Brushed commutation.
Maintenance	Less required due to absence of brushes.	Periodic maintenance is required.
Life	Longer.	Shorter.
Speed/Torque Characteristics	Flat – Enables operation at all speeds 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.

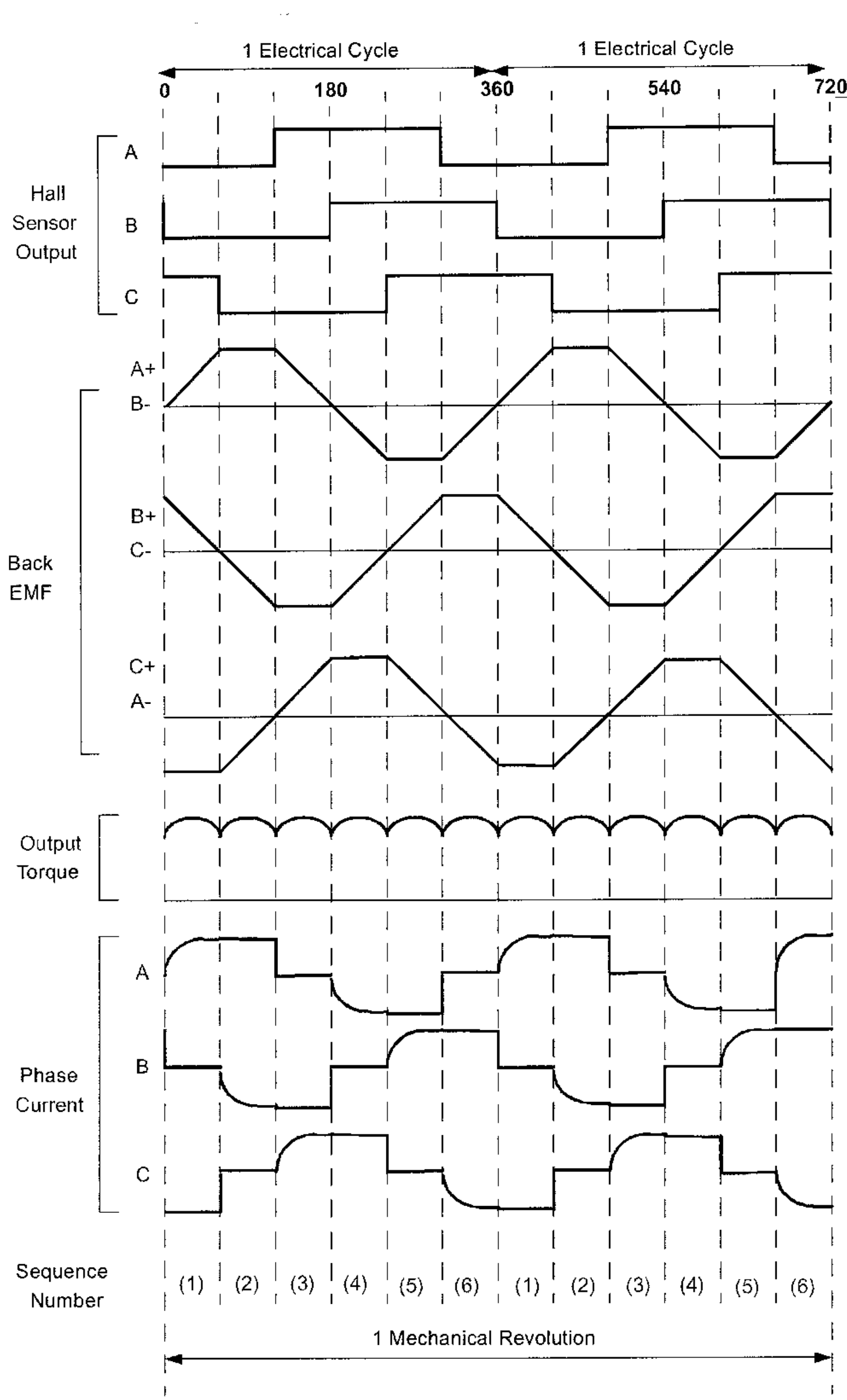
TABLE 2: COMPARING A BLDC MOTOR TO AN INDUCTION MOTOR

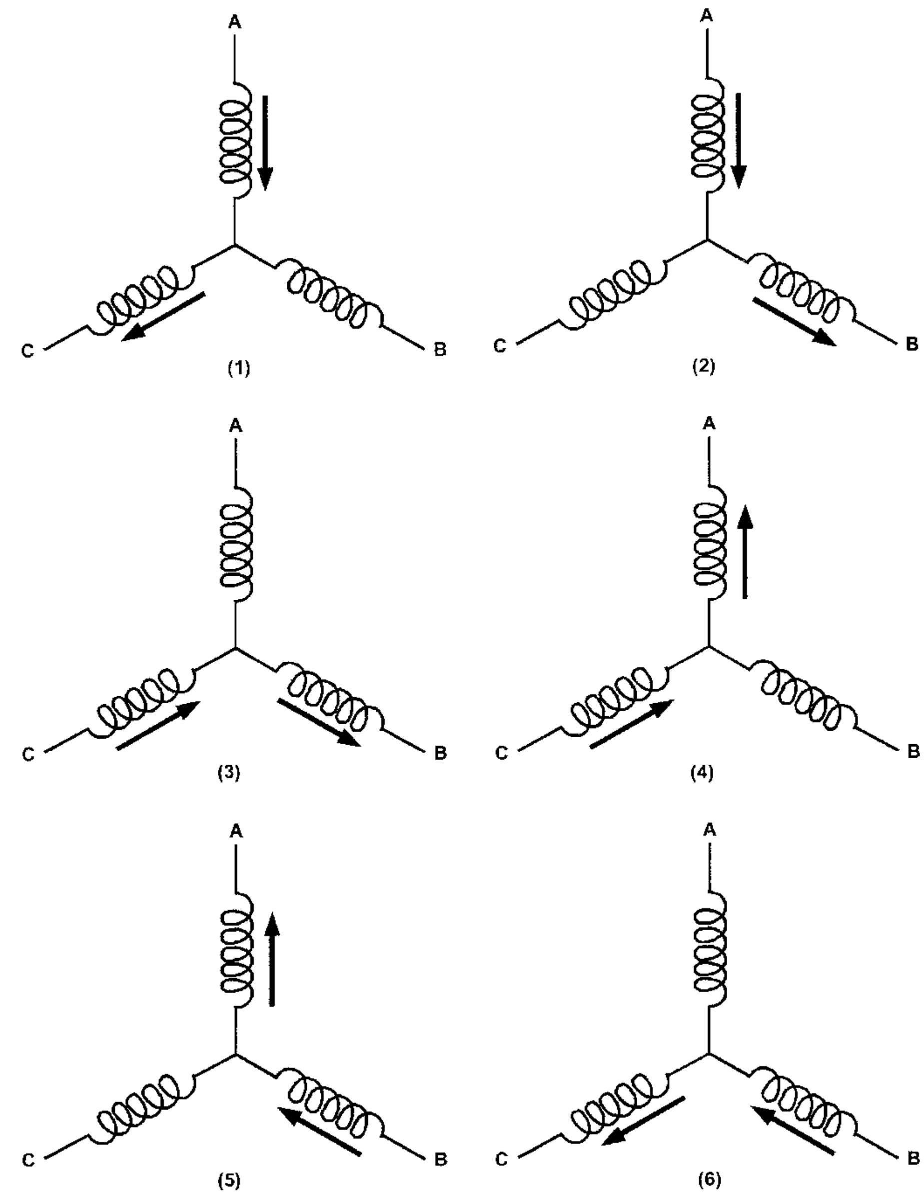
Features	BLDC Motors	AC Induction Motors
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load.	Nonlinear – Lower torque at lower speeds.
Output Power/ Frame Size	High – Since it has permanent magnets on the rotor, smaller size can be achieved for a given output power.	Moderate – 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)

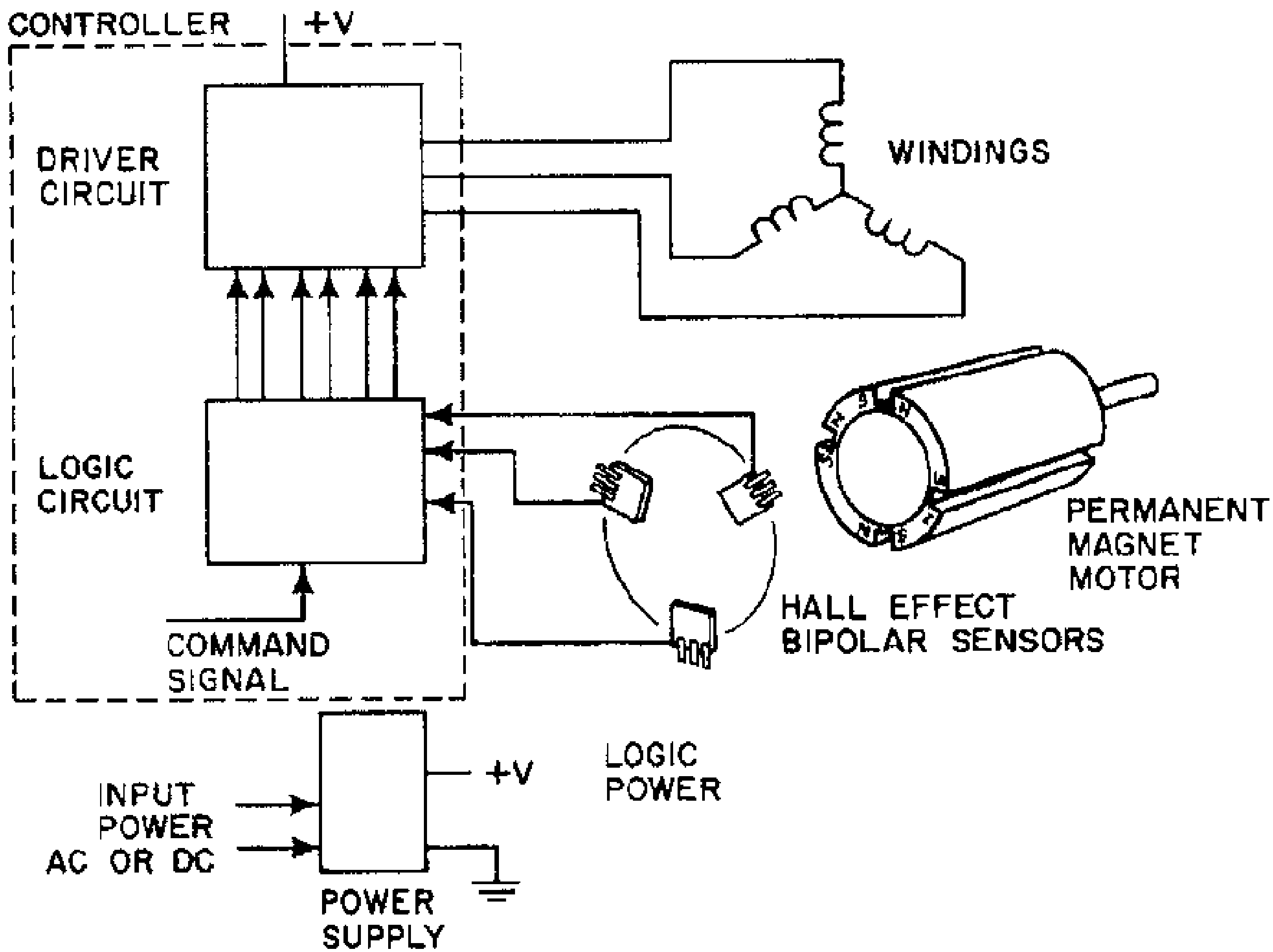
- Hall-Effect Sensors spaced 60 electrical degrees apart
- 6 steps to complete one electrical cycle
- Phase current switching updated every 60 electrical degrees



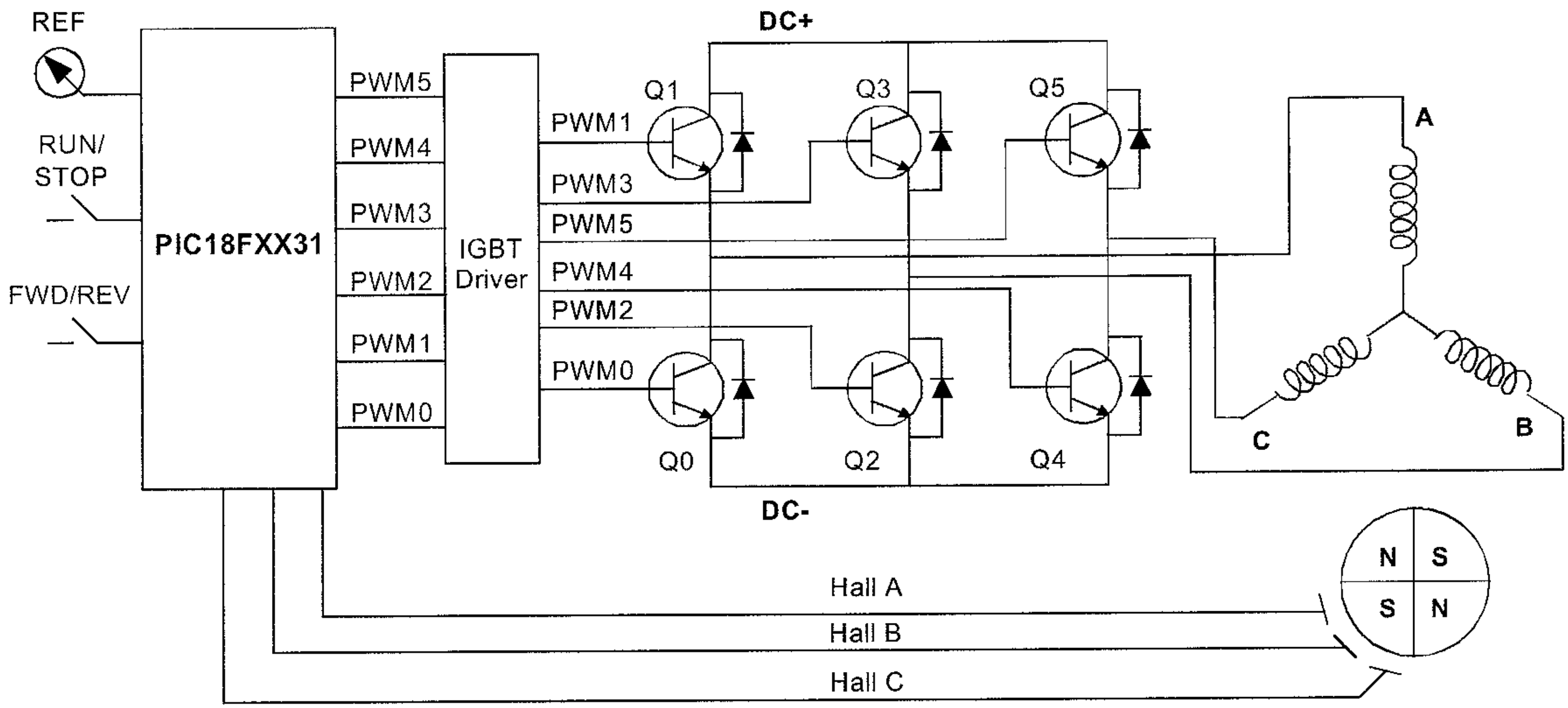

1 Electrical Cycle
1 Electrical Cycle
0
180
360
540
720
Hall Sensor Output
A
B
C
Back EMF
A+
B-
B+
C-
C+
A-
Output Torque
Phase Current
A
B
C
Sequence Number
(1)
(2)
(3)
(4)
(5)
(6)
(1)
(2)
(3)
(4)
(5)
(6)
1 Mechanical Revolution

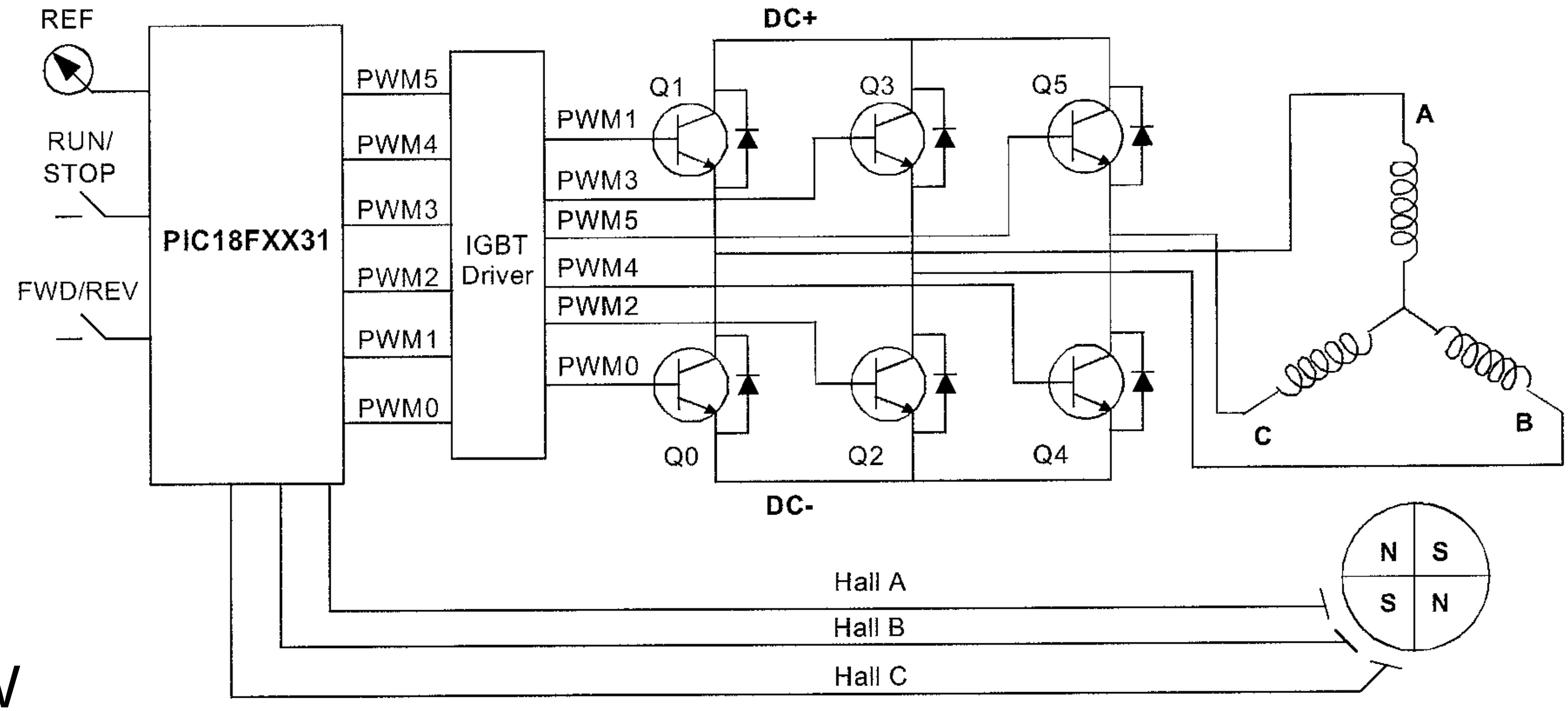

A
B
C
(1)
(2)
(3)
(4)
(5)
(6)

Essential Elements of a Typical BLDC Motor



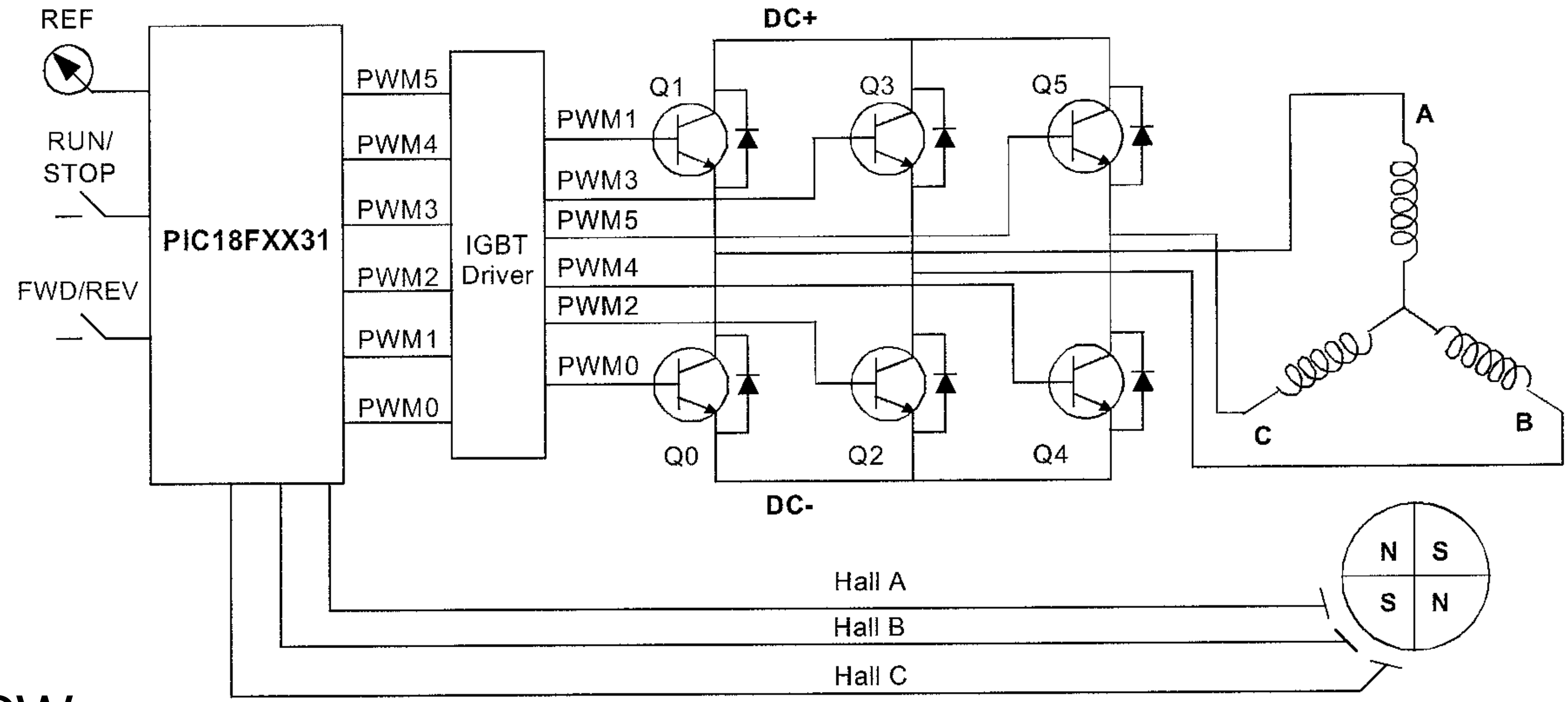
BLDC Control





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+

Brushless Motors

What you need to know.

Motor selection info.

Watts per pound of airplane weight.

- 100w/lbs = trainer/sport
- 150w/lbs = 3D aerobatics
- 200w/lbs = extreme

Watts = volts * current

- 7.4v * 10amps = 74watts
- 11.1v * 25amps = 277watts
- 22v * 50amps = 1110watts

Ex. 16oz sport airplane = 100w motor

746watts = 1 horse power

Motor formulas

Efficiency: Motor Efficiency = Pout/Pin, Pout = (Vin - Iin * Rm) * (Iin - Io)

Motor Kv: Kv = RPM / (Vin - Vloss), Vloss = Iin * Rm

Motor RPM: RPM = Kv * (V - Vloss), Vloss = Iin * Rm

Watts: Watts = V * Iin, Alternately $P=I^2R$ (P = I x I x Rm)

Stalled Motor: Istall = Vin / Rm

Torque constant: Torque constant: Kt=Kb x 1.345, Kb = Voltage constant (Volt/1000 RPM)

Torque Loss: Torque = Kt * (Iin - Io)

Termination: Wye = the number of winds you have performed, Delta = divide the number of turns by 1.73

Watts per Horsepower: 1 horsepower = 746 watts

Kv-Rpm constant: Kv * turns = motor constant, (ex. Kv=1090 * 32T ~= 35000 so, 35000/28T ~= 1250Kv)

Motor formulas - Acronyms

Acronyms:

Rm = Resistance value of the motor, derived from the guage of wire used.

Pout = Power Out of the Motor expressed in Watts

Pin = Power In of the Motor expressed in Watts

Vin = Voltage Into the Motor

Iin = Current Into the Motor

Io = Noload Current of the Motor, derived from running a motor WOT without a prop at varying voltages. Io can be expressed with an associated Voltage and should be.

Kv = K value or voltage constant, the expressed value where the rpm can be surmised by a given voltage. For a 2000 Kv motor an input voltage of 10V would net 20000RPM.

Istall = The load current of a motor which is purposely stalled, hence not turning.

Kt = Torque constant (oz-In/A)

Kb = Voltage constant (Volt/1000 RPM)

Misc. motor info.

PI*(dia./2)^2) = sectional area of wire

~ Delta > Star = .578 (.562 - .526)

~ Star > Delta = 1.73 (1.78 - 1.9)

Doubling the number of winds halves Kv (rpm/volt) and doubles Kt (torque/Ampere),

Doubling stator height halves Kv, doubles Kt and (roughly) doubles maximum power.

Kv-Rpm Constant:

Example:

The 3008-32 motor has a Kv of 1090. If you take 1090 x 32 you get 34,880. If you look at the 3008-28 motor, it has a Kv of 1253.

If you take 1253 x 28 you get 35,084. Based on these 2 numbers, you can see that the constant for the 3008 size motor is right arounf 35,000.

If you take 35,000 and divie that by the number of turns, you will get the approximate Kv of the motor.

Brushless motor construction

The basic 3-phase build

Why build?

- Fun
- Cheap
- Rewarding
- Build the perfect motor for your application.

Electronic Gearing

- Divide 360deg by number of magnets then divide by 3 phases.
  - This provides the degree of movement per step sequence.
- 6 cycle step sequences needed to complete 1 revolution of the magnetic field.
  - A to B / C to B / C to A / B to A / B to C / A to C

Examples:

10 magnet

360deg / 10 mag = 36deg || 36deg / 3 phase = 12deg
(12deg / step) x 6 steps = 72deg. Sequence
360deg / 72deg = 5 or 5:1 gearing

14magnet

360deg / 14 mag = 25.71deg || 25.71deg / 3 phase = 8.57deg
(8.57deg / step) x 6 steps = 51.42deg. Sequence
360deg / 51.42deg = 7 or 7:1 gearing

9-pole magnet options

9-pole stator basically two choices:

- 6 magnets (3:1 gearing)
  - High RPM (Kv), low torque
  - Good for Helis and ducted fans
- 12 magnets (6:1 gearing)
  - Low RPM (Kv), high torque
  - Larger propellers, 3D flying

12-pole magnet options

12-pole stator four choices:

LRK or DLRK wind

- 10 magnets (5:1 gearing)
  - Higher RPM (Kv), lower torque
- 14 magnets (7:1 gearing)
  - Lower RPM (Kv), higher torque

ABC wind

- 8 magnets (4:1 gearing)
  - Higher RPM (Kv), lower torque
- 16 magnets (8:1 gearing)
  - Lower RPM (Kv), higher torque

Wind techniques / options

- 9-pole stator can only be wound using ABC wind
  - ABC - ABCABCABC
- 12-pole stator can be wound either ABC, LRK or DLRK.
  - ABC – ABCABCABCABC (easy, need more magnets)
  - LRK – A-b-C-a-B-c (high wrap count per tooth, less to wind)
  - DLRK – AabBCcaABbcC (low wrap count per tooth, more to wind

12 stator pole wind types

Distributed LRK Winding Diagram (DLRK) for 10 or 14 Magnet Poles

	10 magnet poles	**14 magnet poles**	**16 magnet poles**
Magnetic Pattern	NSNSNSNSNS	NSNSNSNSNSNSNS	NSNSNSNSNSNSNSNS
DLRK Winding	AabBCcaABbcC	AabBCcaABbcC	ABCABCABCABC
LRK Winding	A-b-C-a-B-c	A-b-C-a-B-c	

- “A” and "a" are first phase wire S1
- “B” and "b" are second phase wire S2
- “C” and "c" are third phase wire S3
- Capital (upper case) letter means Clockwise
- Small (lower case) letter means Anti-Clockwise
- “-“ means the stator tooth not wind

Star or Delta connection?

Now, you need to make you own decision to solder the magnet wires to either Star (wye) or Delta system.

Star vs Delta

- ✓ Star (wye) system gives more torque and uses fewer amps.
  In Star system, 1.73 less turns needs to be wound to get the same power and Kv as DELTA system does.

- ✓ Delta system gives 1.73 higher power and amps draw compare to STAR system.
  In Delta system, the Kv is 1.73 higher than Star system while the Kt (Torque) is 1.73 lower

Magnet polarity

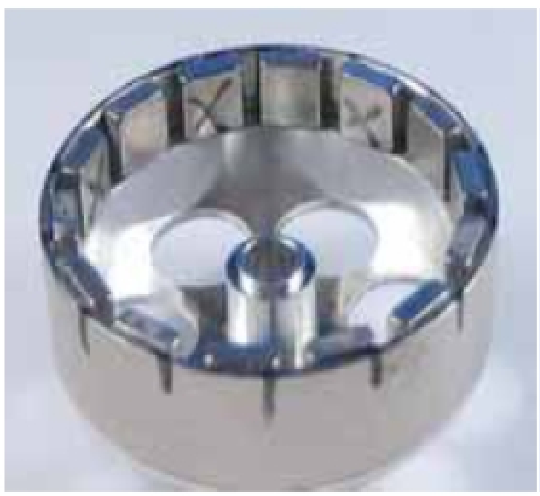
Stack all magnets together. This will assure all the magnet poles facing one end of the stack are the same polarity. Use a marker to mark the face of one of the end magnets, then move that magnet to the other end of the stack. Continue marking and moving magnets until all magnets have one face marked.

Before placing magnets inside the bell, you need to choose the number of magnet poles from the table below.

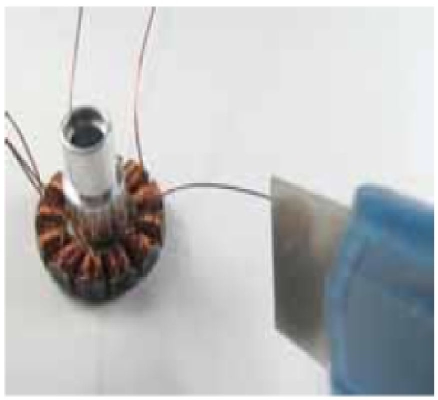
The characteristics of different magnet pole set-ups			
	10 magnet poles	14 magnet poles	16 magnet poles
Magnetic Pattern	NSNSNSNSNS	NSNSNSNSNSNSNS	NSNSNSNSNSNSNSNS
RPM	High	Middle	Low
Torque	Low	Middle	High

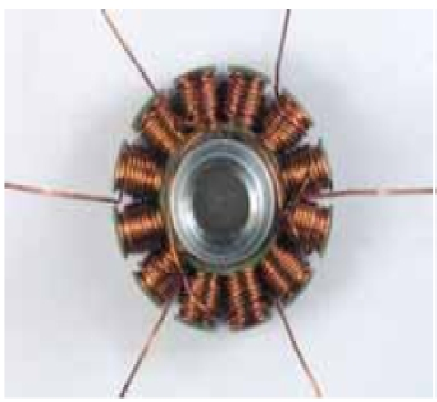
Magnet installation



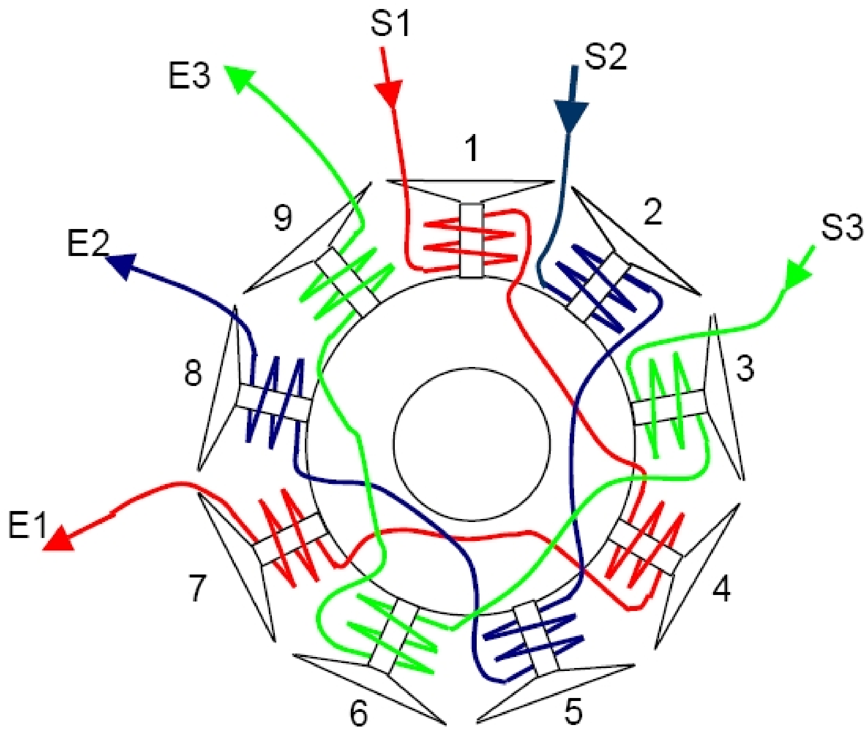

Check for shorts – Solder wires





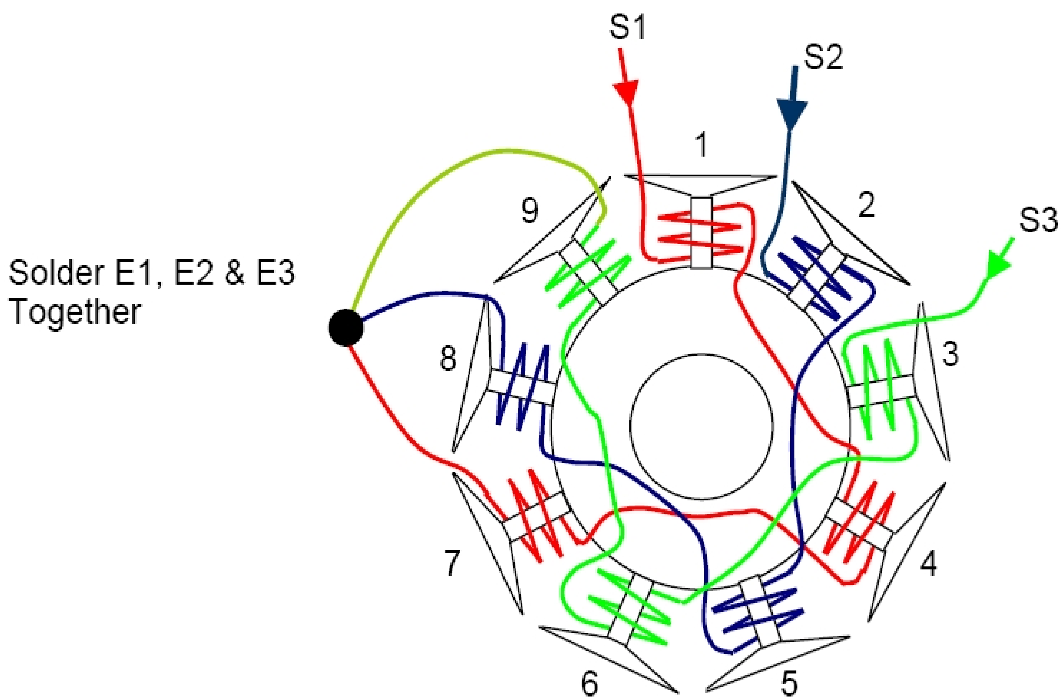
Now, check for any possible shorts between the stator and each wire or between wires S1, S2 and S3. If any shorts are found the wire should be removed and new wire installed. Attempting to run a motor with a short can damage your electronic speed control, battery, or receiver.

9-pole stator – ABC wind

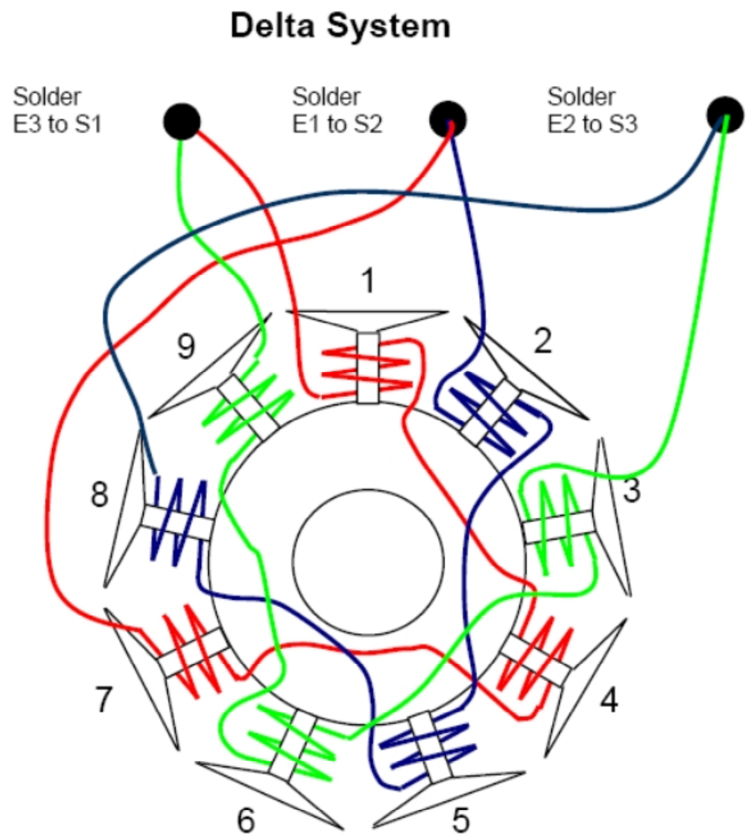


9 pole “Star” connection

Star (wye) system



9 pole “Delta” Connection

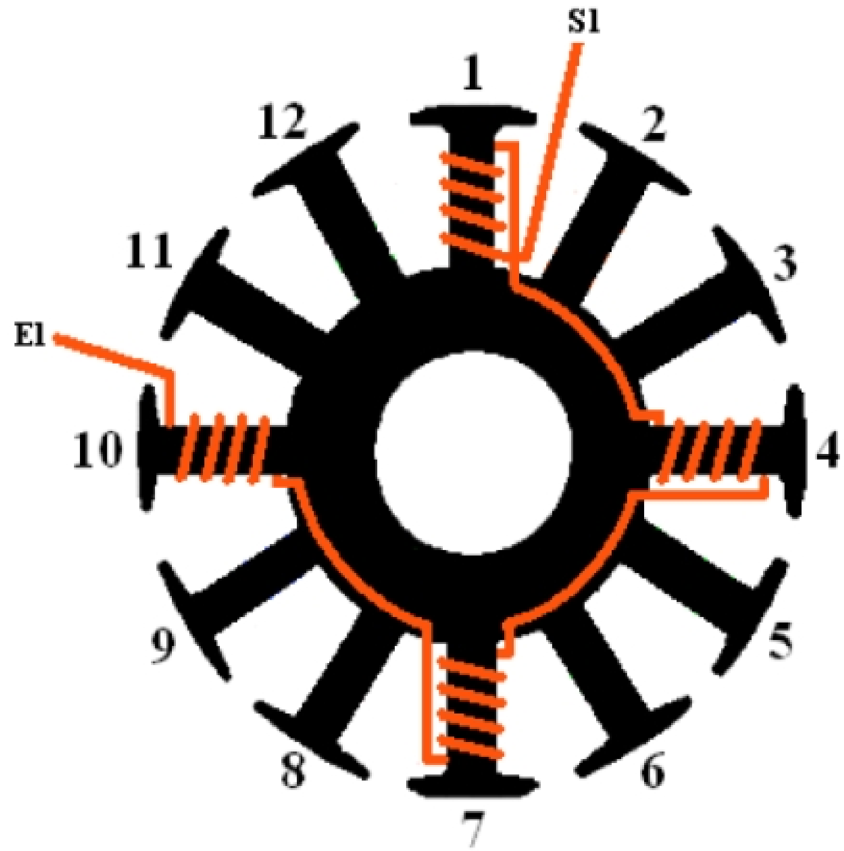


Winding: ABCABCABCABC

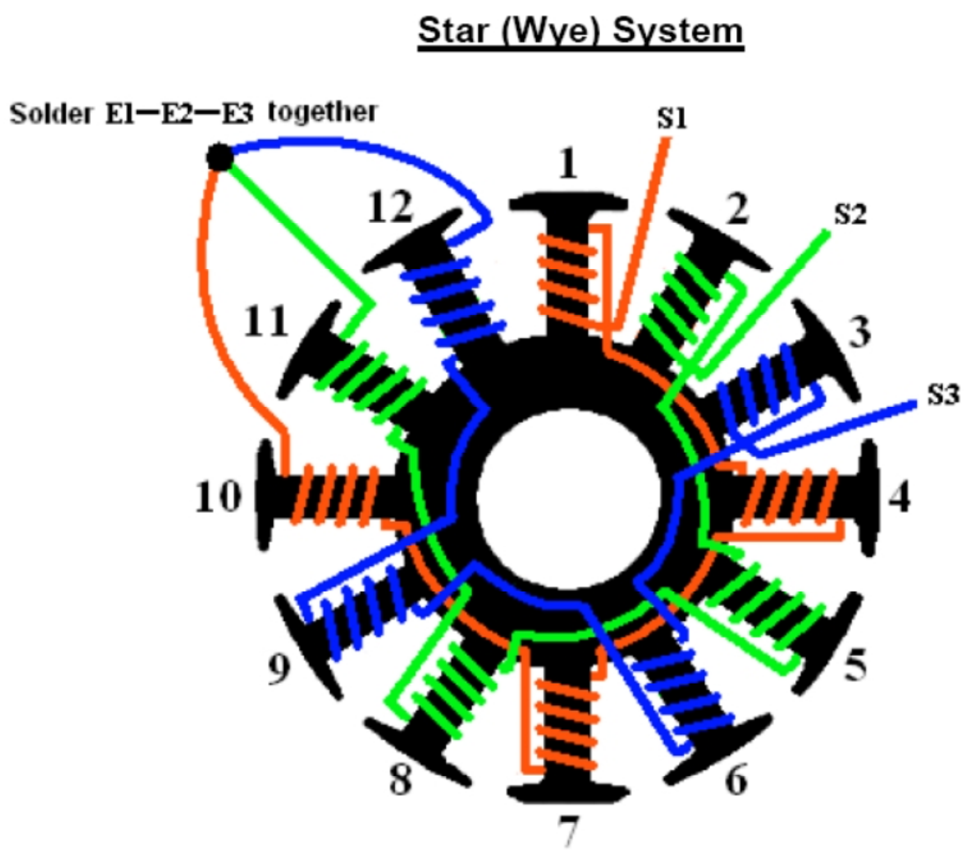
(For 16 magnet poles)

Wind magnet wire in clockwise direction on all stator teeth.

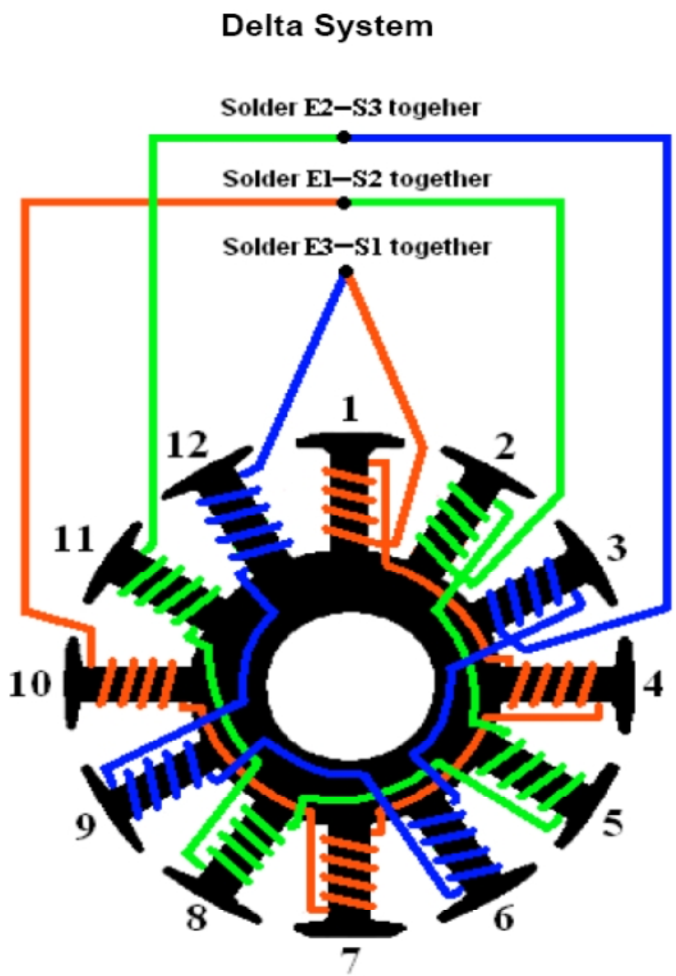
Phase A of the ABC wind 12-pole, 8 or 16-magnets



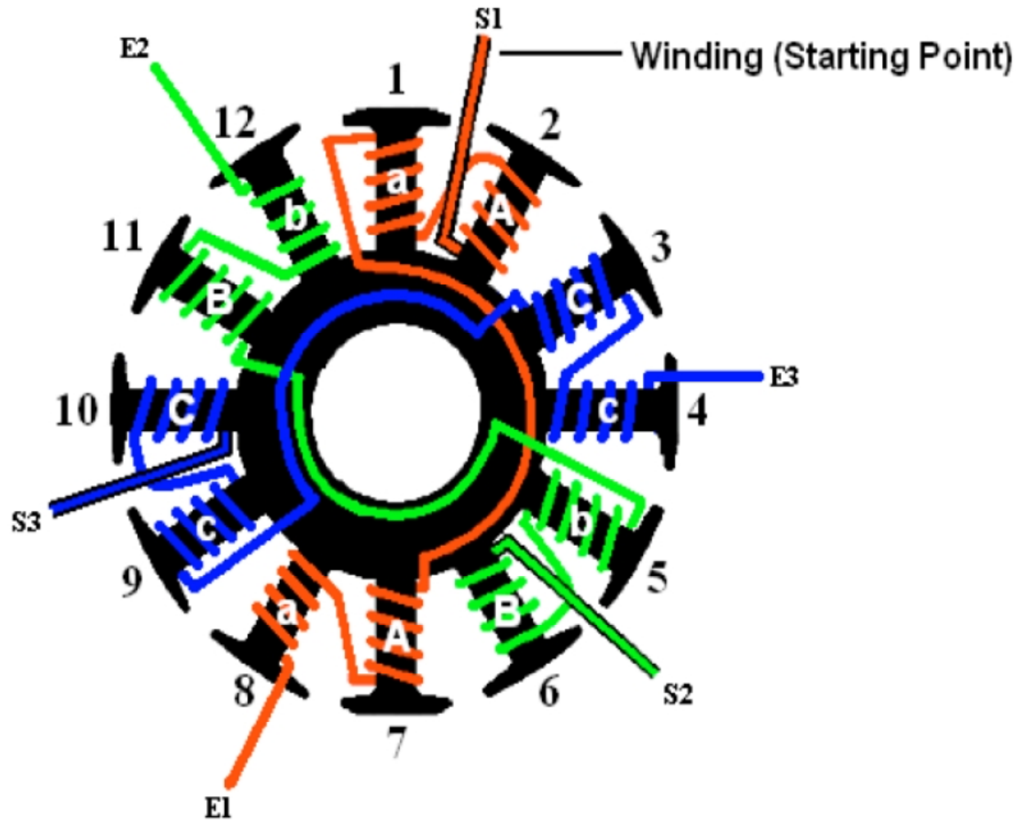
12 pole **ABC** “Star” Connection



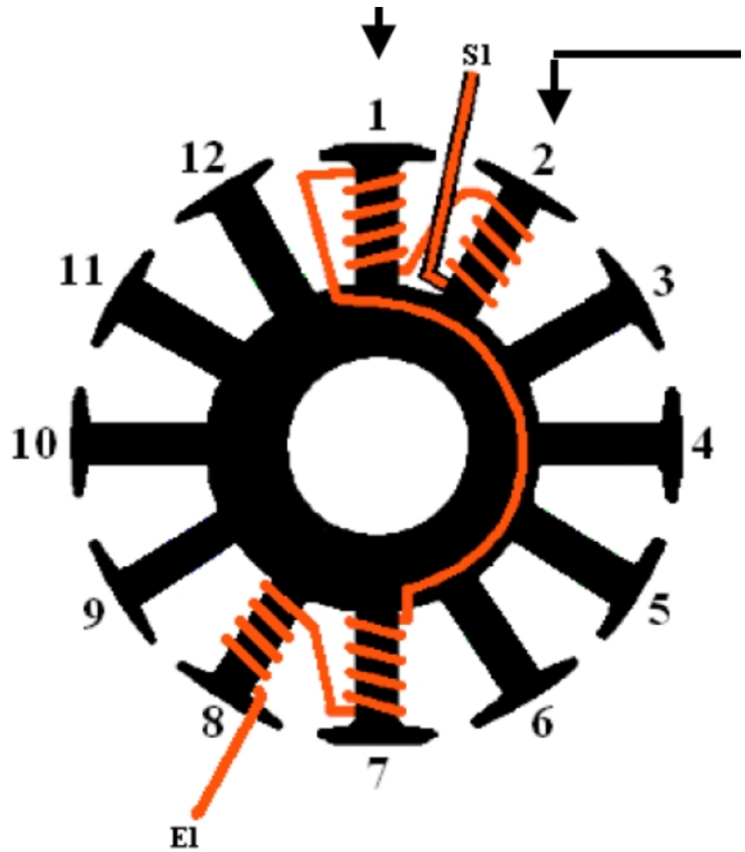
12 pole **ABC** "Delta" Connection



Distributed LRK winding diagram for 10 or 14 magnet poles.



Phase A, DLRK wind



LRK or DLRK

Delta System

Point 1: Solder S1 and E3 together
Point 2: Solder S2 and E1 together
Point 3: Solder S3 and E2 together

Note: Point 1, Point 2 and Point 3 are connected to Electronic Speed Control (ESC)

Star (Wye) System

Solder E1, E2, E3 together

Note: S1, S2 and S3 are connected to ESC.