# FRA231: Robotics Modelling & Experimentation (RMX)

By Bantoon Srisuwan

Lecture 11: Actuator 3

# Lecture Contents

1. Introduction to Brushless DC Motors
2. Comparison with Traditional DC Motors
3. Types and Components
4. Working Principles
5. Rotor Position Sensing Methods
6. Speed Control Systems
7. Motor Characteristics and Applications

# Lecture Objectives

By the end of this lecture, students will be able to:

1. Understand the fundamental principles of Brushless DC Motors
2. Differentiate between BLDC and traditional DC motors
3. Identify key components and types of BLDC motors
4. Comprehend the working principle and control methods
5. Analyze motor characteristics for different applications

# Brushless DC Motor

- What is Brushless DC Motor?

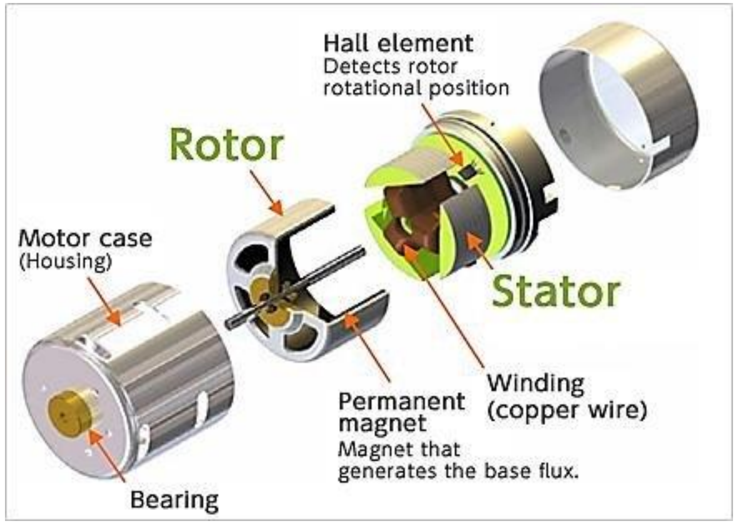
- Why Brushless?

# Brushless DC Motor

# **Brushless DC Motor** – Types and Components

## Outrunner vs Inrunner Brushless DC Motor

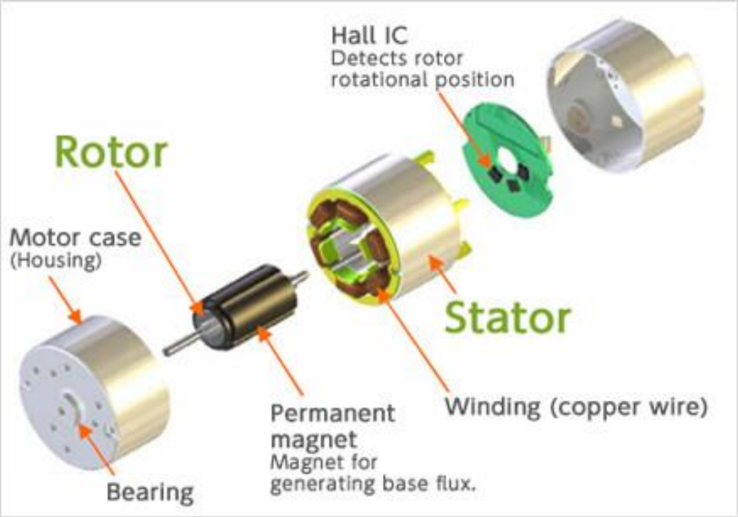
Outrunner BLDC




6 Exploded view of BLDC motor | Download Scientific Diagram

- higher torque
- lower speed
- bad heat dissipation

Inrunner BLDC




DC Motors: Intro to Servos, BLDC motors, Steppers & More | Circuit Crush

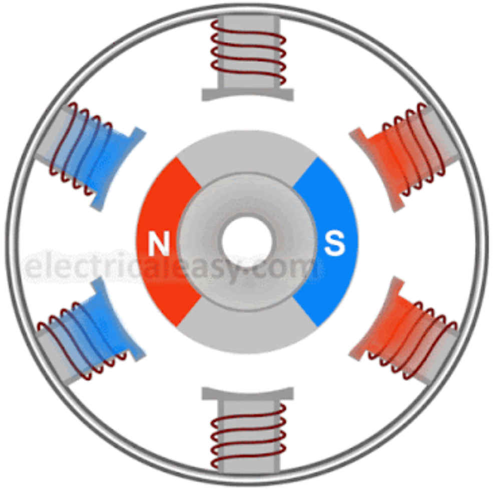
- lower torque
- higher speed
- good heat dissipation

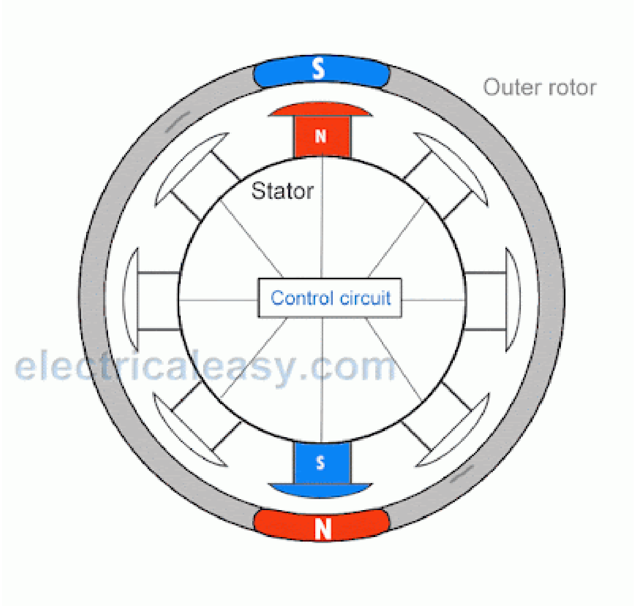
# **Brushless DC Motor** – Working principle

## Rotor magnet and pole pairs

1. Basic Operation:

- Electronic commutation replaces mechanical commutation
- Permanent magnets on rotor
- Electromagnets on stator
- Sequential energizing of stator coils



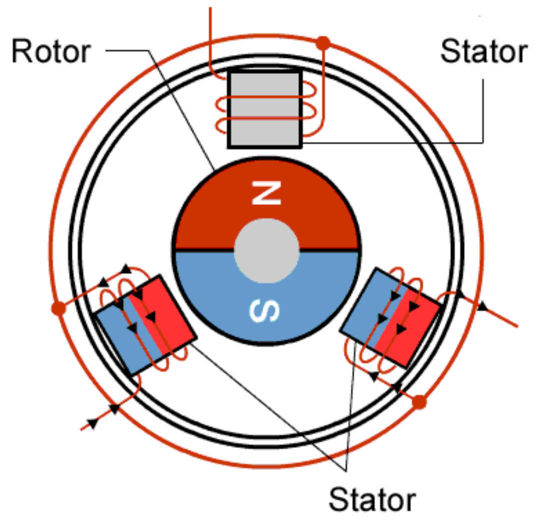

https://www.electricaleasy.com/2015/05/brushless-dc-bldc-motor.html

# **Brushless DC Motor** – Working principle

## Coil exciting sequences concept

2. Commutation Sequence:

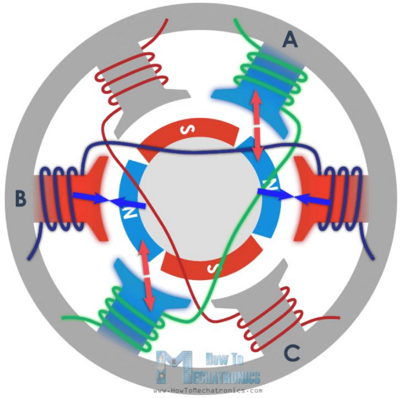
- Six-step commutation
- 120° electrical spacing
- Proper timing for smooth rotation
- Phase energizing patterns

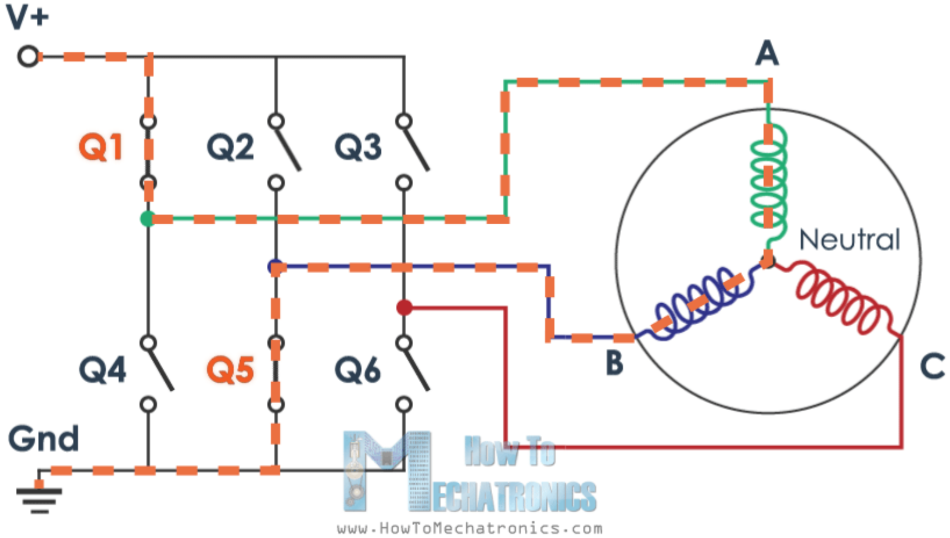


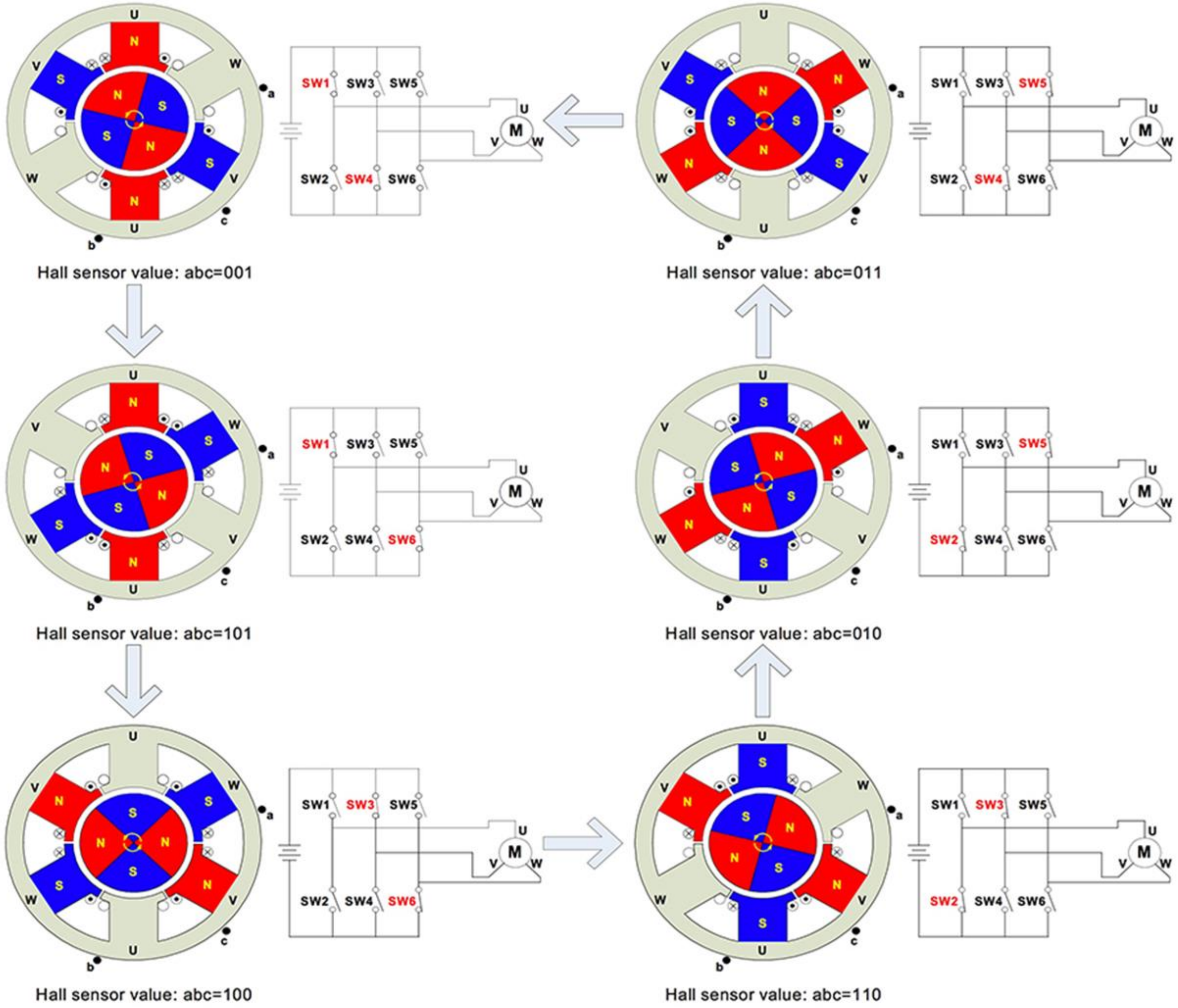

http://fab.academany.org/2020/labs/charlotte/students/sophia-vona/assignments/week12/

# **Brushless DC Motor** – Working principle

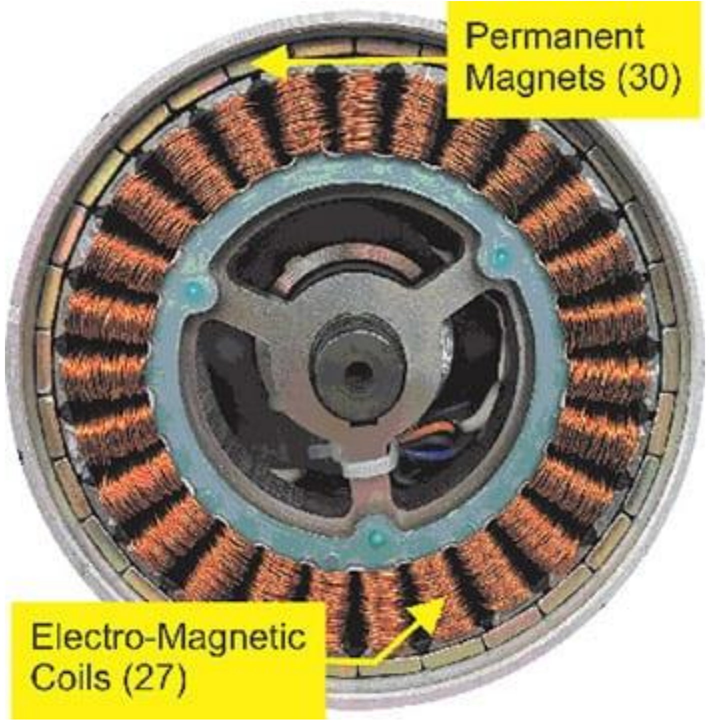
**Coil exciting sequences using a electrical switch**

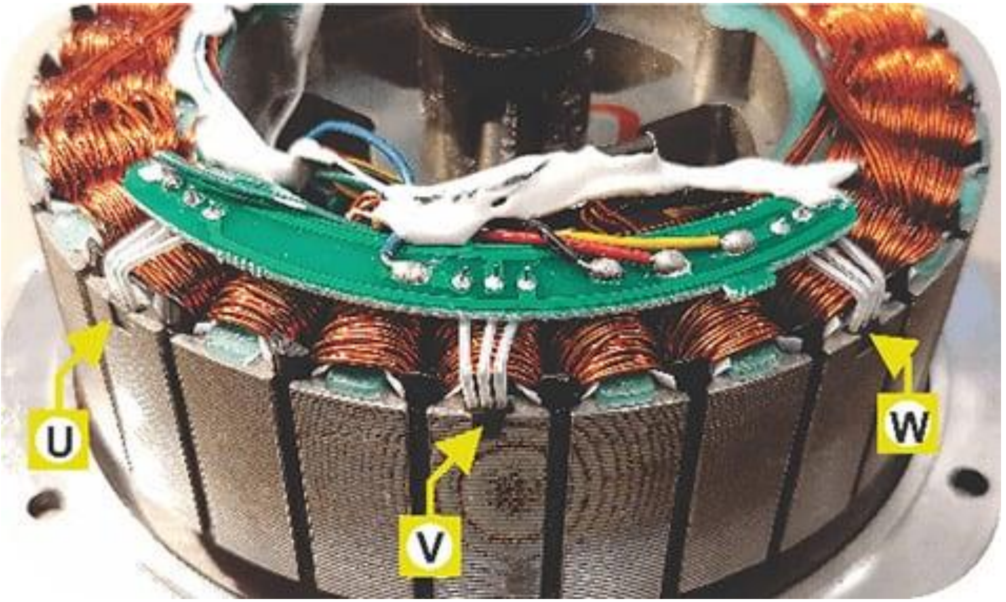


# **Brushless DC Motor** – Rotor position sensing

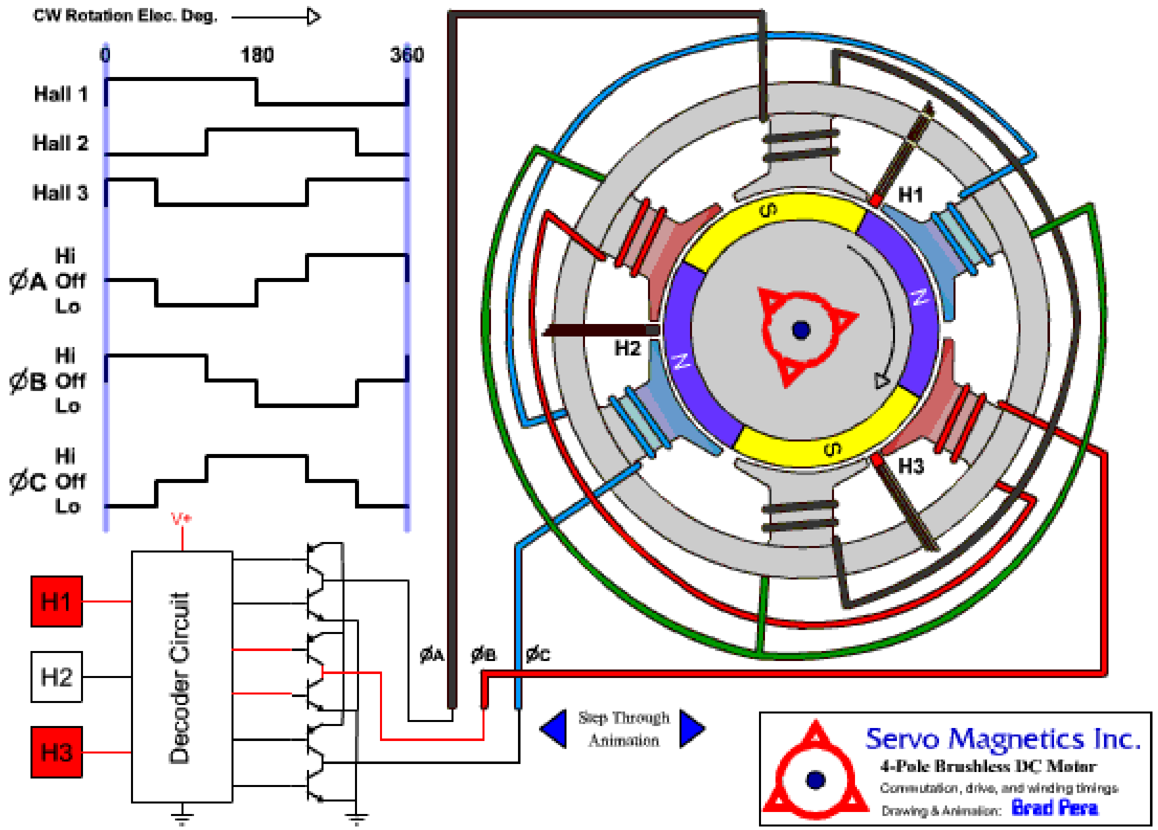


# **Brushless DC Motor** – Rotor position sensing

**Hall effect sensor**

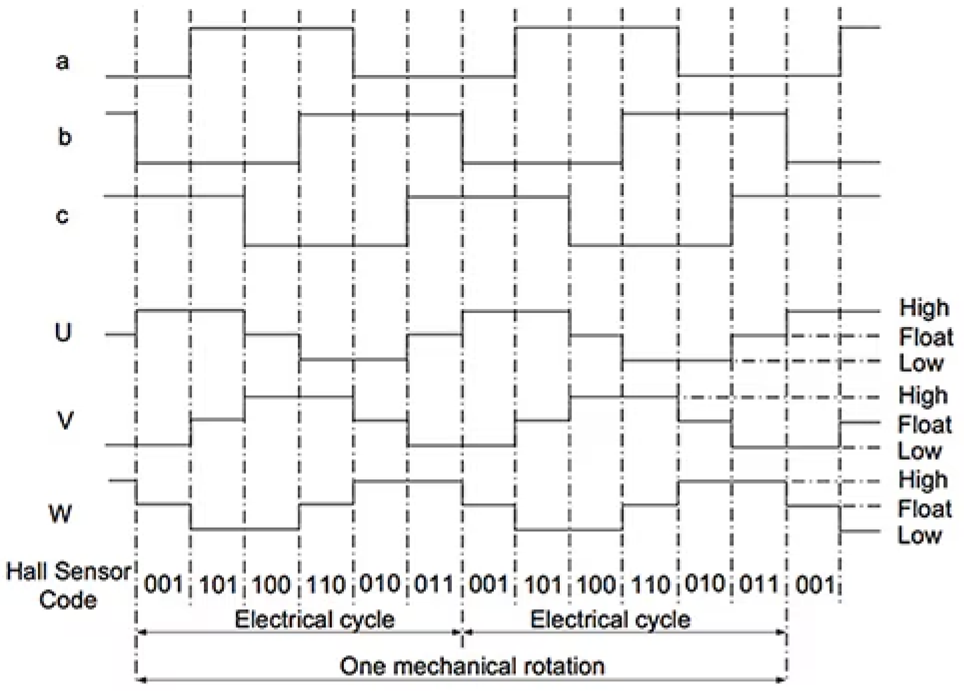
- Working principle
  - Placement (120° apart)
  - Signal interpretation
  - Advantages and limitations

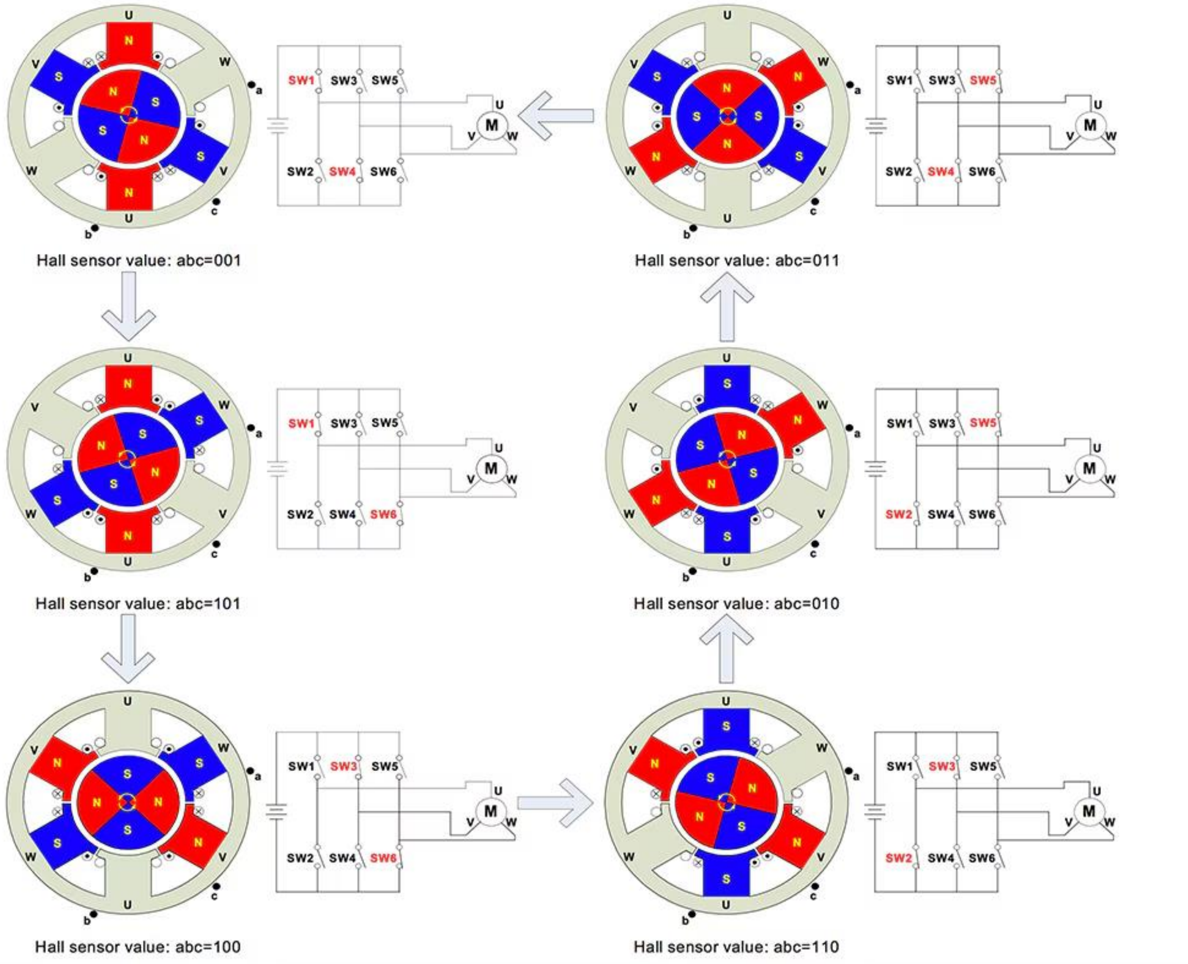



https://www.youtube.com/watch?v=6ELRkeEwlDw&t=1s

# **Brushless DC Motor** – Rotor position sensing

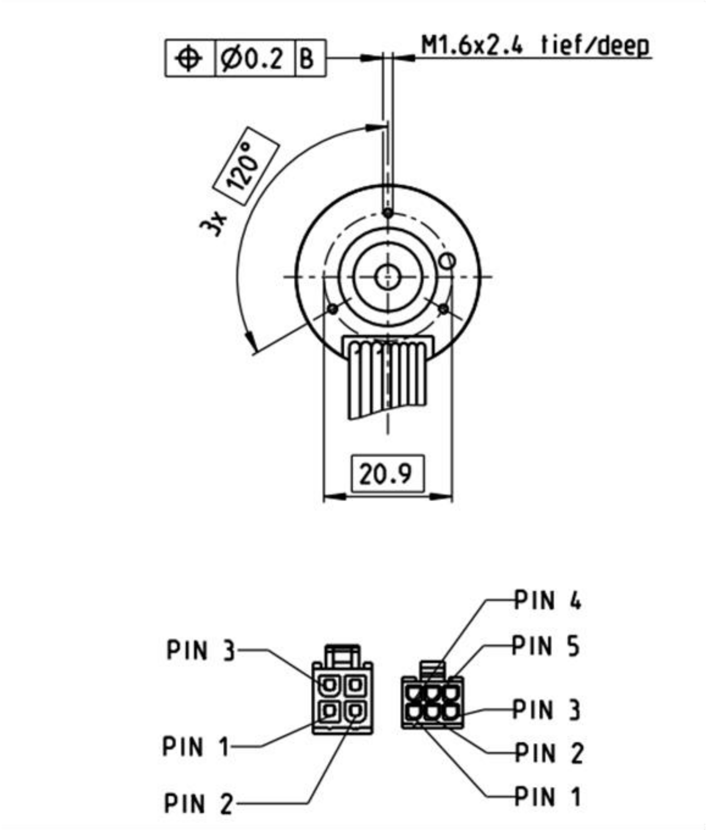
**Hall effect sensor**




https://www.digikey.pl/pl/articles/how-to-power-and-control-brushless-dc-motors

# **Brushless DC Motor** – Hall Sensors Wiring



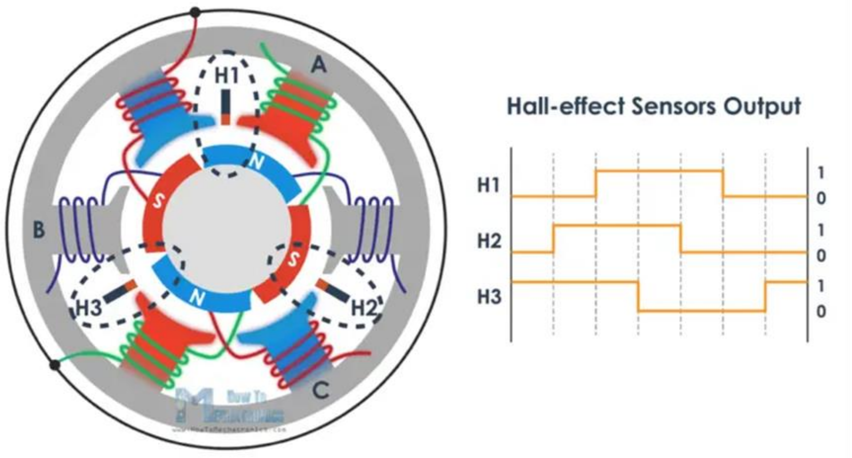


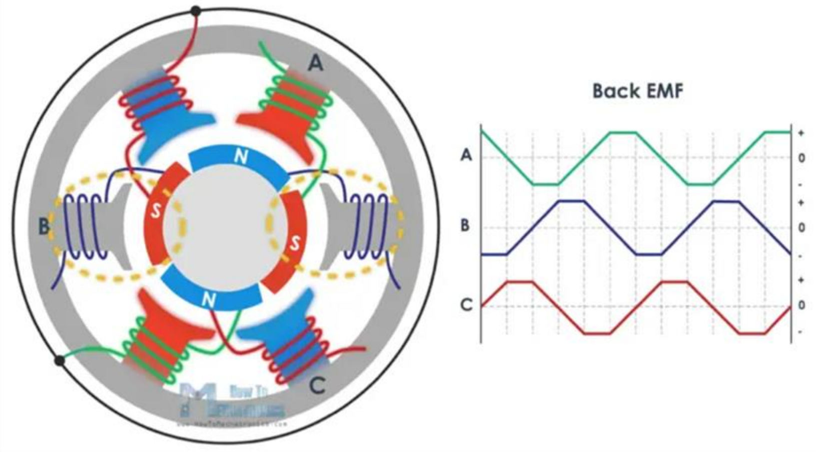
| | | |
|---|---|---|
| **Connection motor** (Cable AWG 20) | | |
| red | Motor winding 1 | Pin 1 |
| black | Motor winding 2 | Pin 2 |
| white | Motor winding 3 | Pin 3 |
| | N.C. | Pin 4 |
| **Connector** | **Part number** | |
| Molex | 39-01-2040 | |
| **Connection sensors** (Cable AWG 26) | | |
| yellow | Hall sensor 1 | Pin 1 |
| brown | Hall sensor 2 | Pin 2 |
| grey | Hall sensor 3 | Pin 3 |
| blue | GND | Pin 4 |
| green | $V_{Hall}$ 3...24 VDC | Pin 5 |
| | N.C. | Pin 6 |

# **Brushless DC Motor** – Rotor position sensing

**Back EMF sensing (Trapezoidal)**

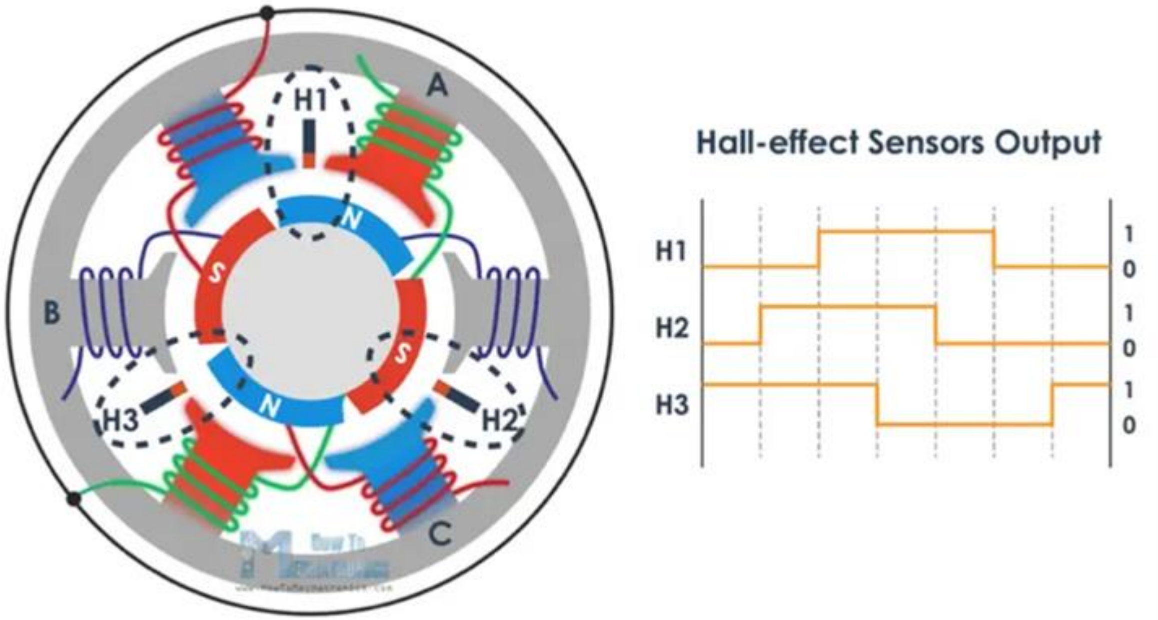
- Sensorless operation
- Zero crossing detection
- Implementation challenges
- Advantages in cost and reliability

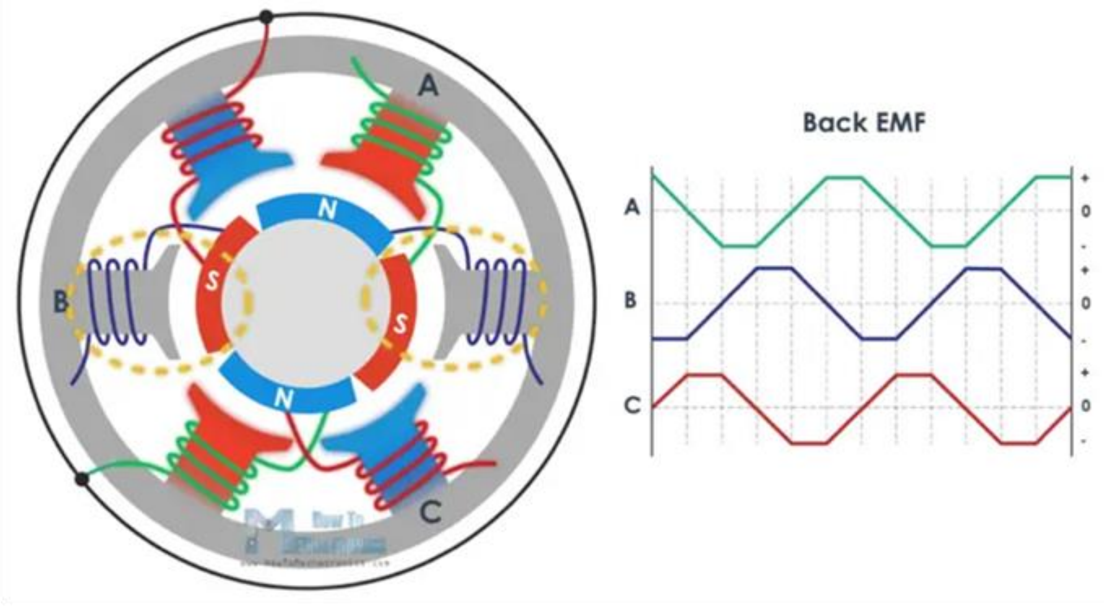


# **Brushless DC Motor** – Rotor position sensing

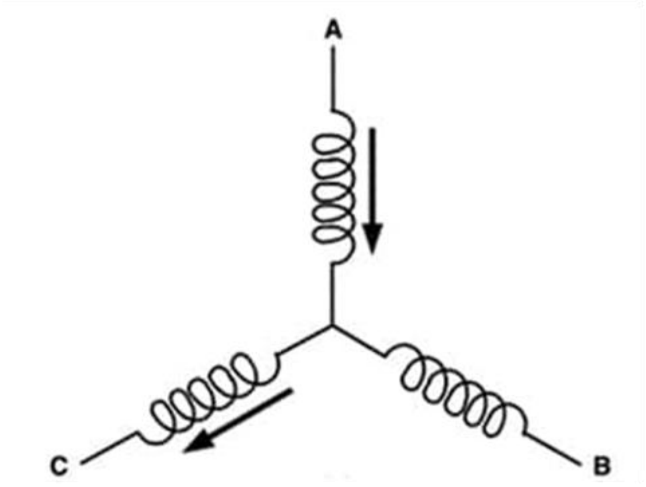
**Zero crossing detection in back EMF signal**

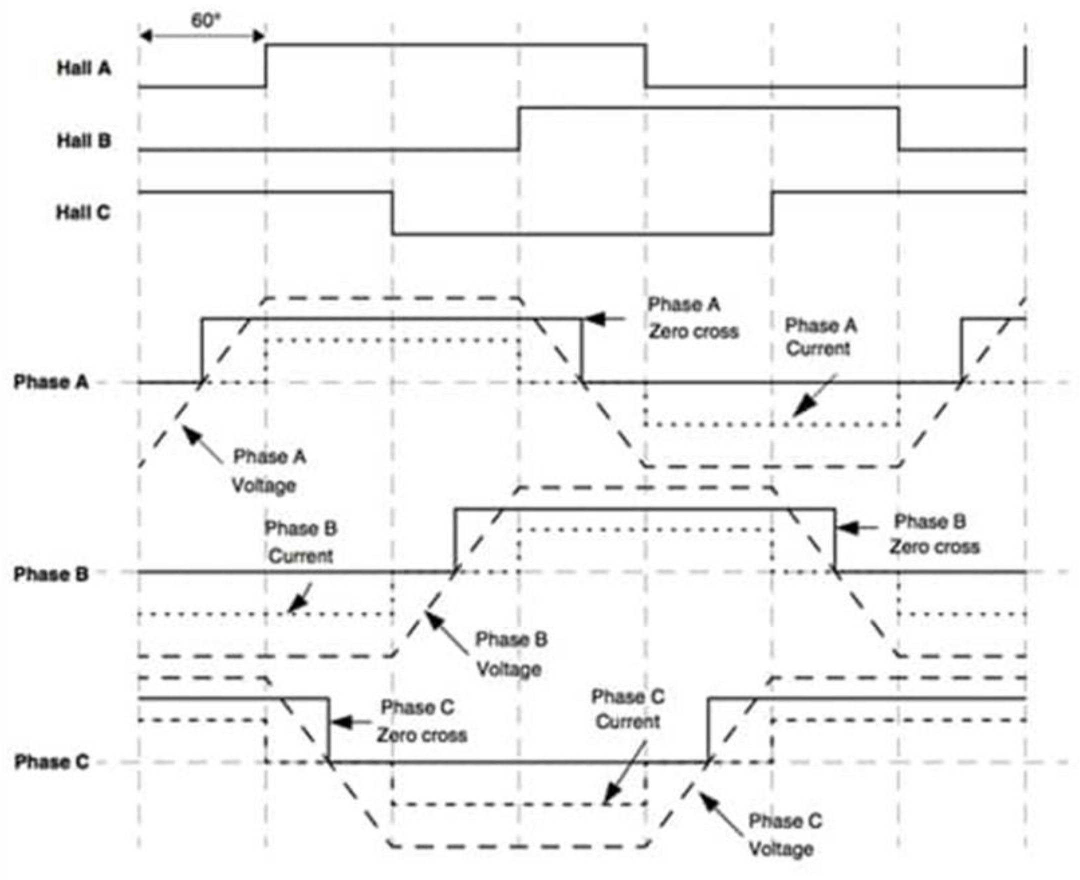


# **Brushless DC Motor** – Rotor position sensing

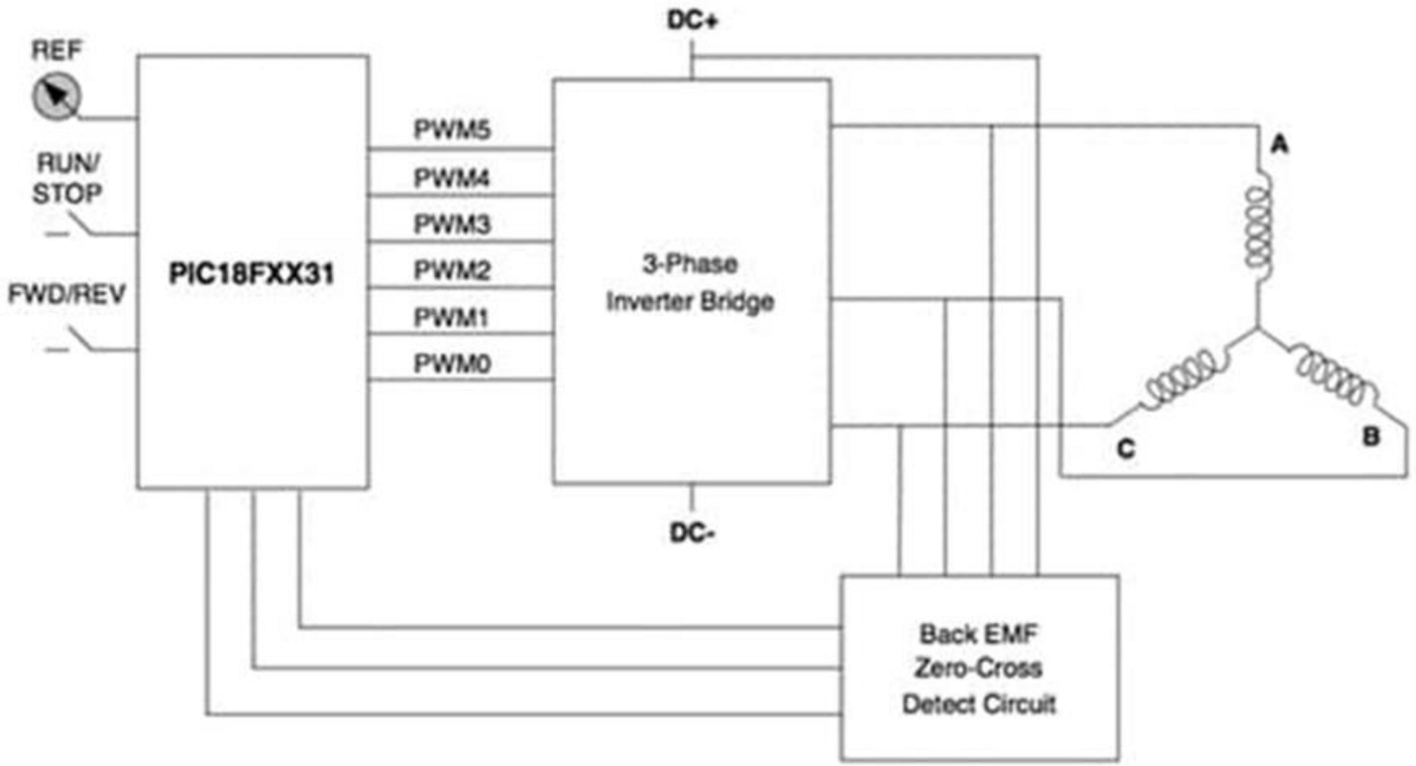
**Zero crossing detection in back EMF signal**

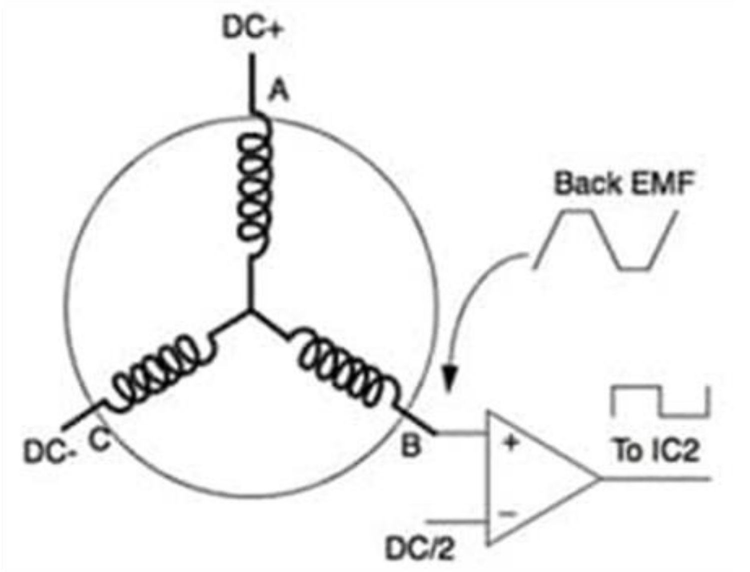


# **Brushless DC Motor** – Rotor position sensing

**Zero crossing detection in back EMF signal**



# **Brushless DC Motor** – Speed controller

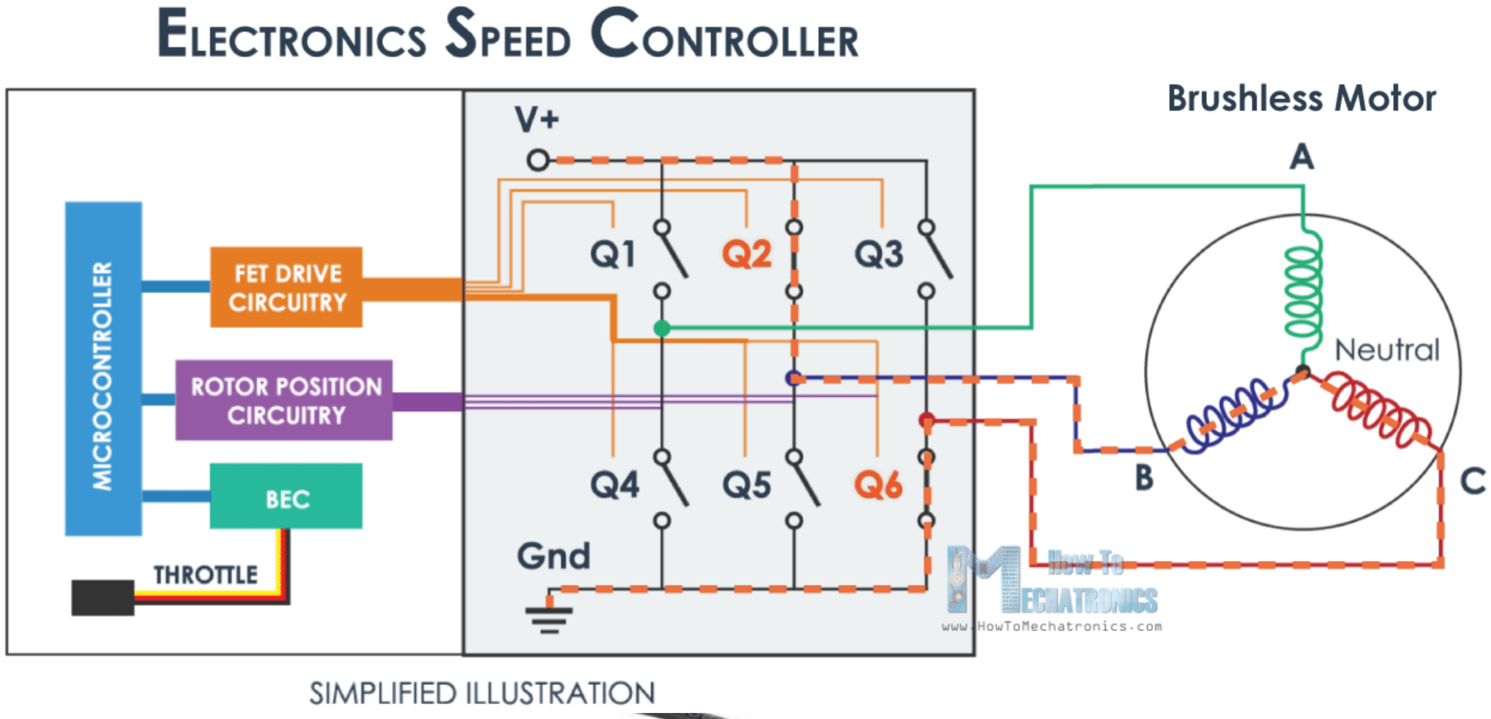
**ESC (Electronics Speed Controller)**

1. Components:
   - Microcontroller
   - Power MOSFETS
   - Current sensors
   - Signal processing circuits

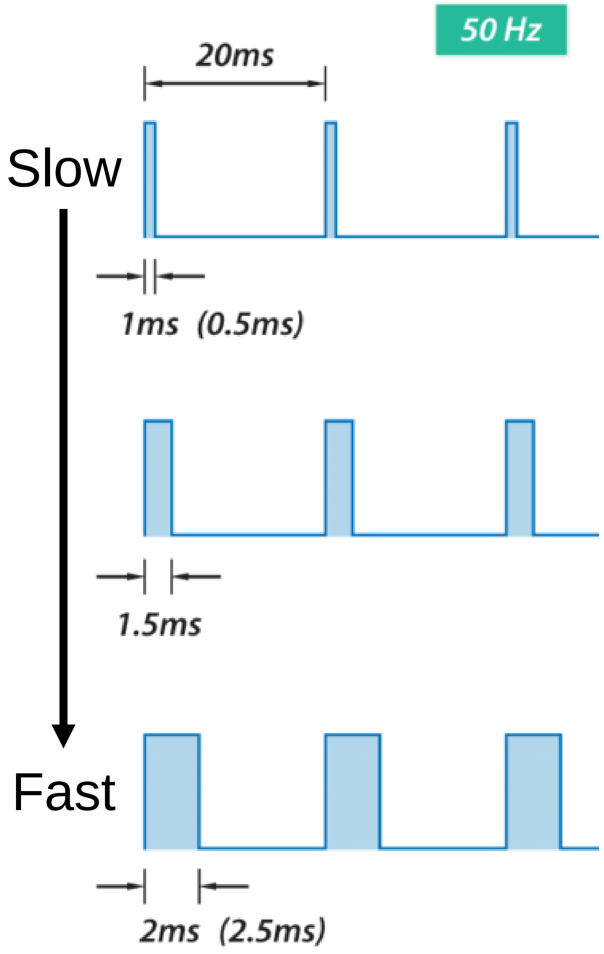
2. Functions:
   - PWM generation
   - Current limiting
   - Temperature monitoring
   - Fault protection
   - Speed regulation

# **Brushless DC Motor** – Speed controller

**ESC (Electronics Speed Controller)**





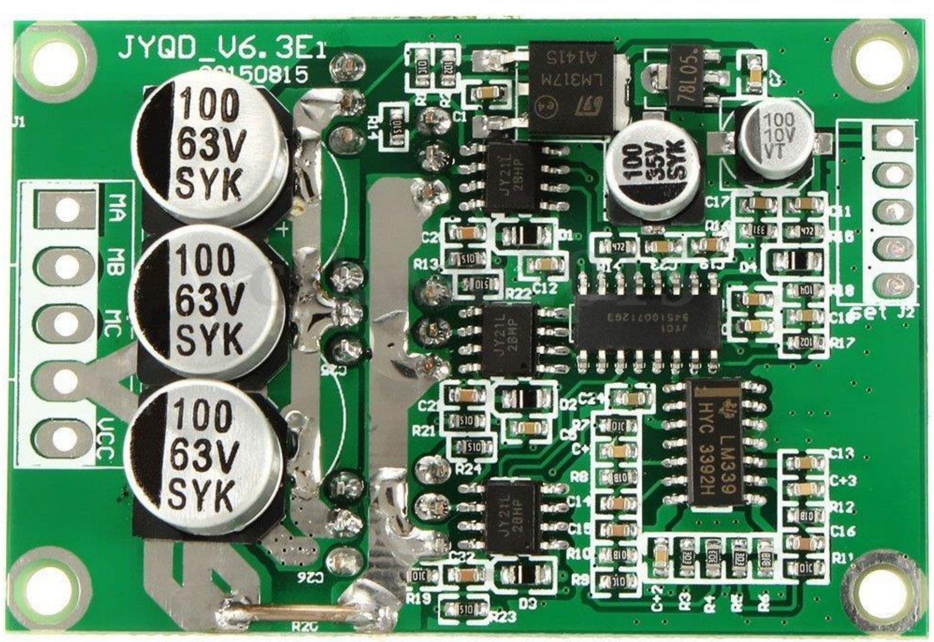


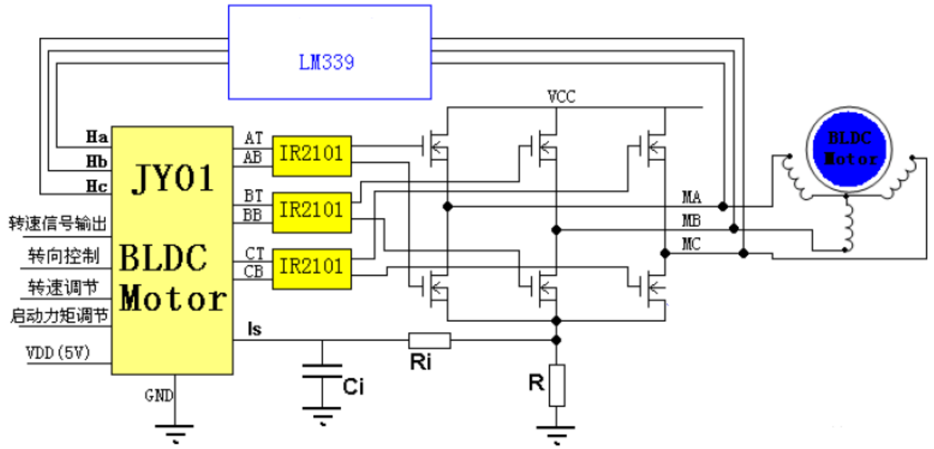


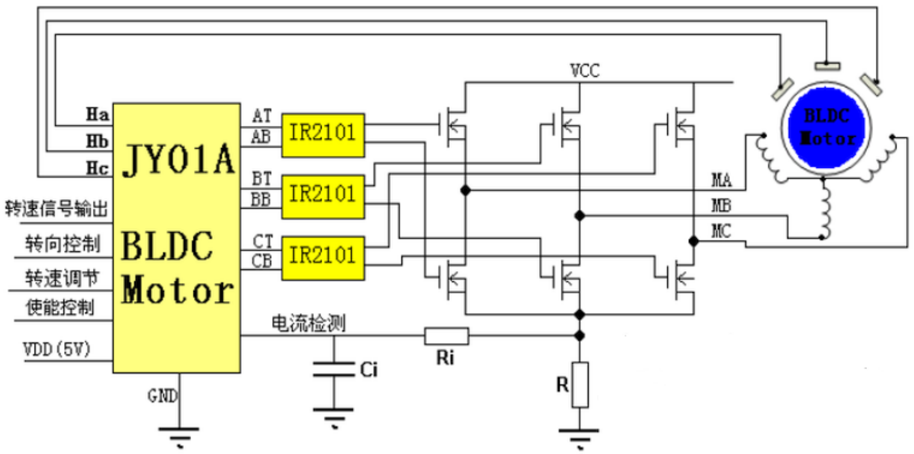

https://howtomechatronics.com/how-it-works/how-brushless-motor-and-esc-work/

# **Brushless DC Motor** – Speed controller

## ESC (Electronics Speed Controller)

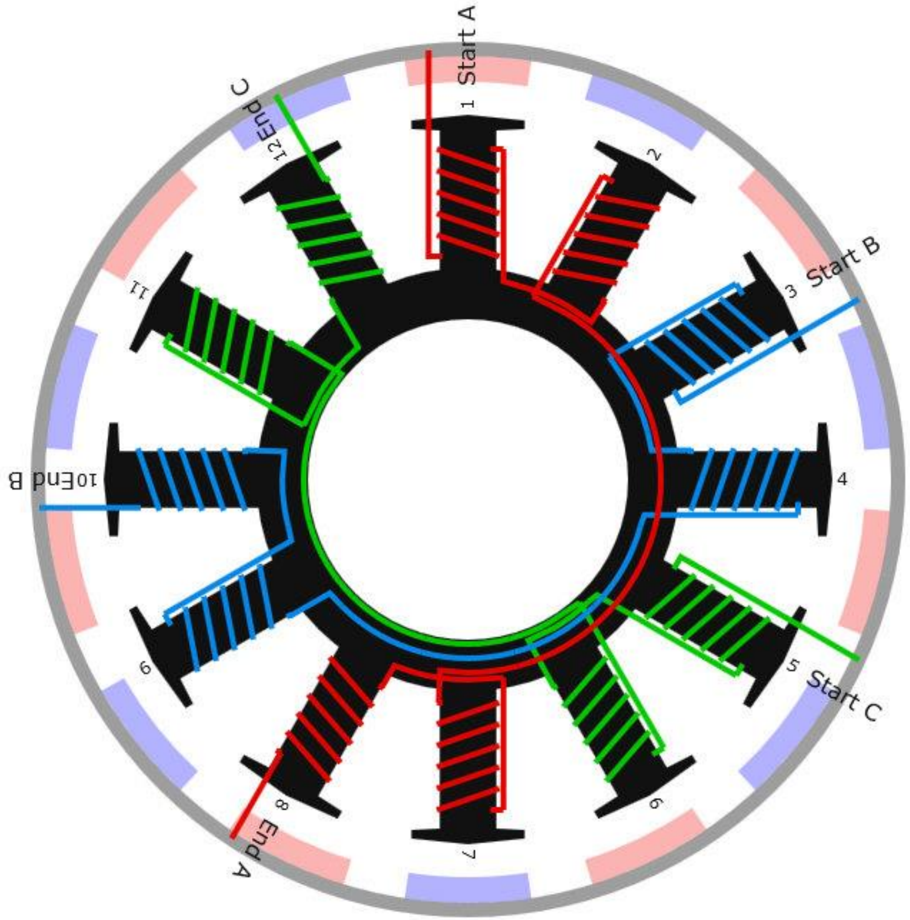


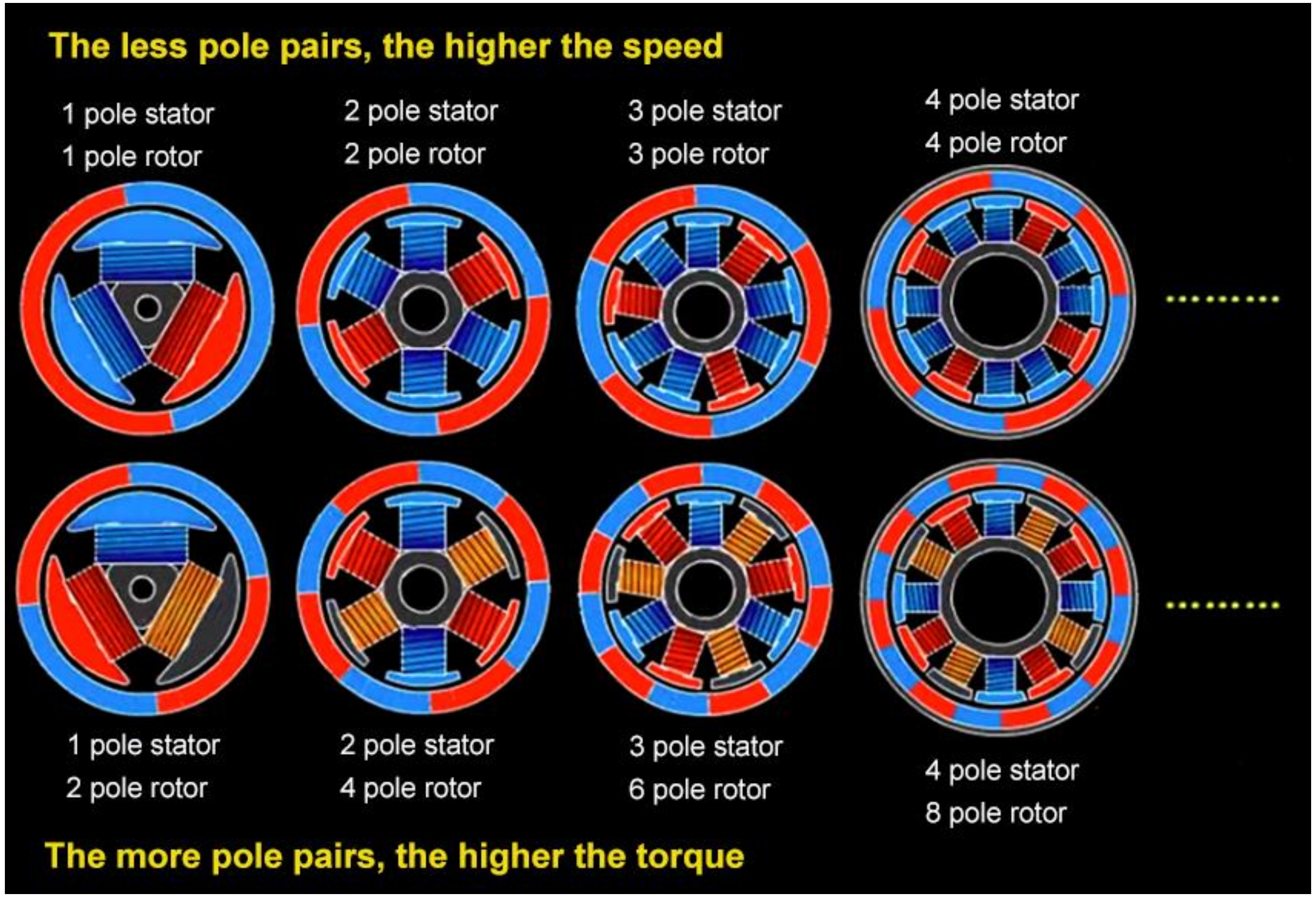



https://grauonline.de/wordpress/?page_id=3122

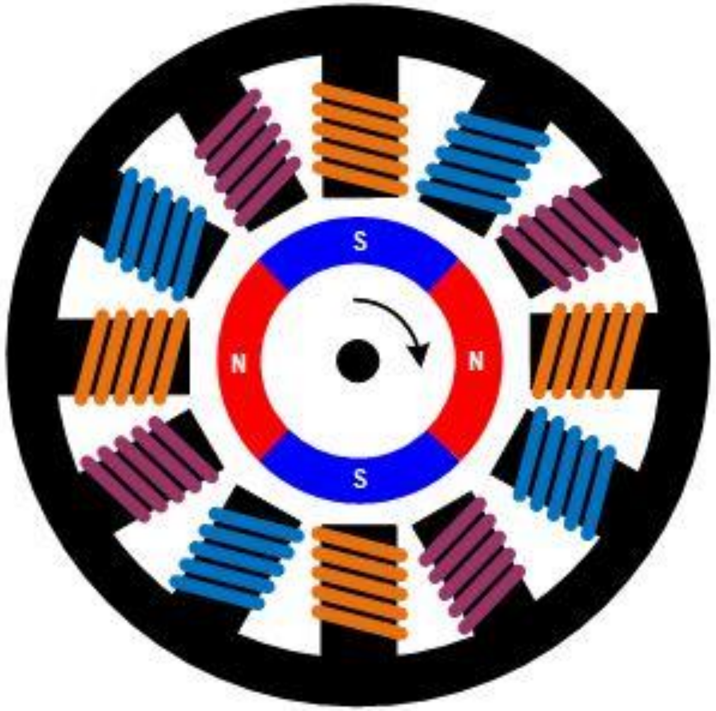
# **Brushless DC Motor** – Rotor VS Stator Pole Pairs



# **Brushless DC Motor** – Rotor VS Stator Pole Pairs


2 Poles




4 Poles

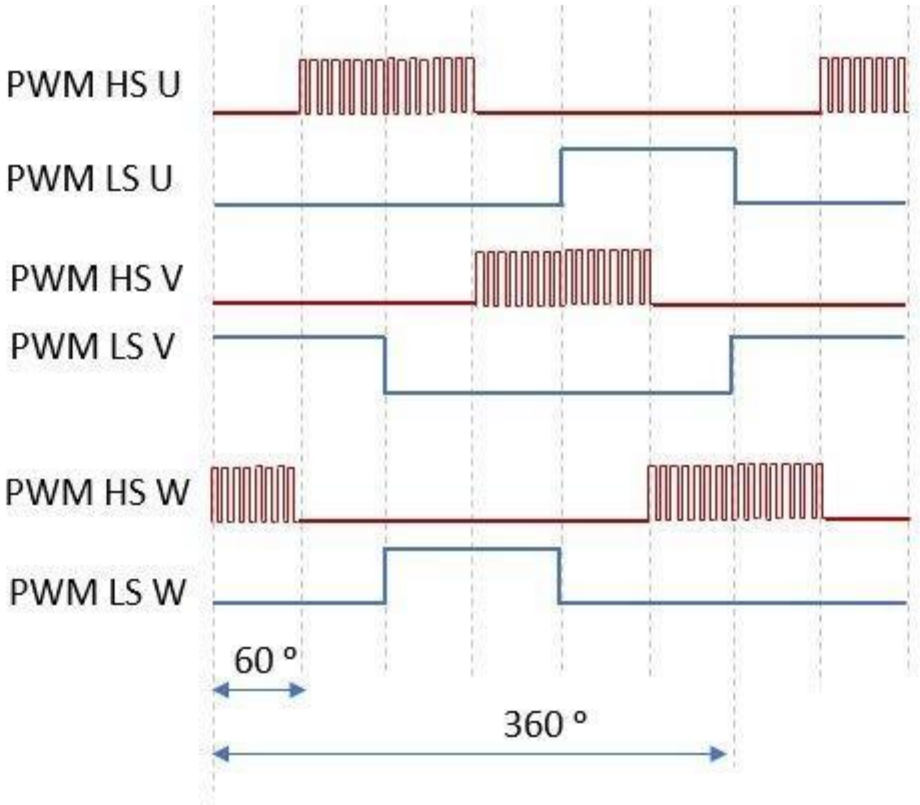
# **Brushless DC Motor** – Torque Control

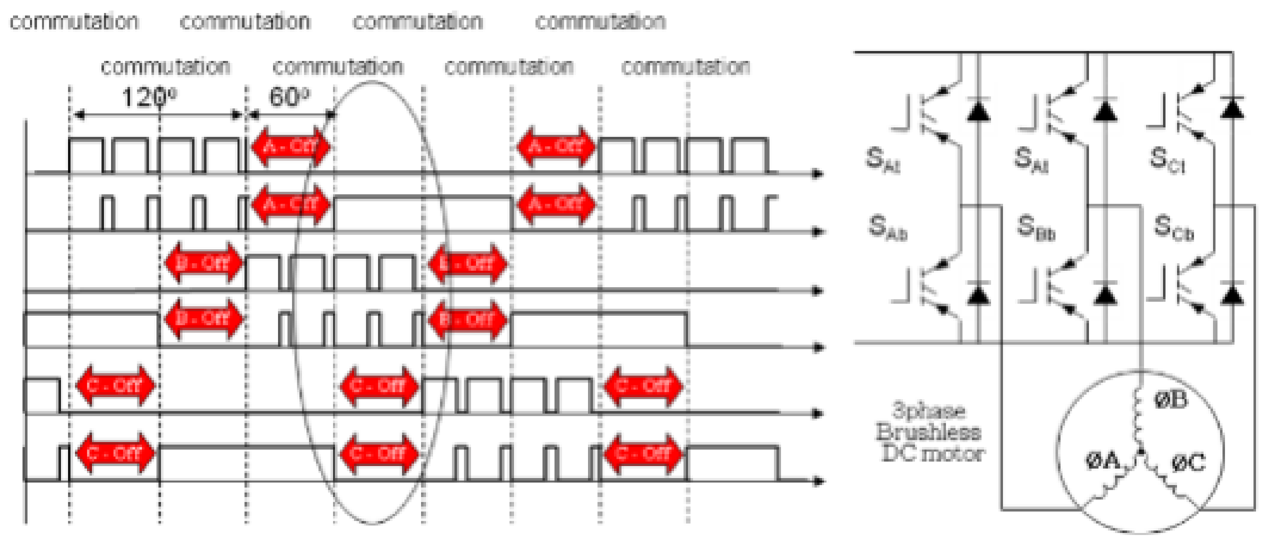
1. PWM (Pulse Width Modulation)
   - Easy to implement
   - Less Processing
   - Trapezoidal EMF
   - Suitable for not precise dynamic control
   - fans, pumps

2. FOC (Field Oriented Control)
   - Sinusoidal control signals
   - More Processing Power
   - Very Precise
   - Robotics, CNC

# **Brushless DC Motor** – Torque Control

PWM (Pulse Width Modulation)

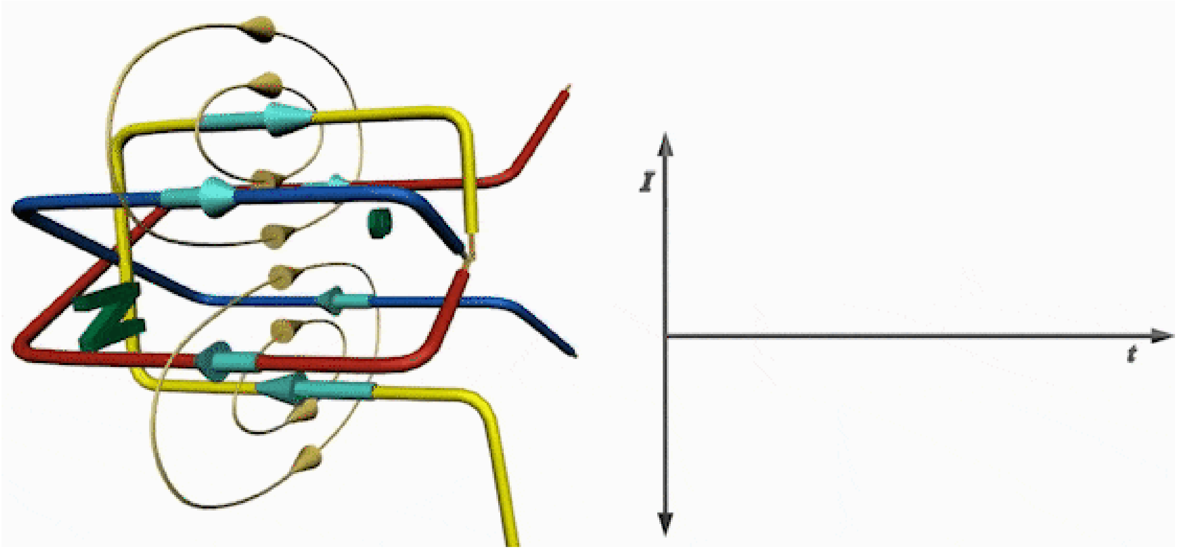


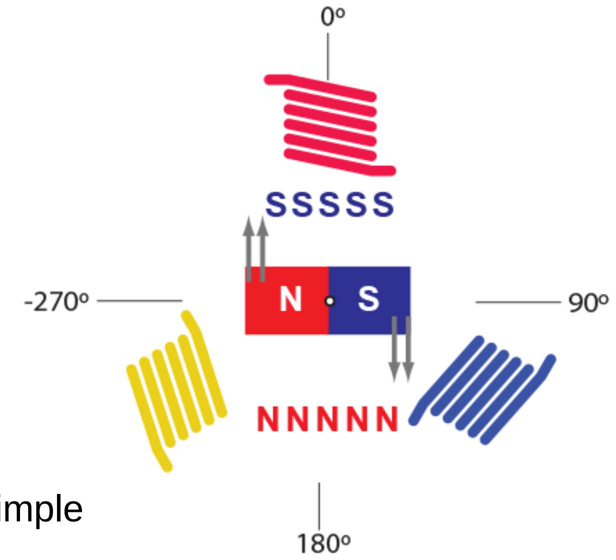

https://electronics.stackexchange.com/questions/474200/bldc-motor-pwm-commutation-scheme

# **Brushless DC Motor** – Torque Control

FOC (Field Oriented Control)








https://www.roboteq.com/applications/all-blogs/13-field-oriented-control-foc-made-ultra-simple

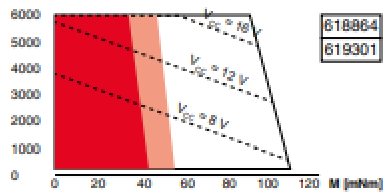
# **Brushless DC Motor** – Motor characteristics

## EC-i 30 ∅30 mm brushless, 20 watt, with integrated electronics

Stock program
Standard program
Special program (on request)

| Part Numbers | | | |
|---|---|---|---|
| | | 5 wire version | |
| | | Enable | Direction |
| | | 618864 | 619301 |
| **Motor Data** (provisional) | | | |
| **Values at nominal voltage** | | | |
| 1 Nominal voltage | V | 24 | 24 |
| 2 No load speed | rpm | 6000 | 6000 |
| 3 No load current | mA | 107 | 107 |
| 4 Nominal speed | rpm | 6000 | 6000 |
| 5 Nominal torque (max. continuous torque) | mNm | 32.6 | 32.6 |
| 6 Nominal current (max. continuous current) | A | 1.19 | 1.19 |
| 33 Max. torque | mNm | 105 | 105 |
| 34 Max. current | A | 6.5 | 6.5 |
| 9 Max. efficiency | % | 75.4 | 75.4 |
| **Characteristics** | | | |
| 35 Type of control | | | |
| 36 Supply voltage $+V_{CC}$ | V | 8...28 | 8...28 |
| 37 Speed set value input | V | 0.42...10.1 | 0.42...10.1 |
| 38 Scale speed set value input | rpm/V | 600 | 600 |
| 39 Speed range | rpm | 250...6060 | 250...6060 |
| 40 Max. acceleration | rpm/s | 6000 | 6000 |

**Operating Range** Comments




Continuous operation
Continuous operation with reduced thermal resistance $R_{th2}$ 50%
Intermittent operation

**maxon Modular System** Details on catalog page 42

**Planetary Gearhead**
∅32 mm
1.0 - 6.0 Nm
Page 398

# **Brushless DC Motor** – Motor characteristics

M 1:1

**ECX SPEED 16 M** ∅16 mm, brushless, BLDC motor

**Key Data: 20/26 W, 5.1 mNm, 55 000 rpm**

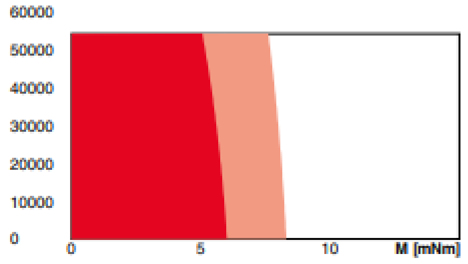
| Motor Data | | | | | |
|---|---|---|---|---|---|
| 1_ Nominal voltage | V | 18 | 24 | 36 | 48 |
| 2_ No load speed | rpm | 49600 | 49600 | 49700 | 49600 |
| 3_ No load current | mA | 236 | 177 | 118 | 88.7 |
| 4_ Nominal speed | rpm | 45100 | 45300 | 45500 | 45200 |
| 5_ Nominal torque (max. continuous torque) | mNm | 4.69 | 4.93 | 5.1 | 4.75 |
| 6_ Nominal current (max. continuous current) | A | 1.59 | 1.24 | 0.852 | 0.601 |
| 7_ Stall torque | mNm | 57.3 | 63.2 | 67.8 | 59.9 |
| 8_ Stall current | A | 16.8 | 13.9 | 9.94 | 6.59 |
| 9_ Max. efficiency | % | 78.1 | 79.1 | 79.8 | 78.6 |
| 10_ Terminal resistance | Ω | 1.07 | 1.73 | 3.62 | 7.29 |
| 11_ Terminal inductance | mH | 0.0502 | 0.0893 | 0.201 | 0.357 |
| 12_ Torque constant | mNm/A | 3.41 | 4.55 | 6.83 | 9.1 |
| 13_ Speed constant | rpm/V | 2800 | 2100 | 1400 | 1050 |
| 14_ Speed/torque gradient | rpm/mNm | 880 | 797 | 743 | 840 |
| 15_ Mechanical time constant | ms | 7.42 | 6.73 | 6.27 | 7.09 |
| 16_ Rotor inertia | gcm² | 0.806 | 0.806 | 0.806 | 0.806 |

| Thermal data | | |
|---|---|---|
| 17_ Thermal resistance housing-ambient | K/W | 20.3 |
| 18_ Thermal resistance winding-housing | K/W | 1.52 |
| 19_ Thermal time constant winding | s | 1.83 |
| 20_ Thermal time constant motor | s | 508 |
| 21_ Ambient temperature | °C | -20...+100 |
| 22_ Max. winding temperature | °C | 125 |
| **Mechanical data ball bearings** | | |
| 23_ Max. speed | rpm | 55 000 |
| 24_ Axial play | mm | 0...0.29 |
| Preload | N | 1.5 |
| Direction of force | | pull |
| 25_ Radial play | | preloaded |
| 26_ Max. axial load (dynamic) | N | 1.5 |
| 27_ Max. force for press fits (static) | N | 60 |
| (static, shaft supported) | N | 2500 |
| 28_ Max. radial load [mm from flange] | N | 10 [5] |
| **Other specifications** | | |
| 29_ Number of pole pairs | | 1 |
| 30_ Number of phases | | 3 |
| 31_ Weight of motor | g | 50 |
| 32_ Typical noise level [rpm] | dBA | 50 [50 000] |

Connection A and B motor (Cable AWG 22)

**Operating Range**

n [rpm] **winding 36 V**




Continuous operation
Continuous operation with reduced thermal resistance $R_{th2}$ 50%
Short term operation

**maxon Modular System** Details on catalog page 34

| maxon gear | Stages [opt.] | maxon sensor | maxon motor control |
|---|---|---|---|
| 341_GPX 16 A/C | 1–2 [3–4] | for motor type A: | 500_ESCON Module 24/2 |
| 342_GPX 16 LN/LZ | 1–2 [3–4] | 454_ENX 16 EASY INT | 501_ESCON 36/3 EC |
| 343_GPX 16 HP | 2–3 [4] | for motor type B: | 501_ESCON Module 50/4 EC-S |
| 344_GPX 16 SPEED | 1–2 | 454_ENX 16 EASY INT Abs. | 501_ESCON Module 50/5 |
| 345_GPX 19 A/C | 3–4 | | 503_ESCON 50/5 |
| 346_GPX 19 LN/LZ | 3–4 | | 505_DEC Module 24/2 |

# **Brushless DC Motor** – Motor characteristics

## Comparing with Brushed DC Motor

**RE 25** ∅25 mm, graphite brushes, 20 watt

Stock program
Standard program
Special program (on request)

| | | Part Numbers | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| according to dimensional drawing | | 118749 | 118750 | 118751 | 118752 | 118753 | 118754 | 118755 | 118756 | 118757 |
| shaft length 15.7 shortened to 4 mm | | 302002 | 302003 | 302004 | 302005 | 302006 | 302007 | 302001 | 302008 | 302009 |
| **Motor Data** | | | | | | | | | | |
| **Values at nominal voltage** | | | | | | | | | | |
| 1 Nominal voltage | V | 9 | 15 | 18 | 24 | 30 | 42 | 48 | 48 | 48 |
| 2 No load speed | rpm | 10000 | 9660 | 10200 | 9560 | 9860 | 11100 | 10300 | 8240 | 5050 |
| 3 No load current | mA | 110 | 60.8 | 53.9 | 36.9 | 30.5 | 25.2 | 20.1 | 15.2 | 8.52 |
| 4 Nominal speed | rpm | 8970 | 8430 | 8850 | 8330 | 8640 | 9920 | 9160 | 7040 | 3830 |
| 5 Nominal torque | mNm | 11.1 | 20.5 | 22.9 | 26.3 | 26.7 | 27.1 | 27.7 | 28.7 | 30 |
| 6 Nominal current (max. continuous current) | A | 1.5 | 1.5 | 1.46 | 1.16 | 0.968 | 0.784 | 0.653 | 0.536 | 0.343 |
| 7 Stall torque | mNm | 232 | 225 | 220 | 243 | 249 | 283 | 264 | 209 | 129 |
| 8 Stall current | A | 29.1 | 15.8 | 13.5 | 10.4 | 8.72 | 7.94 | 6.03 | 3.81 | 1.44 |
| 9 Max. efficiency | % | 76 | 82 | 83 | 85 | 86 | 87 | 87 | 86 | 84 |
| **Characteristics** | | | | | | | | | | |
| 10 Terminal resistance | Ω | 0.309 | 0.952 | 1.33 | 2.32 | 3.44 | 5.29 | 7.96 | 12.6 | 33.4 |
| 11 Terminal inductance | mH | 0.028 | 0.088 | 0.115 | 0.238 | 0.353 | 0.551 | 0.832 | 1.31 | 3.48 |
| 12 Torque constant | mNm/A | 7.96 | 14.3 | 16.3 | 23.4 | 28.5 | 35.6 | 43.8 | 55 | 89.6 |
| 13 Speed constant | rpm/V | 1200 | 670 | 586 | 408 | 335 | 268 | 218 | 174 | 107 |
| 14 Speed/torque gradient | rpm/mNm | 46.5 | 44.7 | 48 | 40.3 | 40.4 | 39.8 | 39.6 | 39.8 | 39.7 |
| 15 Mechanical time constant | ms | 5.68 | 4.87 | 4.77 | 4.55 | 4.47 | 4.4 | 4.37 | 4.37 | 4.35 |
| 16 Rotor inertia | $gcm^2$ | 11.7 | 10.4 | 9.49 | 10.8 | 10.6 | 10.6 | 10.5 | 10.5 | 10.5 |

**Specifications**

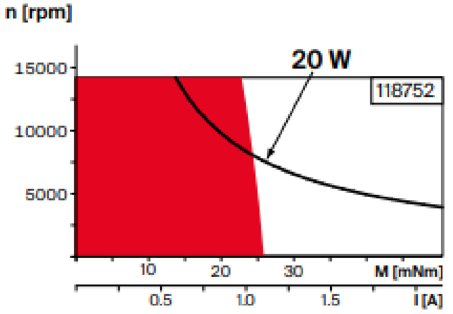
**Thermal data**

| | |
|---|---|
| 17 Thermal resistance housing-ambient | 14 K/W |
| 18 Thermal resistance winding-housing | 3.1 K/W |
| 19 Thermal time constant winding | 12.5 s |
| 20 Thermal time constant motor | 612 s |
| 21 Ambient temperature | -30...+100°C |
| 22 Max. winding temperature | +125°C |

**Mechanical data (ball bearings)**

| | |
|---|---|
| 23 Max. speed | 14000 rpm |
| 24 Axial play | 0.05 - 0.15 mm |
| 25 Radial play | 0.025 mm |
| 26 Max. axial load (dynamic) | 3.2 N |
| 27 Max. force for press fits (static) | 64 N |
| (static, shaft supported) | 800 N |
| 28 Max. radial load, 5 mm from flange | 16 N |

**Operating Range**




**Comments**

**Continuous operation**
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

**Short term operation**
The motor may be briefly overloaded (recurring).

**Assigned power rating**

# **Brushless DC Motor** – Comparison

**Comparison of BLDC vs DC motor**

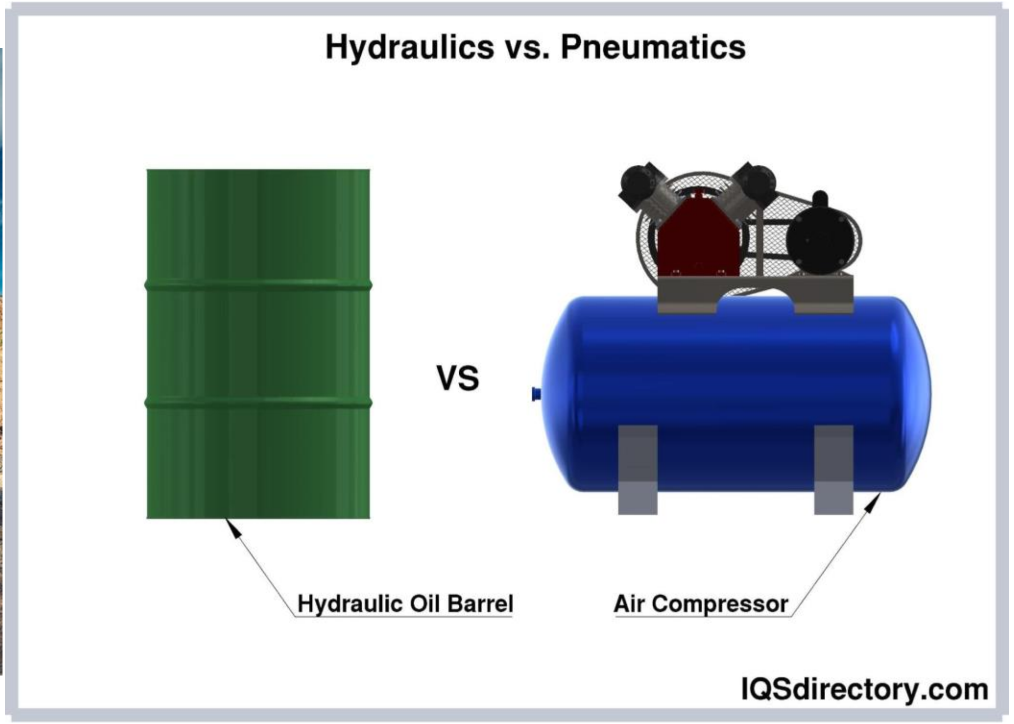
1. Advantages of BLDC Motors:

- Higher efficiency (90-95%)
- Better speed-torque characteristics
- Longer lifespan (no brush wear)
- Lower maintenance
- Better heat dissipation
- Higher speed capability
- Lower electromagnetic interference

2. Disadvantages:

- Higher initial cost
- More complex control system
- Requires electronic commutation
- More sophisticated driver circuits

# Pneumatic and Hydraulic Systems




Fluid Power Systems: Use fluids to transmit force and motion

# Pneumatic and Hydraulic Systems

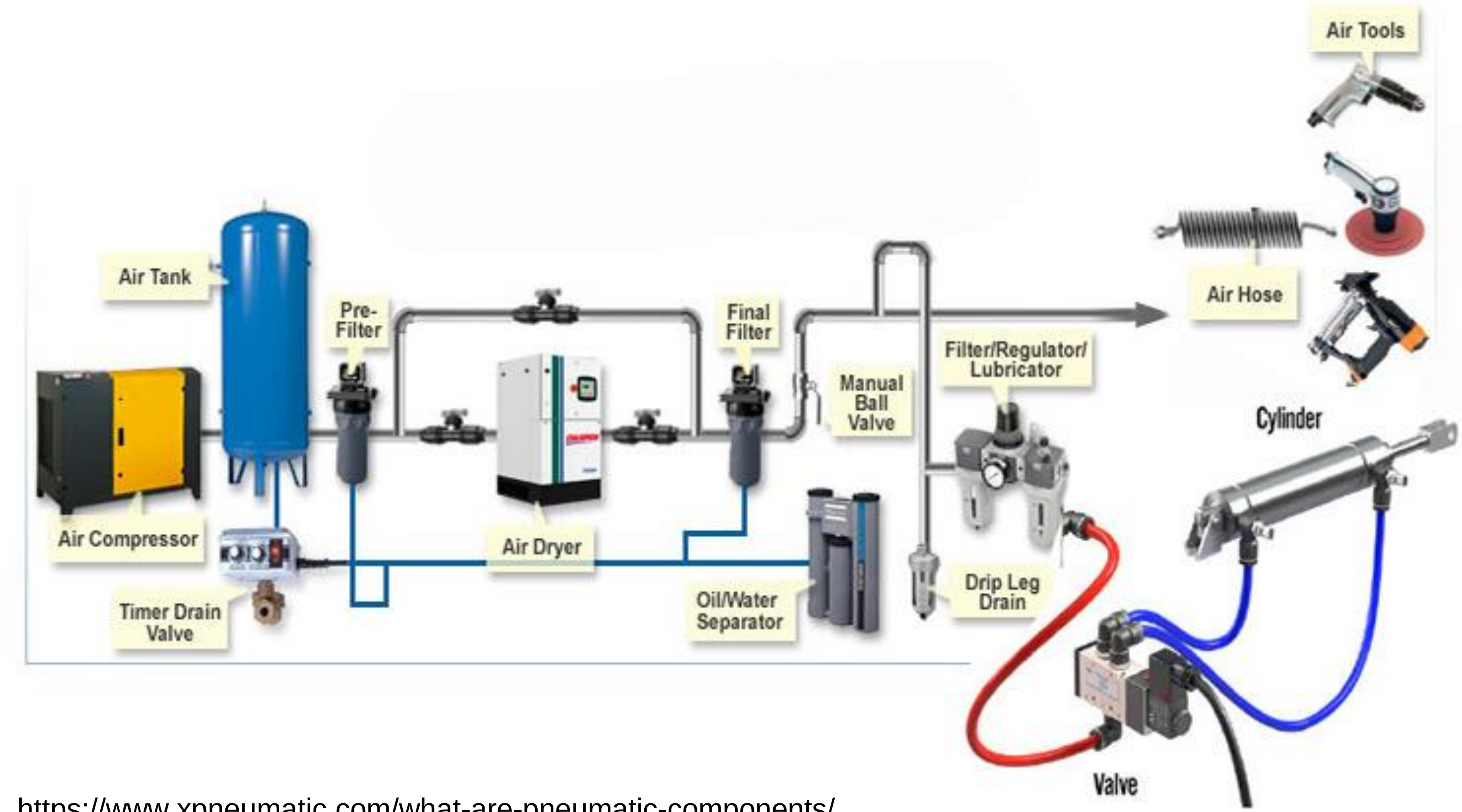
- Fluid Power Systems: Use fluids to transmit force and motion
- Pneumatic Systems: Use compressed air or gas
- Hydraulic Systems: Use incompressible liquids (usually oil)

Both systems convert fluid pressure into mechanical force

# Pneumatic: Working Principle

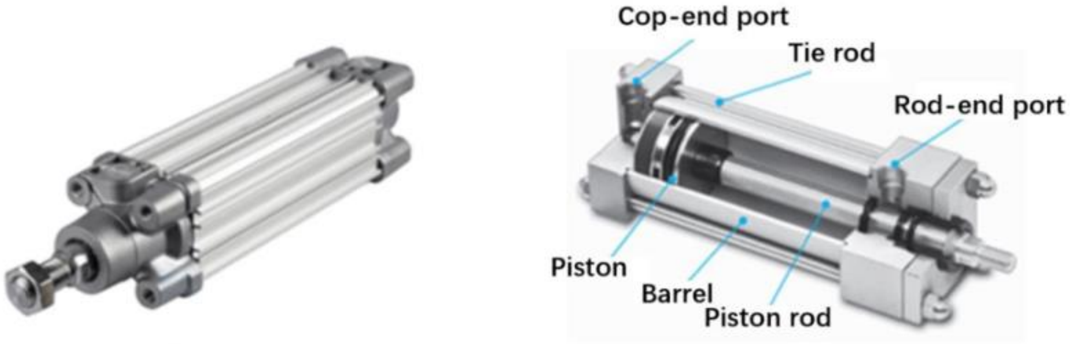
- Air is compressed in a compressor
- Compressed air is stored in receiver tank
- Air pressure typically ranges from 30-150 psi
- Force is transmitted through pipes and tubes
- Actuators convert air pressure to mechanical motion

# Pneumatic: Component

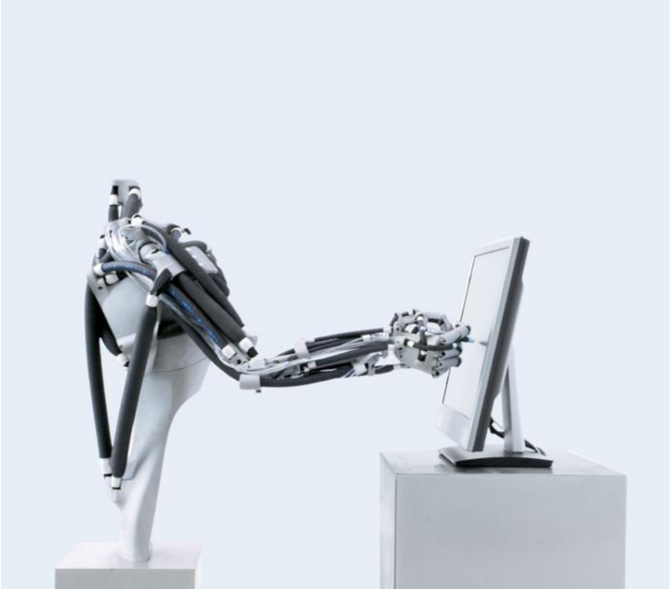


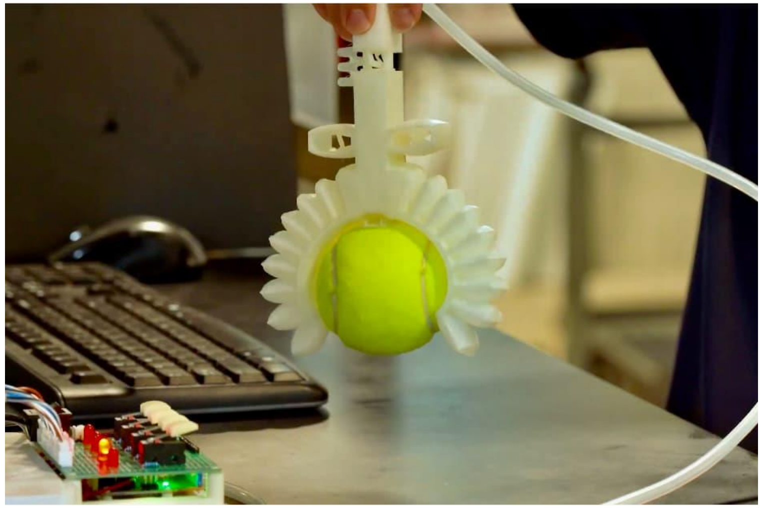

https://www.xpneumatic.com/what-are-pneumatic-components/

# Pneumatic: Actuator




(a) (b)



# Pneumatic: Applications

- Manufacturing assembly lines

- Pneumatic tools (nail guns, drills)

- Automated packaging machines

- Door systems (buses, trains)

- Dental and medical equipment

- Robot end effectors

# Hydraulic: Working Principle

- Liquid is pressurized by a pump

- Pressure can reach several thousand psi

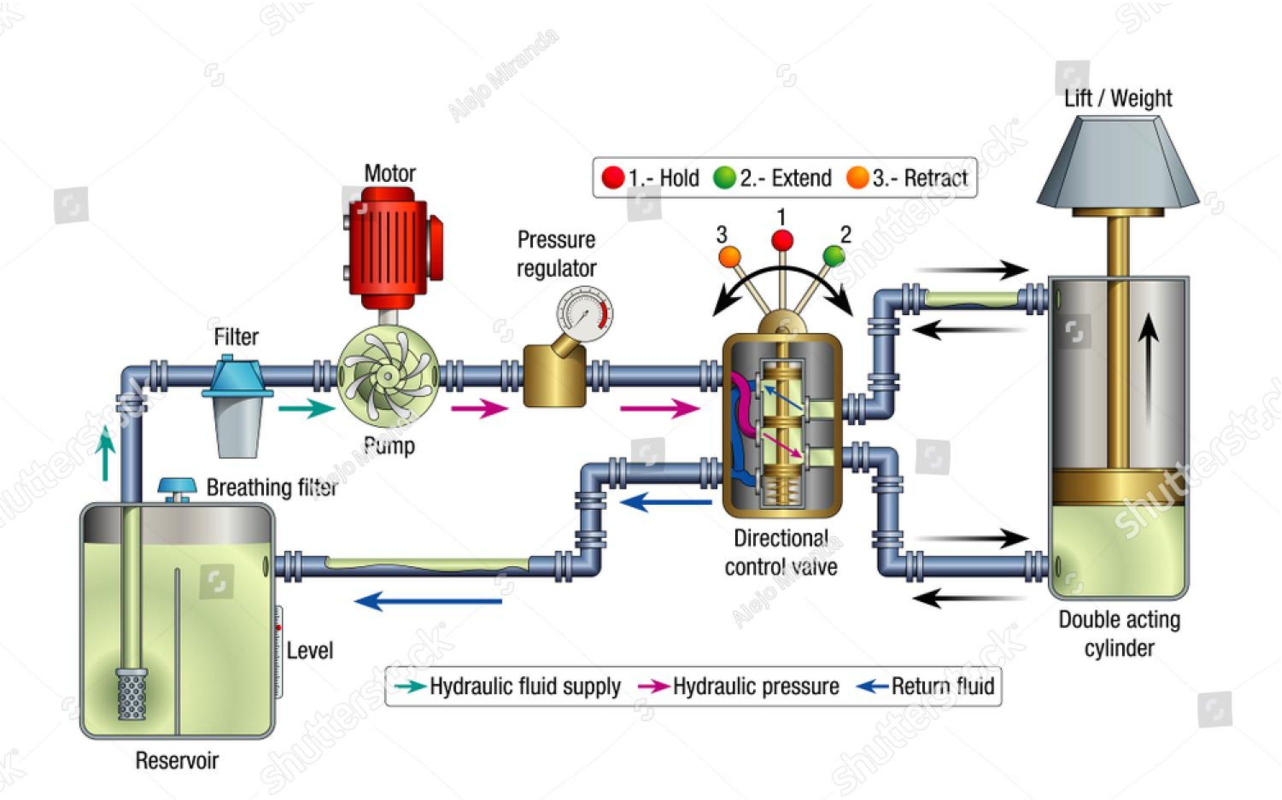
- Incompressible fluid transfers force effectively

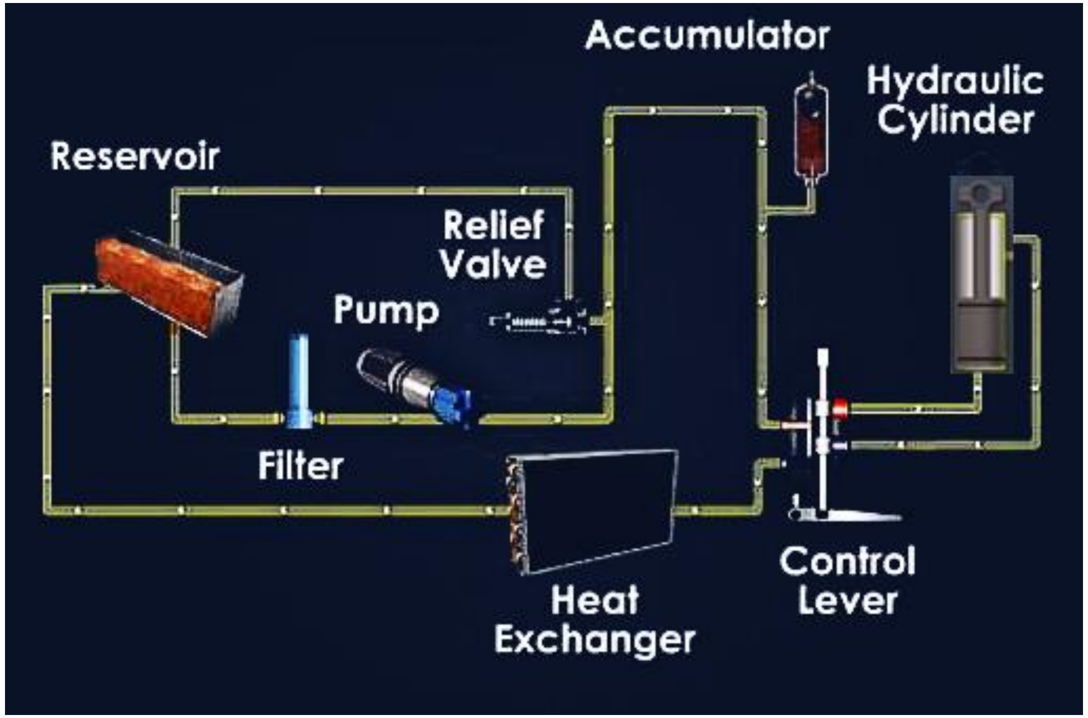
- Higher pressure yields greater force output

  ***Normal hydraulic pressure is between 3,000 and 4,000 PSI

- Energy is transmitted through hydraulic circuits

# Hydraulic: Component




https://www.shutterstock.com/image-vector/basic-hydraulic-system-explanatory-diagram-operation-1098736073

# Hydraulic: Actuator

# Hydraulic: Applications

- Construction equipment (excavators, cranes)
- Vehicle systems (brakes, power steering)
- Industrial machinery
- Aircraft control systems
- Elevators and lifts
- Metal forming machines

# Pneumatic VS Hydraulic - Advantage

**Pneumatic Systems**

- Clean and safe

- Low cost

- Simple maintenance

- Air is freely available

- No fluid leakage concerns

**Hydraulic Systems**

- Higher force output

- More precise control

- Self-lubricating

- Smooth operation

- Better power density

# Pneumatic VS Hydraulic - Limitations

**Pneumatic Systems**

- Less precise control
- Lower force output
- Air compression losses
- Noisy operation
- Moisture concerns

**Hydraulic Systems**

- Higher cost
- Risk of fluid leaks
- Regular fluid maintenance
- More complex system
- Temperature sensitivity

https://www.youtube.com/watch?v=EezdinoG4mk