# POWER ENGINEERING

## #12 3-PHASE INDUCTION MOTORS (I)

2018

University of Glasgow

# 3 Phase Induction Motors

Since its invention in the late 1800's the 3 phase Induction Motor has been the 'workhorse of industry' and even today accounts for approximately 45% of electricity consumption. Sizes range from hundreds of watts to several Megawatts with an equally diverse range of applications; driving industrial pumps and fans, railway traction and elevators drives to name but a few.

*In today's lecture we will investigate:*

- General introduction to Electric Motors
- Types of Motors
- The 3 Phase Induction Motor:
    - Basic Components
    - Stator Windings and rotating magnetic field

# Electric Motor Drive:

**Electrical Power Supply**

AC/DC

**Power Electronic Converter**

*May not be required*

**Electric Motor**

**Mechanical Load**

Fans
Pumps
Traction
Hoists
Conveyers
Washing machines
More Electric Aircraft actuators
Compressors
etc etc etc

Power Flow

**Input Power (W)**

**Losses (W)**

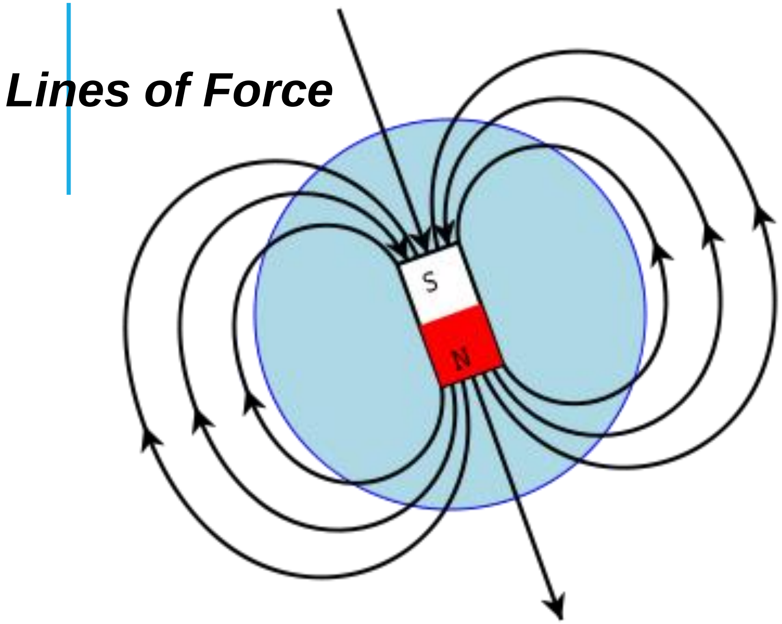
1] Device Losses

**Losses (W)**

1] Copper Loss
2] Iron Loss
3] Friction & Windage Loss
4] Others (Magnet, commutator)?

**Output Power (W)**

# BASIC MAGNETIC FIELD

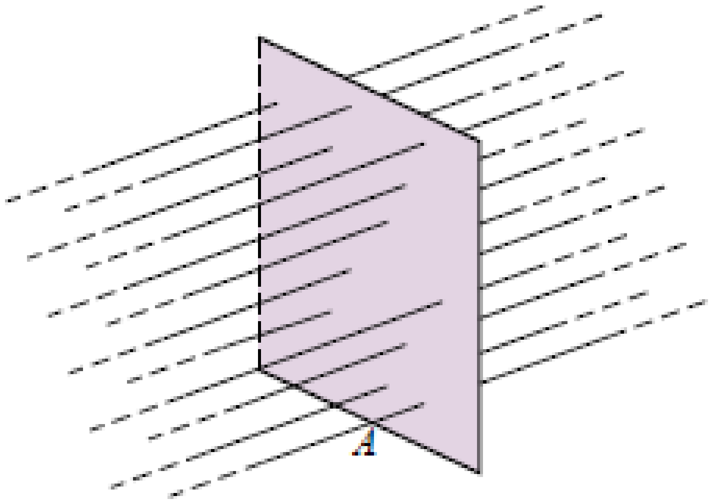



**lifting lots of iron clips via magnet force**

Every magnet has two poles: a north and a south. Two similar magnetic poles repel each other; while opposite magnetic poles attract each other. Magnets have a continuous force around them that is known as a magnetic field. This field enables them to attract other metals.

Lines of force is often used to represent magnetic field, which travel from north pole to south pole. These lines of force are often called the magnetic flux. Here we will try to reveal how generators and motors **use these lines of force to generate electricity, as well as mechanical motion.**

*Magnetic flux*, **Φ**, in units of (Wb)
*Magnetic flux density*, **B**, in units of (Wb/m$^2$ or T)
*Magnetic field intensity*, **H** in units of (A/m)




**Magnetic flux lines crossing a surface**

$$\Phi = B \bullet A$$

**Relative permeability for common materials**

| Material | $\mu_r$ |
|---|---|
| Air | 1 |
| Permalloy | 100,000 |
| Cast steel | 1,000 |
| Sheet steel | 4,000 |
| Iron | 5,195 |

$$B = \mu H = \mu_r \mu_0 H$$

# ELECTRICITY AND MAGNETISM

## ELECTRIC CURRENT PRODUCES MAGNETIC FIELD

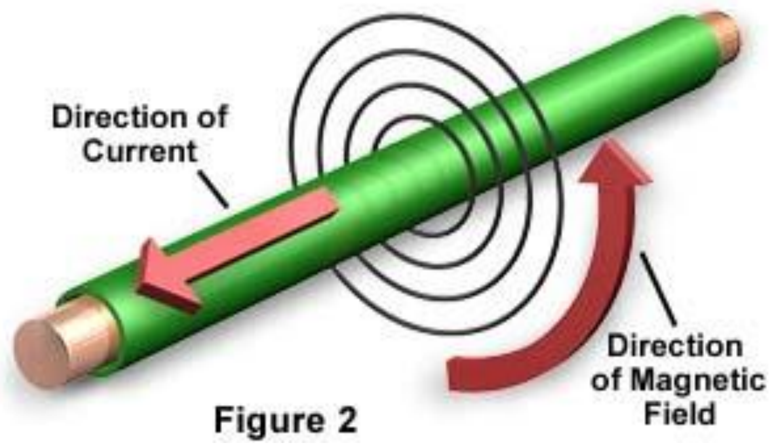



Figure 2

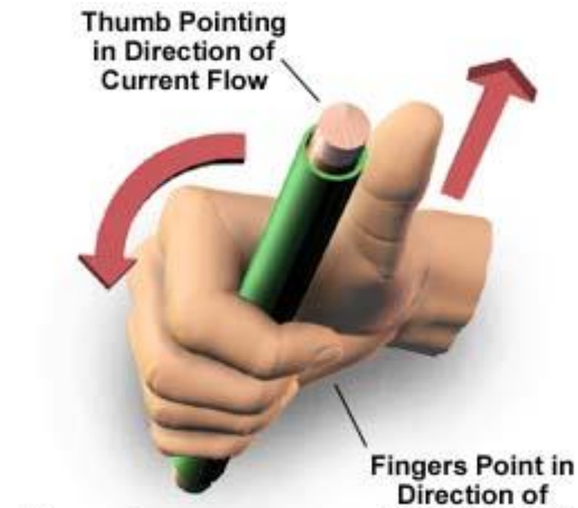
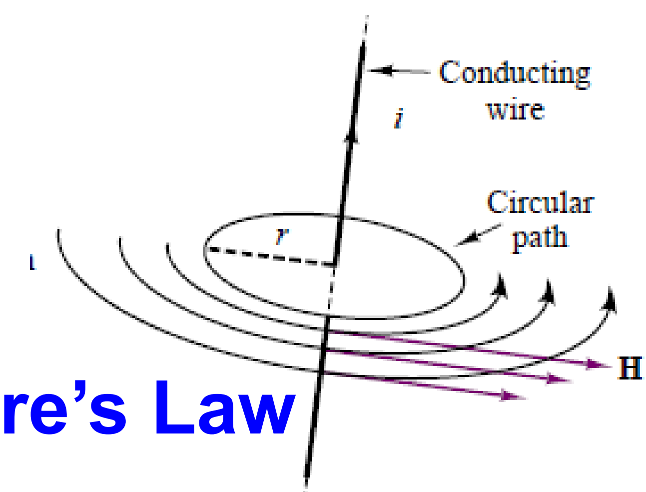


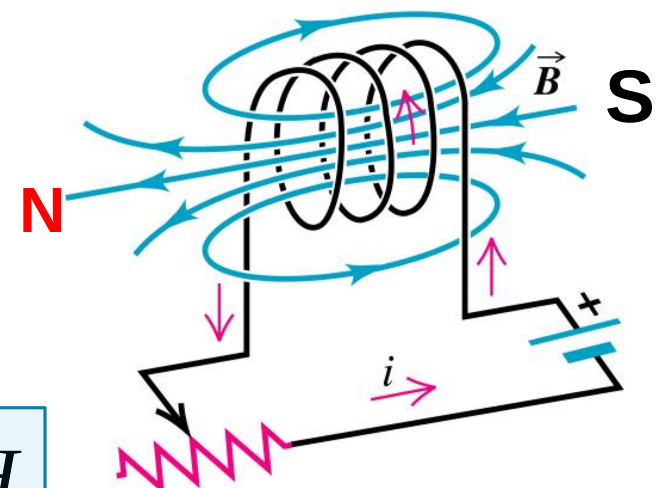

Figure 3

Right-hand Rule




**Ampere's Law**

$$\oint H\,dl = \sum i \;\Rightarrow\; B = \mu H = \mu_r \mu_0 H$$

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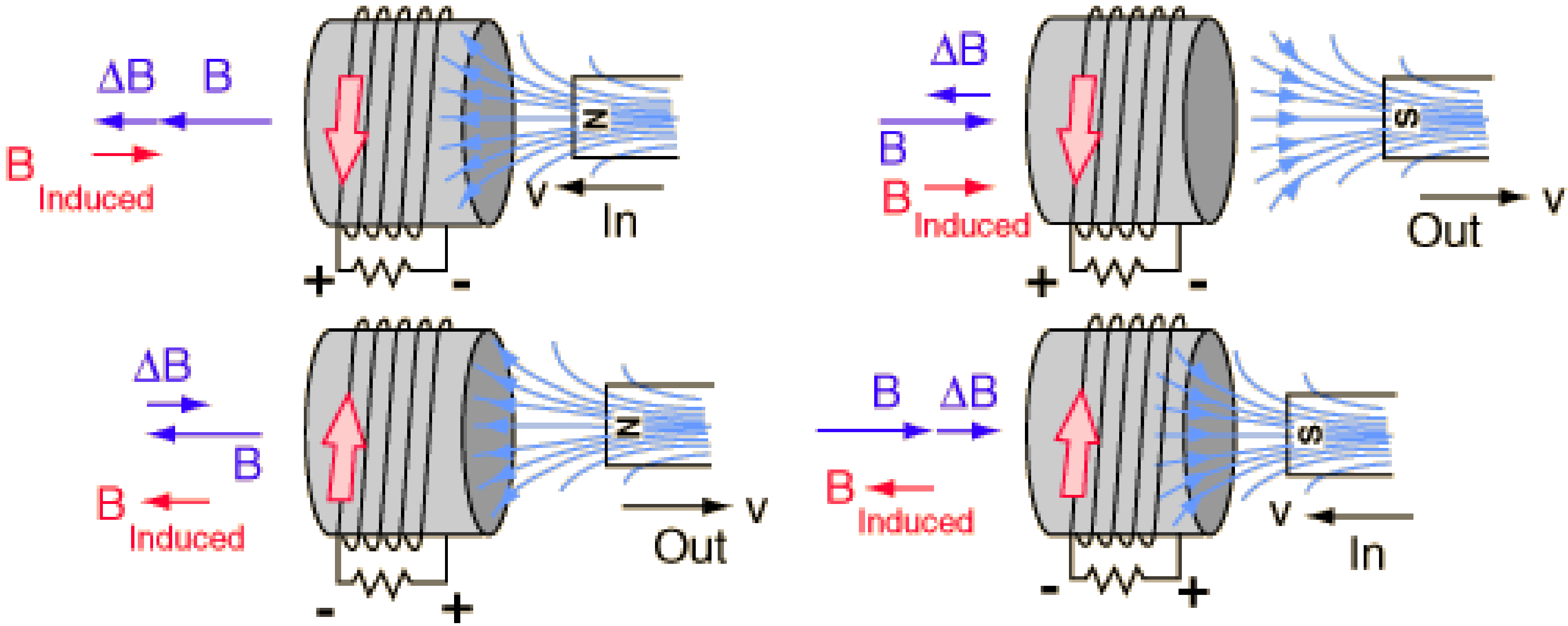
# ELECTRICITY AND MAGNETISM:
## CHANGING MAGNETIC FIELD PRODUCE ELECTRICITY



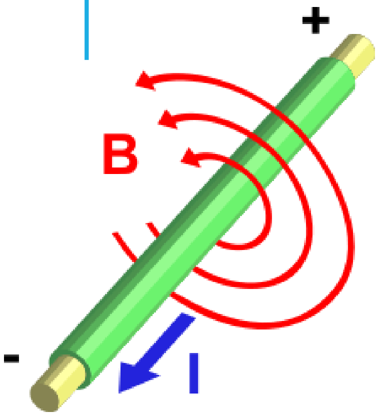

**Faraday's Law**

Electromotive force (emf):
a voltage

$$e = -N \frac{d\Phi}{dt}$$

# ELECTRICITY & MAGNETISM

## BI-DIRECTIONAL CONVERSION



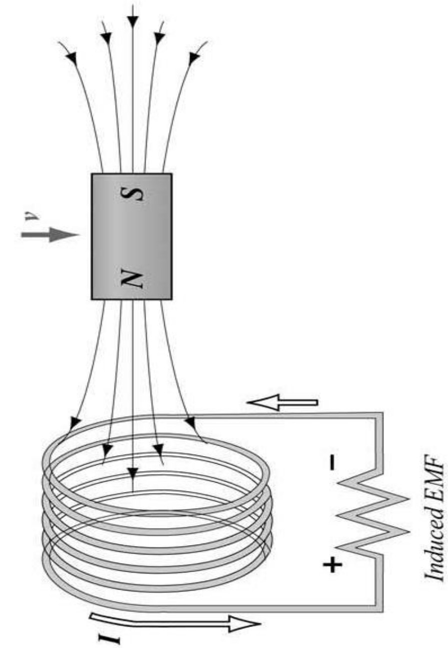

Ampere's Law:

Electric current produces magnetic field

**Electric Field** ⇄ **Magnetic Field**

Faraday's Law

A changing magnetic field gives rise to a voltage

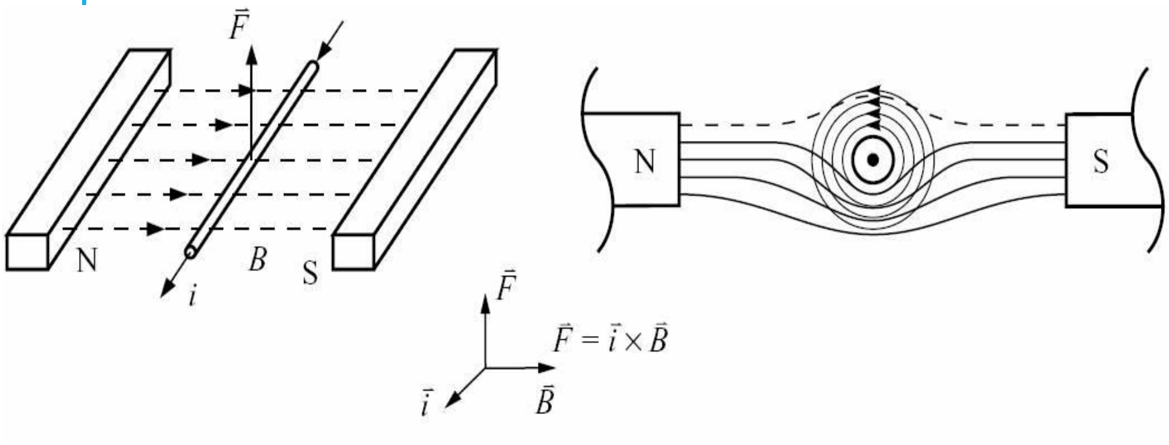



***Electro-magneto-Mechanical***

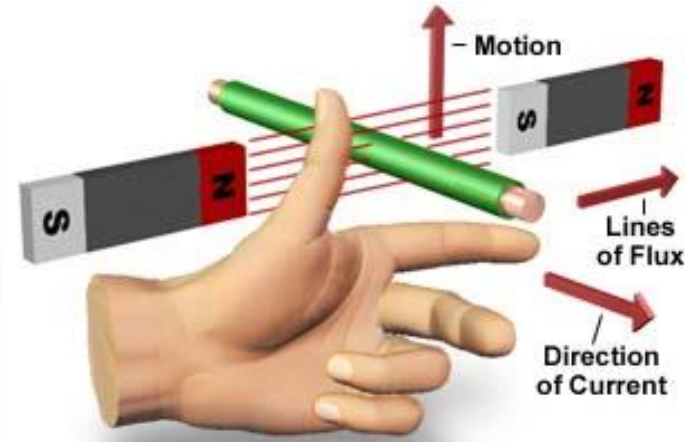
**Electrical Energy** ⟷ **Magnetic Energy** ⟷ **Mechanical Energy**

# ELECTRO-MECHANICAL

## BI-DIRECTIONAL ENERGY CONVERSION

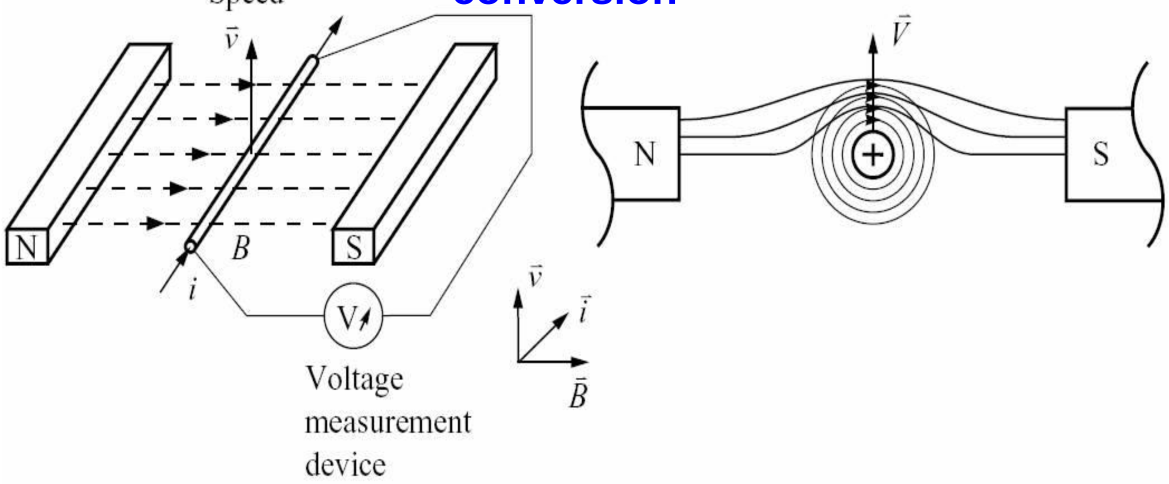



Motor action

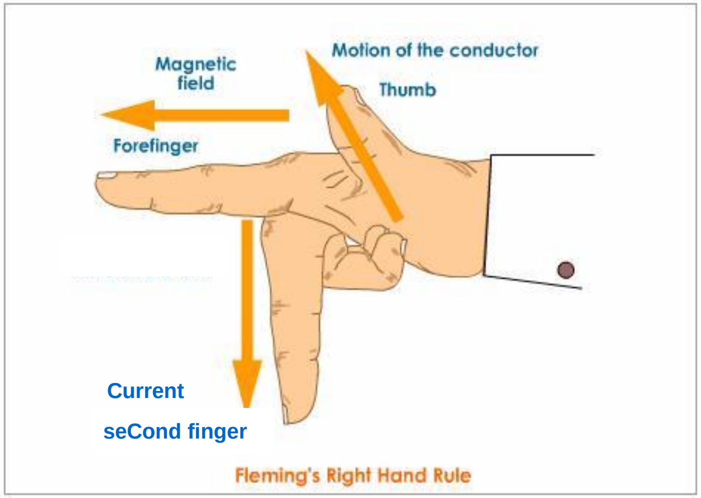



Fleming's Left Hand Rule
(Motors drive on the Left )

**Magnetic Field – medium for electromechanical conversion**




Generator action



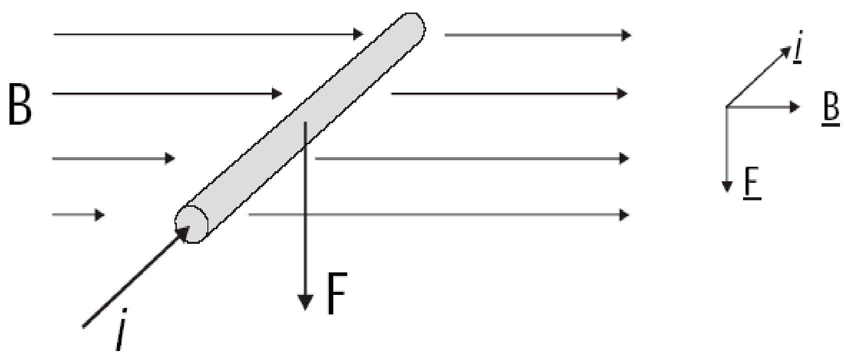

(The letter "g" is in "ri**g**ht" and "**g**enerator")

# ELECTROMECHANICAL TORQUE GENERATION

In motor action, a **force F** will be produced whose direction is orthogonal to both the current and flux and whose magnitude is given by :

$$\boxed{F = B\,l\,i}$$

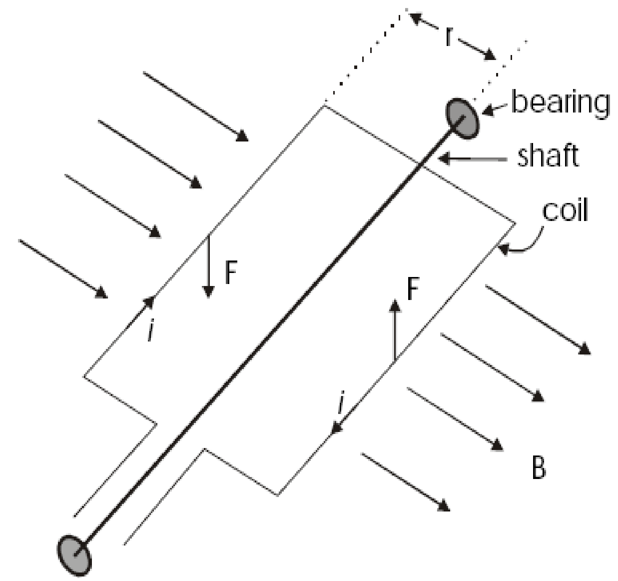
where ***B*** is magnetic flux density (Tesla or T, 1 T = 1 Weber/m$^2$), ***l*** is the length of wire within the field, ***i*** is the current flowing in the wire




Current-carrying wire is shaped into a coil. The net effect of the two forces – one upward and one downward – is to exert a **turning moment** or ***torque*** of value

$$\boxed{T = 2Fr}$$

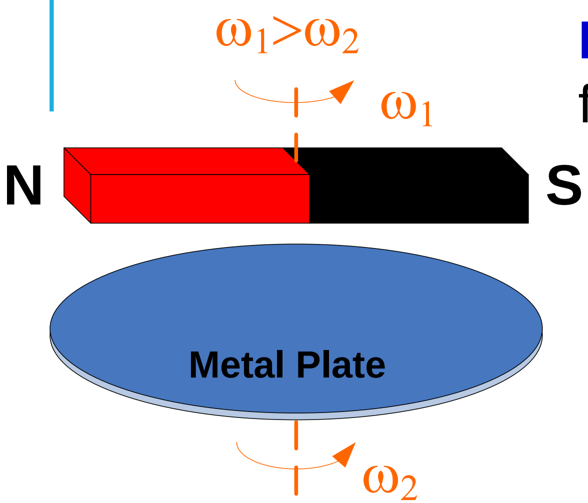
on the coil, where ***r*** is the distance between the centre line of the shaft and the conductor. Rotation direction can be reversed by changing the direction of the current.



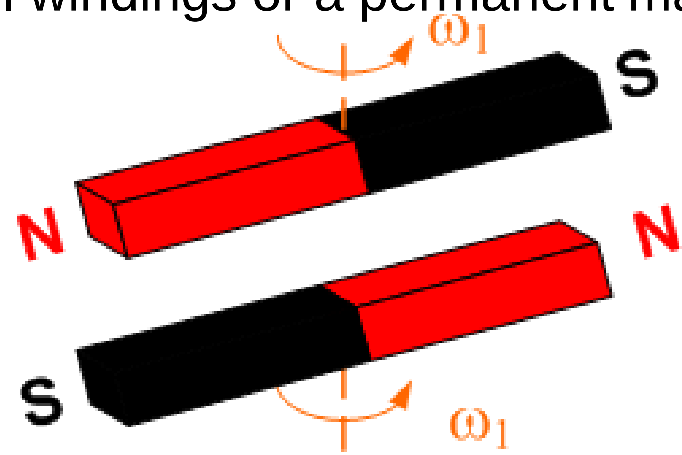
# GENERATE MECHANICAL MOTION

## Interaction between two magnets

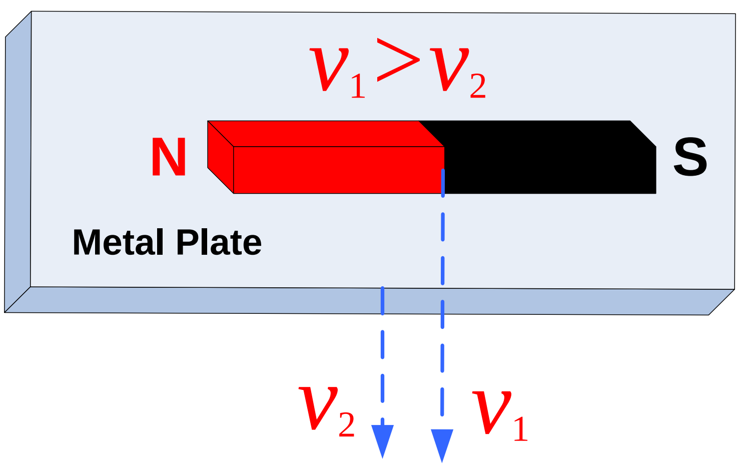
**Note:** The magnet can be a AC or DC current-flowing coil windings or a permanent magnet.



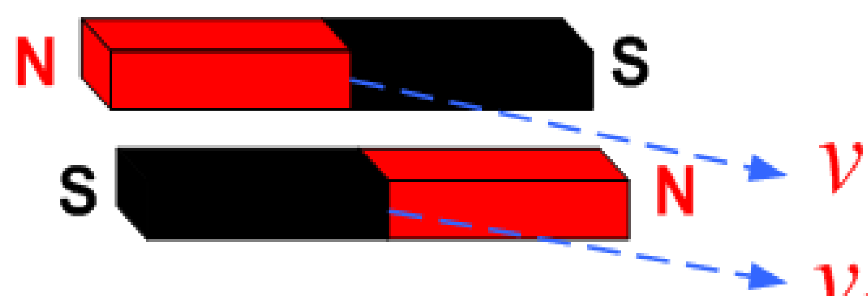

**Rotating Induction**




**Synchronous Rotating**
(stationary with respect to each other)




**Linear (Induction) Moving**




**Linear (Synchronous) Moving**

# TYPES OF ELECTRIC MACHINE

**Interaction between two magnets**

- Opposite magnetic poles attract, and same magnetic poles repel each other.
- Magnets attract iron and seek to move to a position to minimize the reluctance to magnetic flux.
- Current-carrying conductors create an electromagnet and act like a current-controlled magnet.

**ROTATING ELECTRIC MACHINES**

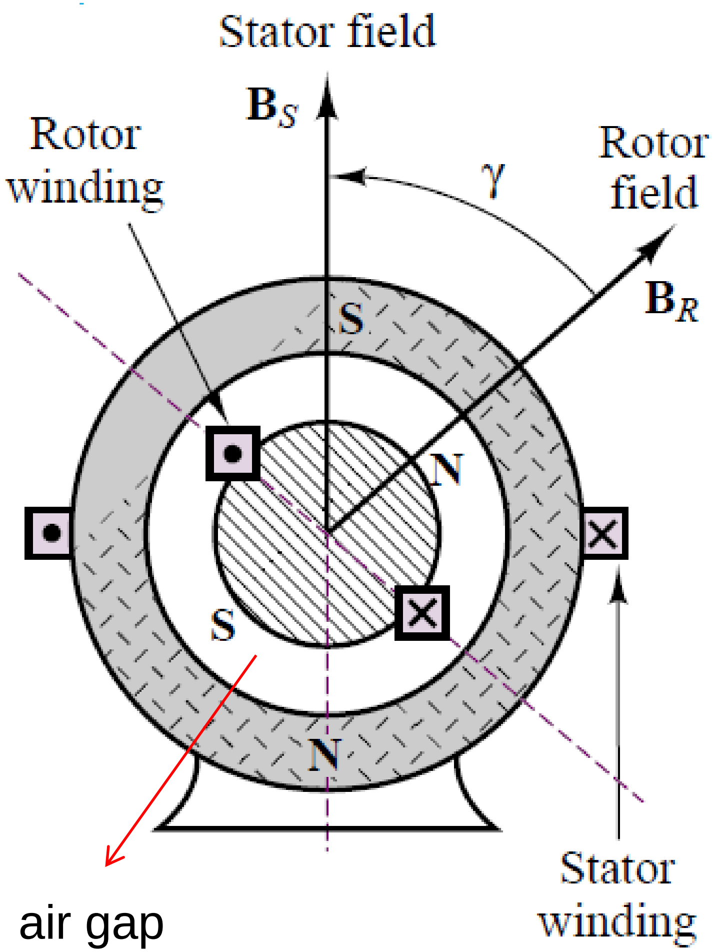
Induction rotating → (AC) Induction motor/generator

Synchronous rotating → Synchronous motor/generator
DC motor/generator
Step motor/generator ………

**LINEAR MOVING ELECTRIC MACHINES**

Linear moving → Linear motor/generator

# ROTATING ELECTRIC MACHINES




**Torque:**

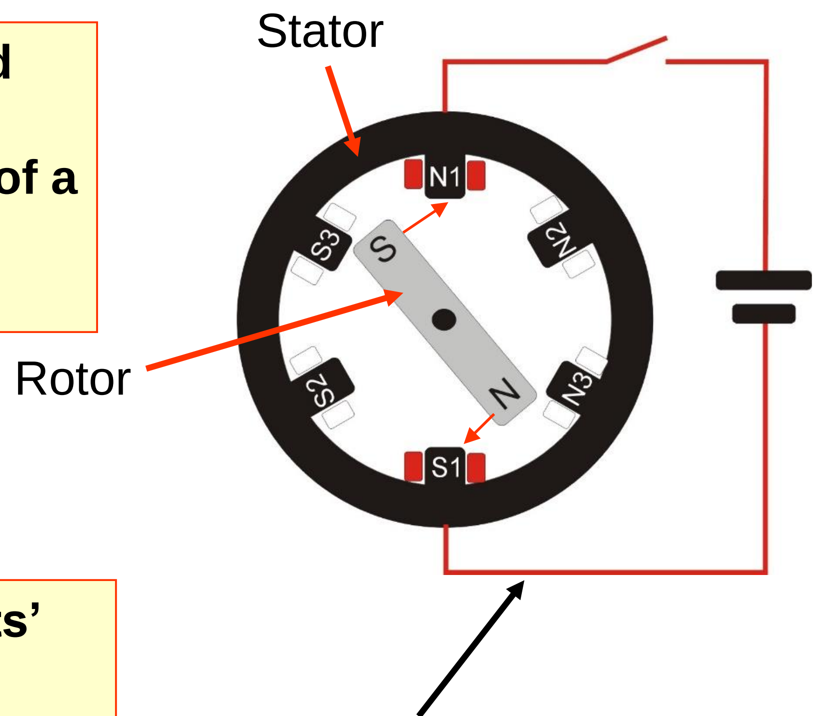
$$T = K \bullet B_r \bullet B_s \bullet \sin\gamma$$

**Rotor** and **Stator** are **two magnets**, which generate magnetic flux using coil windings or permanent magnet. The rotor is mounted on a bearing-supported shaft, which can be connected to *mechanical loads* (*if machine is a motor*) or to a *prime mover* (*if machine is a generator*).

To create a rotating electric motor, the key is **how to use electricity to produce a rotating magnetic field (i.e. a rotating stator magnet) to pull the rotor (magnet) to rotate** about its center of mass**.**

# Motors: General #1

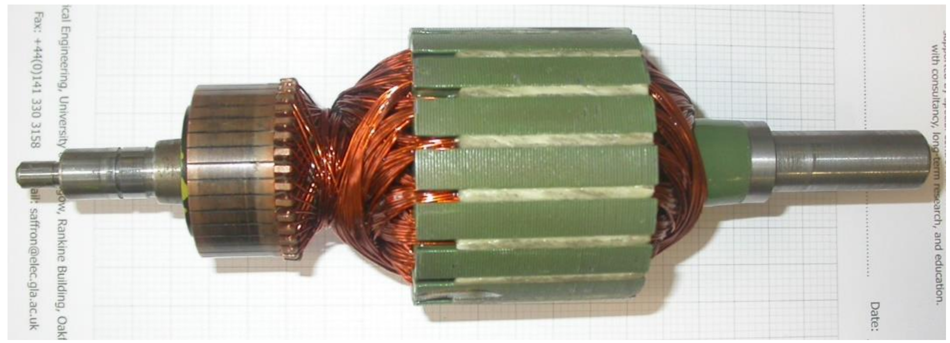
**Torque (rotational force) and mechanical rotation is achieved by the interaction of a stator ‘magnet’ and a rotor ‘magnet’.**




**The stator and rotor ‘magnets’ can be either permanent magnets or created by passing current through copper windings (electromagnets)**

**Typically the current in electromagnets must be switched on and off with respect to the rotor position. This is either achieved through a mechanical *Commutator* or a *Power Electronic Converter***

# Motors: General #2

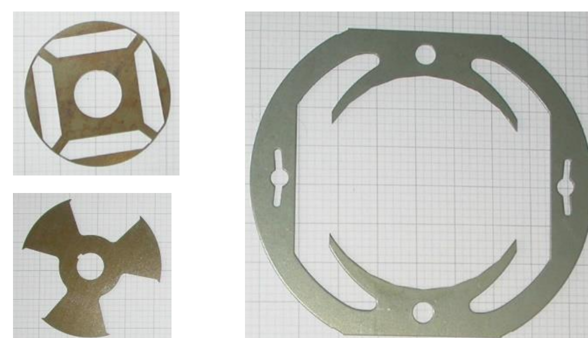


Stators and Rotors are constructed from stacks of insulated (oxidised layer) iron laminations which are typically <0.5mm thick

Laminations are used to reduce the Eddy current iron loss (W) in the machine

The stator or rotor laminations may then have windings or permanent magnets added, dependant on the machine type….

**Typical laminations:**



# Types of Electric Motors:

**‘Classical’:**

- Brushed DC Motor
- Universal Motor
- Induction Motor

**Power Electronic Converter**

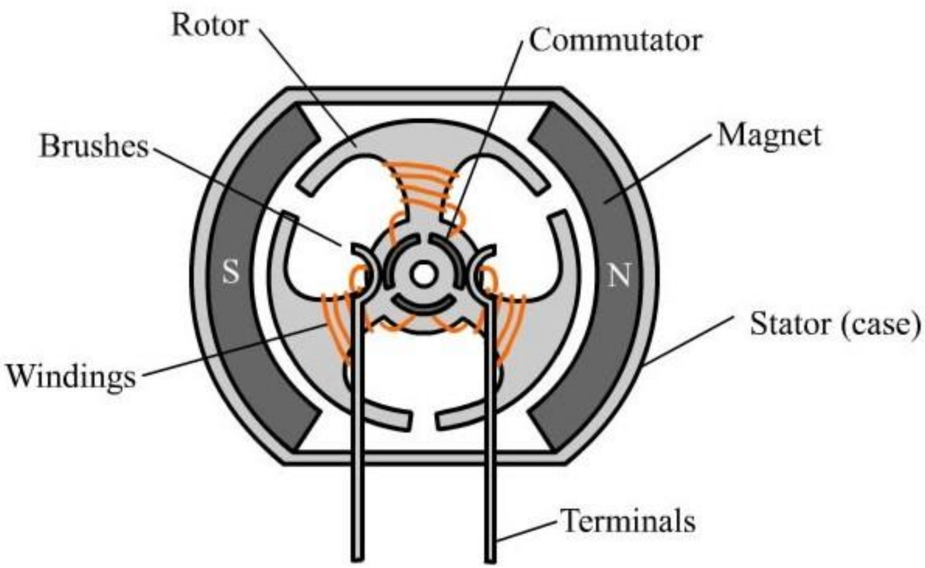
**Modern Brushless:**

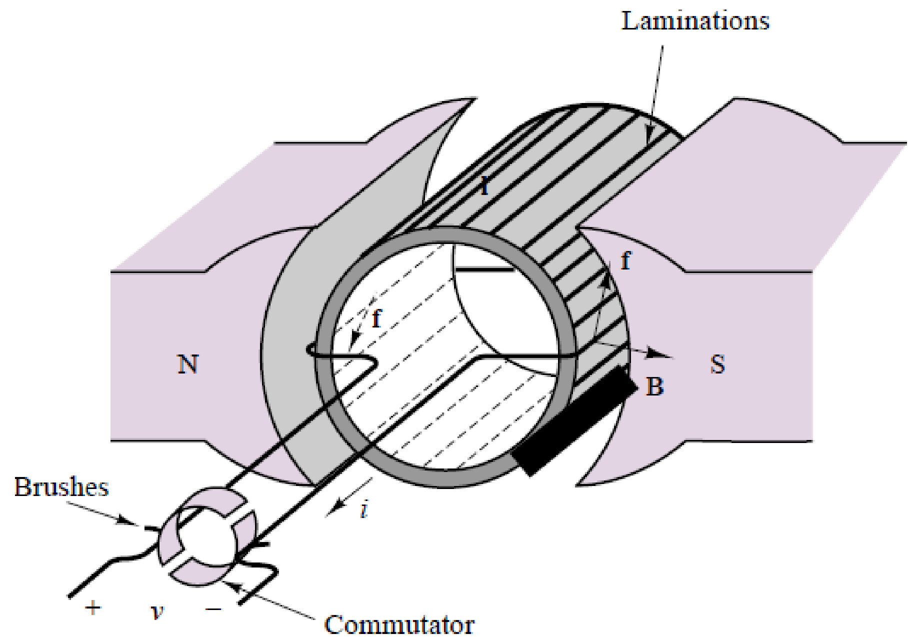
- Stepper Motor
- Switched Reluctance Motor
- Brushless DC Motor

**Power Electronic Converter**

Note: even although the ‘Classical’ motors do not require a Power Electronic Converter their performance can in fact be improved by the inclusion of a Converter

# Brushed DC Motor



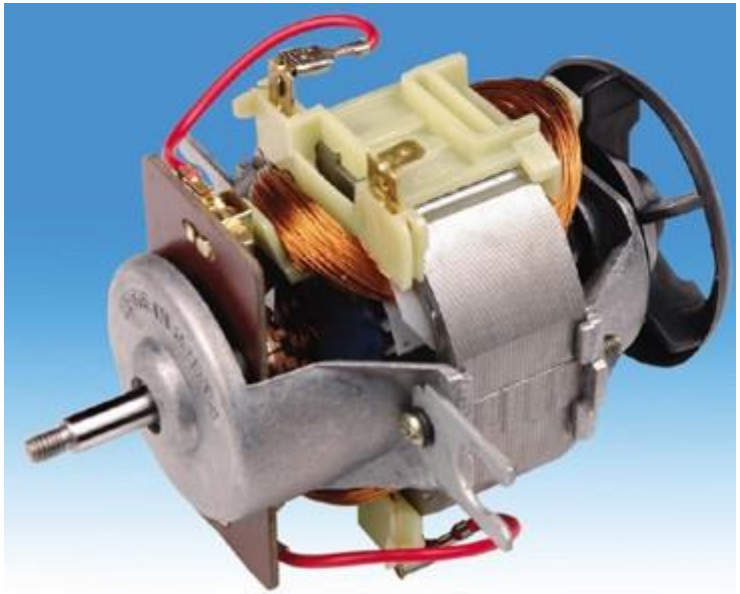




## Applications:

- Automotive Ancillary's: windscreen wipers, window movers etc
- Wheelchair drives, golf buggies

| Power Source | Stator | Rotor | Commutator | Rotor Position Sensor |
|---|---|---|---|---|
| DC | Magnets | Windings | Yes | No |

# Universal DC Motor:

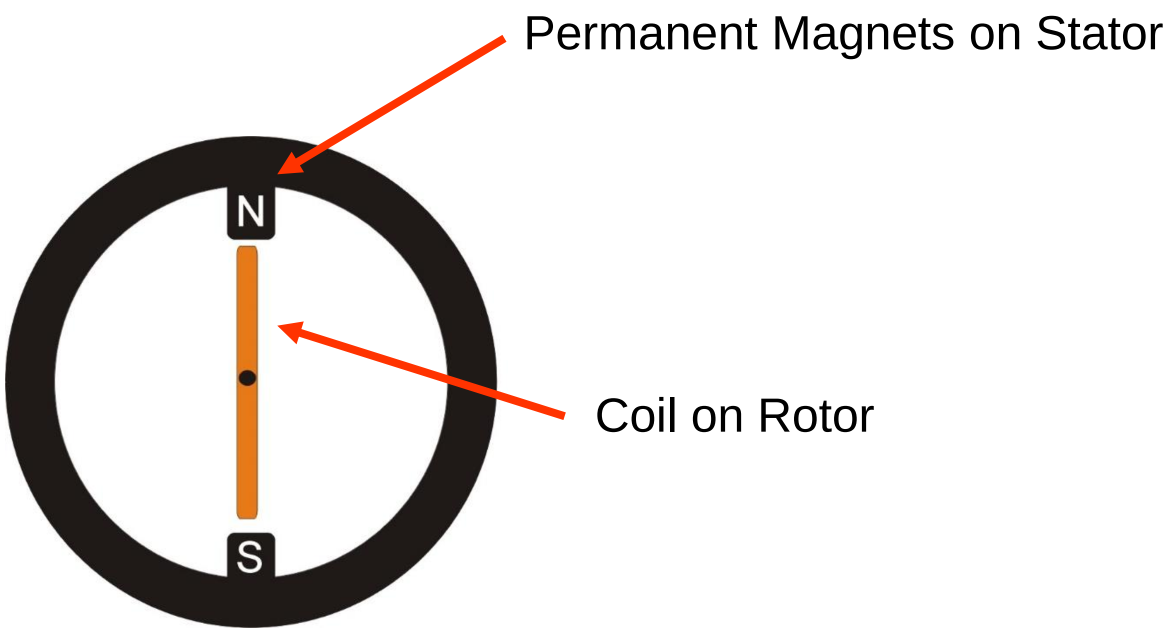


## Applications:

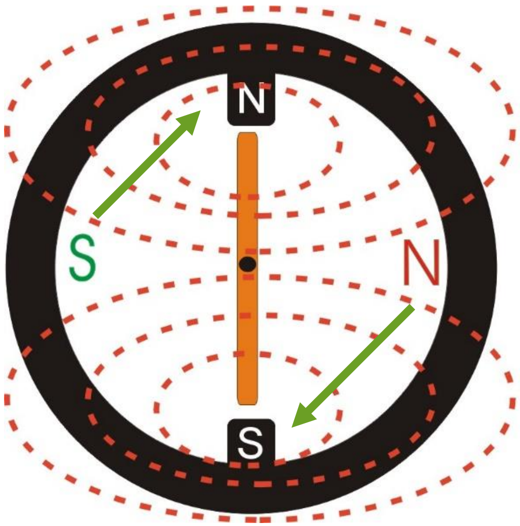
- Consumer electrics: washing machines, vacuum cleaners etc
- Power Tools: drills, screwdrivers, sanders etc
- Gardening tools: lawn movers, strimmers, hedge cutters etc

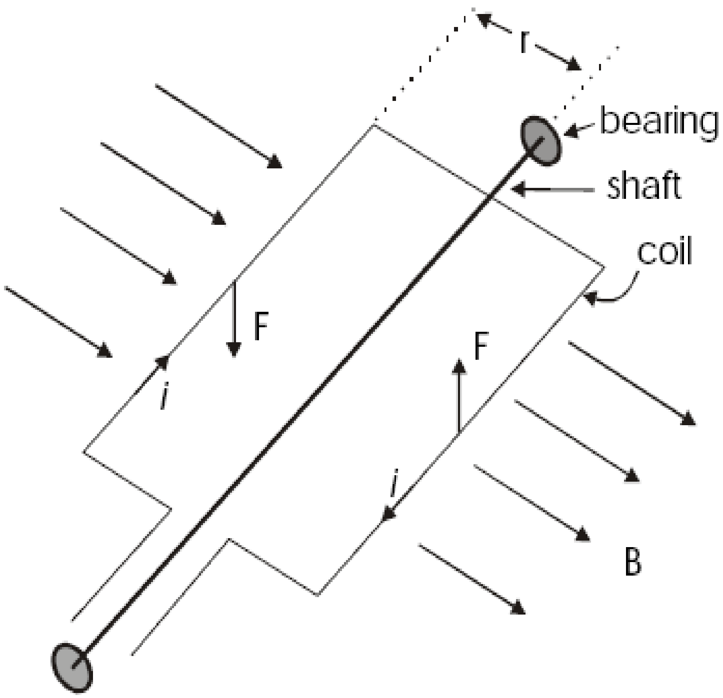
| Power Source | Stator | Rotor | Commutator | Rotor Position Sensor |
|---|---|---|---|---|
| DC/AC | Windings | Windings | Yes | No |

# What is Commutation?



# What is Commutation?



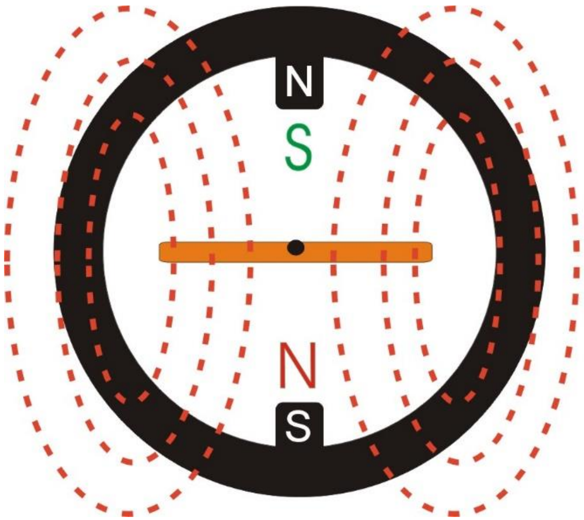




$$T = 2\,F\,r$$

Coil Magnetic Flux pattern if we pass current through the winding

The coil magnetic poles are attracted to the opposite poles on the Stator and the result is that the Rotor rotates clockwise

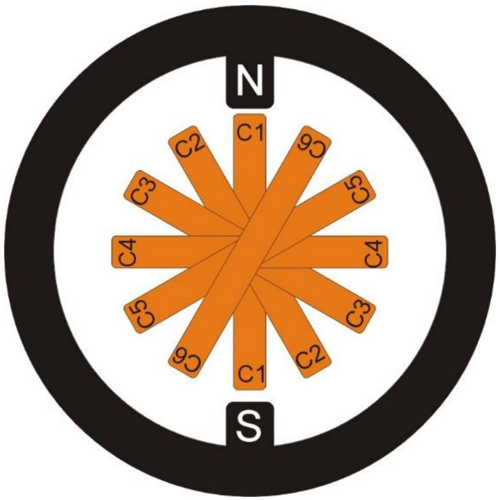
# What is Commutation?

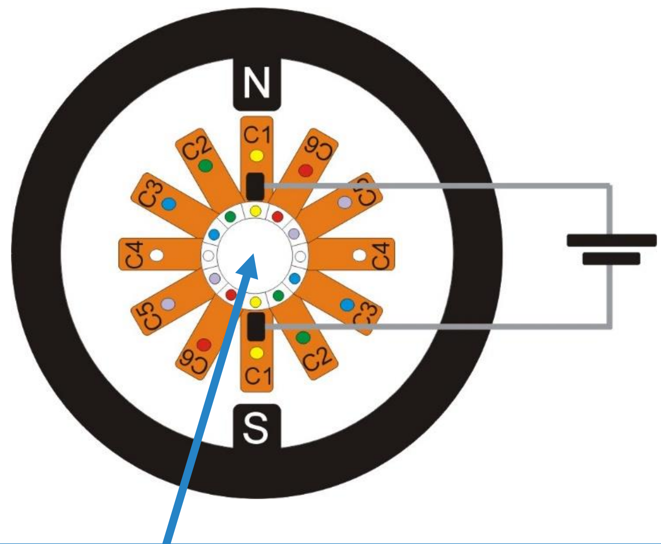



BUT the rotor now locks in this position and therefore we get no further rotation

# Solution

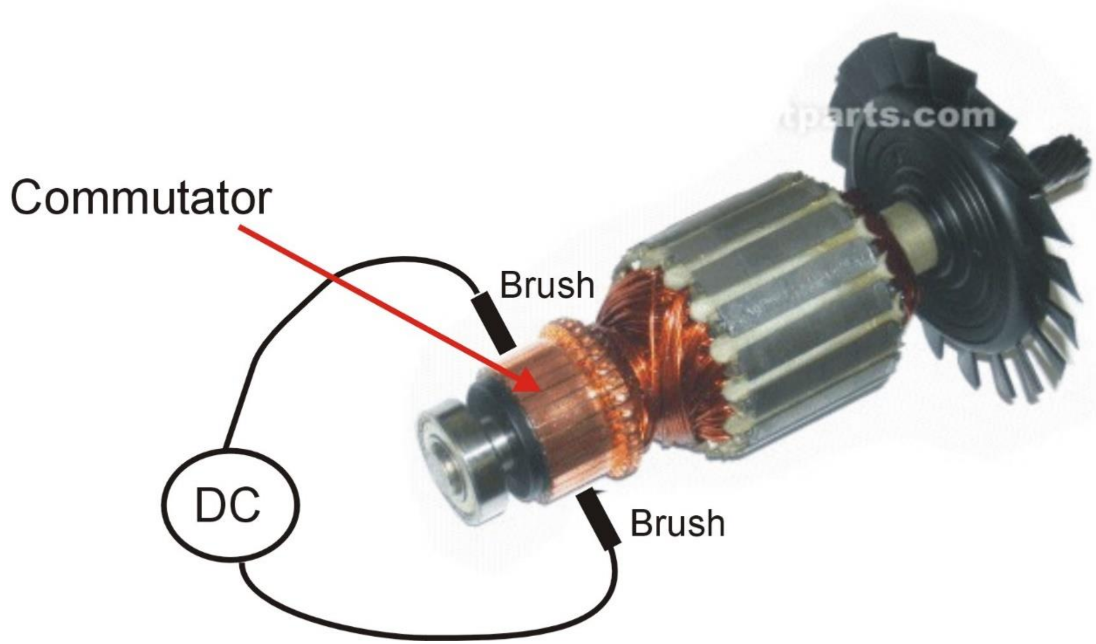
**Have multiple coils on the rotor BUT only have current flowing in ONE coil at any particular time**




The Mechanical Commutator (+ Brushes) selects which Coil to energise

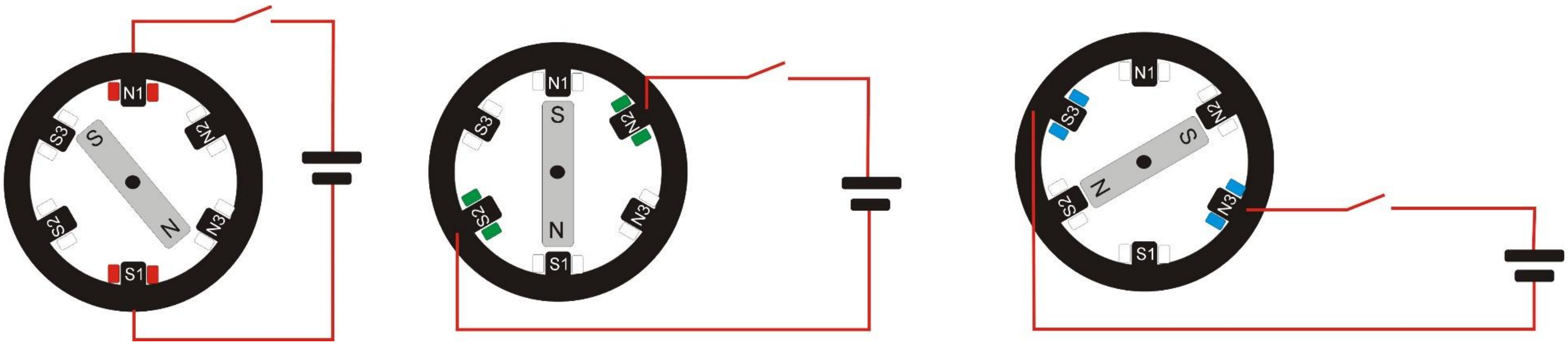
# So what's the big problem with having a Commutator?




**The function of the Commutator is to connect a particular winding (one of many) on the rotor to an external power supply. Because the Commutator is rotating with the rotor we need carbon Brushes to electrically connect the stationary supply to the Commutator. These Brushes wear relatively quickly due to the rotation therefore reliability and maintenance are BIG issues with any machine which needs a Commutator.**

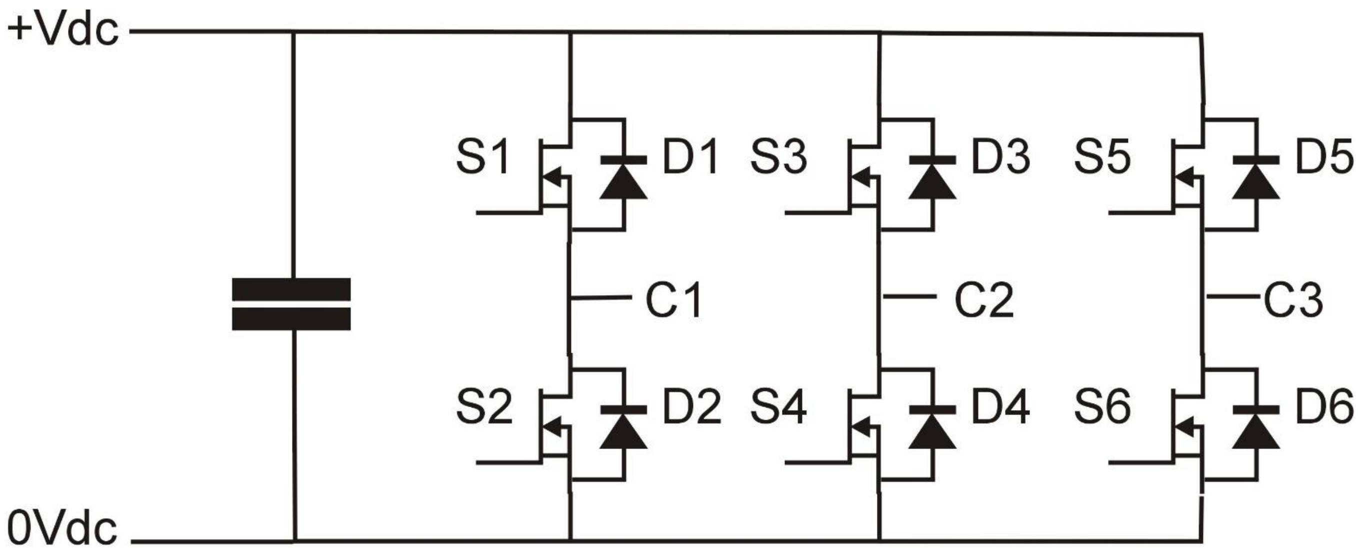
# Alternative: Electronic Commutation (Power Electronic Converter)

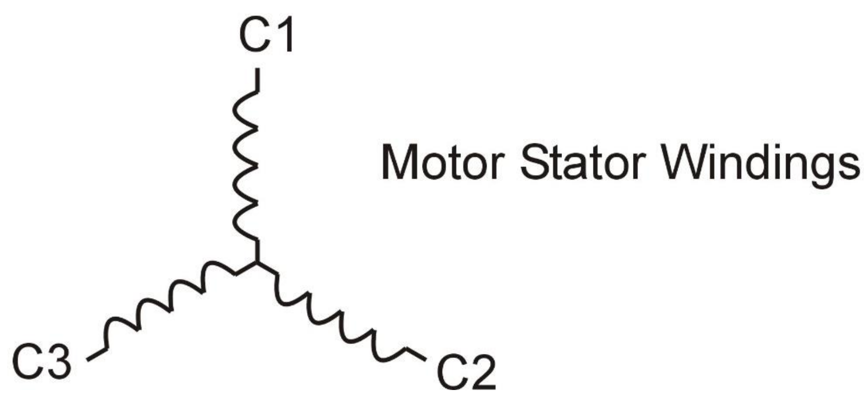
We essentially turn the Brushed DC motor ‘inside out’ and now have permanent magnets on the rotor and electro-magnets on the stator. The stator phase currents are now turned on an off with power electronic switches:



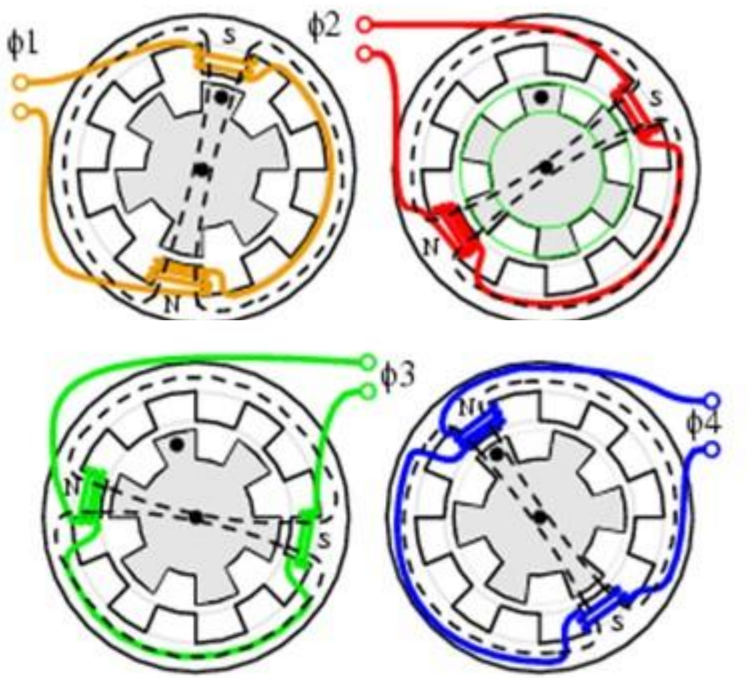

Note that we now need a Rotor Position Sensor to tell the controller which phase to energise at any particular time

# Complete Power Electronic Converter: Brushless DC Drive



# Stepper Motor:

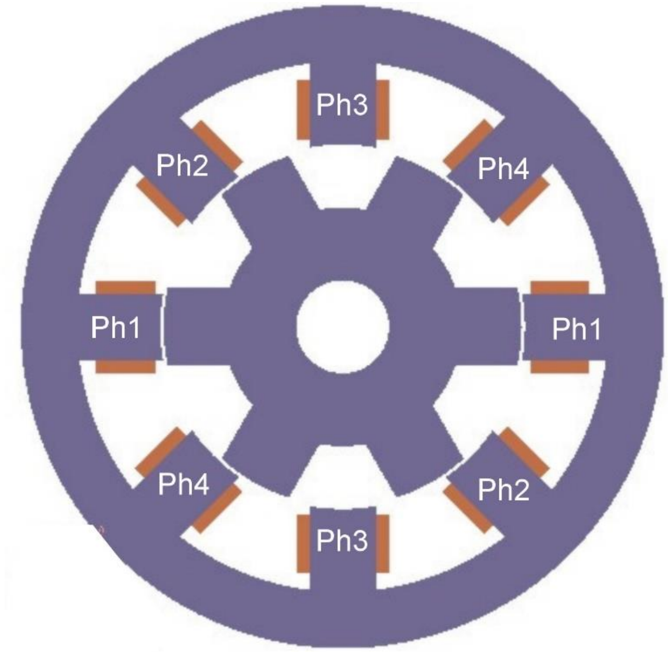



## Applications:

- Computer printers & scanners
- Positioning systems (CNC)
- Optics (mirror positioning)

| Power Source | Stator | Rotor | Commutator | Rotor Position Sensor |
|---|---|---|---|---|
| Power Electronic Converter | Windings | Iron (Magnets) | No | No |

# Switched Reluctance Motor:

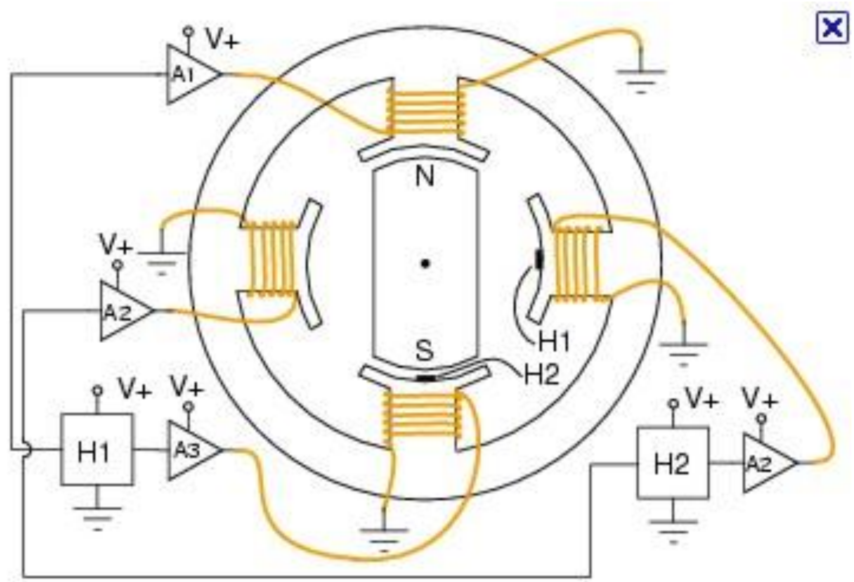



## (Potential) Applications:

- Aircraft Surface Actuators
- Washing machines
- Automotive power steering

| Power Source | Stator | Rotor | Commutator | Rotor Position Sensor |
|---|---|---|---|---|
| Power Electronic Converter | Windings | Iron | No | Yes |

# Brushless DC Motor:

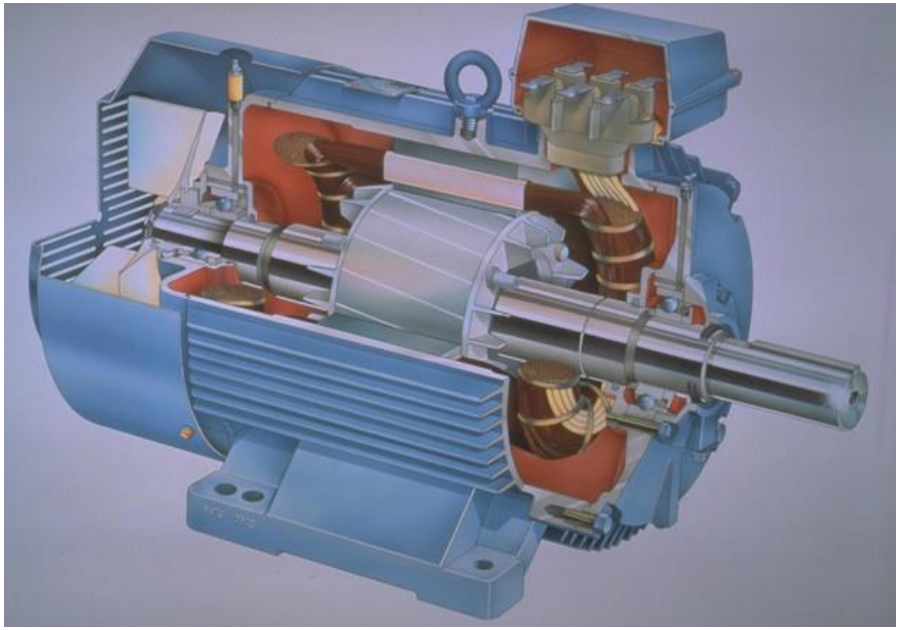



## Applications:

- Aircraft Surface Actuators
- Automotive power steering
- Hybrid Vehicle drive
- Compressors

| Power Source | Stator | Rotor | Commutator | Rotor Position Sensor |
|---|---|---|---|---|
| Power Electronic Converter | Windings | Magnets | No | Yes |

# Induction Motor (No Commutator and No Electronic Converter Required!):



**Applications:**

- Industrial fans and pumps
- Railway traction
- Hoists and lifts

**ie 24/7 applications!**

| Power Source | Stator | Rotor | Commutator | Rotor Position Sensor |
|---|---|---|---|---|
| AC | Windings | Aluminium Cage | No | No |

# Types of Induction Motors:

## Single Phase

Single phase induction motors are common in small (100W+) domestic applications such as central heating pumps, fridge compressors

## Three Phase

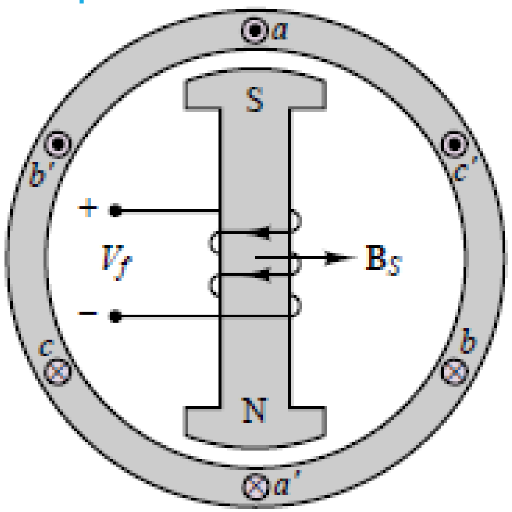
### Squirrel Cage Rotor

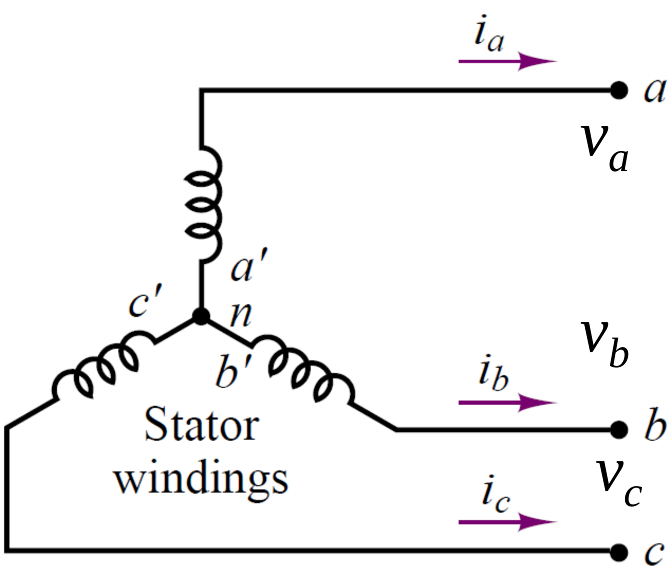
This is the ‘workhorse’ of industry. Sizes range from 1’s to 100’s of kW.

### Wound Rotor

These machines have copper windings on the rotor which are connected to external resistors or a Power Converter using brushes/sliprings. Typically BIG machines >200kW, also used in DFIG Generators

# ROTATING MAGNETIC FIELDS

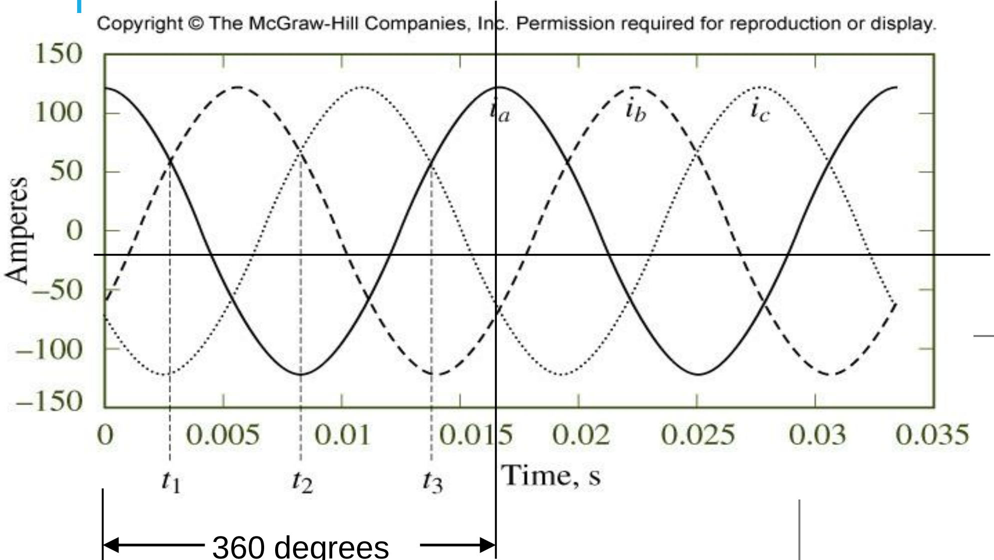



The fundamental principle of operation of AC machines is the generation of a rotating magnetic field, which causes the rotor to turn at a speed that depends on the speed of rotation of the magnetic field.

A rotating magnetic field can be generated in the stator and air gap of an AC machine by means of AC currents as follows: coil windings *a-a'*, *b-b'*, and *c-c'* are geometrically spaced 120° apart, and a three-phase voltage is applied to the coils, three-phase currents also spaced by 120°. The **direction of rotation** can be reversed by interchanging any two phase connection.

# 2-POLES, 3-PHASE ROTATING FIELD




$$\Phi_n = \int v_n dt$$

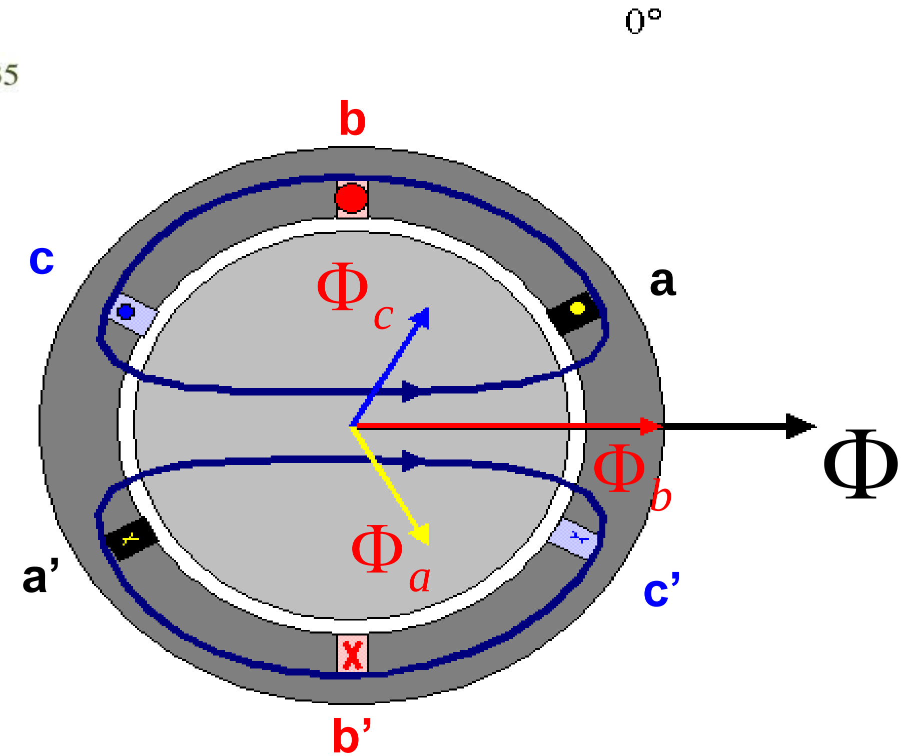
$$n = a, b, c$$

$$i_a(t) = I_m \cos(\omega t)$$

$$i_b(t) = I_m \cos\left(\omega t - 120^\circ\right)$$

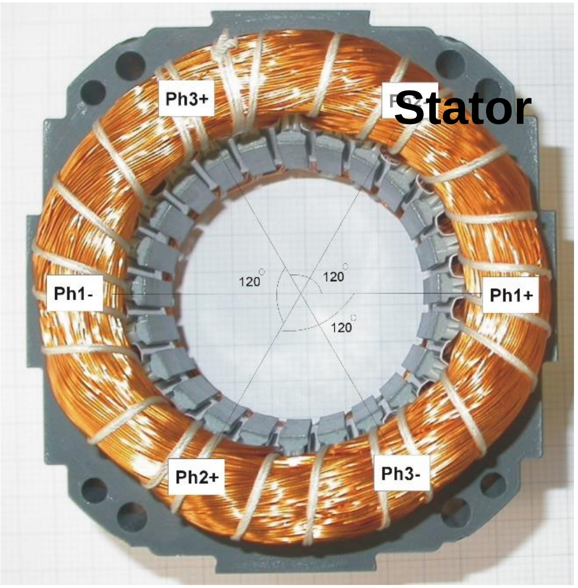
$$i_c(t) = I_m \cos\left(\omega t - 240^\circ\right)$$

where $\omega = 2\pi f$

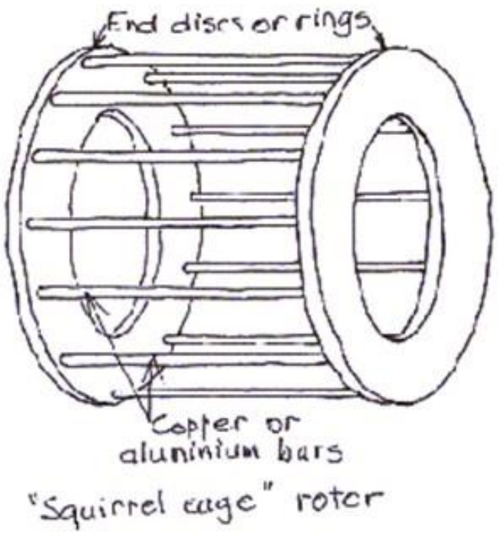


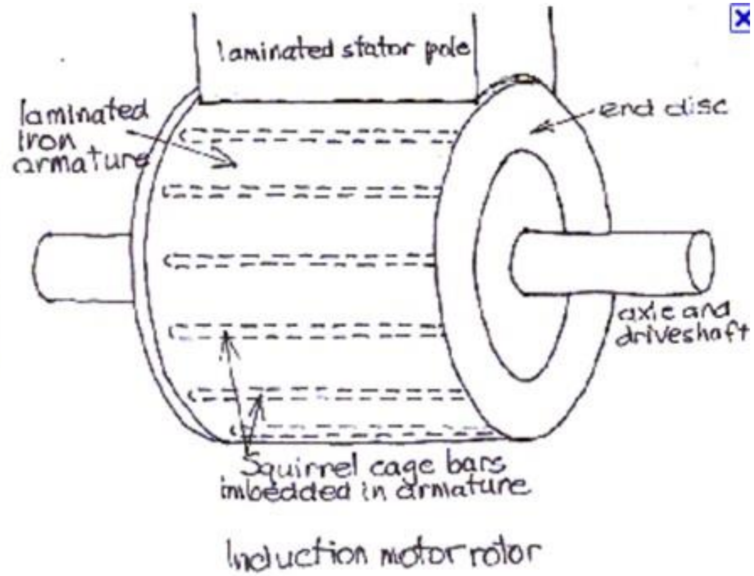

Rotating Airgap Flux

# 3 Phase Squirrel Cage Induction Motor

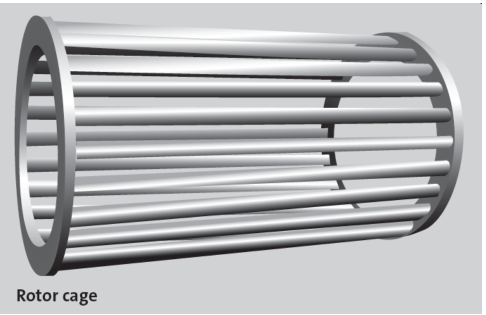


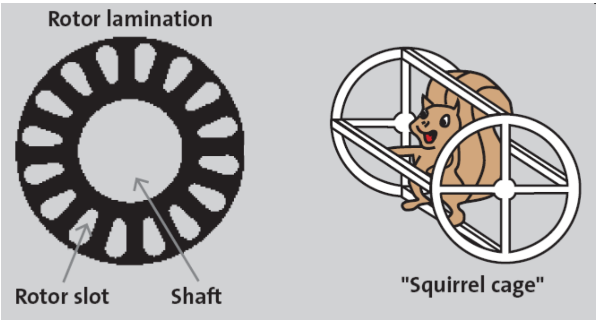

Rotor



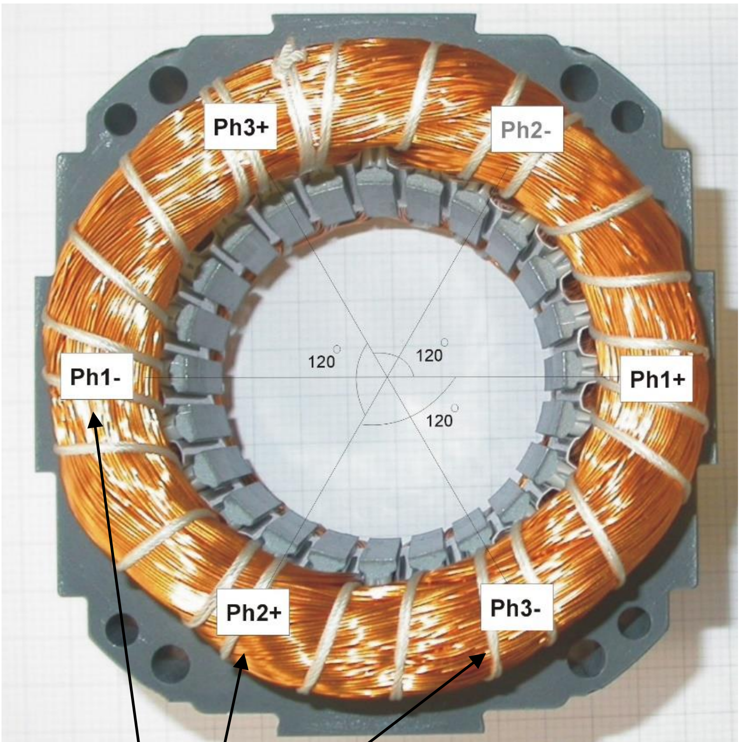



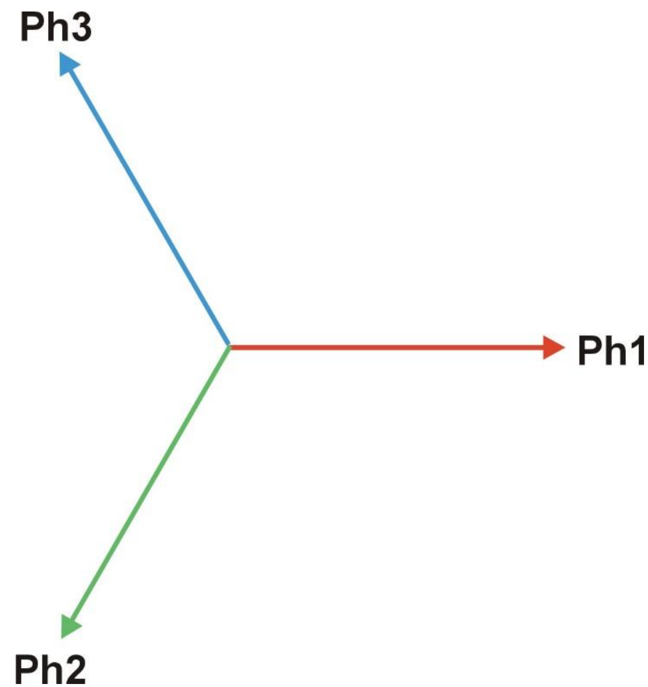

Rotor



## Stator Windings: Mechanical Orientation of 3 Phase Windings



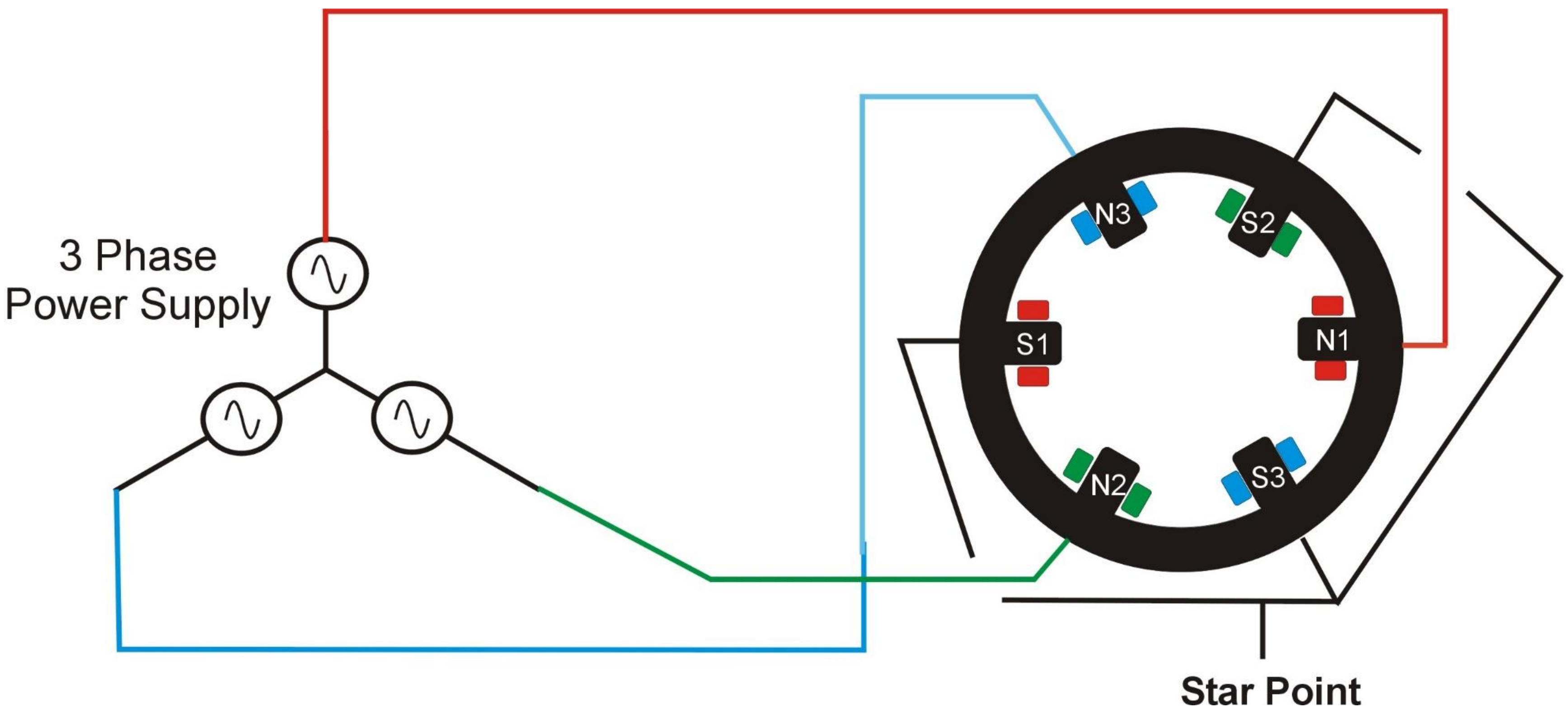




Centres of windings

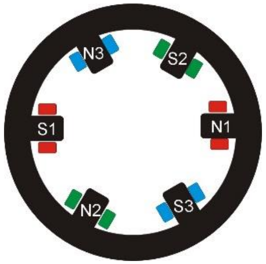
Mechanical orientation of the Three phase windings

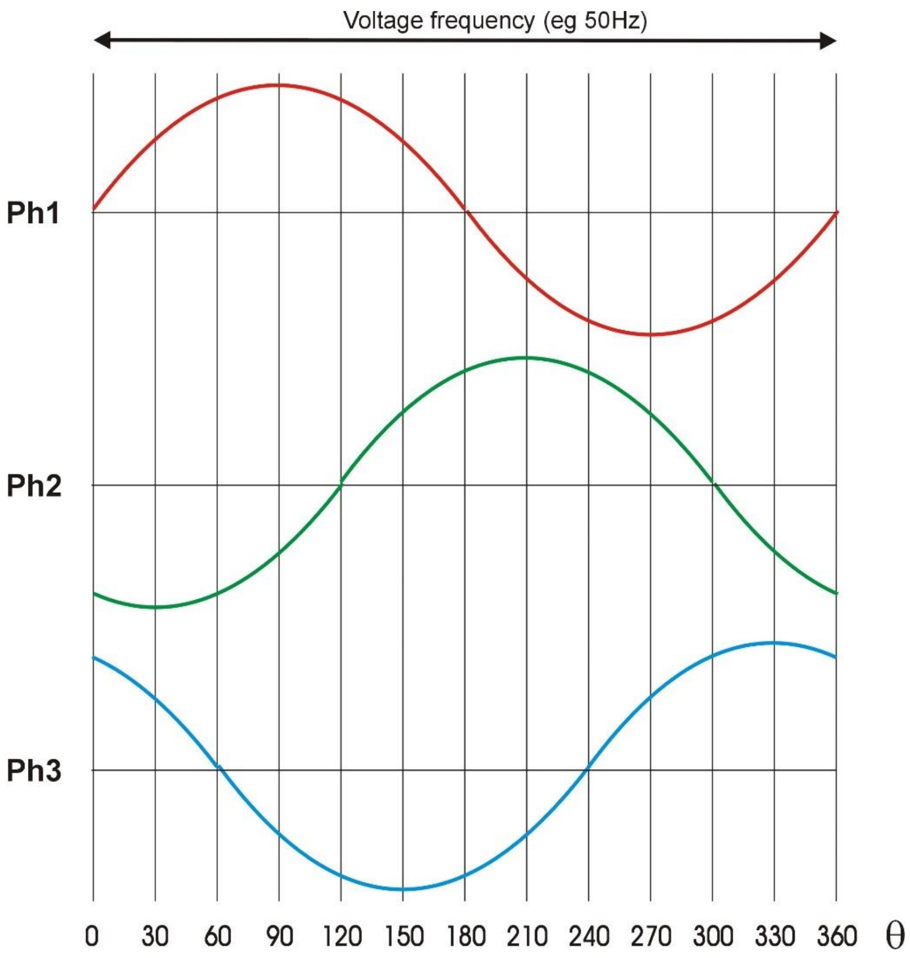
Note: I will use Green instead of Yellow to denote Phase 2 as it is easier to see on the slides

## Stator Windings: Star Connection to 3 Phase Power Supply

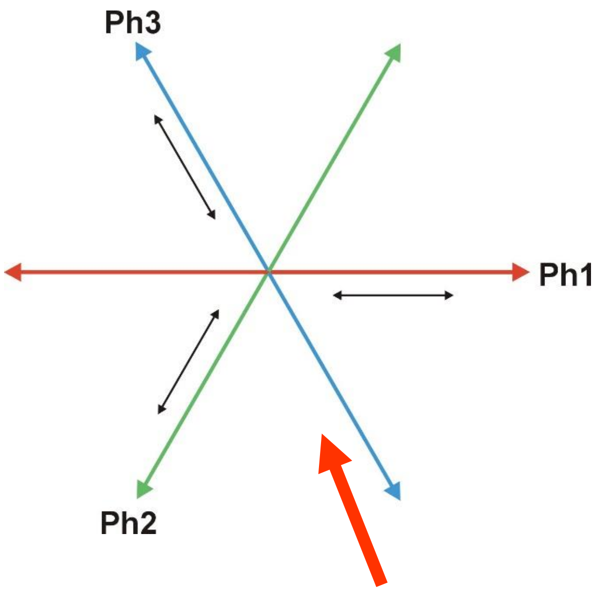


# Stator Windings: 3 Phase Voltages & Voltage Space Vectors

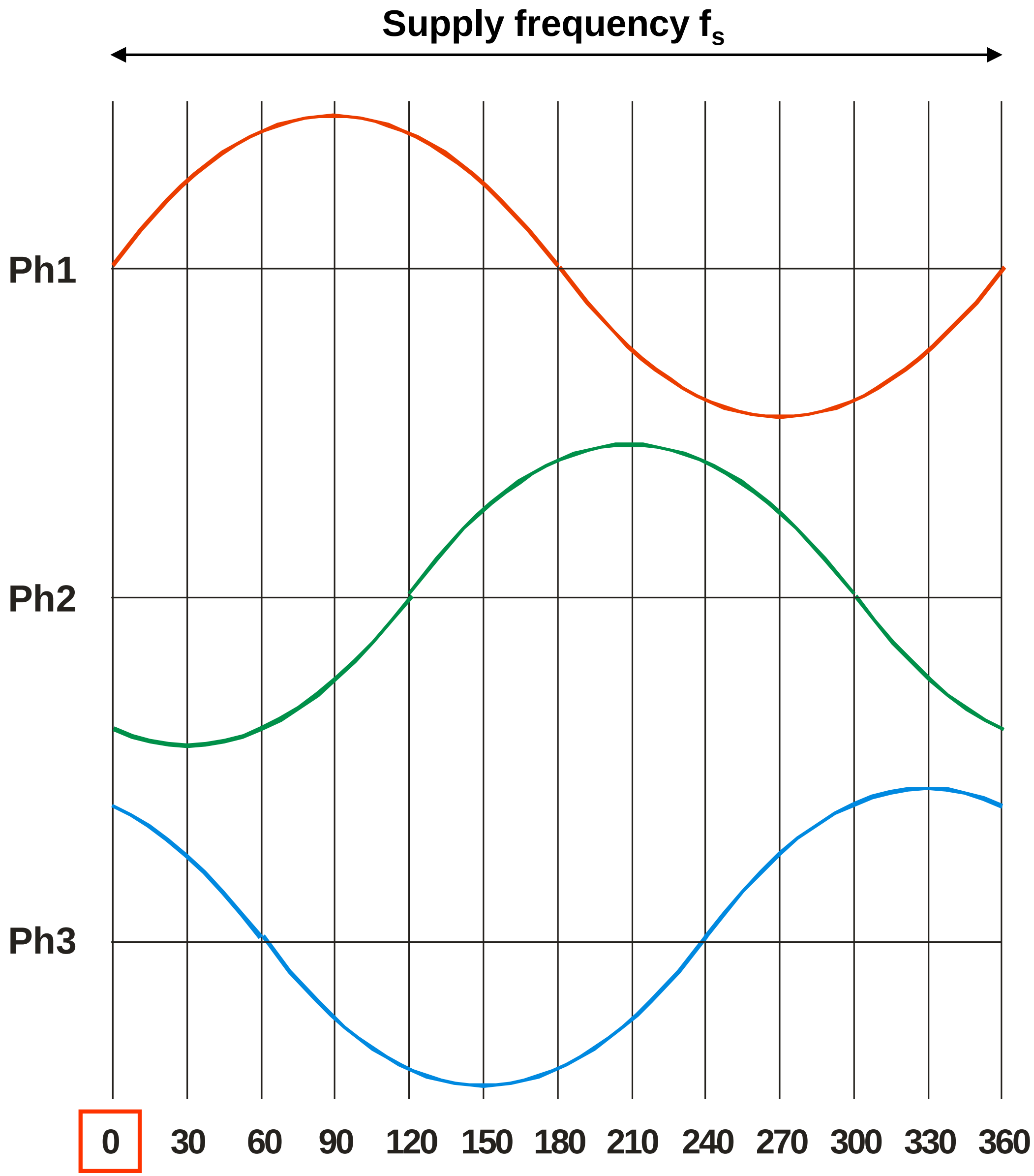



**Voltage Space Vectors:**




vectors fixed in space but magnitudes change wrt time due to sine functions

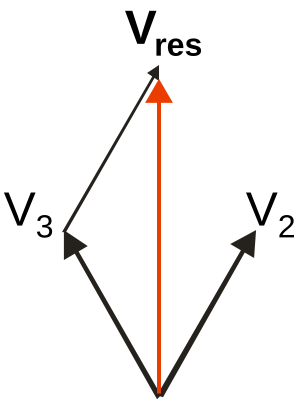


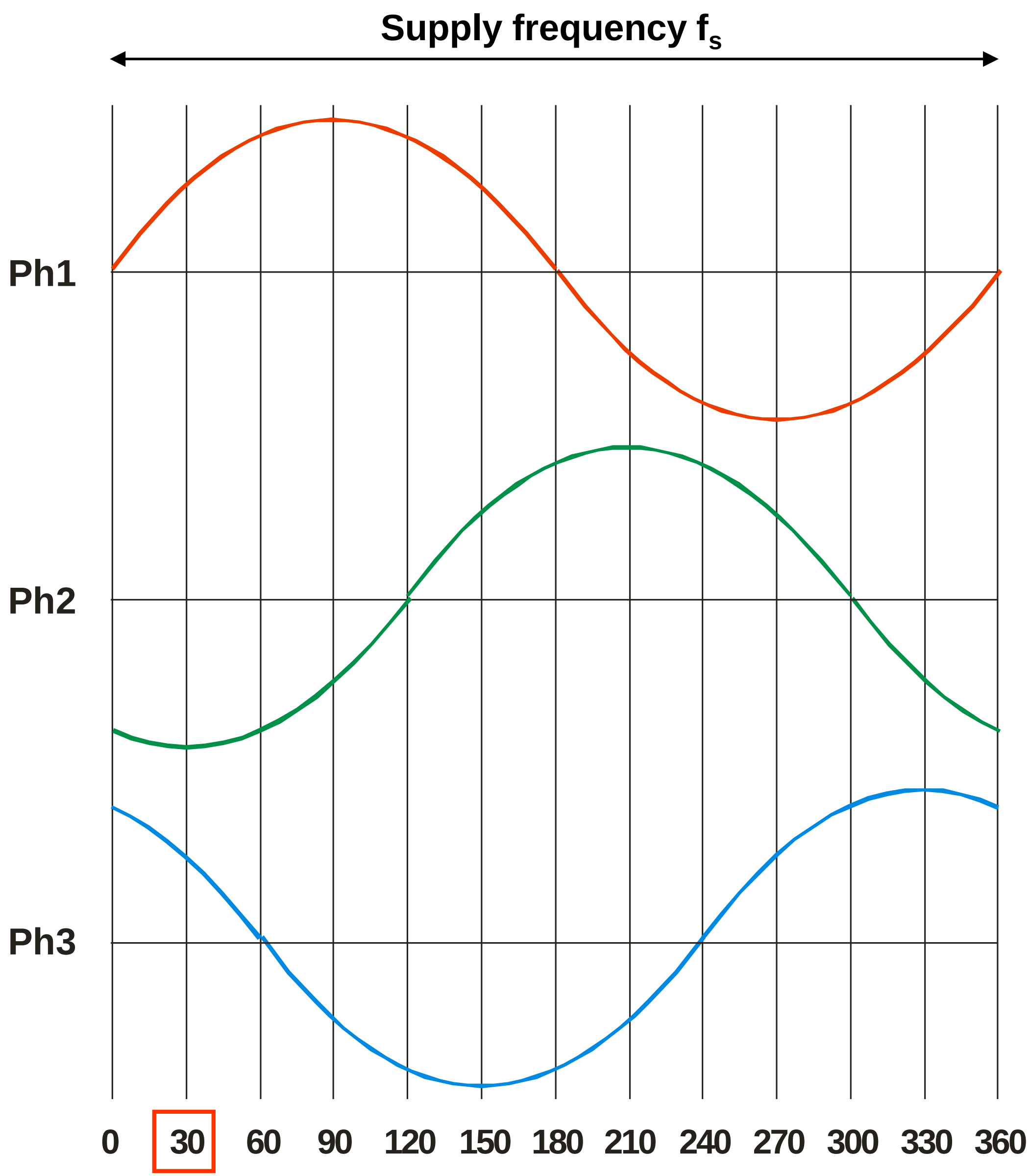

**Phase Voltages**

## 0 Deg:

| | | |
|---|---|---|
| Ph1 | $V_{pk}Sin0$ | 0 |
| Ph2 | $V_{pk}Sin240$ | -0.86 |
| Ph3 | $V_{pk}Sin120$ | 0.86 |

**assume $V_{pk}$=1**

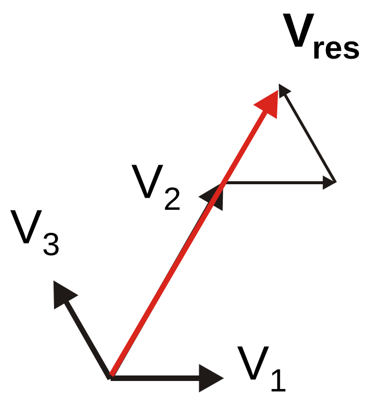


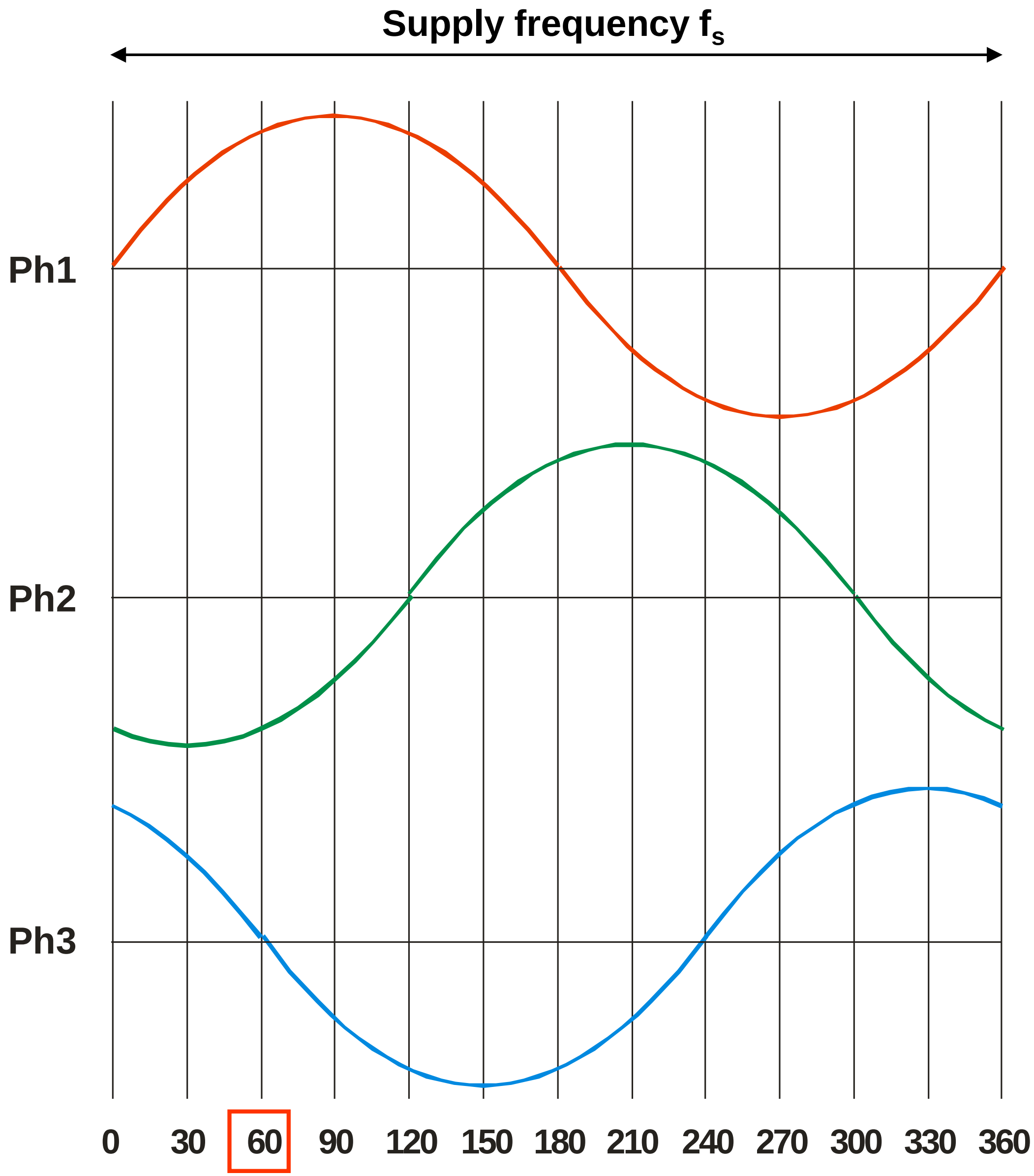



Phase Voltages

## 30 Deg:

| | | |
|---|---|---|
| Ph1 | $V_{pk}Sin30$ | 0.5 |
| Ph2 | $V_{pk}Sin270$ | -1 |
| Ph3 | $V_{pk}Sin150$ | 0.5 |

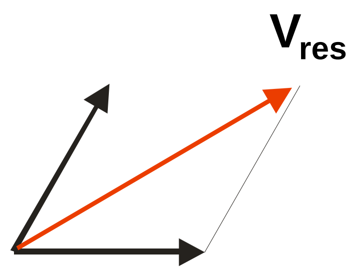


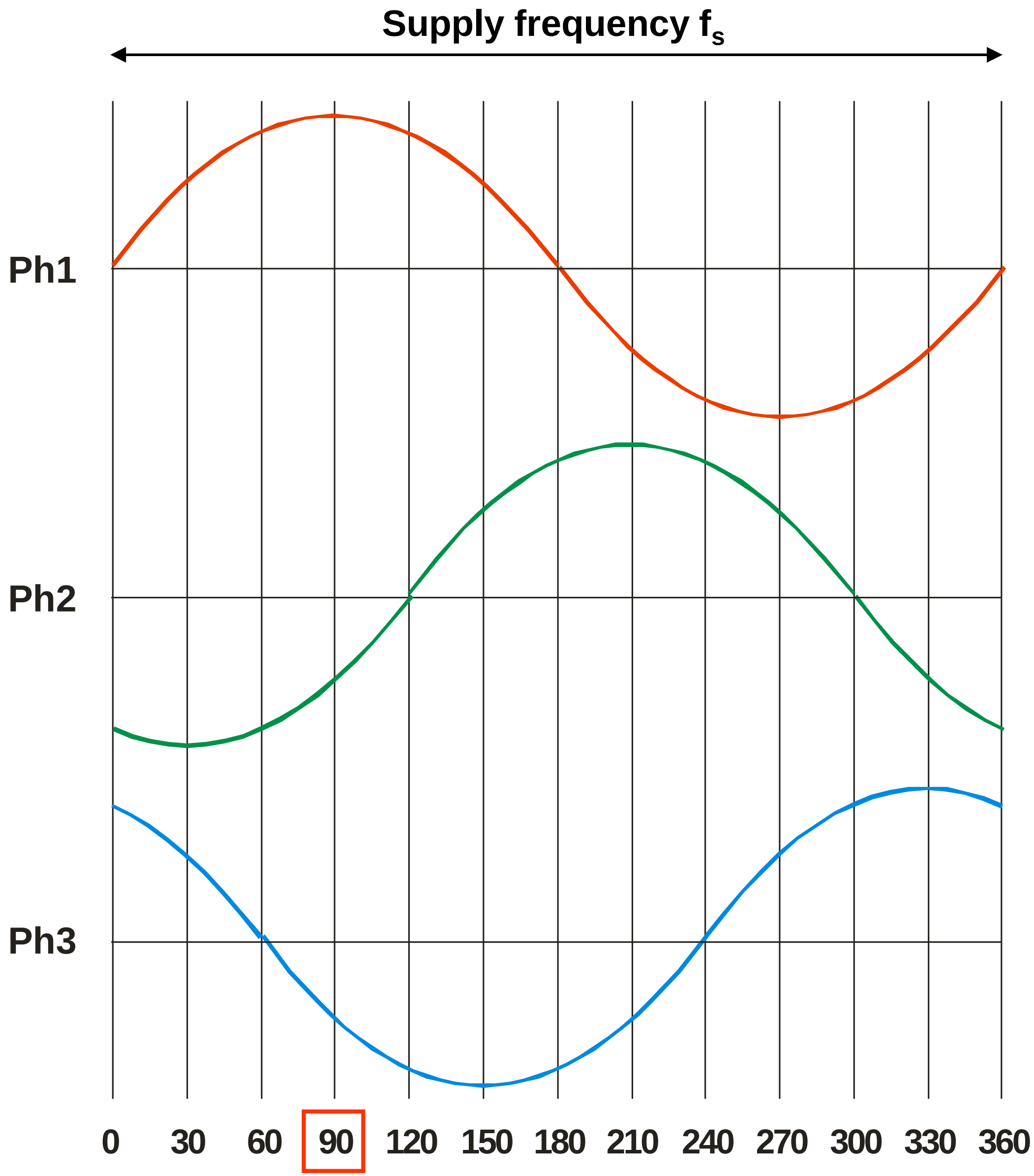



Phase Voltages

## 60 Deg:

| | | |
|---|---|---|
| Ph1 | $V_{pk}Sin60$ | 0.866 |
| Ph2 | $V_{pk}Sin300$ | -0.866 |
| Ph3 | $V_{pk}Sin180$ | 0 |

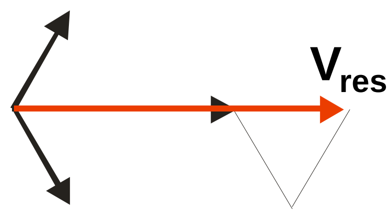





**Phase Voltages**

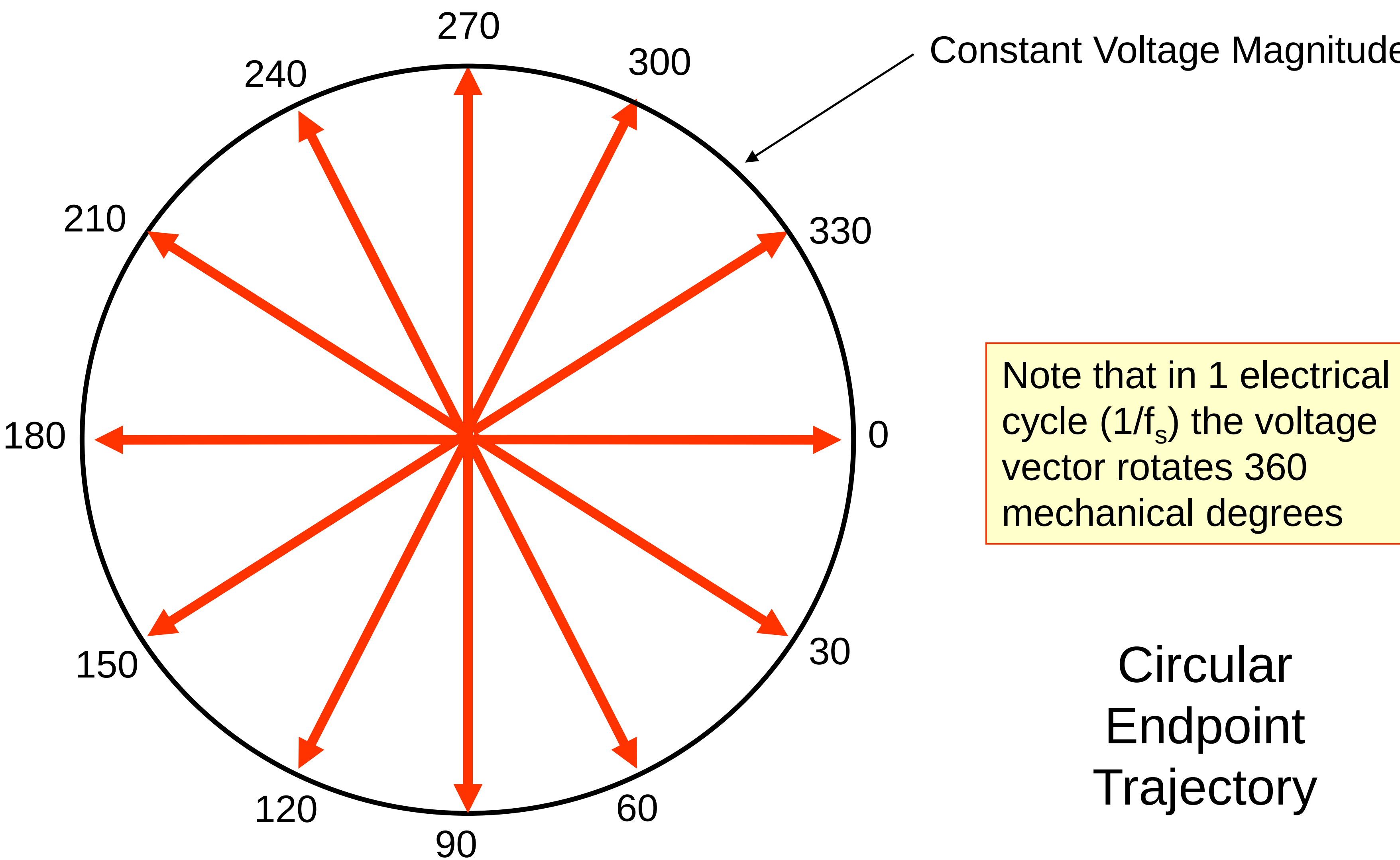
## 90 Deg:

| | | |
|---|---|---|
| Ph1 | $V_{pk}Sin90$ | 1 |
| Ph2 | $V_{pk}Sin330$ | -0.5 |
| Ph3 | $V_{pk}Sin210$ | -0.5 |




**Note: 90° rotation In SPACE!**
**(same resultant magnitude)**

# Resultant Voltage SPACE Vector



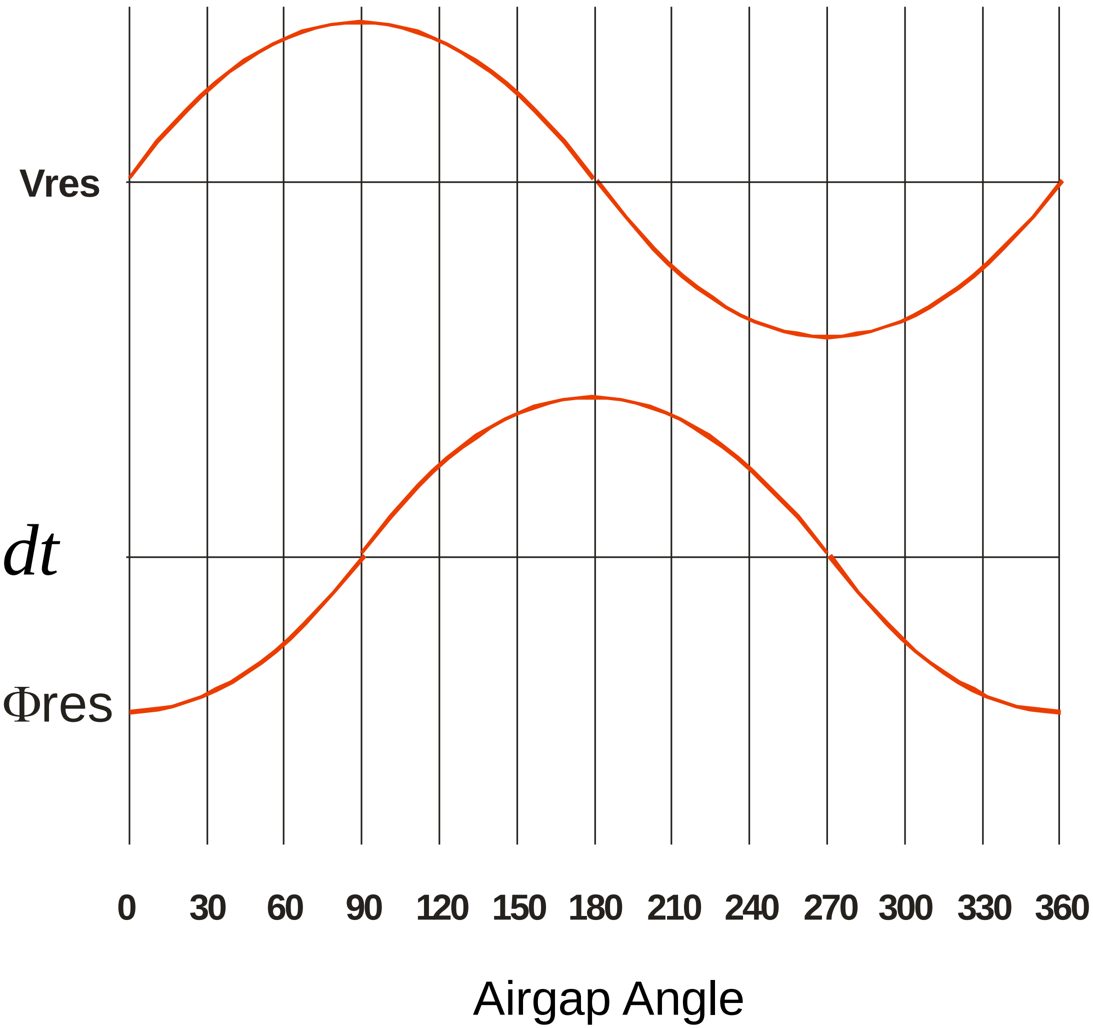

Note that in 1 electrical cycle ($1/f_s$) the voltage vector rotates 360 mechanical degrees

Circular Endpoint Trajectory

# Resultant Airgap Flux

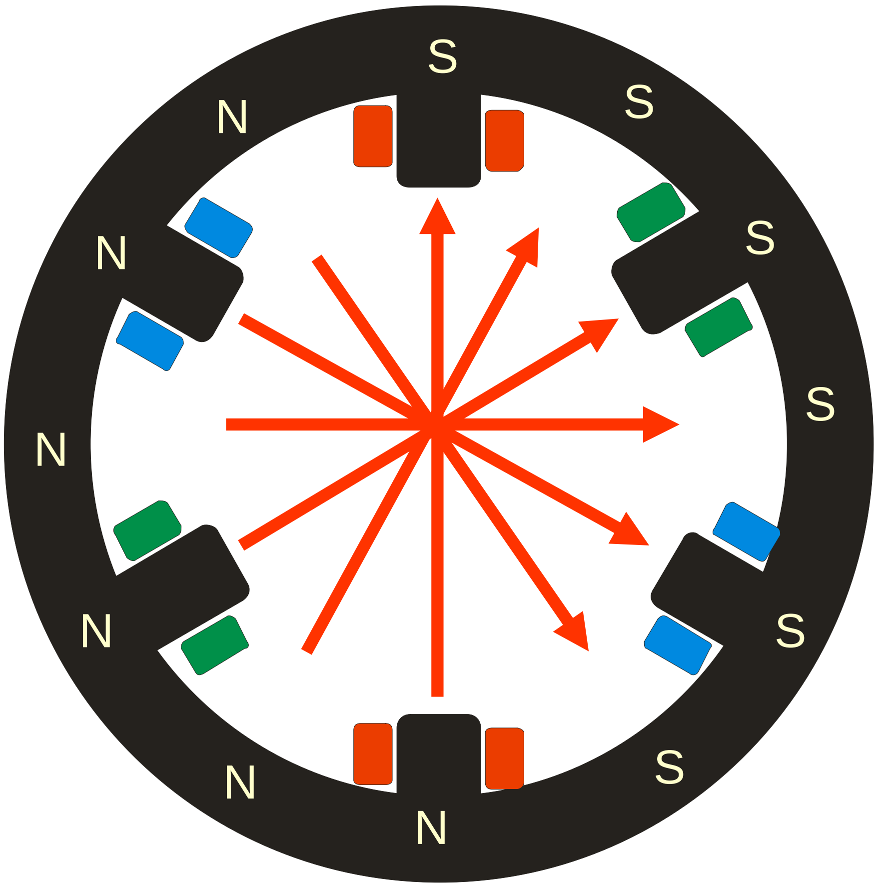

**At a particular point in time**

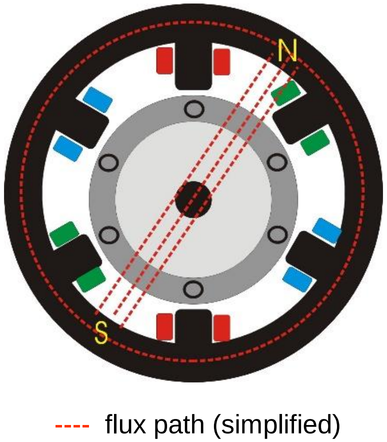
$$\Phi = \int v.dt$$




Note: Sinusoidal Flux distribution
In the airgap

# Resultant Magnetic Flux Rotation

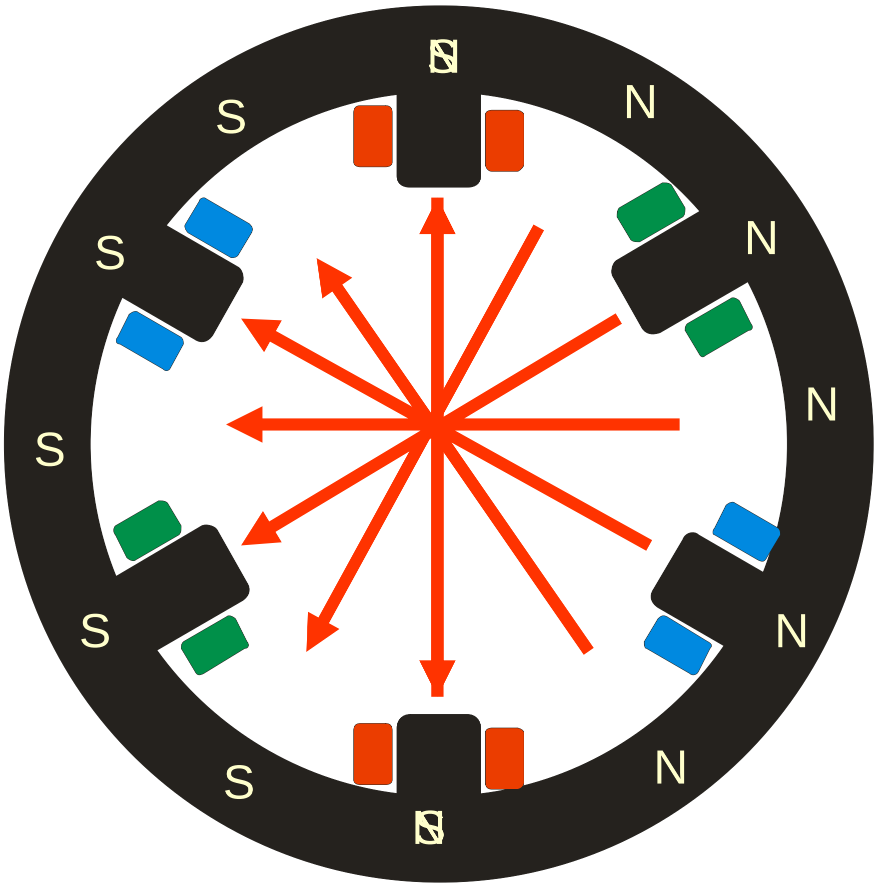


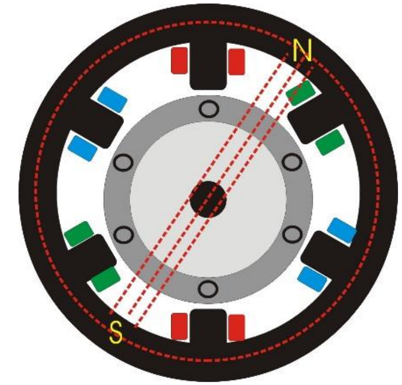




The Magnetic Flux rotates 1 mechanical revolution for 1 period of $f_s$ – this is called the **SYNCHRONOUS SPEED**

Note: this is for a 2 pole machine – see next slide for higher pole number machines

# Resultant Magnetic Flux Rotation




---- flux path (simplified)

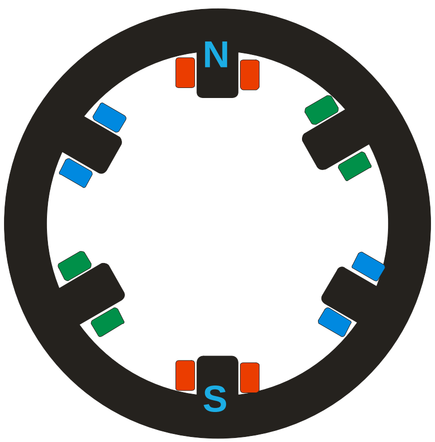
The Magnetic Flux rotates 1 mechanical revolution for 1 period of $f_s$ – this is called the **SYNCHRONOUS SPEED**

Note: this is for a 2 pole machine – see next slide for higher pole number machines

$$\boxed{N_s = 60\, f_s / \left(P/2\right) \quad rpm}$$

# Relationship between Power Supply Frequency ($f_s$), Machine Pole Number (P) & Synchronous Speed ($N_s$)

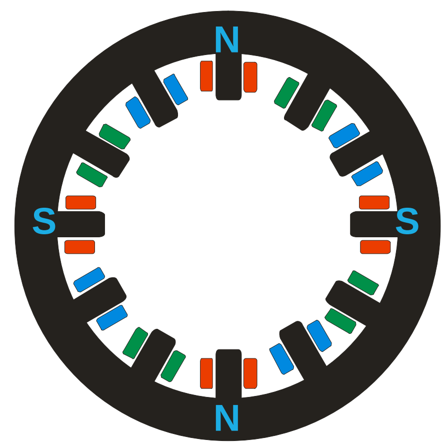
2 Pole Machine (P = 2)




$N_S$ (rpm) = 60 x $f_s$

$$\mathbf{N_S\ (rpm) = \frac{120 \times f_s}{P}}$$

4 Pole Machine (P = 4)

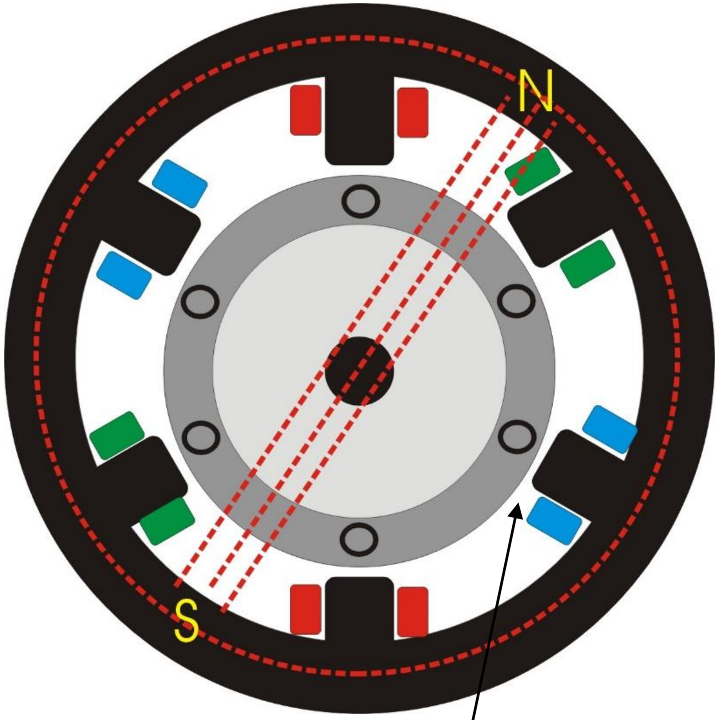



$N_S$ (rpm) = $\frac{60}{2}$ x $f_s$

$$\mathbf{N_S\ (rpm) = \frac{120 \times f_s}{P}}$$

Note: 6 pole machines are common as well

# The story so far:




motor airgap

- The three phase voltages input to the three phase windings produces rotating stator flux in the motor airgap

- The stator flux rotates at SYNCHRONOUS SPEED (rpm) which is set by the supply frequency and the number of poles

In the next lecture we will investigate how currents induced in the rotor cage produce rotor flux which then interacts with the stator flux in the airgap. This results in **rotor torque and mechanical rotation**