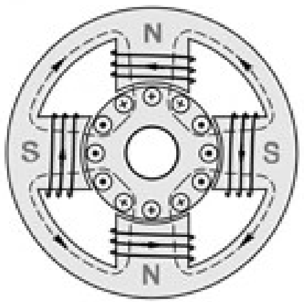
Lecture CM7:
SPECIAL TYPES OF AC DRIVES

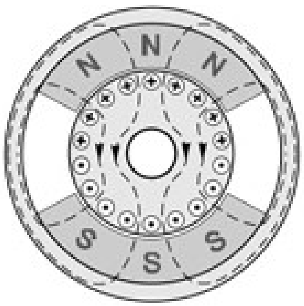
Synchronous Drives.
Servo Drives.
Stepper-Motor Drives.

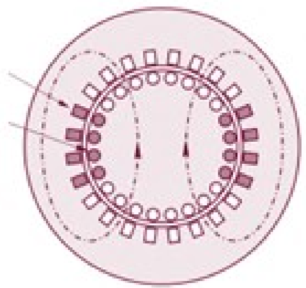
Rotating Electrical Machines

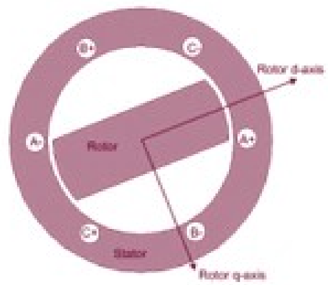
Electrical Machines

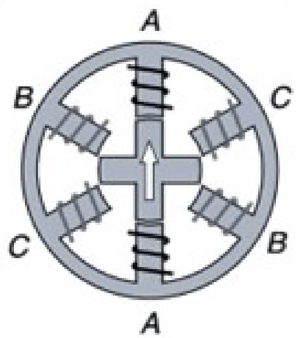
DC Machines		AC Machines		Special Machines
Field Winding	Permanent Magnet	Induction	Synchronous	Step Motor











Synchronous Machines

- As the name suggests the synchronous motors rotates only at synchronous speed.
- The main advantage of synchronous motor is when it run on synchronous speed the loss is very minimal.
- Power Factor of synchronous motor can be varied by varying excitation (field) current flow.
- The synchronous motors are designed to run only at rated synchronous speeds.
- With a help of synchronous motor drives starting, pull in, braking and speed control of synchroneus motors is possible.

Synchronous Machines

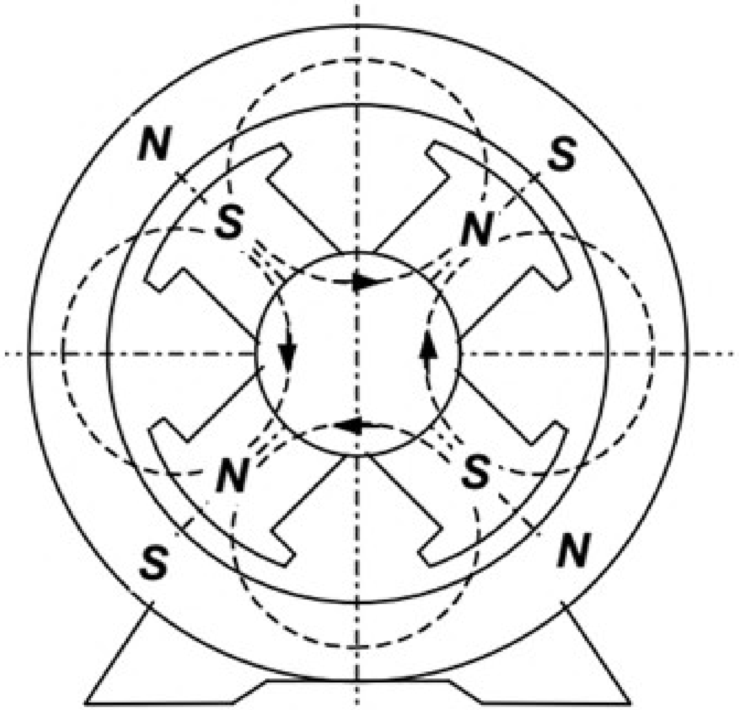
- In the synchronous motor, the stator windings are exactly the same as in the induction motor, so when connected to the 3-phase AC supply, a rotating magnetic field is produced.

$$n_0 = n_2 = \frac{60 \cdot f_1}{2p}\ [\text{min}^{-1}];[\text{rpm}]$$

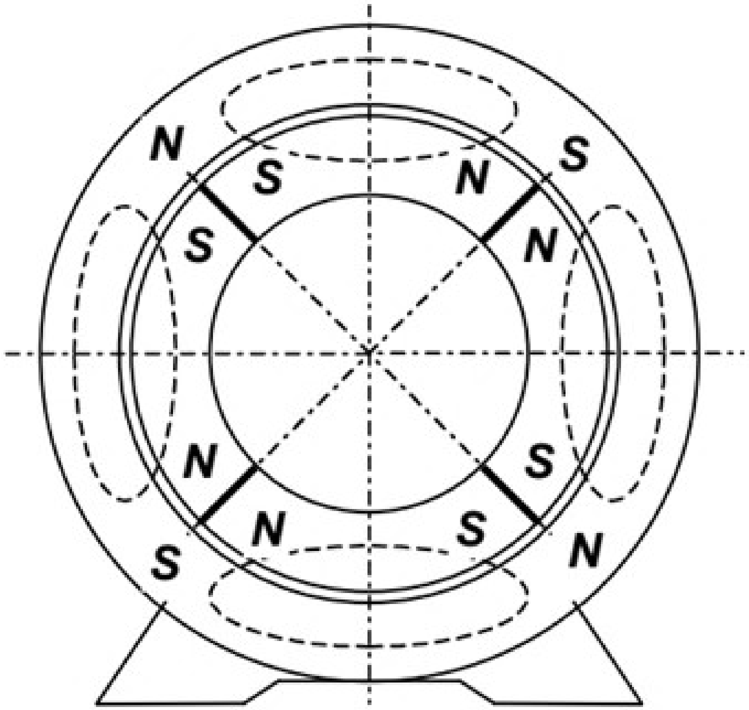
where
n_0 - synchroneus speed of stator magnet flux;
n_2 - rotor speed;
f_1 - input frequency of stator winding;
$2p$ – pole pairs;

Synchronous Machines

- Rotors of synchronous machine are classified as:



Salient pole rotor



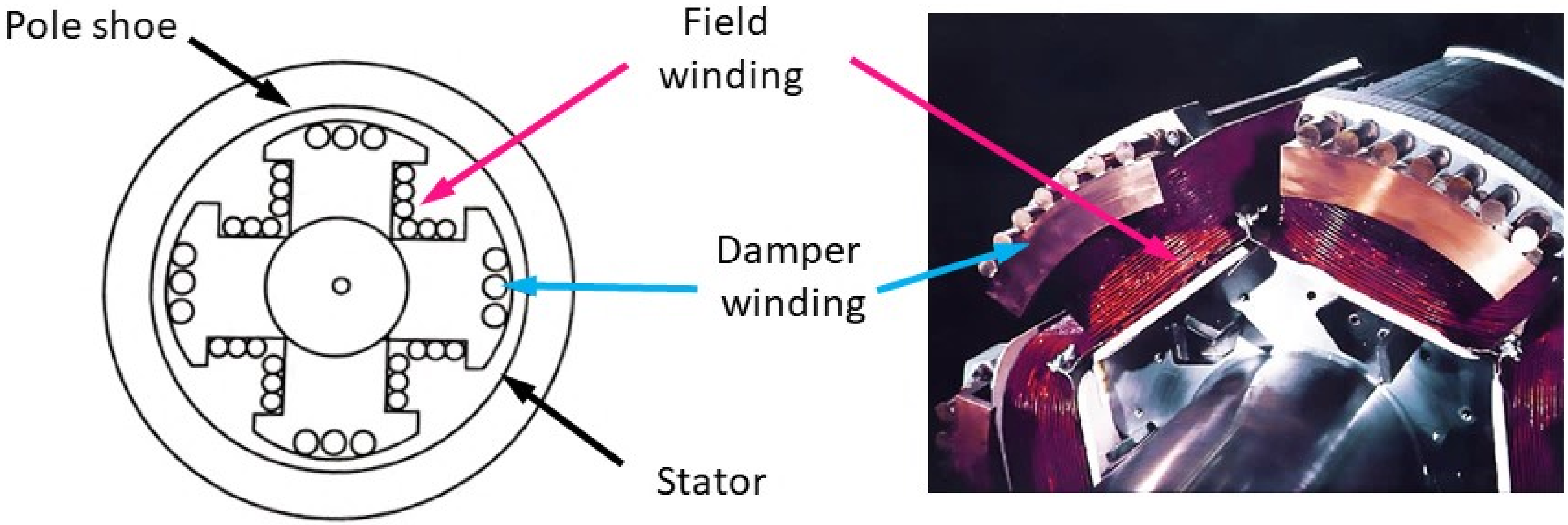
Non-salient pole rotor

Synchronous Machines

- **Salient pole** type of rotor consist of large number of projected poles (salient poles) mounted on a magnetic wheel.
  - ✓ The projected poles are made up from laminations of steel.
  - ✓ The rotor winding is provided on the poles and supported by pole shoes.
- Salient pole rotors have large diameter and shorter axial length.
- Salient pole rotors are generally used in lower speed electrical machines (100 rpm to 1500 rpm).
  - ✓ As the rotor speed is low, more number of poles are required to attain the required frequency.
  - ✓ Typically number of salient poles is between 4 to 60.
- Salient pole rotors generally need **damper windings** to prevent rotor oscillations (hunting) during operation.
- Salient pole synchronous generators are mostly used in hydro power plants.

Synchronous Machines

- **Damper winding** is a short-circuited squirrel-cage winding placed in the pole faces and around the pole shoes of synchronous machines.
- The currents induced in the winding by the periodic variations in synchronous speed having the effect of a damper.



Synchronous Machines

- Non-salient pole rotors are cylindrical in shape having parallel slots on it to place rotor windings.
- Non-salient pole rotors are smaller in diameter but having longer axial length.
- Non-salient pole rotors are used in high speed electrical machines (1500 rpm to 3000 rpm).
- Number of poles of cylindrical rotors is usually 2 or 4.
- Damper windings are not needed in non-salient pole rotors.
- Flux distribution is sinusoidal and hence gives better emf waveform.

- Non-salient pole rotors are used in nuclear, gas and thermal power plants.

Synchronous Machines

- Non-salient pole rotors construction is robust as compared to salient pole rotors.
- Flux distribution of salient pole rotors is relatively poor than non-salient pole rotor, hence the generated emf waveform is not as good as cylindrical (non-salient pole) rotor.
- Windage loss as well as noise of non-salient pole rotor is less as compared to salient pole rotors.

Synchronous Machines

- **Synchronous motor** has a rotor with either a DC excited winding or permanent magnets.

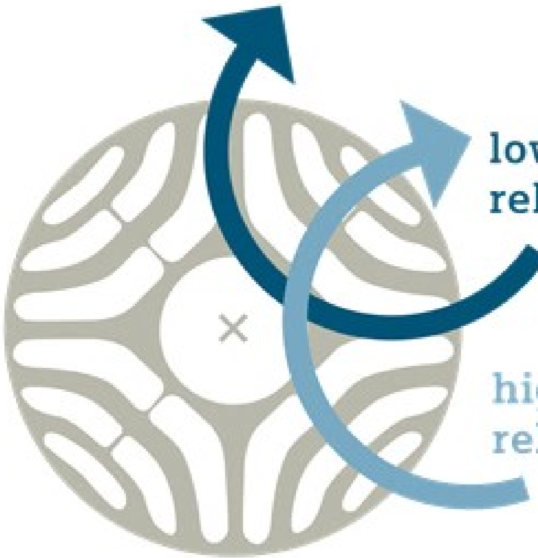
- A **reluctance motor** is a type of electric motor that induces non-permanent magnetic poles on the ferromagnetic rotor.
  - ✓ The rotor of reluctance motor does not have any windings.
  - ✓ The rotor of reluctance motor generates torque through magnetic reluctance.

- **Synchronous reluctance motors** are a step forward compared to permanent magnet motors when the cost of the system is considered.
  - ✓ The rotor of synchronous reluctance motor operates at synchronous speeds **without current-conducting parts.**

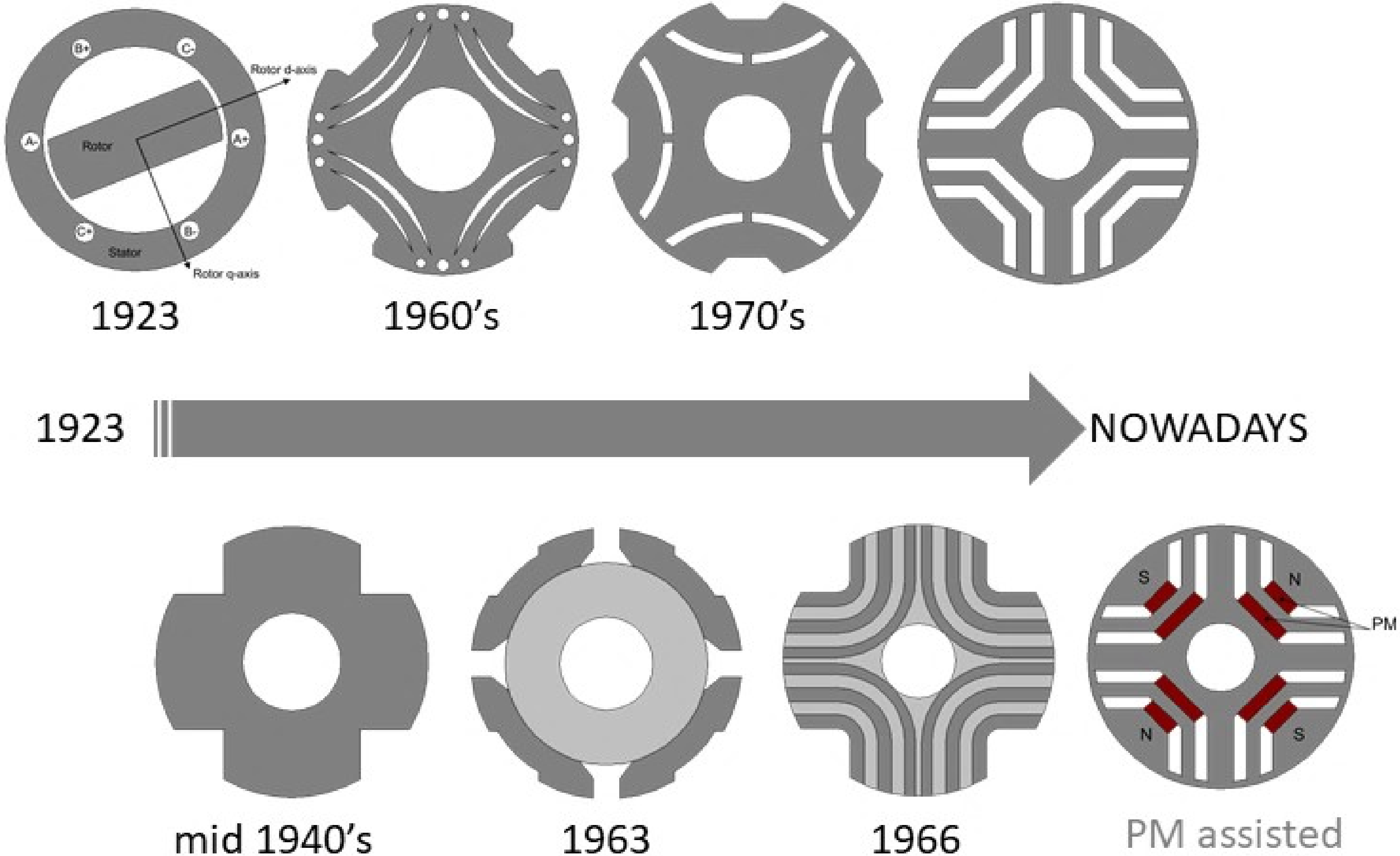
Synchronous Machines

- Reluctance motors operate according to the principle of **magnetic reluctance**.

- The rotor consisting of air and iron has the **least possible magnetic reluctance** in one direction and the **highest possible reluctance** in the direction perpendicular to that.
  - ✓ Because the system always moves toward the lowest magnetic reluctance, rotational movement results.



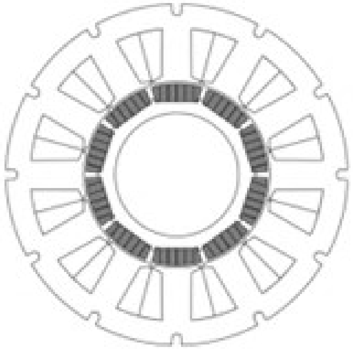
Synchronous Machines



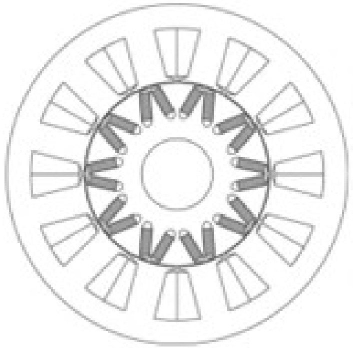
Evolution of Synchronous Reluctance Machine (SynRM)

Synchronous Machines

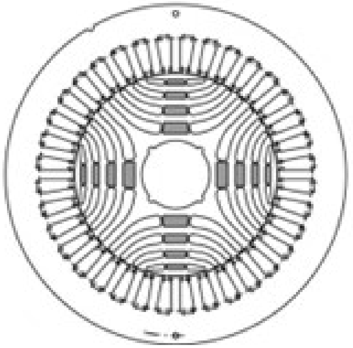
- Thanks to the maximized reluctance torque contribution, PM assisted synchronous reluctance machines (PMSynRMs) can use reduced quantity of rare-earth magnets for the same performance



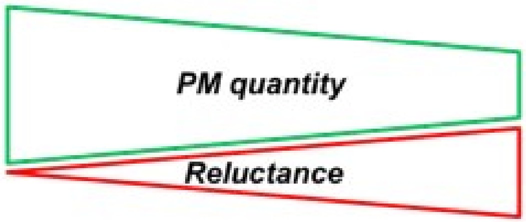
concentrated windings
SPM machine



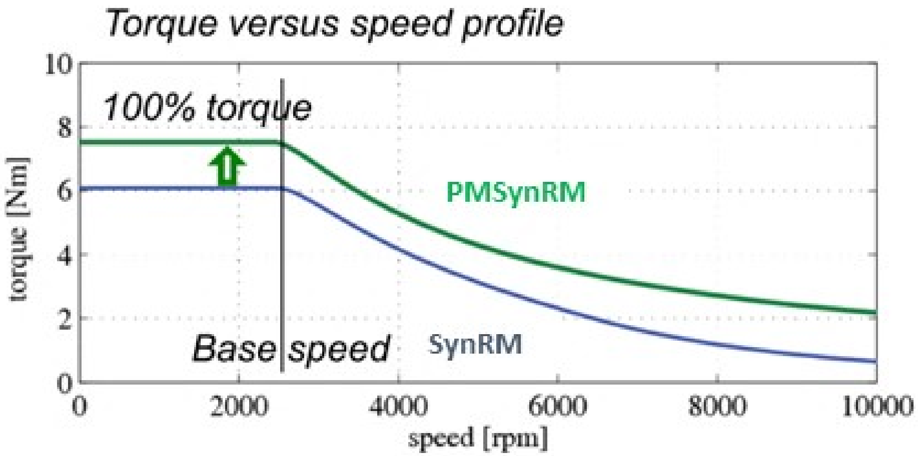
concentrated windings
IPM machine

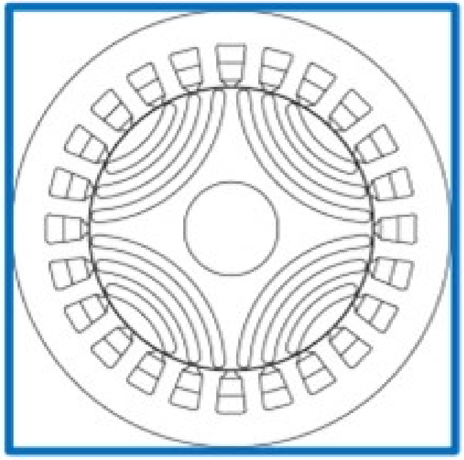


PMSynRM

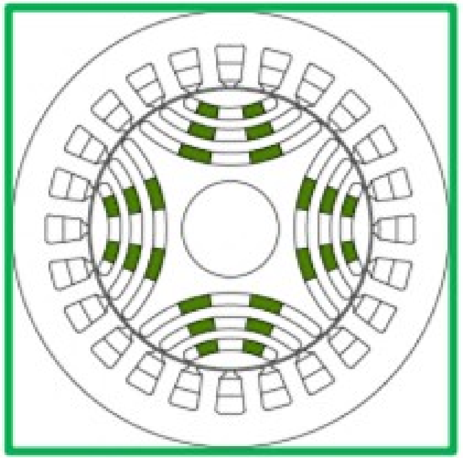


Synchronous Machines

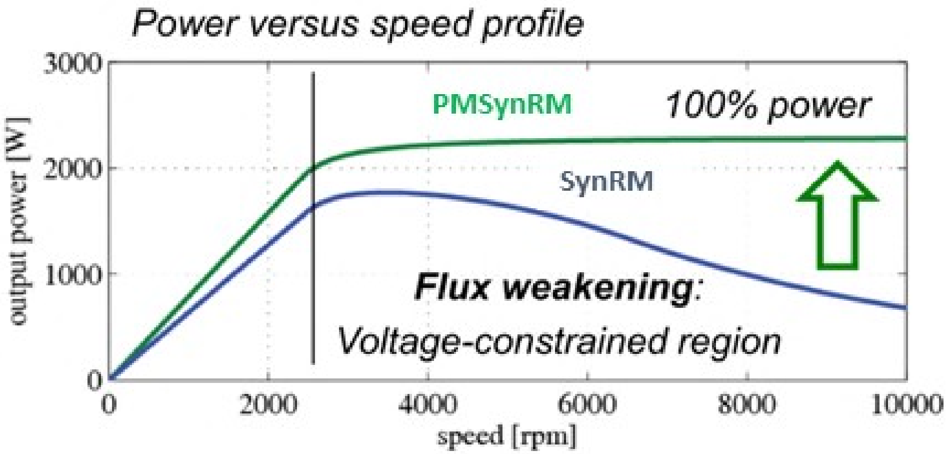




SynRM

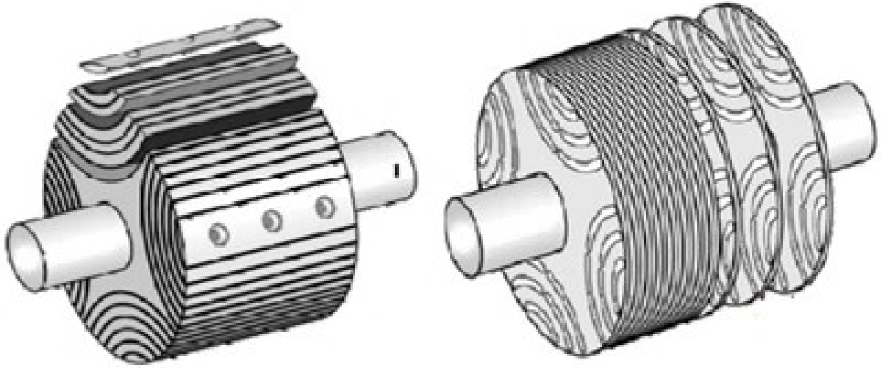


PMSynRM



Synchronous Machine

- **Synchronous reluctance** technology combines the performance of the permanent magnet motor with the simplicity and service-friendliness of an induction motor.
- The rotor has neither magnets nor windings and suffers virtually no power losses.
- Because there are no magnetic forces in the rotor, maintenance is as straightforward as with induction motors.



Starting Synchronous Motors

- Synchronous motors are **not self-starting** motors due to the inertia of the rotor; it cannot instantly follow the rotation of the magnetic field of the stator.

- In case the synchronous motor equiped with damper winding, it can be started as a scuirrle cage induction motor:
  - ✓ at start the rotor of the motor is not given DC supply,
  - ✓ when the motor reaches near synchronous speed pull in takes place.

- Synchronous motor can be started by external motor:
  - ✓ the rotor of the synchronous motor is rotated by an external motor and when the speed of the rotor reaches near synchronous speed, the DC-field is switched on and pull in takes place.
- In case of starting with external motor, the starting torque is very low and this method is not very popular.

Starting Synchronous Motors

- When the rotor of the synchronous motors reaches near synchronous speed, then the DC field supply is switched on and the **pull in process** begins.
  - ✓ As during switching on the DC supply due to the phase angle and torque angle there are various disturbances seen in the motor and there are several slip of poles of air-gap flux is also seen.
  - ✓ As the pull in process is completed the rotor acquires synchronous speed.

- The complete pull in as fast as possible the DC supply should be switched on at the most favorable angle.
  - ✓ Like when the synchronous motor is running as induction motor, the DC supply should be fed when the induction motor is at top speed, this will be the best moment because the speed difference will be least at that point of time.

Braking of Synchronous Motors

- **Dynamic braking** is done by disconnecting the synchronous motor from supply and connecting it across a three phase resistor.
  - ✓ At that time the motor works as a synchronous generator and energy is dissipated at the resistors.

- **Plugging braking** is **not used** for synchronous motors as high plugging current can cause severe disturbance and damage in line.

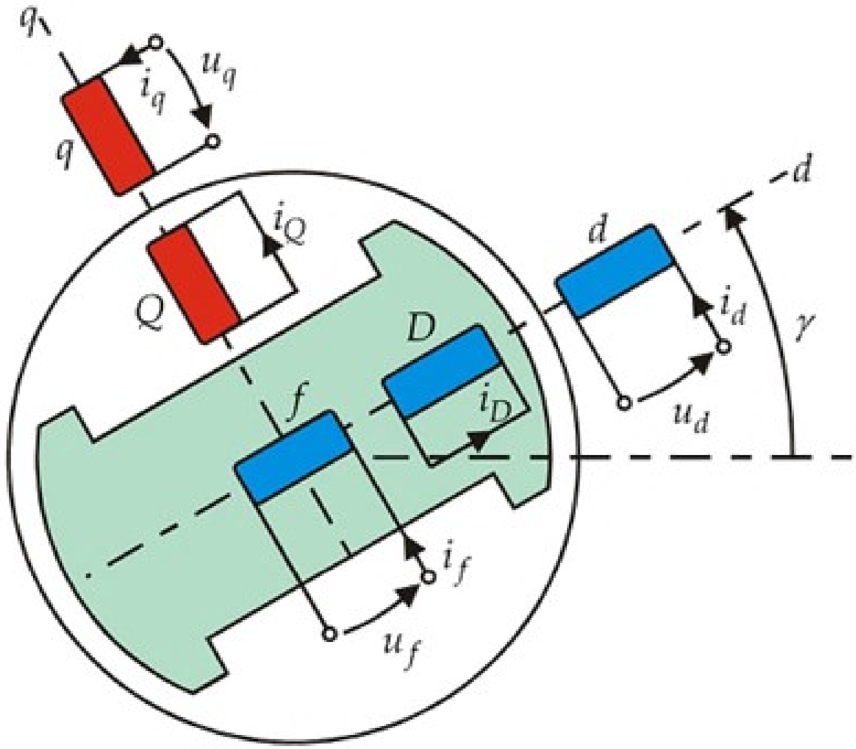
- **Regenerative braking** **cannot be applied** to synchronous motors as they need higher speed than synchronous speed.

Speed Control of Synchronous Motor

- The **synchronous speed** depends on the **frequency of the supply** and **the number of poles** of the rotor.
- Changing the number of poles is not easy, so that method hard to implement.
- Synchronous motors are usually supplied by variable speed drives and speed control is very similar to induction motors.

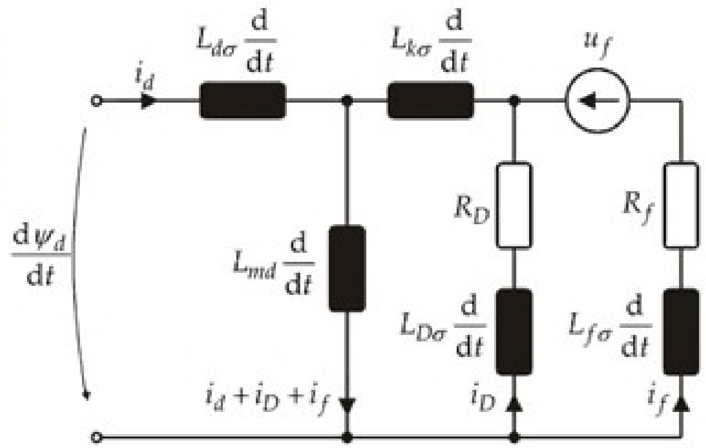
Equivalent Circuit of Synchronous Machine

- Two axis model
- Direct axis (d-axis) along the magnetic axis of the field winding
- Quadratic axis (q-axis) 90° counter clockwise from the d-axis
- **No coupling between the two axis!**

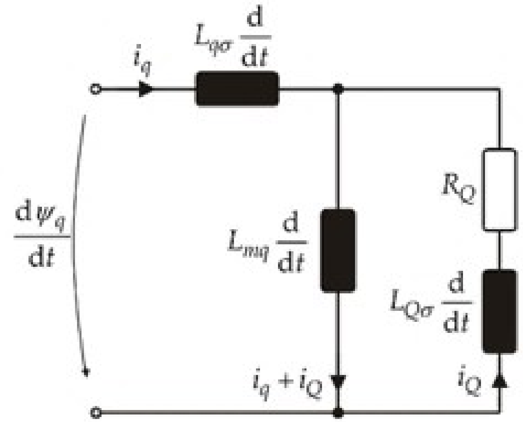


Equivalent Circuit of Synchronous Machine

$$\begin{cases} u_d = R_s i_d - \omega \psi_q + L_{d\sigma} \dfrac{\mathrm{d}i_d}{\mathrm{d}t} + L_{md} \dfrac{\mathrm{d}}{\mathrm{d}t}\left(i_d + i_f + i_D\right) \\ u_f = R_f i_f + L_{f\sigma} \dfrac{\mathrm{d}i_f}{\mathrm{d}t} + L_{md} \dfrac{\mathrm{d}}{\mathrm{d}t}\left(i_d + i_f + i_D\right) \\ 0 = R_D i_D + L_{D\sigma} \dfrac{\mathrm{d}i_D}{\mathrm{d}t} + L_{md} \dfrac{\mathrm{d}}{\mathrm{d}t}\left(i_d + i_f + i_D\right) \end{cases}$$

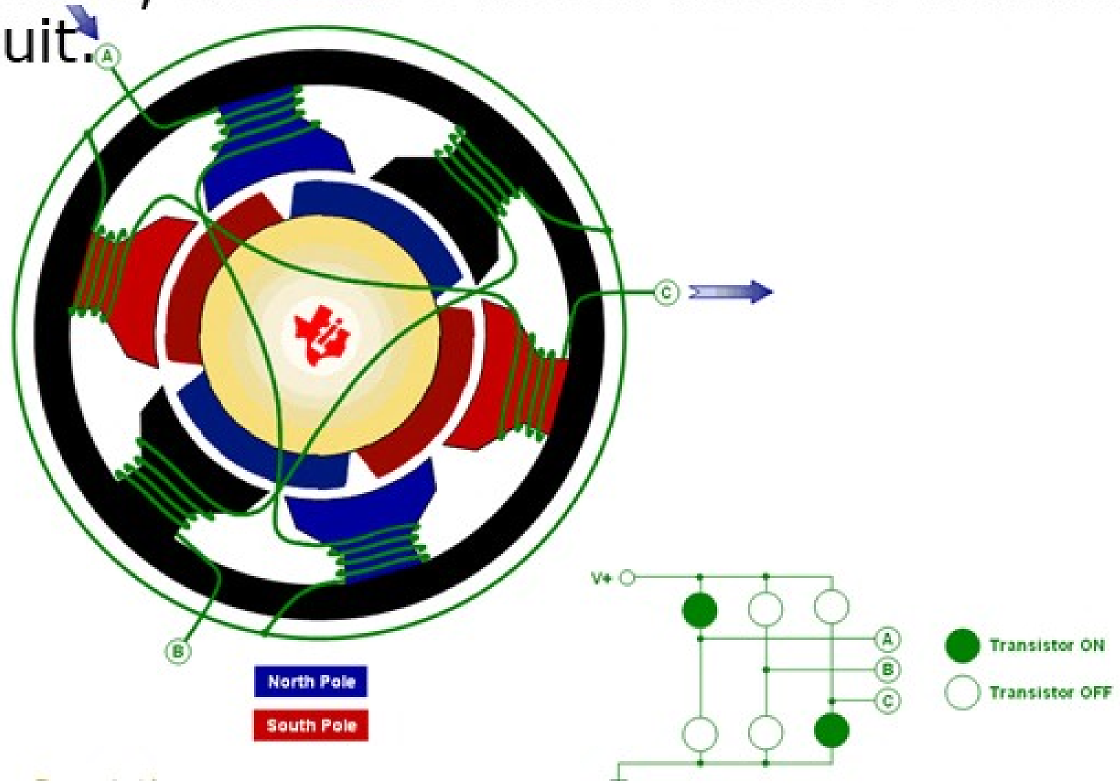


$$\begin{cases} u_q = R_s i_q + \omega \psi_d + L_{q\sigma} \dfrac{\mathrm{d}i_q}{\mathrm{d}t} + L_{mq} \dfrac{\mathrm{d}}{\mathrm{d}t}\left(i_q + i_Q\right) \\ 0 = R_Q i_Q + L_{Q\sigma} \dfrac{\mathrm{d}i_Q}{\mathrm{d}t} + L_{mq} \dfrac{\mathrm{d}}{\mathrm{d}t}\left(i_q + i_Q\right) \end{cases}$$



Brushless DC Motors (BLDC)

- In principle, there is no difference between a brushless DC motor (BLDC) and the self-synchronous permanent magnet motors.
- BLDC replaces the mechanical commutator with electronic commutator, just because of the electronic commutator, the BLDC motor needs a controller to drive the circuit.



Brushless DC Motors (BLDC)

- BLDC motor not only has linear speed regulation performance as the DC motor, but also has the advantages of simple structure, no commutation spark, reliable operation and easy maintenance as the AC motor.
- BLDC is widely used in industrial equipment, instrumentation, household appliances, robots, medical equipment and other fields.
- The commutation circuit of BLDC motor consists of two indispensable parts: drive and control.
- Particularly, the two parts are integrated into a single drive for low power circuit.

Control of BLDC Motors

- **Square-wave control** of BLDC motor uses Hall sensor or sensorless estimation algorithm to obtain the position of the motor rotor, and then commutates six times in the 360° electrical cycle according to the position of the rotor (commutate per 60°).
- BLDC motor outputs a specific direction force at each commutation position, so it can be said that positional accuracy of the square-wave control is electrical 60°.
- In this control method, the phase current waveform of the motor approaches the square wave, so it is called square-wave control.

- **Square-wave control** of BLDC motor is suitable for occasions where motor rotation **performance is not very high.**

Control of BLDC Motors

Advantage of BLDC motor square-wave control include:

- ☺ simple control algorithm,
- ☺ low hardware cost,
- ☺ higher motor speed, that can be obtained by using ordinary controller.

Disadvantage of square-wave control include:

- ☹ large torque ripple,
- ☹ a certain current noise,
- ☹ efficiency is not up to the maximum.

Control of BLDC Motors

- **Sine wave control** of BLDC motors uses the SVPWM wave and outputs the three-phase sine-wave voltage, corresponding current is sinusoidal current.
- In such a control mode, there's no concept of commutation as the square-wave control, nor it thinks that infinite commutations have been occurred in an electric cycle.
- Obviously, sine wave control has smaller torque ripple and less current harmonics than the square-wave control, its control is more "exquisite".
- However, it has higher performance requirements for controller than the square-wave control, the motor efficiency can not be maximum.
- Sine wave control realizes the control of voltage vector and indirectly realizes the current control, but it can not control the direction of current.

Control of BLDC Motors

- **FOC control** of BLDC motor can be regarded as an upgraded sine wave control, it realizes the control of current vector, namely realizing the vector control of motor's stator magnetic field.

- As FOC control controls the direction of motor's stator magnetic field, it can keep the motor's stator magnetic field and the rotor magnetic field at 90° all the time, thus achieving a maximum torque output under a certain current.

Control of BLDC Motors

Advantages of BLDC motor FOC control include:

- ☺ small torque ripple,
- ☺ high efficiency,
- ☺ low noise,
- ☺ fast dynamic response.

Disadvantages include:

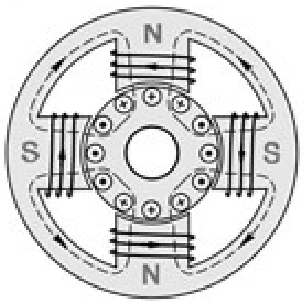
- ☹ high hardware cost,
- ☹ higher requirement for the controller performance,
- ☹ motor parameters need to be matched.

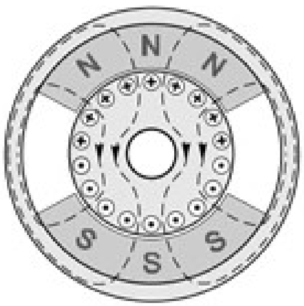
- Due to its distinct advantages, FOC control has gradually replaced the traditional control mode in many applications and won great favor in motion control field.

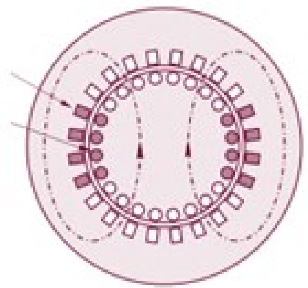
Rotating Electrical Machines

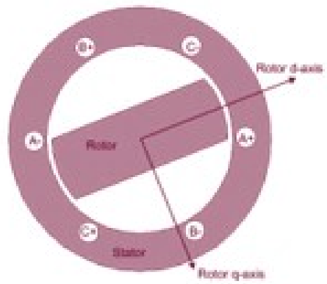
Electrical Machines

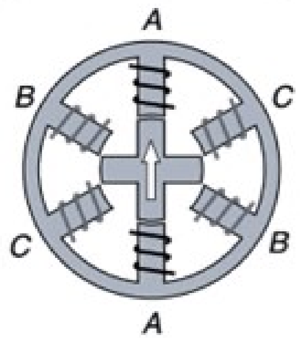
DC Machines		AC Machines		Special Machines
Field Winding	Permanent Magnet	Induction	Synchronous	Step Motor







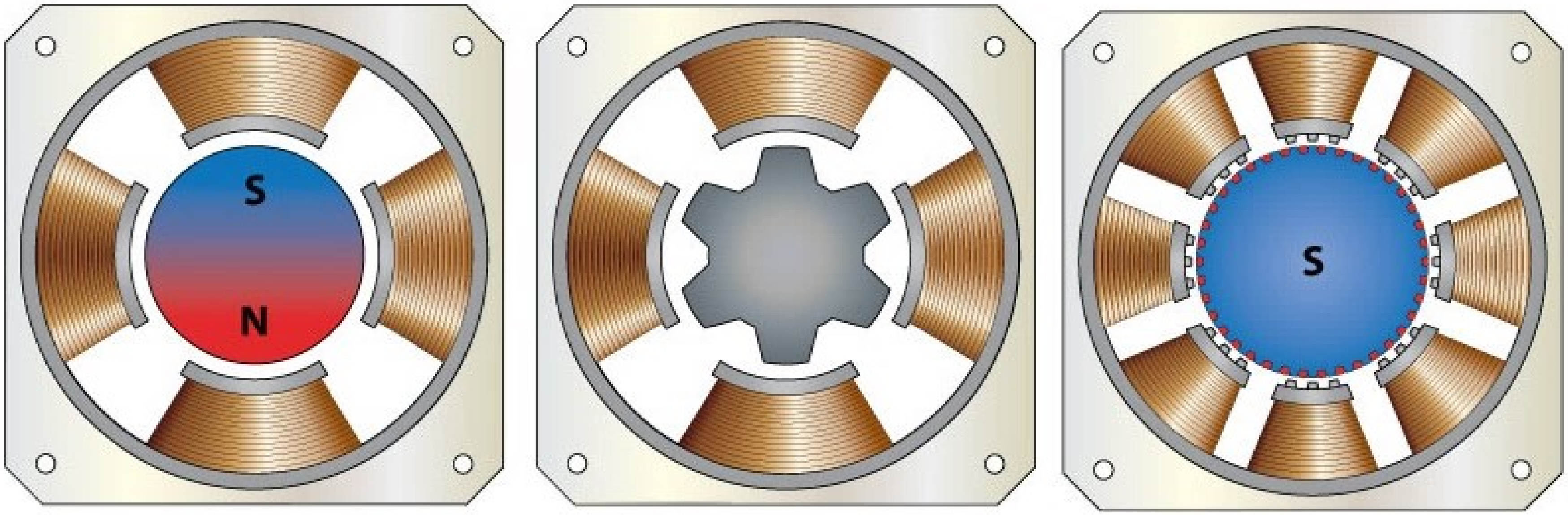




Stepper motors

Types of Stepper Motors:

a) Permanent Magnet (PM) Stepper Motor
b) Variable Reluctance (VR) Stepper Motor
c) Hybrid Stepper Motor



(a) (b) (c)

Stepper motors

- The **Permanent Magnet (PM) stepper motor** have permanent magnet rotors with no teeth.
  - ✓ PM rotors are magnetized perpendicular to the axis. When the four phases are energized in sequence, the rotor rotates as it is attracted to the magnetic poles.
  - ✓ The Permanent Magnet stepper motor generally has step angles of 45° to 90° and tends to step at relatively low rates, but produce high torque and excellent damping characteristics.

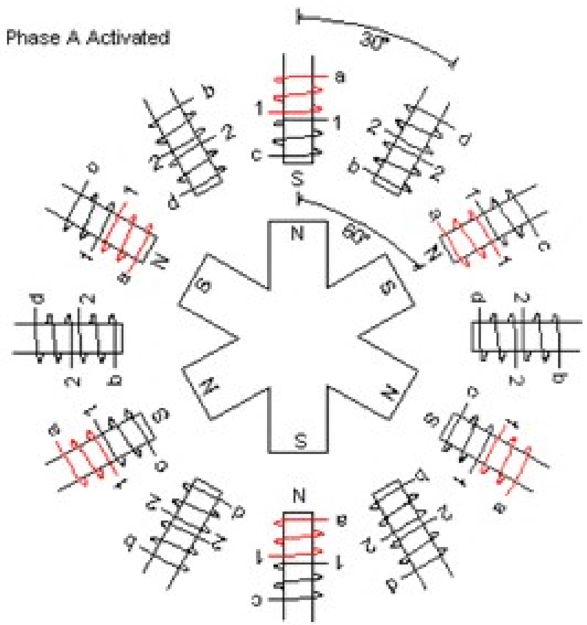
- The **Variable Reluctance stepper motor** is known for having a soft iron multiple rotor and a wound stator construction.
  - ✓ The Variable Reluctance stepper motor generally operates in step angles from 5 ° to 15° at relatively high step rates. They also possess no detent torque.

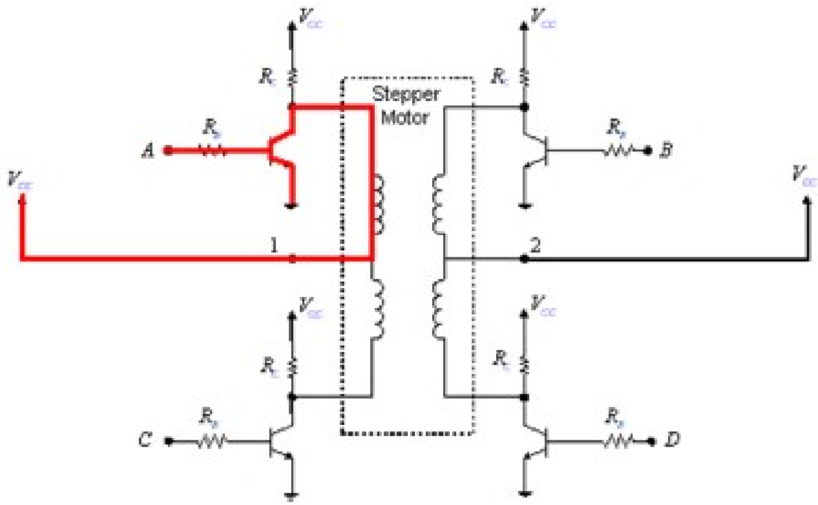
Stepper motors

- The **Hybrid stepper motor** combines qualities from the permanent magnet and variable reluctance stepper motors.
  - ✓ The Hybrid stepper motor has some of the desirable features of each.
  - ✓ Hybrid stepper motor type of stepper motor has a high detent torque, excellent holding and dynamic torque, and they can operate in high stepping speeds.
  - ✓ Step angles of 0.9 ° to 5.0 ° degrees are normally seen in the Hybrid stepper motor.
  - ✓ Bifilar windings are generally supplied to this stepper motor, so that a single power supply can be used to power the stepper motor.

Stepper motors

- A **stepper motor** is a BLDC that divides a full rotation into a number of equal steps.
- The motor's position can then be commanded to move and hold at one of these steps without any position sensor for feedback, as long as the motor is carefully sized to the application in respect to torque and speed.





Stepper motors

- Stepper motors are DC motors that move in discrete steps.
- Stepper motors have multiple coils that are organized in groups called "phases".
- By energizing each phase in sequence, the motor will rotate, one step at a time.
- With a computer controlled stepping it is possible to achieve very precise positioning and/or speed control.
- For this reason, stepper motors are the motor of choice for many precision motion control applications.

How does a Stepper Motor work?

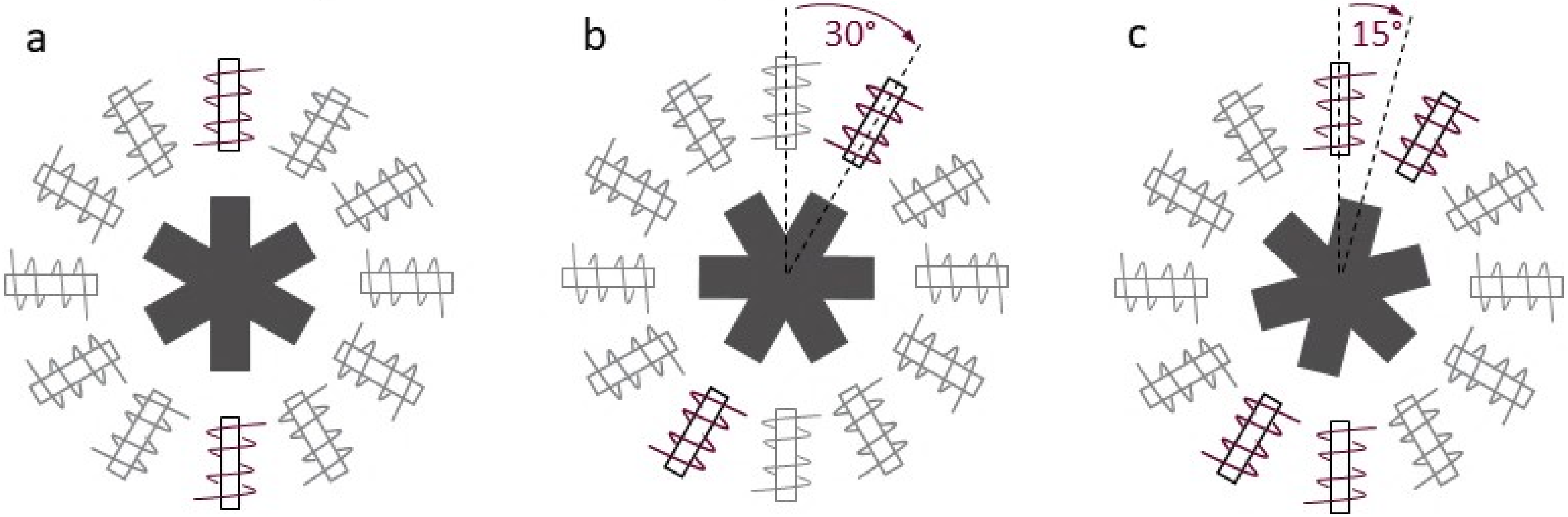
The stepper motor rotor is a permanent magnet, when the current flows through the stator winding, the stator winding to produce a vector magnetic field. The magnetic field drives the rotor to rotate by an angle so that the pair of magnetic fields of the rotor and the magnetic field direction of the stator are consistent. When the stator's vector magnetic field is rotated by an angle, the rotor also rotates with the magnetic field at an angle. Each time an electrical pulse is input, the motor rotates one degree further. The angular displacement it outputs is proportional to the number of pulses input and the speed is proportional to the pulse frequency. Change the order of winding power, the motor will reverse. Therefore, it can control the rotation of the stepping motor by controlling the number of pulses, the frequency and the electrical sequence of each phase winding of the motor.

Stepper motors

- **Switched reluctance motors (SRM)** are very large stepping motors with a reduced pole count, and generally are closed-loop commutated.
- While the stepper is designed foremost for open-loop operation, the SRM is designed for self-synchronous operation, the phases being switched by signals derived from a shaft-mounted rotor position detector (feedback).
- In terms of performance of SRM, at all speeds below the base speed continuous operation at full torque is possible.
- Above the base speed, the flux can no longer be maintained at full amplitude and the available torque reduces with speed.

Control of Stepper Motors

- In one-phase on - full step (a,b) the motor is operated with only one phase energized at a time.
  - ✓ This mode requires the least amount of power from the driver of any of the excitation modes.
- In two-phase on - full step, (c) , the motor is operated with both phases energized at the same time.
  - ✓ This mode provides improved torque and speed performance.
  - ✓ Two-phase on provides about 30% to 40% more torque than one phase on, however it requires twice as much power from the driver.



Control of Stepper Motors

- Stepper motors are designed as an **open loop system**.
  - ✓ A pulse generator sends out pulses to the phase sequencing circuit.
  - ✓ The phase sequencer determines which phases need to be turned off or on as described in the full step and half step information.
  - ✓ The sequencer controls the big power FETs which then turns the motor.

- With an open loop system, however, there is no position verification and no way to know if the motor made its commanded move.

Control of Stepper Motors

- The most popular method of **closing the loop** is adding an encoder on the back shaft of a double shafted motor.
  - ✓ The encoder is made up of a thin disc with lines on it. The disc passes between a transmitter and a receiver. Each time a line comes between the two, a pulse is output on the signal lines. These pulses are fed back to the controller which keeps count of them.
- Usually, at the end of the move the controller compares the number of pulses sent to the driver with the number of encoder pulses sent back.
  - ✓ A contorl routine is usually written that if the two numbers are different, the difference is then made up. If the numbers are the same, no error has occurred and motion continues.
- Closed loop control method has next drawbacks: cost, complexity, and response.
  - ✓ The additional cost of the encoder, along with the increase in sophistication of the controller add cost to the system.
  - ✓ Also, since the correction (if any) is done at the end of the move, additional time could be added into the system.

Control of Stepper Motors

Advantages of Stepper Motors:

- The rotation angle of the motor is proportional to the input pulse.
- The motor has full torque at standstill (if the windings are energized).
- Precise positioning and repeatability of movement since good stepper motors have an accuracy of 3 to 5% of a step and this error is non-cumulative from one step to the next.
- Excellent response to starting/stopping/reversing.
- Very reliable since there are no contact brushes in the motor. Therefore the life of the step motor is simply dependent on the life of the bearing.
- …

Control of Stepper Motors

Advantages of Stepper Motors:

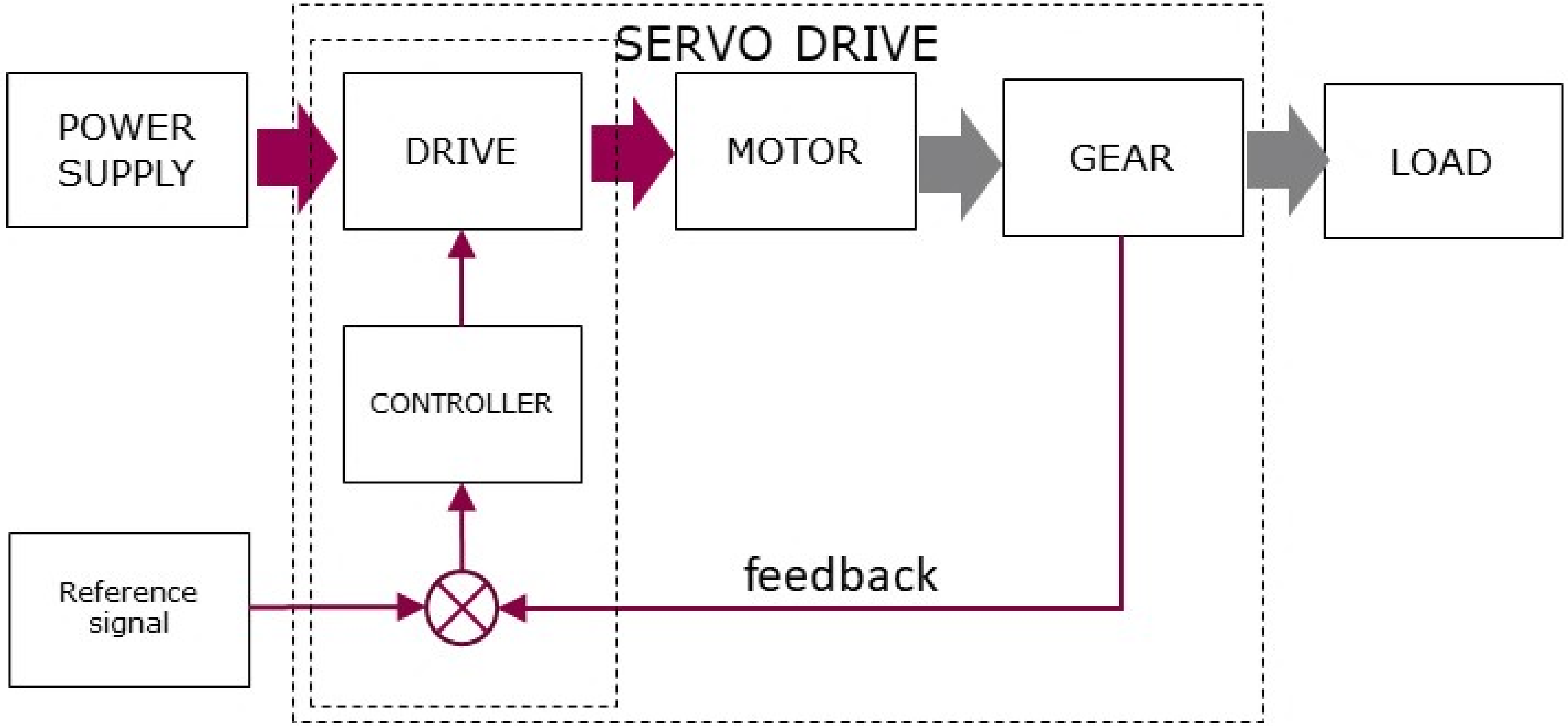
- …
- The stepper motors response to digital input pulses provides open-loop control, making the motor simpler and less costly to control.
- It is possible to achieve very low speed synchronous rotation with a load that is directly coupled to the shaft.
- A wide range of rotational speeds can be realized as the speed is proportional to the frequency of the input pulses.

Servo motors

- A **servo motor** is a simple electric motor, controlled with the help of servomechanism.
  - ✓ If the motor as a controlled device, associated with servomechanism is DC motor, then it is commonly known as a DC Servo Motor.
  - ✓ If AC operates the controlled motor, it is known as a AC Servo Motor.
- Servo systems consist of four main components: a motor, a drive, a controller, and a feedback device, which is typically an encoder.

Servo drives

- **Servo drive** monitors the feedback signal from the servomechanism and continually adjusts for deviation from expected behavior.



Servo drives

- The **controller** and **drive** work together to determine what the motor needs to do (the controller) and send the necessary electrical energy to the motor to make it happen (the drive).
- The controller is responsible for calculating the path or trajectory required and sending low-voltage command signals to the drive.
- The drive then sends the necessary voltage and current to the motor to achieve the required motion.
- The drive can control torque, velocity, or position, although in servo systems, the most common parameter to be controlled is torque.

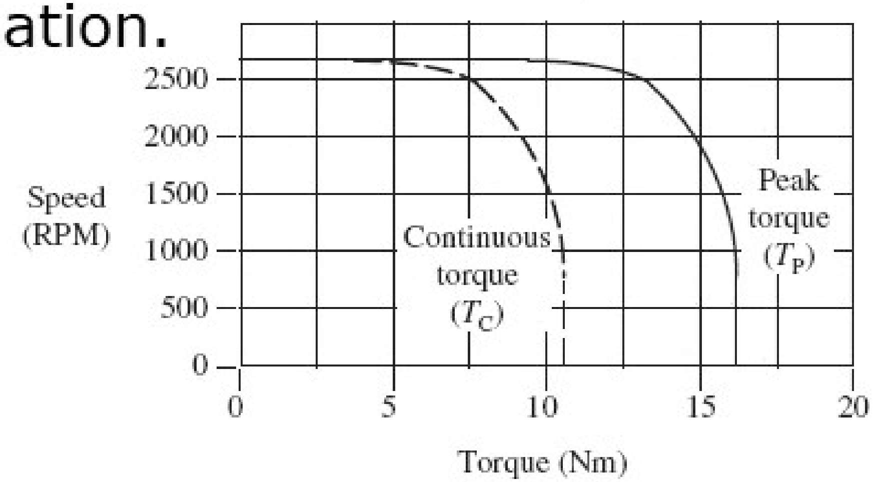
Servo drives

- Servo motor torque is directly related to current, as shown by the equation:

$$T = K_T \cdot I$$

Where:
- ✓ T - *torque*
- ✓ K_T - *motor constant*
- ✓ I - *current*

- Often, the torque-speed curve of servo drive is specific to a certain motor-drive combination.
  - ✓ This is because the continuous and peak torque capabilities of the motor are affected by the thermal properties of both the motor and of the drive.
  - ✓ Inefficiencies in the motor cause it to produce heat, which can degrade bearing lubrication and insulation around the windings.



Servo drives

Advantages:

- ☺ If a heavy load is placed on the motor, the driver will increase the current to the motor coil as it attempts to rotate the motor. There is no out-of-step condition.
- ☺ High-speed operation is possible.

Disadvantages:

- ☹ Since the servomotor tries to rotate according to the command pulses but lags, it is not suitable for precision control of rotation.
- ☹ Higher cost.
- ☹ When stopped, the motor's rotor continues to move back and forth one pulse, so that it is not suitable if you need to prevent vibration

Differences between Stepper Motors and Servo Motors

- Stepper Motors have a large number of poles, magnetic pairs generated by a permanent magnet, or an electric current. Servo motors have very few poles; each pole offers a natural stopping point for the motor shaft.

- The torque of a stepper motor at low speeds is greater than a servo motor of the same size.

- Stepper motor operation is synchronized by command pulse signals output from the pulse generator. In contrast, the servomotor operation lags behind the command pulses.

How to choose between Stepper Motors and Servo Motors?

Understanding the application requirements by answering these questions is the first step in making a design selection between a stepper and a servo motion control system:

- How heavy is the load to be moved, and at what speeds?
- Torque requirements?
- Is torque limiting required?
- Is holding torque required?
- Position resolution required?
- Running speeds?
- Does the load change throughout the move?

Once these questions have been answered, the following design considerations will help guide the decision.

How to choose between Stepper Motors and Servo Motors?

Feature	Servo	Stepper
Position Feedback	Required	Optional
Torque vs Speed	Constant	Varies
Holding Torque	No	Yes
Torque Control	Yes	No
Tuning Required	Yes	No
Support Dynamic Loads	Yes	No
Low Speed Smoothness	Good	Excellent
Programming	Complex	Simple
Size	Larger	Smaller

How to choose between Stepper Motors and Servo Motors?

- **Position Feedback** – Servo systems run closed loop, so position feedback is a requirement. A stepper system runs open loop, with position commanded to move and hold at one of its steps without any feedback required. An incremental or multi-turn absolute encoder can be added as an option in stepper motor applications requiring more precise positioning.

- **Torque versus Speed** – The weight of the load and the speed at which it needs to be moved help determine the torque requirements. Servo motors have constant torque across their speed range, while stepper motors have higher torque at low speeds and less at high speeds.

How to choose between Stepper Motors and Servo Motors?

- **Holding Torque** – Holding torque is the amount of torque needed to move the motor one full step when the windings are energized but the rotor is stationary. Stepper motor torque is usually measured in ounces per inch. Stepper holding torque can be regulated by the amount of current (idle current) put through the motor at rest. At 100 percent idle current, full torque can be expected from a motor. A servo motor does not have this function, one of the factors contributing to its lower torque at low speed as compared to a stepper motor. Positioning applications where the motor shaft may experience minor rotational force at rest require holding torque. Typical applications where the holding torque provided by stepper motors is required include camera, diverter gate and vertical load positioning.

How to choose between Stepper Motors and Servo Motors?

- **Torque Control** – The current control of a servo motor is a much more complex compared to a stepper motor, with the regulation of the current going through the servo motor helping to regulate the torque. This makes servo motors a good fit for applications where torque must be managed, such as web control.

- **Tuning Required** – Servo systems require tuning, which can make control quite complex. For example, if a load is running at very slow speeds, substantial oscillation may occur without proper tuning. The straightforward control of a stepper motor does not require tuning, resulting in simpler control.

How to choose between Stepper Motors and Servo Motors?

- **Support Dynamic Loads** – Servo motors can support dynamic loads, so if the expected load increases, the servo can respond with peak torque. Stepper motors don't have this feature.
  - ✓ Dynamic load applications where the weight changes often and unpredictably benefit from servo motors. Conveyors moving variable weight products are a good example.

- **Low Speed Smoothness** – Stepper motors have excellent low speed smoothness, with features such as micro stepping providing precise speed change without the drift and hunting often found with servo systems. Applications requiring low speed smoothness include pumps, video scanners, optical measuring systems and low-speed conveyors.

How to choose between Stepper Motors and Servo Motors?

- **Programming** – Designers and engineers are often challenged by the complexity of programming servo systems. By contrast, stepper system programming is much simpler, reducing required design effort by eliminating cryptic coding. This enables quick implementation in a wide variety of applications. Integrated PLC and stepper motion control systems simplify applications using user-defined macro instructions embedded in PLC programming software, configured with drag and drop commands to perform control of multiple axis, typically up to 12.

How to choose between Stepper Motors and Servo Motors?

- **Size** – Stepper motors are more compact then servo motors, allowing them to fit into smaller spaces in machines. Smaller size also makes it easier to integrate a stepper motor, drive and controller into one housing. This self-contained stepper motion control system simplifies integration and installation, reduces field wiring and saves space.