EE3124 Introduction to Electric Machines and Drives

7-Special Machines and Applications

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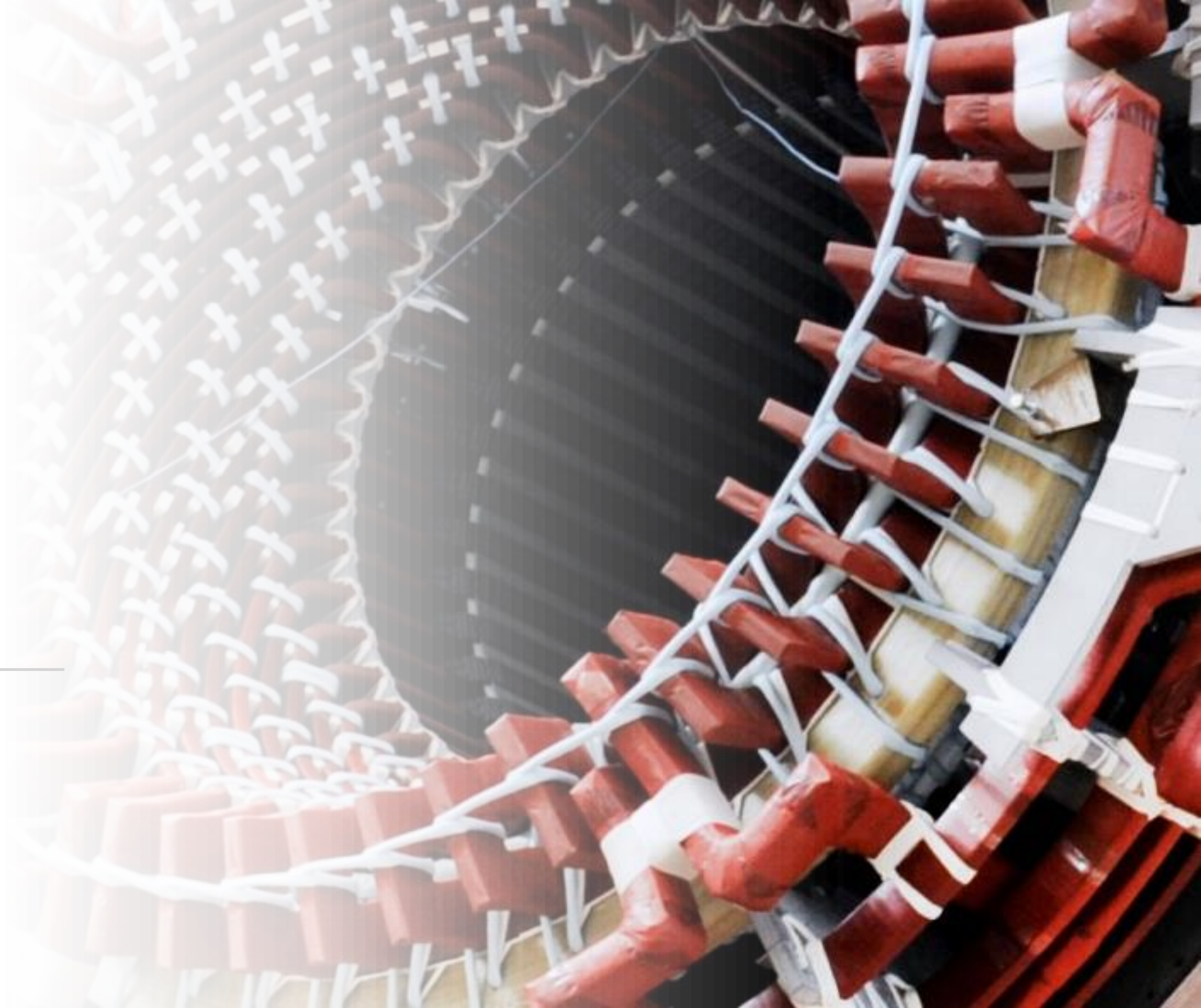
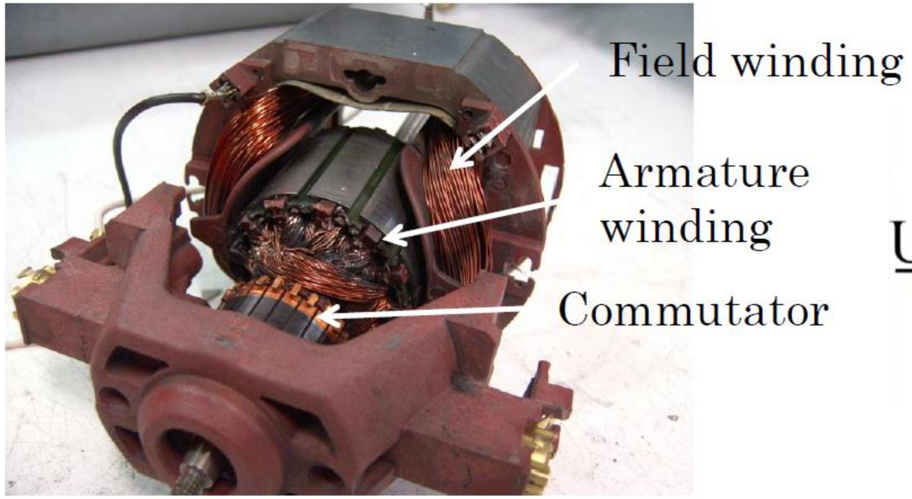


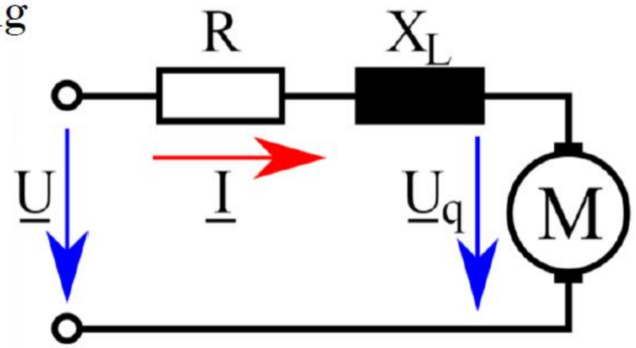
Outline

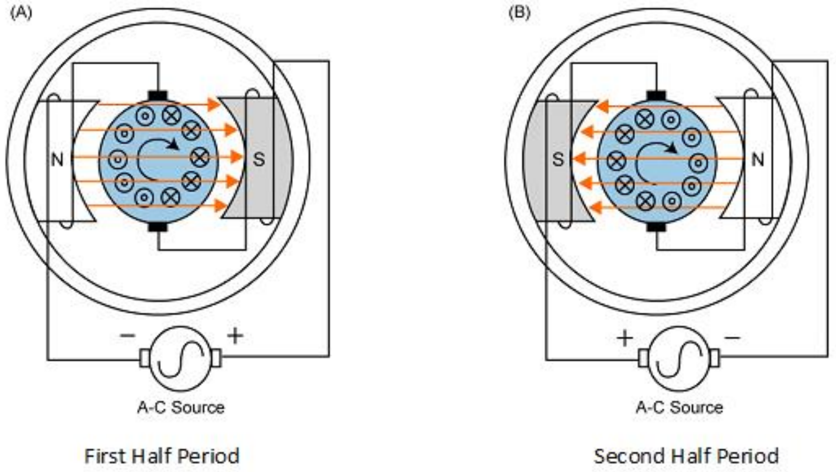
- Universal Motor
- Permanent Magnet (PM) Brushless DC Machines (BLDC)
- Switched Reluctance Machine (SRM)
- Starting Single-Phase Induction Motors
- Double Stator or Rotor PM Vernier Machine

Universal Motor

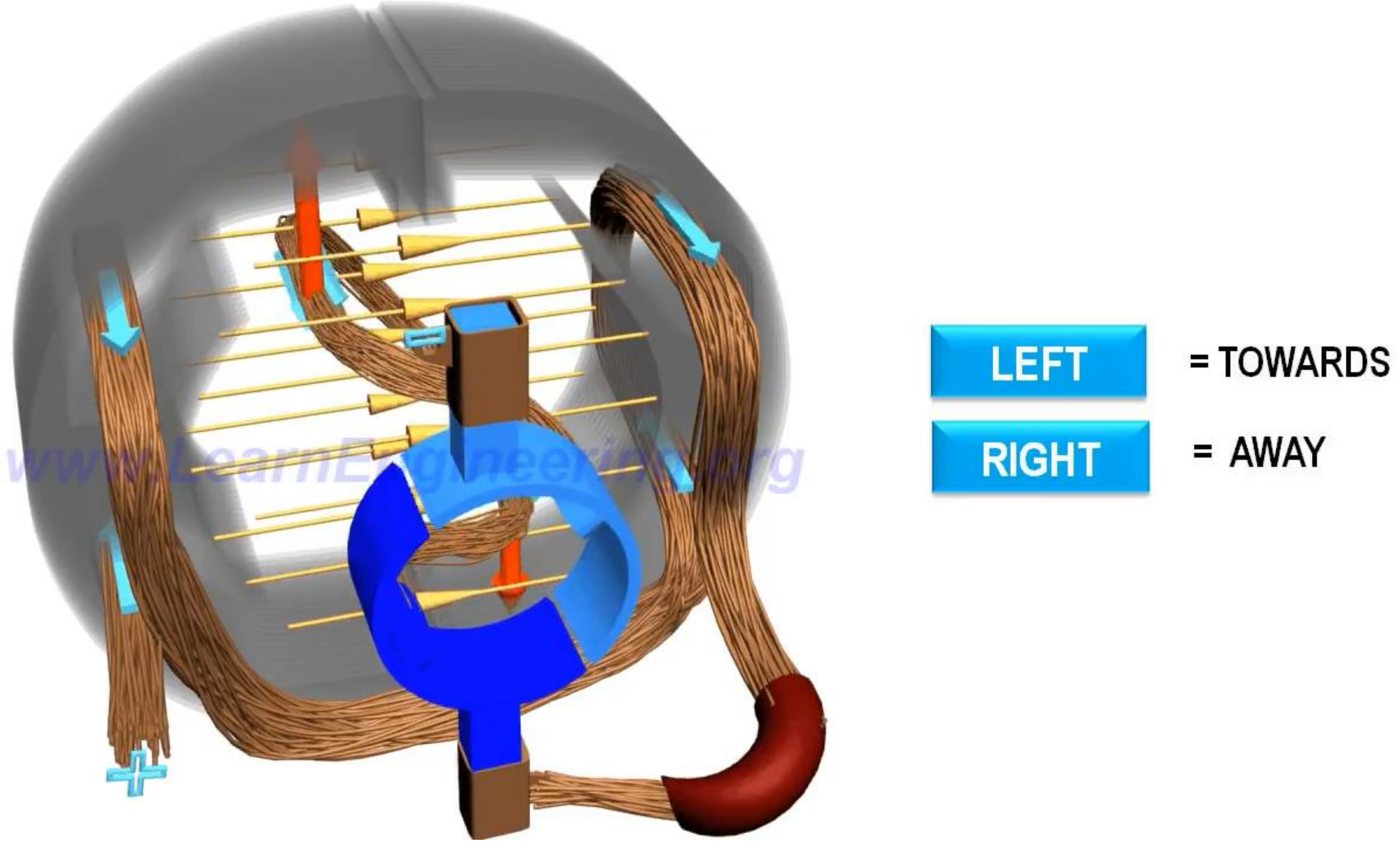
- ❑ It is actually a series DC motor in which the supply voltage is the main AC.
- ❑ It takes the advantages of high starting torque and low-speed high-torque feature. In order for a series dc motor to function effectively on ac, its rotor and stator frame must be completely laminated.
- ❑ If they were not completely laminated, their core losses would be enormous.







How does an Universal Motor Work?



Resource: https://www.youtube.com/watch?v=0PDRJKz-mqE

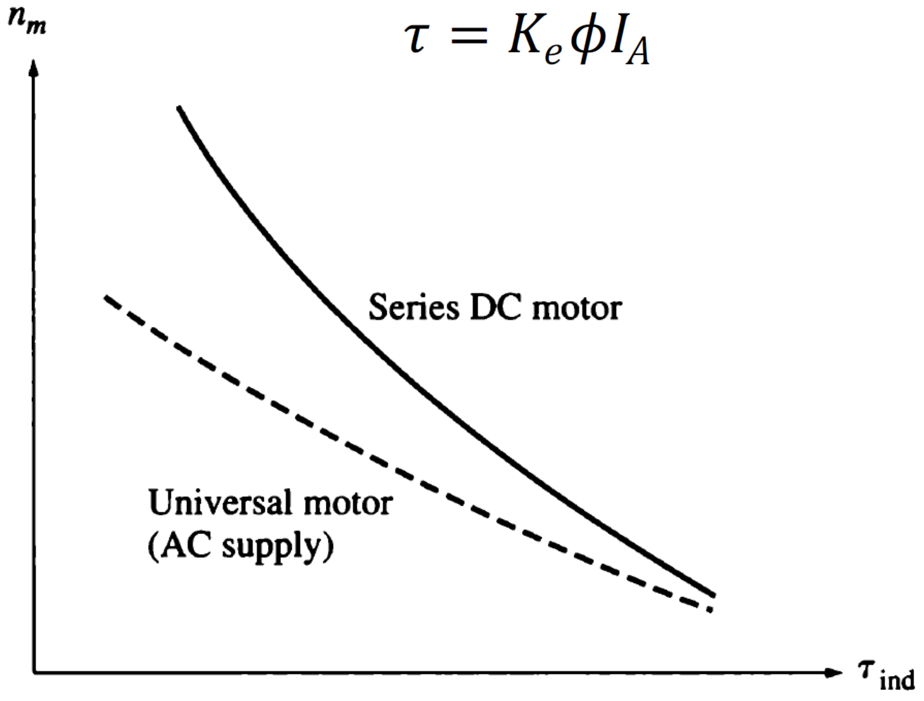
Universal Motor

- The torque-speed characteristic of a universal motor is shown underneath. It differs from the torque-speed characteristic of the same machine operating from a DC voltage source for two reasons:

$$E_A = K_e \phi \omega_m$$

$$\tau = K_e \phi I_A$$

1) The armature and field windings have quite a large reactance at 50 or 60 Hz. A significant part of the input voltage is dropped across these reactances, and therefore E_A is smaller for a given input voltage during ac operation than it is during dc operation. Since the motor is slower for a given armature current and induced torque on alternating current than it would be on direct current.
2) The peak voltage of an AC system is square root 2 its rms value, so magnetic saturation could occur near the peak current in the machine. This saturation could significantly lower the rms flux of the motor for a given current level, tending to reduce the machine's induced torque.



Example 1: Universal Motor

- A washing machine is driven by the universal motor, which is powered by single-phase AC mains having 200 V_{rms} and 50 Hz. The armature winding of the motor has the resistance and inductance of 0.4 Ω and 3 mH, respectively. The field winding of the motor has the resistance and inductance of 0.8 Ω and 6 mH, respectively. When the washing machine operates at full load torque, the motor draws 10 A_{rms} and runs at 1000 rpm.

When the washing machine operates at half load torque.

a) Calculate the input current and

b) Output speed of the motor

Example 1: Universal Motor

Solution

$$E_{rms} = V_{rms} - I_{rms} Z$$

$$Z = \left|(R_a + j\omega L_a) + (R_f + j\omega L_f)\right|$$

$$Z = \left|(0.4 + j2\pi 50 \times 3 \times 10^{-3}) + (0.8 + j2\pi 50 \times 6 \times 10^{-3})\right| = 3.072\Omega$$

RMS value $E_{rms} = 200 - 10 \times 3.072 = 169.28\ \text{V}$

Average value for full-cycle

$$E = \sqrt{2} E_{rms} \times 2/\pi = 152.41\ \text{V}$$

$$I_a = \sqrt{2} I_{rms} \times 2/\pi = 9\ \text{A}$$

$$E'_{rms} = 200 - 7.07 \times 3.072 = 178.28\ \text{V}$$

$$E' = 160.51\ \text{V}$$

Since $T = K_e \phi I_a \propto I_a^2$

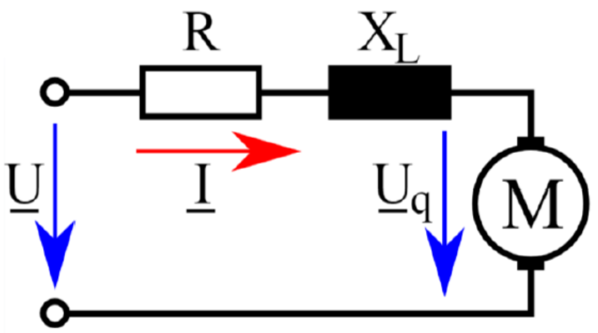
Since $E = K_e \phi \omega \propto \omega I_a$

Average value for full-cycle

$$I'_a = I_a \sqrt{\frac{T'}{T}} = \frac{9}{\sqrt{2}} = 6.36\ \text{A}$$

$$\omega' = \left(\frac{E'}{E}\right)\omega\left(\frac{I_a}{I'_a}\right) = \left(\frac{160.51}{152.41}\right)1000\left(\frac{9}{6.36}\right) = 1490.3\ \text{rpm}$$

RMS value $I'_{rms} = 7.07\ \text{A}$



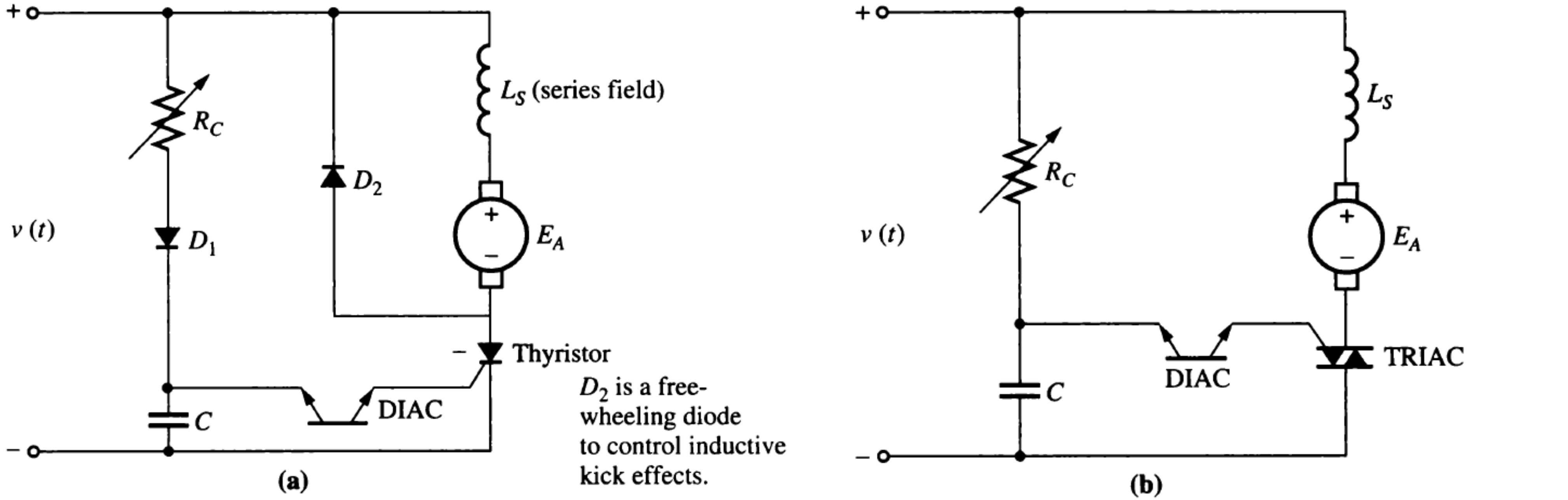
$$E_A = K_e \phi \omega_m$$

$$\tau = K_e \phi I_A$$

https://www.electronics-tutorials.ws/diode/diode_6.html

Speed Control of Universal Motor

- The best way to control the speed of a universal motor is to vary its rms input voltage. The higher the rms input voltage, the greater the resulting speed of the motor.
- In practice, the average voltage applied to such a motor is varied with one of the silicon controlled rectifier (SCR) or triode for alternating current (TRIAC) circuits. The variable resistors shown in these figures are the speed adjustment knobs of the motors.



Sample universal motor speed-control circuits. (a) Half-wave; (b) full-wave.

Advantages and Limitations

- It is compact and gives more torque per ampere than any other single-phase motor. It is therefore used where light weight and high torque are important.

- It has the sharply drooping torque-speed characteristic of a dc series motor, so it is not suitable for constant-speed applications.

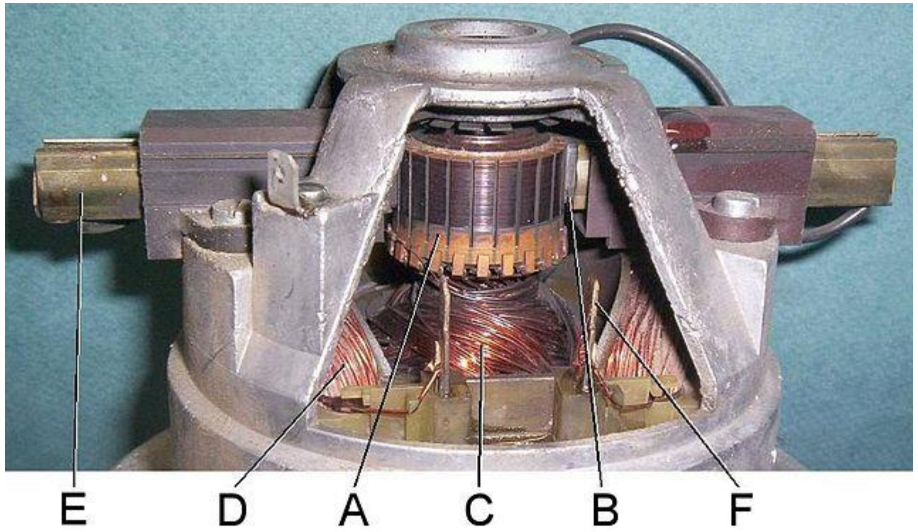
- The commutation of the motor will be much poorer than it would be with a dc source. The extra sparking at the brushes is caused by transformer action inducing voltages in the coils undergoing commutation. These sparks significantly shorten brush life and can be a source of radio frequency interference in certain environments.

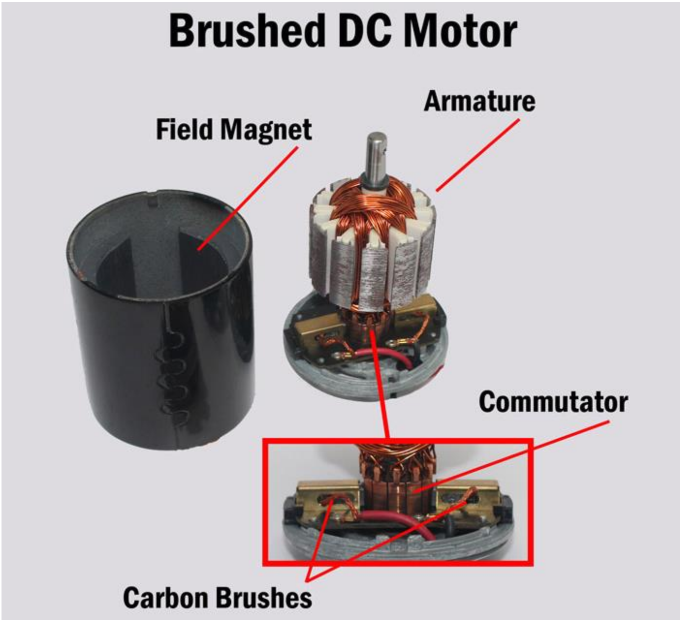
Typical Applications of Universal Motor

- Universal motors are best-suited for devices are used only intermittently and often have high starting-torque demands.
- Typical applicants for this motor are vacuum cleaners, drills, similar portable tools, and kitchen appliances such as food mixer / chopper.

Limitation of Permanent Magnet DC Machines

- The brush and commutator in the DC motor produces automatic switching of the currents in the rotating armature coils so that the current pattern is stationary while the conductors themselves rotate.
- The main high power involved in electromechanical conversion is transferred to the rotor through stationary carbon brushes which are in rubbing contact with the copper segments of the commutator. Thus conventional permanent magnetic DC motor is poor in mechanical design.



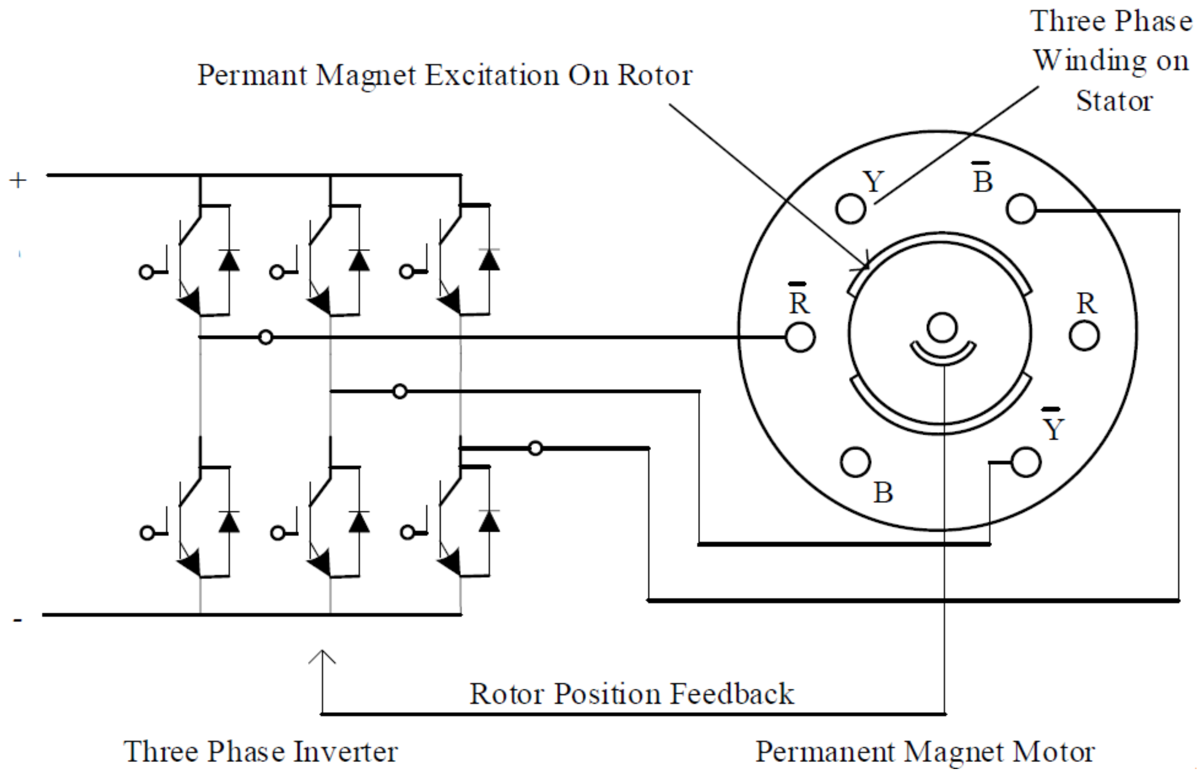


Permanent Magnet (PM) Brushless DC Machines (BLDC)

- How can the principles of action of a DC motor be preserved if it is "turned inside out", i.e. if the high power winding is put on the stationary side of the motor and the field excitation is on the rotor?
- The answer is that the position of the rotor has to be observed and used to control the switching of currents into the stationary winding so that the current pattern in the stationary winding rotates in self-synchronism with the field, thus producing continuous torque.

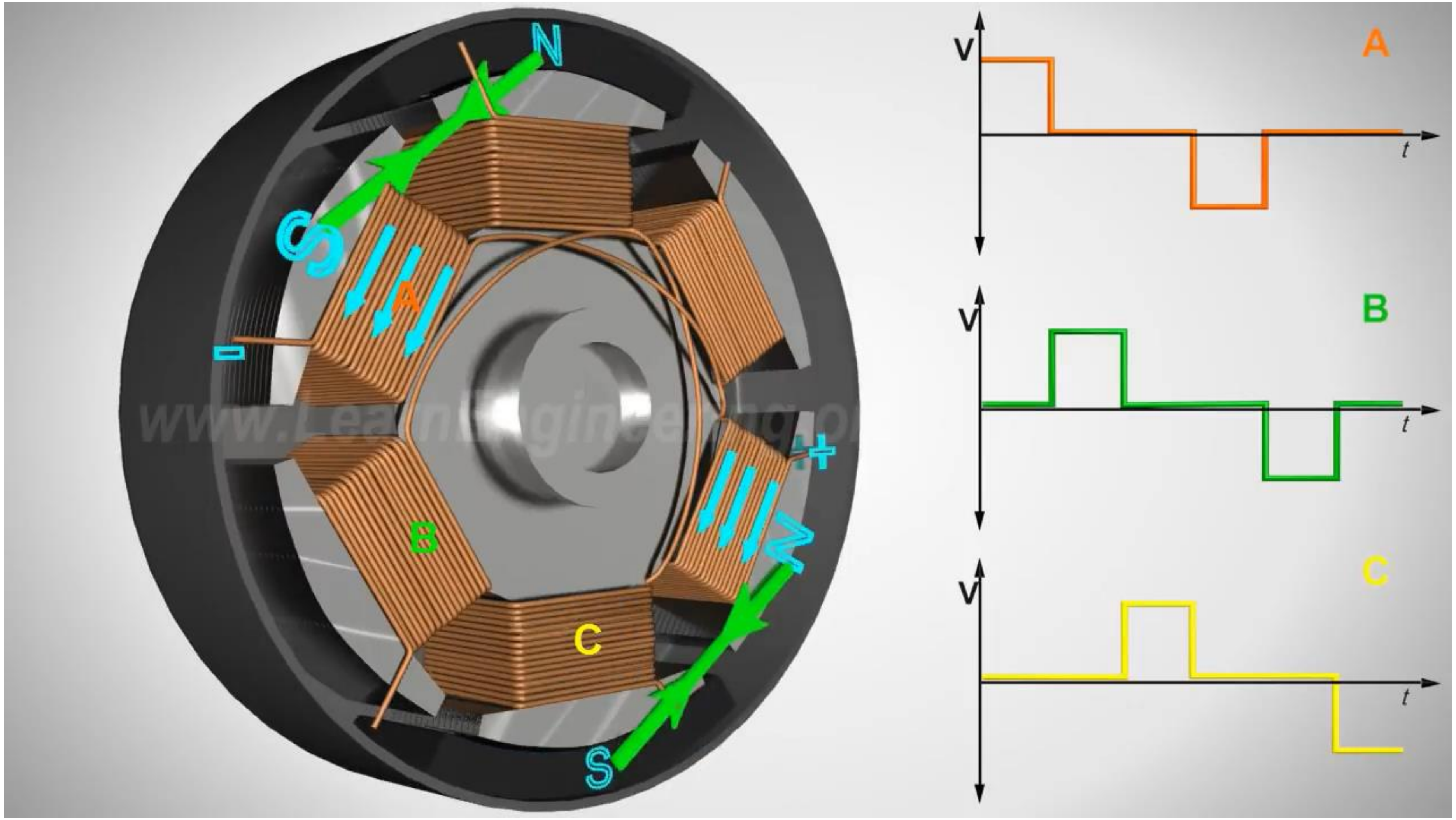
Permanent Magnet (PM) Brushless DC Machines

- An inverter is needed to switch the currents into the windings. In practice most brushless DC motors use permanent magnet excitation and three phase inverters.
- Note that the inverter takes the place of the commutator and a three-phase inverter is equivalent to a three segment commutator.



Permanent Magnet (PM) Brushless DC Machines

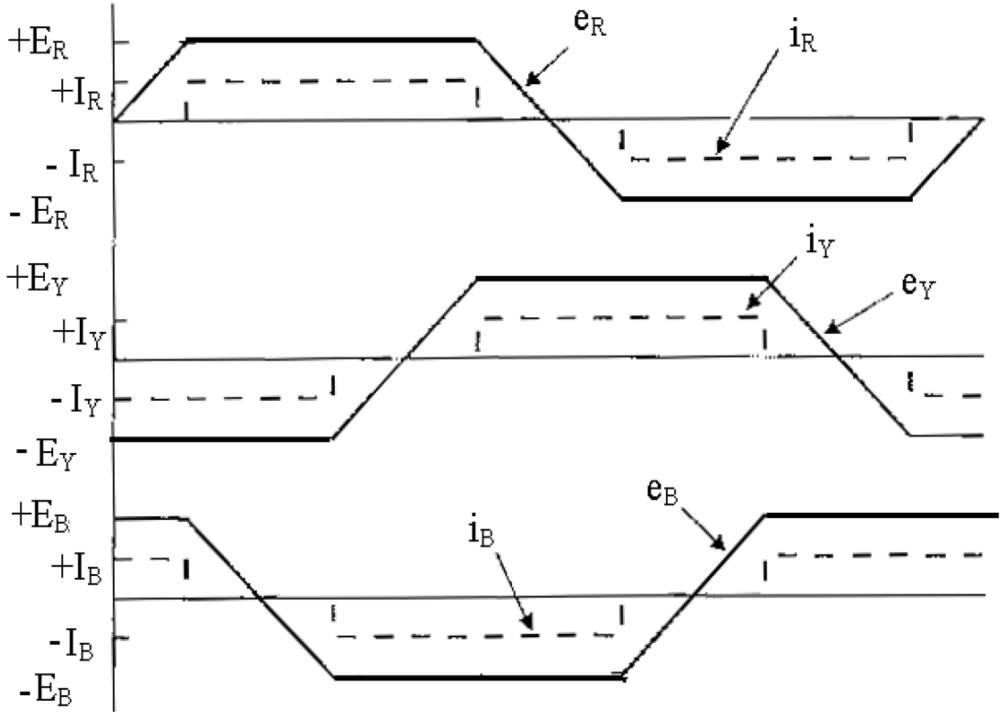
- How does the PM brushless DC motor work?

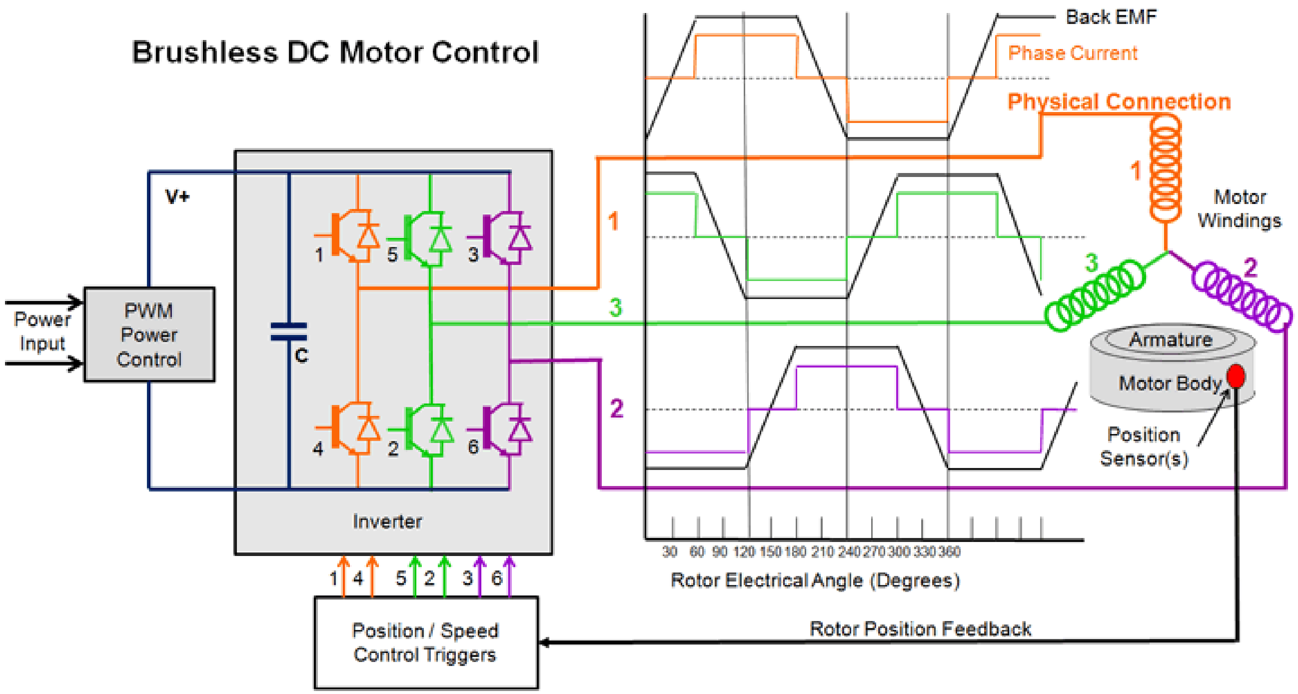


Resource: https://www.youtube.com/watch?v=bCEiOnuODac

Permanent Magnet (PM) Brushless DC Machines

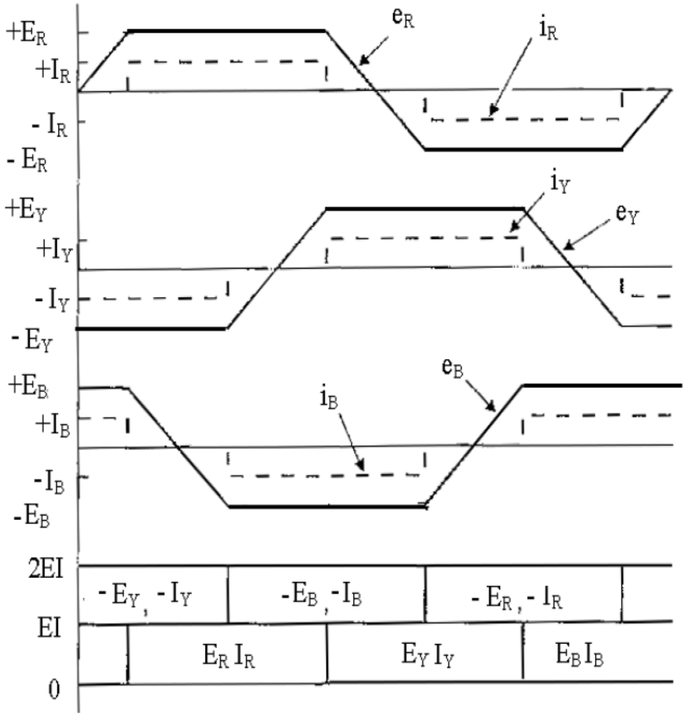
- The principle of operation can be described when the rotor is rotated at a constant speed, with the stator windings open circuit then the induced voltages, e_R, e_Y, e_B would be observed.
- The waveform is constant amplitude for 120º during the positive and negative half cycles. e_R, e_Y and e_B form a balanced three phase set.





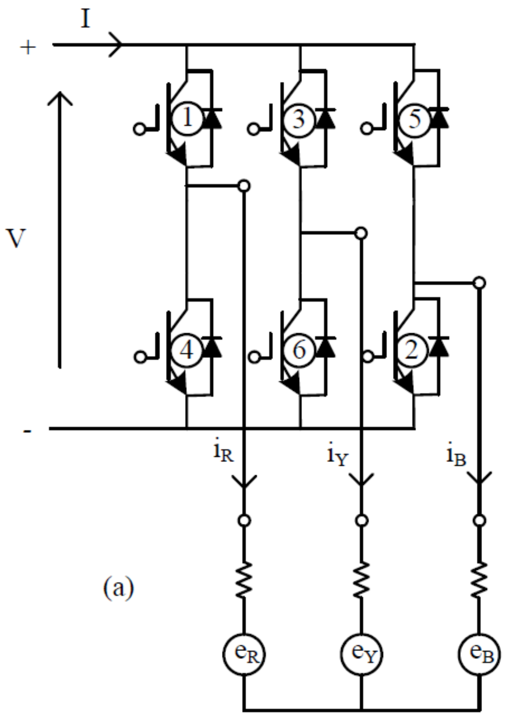
Permanent Magnet (PM) Brushless DC Machines

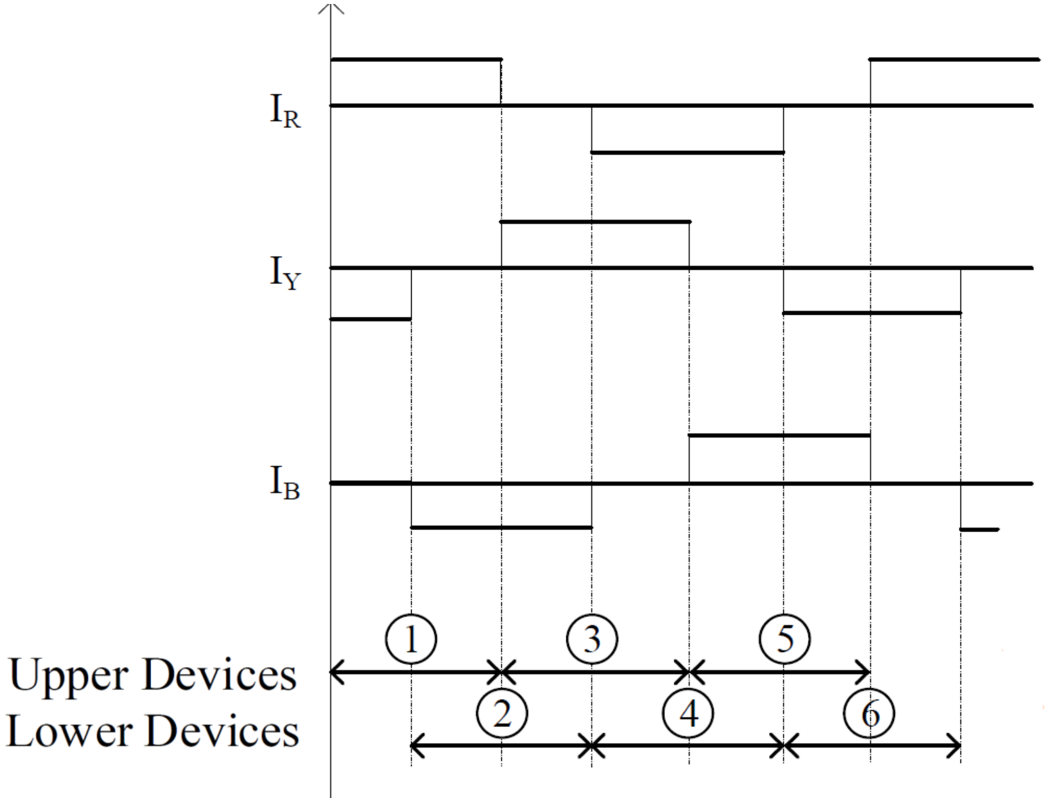
- Now assume that quasi square currents i_R, i_Y and i_B, are fed into the windings as shown. During the 120° in the positive half cycle when e_R and i_R are both constant the electrical power converted to mechanical power is $E_R I_R$. Similarly during the negative half cycle the converted power is $(-E_R)(-I_R)$.
- The other two phases produce patterns that are the same in shape but shifted in time with the result that the converted power is constant and equal to 2EI .



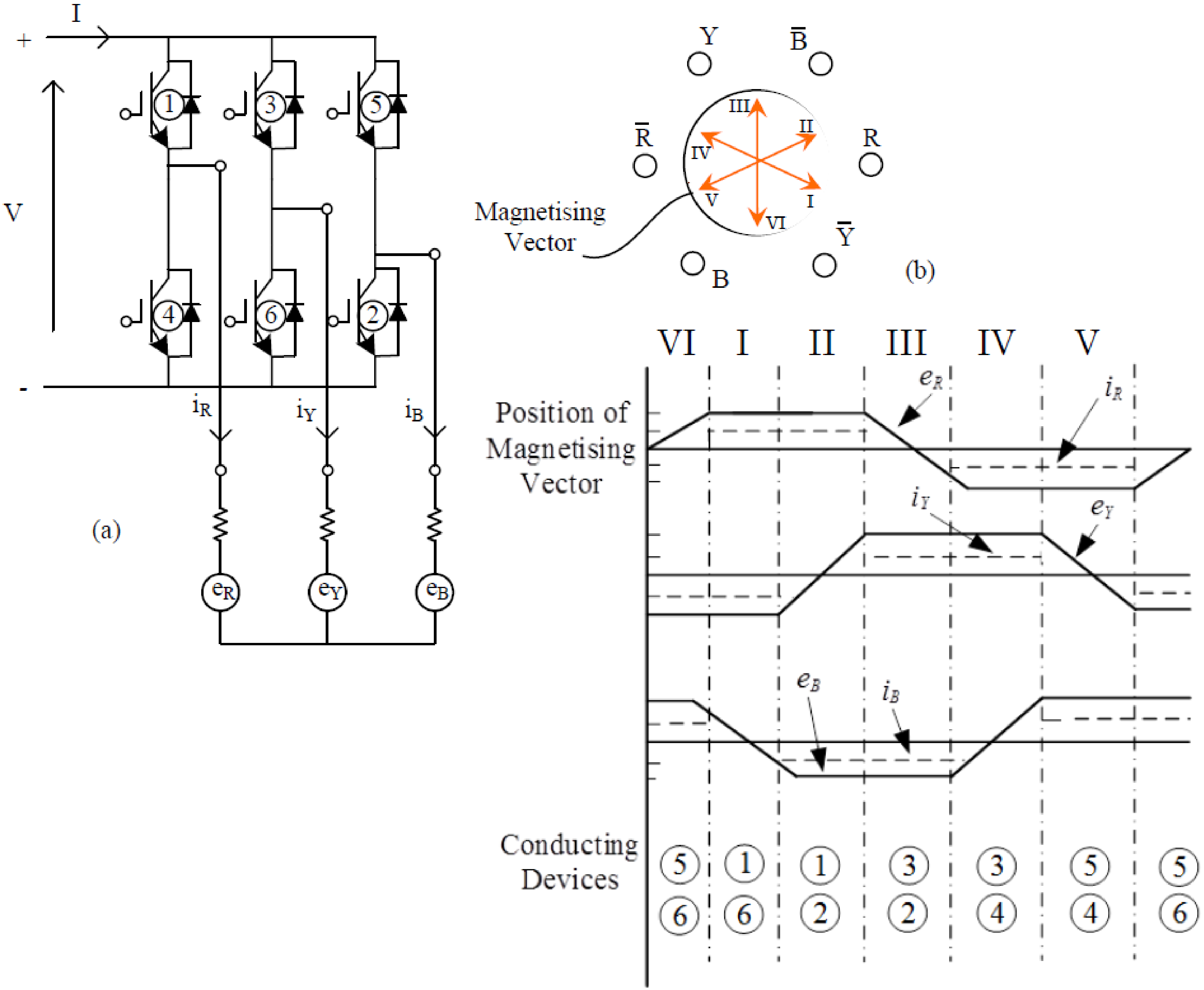
Permanent Magnet (PM) Brushless DC Machines

- The three currents may be supplied by a three-phase inverter. It is important to note that only one upper and one lower inverter device conduct at any one time - each device conducts for 120° of the current waveform period, the commutation of the lower devices taking place in the middle of the conduction intervals of the upper devices. As a result a ripple-free DC current is drawn from the DC source.





Permanent Magnet (PM) Brushless DC Machines



Permanent Magnet (PM) Brushless DC Machines

(a) shows each phase has resistance R_{ph}, and induced voltage e_R, e_Y, e_B. In theory each phase also has inductance but this can be neglected for most steady state purposes in small machines.

(b) shows the N-S magnetization vector (arrow head is N) of the rotor at six positions, I, II........ VI with respect to the phase windings.

In position I the middle of the N pole is centered on the red conductors and represents the mid-point of the positive half cycle of the red phase voltage.

It can be seen that to provide the quasi square current waveforms two devices are on at any instant in time. Furthermore, looking at the top row of devices, (1) is on for 120^o, followed by (3) for 120^o followed by (5) for 120^o, with this cycle repeating continuously.

Permanent Magnet (PM) Brushless DC Machines

- It is evident from this pattern that the top three devices in effect steer a constant current from the DC source successively into the three stator phases. This is why the system is known as a brushless DC motor: because from the DC source it extracts a DC current and can be represented by DC motor equations.
- It can be observed that only two phases are operating at any instant in time. The equations associated to the operation are

$$V' = IR' + E' \qquad R' = 2 \times R_{ph}$$

$$V' = V - 2V_{os} \qquad E' = 2 \times E_{ph}$$

where V_{os} is the on-state voltage of an inverter switching device.

- Therefore, the conventional DC motor equations can be applied.

$$2E_{ph} = k\phi\omega$$

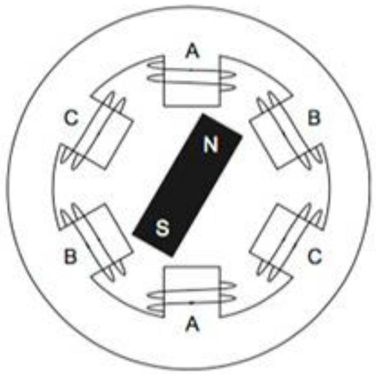
$$\tau = k\phi I$$

$$\tau = \frac{E'I}{\omega}$$

$$\Rightarrow \quad \tau = \frac{k\phi V}{2R_{ph}} - \frac{k^2\phi^2\omega}{2R_{ph}}$$

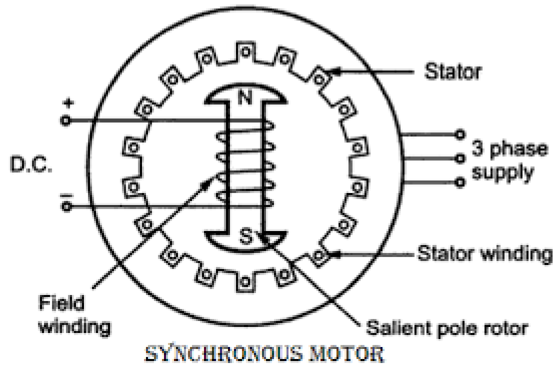
where k represents both the back EMF constant and torque constant. Neglect the voltage drop across the semiconductor switch.

Difference between BLDC and Synchronous AC Motors



❑ Similarities in construction

- BLDC and synchronous AC motors are both brushless
- Both BLDC and synchronous AC motors have permanent magnets.
- The stator is made of steel laminations, with windings (typically three) placed in slots cut axially in the laminations.

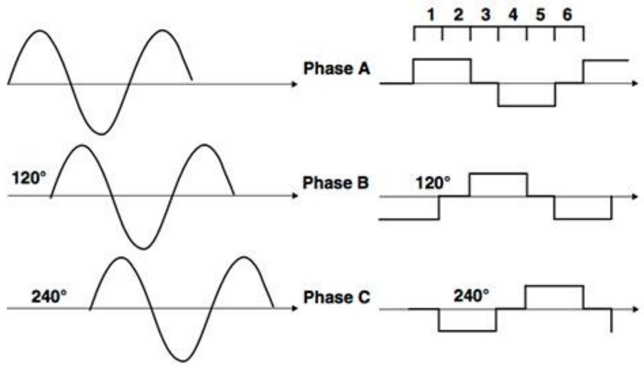


❑ Differences in operation and performance

- In BLDC motors, the stator coils are wound trapezoidally, and the back-EMF produced has a trapezoidal wave form, so requiring direct current to get best performance.
- In contrast, synchronous AC motors are wound sinusoidally and produce a sinusoidal back-EMF, so requiring sinusoidal drive current in order to achieve the best performance.
- The trapezoidal drive current used by BLDC motors tends to produce a greater amount of audible and electrical noise in comparison to sinusoidally driven synchronous AC motors.

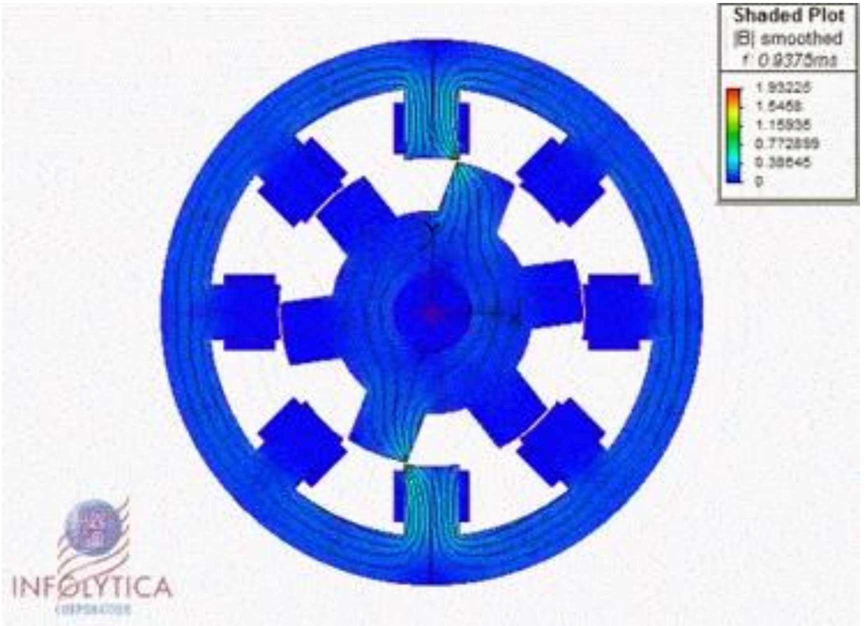
❑ Advantages

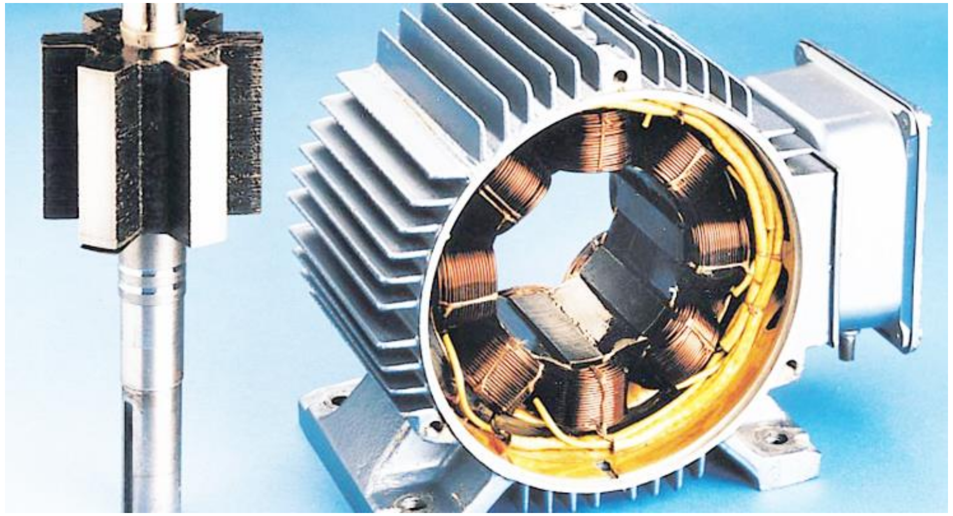
1. Relatively high efficiency
2. Long life and high reliability
3. Little or no maintenance
4. Very little RF noise compared to a dc motor with brushes
5. Very high speeds are possible (greater than 50,000 r/min)



Switched Reluctance Machine (SRM)

- The switched reluctance (SR) machine has a simple, robust and low-cost structure. Unlike the induction and synchronous machines, it is particularly suitable for high-speed operation without suffering from mechanical failure due to high centrifugal force.
- However, the SR machine generally suffers from lower torque density, higher torque ripple and larger acoustic noise than its counterparts.

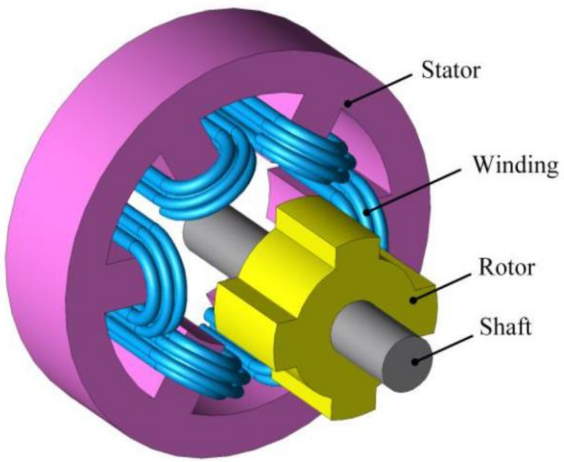


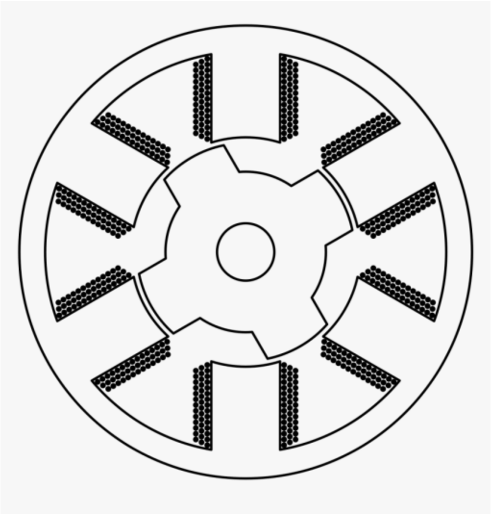


https://www.youtube.com/watch?v=qDon7Nrj1Tk

Switched Reluctance Machine (SRM)

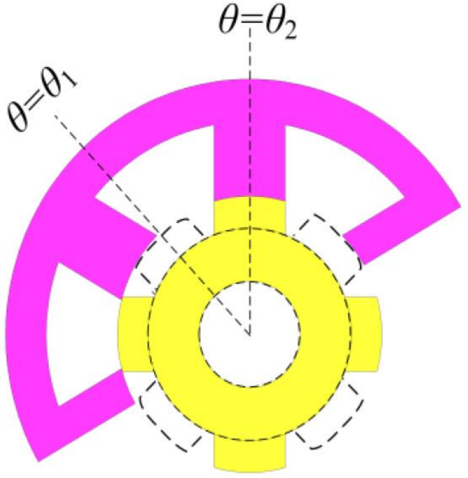
- The SR machine has salient poles, actually teeth, on both the stator and rotor in which it has installed multiphase concentrated windings in the stator, but with no copper winding or PM piece in the rotor. Due to the salient nature of both the stator and rotor poles of the SR machine, the reluctance of the magnetic flux path for each phase winding varies with the rotor position.
- Thus, the principle of torque production is based on the 'minimum reluctance' rule, namely a rotor pole tends to align with the excited stator pole so that the reluctance of the magnetic flux path is minimum.

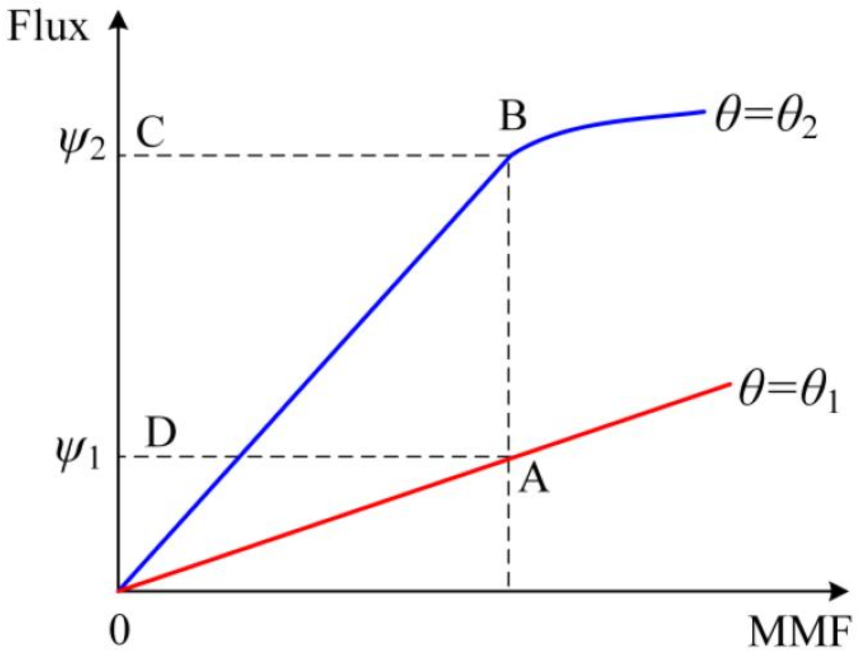




Switched Reluctance Machine (SRM)

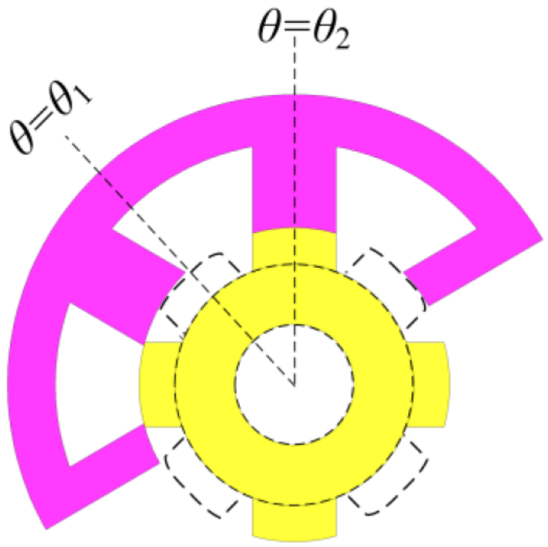
- When they are excited with a current i, a magnetic flux is established. The flux versus magnetomotive force (MMF) characteristics are plotted for the unaligned position between the stator and rotor poles at $\theta = \theta_1$ and the aligned position between the stator and rotor poles at $\theta = \theta_2$.

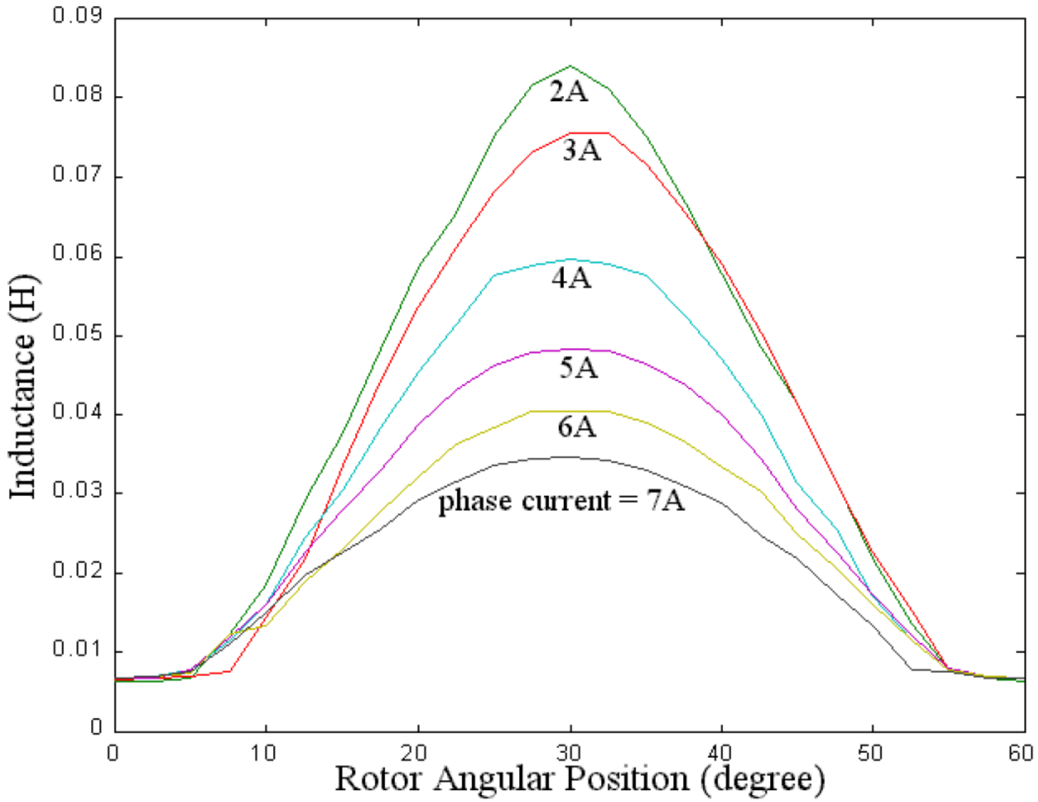




Switched Reluctance Machine (SRM)

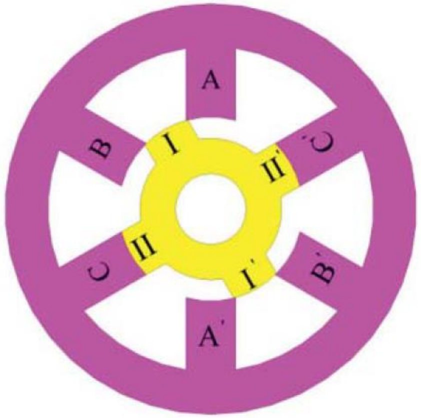
- Inductance of the phase in SRM is changed when the rotor rotates to a different position. Because of the saturation of the phase windings, inductance of the phase is dependent on input current. In short, phase inductance is a function of phase current and angular position.

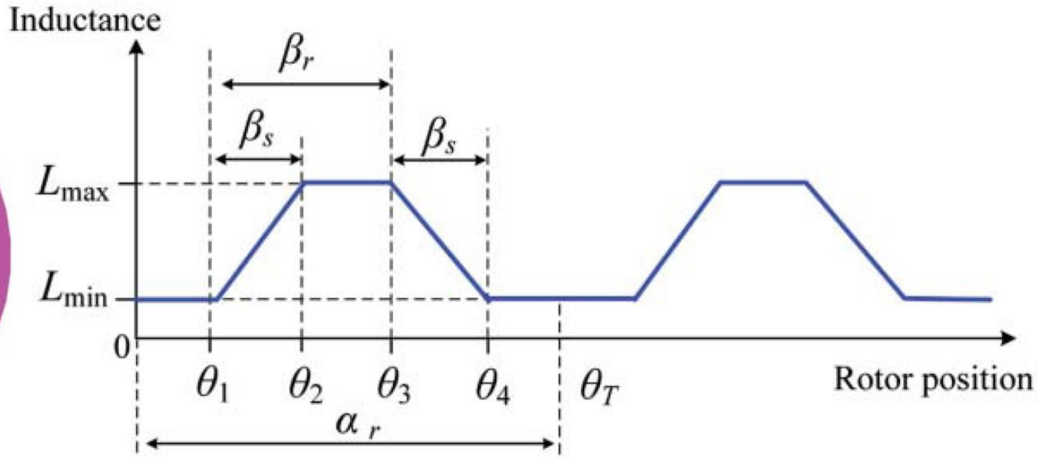


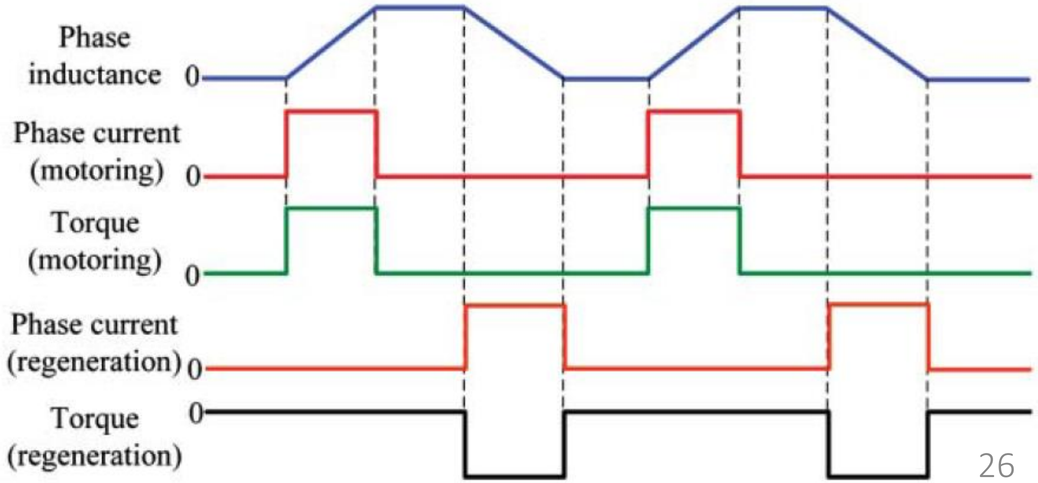


Switched Reluctance Machine (SRM)

- Along the variation of phase inductance versus rotor position, there are five regions.
  - $0 - \theta_1$: The stator and rotor poles have no overlapping, termed the unaligned position, so that the magnetic flux and hence the inductance (L_{min}) are minimum and kept constant. Thus, this region does not contribute to torque production.
  - $\theta_1 - \theta_2$: The stator and rotor poles start to have overlapping from θ_1 to θ_2, so that the magnetic flux and hence the phase inductance increase with the rotor position, giving a positive $dL/d\theta$. When a current is applied in this region, a positive torque is created for motoring operation. It should be noted that the polarity of the applied current does not affect the polarity of the developed torque.

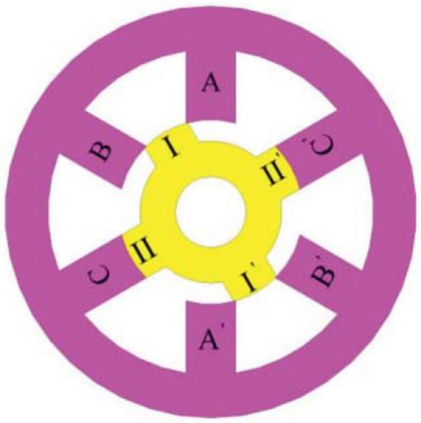


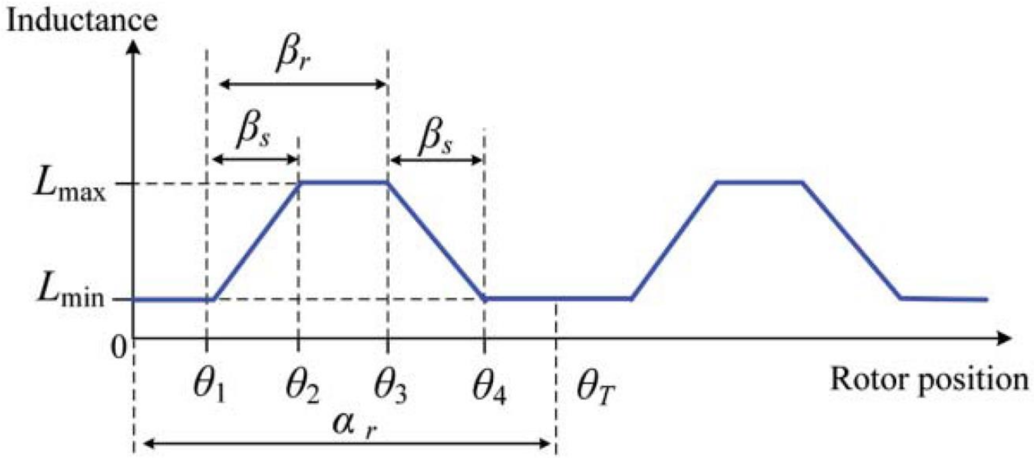


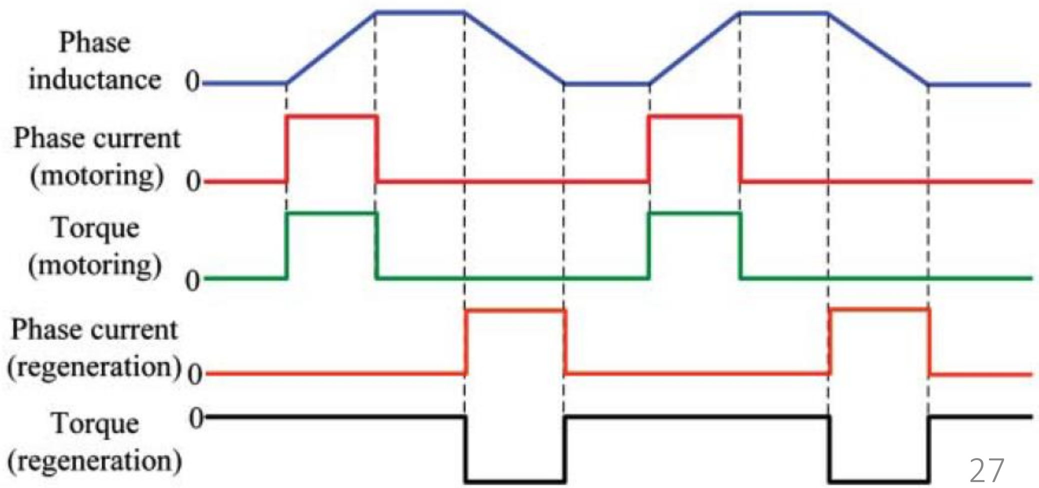


Switched Reluctance Machine (SRM)

- $\theta_2 - \theta_3$: Within this region, the stator and rotor poles completely overlap, termed the aligned position, and the movement of rotor pole does not change the overlapping. The corresponding magnetic flux and hence the phase inductance (Lmax) are maximum and kept constant. As there is no change in the inductance, there is no torque production.
- $\theta_3 - \theta_4$: The stator and rotor poles start to reduce overlapping from θ_3 to θ_4, so that the magnetic flux and hence the phase inductance decrease with the rotor position, giving a negative $dL/d\theta$. when a current is applied, no matter positive or negative, a negative torque can be created for regeneration operation.
- $\theta_4 - \theta_T$: The stator and rotor poles are at the unaligned position again so that the phase inductance is kept constant at L_{min} and no torque is produced.

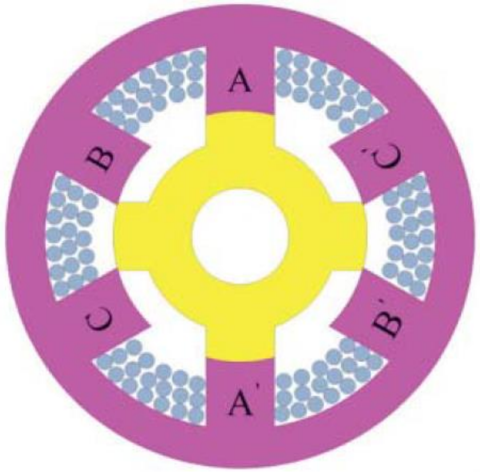


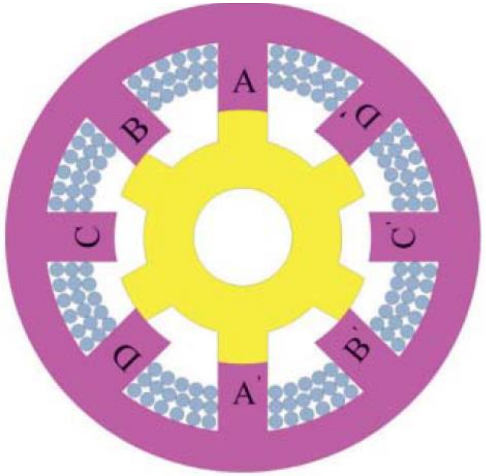


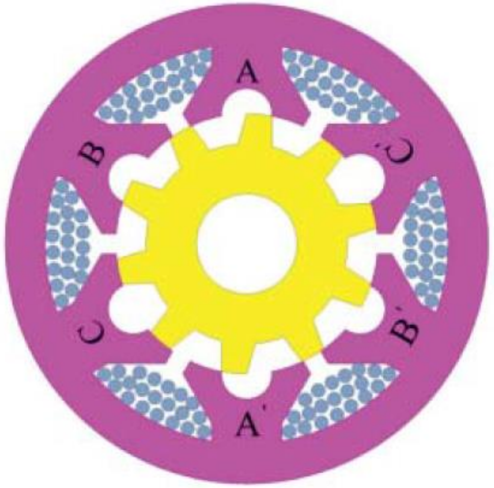


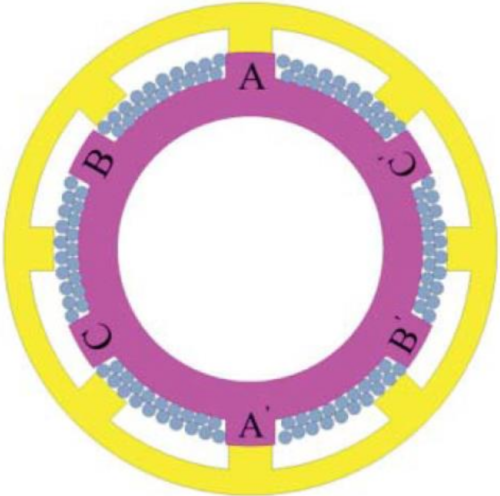
Switched Reluctance Machine (SRM)

- There are many possible topological structures for the SR machine, mainly depending on the number of phases as well as the numbers of stator and rotor poles. There are two basic SR machine topologies, namely the three-phase 6/4-pole topology which has six stator poles and four rotor poles, and the four-phase 8/6-pole topology which has eight stator poles and six rotor poles.
- The three-phase 6/4-pole SR machine has the advantages of lower cost and better phase-advancing capability for high-speed operation. However, it suffers from higher torque ripple and acoustic noise.









Switched Reluctance Machine (SRM)

- The four-phase 8/6-pole SR machine has better starting torque and lower torque ripple, but requires more power devices and higher converter cost.
- To minimize the switching frequency and iron losses, the number of rotor poles should be selected as small as possible. On the contrary, the higher the number of rotor poles, the lower the torque ripple is resulted. Meanwhile, by increasing the number of phases, the torque ripple can be reduced, but the SR converter cost will be increased.

The number of stator poles N_s and the number of rotor poles N_r are generally governed by:

$$N_s = 2\,k\,m$$

$$N_r = 2\,k\,(m+q)$$

where m is the number of phases, k is a positive integer, and q is a positive or negative integer. When the rotor speed is ω, the switching frequency f_s of a particular phase is given by

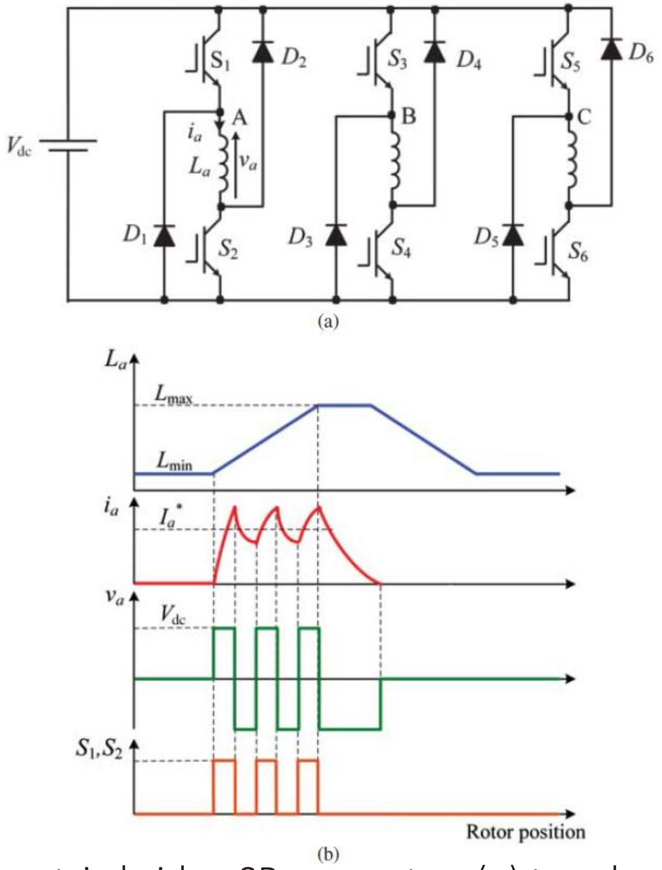
$$f_s = \frac{\omega}{2\pi} N_r$$

Common combinations of phase and pole numbers of SR motors

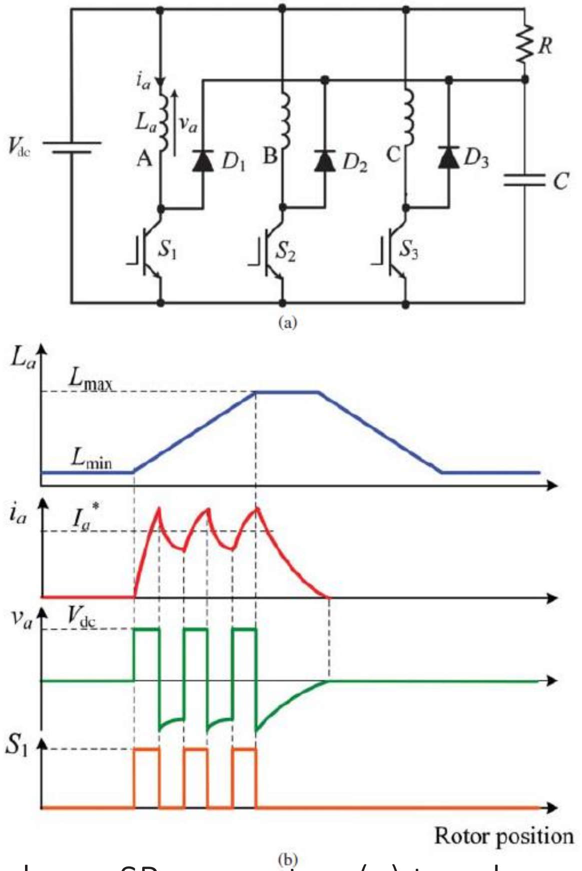
m	N_s	N_r	k	q
3	6	4	1	−1
3	6	8	1	+1
3	6	10	1	+2
3	12	8	2	−1
3	18	12	3	−1
3	24	16	4	−1
3	24	32	4	+1
4	8	6	1	−1
4	16	12	2	−1
4	16	20	2	+1
5	10	4	1	−3
5	10	6	1	−2
5	10	8	1	−1

Converters and Control for SRM

- Differing from other AC machines, the SR machine produces torque, which is independent of the current polarity. Thus, conventional bridge inverters adopted by AC machines are not used for SR machines.



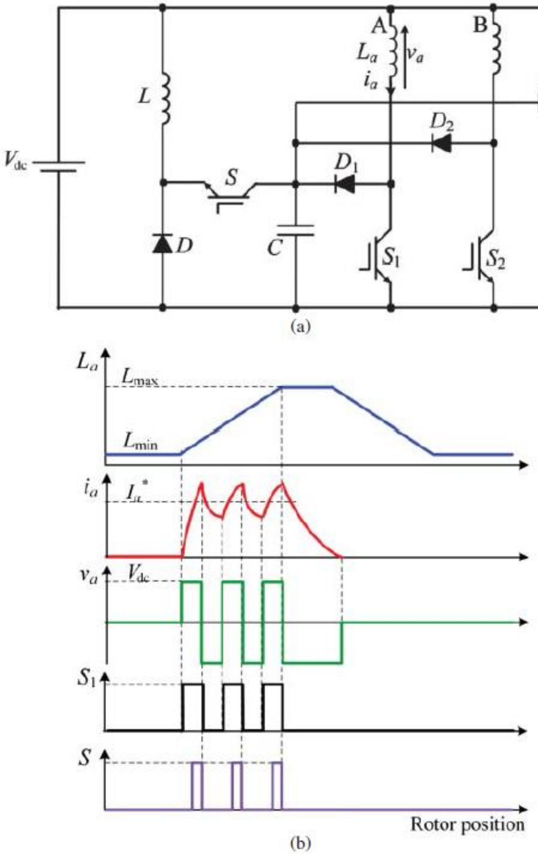
Asymmetric bridge SR converter: (a) topology and (b) operating waveforms



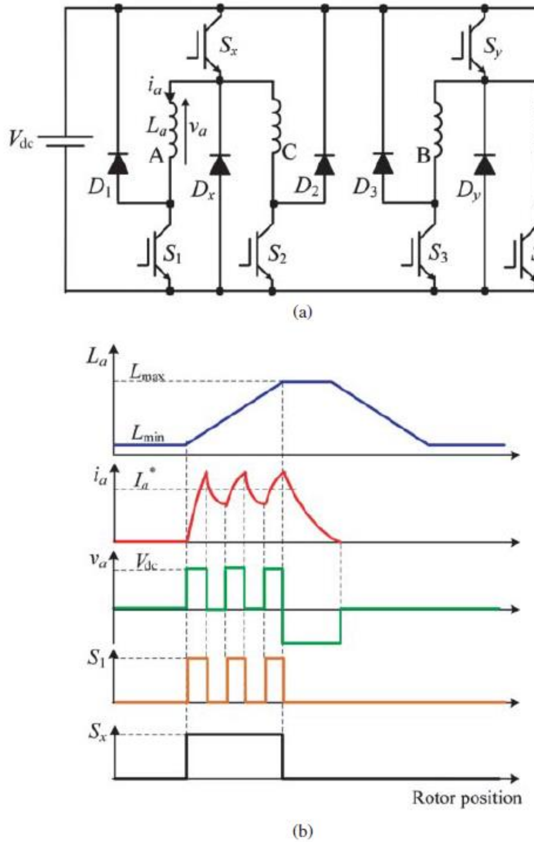
R-dump SR converter: (a) topology and (b) operating waveforms.

Converters and Control for SRM

- The main disadvantage of this topology is that the negative voltage across the phase winding is limited by the difference between the voltage across the capacitor and the DC supply voltage, which slows down the current commutation.



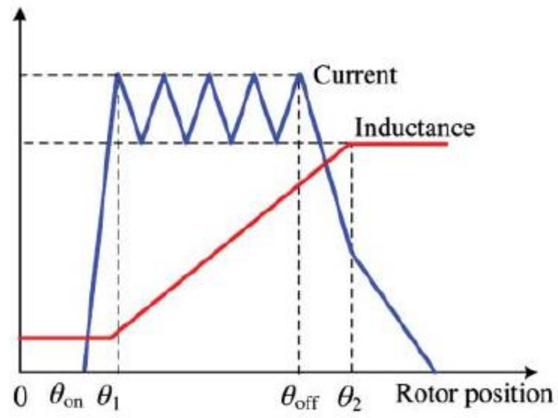
C-dump SR converter: (a) topology and (b) operating waveforms



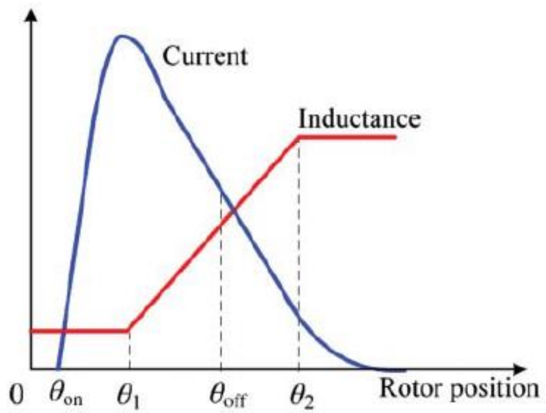
1.5m-switch SR converter: (a) topology and (b) operating waveforms

Converters and Control for SRM

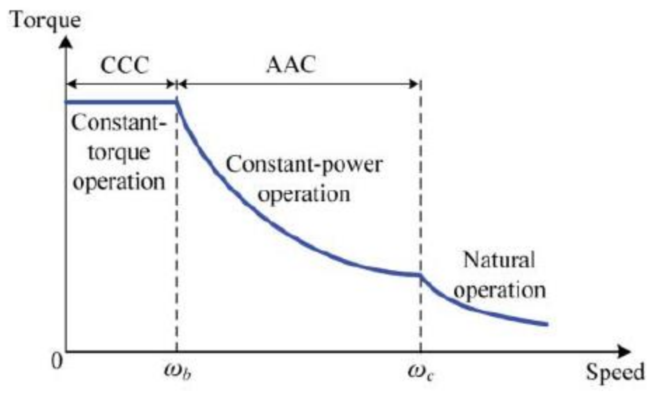
- As the principle of operation of the SR motor is fundamentally different from that of the conventional AC motors, the corresponding speed control schemes will be described first. Then, in order to alleviate the major drawback of the SR motor – relatively large torque ripples, the torque-ripple minimization (TRM) control will be discussed in detail. Moreover, because of the doubly salient structure, the SR motor is particularly suitable for position sensorless control.
- Speed Control: the current chopping control (CCC) and the advance angle control (AAC).



Current chopping control for constant-torque operation



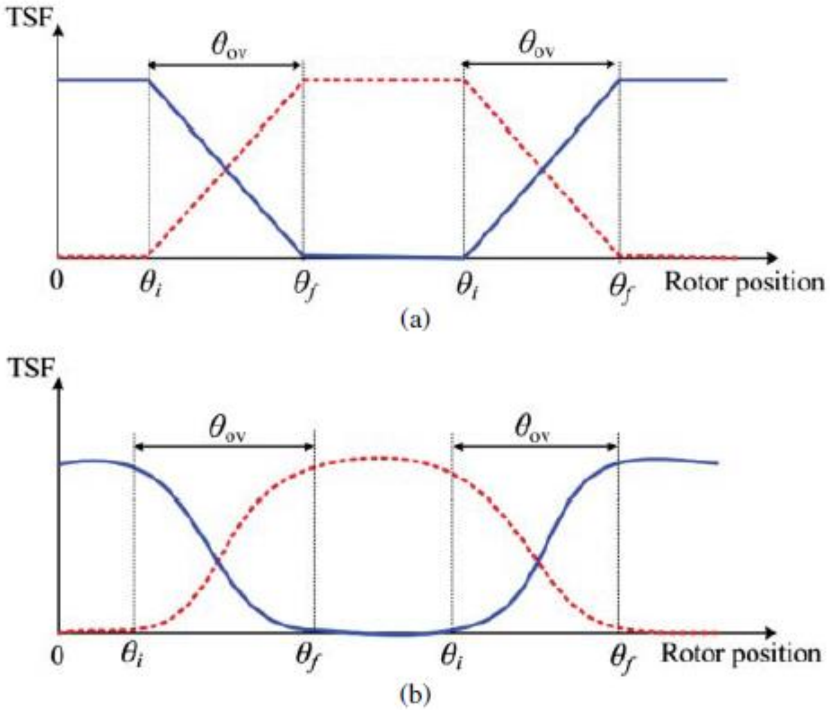
Advance angle control for constant-power operation



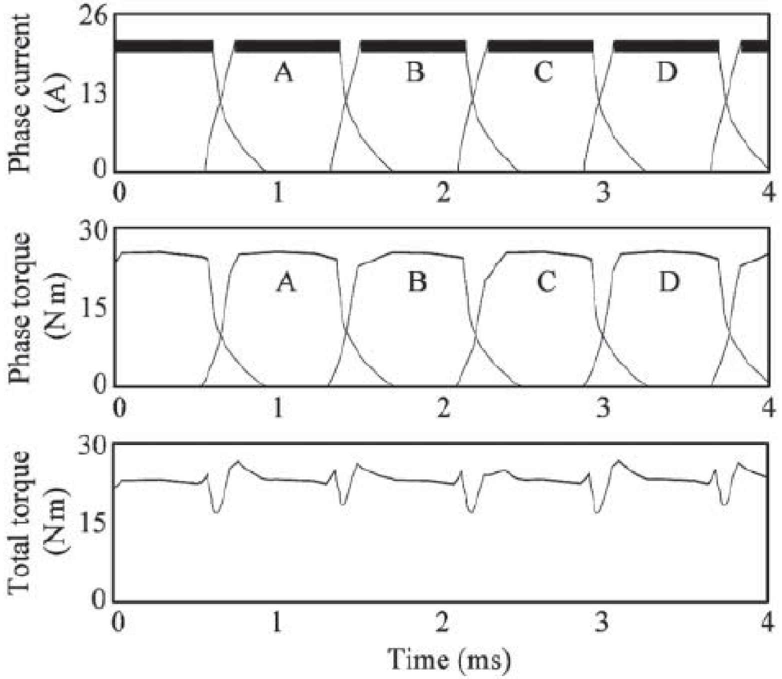
Torque-speed capability of SR motor

Converters and Control for SRM

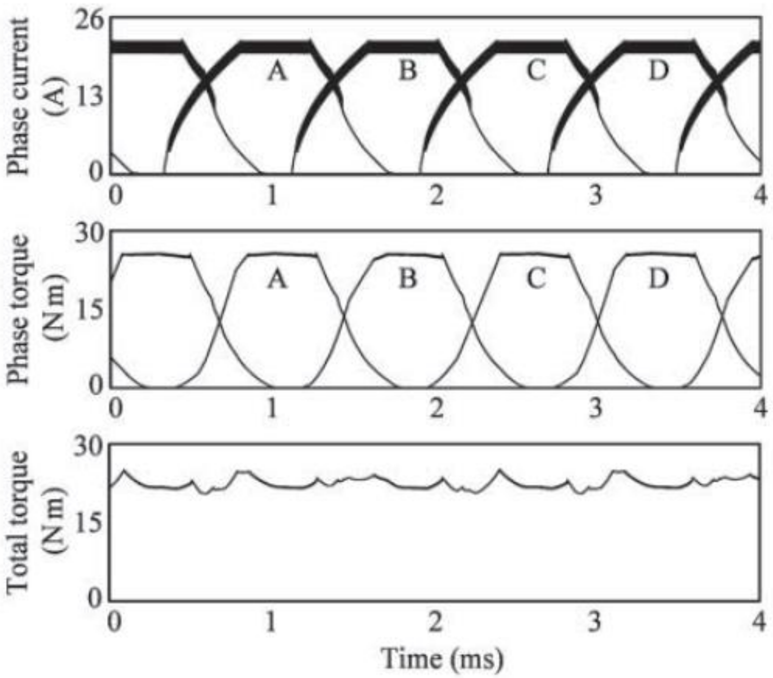
- Torque-Ripple Minimization Control: the direct instantaneous torque control and torque-sharing function (TSF) have gained attention for TRM control of SR motors. The TSF takes the definite advantage of easier implementation and higher cost-effectiveness.



Torque transfer functions: (a) linear and (b) nonlinear



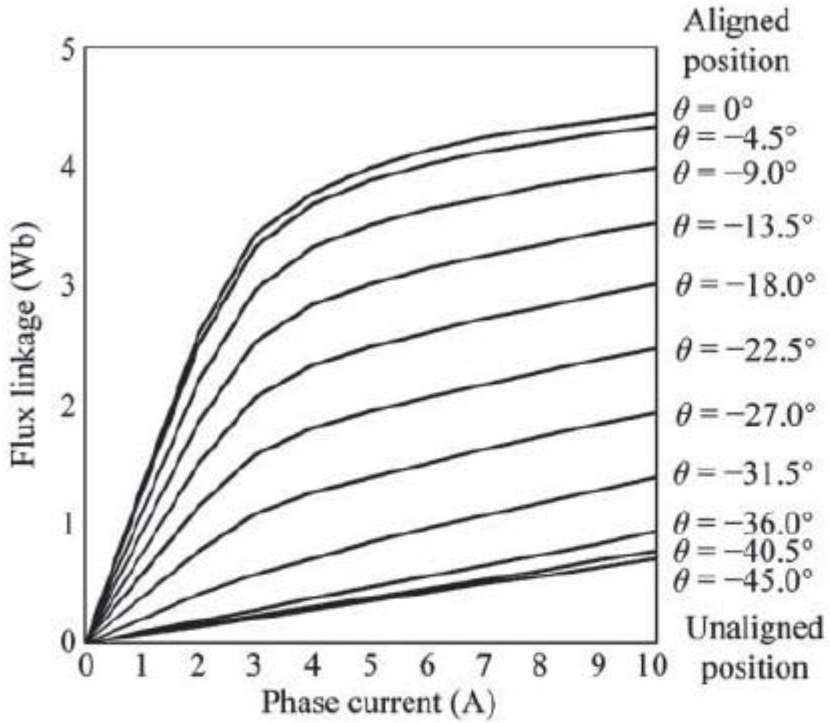
Operating waveforms without using torque-ripple minimization control



Operating waveforms with using torque-ripple minimization control

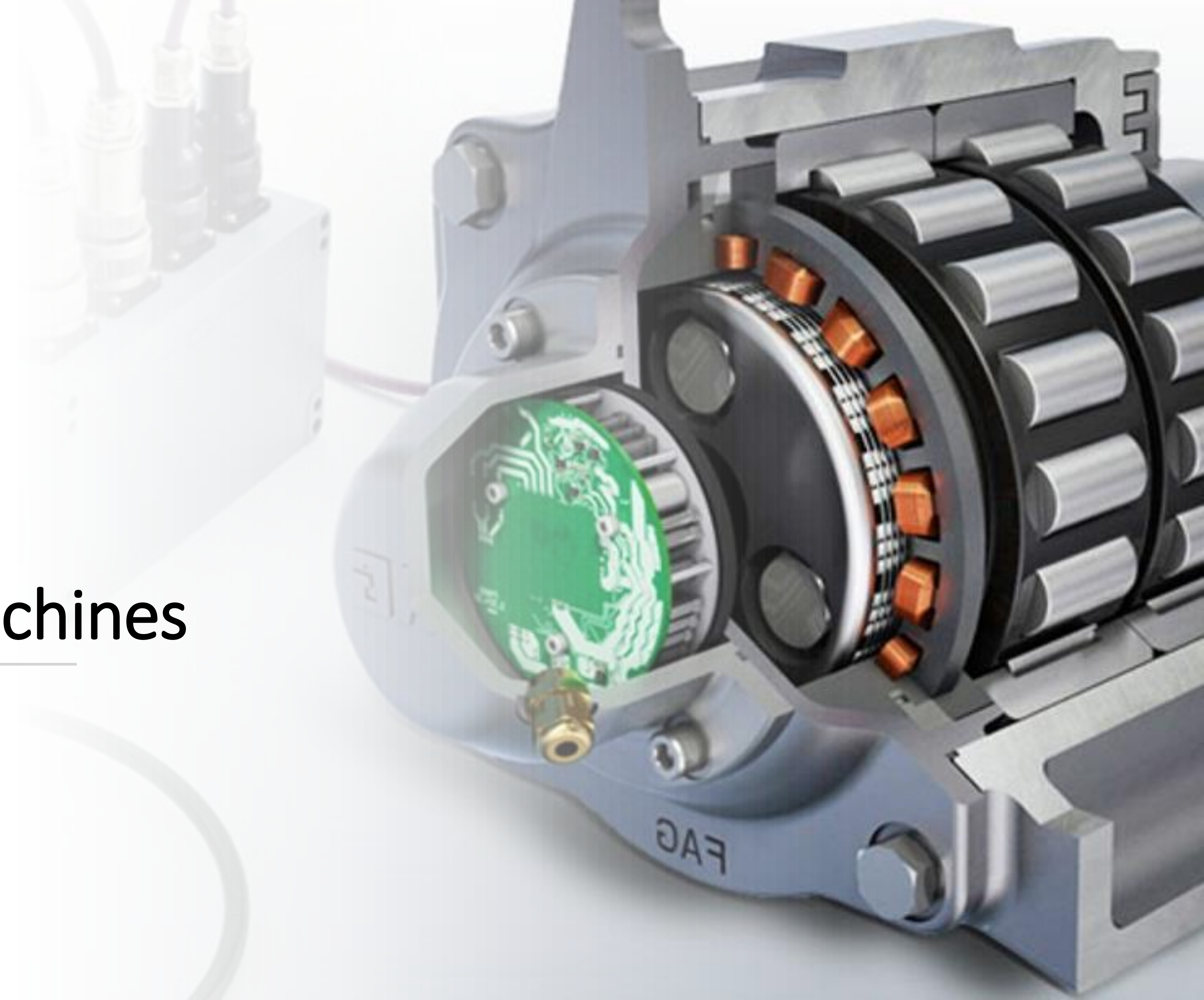
Converters and Control for SRM

- Position Sensorless Control: Many position sensorless control methods were developed over the past two decades. The commonly adopted position sensorless control methods can be categorized as
  - Flux linkage-based method.
  - Inductance-based method.
  - Signal injection-based method.
  - Current-based method.
  - Observer-based method.



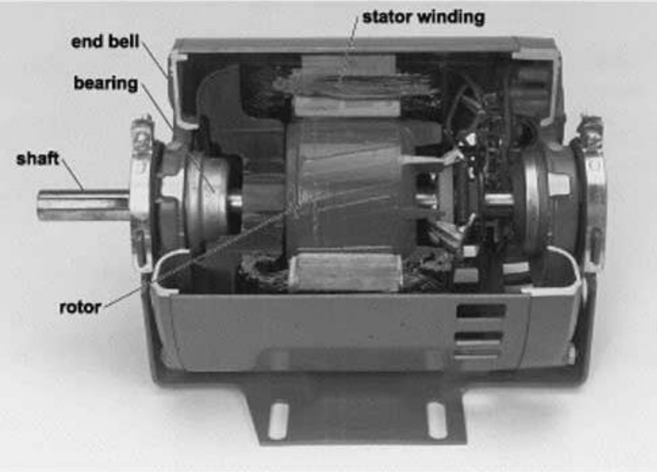
Relationship between flux linkage, phase current, and rotor position of SR motor

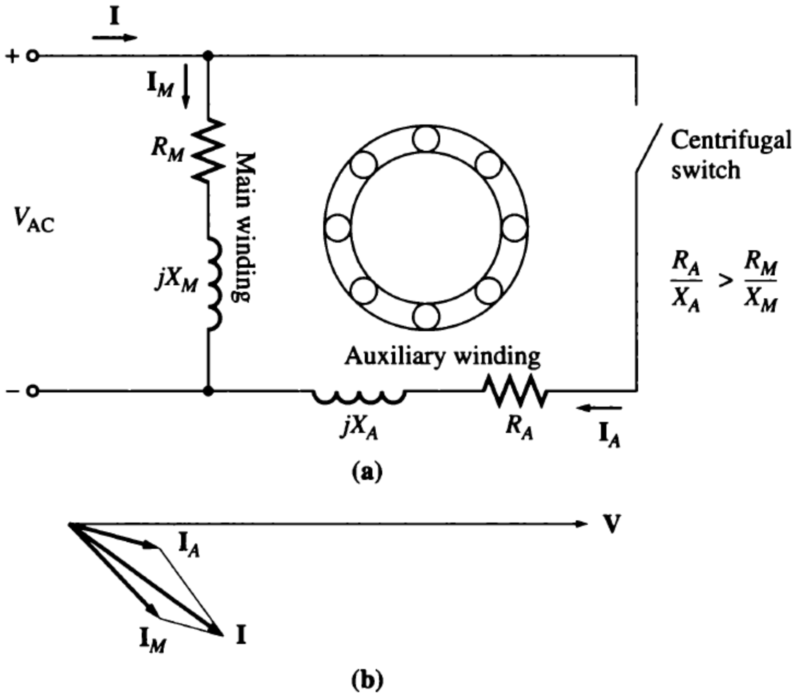
Other Special Machines

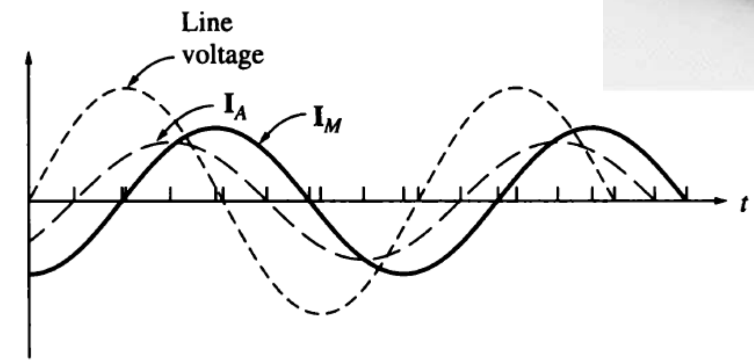


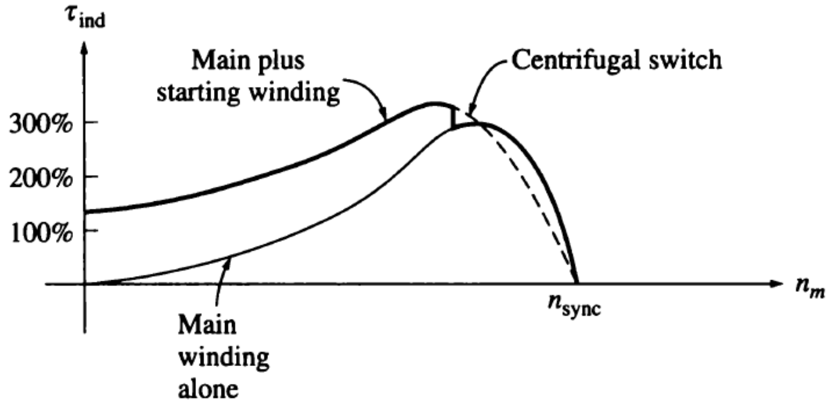
Starting Single-Phase Induction Motors

- A single-phase induction motor has no intrinsic starting torque.
- The three major starting techniques are
  1. Split-phase windings
  2. Capacitor-type windings
  3. Shaded stator poles





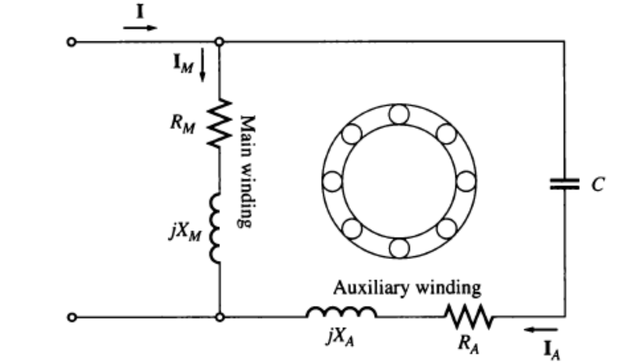


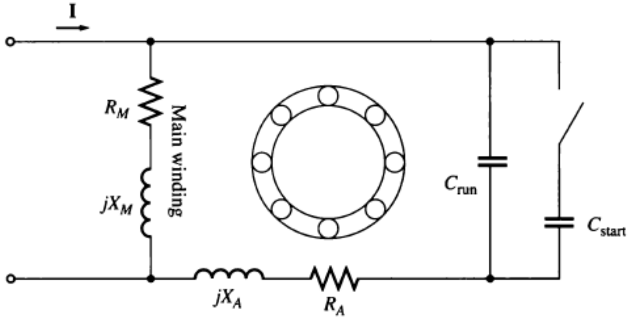


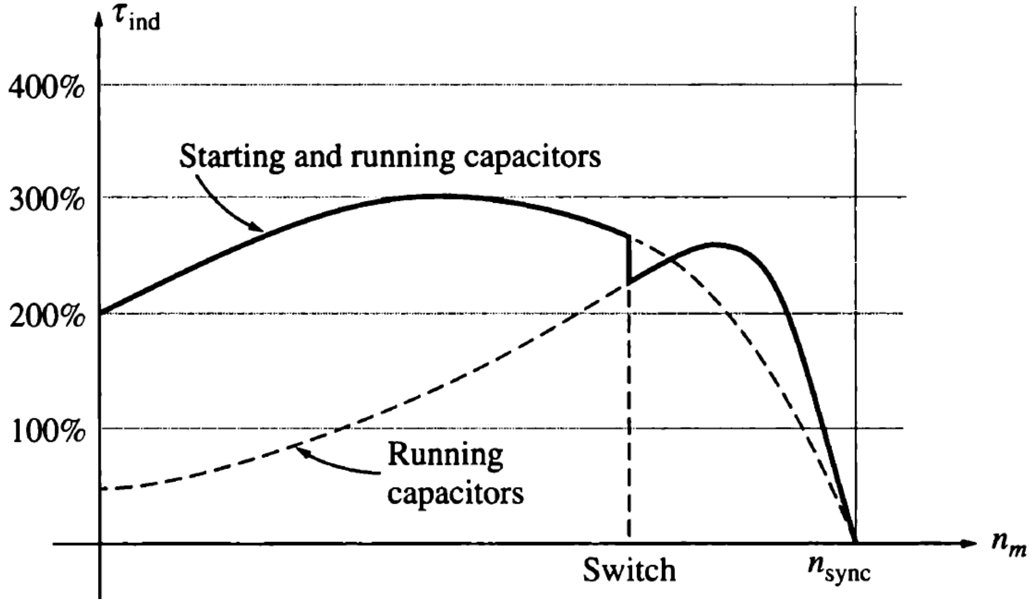
Starting Single-Phase Induction Motors

2. Capacitor-Start or Start-and-Run Motors

- In a capacitor-start motor, a capacitor is placed in series with the auxiliary winding of the motor. By proper selection of capacitor size, the magnetomotive force of the starting current in the auxiliary winding can be adjusted to be equal to the magnetomotive force of the current in the main winding, and the phase angle of the current in the auxiliary winding can be made to lead the current in the main winding by 90°.



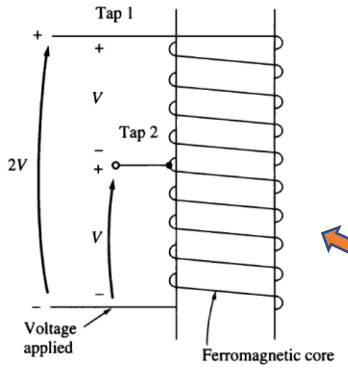


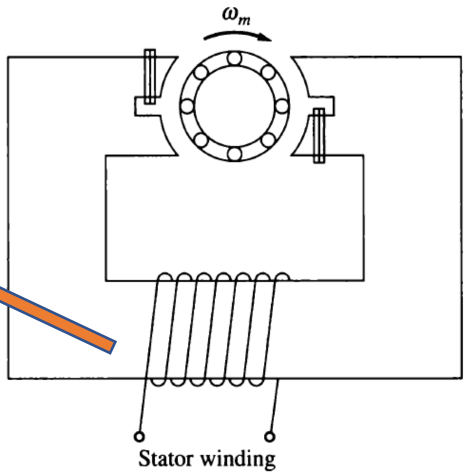


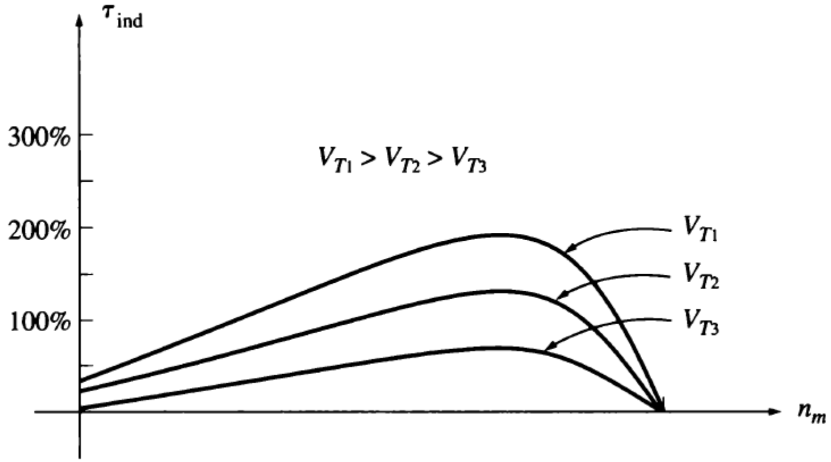
Starting Single-Phase Induction Motors

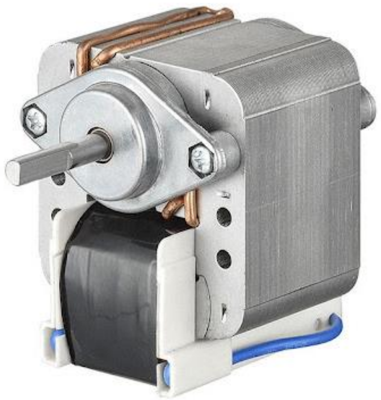
3. Shaded-Pole Motors

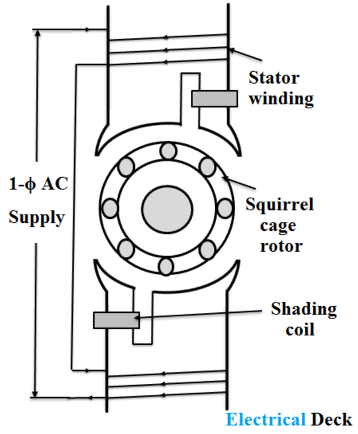
- A shaded-pole induction motor is an induction motor with only a main winding. Instead of having an auxiliary winding, it has salient poles, and one portion of each pole is surrounded by a short-circuited coil called a shading coil.
- When the pole flux varies, it induces a voltage and a current in the shading coil which opposes the original change in flux. This opposition retards the flux changes under the shaded portions of the coils and therefore produces a slight imbalance between the two oppositely rotating stator magnetic fields.







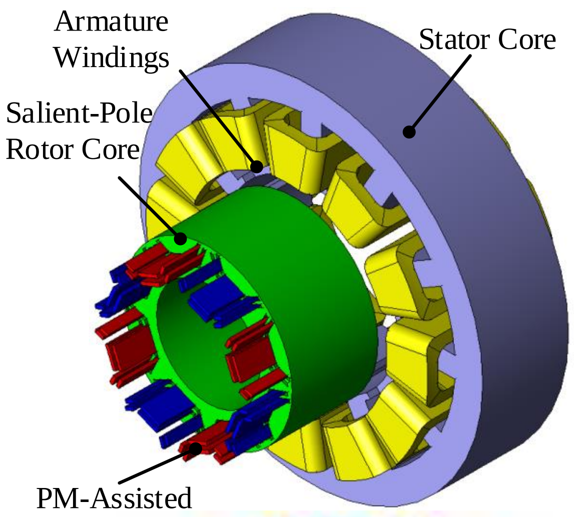


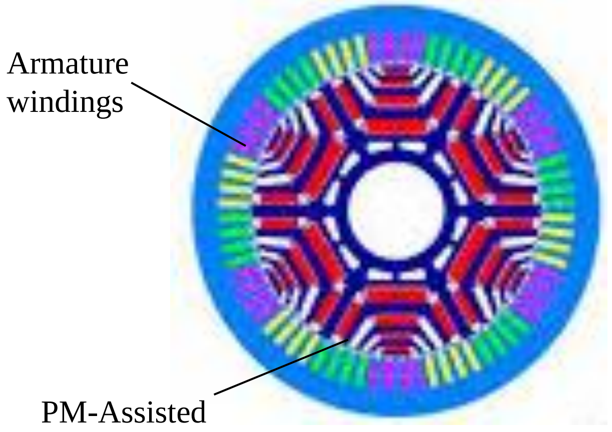


Permanent Magnet Synchronous Reluctance Machine

- Permanent-magnet assisted synchronous reluctance machine (PMA-SynRM) is a kind of reluctance machine with the assistance of PMs. It takes great advantage of the rotor pole saliency.

  - ✓ Saliency pole topology;
  - ✓ Large reluctance torque;
  - ✓ Less rare-earth PM;
  - ✓ Flux-weakening capacity;
  - ✓ Tricky rotor design and optimization;
  - ✓ Improves the machine reliability;
  - ✓ Popular for industrial application.

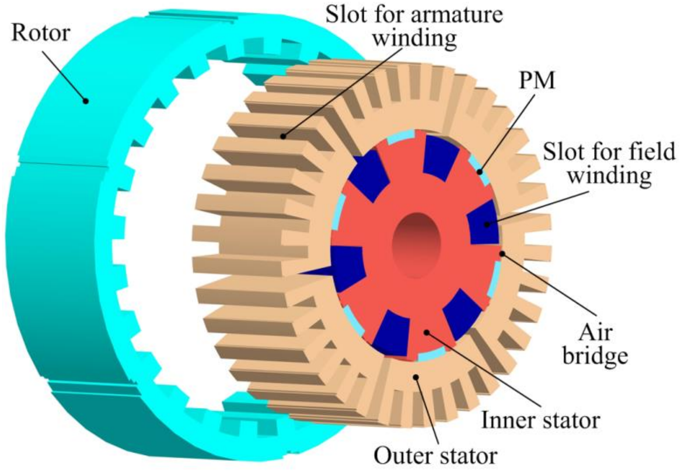


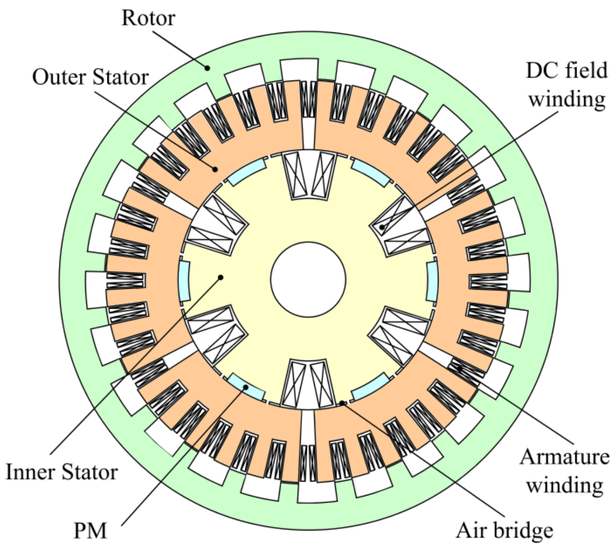


Merit: high torque density and few PMs

PM Hybrid Brushless Machine

- ✓ Hybrid field excitation by PMs and DC windings;
- ✓ Solid iron rotor, hence very robust;
- ✓ Outer-rotor inner-stator topology;
- ✓ Wide flux regulation range;
- ✓ Flux strengthening for boosting T;
- ✓ Flux weakening for high-speed opt.;
- ✓ Flux tuning for optimal efficiency.





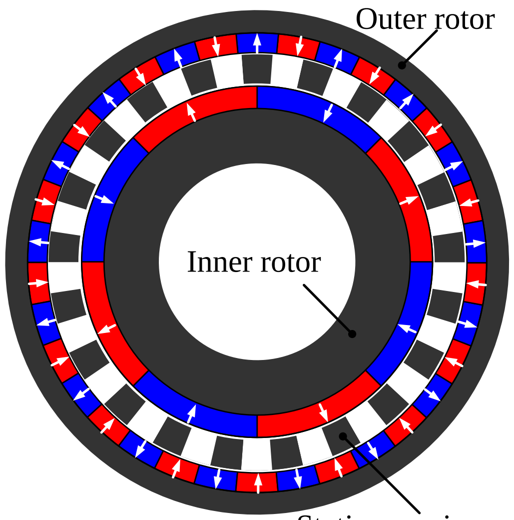
Merit: wide-speed flux-control

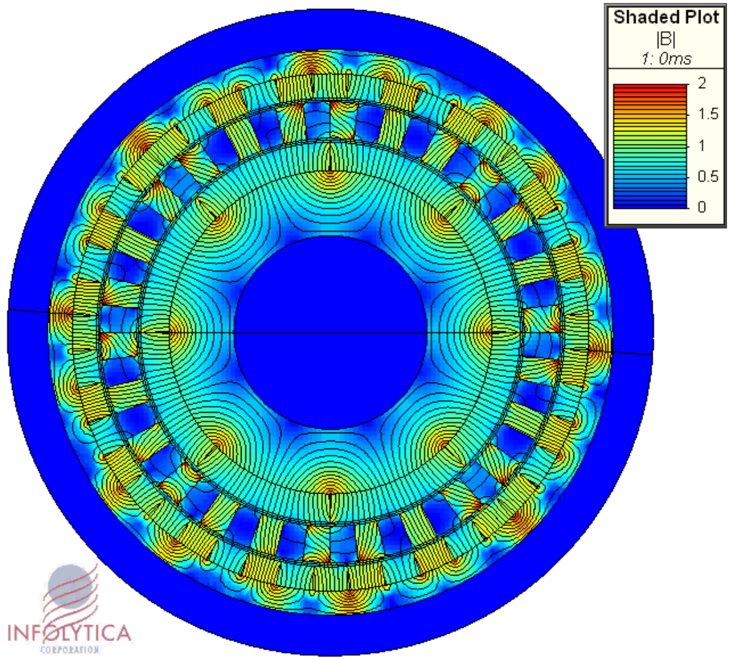
Magnetic-geared PM Machine (Magnetic Gear)

- ✓ Magnetic Gear:
- ✓ Torque density – up to 300 kNm/m3, even higher than some mechanical ones.
- ✓ Pros: No mechanical contact, remove shortcomings from mechanical ones.
- ✓ Cons: special design & under research.

$$N_s = p_1 + p_2 \qquad G_r = \frac{\omega_1}{\omega_2} = -\frac{p_2}{p_1}$$

- Coaxial arrangement;
- No mechanical wear or tear.





Magnetic-geared PM Machine (Magnetic Gear)

Mechanical gear:

- ✓ Purpose: speed variation & torque transmission.
- ✓ Torque density – up to 500 kNm/m3, which implies the capability to transmit torque within the unit volume size.
- ✓ Pros: very high torque density.
- ✓ Cons: cased by the contact mechanism:

  Friction loss;

  Audible noise;

  Mechanical vibration;

  Need of regular lubrication and maintenance.

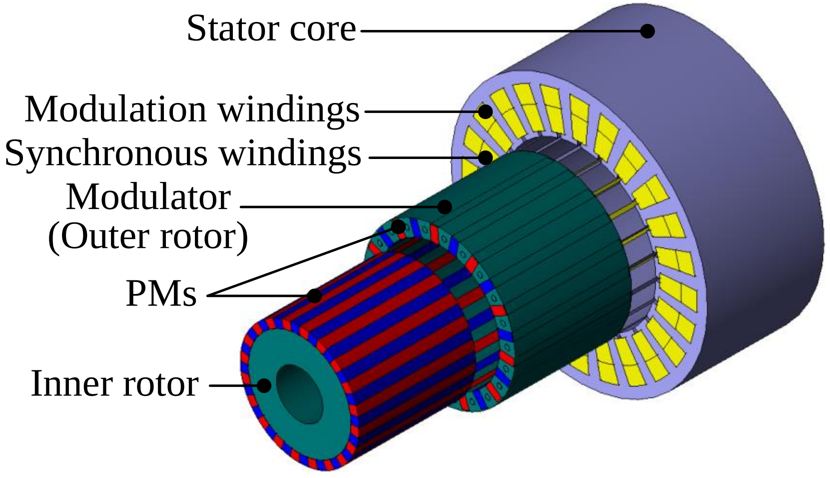
Merit: Low-speed high-torque.

Magnetic-geared PM Machine (Magnetic Gear)

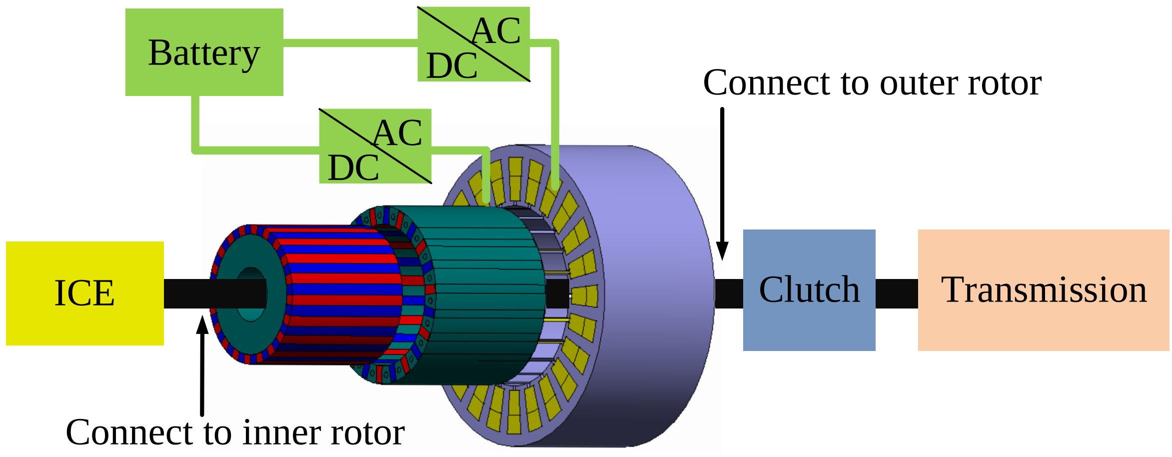
- Design principle:

$$p_{in} + p_a = Q$$

- Double-rotor double-winding topology;
- Magnetic gearing effect;
- Flux controllable;
- Compact structure;
- Multi operational modes.



Integration of motors and gearboxes within E-CVT



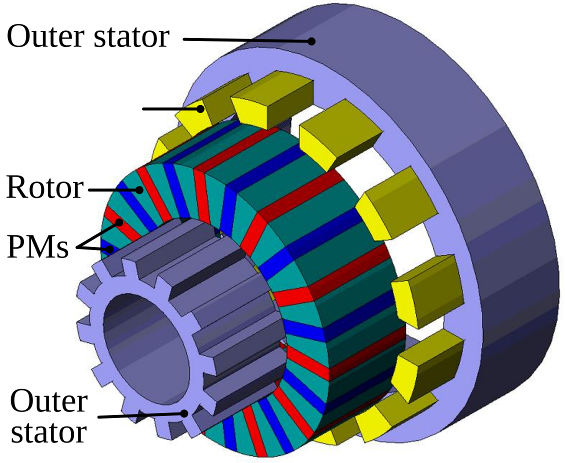
Double Stator PM Vernier Machine

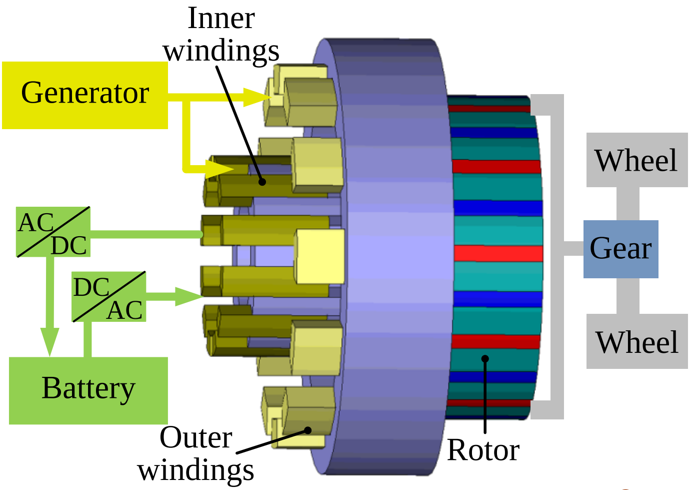
- ✓ Design principle:

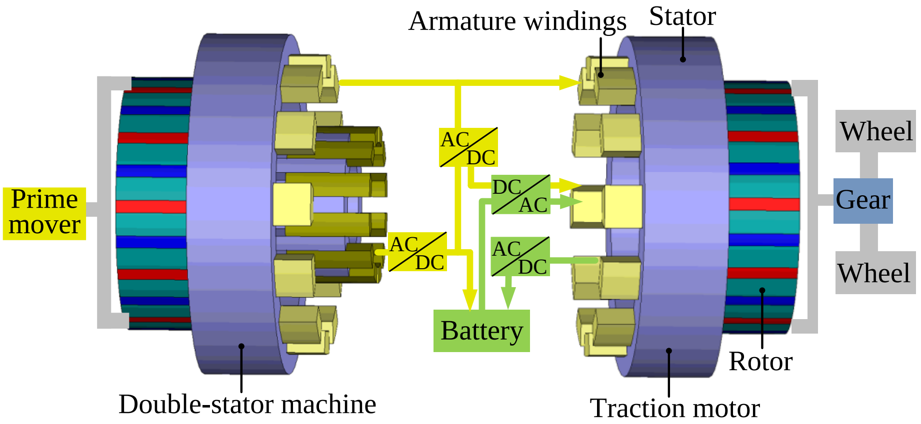
$$p_a = p_s - p_r$$

- ✓ Double-stator mid rotor topology;
- ✓ Flux-concentrating effect;
- ✓ Wide flux regulation range;
- ✓ High torque density and space utility;
- ✓ Multi operational modes;

Merit: simple structure and high flexibility





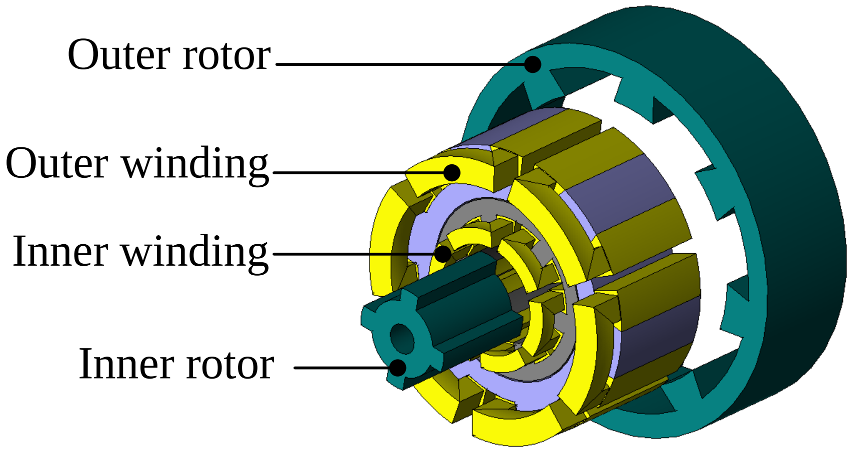


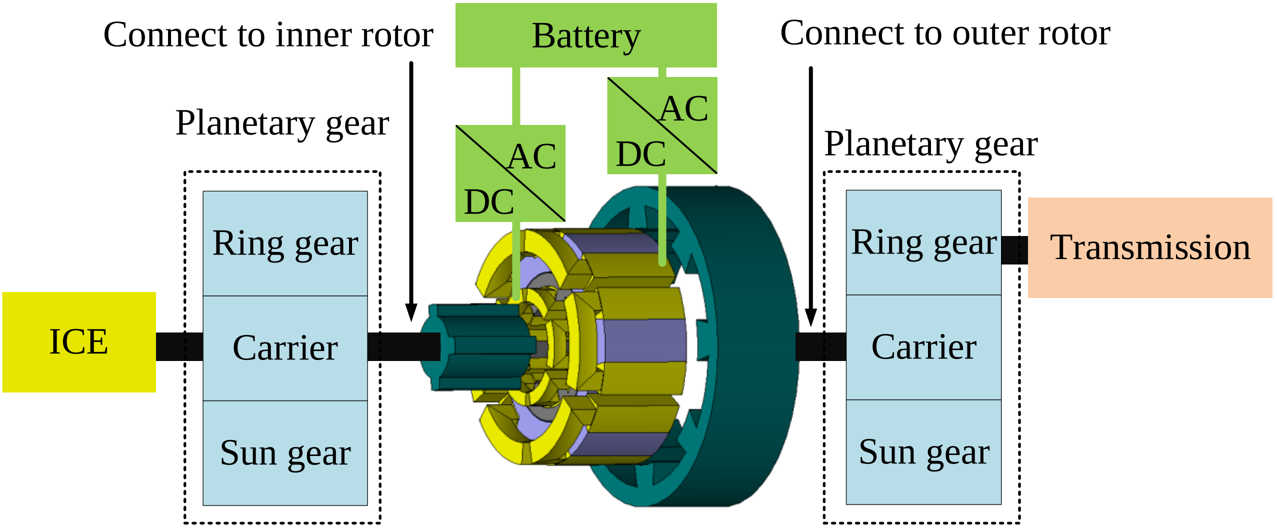
System configuration of E-CVT system with utilization of DS-PMV machine.

Double-Rotor Switched Reluctance Machine

- **Double-rotor switched reluctance machine (DRSRM)** is an SRM with two rotors. It can be actually regarded as the physical combinations of two switched reluctance machines. The operation principle of the DRSRM is the same as single-rotor switched reluctance machine.
  - ✓ Doubly-salient topology;
  - ✓ Robust and compact structure;
  - ✓ No PM;
  - ✓ Different working modes;
  - ✓ Great torque ripple;
  - ✓ Inherit all the cons and pros of single-rotor SRMs.

Merit: compact structure and low cost





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