<u>Construction and Working of Brushless DC Motors</u>

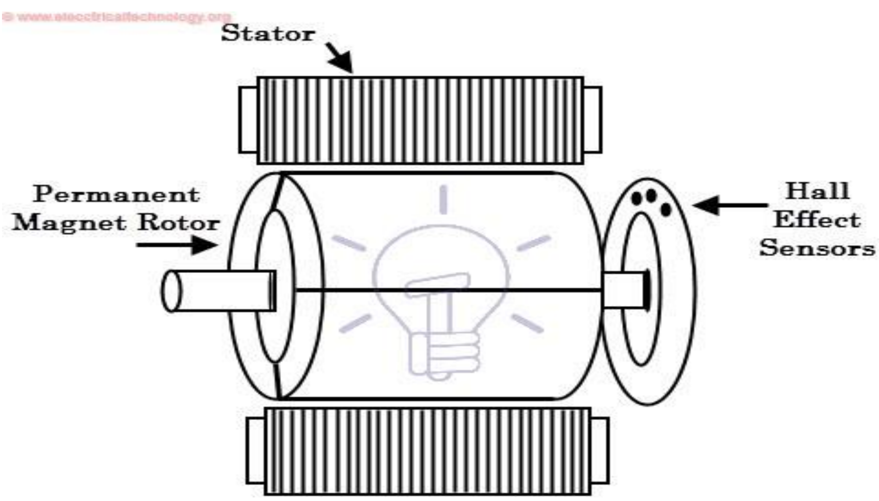
Electrical equipment often has at least one motor used to rotate or displace an object from its initial position. There are a variety of motor types available like induction motors, servomotors, DC motors (brushed and brushless), etc. to be used depending upon the application requirements. Most new designs are inclined towards Brushless DC Motors.

BLDC motors are superior to brushed DC motors in many ways, such as ability to operate at high speeds, high efficiency, and better heat dissipation. They are an indispensable part of modern drive technology, most commonly employed for actuating drives, machine tools, electric propulsion, robotics, computer peripherals and also for electrical power generation. With the development of sensor-less technology besides digital control, these motors have become very effective in terms of total system cost, size and reliability.

A brushless DC motor (known as BLDC) is a permanent magnet synchronous electric motor which is driven by direct current (DC) electricity and it accomplishes electronically controlled commutation system (commutation is the process of producing rotational torque in the motor by changing phase currents through it at appropriate times) instead of a mechanically commutation system. BLDC motors are also referred as trapezoidal permanent magnet motors.

<u>Construction:</u>

BLDC motors have many similarities to AC induction motors and brushed DC motors in terms of construction and working principles respectively. Like all other motors, BLDC motors also have a rotor and a stator.BLDC motors can be constructed in different physical configurations. Depending on the stator windings, these can be configured as single-phase, two-phase, or three-phase motors. However, three-phase BLDC motors with permanent magnet rotor are most commonly used.



Stator

Stator of a BLDC motor made up of stacked steel laminations to carry the windings. These windings are placed in slots which are axially cut along the inner periphery of the stator. These windings can be arranged in either star (Y) or Delta (Δ). The major difference between the two patterns is that the Y pattern gives high torque at low RPM and the Δ pattern gives low torque at low RPM. This is because in the Δ configuration, half of the voltage is applied across the winding that is not driven, thus increasing losses and, in turn, efficiency and torque. Most BLDC motors have three phase star connected stator.

Each winding is constructed with numerous interconnected coils, where one or more coils are placed in each slot. In order to form an even number of poles, each of these windings is distributed over the stator periphery. The stator must be chosen with the correct rating of the voltage depending on the power supply capability. For robotics, automotive and small actuating applications, 48 V or less voltage BLDC motors are preferred.

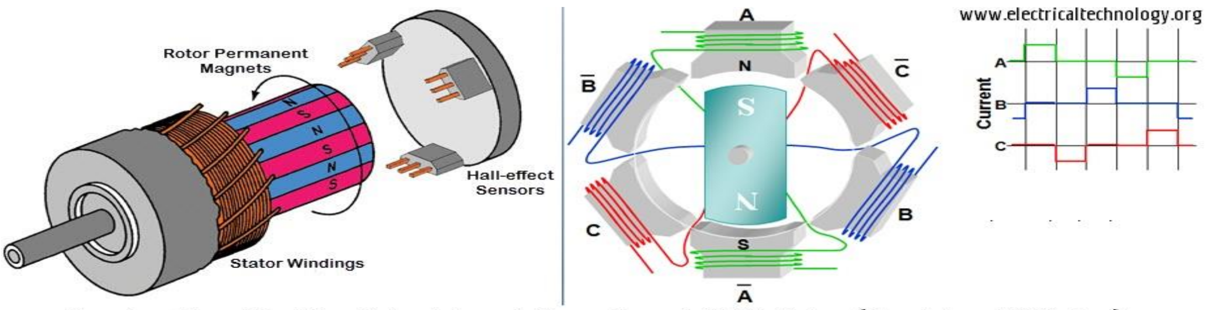
Rotor

BLDC motor incorporates a permanent magnet in the rotor. The number of poles in the rotor can vary from 2 to 8 pole pairs with alternate south and north poles depending on the application requirement. In order to achieve maximum torque in the motor, the flux density of the material should be high. A proper magnetic material for the rotor is needed to produce required magnetic field density. The rotor can be constructed with different core configurations such as the circular core with permanent magnet on the periphery, circular core with rectangular magnets, etc.

Hall Sensors
Hall sensor provides the information to synchronize stator armature excitation with rotor position. Since the commutation of BLDC motor is controlled electronically, the stator windings should be energized in sequence in order to rotate the motor. Before energizing a particular stator winding, acknowledgment of rotor position is necessary. So the Hall Effect sensor embedded in stator senses the rotor position.

Most BLDC motors incorporate three Hall sensors which are embedded into the stator. Each sensor generates Low and High signals whenever the rotor poles pass near to it. The exact commutation sequence to the stator winding can be determined based on the combination of these three sensor's response.

Working Principle and Operation of BLDC Motor
BLDC motor works on the principle similar to that of a conventional DC motor, i.e., the Lorentz force law which states that whenever a current carrying conductor placed in a magnetic field it experiences a force. As a consequence of reaction force, the magnet will experience an equal and opposite force. In case BLDC motor, the current carrying conductor is stationary while the permanent magnet moves.

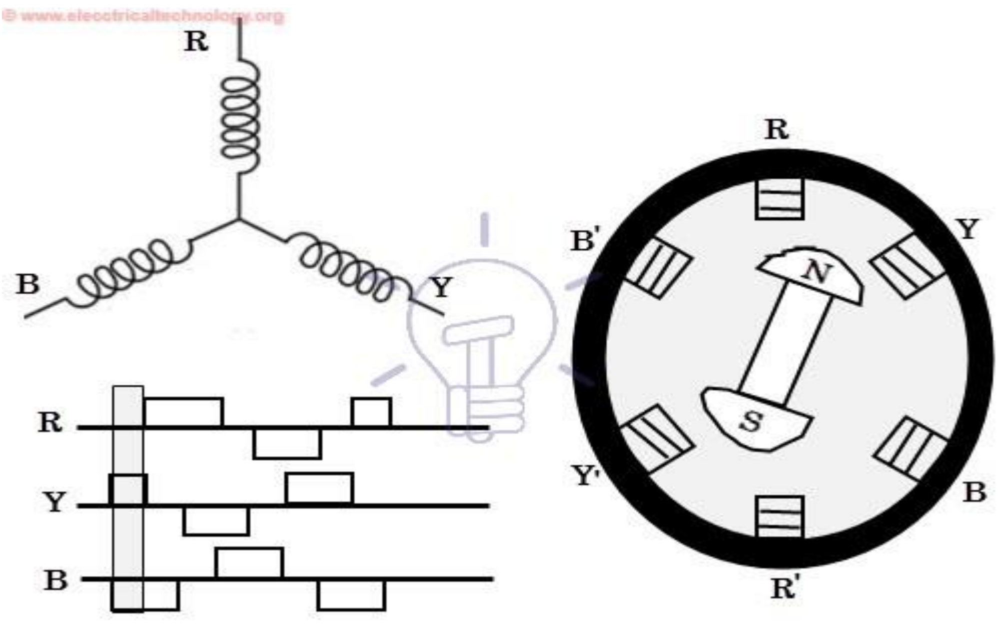


Construction, Working Principle and Operation of BLDC Motor (Brushless DC Motor)

When the stator coils are electrically switched by a supply source, it becomes electromagnet and starts producing the uniform field in the air gap. Though the source of supply is DC, switching makes to generate an AC voltage waveform with trapezoidal shape. Due to the force of interaction between electromagnet stator and permanent magnet rotor, the rotor continues to rotate.

Consider the figure below in which motor stator is excited based on different switching states. With the switching of windings as High and Low signals, corresponding winding energized as North and South poles. The permanent magnet rotor with North and South poles align with stator poles causing motor to rotate.

Observe that motor produces torque because of the development of attraction forces (when North-South or South-North alignment) and repulsion forces (when North-North or South-South alignment). By this way motor moves in a clockwise direction.



Switching Sequence

BLDC Motor

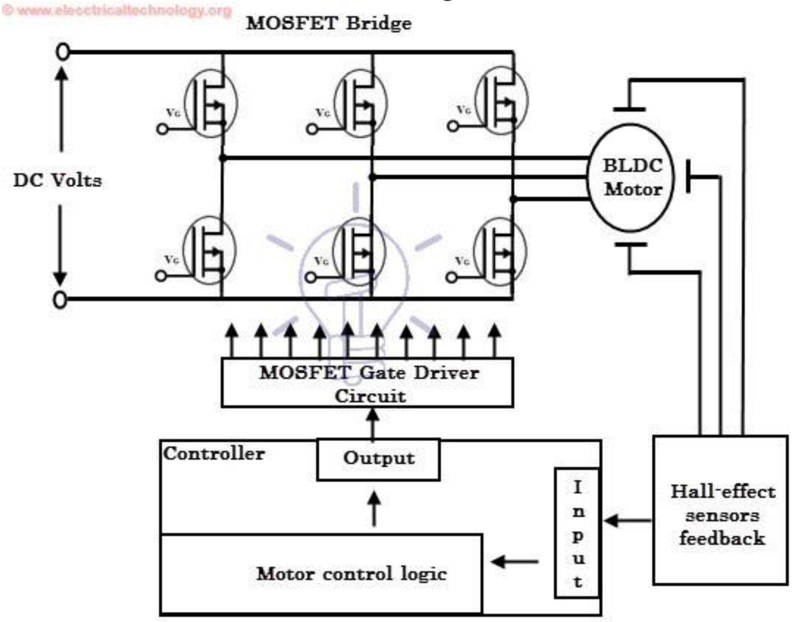
Here, one might get a question that how we know which stator coil should be energized and when to do. This is because; the motor continuous rotation depends on the switching sequence around the coils. As discussed above that Hall sensors give shaft position feedback to the electronic controller unit.

Based on this signal from sensor, the controller decides particular coils to energize. Hall-effect sensors generate Low and High level signals whenever rotor poles pass near to it. These signals determine the position of the shaft.

Brushless DC Motor Drive

As described above that the electronic controller circuit energizes appropriate motor winding by turning transistor or other solid state switches to rotate the motor continuously. The figure below shows the **simple BLDC motor drive circuit** which consists of MOSFET bridge (also called as inverter bridge), electronic controller, hall effect sensor and BLDC motor.

Here, Hall-effect sensors are used for position and speed feedback. The electronic controller can be a microcontroller unit or microprocessor or DSP processor or FPGA unit or any other controller. This controller receives these signals, processes them and sends the control signals to the MOSFET driver circuit.



In addition to the switching for a rated speed of the motor, additional electronic circuitry changes the motor speed based on required application. These speed control units are generally implemented with PID Controller to have precise control. It is also possible to produce four-quadrant operation from the motor whilst maintaining good efficiency throughout the speed variations using modern drives.

Advantages of BLDC Motor

BLDC motor has several advantages over conventional DC motors and some of these are

- It has no mechanical commutator and associated problems
- High efficiency due to the use of permanent magnet rotor
- High speed of operation even in loaded and unloaded conditions due to the absence of brushes that limits the speed
- Smaller motor geometry and lighter in weight than both brushed type DC and induction AC motors
- Long life as no inspection and maintenance is required for commutator system
- Higher dynamic response due to low inertia and carrying windings in the stator
- Less electromagnetic interference
- Quite operation (or low noise) due to absence of brushes

Disadvantages of BLDC Motor

- These motors are costly
- Electronic controller required control this motor is expensive
- Not much availability of many integrated electronic control solutions, especially for tiny BLDC motors
- Requires complex drive circuitry
- Need of additional sensors

Applications of BLDC Motors

Brushless DC motors (BLDC) are used for a wide variety of application requirements such as varying loads, constant loads and positioning applications in the fields of industrial control, automotive, aviation, automation systems, health care equipments, etc. Some specific applications of BLDC motors are

- Computer hard drives and DVD/CD players
- Electric vehicles, hybrid vehicles, and electric bicycles
- Industrial robots, CNC machine tools, and simple belt driven systems
- Washing machines, compressors and dryers
- Fans, pumps and blowers

Torque and Efficiency

For the study of electric motors, torque is a very important term. By definition, torque is the tendency of force to rotate an object about its axis.

$$Torque\ (Newton - meters) = Force\ (Newton)\ X\ Distance\ (meters)$$

Thus, to increase the torque, either force has to be increased – which requires stronger magnets or more current – or distance must be increased – for which bigger magnets will be required. Efficiency is critical for motor design because it determines the amount of power consumed. A higher efficiency motor will also require less material to generate the required torque.

$$Efficiency = \frac{Output\ Power}{Input\ Power}\%$$

Where,

$$Output\ Power = Torque\ X\ Angular\ Velocity,\ \text{and}$$

$$Input\ Power = Voltage\ X\ Current$$

Having understood the above provided equations, it becomes important to understand the speed vs. torque curve.

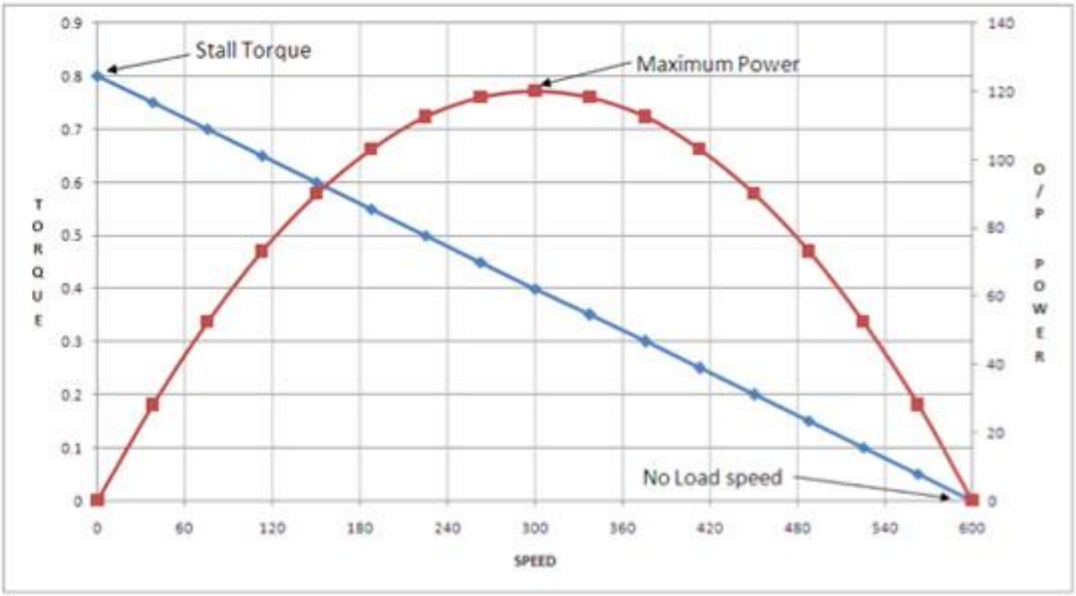


Figure 5: Speed-Torque-Power curve

As can be seen from the graph-

- With an increase in speed, the torque reduces (considering the input power is constant).
- Maximum power can be delivered when the speed is half of the “no load” speed and torque is half of the stall torque.

Comparison of BLDC motor with other motors

Feature	Brushless DC motor	Brushed DC motor	Induction Motor
Mechanical Structure	Field magnets on the stator and rotor are made of permanent magnets	Field magnets on the rotor and stator are made of permanent magnets or electromagnets	Both the rotor and stator have windings but the AC lines are connected to the stator
Maintenance	Low or no maintenance	Periodic maintenance because of brushes	Low maintenance
Speed-Torque characteristics	Flat – Operation at all speeds with rated load	Moderate – Loss in torque at higher speeds because of losses in brushes	Non-linear
Efficiency	High – No losses in the brushes; Stator is on the outer periphery and is thus able to dissipate more heat and produce more torque	Moderate – Losses in the brushes; Rotor is on the inner periphery	Low – Heat and current losses in both rotor and stator; High efficiency Induction motors are also available (higher cost)
Commutation method	Using solid state switches	Mechanical contacts between brushes and commutator	Special starting circuit is required
Speed range	High – No losses in brushes	Moderate – Loses in brushes	Low – Determined by the AC line frequency; Increases in load further reduces speed
Electrical noise	LOW	High – Because of brushes	LOW
Detecting method of rotor's position	Hall sensors, optical encoders, etc.	Automatically detected by brushes and commutator	NA
Direction reversal	Reversing the switching sequence	Reversing the terminal voltage	By changing the two phases of the motor input
Control requirements	A controller is always required to control the commutation sequence	No controller is required for a fixed speed; controller required for variable speed	No controller is required for a fixed speed; controller required for variable speed
System cost	High – Because of external controller requirement	Low	Low

Switched Reluctance Motors

Electric machines can be broadly classified into two categories on the basis of how they produce torque − electromagnetically or by variable reluctance. In the first category, motion is produced by the interaction of two magnetic fields, one generated by the stator and the other by the rotor. Two magnetic fields, mutually coupled, produce an electromagnetic torque tending to bring the fields into alignment. The same phenomenon causes opposite poles of bar magnets to attract and like poles to repel. The vast majority of motors in commercial use today operate on this principle. These motors, which include DC and induction motors, are differentiated based on their geometries and how the magnetic fields are generated. Some of the familiar ways of generating these fields are through energized windings, with permanent magnets, and through induced electrical currents.

In the second category, motion is produced as a result of the variable reluctance in the air gap between the rotor and the stator. When a stator winding is energized, producing a single magnetic field, reluctance torque is produced by the tendency of the rotor to move to its minimum reluctance position. This phenomenon is analogous to the force that attracts iron or steel to permanent magnets. In those cases, reluctance is minimized when the magnet and metal come into physical contact. As far as motors that operate on this principle, the switched reluctance motor (SRM) falls into this class of machines.

The Switched Reluctance Motor is a brushless AC motor.The switched reluctance motor (SRM) is a type of a stepper motor, an electric motor that runs by reluctance torque. Unlike common DC motor types, power is delivered to windings in the stator rather than the rotor. This greatly simplifies mechanical design as power does not have to be delivered to a moving part, but it complicates the electrical design as some sort of switching system needs to be used to deliver power to the different windings.

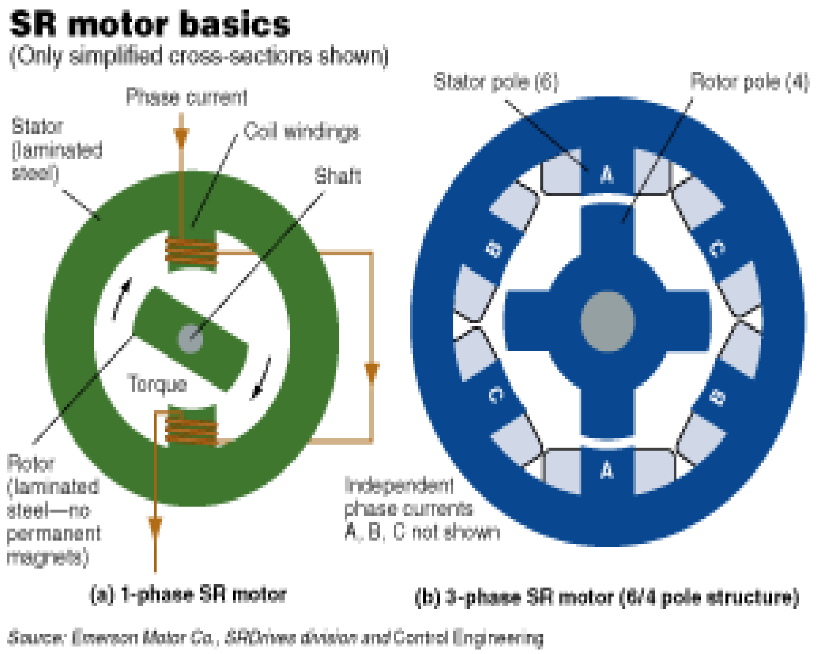
Construction

The SRM is the simplest of all electrical machines. Only the stator has windings. The rotor contains no conductors or permanent magnets. It consists simply of steel laminations stacked onto a shaft.

It is because of this simple mechanical construction that SRMs carry the promise of low cost, which in turn has motivated a large amount of research on SRMs in the last decade.

The mechanical simplicity of the device, however, comes with some limitations. Like the brushless DC motor, SRMs cannot run directly from a DC bus or an AC line, but must always be electronically commutated. Also, the saliency of the stator and rotor, necessary for the machine to produce reluctance torque, causes strong non-linear magnetic characteristics, complicating the analysis and control of the SRM. Not surprisingly, industry acceptance of SRMs has been slow. This is due to a combination of perceived difficulties with the SRM, the lack of commercially available electronics with which to operate them, and the entrenchment of traditional AC and

DC machines in the marketplace. SRMs do, however, offer some advantages along with potential low cost. For example, they can be very reliable machines since each phase of the SRM is largely independent physically, magnetically, and electrically from the other motor phases. Also, because of the lack of conductors or magnets on the rotor, very high speeds can be achieved, relative to comparable motors. Disadvantages often cited for the SRM; that they are difficult to control, that they require a shaft position sensor to operate, they tend to be noisy, and they have more torque ripple than other types of motors; have generally been overcome through a better understanding of SRM mechanical design and the development of algorithms that can compensate for these problems.



Working Principle

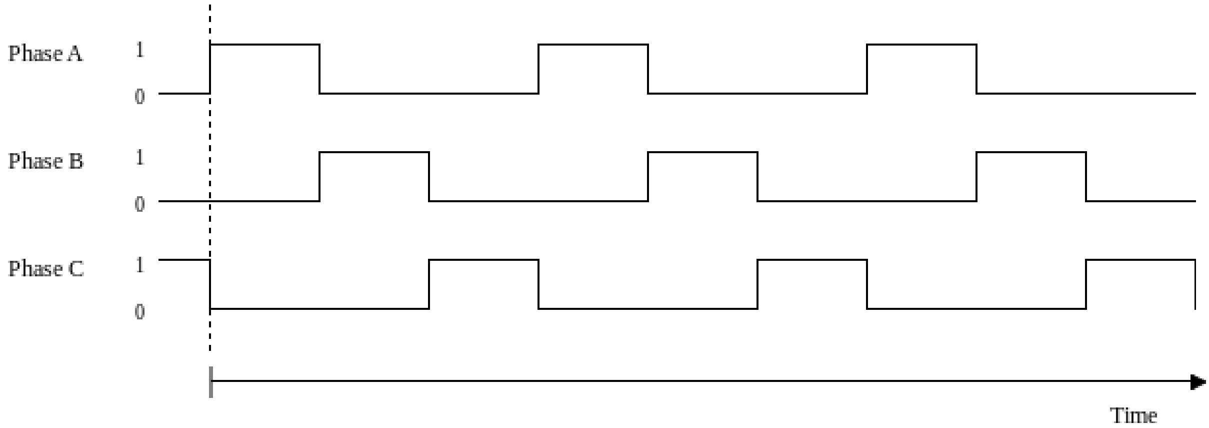
The basic operating principle of the SRM is quite simple; as current is passed through one of the stator windings, torque is generated by the tendency of the rotor to align with the excited stator pole. The direction of torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flow through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase's excitation with the rotor position. By varying the number of phases, the number of stator poles, and the number of rotor poles, many different SRM geometries can be realized.

Generally, increasing the number of SRM phases reduces the torque ripple, but at the expense of requiring more electronics with which to operate the SRM. At least two phases are required to guarantee starting, and at least three phases are required to insure the starting direction. The number of rotor poles and stator poles must also differ to insure starting.

The SRM has wound field coils as in a DC Motor for the stator windings. The rotor however has no magnets or coils attached. It is a solid salient-pole rotor (having projecting magnetic poles) made of soft magnetic material (often laminated-steel). When power is applied to the stator windings, the rotor's magnetic reluctance creates a force that attempts to align the rotor pole with the nearest stator pole. In order to maintain rotation, an electronic control system switches on the windings of successive stator poles in sequence so that the magnetic field of the stator "leads" the rotor pole, pulling it forward. Rather than using a troublesome high-maintenance mechanical commutator to switch the winding current as in traditional motors, the switched-reluctance motor uses an electronic position sensor to determine the angle of the rotor shaft and solid state electronics to switch the stator windings, which also offers the opportunity for dynamic control of pulse timing and shaping. This differs from the apparently similar induction motor which also has windings that are energised in a rotating phased sequence, in that the magnetization of the rotor is static (a salient pole that is made 'North' remains so as the motor rotates) while an induction motor has slip, and rotates at slightly less than synchronous speed. This absence of slip makes it possible to know the rotor position exactly, and the motor can be stepped arbitrarily slowly.

Simple Switching

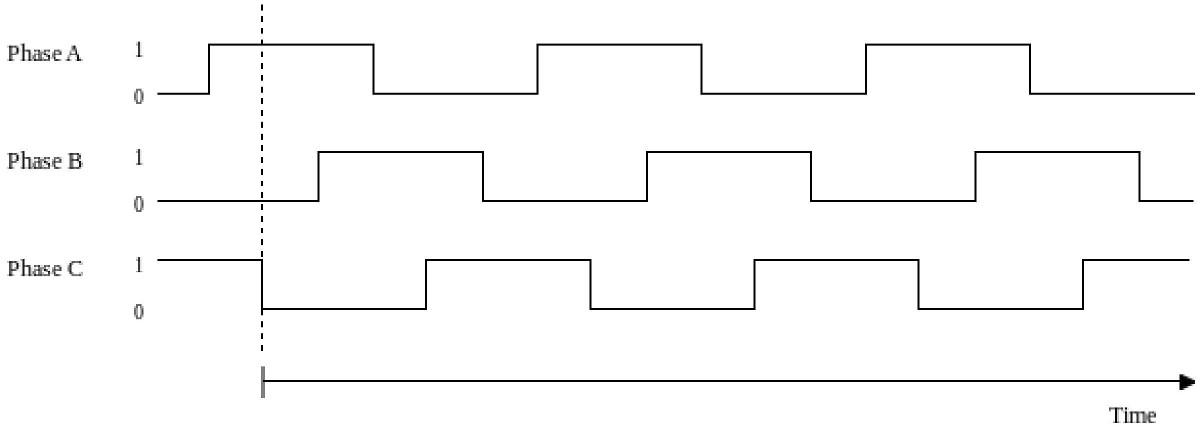
If the poles A0 and A1 are energised then the rotor will align itself with these poles. Once this has occurred it is possible for the stator poles to be de-energised before the stator poles of B0 and B1 are energized. The rotor is now positioned at the stator poles b. This sequence continues through c before arriving back at the start. This sequence can also be reversed to achieve motion in the opposite direction. This sequence can be found to be unstable while in operation, under high load, or high acceleration or deceleration, a step can be missed, and the rotor jumps to wrong angle, perhaps going back one instead of forward three.



Improved sequence

A much more stable system can be found by using the following "quadrature" sequence. First, stator poles like A0 and A1 are energized. Then stator poles of B0 and B1 are energized which pulls the rotor so that it is aligned in between the stator poles of A and B. Following this the stator poles of A are de-energized and the rotor continues on to be aligned with the stator poles of B, this sequence continues through BC, C and CA before a full rotation has occurred. This sequence can also be reversed to achieve motion in the opposite direction. As at any time two coils are energised, and there are more steps between positions with identical magnetisation, so the onset of missed steps occurs at higher speeds or loads.

In addition to more stable operation, this approach leads to a duty cycle of each phase of 1/2, rather than 1/3 as in the simpler sequence.



Control

The control system is responsible for giving the required sequential pulses to the power circuitry in order to activate the phases as required. While it is possible to do this using electro-mechanical means such as commutators or simple analog or digital timing circuits, more control is possible with more advanced methods.

Many controllers in use incorporate programmable logic controllers (PLCs) rather than electromechanical components in their implementation. A microcontroller is also ideal for this kind of application since it enables a very precise control of the phase activation timings. It also gives the possibility of implementing a soft start function in software form, in order to reduce the amount of hardware required.