Departamento de
Ingeniería Industrial
Universidad de La Laguna

TEMA IV: OTRAS MÁQUINAS

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BLDC MOTOR – BRUSHLESS DC MOTOR (ELECTRONICALLY-COMMUTATED (EC) MOTOR)

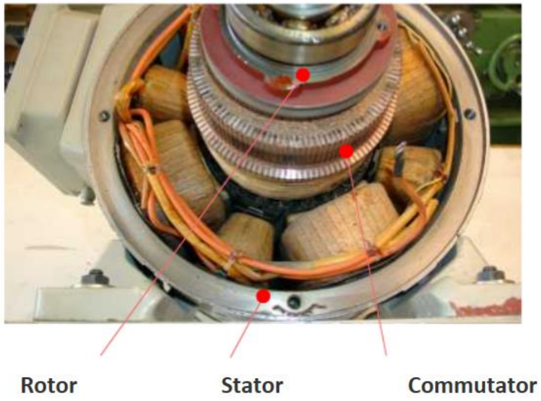
Introduction. BLDC motor

DC motors are very popular machines for drive technology due to their controllability both in terms of torque and speed. The torque is proportional to the current and independent of the speed.

However, DC motors have one huge disadvantage:

The commutator (see photograph) of a DC machine requires maintenance at regular intervals because the carbon brushes wear down due to the friction with the copper laminated sheets of the commutator. Consequently, the commutator is the greatest weakness of a DC motor.

A commutator is needed to be able to supply a current to the coils in the rotor relative to the magnetic field of the stator.



Introduction. BLDC motor

One solution would be to replace the commutator with external, electronic valves, but this does not solve the problem of how to get power to the rotor. If we look to the design of a permanently excited DC machine for a solution, then it may be seen that the rotor windings and the permanent magnets of the stator are capable of being swapped over. Doing this provides you with a permanently excited synchronous machine (PSM).

This solves the problem of how to get power transferred to the rotor. Now the external commutator only needs to switch the windings at the right time (i.e. when the rotor is in the appropriate position. This new design also offers many more additional advantages:

- Higher efficiency since the design means less space is needed
- Elimination of temperature-critical components in the machine
- Heat can be released directly through the outer wall
- No further need for maintenance
- Rotor can be immersed in fluids (protection classes)
- Lower noise factor
- Less rotor inertia: improved acceleration or deceleration
- Identical operating response to a conventional DC motor
- The potential number of magnetic pole pairs can easily range from 2 to16

Introduction. BLDC motor

BLDC machines have gradually been developed from DC motors and permanently excited synchronous motors over the last 50 years. It was with the emergence of transistor semiconductors (electronic valves) that the idea of a BLDC motor first appeared.

For the first time, the development of semiconductor components made it possible to achieve multi-phase drive of a permanently excited motor with variable frequencies and thus significantly reduce the initial run-up problems afflicting such machines. Also, new and better magnetic materials were being developed, e.g. using rare-earth metals. This boosted the effectiveness of permanently excited synchronous machines.

The operating response of a permanently excited synchronous machine with a rotor-speed adjusted feed frequency closely matches the response of a DC machine in terms of speed, torque and current.

Due to the simple design, this type of motor is very cost-effective.

Introduction. BLDC motor

The difference between a DC motor and a brushless DC motor (BLDC) or electronically-commutated (EC) motor is in the design: windings are located in the stator with permanent magnets in the rotor. Commutation is performed by means of semiconductor components. It is difficult to say why people refer to a brushless DC motor, since the design is far more reminiscent of a permanently excited synchronous motor. The operating response of a BLDC motor with closed-loop control is more like that of a DC motor, however, so this might be the reason for the nomenclature.

Another difference between a BLDC motor and a permanently excited synchronous motor is the power supply. A permanently excited synchronous motor is powered via a sinusoidally-shaped current, whereas a BLDC motor is normally powered by a current with a square-wave form. This is reflected in the characteristic for the magnetic flux. A permanently excited synchronous machine is designed so that magnetization is brought about following a sinusoidal curve. In contrast a BLDC motor is magnetized in a fashion that is more trapezoidal in nature. If you switch the two types of machines on and measure the voltage present at the unconnected terminals, the voltage characteristic will either be sinusoidal or not.

Introduction. BLDC motor

Disadvantages of BLDC motors as compared to DC machines:

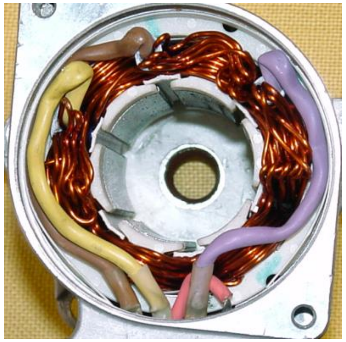
- The standard range tends to be in the upper speed range
- Additional semiconductors are required
- Rotor position detection is required
- Open-loop control is required for the winding current
- The simplest form of DC machine needs only a mains switch to control it(on/off)
- Increased technical complexity leads to additional sources of error
- Added costs for electronic commutation must be offset by long service life.

Introduction. BLDC motor

Like any electrical machine BLDC motors consist of a stationary component and a moveable (mostly rotating) part. The stationary part is called the stator and the rotating component of the machine is called the rotor.

A rotor equipped with permanent magnets

The photograph below shows a stator including windings

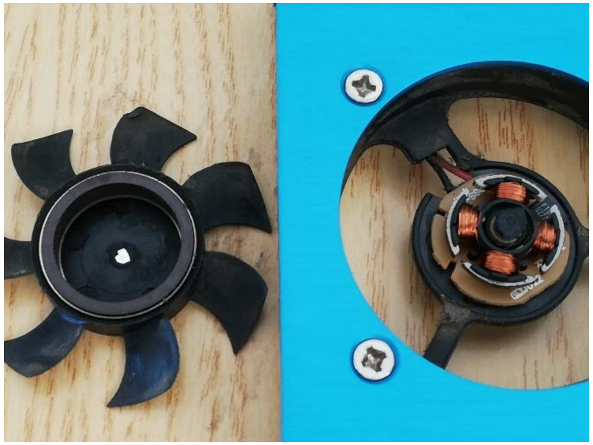


The number of pole pairs here is two. The number of pole pairs determines the ratio of the mechanical rotation of the rotor to the rotation of the electrical field. In this case where the number of pole pairs is two, two electrical rotations are required so that the rotor can complete one actual revolution.

$$n_{mech} = \frac{f_{el}}{p}$$

Introduction. BLDC motor

One more possible design of BLDC motor is **an external rotor model**. In this version the stator with its windings is located on the inside of the motor. The permanent magnets rotate around the stator. This design is typical for ventilator or fan drives, which are mostly operated using two phases:



The permanent magnets are in a staggered arrangement inside the fan impeller (wheel). Electronic commutation is controlled by a Hall sensor (located at the top right between the poles).

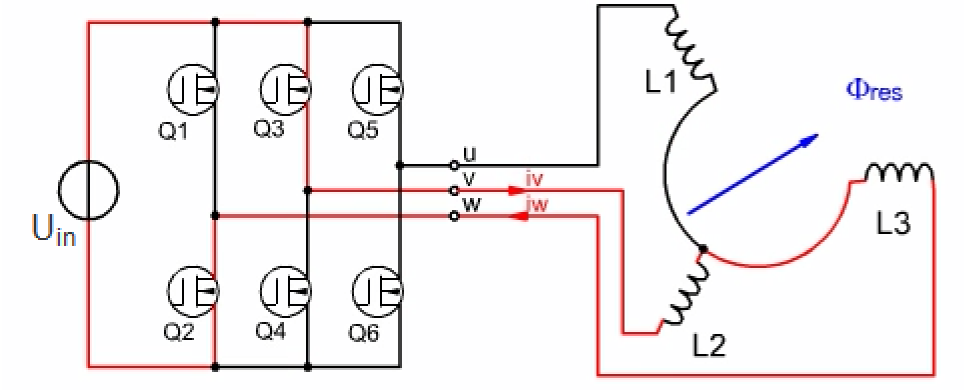
Introduction. BLDC motor

How BLDC motors work

The windings in the stator generate a magnetic field once a voltage is applied to them. The permanent magnets on the rotor are forced to align themselves with this magnetic field.

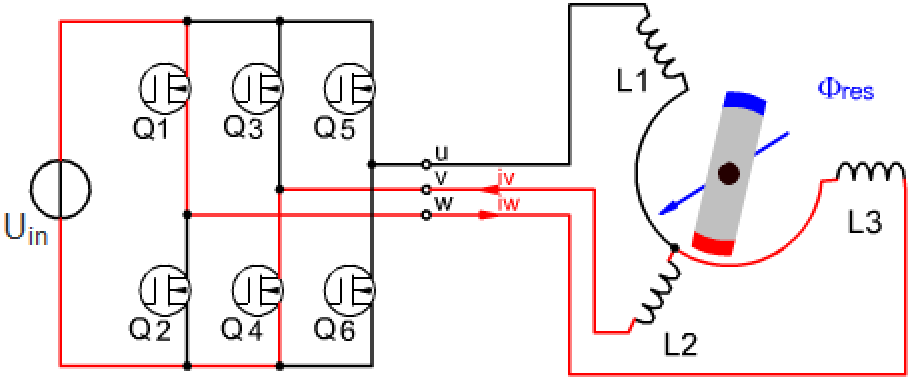
If the magnetic field is continuously switched such that the rotor is constantly realigning itself in one specific direction, rotation can be obtained. The stator windings enable magnetic fields to be generated in different directions. Since the windings are connected together in a star configuration, at least two windings must always be supplied with current. This makes it possible to have 6 magnetic field directions. Different directions of current flow in the windings can be achieved using a bridge circuit with 6 transistors.

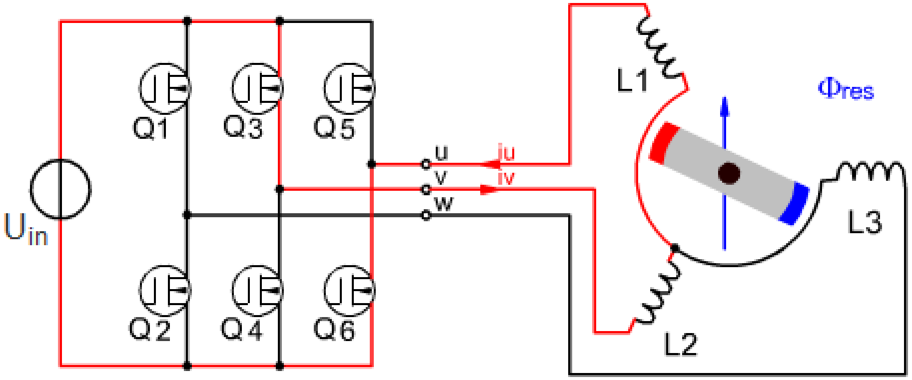
The following animation demonstrates the magnetic flux inside the motor:



How BLDC motors work

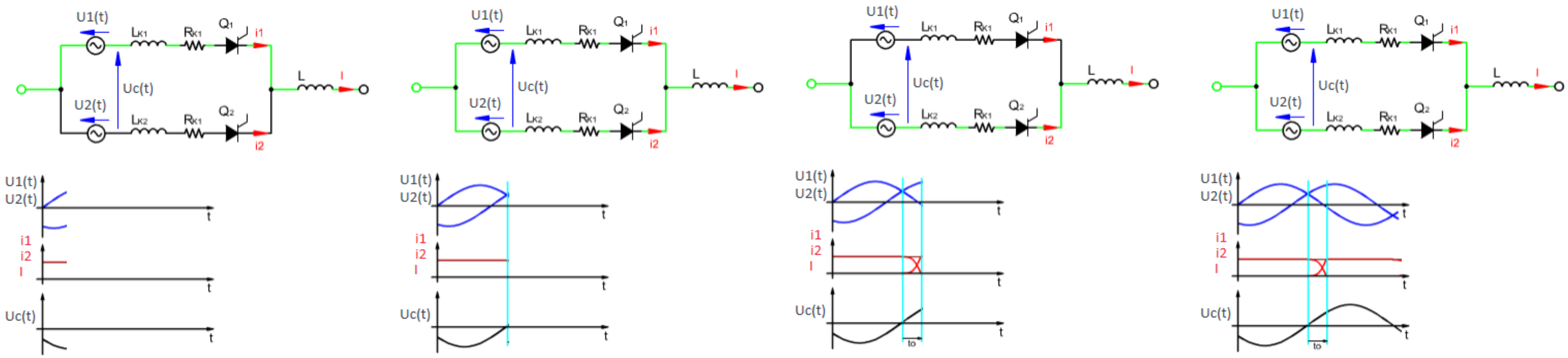
During this process the rotor executes a rotation subject to the magnetic field generated in the stator by induction. The following animation illustrates this:





Electronic commutation

As mentioned in the introduction, commutation must take place outside of the motor. Commutation in general implies some change, switching or interchange. In this instance, commutation means moving or changing from a current-carrying phase branch to a different branch that will then itself be carrying a current. The following animation demonstrates the simplest case where current is switched from one branch to another branch:



The commutation voltage Vc is supplied via voltage sources V1 and V2. The semiconductor valves Q1 and Q2 trigger after the commutation voltage Vc has passed through zero. It is possible to imagine the current being governed by the large inductor L at the output. Since the current flow is almost constant, an period of overlap (commutation time) t0 is the result.

Electronic commutation

For the sake of comparison: in conventional DC machines the current for the windings is controlled by the commutator. The rotor's rotational motion cannot keep the current flowing as shown in the above illustration. So-called brush sparking is caused when the currents become high.

When the current flowing in the windings is switched using semiconductors then we refer to electronic commutation.

Advantages and purpose of electronic commutation over the traditional mechanical commutation found in DC motors:

- **There is no wear and tear on commutator brushes (reducing maintenance).**
- **Interference (radio, EMC) is reduced as there is no brush sparking.**
- **The space for the commutator can be saved = more compact design, 1/3 less space needed.**
- **A higher power density is achieved due to a more compact design.**
- **Higher speeds are possible.**
- **Areas of application can be extended to include hazardous explosive environments etc.**

The purpose of electronic commutation is to modify the power currents to the magnetic field of the rotor in an optimum manner. As such the angle between the magnetic flux of the stator windings and the rotor should amount to <= 90°. This angle ensures that the maximum possible torque is obtained.

Current characteristics of BLDC motors

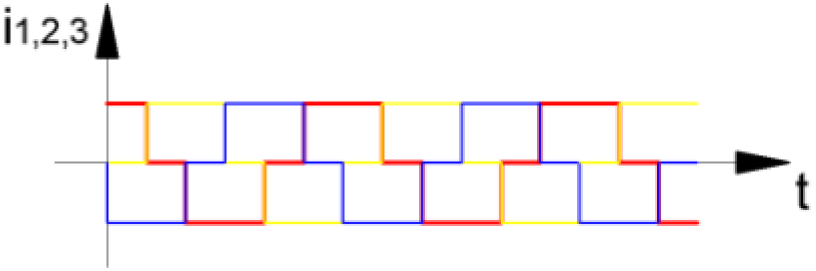
There are two different options when choosing the appropriate current characteristics for the motor:

- Sinusoidal current characteristic
- Trapezoidal or block-shaped current characteristic

When considering the application, it is imperative to know which current characteristic is the most suitable or appropriate. A distinction need no longer be drawn as to whether we are dealing with a permanently excited synchronous machine or a BLDC machine. This reflects the fact that there is a seamless transition between the two.

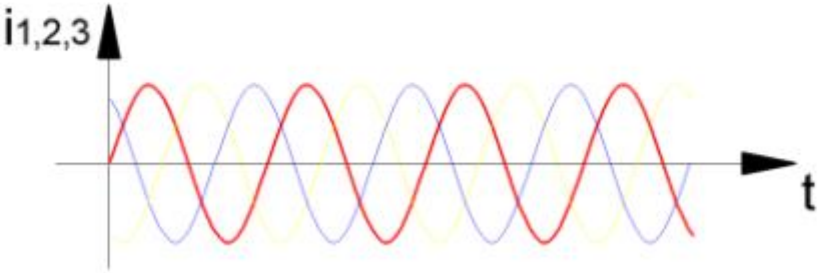
A distinction can however be made between a BLDC motor and a permanently excited synchronous machine as regards the waveform of the current supplied: a permanently excited machine is always supplied by a sinusoidal current.

If we are dealing with a simple application, like operating a pump, where there are limited torque fluctuations, no sudden load changes etc., then a **block-shaped current** characteristic is sufficient:



Current characteristics of BLDC motors

If, however, the torque and speed fluctuation need to be kept as small as possible, as is the case with servo drives, for example, a sinusoidal characteristic must be used. For that the rotor position signal has to have much finer resolution than is the case with block-shaped current characteristics. In the case of block-shaped current characteristics, 6 possible rotor positions are enough to operate the motor.



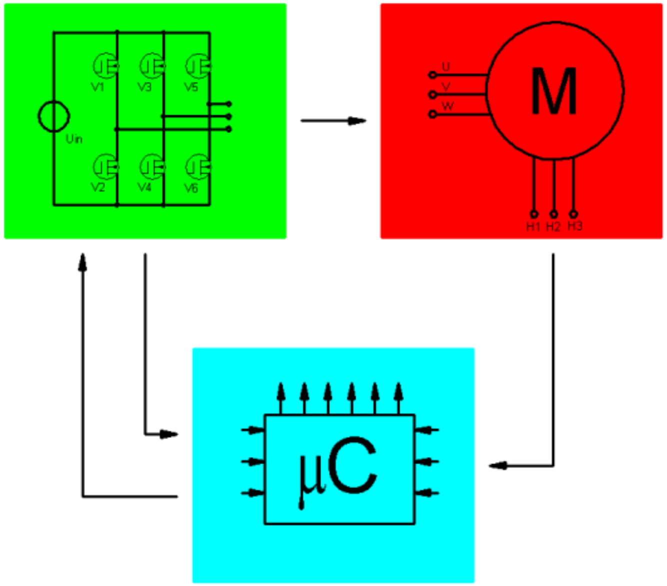
The block-shaped current characteristic causes vibrations, torque ripple and noise

Control design for a BLDC motor

The fully controlled six-pulse bridge circuit is controlled either via a programmable microcontroller or using hard-wired ICs, depending on the operating requirements.

Here too, the decision to utilise one method or the other depends on the application. For example, if you need to control a sinusoidal current, the so-called "voltage model" is the most sensible solution. This model is very algorithm-intensive but can be ably handled nowadays using a relatively inexpensive 16-bit microcontroller. The parameters needed in this case to carry out automatic control are computed from relatively few input variables. In addition to these variables that need constant measuring, there are some additional mechanical parameters for the respective machines that need entering.

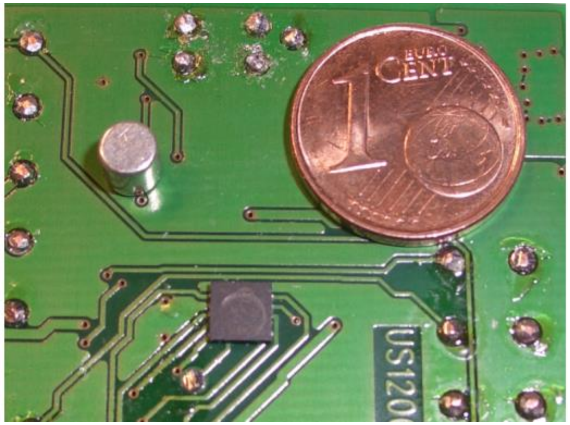
The following image shows the general structure of a BLDC design:



Detecting rotor position

There are different ways of detecting the rotor position in BLDC motors. Rotor position detection is necessary because, unlike DC machines, correct supply of power to the windings does not take place automatically.

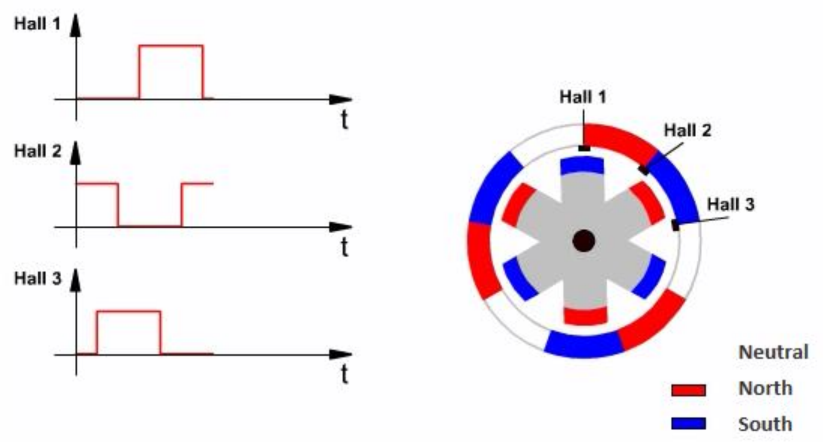
In the meantime there are ICs which can simulate the standard detection systems (see below). These ICs operate with the aid of Hall sensors. These utilise a permanent magnet attached to the rotor shaft, opposed to which an IC of this type is situated on the housing. This permits speeds of up to 100 000 rpm to be achieved with precise detection of the rotor position. In the image below, just such a component this is shown together with the corresponding magnets (top left):

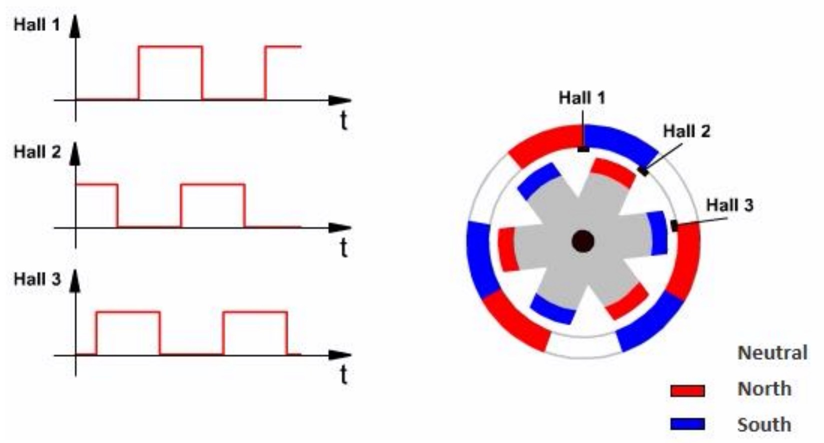


Detecting rotor position. Hall sensors

Rotor position is easily determined using Hall sensors. In such a system 3 Hall sensors are arranged staggered at intervals of 120° angles inside the machine's stator. The subsequent animation illustrates the functional principle and how it works:

When a Hall sensor detects a magnetic pole on the rotor, current is set in a particular direction through the windings via the bridge circuit. The right current variant of the six possible ones needed for the inductors is determined using a table and set via the transistors of the bridge circuit.

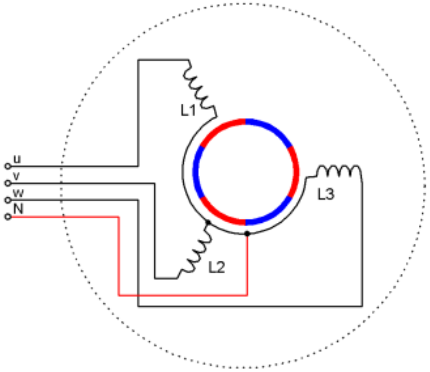




Detecting rotor position. Back e.m.f.

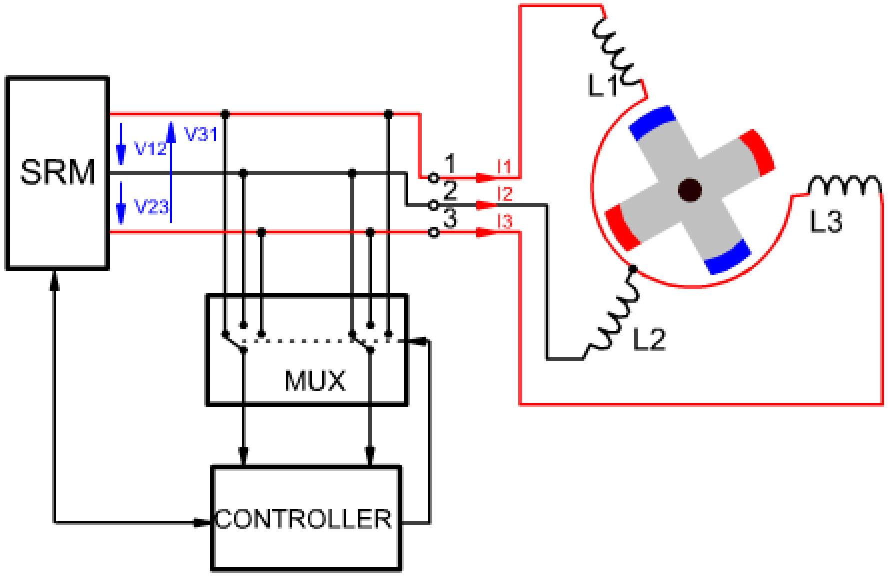
When the rotor rotates, a voltage is also induced in windings not presently being supplied current (internally induced machine voltage known as back EMF). In order to induce a voltage, the rotor must rotate at a certain minimum speed.

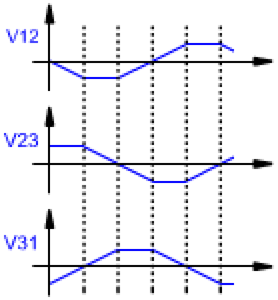
The main problem involving back e.m.f is the lack of a neutral terminal:



The star or neutral point is not generally provided with a terminal for connecting it and thus only measurement via the phase-to-phase voltage remains a possibility. Here the zero crossover of the voltage is determined for the unconnected phase with respect to on the one of the other phases and the subsequent commutation is triggered

Detecting rotor position. Back e.m.f.





Zero-Crossing	V12▼	V31▲	V23▼	V12▲	V31▼	V23▲
I1	0	-1	-1	0	1	1
I2	1	1	0	-1	-1	0
I3	-1	0	1	1	0	-1

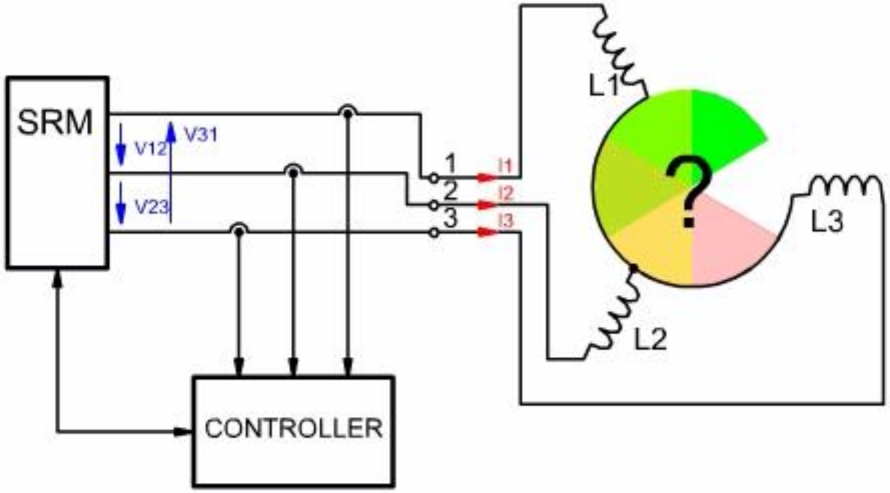
1 : from supply
-1: to supply
0 : no Current

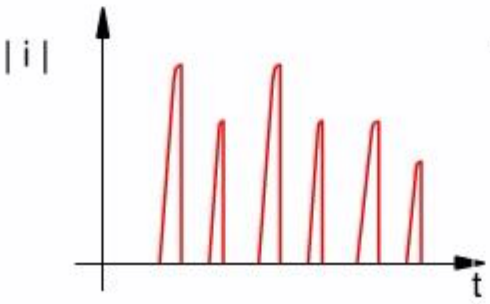
(SCM: static converter module)

Detecting rotor position. Pole detection

Pole detection utilises current pulses to make use of the saturation of the stator winding. In addition to the magnetic flux from the permanent magnets of the rotor poles, the stator winding also generates a magnetic flux. The overall flux determines from these aspects (winding flux, rotor flux) either adds to or weakens the saturation of the inductors in the motor. When the components of the motor are more saturated the current in the windings is correspondingly larger.

Saturation occurs sooner or later depending on the position of a pole. The current peaks in the corresponding winding allow the position of the rotor to be identified to an accuracy of 60°.

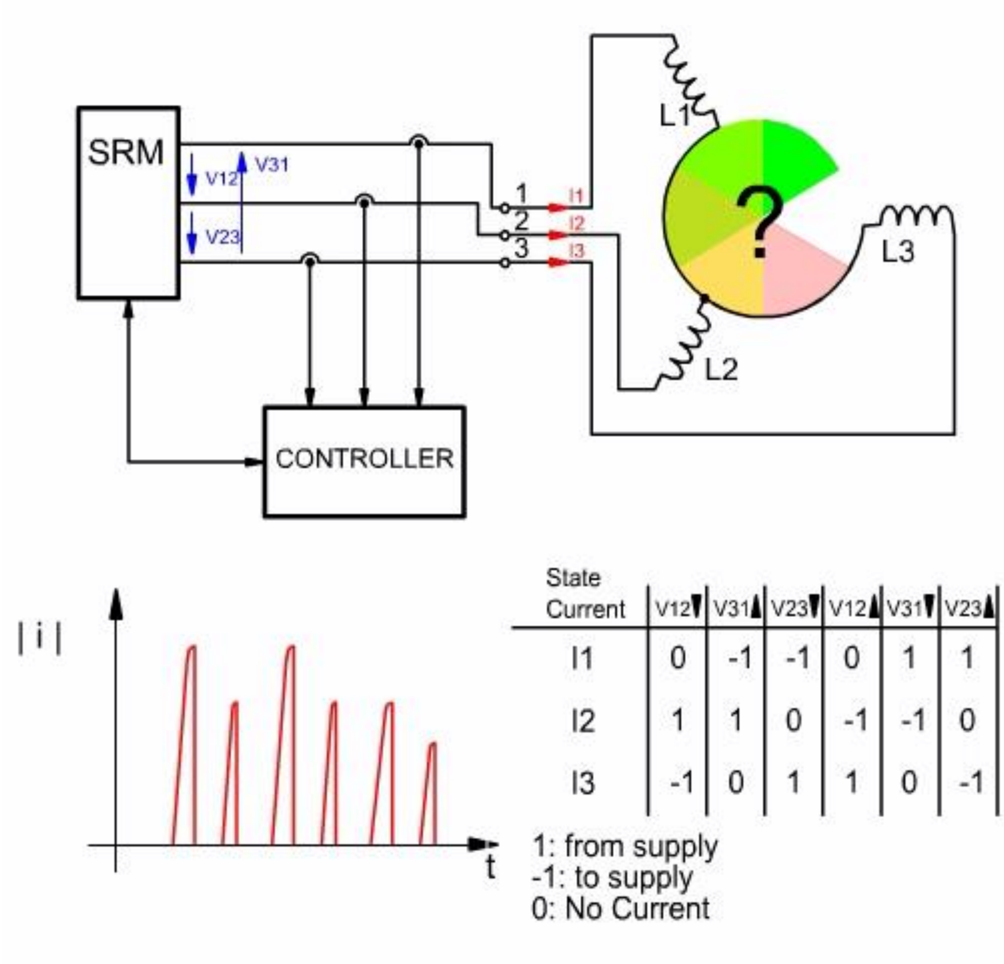




State Current	V12▼	V31▲	V23▼	V12▲	V31▼	V23▲
I1	0	-1	-1	0	1	1
I2	1	1	0	-1	-1	0
I3	-1	0	1	1	0	-1

1: from supply
-1: to supply
0: No Current

Detecting rotor position. Pole detection



State Current	V12▼	V31▲	V23▼	V12▲	V31▼	V23▲
I1	0	-1	-1	0	1	1
I2	1	1	0	-1	-1	0
I3	-1	0	1	1	0	-1

1: from supply
-1: to supply
0: No Current

In the animation the magnetic north pole is being sought. The pattern of colours is determined via the current peaks. This serves to identify the present position of the rotor and the sector containing the north pole.

The pattern of current peaks is characteristic for the areas relating to 60° and can be compared with a table. The position is derived by superimposing the three measurements.

The position also identifies what will be the next switching state. The example in the animation shows how the next switching position is determined for rotation of the rotor in a clockwise direction.

Detecting rotor position. Pole detection

There are a variety of names for this and other similar methods that are used by various manufacturers.
Some examples:

- ❑ PING methods(Agile Systems)
- ❑ INFORM = INdirect Flux detection by On-line Reactance Measurement (TU Vienna)
- ❑ SMART START (Fairchild)

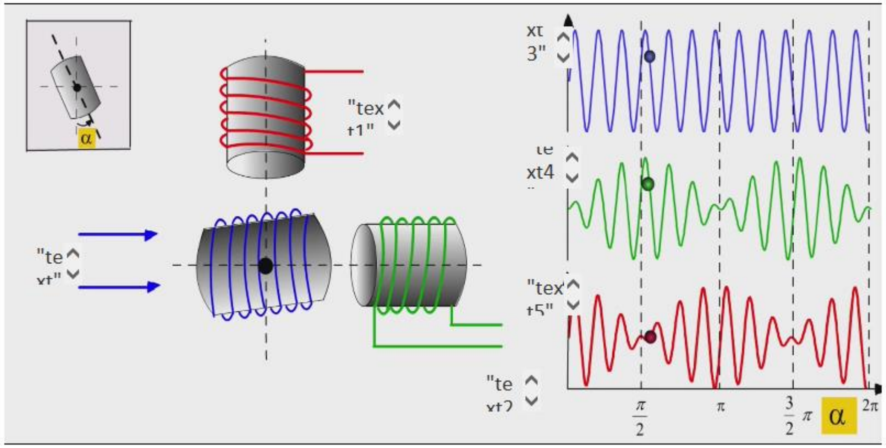
This kind of position detection only works up to a certain speed since the time it takes to make the detection subtracts from the time possible to execute control. Full control of 120° per phase becomes impossible at higher speeds.

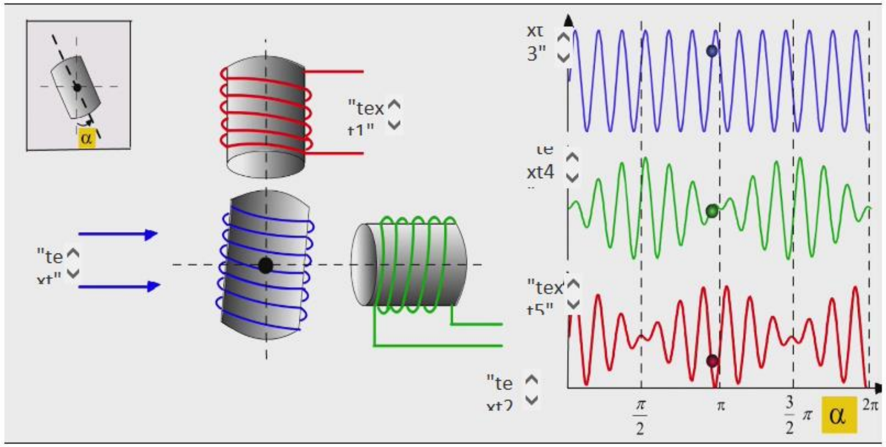
Detecting rotor position. Resolver (rotation angle sensor)

A resolver converts mechanical angular positions into analog electrical signals, which can then be transmitted and processed further. The resolver consists of a rotatable rotor and a stationary stator. The rotor shaft can be connected to the housing via ball bearings (internally mounted rotary encoder) or have no direct link to the housing (externally mounted rotary encoder), in which case the shaft must have a hollow design.

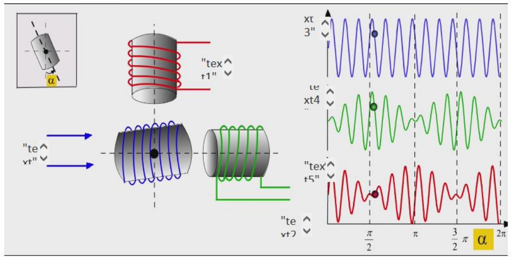
Determination of rotor angle

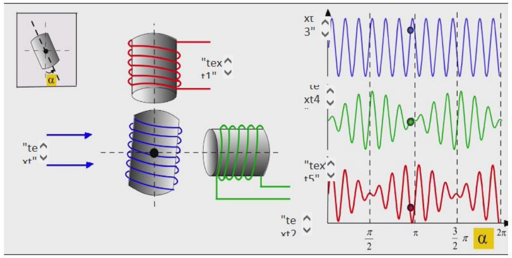
The animation below shows a resolver's operating principle





Detecting rotor position. Resolver (rotation angle sensor)





The resolver's rotor is supplied with a high-frequency alternating voltage (2 ... 10 kHz).

$$U_R = A\sin(\omega t)$$

Produced as a result in the stator coils respectively are alternating voltages whose frequencies are identical, and whose amplitude depends on the angle between the rotor coil and corresponding stator coil. When both coils have the same alignment (angle $\alpha = 0$), the induced voltage's amplitude is maximized. When the coils are at right angles to each other, the induced voltage is zero. The voltage induced in the first stator winding is defined as follows:

$$U_{S1} = k\,A\sin(\alpha)\sin(\omega t)$$

The voltage for the second winding is defined by: $U_{S2} = k\,A\cos(\alpha)\sin(\omega t)$.

The factor *k* indicates the transmission ratio between the stator and rotor. Both stator voltages are therefore mutually displaced by 90° at all times. The rotor angle α can thus easily be calculated through division of the two stator voltages:

$$\alpha = \arctan\frac{U_{S1}}{U_{S2}}$$

Detecting rotor position. Resolver (rotation angle sensor)

Within a pole pitch, the resolver supplies an absolute position signal. The resolver's signal can also be used to ascertain speed and simulate incremental encoding for position control. As part of the encoder, the resolver itself requires no electronic components. For this reason, the resolver is robust and cost effective. An industrial resolver is illustrated adjacently.

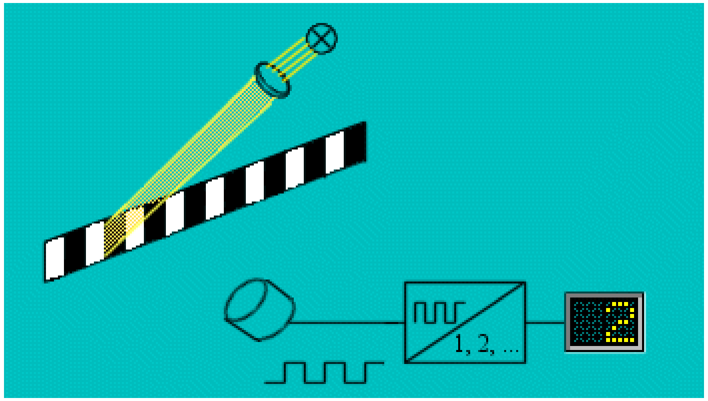
https://www.minebeamitsumi.com/english/strengths/column/resolver/#:~:text=Basic%20mechanism%20of%20resolver&text=To%20control%20the%20motor%20according,a%20sensor%20for%20these%20tasks.

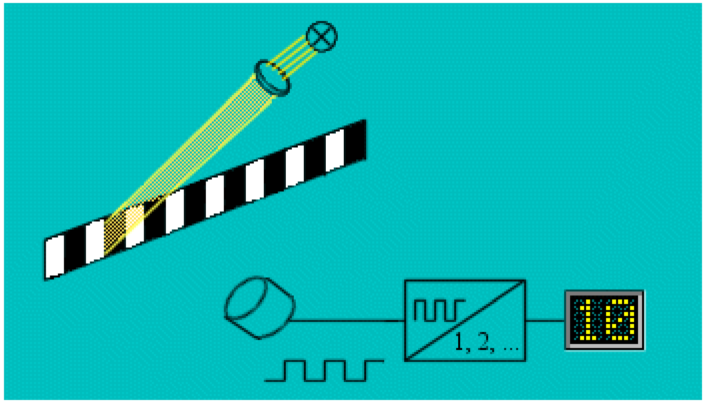
Detecting rotor position. Incremental encoder

An incremental rotary encoder converts speed into a discrete number of pulses. The encoder operates opto-electronically with resolutions of up to 5000 pulses per revolution.

Function of an optical encoder

The example in the animation demonstrates the functionality of an optical encoder with reflective light sampling. A focused beam from a light source (at the top) impinges on a bar furnished with alternately reflective and non-reflective stripes. Light rays striking the reflective stripes and subsequently reflected are detected by a photo diode (at the bottom). The diode accordingly supplies a pulse sequence whose frequency is proportional to the striped bar's velocity. The pulse count serves as a measure of the distance travelled, and can be registered by means of a downstream counter, for instance.

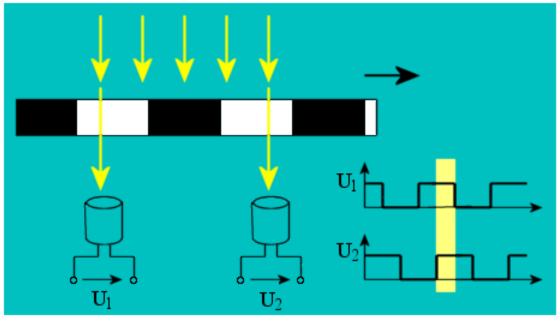


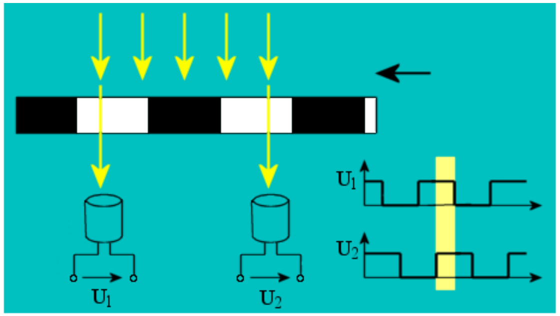


Detecting rotor position. Incremental encoder

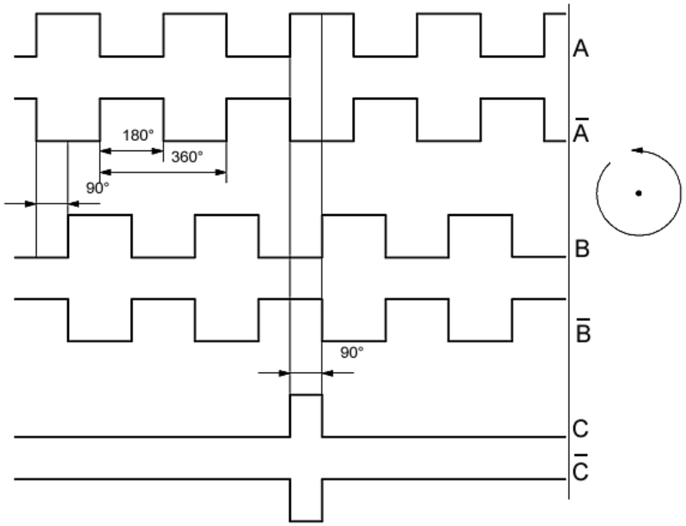
Incremental encoder's signals

Incremental encoders typically have two tracks A and B, as well as a zero-pulse track C. Signal inversion results in a total of 6 signals. Tracks A and B are displaced by 90°. The zero pulse is detected using a separate light barrier and supplied as a reference signal in one pulse per revolution.

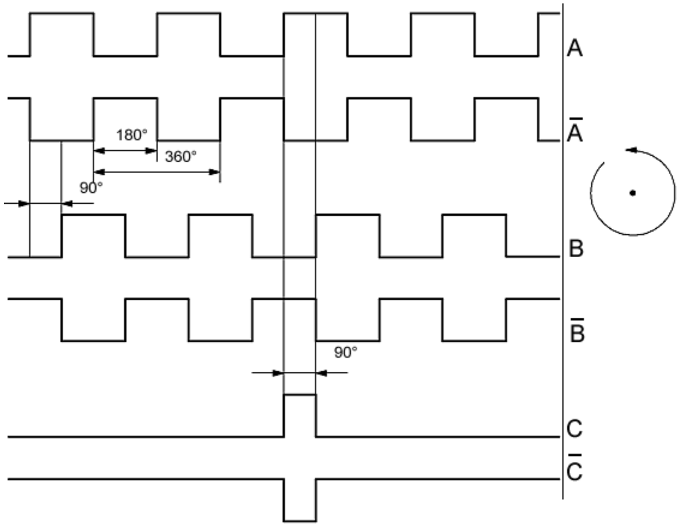




https://www.impulseautomation.co.uk/rotary-encoders/incremental-rotary-encoders/hengstler-ri58-d-incremental-rotary-encoder/



Incremental encoder with zero-track and inverted signals



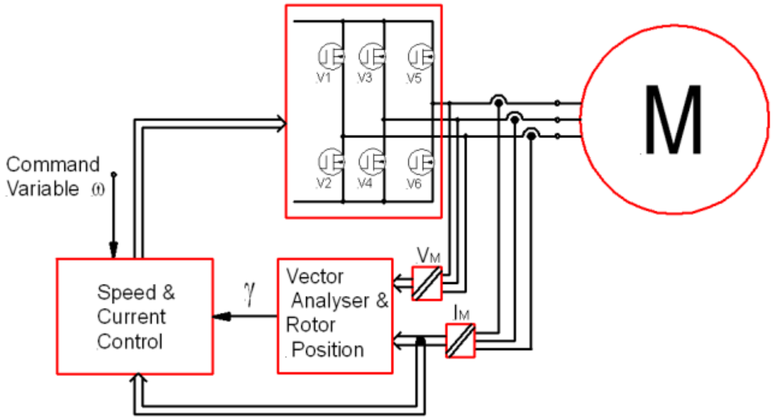
Detecting rotor position. Sensorless control

Closed-loop sensorless control of a BLDC machine normally involves a synthesis of pole detection for low speeds and back e.m.f measurement at higher speeds. As such, the machine is controlled starting from a stationary position using pole recognition and switches over to back e.m.f. for higher speeds. This type of rotor position detection is not suitable for highly dynamic motor starts.

It is also possible to run the BLDC motor up without using a feedback loop for the rotor position (stepper motor operation) and subsequently switch to rotor position detection via back e.m.f . This procedure makes sense, for example, with fan motors that operate at higher speeds because the speed at the lower run-up range tends to be unimportant. This type of sensorless control is sufficient for most applications (low load fluctuation, minimum speed, automatic speed and torque control), as is the case, for example, with blowers or pump drives.

Detecting rotor position. Sensorless control

There are again various possibilities for detecting rotor position. As mentioned above it is normally some sort of synthesis that is utilised. The following image demonstrates the design structure for sensorless closed-loop control, where the rotor position is determined using the output voltage and the output current:



Here a vector analyser outputs the momentary rotor position g based on the output current and output voltage. This is followed by the automatic current and speed control which is dealt with later.

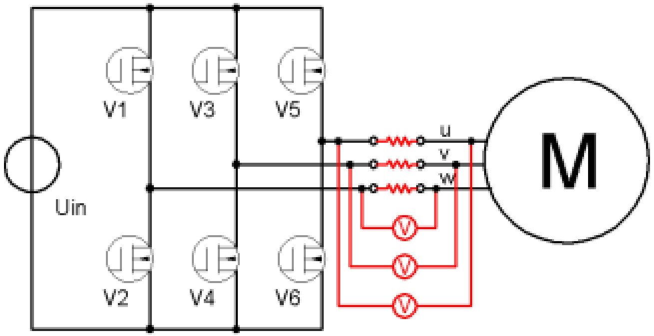
The complete control function can now be housed in a single module with no feedback lines from the motor required. No further connections are needed.

Sensorless closed-loop control is by far the most economical solution when large numbers of units are needed. There is no need to use separate sensors, only the current within the voltage supply has to be measured . As such, the open- and closed-loop control unit is able to assume the function of rotor position detection. Hence the motor is just a motor without any sensor equipment. Using factory-made ICs, closed-loop control and rotor position evaluation can be carried out in its entirety making it cheaper to manufacture, assemble and operate the voltage and current sensors. This means lower costs.

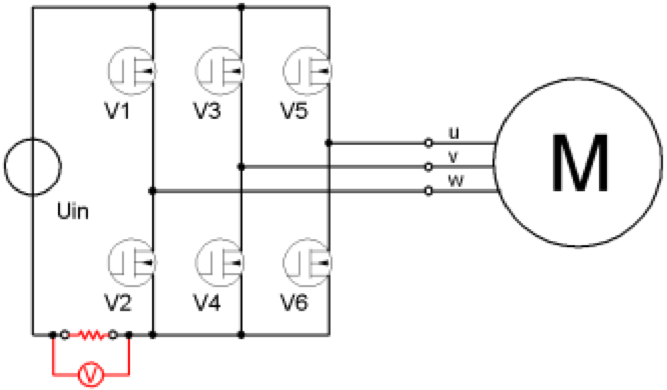
Current detection

One solution involves linear Hall sensors which are used to directly derive the induced line-to-line currents.

A more economical and less complex variation involves connecting resistors to the motor terminals then measuring the voltage drop across them to determine the current flow.

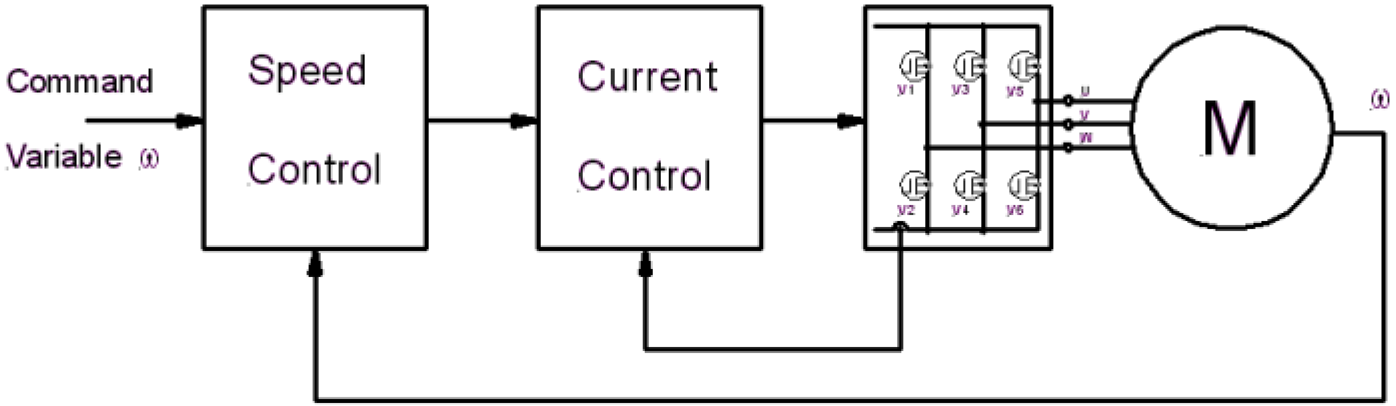


The most inexpensive solution is to connect a measurement resistor in the input and output arms of the DC circuit:



Close-loop control of a BLDC motor

A control loop is comprised of the controller, the controlled system (the machine itself) and the feedback loop of the variable to be controlled leading to the control loop's input. The controlled and manipulated variables exercise a mutual influence on each other. Thus the response of the system is dynamic in nature:



Closed-loop control of a BLDC machine is simple because the speed and current have already been measured and these variables can be used directly. As mentioned above, the stator current is proportional to the torque as is standard for DC machines. As such, a higher torque, i.e. a higher stator current, must be set in order to obtain a higher speed. A greater stator current increases the acceleration of the rotor. Consequently the angular velocity or speed is increased.

Close-loop control of a BLDC motor

Closed-loop control of a BLDC machine is accomplished using two controllers: These controllers are responsible for:

- Current control (controlling the torque)
- Speed control

These controllers are configured in a cascaded loop - sometimes the loops in this type of control structure are called primary and secondary control loops.

The automatic control loop has a secondary current controller.

In brief:

The closed-loop speed control system must pre-set a current which the current controller then sets. This results in a change in speed. The speed controller then corrects the speed via a change in current.

Close-loop control of a BLDC motor. Close-loop current control

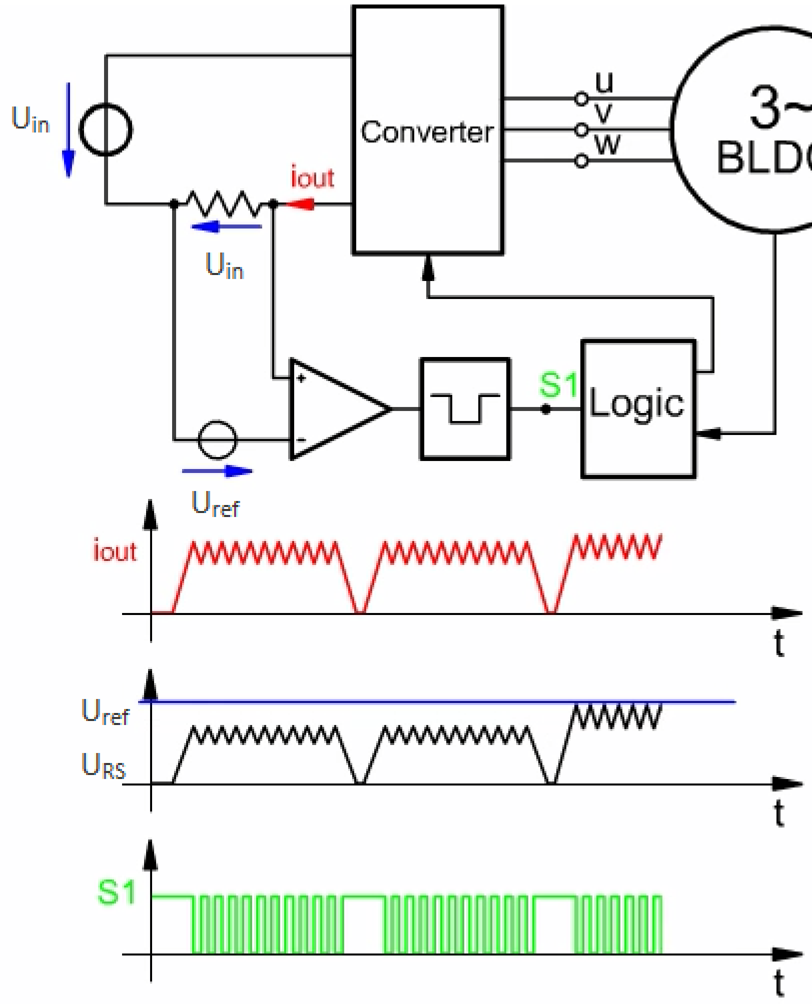
One simple possibility for regulating the current consists of switching the current on and off between two limits (two-point control). This is how current is used to set a maximum torque.

The current builds up in two arms of the bridge circuit, after two transistors are switched through on a diagonal. In the process the current is monitored and upon reaching a certain value, switches one of the transistors off. The result of this is that the current continues to flow in the static converter and thus slowly fades until the current has dropped below a particular value. Then the transistor previously switched off is switched back on again.

The mean value of the current then corresponds to the desired current, which is intended to flow in the windings. Thus, speed can now be regulated by setting a higher or a lower mean current value.

This type of closed-loop current control constitutes a good solution when the power supply signal is block-shaped. The desired variable (reference variable) is always the same magnitude during the supply of power throughout the 60° range of the individual steps.

Close-loop control of a BLDC motor. Close-loop current control



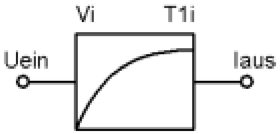
Close-loop control of a BLDC motor. Closed-loop speed control

To be able to set a certain speed, the current control loop is superposed with a speed control loop, which sets the currents reference variable (IA).

This speed control loop with secondary current control is already implemented in most BLDC control ICs. To be able to configure automatic control loops, all you have to take into consideration in the IC are the machine parameters (winding resistances, inductances etc.).

Simpler control ICs for BLDC machines have an analog input. A variable voltage is connected via this analog input. The IC then sets a current (torque) in accordance with the applied voltage.

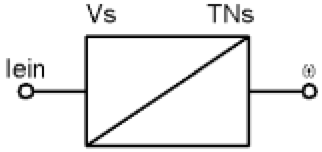
The simplified control IC can be depicted as a PT1 element (with time delay of the first order):



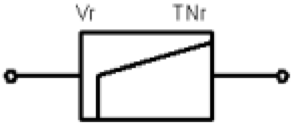
Here Vi constitutes the transfer coefficient (gain factor) and T1i is the time delay constant. The symbol shows the characteristic found at the output.

Close-loop control of a BLDC motor. Closed-loop speed control

The control IC provides a current via the internal static converter. This current generates a magnetic flux in the motor windings, which exercises a force on the rotor (Lorentz force). The rotor now commences to rotate and to slowly accelerate. This response is depicted using the subsequent block module of an integral-action element or integrator

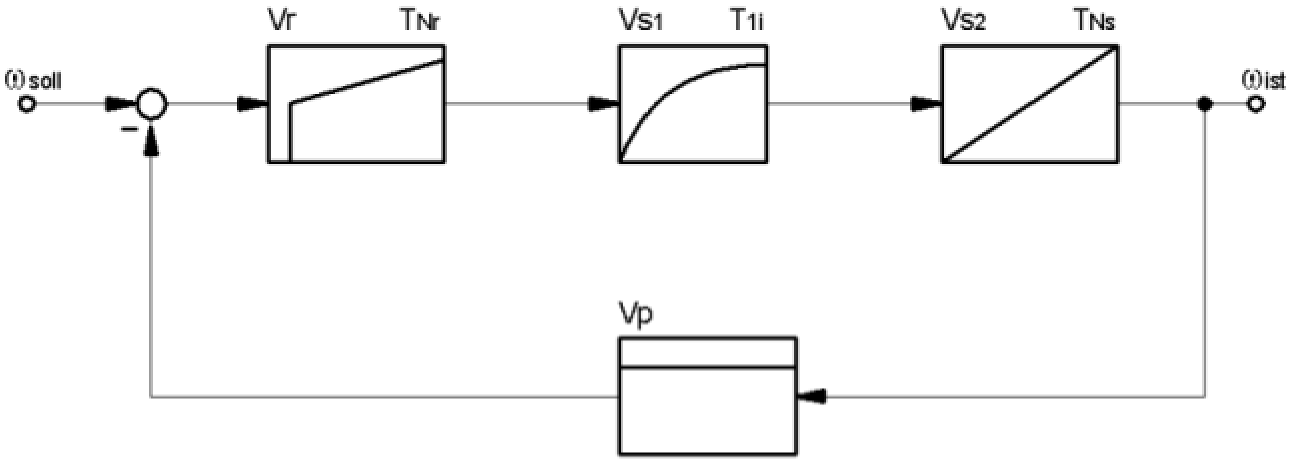


A PI controller is provided as the controller. This controller provides an output signal (P-component) that is proportional to the input signal. Additionally the output signal is increased until there is no longer a signal at the input. The control loop reaches a precise steady-state. This is accomplished by the I-action component. The following diagram shows the PI controller:



Close-loop control of a BLDC motor. Closed-loop speed control

If we place the block modules of the control structure in series, we obtain the following control loop with controller:



The factor Vp is the adjustment or correction factor for the reference variable. It serves as a conversion factor since the actual speed voltage does not necessarily coincide with the desired voltage for the speed.

The transfer function of the control loop without controller is as follows:

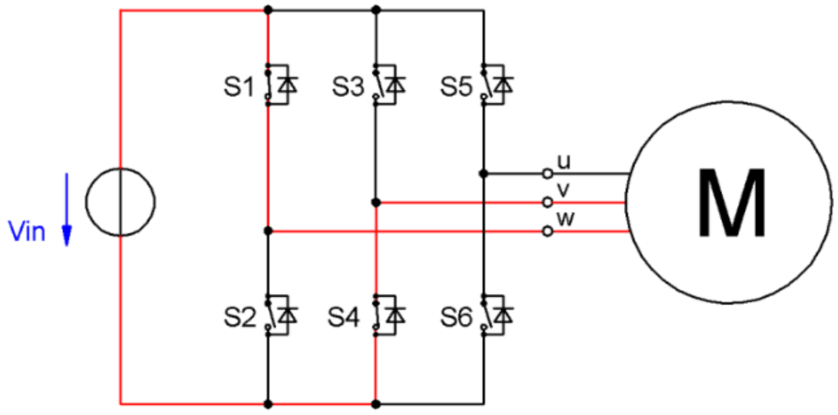
$$F_o(s) = \frac{\omega_{ist}(s)}{\omega_{soll}(s)} = Vr \cdot \frac{1 + s \cdot T_{Nr}}{s \cdot T_{Nr}} \cdot Vs_1 \cdot \frac{1}{1 + s \cdot T_{1i}} \cdot Vs_2 \cdot \frac{1}{s \cdot T_{Ns}} \cdot Vp$$

Braking

In drive technology it may be required that the motor is forced to come to a stop as soon as possible. Causes for this may be an emergency shut-off due to faulty operation or physical injury to persons up to and including a desired switch-off after a predetermine objective has been reached.

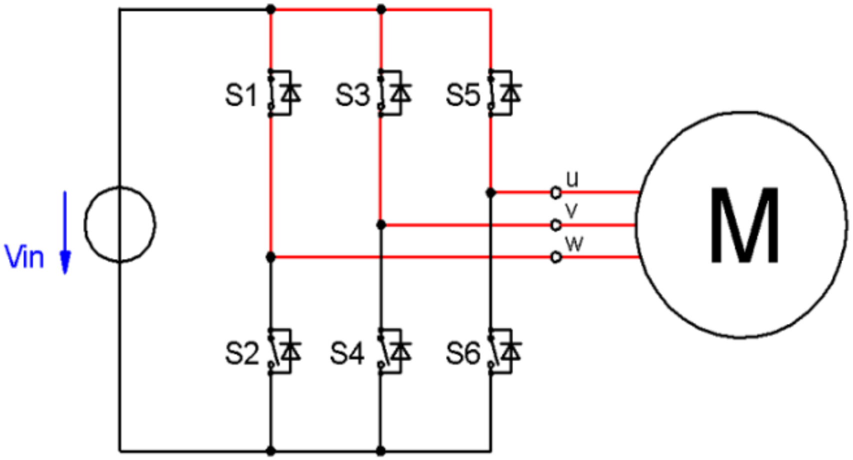
For the braking process transistors in either the top or bottom half of are switched off. Current then continues to flow either in the top or bottom section of the bridge after having been commutated by an additional semiconductor:

In the following circuit, two windings are supplied with current and current flows from W to V. For ease of understanding and simplification, the transistors have been replaced by switches:



Braking

In the following illustration the brake is connected. This causes the upper switches to close:



Due to this short-circuiting, current is generated in all of the windings as a result of back emf. This current can become quite substantial and be maintained for some time, depending on high the motor's inertia is.

Resumen: Motor Brushless (motor de c.c. sin escobillas)

1. El motor tiene una disposición inversa a la clásica:

- El inductor está en el rotor y está formado por imanes permanentes con una estructura de polos lisos.
- El inducido está en el estator y no tiene colector de delgas, la conmutación se hace con interruptores electrónicos.

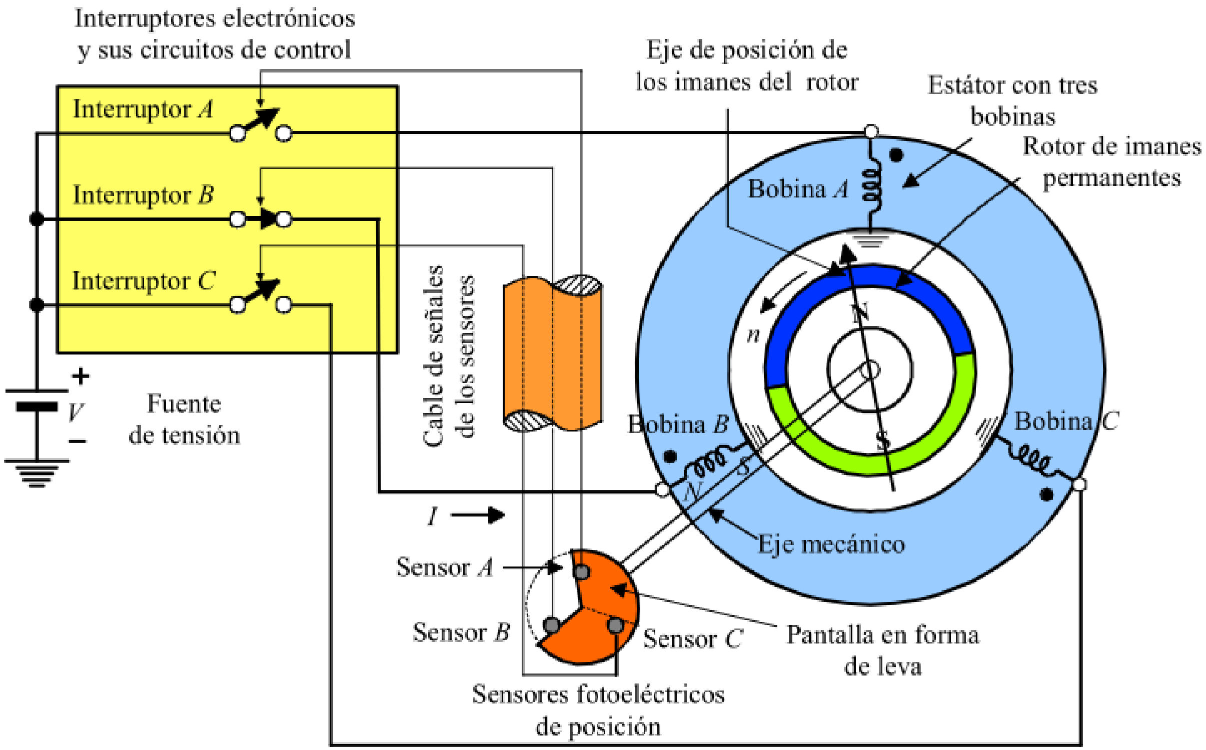
2. En un motor c.c. clásico el numero de bobinas (por tanto, de delgas) es elevado, produciendo muchas conmutaciones en cada vuelta. En un motor brushless, si usa muchas conmutaciones necesita muchos interruptores electrónicos y el coste del sistema de control sería elevado. Por ello sólo tiene tres bobinas, por lo que se requiere sólo de tres interruptores electrónicos y una fuente de alimentación de c.c. (equivales a un motor convencional con 3 delgas).

3. Tienen sensores para detectar la posición del rotor para que las conmutaciones electrónicas se realicen justo en el momento preciso (esto se hace de forma automática en motores clásicos con las delgas).

Los sensores pueden ser fotoeléctricos o magnéticos (efecto Hall)

Resumen: Motor Brushless (motor de c.c. sin escobillas)

Si tenemos 3 sensores fotoeléctricos, cubre cada un rango de 120º, colocados delante de una pantalla con una abertura de 120 º que se mueve con el rotor. El motor al girar hace que se active un sensor que manda cerrar un interruptor, haciendo que circule una corriente continua por la bobina correspondiente, de tal forma que se crea un polo norte y uno sur, que interaccionan con los imanes del rotor, y hace que el rotor se oriente con la bobina. Al moverse el rotor, el siguiente sensor se activa y se cierra el interruptor de la siguiente bobina, de tal forma que el rotor va avanzando y se genera un movimiento continuo.



Estos motores no necesitan casi mantenimiento

Al no tener colector de delgas no hay chisporroteos, eliminando así, el riesgo de explosión o de emisión de radiaciones electromagnéticas, que interfieran con los sistema de comunicaciones.

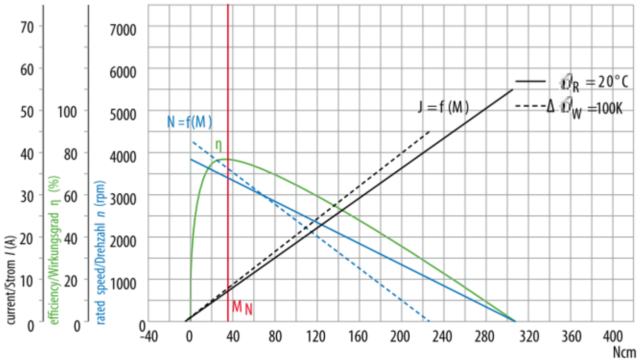
La velocidad depende del ritmo de conmutación de los interruptores electrónicos.

El control de la corriente que circula por las bobinas y el ritmo de conmutación de los interruptores determinan la curva par-velocidad de estos motores que es similar a los motores clásicos de c.c. tipo derivación (shunt).

Ejemplo: Motor Brushless

BG 62 S, 60 - 130 Watt

- *3-phase BLDC motor with high-quality and 4-pole rare earth-magnets*
- *Available in 3 motor lengths*
- *Low noise level | Low cogging forces*
- *High voltage windings available*
- *Version integrated hall sensors for rotor positiondetection*
- *Can be combined with encoders, brakes and gearboxes within our modular system*

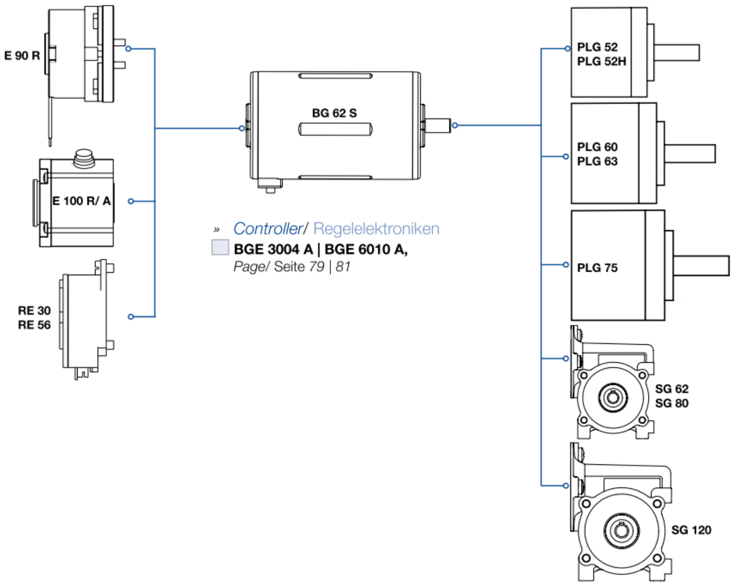


BG 62 Sx60, 24V

Data/ Technische Daten		BG 62 Sx30	BG 62 Sx45	BG 62 Sx60
Nominal voltage/ Nennspannung	VDC	24	24	24
Nominal current/ Nennstrom	A*)	3.7	5.1	6.8
Nominal torque/ Nennmoment	Ncm*)	20	27	36
Nominal speed/ Nenndrehzahl	rpm*)	3000	3210	3350
Friction torque/ Reibungsmoment	Ncm*)	2.7	3.4	4.9
Peak stall torque/ Max. Anhaltemoment	Ncm**)	131	211	307
No load speed/ Leerlaufdrehzahl	rpm*)	3855	3855	3865
Maximum output power/ Maximale Abgabeleistung	W**)	110	182	274
Torque constant/ Drehmomentkonstante	Ncm A-1***)	6.8	6.7	6.7
Terminal Resistance/ Anschlußwiderstand	Ω***)	0.9	0.52	0.34
Terminal inductance/ Anschlußinduktivität	mH***)	1.5	0.95	0.67
Peak current/ Zulässiger Spitzenstrom (2 sec.)	A**)	23.5	38.7	56
Rotor inertia/ Rotor Trägheitsmoment	gcm²	185	262	353
Weight of motor/ Motorgewicht	kg	1.15	1.4	1.65

*) DJ_w = 100 K; **) J_R = 20°C ***) *only for hall version*/ nur für Hall-Version

Modular System/ Modulares Baukastensystem



- *Brakes & Encoder*/ Bremsen & Anbauten

RE 90 R,
Page/ Seite *102*
E 100 R/ A,
Page/ Seite *102*

RE 30,
Page/ Seite *104*
RE 56,
Page/ Seite *104*

- *Controller*/ Regelelektroniken

☐ **BGE 3004 A | BGE 6010 A,**
Page/ Seite *79 | 81*

- *Planetary gearbox*/ Planetengetriebe

PLG 52, (1.2 - 24 Nm),
Page/ Seite *90*
PLG 52 H, (1.2 - 24 Nm),
Page/ Seite *91*
PLG 60, (5 - 25 Nm),
Page/ Seite *92*
PLG 63, (5 - 100 Nm),
Page/ Seite *93*
PLG 75, (25 - 160 Nm),
Page/ Seite *94*

- *Worm gearbox*/ Schneckengetriebe

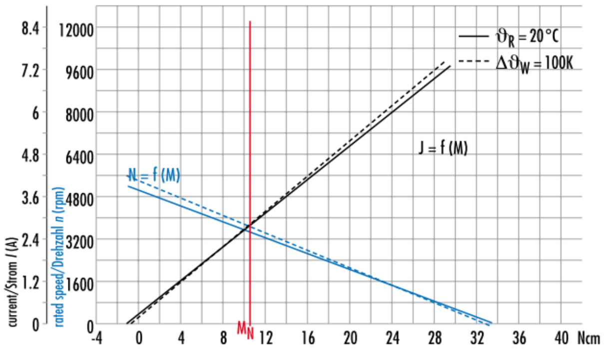
SG 62, (1 - 1.5 Nm),
Page/ Seite *97*
SG 80, (2 - 8 Nm),
Page/ Seite *98*
SG 120, (8 - 30 Nm),
Page/ Seite *99*

Ejemplo: Motor Brushless

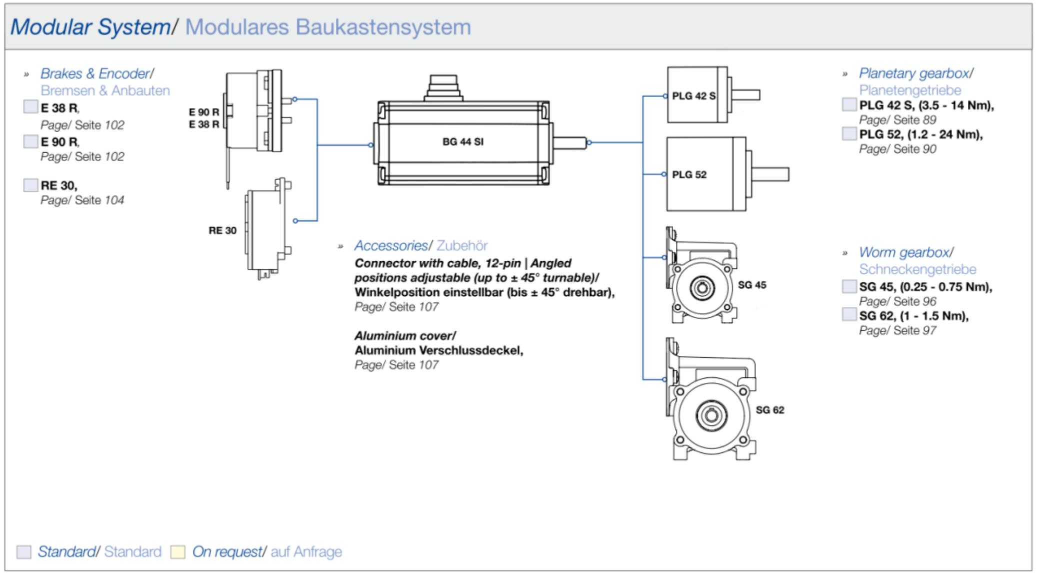
dunkermotoren
advanced motion solutions

BG 44 SI, 20 - 40 Watt

- *Highly dynamic 3-phase EC motor with 4-pole neodymium magnet*
- *With integral speed controller for 4-quadrant drive*
- *Two fixed speeds, and acceleration and de-acceleration ramps can be stored in memory*
- *The motor is supplied as standard with a 12-pin connector*



BG 44x50 SI, 24V



Modular System/ Modulares Baukastensystem

- *Brakes & Encoder*/ Bremsen & Anbauten
  - ☐ **E 38 R**, *Page*/ Seite *102*
  - ☐ **E 90 R**, *Page*/ Seite *102*
  - ☐ **RE 30**, *Page*/ Seite *104*
- *Accessories*/ Zubehör
  - ***Connector with cable, 12-pin | Angled positions adjustable (up to ± 45° turnable)*/ Winkelposition einstellbar (bis ± 45° drehbar),** *Page*/ Seite *107*
  - ***Aluminium cover*/ Aluminium Verschlussdeckel,** *Page*/ Seite *107*
- *Planetary gearbox*/ Planetengetriebe
  - ☐ **PLG 42 S, (3.5 - 14 Nm),** *Page*/ Seite *89*
  - ☐ **PLG 52, (1.2 - 24 Nm),** *Page*/ Seite *90*
- *Worm gearbox*/ Schneckengetriebe
  - ☐ **SG 45, (0.25 - 0.75 Nm),** *Page*/ Seite *96*
  - ☐ **SG 62, (1 - 1.5 Nm),** *Page*/ Seite *97*

☐ *Standard*/ Standard ☐ *On request*/ auf Anfrage

Tema IV: OTRAS MÁQUINAS

AXIAL FLUX MACHINES

Background

The axial flux permanet magnet (AFPM) brushless machine (disc-type machine) is a attractive alternative to its cylindrical radial flux counterpart due to the pancake shape, compact construction and high torque density.

AFPM motors are particularly suitable for electrical vehicles, pumps, valve control, centrifuges, fans, machine tools, hoists, robots and manufacturing.

http://www.yasamotors.com/products/

http://koenigsegg.com/regera/

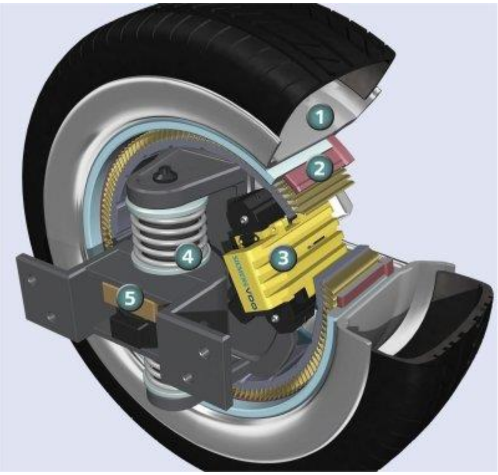
http://www.evsmotor.co.kr/eng/app/electric-motorbikes.php

The history of electrical machines reveals that the earliest machines were axial flux machines (M. Faraday, 1831, anonymous inventor with initials P.M., 1832, W. Ritchie, 1833, B. Jacobi, 1834). However, shortly after T. Davenport (1837) claimed the first patent for a radial flux machine, conventional radial flux machines have been widely accepted as the mainstream configuration for electrical machines.

Background

Prototype-wheel motor of Siemens

https://www.youtube.com/watch?v=2wP4F8MDuqw



Detail Drum Michelin Active Wheel system

https://www.youtube.com/watch?v=-4ygUCbHjTc

Background

AFPM generators are suitable in wind turbines and portable generators sets.

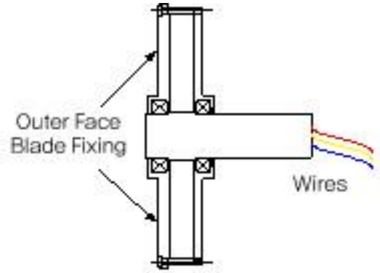
Figure 1. Experimental wind power plant and the used single sided axial flux permanent magnet generator.

FLUX Magazine N° 47 - January 2005 - CEDRAT - CEDRAT TECHNOLOGIES - MAGSOFT Corp.

SEOYOUNG TECH

https://www.youtube.com/watch?v=U8AeZUNNUe8

http://www.evsmotor.co.kr/eng/app/wind-force-power-generator.php#top



Background

The electromagetic design of AFPM machines is similar to its radial flux PM (RFPM) counterparts with cilindrical rotors. However, the mechanical design , thermal analysis and assembly process are more complex.

The large diameter rotor with its high moment of inertia can be utilised as a flywheel.

Since a large number of poles can be accommodated, these machines are ideal for low speed applications, as for exameple, electromechanical traction drives, hoists or wind generators.

The unique disc-type profile of the rotor and stator fo AFPM machines makes it possible to generate diverse and interchangeable desings. AFPM machines can be designed as single air gap or multiple air gaps machines, with slotted, slotless or even totally ironless armature. Low power AFPM machines are frequently designed as machines with slotless windings and surface PMs.

Types of axial flux PM machines

- AFPM machines were first introduced in late 70s and early 80s (Campbell, 1975; Leung and Chan, 1980; Weh et al., 1984).

- Growing interest in AFPM machines in several applications due to their high torque-to-weight ratio and efficiency as an alternative to conventional radial-flux machines was significant in the last decade.

- Basically, each radial-flux-machine type has its corresponding axial-flux version (Cavagnino et al., 2002).

Each type of radial flux machines should have its corresponding axial flux (disc type) version. In practice, disc type machines are limited to the following three types:

- PM d.c. commutator machines.
- PM brushless d.c. and synchronous machines.
- Induction machines.

Similar to its RFPM counterpart, the AFPM d.c. commutator machine uses PMs to replace the electromagnetic field excitation system. The rotor (armature) can be designe as a wound rotor or printed winding rotor.

Features of AFPM machines

http://esatjournals.org/Volumes/IJRET/2013V02/I12/IJRET20130212067.pdf

Axial-flux permanent-magnet (AFPM) machines have many unique features:

- For being permanent magnet, they usually are more efficient, as field excitation losses are eliminated, reducing rotor losses significantly.
- Machine efficiency is thus greatly improved, and higher power density achieved.
- Axial-flux construction has less core material, so, high torque-to-weight ratio.
- Also, AFPM machines have thin magnets, so are smaller than radial flux counterparts.
- AFPM machine size and shape are important features in applications where space is limited, so compatibility is crucial.
- The noise and vibration they produce are less than those of conventional machines.
- The air gaps are planar and easily adjustable.
- The direction of main air-gap can be varied, so derivation of various discrete topologies is possible.

Scientific Research and Essays Vol. 6(12), pp. 2525-2549, 18 June, 2011 Available online at http://www.academicjournals.org/SRE DOI: 10.5897/SRE11.334 ISSN 1992-2248 ©2011 Academic Journals

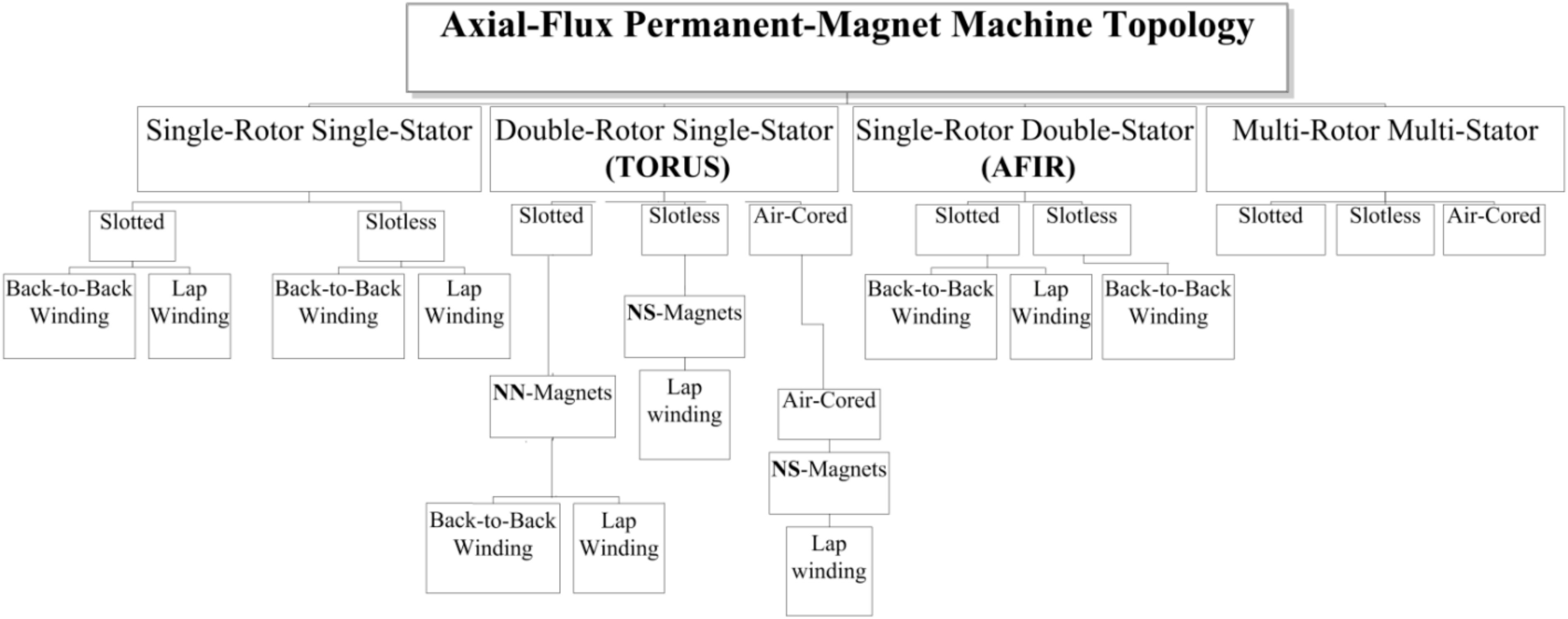
Axial-flux permanet-magnet machine construction

- DC brushless and AC synchronous machines are equal in structure but differ in operation principle:
  - EMF waveform generated by DC brushless is trapezoidal. In AC synchronous it is sinusoidal.
  - In construction, brushless AFPM can be (Gieras et al., 2008)
    - ✓ single-sided or double-sided,
    - ✓ with or without armature slots,
    - ✓ with or without armature core,
    - ✓ with internal or external permanent-magnet rotors,
    - ✓ with surface-mounted or interior permanent-magnet,
    - ✓ and as single-stage or multi-stage

Fig 1 Different structures for AFPM machines, a) Structure with one rotor and one stator, b) Multi-disc structure, c) TORUS type, and d) AFIPM type.

Gieras JF, Wang RJ, Kamper MJ (2008). Axial Flux Permanent Magnet Brushless Machines. Springer Verlag.

Axial-flux permanet-magnet machine construction



Axial-Flux Permanent-Magnet Machine Topology

- Single-Rotor Single-Stator
  - Slotted
    - Back-to-Back Winding
    - Lap Winding
  - Slotless
    - Back-to-Back Winding
    - Lap Winding
- Double-Rotor Single-Stator (TORUS)
  - Slotted
    - NN-Magnets
      - Back-to-Back Winding
      - Lap Winding
  - Slotless
    - NS-Magnets
      - Lap winding
  - Air-Cored
    - Air-Cored
      - NS-Magnets
        - Lap winding
- Single-Rotor Double-Stator (AFIR)
  - Slotted
    - Back-to-Back Winding
    - Lap Winding
  - Slotless
    - Back-to-Back Winding
- Multi-Rotor Multi-Stator
  - Slotted
  - Slotless
  - Air-Cored

Figure 1. Various topologies of AFPM machines and their winding configurations.

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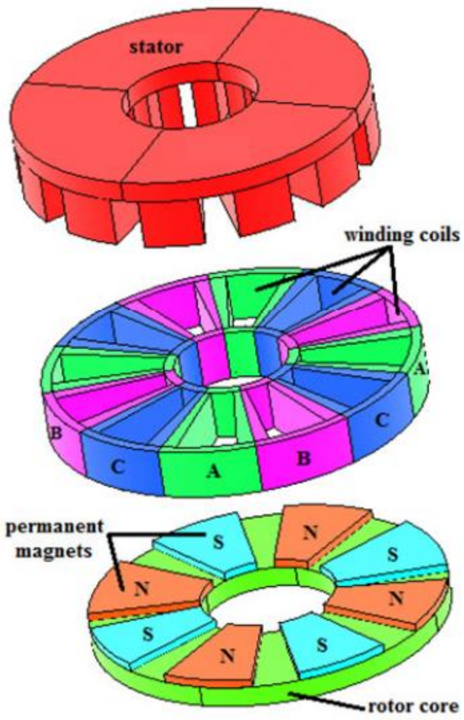
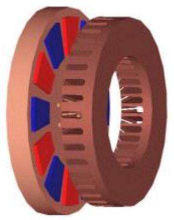
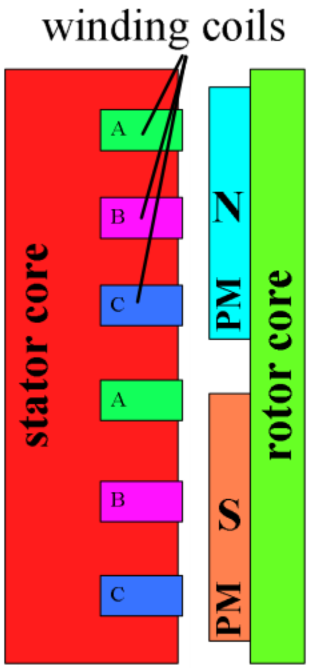
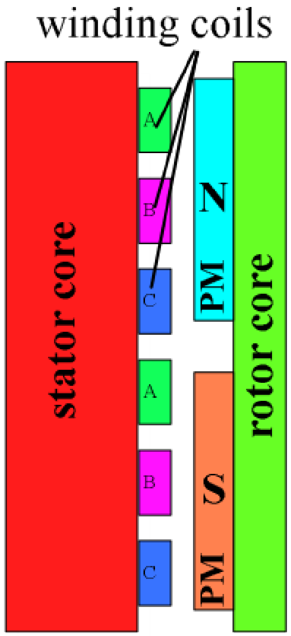
Construction of single-sided AFPM machine







Slotted-stator



Slotless-stator

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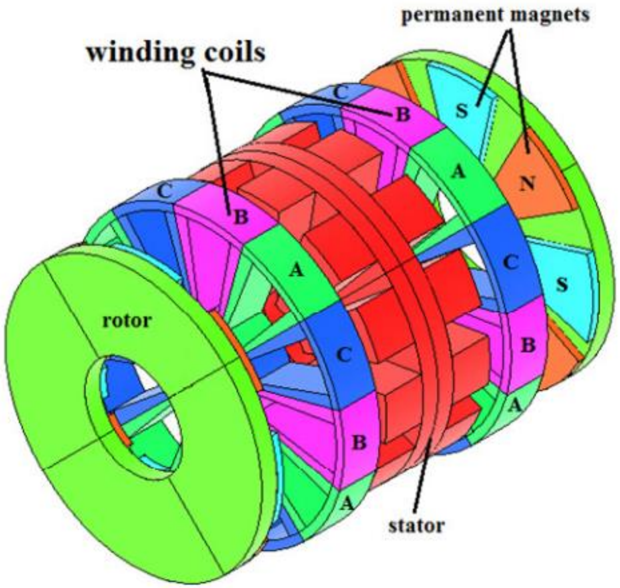
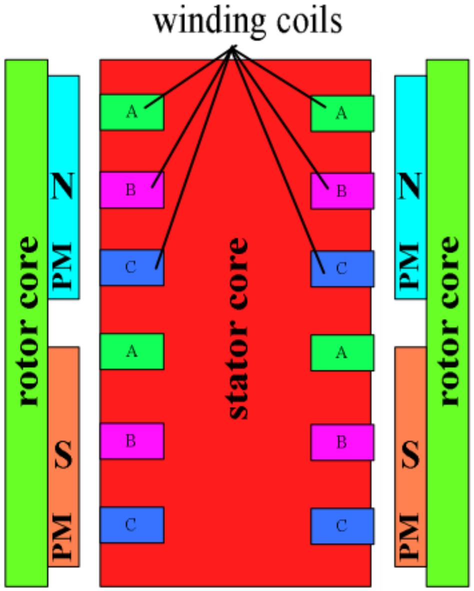
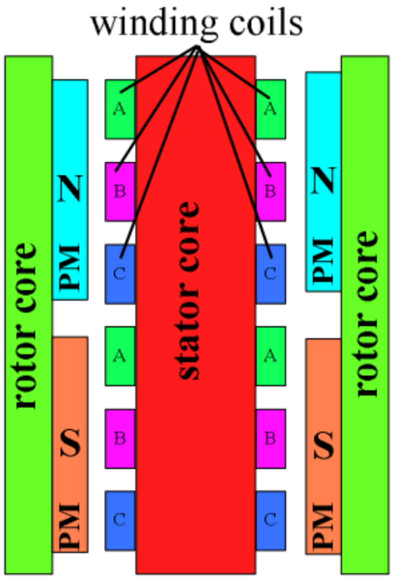
Construction of single-stator double-rotor AFPM machine

TORUS N-N





Slotted-stator



Slotless-stator

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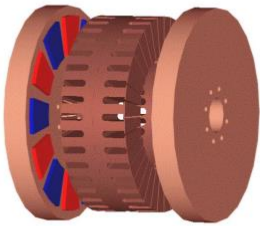
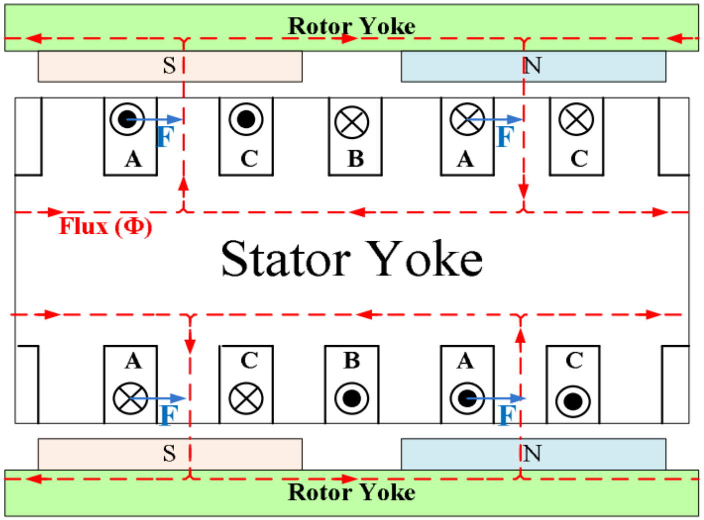
Flux paths for single-sator double-rotor AFPM machine

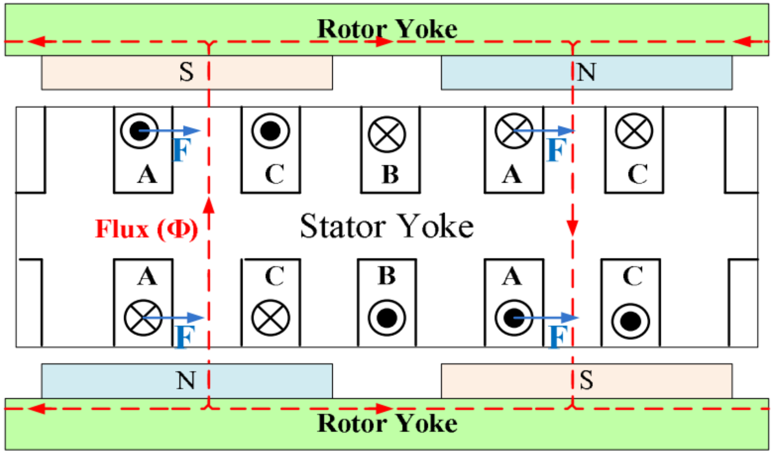


TORUS N-N



North-north magnet arrangement

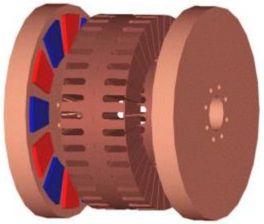
TORUS N-S



North-south magnet arrangement

Scientific Research and Essays Vol. 6(12), pp. 2525-2549, 18 June, 2011 Available online at http://www.academicjournals.org/SRE DOI: 10.5897/SRE11.334 ISSN 1992-2248 ©2011 Academic Journals

Flux paths for single-sator double-rotor AFPM machine



TORUS N-N

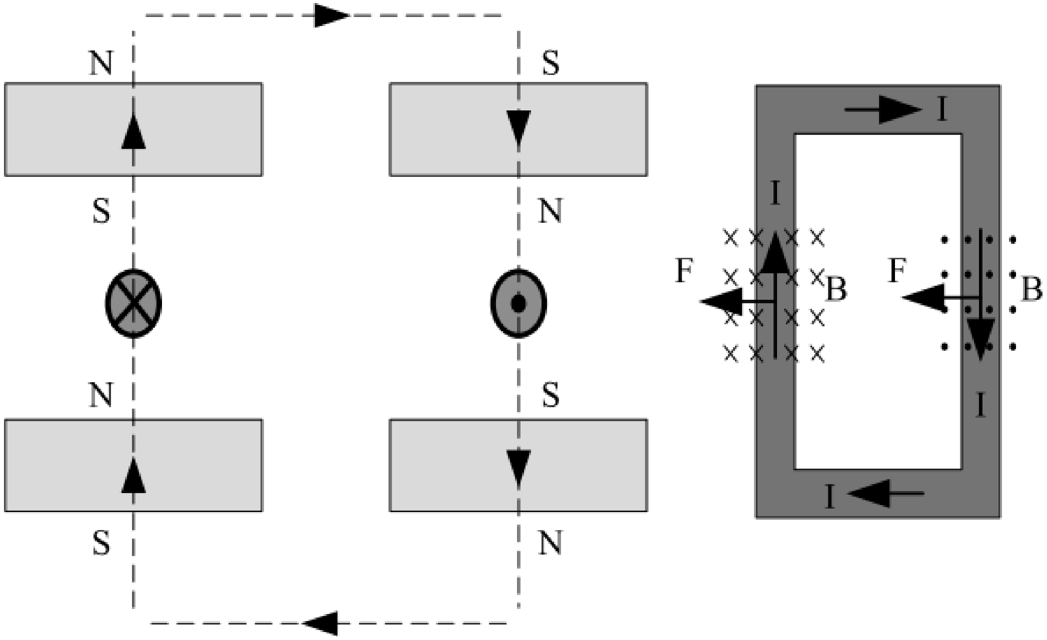
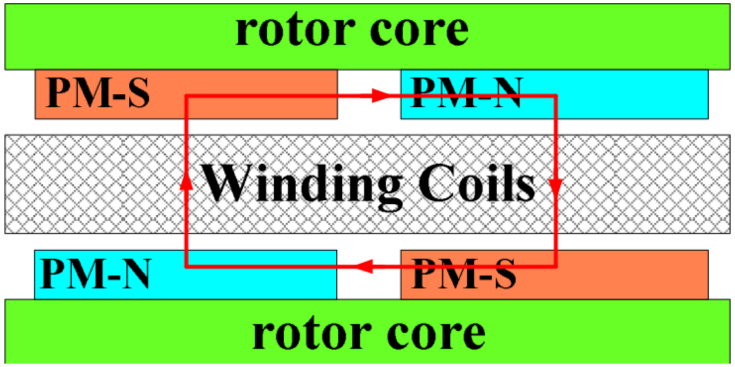


Fig. 2. Motor working principle

Proceedings of 2013 IEEE Internatinal Conference on Mechatronics and Automation August 4-7, Takamatsu, Japan, Jianguo Dai and Siqin Chang, School of Mechanical Engineering. Nanjing University of Science and Technology, China

Coreless TORUS

Coreless AFPM: coreless TORUS

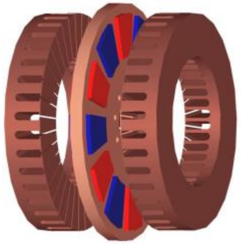


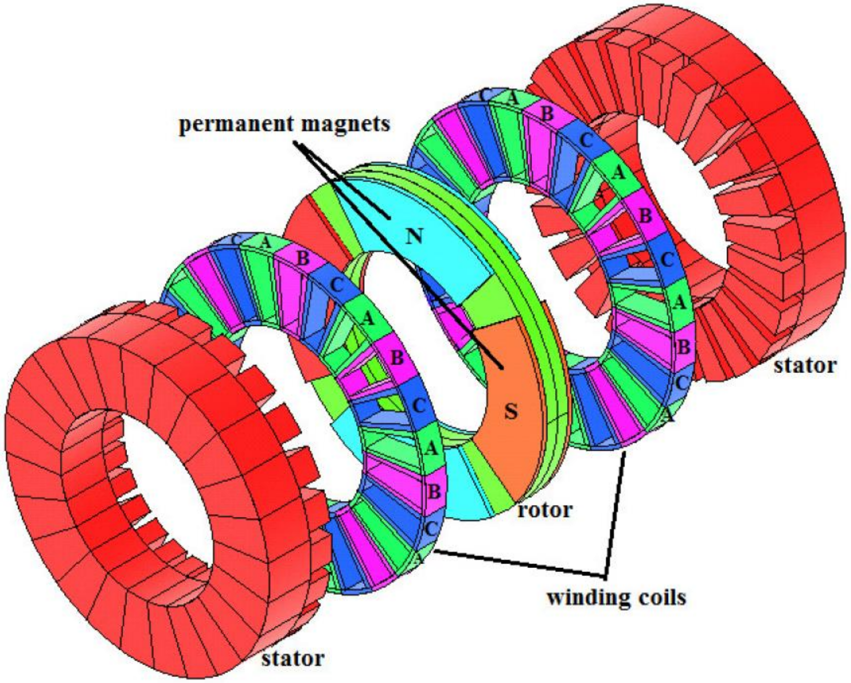
Its main feature is elimination of stator yoke, as in NS TORUS main flux flows from one rotor to another rather than travels circumferentially along stator core.

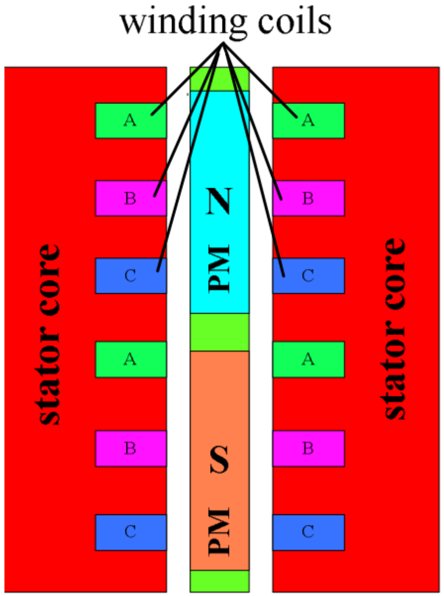
The rotor has windings only, and the rotor has surface magnet as in other AFPM machines. This type of AFPM machine is efficient as there are no iron losses.

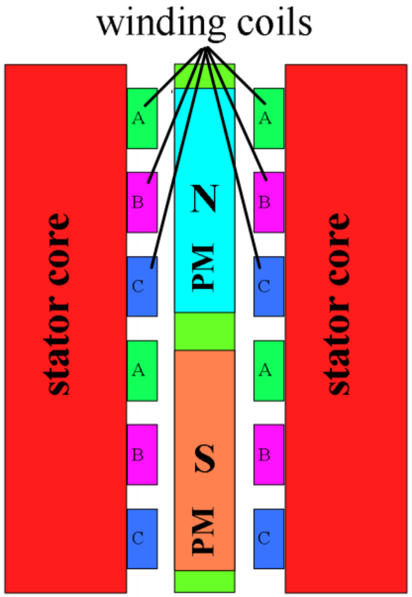
Construction of single-rotor double-stator AFPM

Axial-flux interior-rotor machine: AFIR



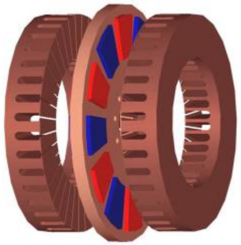


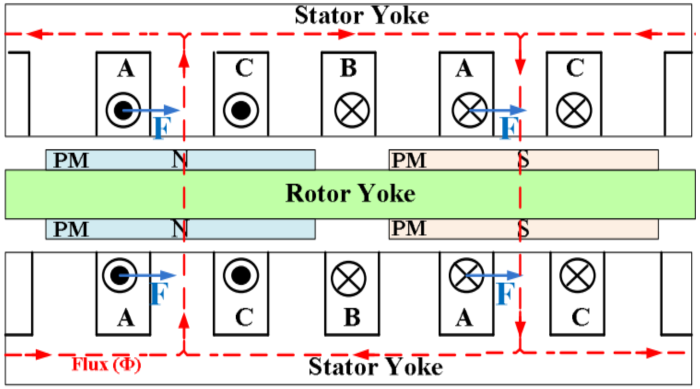




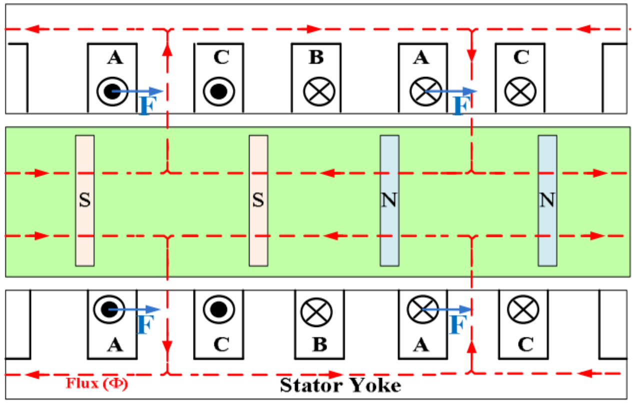
Construction of single-rotor double-stator AFPM

Axial-flux interior-rotor machine: AFIR

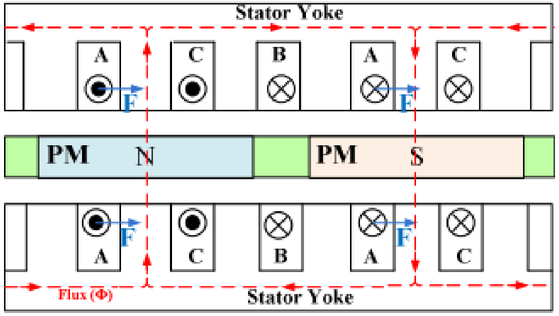




Surface permanent-magnet

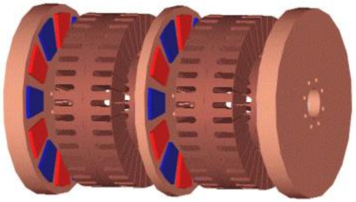


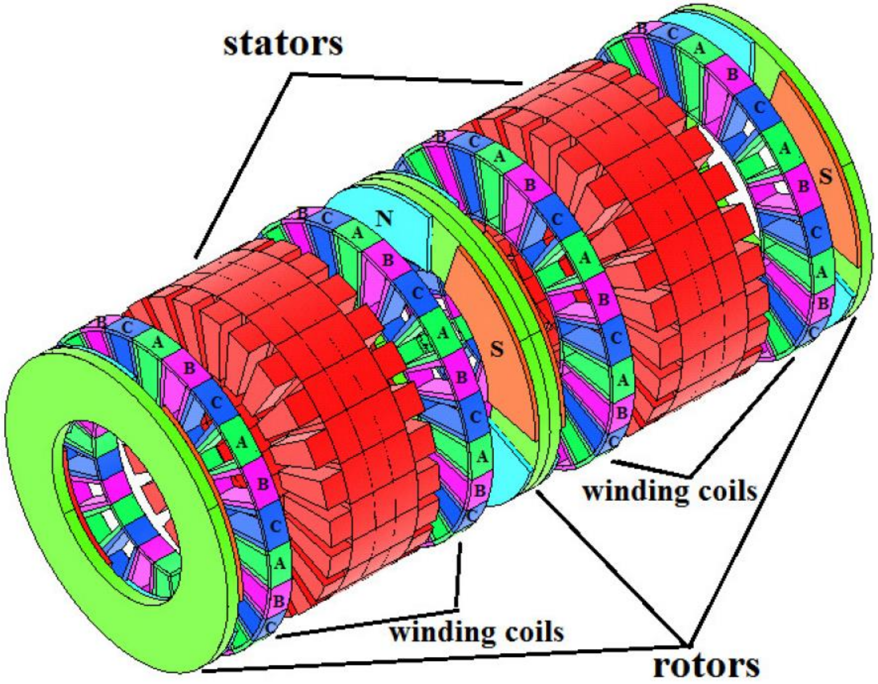
Buried permanent-magnet

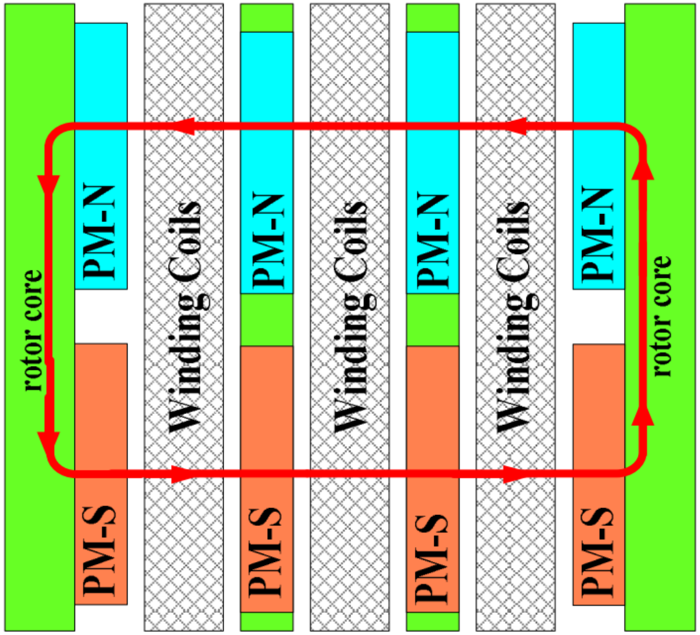


Structure without steel disk

Construction of multistage AFPM machine



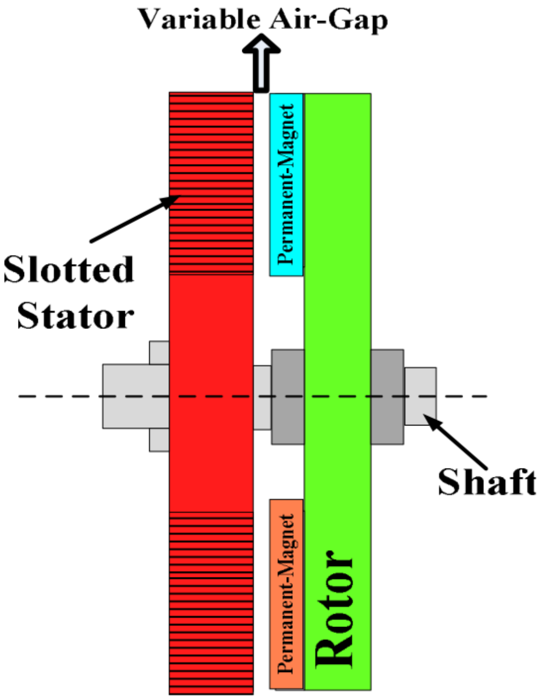


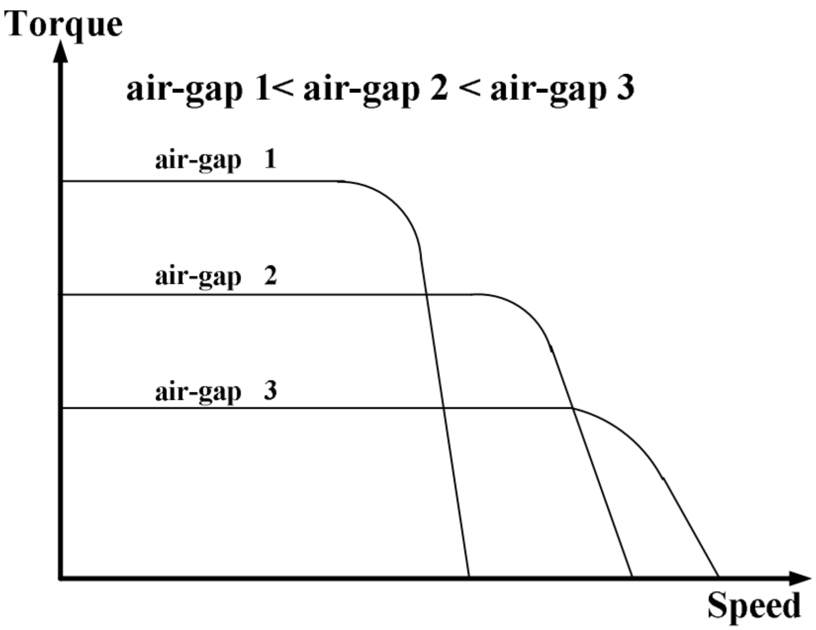


Multistage AFPM coreless stator machine

AFPM with variable air-gap and its torque-speed characteristic

This AFPM machine with variable air-gap optimizing machine performance and allowing flux-weakening. It suits flux-weakening applications such as electric traction.





Driving and controlling a AFPM

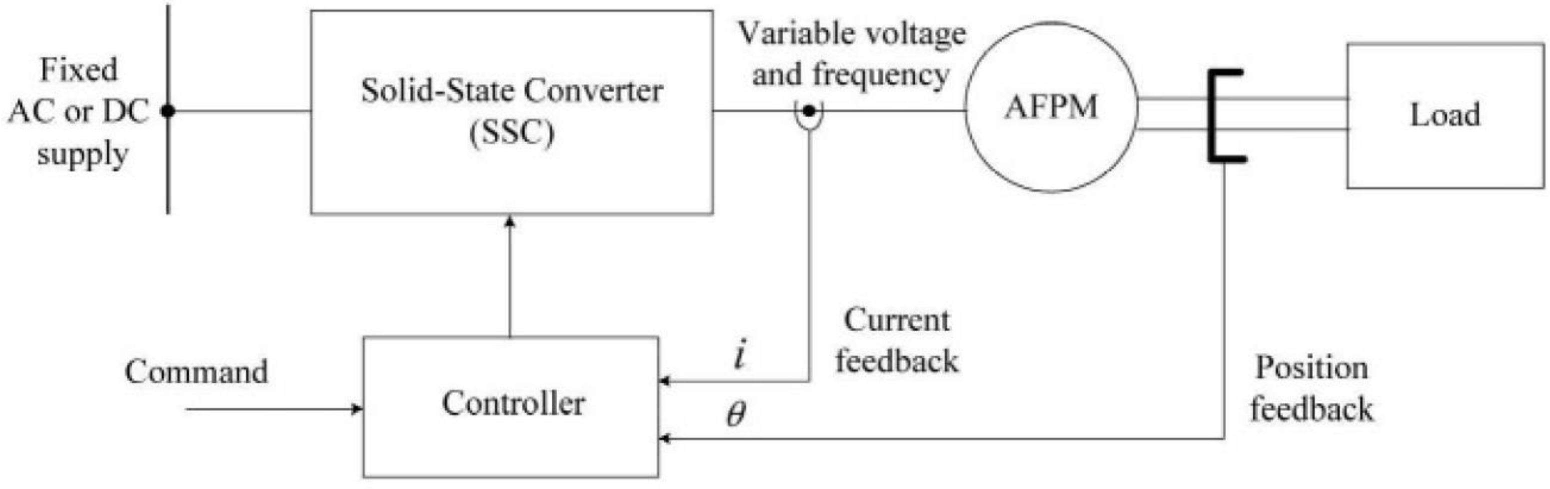


Figure 7.1. Converter-fed AFPM machine drive.

Axial Flux Permanent Magnet Brushless Machines **Authors:** Jacek F. Gieras, Rong-Jie Wang, Maarten J. Kamper ISBN: 978-1-4020-2661-4 (Print) 978-1-4020-2720-8 (Online)

For variable speed operation of the AFPM machine both the frequency and magnitude of the supply voltage must be adjustable. This requires a solid-sate converter to be used between the fixed a.c. or d.c. supply and the terminals of the AFPM machine. To have good positions and/or speed control of the converter-fed AFPM machine driver, the torque and therefore the current of the machine must be controlled. For current control, information of the phase current as well as the position of the rotor is necessary. Thus, both the current and the rotor position of the AFPM machine is sensed and fed back to the controller. The controller in its turn controls the supply voltage and frequency of the AFPM machine via the solid-state converter (inverter).

Driving and controlling a AFPM

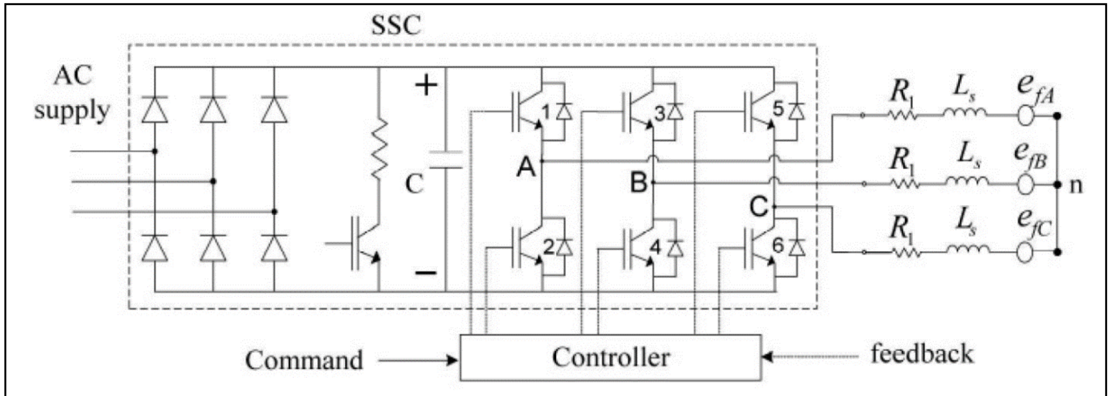
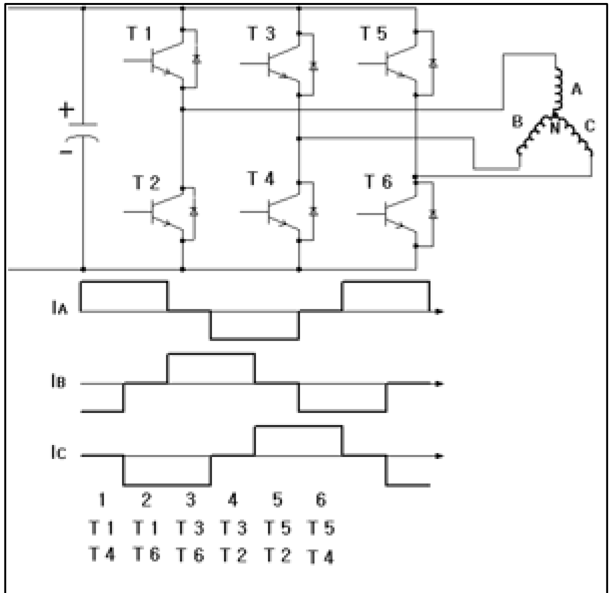


Figure 7.4. Solid-state a.c.–a.c. converter and equivalent three-phase AFPM machine connection.

Axial Flux Permanent Magnet Brushless Machines **Authors:** Jacek F. Gieras, Rong-Jie Wang, Maarten J. Kamper
ISBN: 978-1-4020-2661-4 (Print) 978-1-4020-2720-8 (Online)



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For variable speed operation of the AFPM machine both the frequency and magnitude of the supply voltage must be adjustable. This requires a solid-sate converter to be used between the fixed a.c. or d.c. supply and the terminals of the AFPM machine. To have good positions and/or speed control of the converter-fed AFPM machine driver, the torque and therefore the current of the machine must be controlled. For current control, information of the phase current as well as the position of the rotor is necessary. Thus, both the current and the rotor position of the AFPM machine is sensed and fed back to the controller. The controller in its turn controls the supply voltage and frequency of the AFPM machine via the solid-state converter (inverter).

Driving and controlling a AFPM

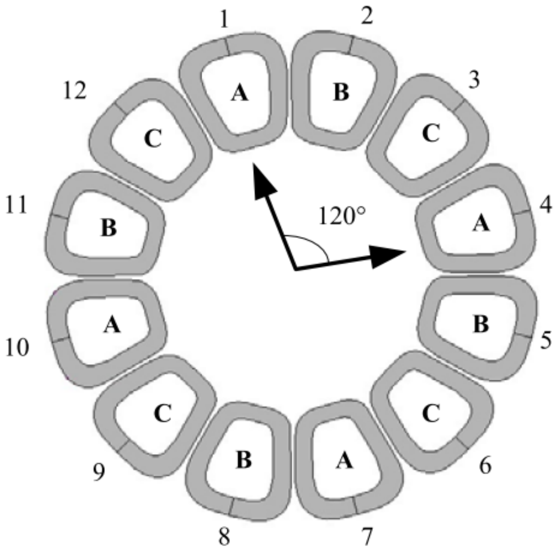


Fig. 4. Motor winding distribution

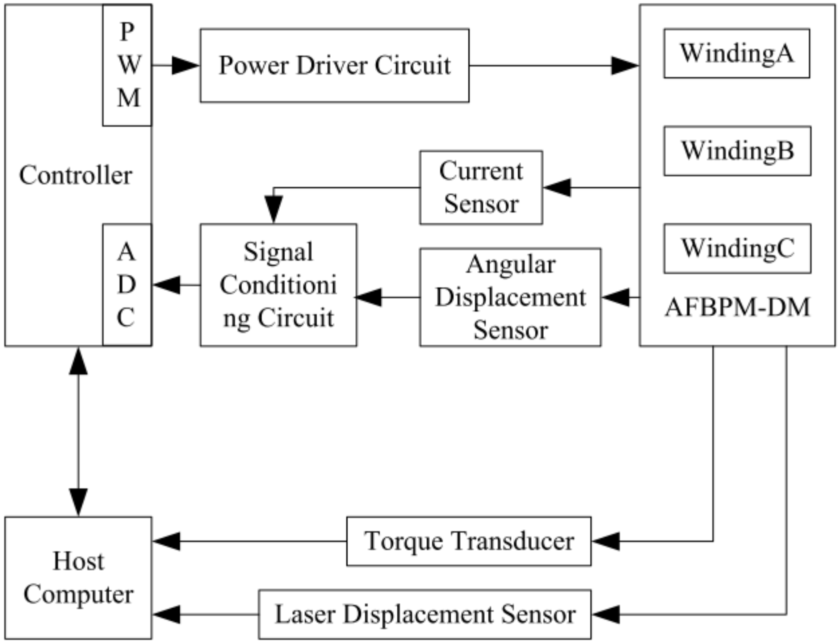


Fig. 5. Driving and controlling diagram of AFBPM-DM

Jiangyo Dai and Siqin Chang. Design, analysis and Improvement of a Disc Motor. Proceedings of 2013 IEEE. Internatinal Conference on Mechatronics and Automation. Japan

Tema IV: OTRAS MÁQUINAS

MÁQUINAS DE RELUCTANCIA VARIABLE (RELUCTANCIA CONMUTADA)

Introducción. Motores de pasos

Los motores de pasos son en esencia dispositivos motrices incrementales. Un motor de pasos recibe un tren de pulsos rectangular y responde girando su eje el número de grados que dicte el número de pulsos en el tren recibido.

El tren de pulsos se controla por medio de una microcomputadora o un circuito electrónico. Como resultado, un motor de pasos es mucho más compatible con circuitos electrónicos digitales y puede formar una interfaz entre un ordenador y un sistema mecánico.

Se aplican en impresoras, controles de unidades lectoras de discos, robots y herramientas de control numérico. Los motores de pasos pueden clasificarse en tres grandes categorías:

- de reluctancia variable,
- de imanes permanentes e
- híbridos.

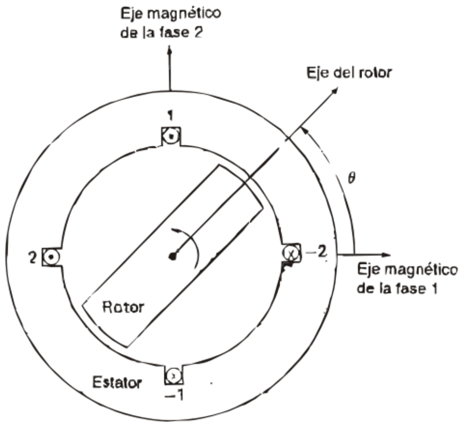
Máquinas de reluctancia variable (o de reluctancia conmutada)

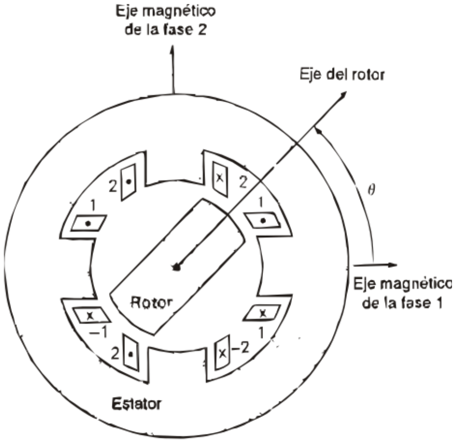
Las máquinas de reluctancia variable constan de un estator con devanados de excitación, y un rotor magnético de polos salientes. No se necesitan conductores en el rotor porque el par se produce por la tendencia del rotor a alinearse con la onda de flujo producida por el estator que trata de maximizar los encadenamientos de flujo de dicho estator que originan por una corriente aplicada en él.

Se pueden clasificar las máquinas de reluctancia variable en dos tipos:

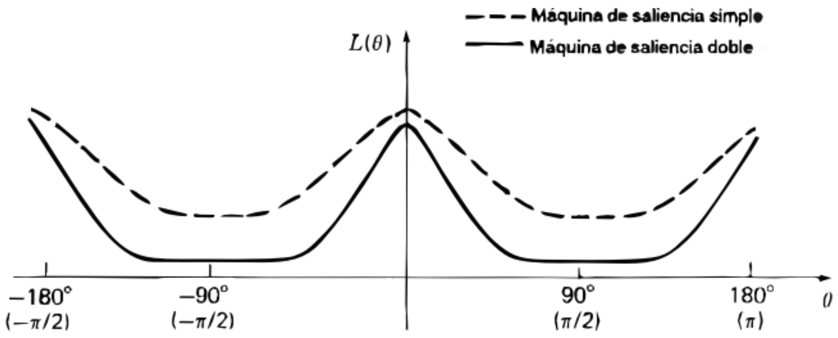
- de polo saliente simple y
- de polo saliente doble.

En ambos casos sus particularidades más notables consisten en no tener devanados ni imanes permanentes en sus rotores, y que la fuente única de excitación costa de devanados en el estator.





Máquinas de reluctancia variable (o de reluctancia conmutada)



Gráficas de inductancia contra θ para las máquinas de reluctancia variable de la figura

Para producir par se deben diseñar las máquinas de reluctancia variable de tal modo que varíen las inductancias del devanado del estator con la posición del rotor. La inductancia de cada devanado de fase de estator varía con la posición del rotor de tal modo que la inductancia es máxima cuando los dos ejes son perpendiculares.

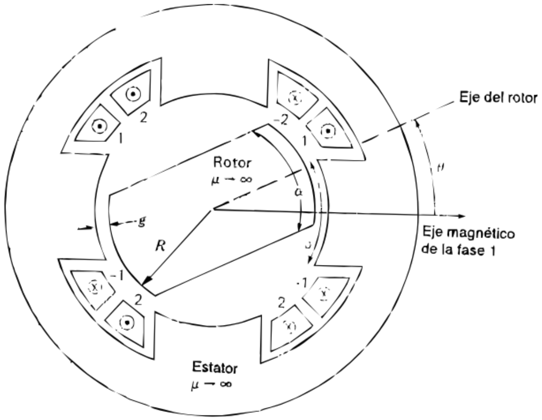
La relación entre los encadenamientos de flujo y la corriente es bastante sencilla para estas dos máquinas, debido a que se pueden argumentar razones de simetría para demostrar que la reluctancia del hierro de la máquina sea muy pequeña, entonces los encadenamientos de flujo mutuos entre los devanados de las dos fases serán despreciables, y por lo tanto, la inductancia muta fase a fase se podrá considerar como cero. Así

$$\lambda_1 = L_{11}(\theta)i_1 = L(\theta)i_1 \qquad \lambda_2 = L_{22}(\theta)i_2 = L(\theta - 90^{\mathrm{o}})i_1 \qquad T = \frac{1}{2}i_1^2\frac{dL(\theta)}{d\theta} + \frac{1}{2}i_2^2\frac{dL(\theta-90^{\mathrm{o}})}{d\theta}$$

Máquinas de reluctancia variable (o de reluctancia conmutada)

Aunque se puede hacer que ambos tipos de diseño trabajen, es frecuente que el tipo de doble polo saliente sea la alternativa más favorable porque en general puede producir un par mayor para determinado tamaño de armazón. Debido a su geometría, una estructura de polo saliente doble tendrá por lo general una menor inductancia mínima y con ello un mayor valor de par, ya que

$$\frac{dL(\theta)}{d\theta} \approx \frac{L_{\max} - L_{\min}}{\Delta\theta}$$

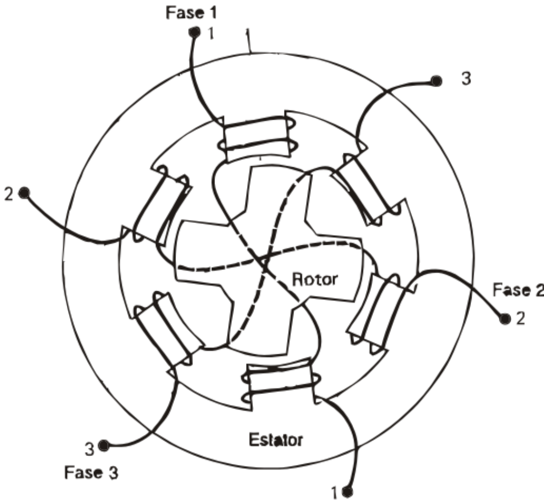


Por este motivo las máquinas de polo saliente doble son el tipo predominante de máquinas de reluctancia variable

Máquinas de reluctancia variable (o de reluctancia conmutada)

Una vez que se determina la estructura básica de una máquina de reluctancia variable, L_{max} queda bien determinada por cantidades tales como el número de vueltas, la longitud del entrehierro y las dimensiones básicas de los polos. El reto para el diseñador de estas máquinas es lograr un valor pequeño de L_{min}. Esta es una tarea difícil debido a que L_{min} está muy influido por los flujos de dispersión y por otras cantidades que son difíciles de calcular y de analizar.

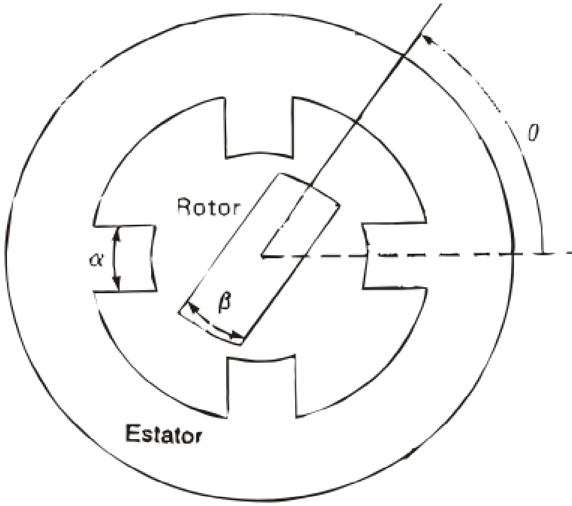
Cómo se muestra en el siguiente ejemplo, la geometría de una máquina simétrica de reluctancia variable con entrehierro uniforme da lugar a posiciones del rotor para las que no se pueden desarrollar pares para alguna combinación de excitación de los devanados de fase del rotor. Se puede ver que estos pares de valor cero se presentan en posiciones del rotor en las que las fases del estator están simultáneamente en una posición de inductancia ya sea máxima o mínima. Como el par depende de la derivada de la inductancia con respecto a la posición angular, este alineamiento simultáneo de puntos de inductancia máxima o mínima ocasiona necesariamente un par cero.



En una máquina de reluctancia variable 6/4 (6 polos en estor y 4 en rotor), por ejemplo, no es posible la alineación simultánea de inductancias de fase. Por lo que esta máquina no tiene posición de cero-par. Por lo que se elimina la posibilidad de que el rotor se peque en una de estas posiciones permaneciendo inmóvil, y que sea necesario moverlo en forma mecánica a una posición nueva antes de poderlo arrancar.

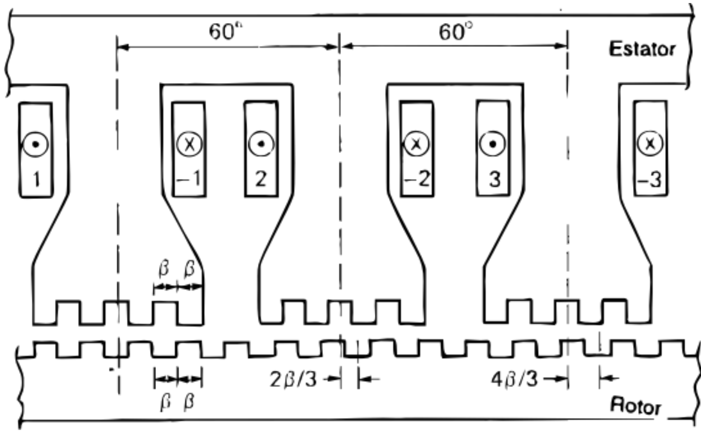
Máquinas de reluctancia variable (o de reluctancia conmutada)

Si la relación m/n o n/m es un número entero habrá posiciones de cero-par.
En algunos casos las limitaciones de diseño pueden obligar a que sea deseable tener una relación entera de polos. En estos casos es posible eliminar las posiciones de cero-par construyendo una máquina con un rotor asimétrico. Por ejemplo, se puede hacer que el radio del rotor varíe con el ángulo.



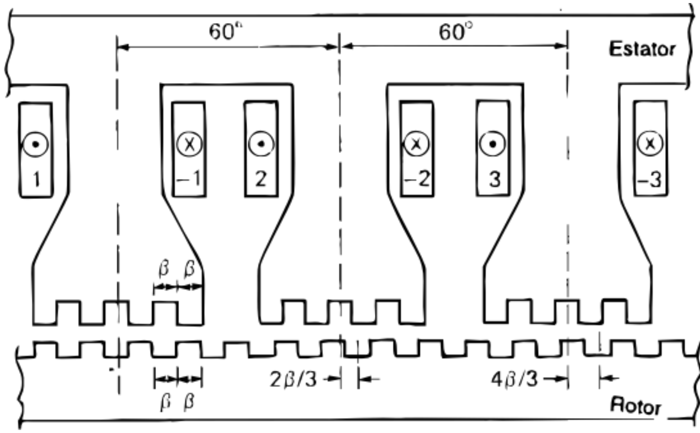
Un procedimiento alternativo para construir una máquina de reluctancia variable de relación polar entera sin posiciones de cero-par es fabricar un conjunto de dos más máquinas en serie, alineadas de tal manera que cada una esté desplazada determinado ángulo con respecto a las demás, con todos los rotores compartiendo una eje común. De este modo las posiciones de cero-par de las máquinas individuales no quedarán alineadas y con ello la máquina completa no tendrá pares de valor cero.

Otra configuración posible es si se subdividen los polos principales del estator y del rotor mediante la adición de dientes individuales (que se pueden considerar como un conjunto de polos pequeños excitados en forma simultánea por un devanado único). Esta máquina se llama máquina de reluctancia variable dentada.



Máquinas de reluctancia variable (o de reluctancia conmutada)

Otra configuración posible es si se subdividen los polos principales del estator y del rotor mediante la adición de dientes individuales (que se pueden considerar como un conjunto de polos pequeños excitados en forma simultánea por un devanado único). Esta máquina se llama máquina de reluctancia variable dentada.



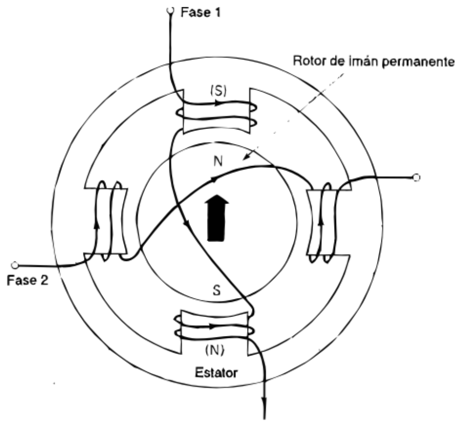
Note que este número de dientes del rotor y el valor correspondiente de β se escogieron de modo que cuando estén alineados los dientes del rotor con los del polo de la fase 1 de estator, no están alineados con los de las fases 2 y 3. De este modo la excitación sucesiva de las fases del estator provocará un giro del rotor.

Se puede emplear la técnica del dentado para crear máquinas de reluctancia variable capaces de trabajar a velocidades bajas y con alto par para determinado consumo de potencia en estator, y con exactitud muy grande en la posición del rotor.

A fin de desarrollar un par en el motor y hacer girar el rotor en determinado sentido, la posición del rotor debe determinarse mediante sensores. Esto hace que el sistema de control es más complejo, pero con la introducción de nuevos circuitos de conmutación de potencia electrónicos y micro-electrónicos, los circuitos de control y de mando de un motor de reluctancia se ha vuelto efectivos en costo para muchas aplicaciones en las que se usaban tradicionalmente motores de c.c. o de inducción.

Motores de pasos de imanes permanentes

Un motor de paso tipo imán permanente (PM) difiere del de reluctancia variable en que su rotor está formado por imanes permanentes. La construcción del estator de un motor de pasos tipo PM es igual a la de uno de reluctancia variable. En la siguiente figura se muestra un motor de pasos tipo PM bifásico con rotor de dos polos



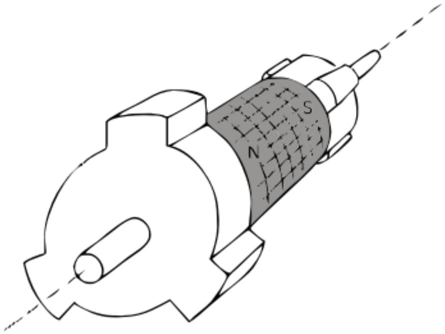
Cuando se excita una fase individual, el rotor tiende a alinearse con ella. A diferencia del motor de reluctancia variable, la alineación del rotor en el motor de pasos PM depende de la dirección de las corrientes de fase. Si se invierten éstas se hará que el rotor invierta su orientación. En el motor de pasos de PM, a diferencia del de reluctancia variable, se generará el par que tiende a alinear al rotor con los polos del estator aun cuando no haya excitación aplicada a los devanados de fase. Así el rotor tendrá posiciones particulares de descanso sin excitación.

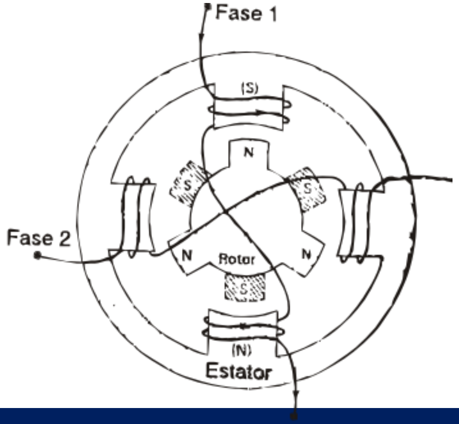
Motor de pasos híbrido

Este motor combina las características de los motores de reluctancia variable y de imán permanente.

La configuración del motor de pasos híbrido se parece mucho a la de un motor de pasos de reluctancia variable de varios conjuntos. En el rotor dos conjuntos idénticos de rotor están desplazados axialmente a lo largo del eje y están desplazados en un ángulo igual a la mitad del paso polar del rotor. A diferencia del motor de pasos de reluctancia variable de varios conjuntos, en el híbrido los conjuntos del rotor están separados por un imán permanente dirigido axialmente. Como resultado de ello se puede considerar que un extremo del rotor tiene un polo norte magnético y el otro un polo sur.

El diseño híbrido de motor de pasos presenta ventajas sobre el de imán permanente. Puede alcanzar con facilidad tamaños de pasos pequeños con una estructura sencilla de imán, mientras que un motor sólo de imán permanente necesitaría un imán permanente de varios polos. En comparación con el motor de pasos de reluctancia variable, el tipo híbrido puede necesitar menos excitación para lograr un par determinado debido a que algo de la excitación es suministrada por el imán permanente. Además, el motor de pasos híbrido tiende a mantener su posición cuando se quita la excitación del estator, al igual que el de imán permanente.



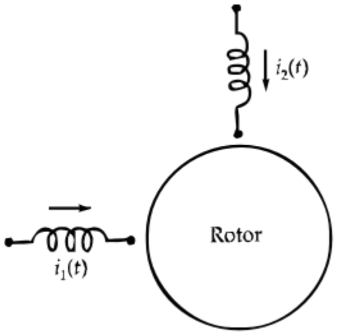


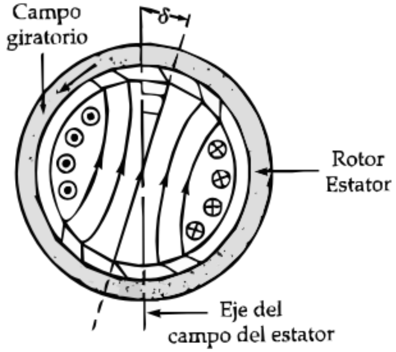
Tema IV: OTRAS MÁQUINAS

MOTORES DE HISTÉRESIS

Motor de histéresis

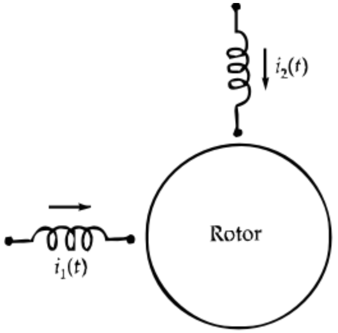
Estos motores utilizan la propiedad de histéresis de los materiales magnéticos para desarrollar un par. El estator puede tener un devanado de fase uniformemente distribuido trifásico o monofásico. En un motor de histéresis monofásico, el devanado del estator se conecta como motor de condensador dividido permanente. El condensador se selecciona de modo que pueda alcanzarse en forma aproximada una condición bifásica equilibrada, de modo que casi se establezca un campo giratorio uniforme. El rotor es un material magnético sólido duro sin dientes ni devanados.

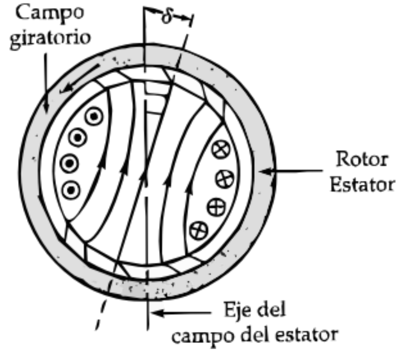




Cuando se excita el devanado el estator, en el entrehierro del motor se establece un campo giratorio. El campo giratorio magnetiza el rotor e induce tantos polos en su periferia como polos tenga el estator. Debido a la gran pérdida por histéresis en el rotor, el flujo magnético que se desarrolla en él se encuentra en atraso respecto de la fuerza magnetomotriz del estator. Luego, existe un ángulo del rotor, δ, entre los ejes magnéticos del rotor y del estator. Cuanto mayor sea la pérdida debida a la histéresis, más grande será el ángulo entre los ejes magnéticos del rotor y el estator. Debido a la tendencia de los polos magnéticos del rotor para alinearse a sí mismos con los del estator, se produce un par finito, llamado par de histéresis, proporcional al producto del flujo en el rotor y la f.m.m. del estator y el seno del ángulo del rotor, δ. Por tanto, un rotor con un ciclo de histéresis grande da lugar a un par de histéresis más elevado.

Motor de histéresis





Como el rotor es un material magnético sólido, se inducen corrientes parásitas en él debido al campo magnético del estator en tanto haya un movimiento relativo entre el campo magnético del estator y del rotor. Tales corrientes producen sus propios campos magnéticos y, por ende, su propio par, el cual incrementa aún más el par total que desarrolla el motor. El par debido a las corrientes parásitas es proporcional al deslizamiento del motor, con valor máximo en reposo e igual a cero cuando se alcanza la velocidad síncrona.

Ventajas:
- Par constante.
- Rotor lizo, para operaciones silenciosas y sin vibraciones

Limitaciones:
- La potencia de salida es ¼ que la de un motor de inducción de la misma dimensión.
- Baja eficiencia.
- Bajo factor de potencia
- Par bajo y variable.

Encuentra su aplicación en aquellas donde se necesite velocidad constante (reloj eléctrico), en reproductores o grabadores de sonido, etc.

Tema IV: OTRAS MÁQUINAS

MOTORES DE INDUCCIÓN LINEALES

Motores de inducción lineales

Hasta ahora hemos estudiado los principios fundamentales de operación de máquinas eléctricas que producen rotación o movimiento circular. Cada máquina rotatoria puede tener su contraparte lineal. Sin embargo, el motor de inducción lineal es el que más se utiliza en un amplio espectro de aplicaciones industriales, tales como el transporte terrestre de alta velocidad, sistemas de puertas deslizantes, etc.

(a) Magnetically levitated train HSST (b) Subway driven by linear motors.

[1] Y. Nozaki, T. Yamaguchi, and T. Koseki: "Practical Equivalent Circuit Model of Linear Induction Motors for Urban Transportation System Depending on Secondary Speed Based on Electromagnetic Analysis," ICEMS2006, LS3B-1, Nov-2006, Nagasaki

Motores de inducción lineales

Si se corta un motor de inducción y se extiende en un plano, se obtiene un motor de inducción lineal. El estator y el rotor del motor giratorio corresponden a los lados primario y secundario, respectivamente, del motor de inducción lineal. El lado primario consta de un núcleo magnético con un devanado trifásico; el lado secundario puede constar simplemente de una placa de metal.

En un transporte terrestre de alta velocidad se utilizan un primario corto (parte integral del vehículo) y un secundario largo (vía).

Cuando el voltaje de suministro se aplica al devanado primario de un motor de inducción lineal trifásico, el campo magnético que se produce en la región del entrehierro viaja a velocidad síncrona. La interacción del campo magnético con las corrientes inducidas en el secundario ejercen un empuje sobre éste para moverlo en la misma dirección si el primario se mantiene estacionario. Por otro lado, si el lado secundario es estacionario y el primario tiene libertad de movimiento, éste se moverá en la dirección opuesta a la del campo magnético.