Unit 2: Electric Motor Drives for EV applications

Syllabus

Concept of EV motors, Classification of EV motors, and Comparison of Electric motors for EV applications, Recent EV motors, BLDC and SRM, axial flux motor. Introduction to power electronics converters, DC-DC converter, speed control of dc motor, BLDC motor driving schemes.

Concept of EV Motors

Electric vehicles (EVs) are becoming a popular green alternative to internal combustion engine (ICE) vehicles, the dominant driver for over 100 years. EVs operate via an electric motor powered by battery energy.

The propulsion system is the heart of an EV, and the electric motor sits right in the core of the system. The motor converts electrical energy that it gets from the battery into mechanical energy which enables the vehicle to move. It also acts as a generator during regenerative action which sends energy back to the energy source. Based on their requirement, EVs can have different numbers of motors: the Toyota Prius has one, the Acura NSX has three—the choice depends on the type of the vehicle and the functions it is supposed to provide. Listed the requirements for a motor for EV use which includes high power, high torque, wide speed range, high efficiency, reliability, robustness, reasonable cost, low noise and small size. Direct current (DC) motor drives demonstrate some required properties needed for EV application, but their lack in efficiency, bulky structure, lack in reliability because of the commutator or brushes present in them and associated maintenance requirement made them less attractive .With the advance of power electronics and control systems, different motor types emerged to meet the needs of the automotive sector, induction and permanent magnet (PM) types being the most favoured ones .

There are various types of motors used for EVs.

EVs use traction motors that are capable of delivering torque to the wheels. Electric motors can be roughly divided into two types: DC and AC motors. Both types can be used in EV applications.

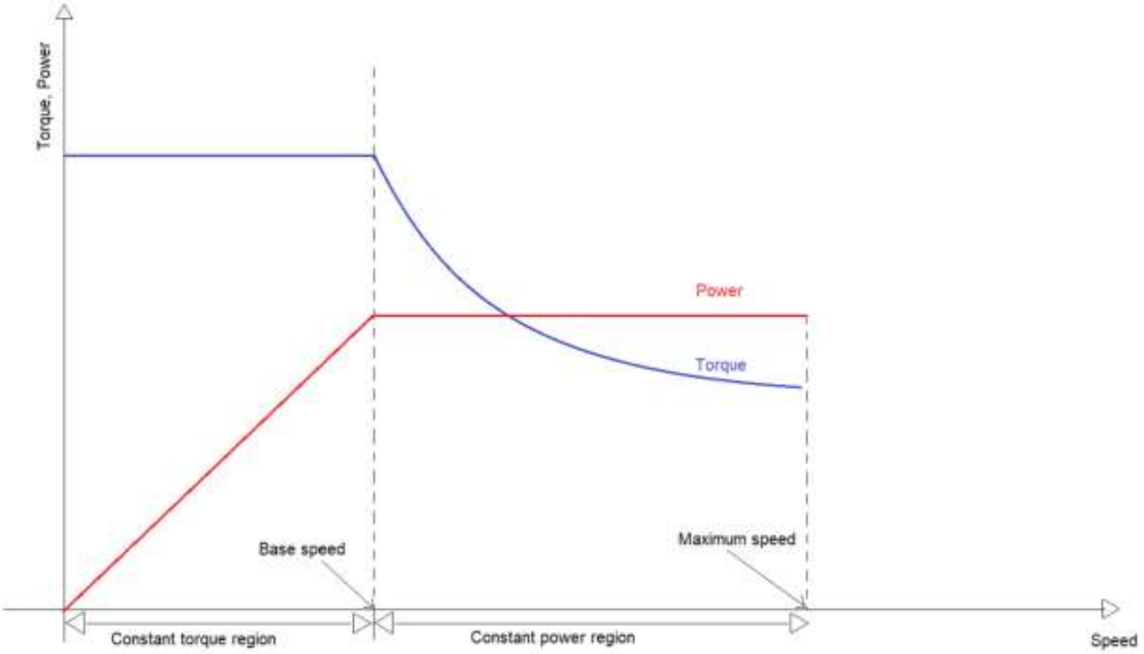
DC motors are robust and allow simple control. They can be made as brushed and brushless DC motors. Brushed DC motors are a mature technology that provides low cost, high torque at low speed, and easy speed control. These features are very important for traction motors. However, brushed DC motors are not widely used in EVs because of their disadvantages, which include large size, low efficiency, and requirement for frequent maintenance due to the brush and collector structure. Brushless DC motors have a much higher efficiency. These motors use an electronic commutator/inverter instead of the brushes.

Compared to DC motors, the advantages of AC motors are high efficiency, less maintenance, higher reliability, and regenerative capability that enables braking energy to be returned to the batteries.

Features of an EV Motor

An EV's motor and electronics efficiency directly influences the battery weight, because the lost power needs to be compensated. Every 1% lower efficiency requires 1% more power from the battery (meaning more batteries).

The EV's performance directly depends on the electrical motor specifications. The performance of the motor is determined by the torque-speed and power-speed characteristic of the traction motor.



The grade ability and maximum speed are important parameters in these curves. The desired motor grade ability requires high torque at low speed, enabling proper starting and acceleration. The EV motor needs to have high power at high speed and a wide speed range in the constant power region as shown in Figure 1. The constant torque operating region is important at low speed to provide a good start and up-hill drive. The constant power region determines the maximum EV speed on flat surfaces.

When the base speed is achieved, the motor reaches its rated power limit and the motor torque decreases proportionally to the square of speed. The constant power region starts beyond base speed in the range from base speed up to maximum motor speed. This range is different in different motor types and it is an important parameter when selecting the proper EV motor type. Also, the motor operation range can be adjusted by using the corresponding control drives.

Selecting the proper output characteristic of an EV motor is a challenge because it is necessary to find the balance between acceleration performance and wide speed range in the constant power region. When increasing the constant power region, the power requirement for acceleration performance is decreased. The torque requirement is increased which influences the motor size and its final price.

These are the features we desire in an EV motor:

- High efficiency
- High instant power
- Fast torque response
- High power density
- Low cost
- High acceleration
- Robustness

We will now look at how these features stack up in the following motor types:

1. DC motors
2. Permanent Magnet Brushless DC motors (PM BLDCs)
3. Induction motors
4. Permanent Magnet Motors
5. Switched Reluctance Motors (SRM)

DC Motor

The biggest advantages of DC motors in EVs are robust construction and simple control. DC motors have appropriate torque-speed characteristics providing high torque at low speed. Their main disadvantages are size, low efficiency, low reliability and high maintenance, and limited speed because of the friction between brushes and collectors. There are two DC motor types: brushless and brushed DC motors. The latter are increasingly suppressed because of the advances in power electronics.

Permanent Magnet Brushless DC Motor (PM BLDC)

PM BLDC motors use permanent magnets instead of the rotor windings. Since they do not include rotor losses their efficiency is higher than inductive motors. PM BLDC motors have a short constant power operation region because of their permanent magnet field weakened by a stator field. Since EVs require a wider constant power region, this can be extended by using conduction angle control where the speed range may reach three to four times the base speed.

The permanent magnets also limit the motor torque to be high. The magnets are significantly influenced by the high temperature which reduces the remnant flux density and thus the motor torque capacity. The mechanical forces and magnet prices are the biggest disadvantages of this type of motor. The increased centrifugal forces caused by higher motor rotation speed can cause safety issues due to the possible breaking of the magnets.

Induction Motor (IM)

This motor type is very common in EVs because of its simple construction, high reliability, robustness, simple maintenance, and low cost and operation at different environmental conditions. IMs can be naturally de-excited if the inverter faults, an important safety advantage for EVs. The field-oriented vector control of IMs is industrially standardized.

The disadvantages of IMs are slightly lower efficiency (compared to PM motors), higher power losses (increased because of the cage losses), and a relatively low power factor. The weakening of the flux can be used to extend the speed range in the constant power operation region. This region can be extended by using dual inverters as well. Rotor losses can be also reduced by careful motor design.

Figure 2: Construction of an induction motor. (Image courtesy of Orientalmotor.)

Permanent Magnet Synchronous Motor (PMSM)

PMSMs, similar to BLDCs, have permanent magnets in the rotor. Unlike BLDC motors that have a trapezoidal back electromotive force (EMF) waveform, PMSMs have a sinusoidal back EMF. They have a simple construction, high efficiency, and high power density, thus they are suitable to be used as traction motors (common in hybrid vehicles, EVs, and buses). PMSM motors have a higher efficiency compared to IMs. The drawbacks of this type are high costs, eddy current loss in PMs at high speed, and a reliability risk because of the possible breaking of the magnets.

There are two varieties of PMSM motors: surface-mounted permanent magnet (SPM) and interior permanent magnet (IPM) synchronous motor drives. IPM motors have better performance than SPMs, but the downside is their complex design.

Switched Reluctance Motor (SRM)

The benefit of SRMs is their high torque component, enabling their use in many applications such as wind energy, generator starter systems in gas turbine engines, and high-performance aerospace applications. Moreover, their advantages in EVs include their robustness, simple control, high efficiency, wide constant power operation region, fault tolerance, and effective torque-speed characteristics. Since they do not contain brushes, collectors, or magnets, the maintenance of SRMs is very simple and effective and their price is very competitive.

The absence of magnets eliminates the problem with mechanical forces, enabling the motor to operate at a high speed. Since the motor's windings are not used, there are no copper losses in the rotor ensuring the rotor temperature is lower than other motor types. Since the phases are not connected, SRM motors can continue their operation even when one of the phases disconnects. SRM rotors have a lower inertia than other motor types. The drawbacks of this motor type are increased vibration and acoustic noise. In addition, the salient-pole rotor and stator construction cause high torque ripple. The high rotor inductance ratio allows sensor-less control to perform.

Proper motor design enables the wide constant power operation region, which in turn allows operation at high speeds. SRMs have a suitable torque/power speed characteristic for EV applications.

Comparison and Evaluation

Characteristics		**Motor type**		
	DC	**IM**	**PM**	**SRM**
Power density	Low	Medium	Very high	Medium
Efficiency	Low	Medium	Very high	Medium
Controllability	Very high	Very high	High	Medium
Reliability	Medium	Very high	High	Very high
Technological maturity	Very high	Very high	High	High
Cost	Low	Very low	High	Low

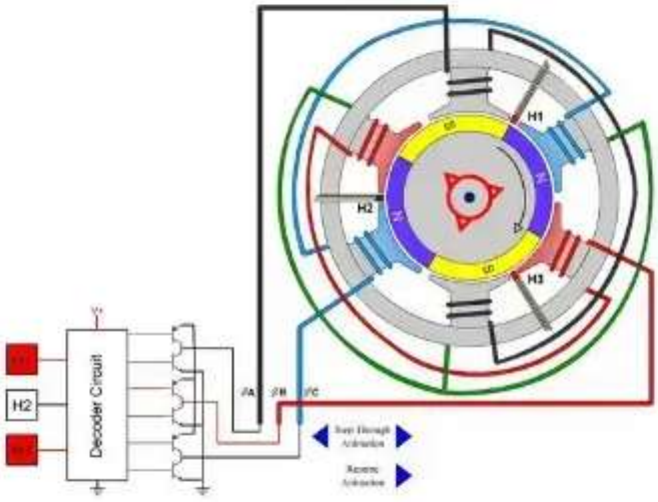
It is noticeable that the IM motor type has all the characteristics suitable for EVs. In this application, safety is one of the most important considerations and the SRM and IM types provide driving safety. However, the rated speed of IM is relatively low. PM has a higher power factor and efficiency in low-speed region.

The SRM type does not use brush collectors and magnets and thus has fewer maintenance requirements. This type also has lower power losses than other types. This is because of the short winding ends and their total length. The rotor does not contain conductors enabling low rotor temperature and easy cooling, which is one of the main advantages of SRM type motors. SRM operates at high speeds in a wide constant power region and allows the extremely high-speed operation. Besides this, the motor is lightweight, competitive and has high efficiency. If all characteristics are considered, SRM is the most suitable motor type for EVs.

Brushless DC Motor

A **brushless DC motor** (also known as a **BLDC motor** or **BL motor**) is an electronically commuted DC motor which does not have brushes. The controller provides pulses of current to the motor windings which control the speed and torque of the synchronous motor.

These types of motors are highly efficient in producing a large amount of torque over a vast speed range. In brushless motors, permanent magnets rotate around a fixed armature and overcome the problem of connecting current to the armature. Commutation with electronics has a large scope of capabilities and flexibility. They are known for smooth operation and holding torque when stationary.



Primary efficiency is a most important feature for BLDC motors. Because the rotor is the sole bearer of the magnets and it doesn't require any power. I.e. no connections, no commutator and no brushes. In place of these, the motor employs control circuitry. To detect where the rotor is at certain times, BLDC motors employ along with controllers, rotary encoders or a Hall sensor.

Construction of Brushless DC motor

In this motor, the permanent magnets attach to the rotor. The current-carrying conductors or armature windings are located on the stator. They use electrical commutation to convert electrical energy into mechanical energy.

The main design difference between a brushed and brushless motors is the replacement of mechanical commutator with an electric switch circuit. A BLDC Motor is a type of synchronous motor in the sense that the magnetic field generated by the stator and the rotor revolve at the same frequency.

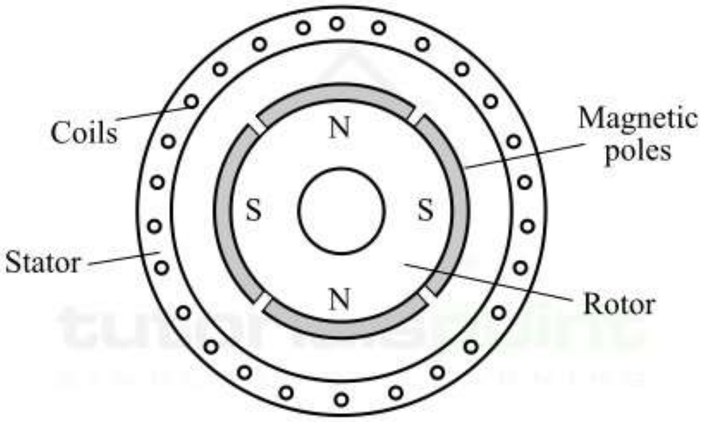


Figure - Construction of Brushless DC Motor

In the case of brushless DC motors, the stator consists of the armature winding, while the rotor consists of the permanent magnets. These motors use electronic commutation system to convert electrical energy into mechanical energy. Therefore, in brushless DC motors, the mechanical commutator in brushed DC motor is replaced with an electronic switching circuit.

In the brushless DC motors, the magnetic field is switched with the help of an amplifier that is triggered by a commutating device such as an encoder.

Therefore, the brushless DC motor consists of a rotor with permanent magnets and a stator with armature windings. The stator armature windings are energized from a DC supply in a sequence to produce a rotating magnetic field which interacts with the rotor magnets and causes it to rotate.

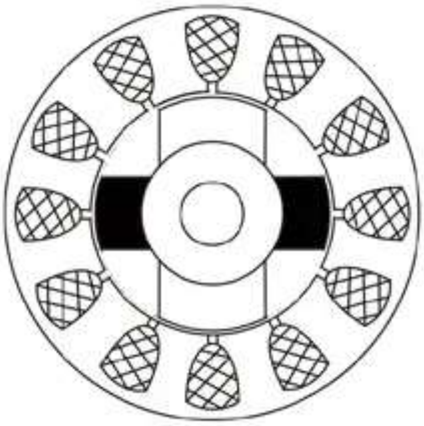
In a BLDC motor, the electronic controller uses an encoder or a Hall Effect sensor to detect the position of the rotor and regulates the current through the armature winding accordingly. This allows the brushless DC motor to operate smoothly and efficiently.

The other major components of the brushless DC motor include rotor shaft, bearings, cooling system, etc. Hence, the overall construction of a brushless DC motor is more complex as compared to an ordinary brushed DC motor.

Basically, BLDC are of two types, one is **outer rotor motor** and other is **inner rotor motor**. The basic difference between the two is only in designing, their working principles are same.

Inner Rotor Design

In an inner rotor design, the rotor is located in the centre of the motor and the stator winding surround the rotor. As the rotor is located in the core, rotor magnets do not insulate heat inside and heat get dissipated easily. Due to this reason, inner rotor designed motor produces a large amount of torque and validly used.



Inner Motor

Outer Rotor Design

In outer rotor design, the rotor surrounds the winding which is located in the core of the motor. The magnets in the rotor trap the heat of the motor inside and do not allow to dissipate from the motor. Such type of designed motor operates at lower rated current and has low cogging torque.

Outer Motor

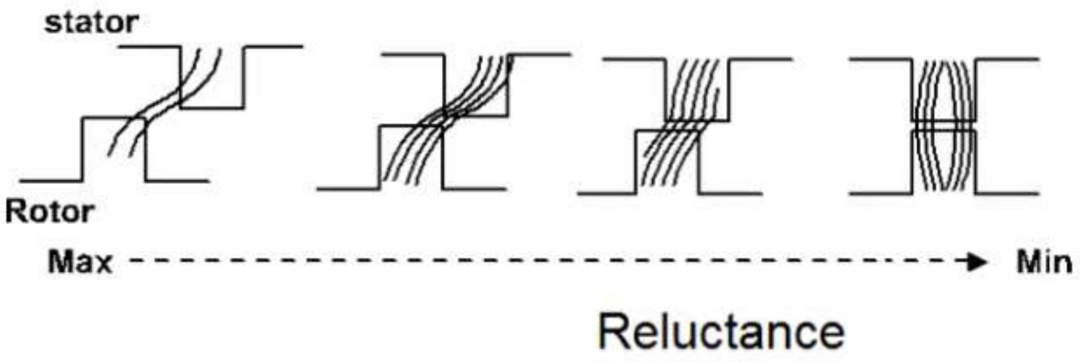
Advantages of BLDC Motors

- One big advantage is efficiency, as these motors can control continuously at maximum rotational force (torque). Brushed motors, in contrast, reach maximum torque at only certain points in the rotation. For a brushed motor to deliver the same torque as a brushless model, it would need to use larger magnets. This is why even small BLDC motors can deliver considerable power.
- The second big advantage—related to the first—is controllability. BLDC motors can be controlled, using feedback mechanisms, to delivery precisely the desired torque and rotation speed. Precision control in turn reduces energy consumption and heat generation, and—in cases where motors are battery powered—lengthens the battery life.
- BLDC motors also offer high durability and low electric noise generation, thanks to the lack of brushes. With brushed motors, the brushes and commutator wear down as a result of continuous moving contact, and also produce sparks where contact is made. Electrical noise, in particular, is the result of the strong sparks that tend to occur at the areas where the brushes pass over the gaps in the commutator. This is why BLDC motors are often considered preferable in applications where it is important to avoid electrical noise.

Switched Reluctance motor

An electric motor like SRM (switched reluctance motor) runs through reluctance torque. Different from the types of common brushed DC motor, power can be transmitted to windings within the stator instead of the rotor. An alternate name of this motor is VRM (Variable Reluctance Motor). For a better operation of this motor, it uses a switching inverter. The control characteristics of this motor are the same as dc motors which electronically commutated. These motors are applicable where sizing, as well as horsepower (hp) to weight, is critical.

Switched reluctance motor works based on the variable reluctance principle. The rotating magnetic field is created with the help of power electronics switching circuit. The main concept is the reluctance of the magnetic circuit is depending upon the air gap. Hence, by changing the air gap between the rotor and stator, we can change the reluctance of the motor.



Note: reluctance is nothing but a resistance to the magnetic flux. (Opposes the magnetic flux. For Electrical circuit it is resistance and magnetic circuit it is reluctance).

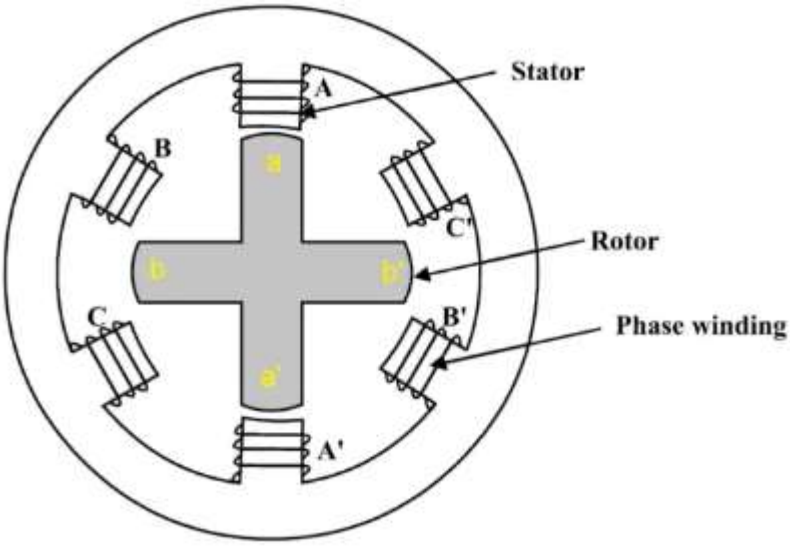
Construction of SRM

In switched reluctance motor, the stator and rotor have projected pole made up of soft iron and silicon stampings. Silicon stamping is used to reduce hysteresis losses.

Stator => Inward projection

Rotor => Outward projection.

The rotor does not have winding and stator only carries main field winding. Each winding in the stator is connected in series with the opposite poles to increase the MMF of the circuit. It is called phase winding. Refer to fig AA’, BB’ and CC’.



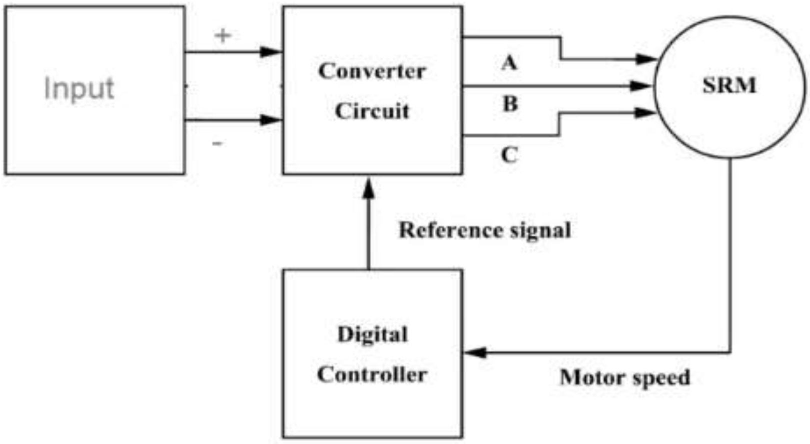
Pole concern, the number of poles in the stator will be around 6 to 8 numbers. But the rotor carries less number of poles with respect to the stator. The rotor poles will be 4 to 8 numbers. By increasing the number of poles we can get a low angle of rotation from the motor. The rotor’s shaft is mounted with a position sensor. The position sensor is used to determine the position of the rotor by a control circuit.

The control circuit always collects the information of the rotor position and based on that the controller gives the input to the motor.

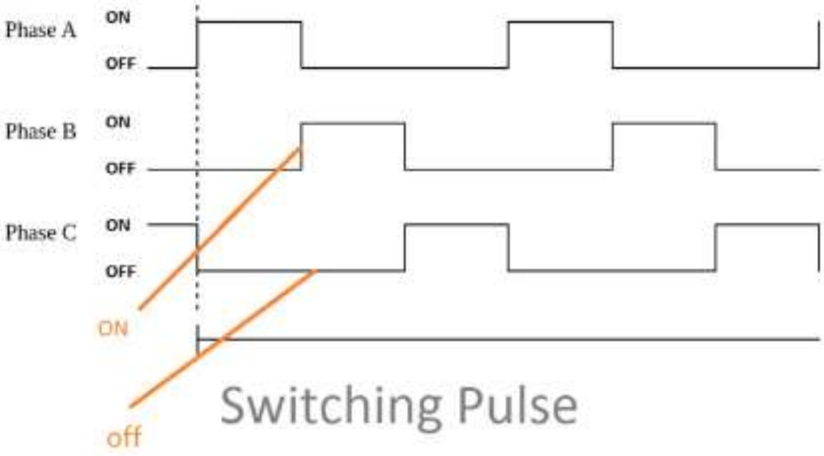
Block diagram of SRM

The DC input is connected to the driver/converter circuit and the output is connected to the motor. The rotor sensor’s feedback wire is connected to the controller circuit and it provides the position of the rotor with reference to the reference axis.

Finally, the controller collects all information and based on that, reference will be given to the stator. Also, the controller monitors the motor current to protect the motor from internal and external faults.



Also, note that the output of the controller is DC. And the output will be as shown in the figure



Working Principle

The working principle of switched reluctance motor is simple, let we take an iron piece. If we keep it in a magnetic field means, the iron piece will align with the minimum reluctance position and get locked magnetically.The same principle is followed in the switched reluctance motor. The minimum reluctance portion of the rotor tries to align itself with the stator magnetic field. Hence the reluctance torque is developed in the rotor.

In our motor, let us consider the following notation for better understanding.

Stator Poles:

AA’ poles axis for A phase

BB’ poles axis for B phase

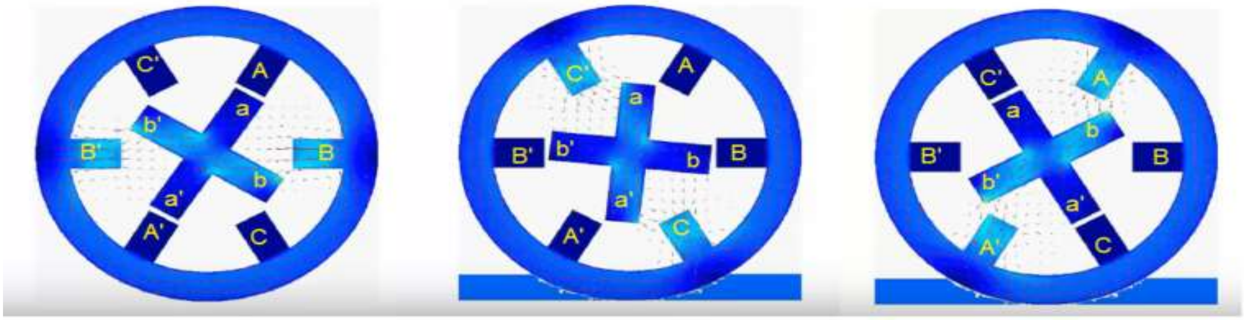
CC’ poles axis for C Phase

aa’ rotor poles axis for Position 1

bb’ rotor poles axis for position 2

Now the input is given to the A-phase, other B and C phase neither maximum nor minimum, then stator pole axis AA‘ and rotor pole axis aa‘ are in alignment. Ref picture Fig 1.4

Figure 1.4 indicates that the A-phase reached the minimum reluctance position.



AA' Align With aa'

BB' Align With bb'

CC' Align With aa'

SRM Working

Because the air gap between the stator and rotor is very less, and they are minimum reluctance position as compared with other poles. Then,

$$Torque = \frac{dLa}{d\theta} = 0$$

$$La = Phase\ Inductance$$

$$\theta = Angle\ of\ rotation$$

Now, Phase A will be turned off and the B phase is energized. Then the rotor axis bb' turns to stator axis BB'. Move clockwise as per our diagram. By changing the polarity of the motor, we can easily reverse the motor. The torque develops since the reluctance changes from maximum to a minimum. The developed torque is equal to

$$Torque = \left(\frac{1}{2}\right) i_B^2 \left(\frac{dLb}{d\theta}\right)$$

The rotor movement is depending upon the number of poles and in our case, we get 30 deg rotation by energizing one phase at a time. Here torque is nothing but a rotor movement only. When the shaft reaches to position BB'. Then there is no torque.

$$Torque = \frac{dLb}{d\theta} = 0$$

Now the B phase will be turned off, and the C phase will be turned on. Then the torque is developed because of rotor axis aa' is aligned with the stator axis CC'. The rotor continues to rotate for another 30deg.

Again C will be turned off and A will be stared. The motor operation continues until the input power supply. Here you can observe that the motor is rotating by self. Thus Switched reluctance motors are self-starting motor.

The control circuit continuously monitors the motor speed and input current. if the motor speed falls with respect to the reference, then the control considers as there is a requirement of high torque. Therefore, it increases the input current to the motor to meet the speed requirement. In case if the motor current is reached beyond the full load current, it trips the motor.

Advantages

The **advantages of a switched reluctance motor** include the following.

- These motors are very simple & the rotors in this motor are extremely strong
- These motors are applicable for high-speed applications.
- The VFDs (variable frequency drives) of this motor are somewhat simpler as compared with conventional VFDs.
- This motor doesn’t use any additional ventilation system when the stator, as well as rotor slots, is projected. So the airflow can be maintained among the slots.
- These are less expensive because of the nonexistence of permanent magnets.
- Fault tolerance is high
- This motor works with a simple two-phase or three-phase pulse generator.
- Phase losses do not change the operation of the motor.
- Once the phase sequence is changed then the motor direction will be changed.
- Inertia Ratio or High Torque
- Self-starting without using additional arrangements

Axial Flux Motor

A motor is a mechanism that transforms the motor’s energy into mechanical energy. Its operation is based on the electromagnetic interaction of the magnetic field created by the structure’s coil and magnet. It is classified into two categories based on the direction of the magnetic field: axial flux motors and radial flux motors. The gap between the rotor and stator, and hence the direction of magnetic flux between the two, is positioned parallel to the axis of rotation in an axial flux motor, rather than radially as in the more typical radial gap motor.

Axial flux motors are considered the ultimate future of electric vehicles and most importantly of electric aviation because they have a high torque-to-weight ratio, which is ideal for aircraft.

In a radial flux motor, the magnetic flux is perpendicular to the axis of rotation. In an axial flux type the axis of rotation is parallel to flux lines as shown in fig.

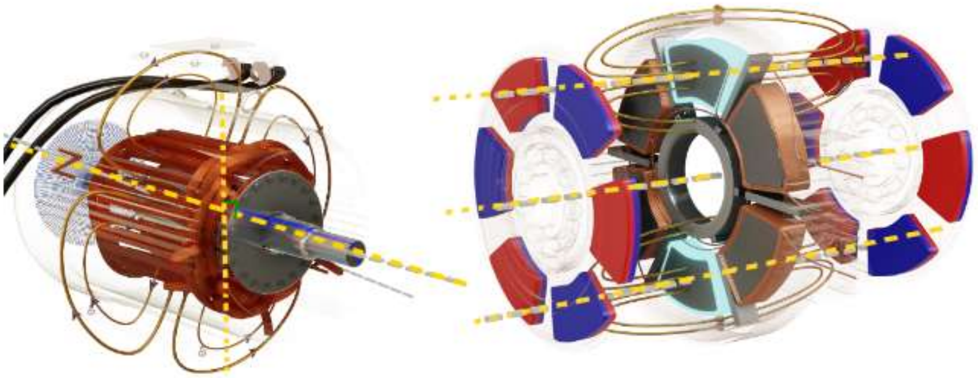


Fig 1 : Radial flux motor And Axial flux motor

Working of Axial Flux Motor

When I energise the coil, they become electromagnets. The axial motor's operation depends on the interaction between the permanent magnet and the electromagnets. In the design of axial flux motors have fixed coils and freely rotating permanent magnets are the Axial flux motor's coil arrangement, as shown in fig 2.

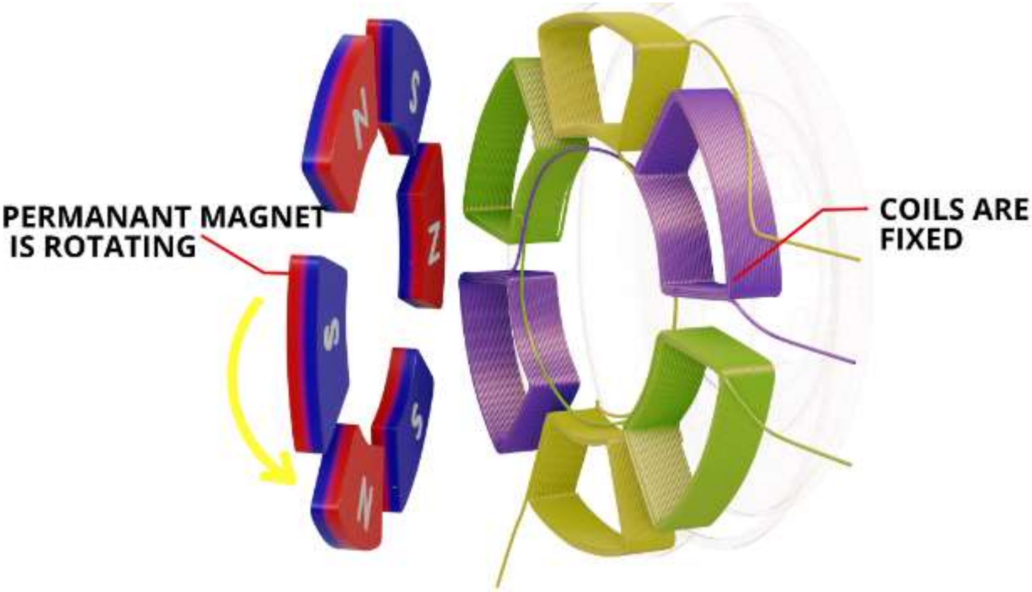


Fig 2 : Axial flux motors coil arrangement

When we energised coil A with DC current, the S pole of the rotor is attracted to the stators opposite N pole (refer fig 3a). Simultaneously, the like poles repel. The tangential force components make the rotor rotate (refer fig 3b). When the rotor aligns with coil A, the net force acting on the permanent magnet becomes zero.

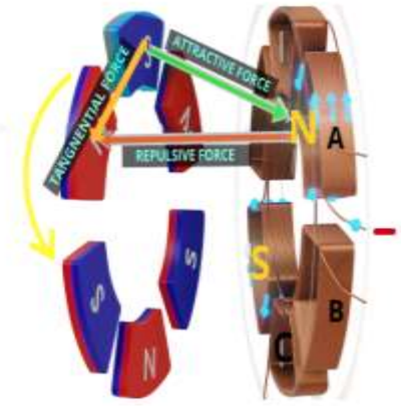


Fig 3a : Tangential force components make the rotor rotate.

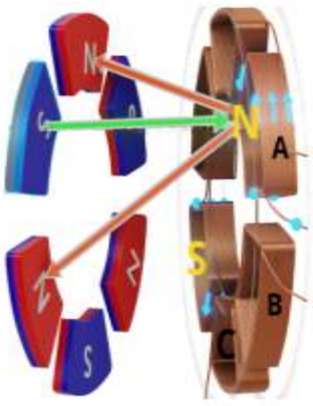


Fig 3b : Net force acting on the magnet becomes zero.

So now (refer Fig 3b) Because of zero net force Will the rotor motion stop at this point? No. The rotor's speed or the inertia effect causes it to travel ahead of the perfect alignment angle. During this time, the next coil B gets energised (refer fig 4). The rotor then reaches near to coil B because of the same forces of attraction and repulsion.

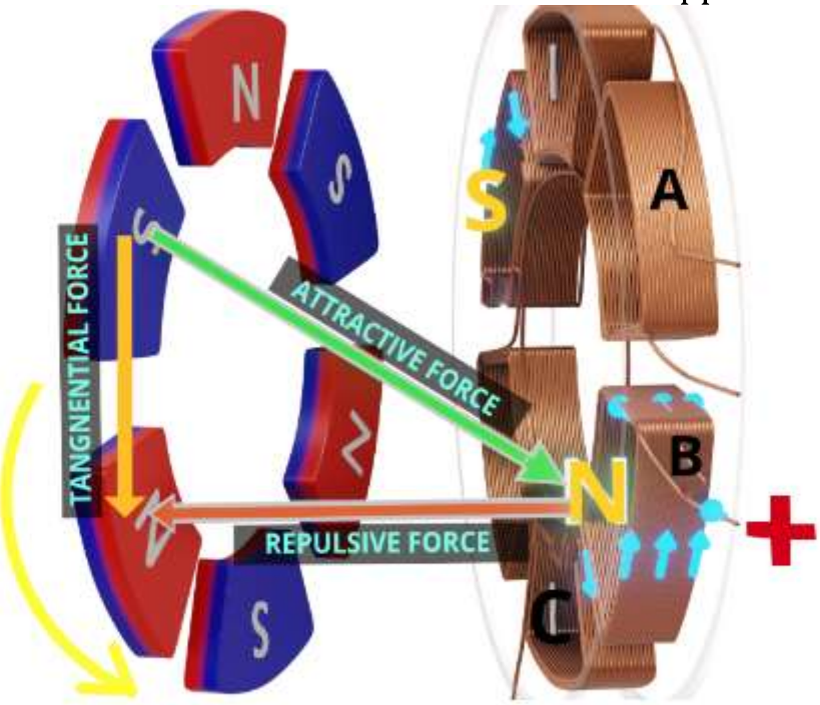


Fig 4 : Coil B gets energised

Later, coil C gets energised. After that, in the next half-rotation, coil A energises again, but this time with the opposite polarity, just by changing the supply directions. The process constantly repeats and the rotor continues to rotate. However, in this operation two coils are always dead(example coil B energised in Fig 4). These dead coils drastically reduce the motor's power output.

To solve the issue, just energise one more coil pair by simply passing the opposite polarity current through the second coil. at the stator side two south poles are together. Here again a net tangential force is developed (refer Fig 5). The combined effect produces more torque and power output from the rotor. Interestingly, this process also ensures that the motor has a constant torque output.

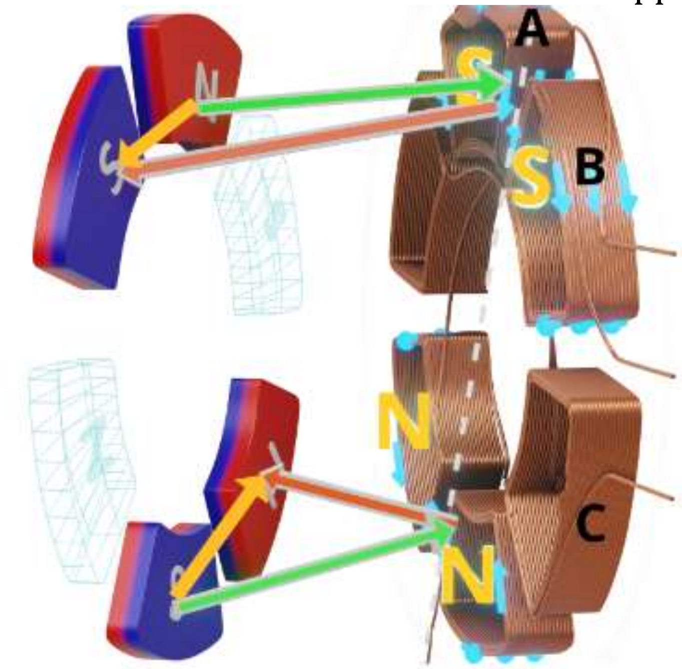


Fig 5 : By passing the opposite polarity current through the second coil net tangential force is developed

The sensor determines the rotor's position, and based on this information, the controller decides which coil to energise.

Axial flux vs Radial flux motor

The first differentiating factor is the flux flow path in the machines. When compared the magnetic flux pattern of both the motors, the axial motor's flux flow path is much more dense and shorter when compared to the induction motor.

The second differentiating factor is the larger diameter. In axial flux motors, the rotor magnets can be located further away from the central rotating axis. a larger radius allows the motor to generate more torque.

Made it clear by this simple torque equation.

Torque = Radius X Force

However, if we try to increase the diameter of the induction motors, the rotor's inertia will increase, which can lead to the motor sniffing up huge currents during the start.

Axial flux motor's keep this issue under control, as the rotors already have less inertia. These lightweight motors are the best choice for electric aeroplanes. So because of an incredible efficiency level and their compact size axial flux motors can even become a good choice in electric cars.

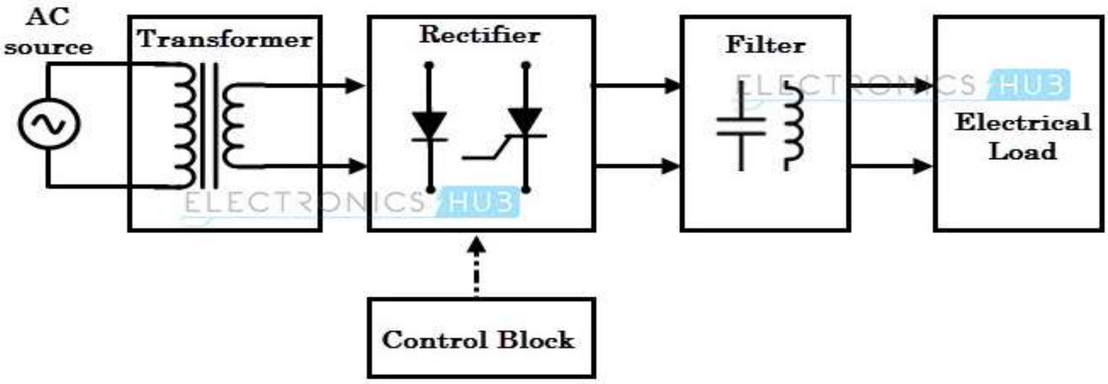
Power Electronic Converter

A power electronic converter is an electrical device that is used to convert one form of electrical energy to another. They are widely used in a variety of applications such as power supplies, motor drives, renewable energy systems, and electric vehicles.

Power electronic converters typically use solid-state devices, such as power MOSFETs or IGBTs, to switch electrical energy on and off rapidly. These devices are used in combination with passive components, such as inductors and capacitors, to transform the electrical energy from one form to another. The most common types of power electronic converters include AC-DC, DC-AC, DC-DC, and AC-AC converters.

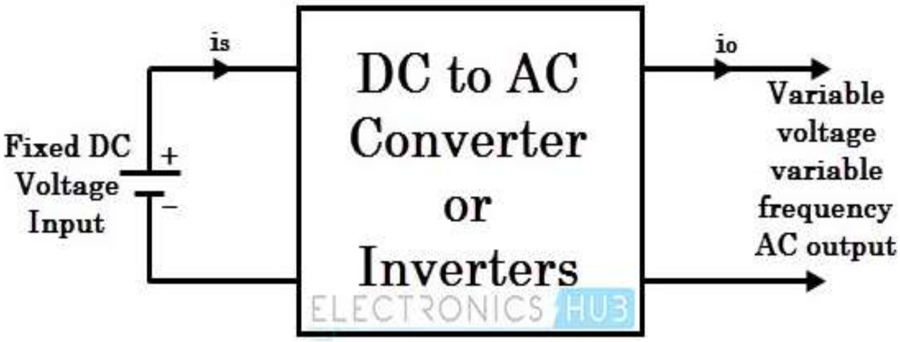
AC-DC Converters

- An AC to DC converter is also called a rectifier, which converts AC supply from main lines to DC supply for the load. The block diagram of an AC to DC converter is shown in figure below.
- The essential components in this rectifier include transformer, switching unit, filter and a control block.
- The transformer adjusts the primary AC source supply to the input of rectifier stage. Usually it is a step-down transformer that reduces the supply voltage to a circuit operating range.
- The rectifier converts the low voltage AC supply into DC supply.
- It comprises diode and/or thyristors based on type of rectifier. The output of the rectifier is of pulsed DC and hence it is filtered using filter circuit, which is usually made with a capacitor or a choke.
- The control block controls the firing angle of thyristors in case of phase controlled rectifiers.
- Since the diode is not a controllable device, control block is not needed in case of diode rectifiers.



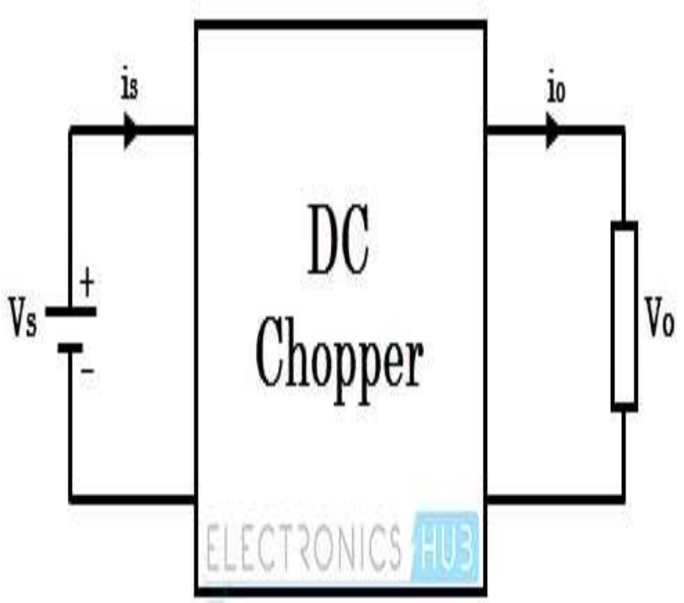
DC-AC Converter

- These converters are connected between DC source of fixed input, and variable AC load. Most commonly, these DC to AC converters are called as inverters.
- An inverter is a static device that converts fixed DC supply voltage to variable AC voltage.
- Here the fixed DC voltage is obtained from batteries or by DC link in most power electronic converter.
- The output of the inverter can be variable/ fixed AC voltage with variable/fixed frequency.
- This conversion from DC to AC along with variable supply is produced by varying the triggering angle to the thyristors. Most of the thyristors used in inverters are employed with forced commutation technique.
- These can be single phase or three phase inverter depending on the supply voltage. These converters are mainly divided into two groups. One is PWM based inverters and other multilevel inverters.



DC-DC Converter

- Many DC operated applications need different levels of DC voltage from a fixed DC source.
- Some of these applications include subway cars, DC traction systems, control of large DC motors, battery operated vehicles, trolley buses, etc. They require variable DC to produce variable speed, so a power conversion device is needed.
- A DC chopper is a static device that converts a fixed input DC voltage to variable DC output or a fixed DC output of different magnitude (which can be lower or higher) than input value. The block diagram of a DC chopper is shown in figure below.
- The chopper circuit is connected between DC input source and DC load.
- This chopper consists of power electronic switching devices such as thyristors which are connected in such a way that they produce required DC voltage to the load.



- The output voltage is controlled by adjusting ON time of the thyristor (or switch) which turn changes the width of DC voltage pulse at the output. This method of switching is called as pulse width modulation (PWM) control.
- The output of the chopper can be less or greater than the input and also it can be fixed or variable. These can be unidirectional or bidirectional devices based on the application it is intended for.
- DC choppers are mainly used in DC drives, i.e., electric vehicles and hybrid electric vehicles.

AC-AC Converter

- AC/AC converters connect an AC source to AC loads by controlling amount of power supplied to the load. This converter converts the AC voltage at one level to the other by varying its magnitude as well as frequency of the supply voltage.
- These are used in different types of applications including uninterrupted power supplies, high power AC to AC transmission, adjustable speed drives, renewable energy conversion systems and aircraft converter systems.

DC-DC Converters

There are three basic types of dc-dc converter circuits, termed as buck, boost and buckboost. In all of these circuits, a power device is used as a switch. This device earlier used was a thyristor, which is turned on by a pulse fed at its gate. In all these circuits, the thyristor is connected in series with load to a dc supply, or a positive (forward) voltage is applied between anode and cathode terminals. The thyristor turns off, when the current decreases below the holding current, or a reverse (negative) voltage is applied between anode and cathode terminals. So, a thyristor is to be force-commutated, for which additional circuit is to be used, where another thyristor is often used.

Buck Converters (dc-dc)

A buck converter (dc-dc) is shown in Fig. a. Only a switch is shown, for which a device as described earlier belonging to transistor family is used. Also a diode (termed as free wheeling) is used to allow the load current to flow through it, when the switch (i.e., a device) is turned off. The load is inductive (R-L) one. In some cases, a battery (or back emf) is connected in series with the load (inductive). Due to the load inductance, the load current must be allowed a path, which is provided by the diode; otherwise, i.e., in the absence of the above diode, the high induced emf of the inductance, as the load current tends to decrease, may cause damage to the switching device. If the switching device used is a thyristor, this circuit is called as a step-down chopper, as the output voltage is normally lower than the input voltage.

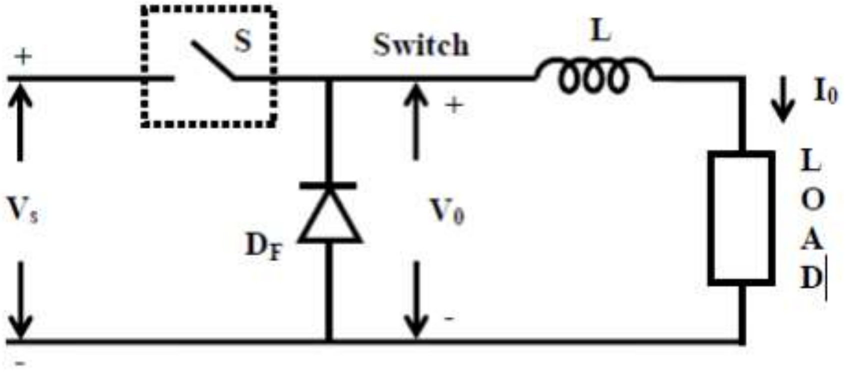
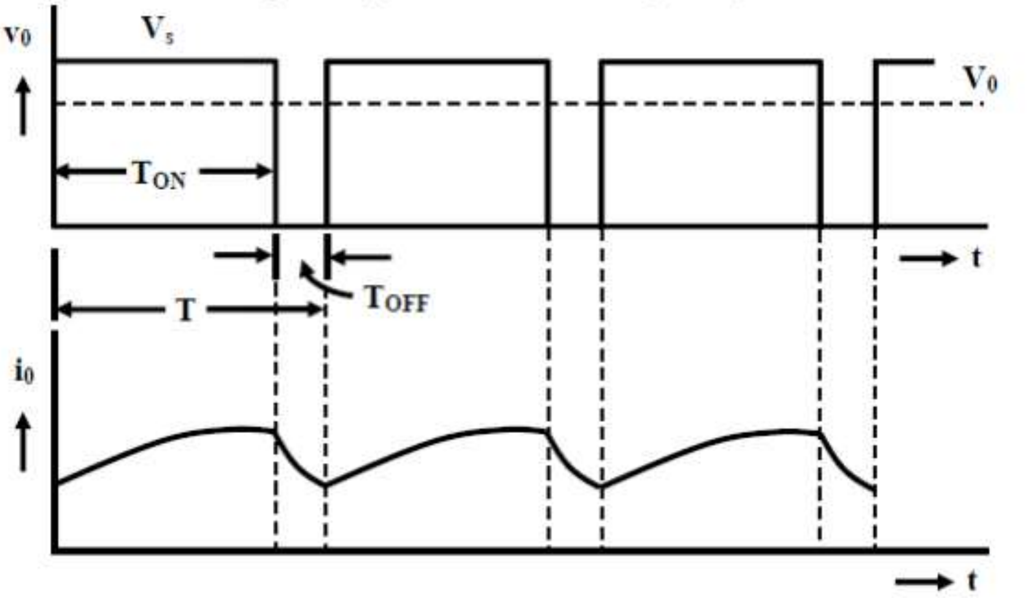
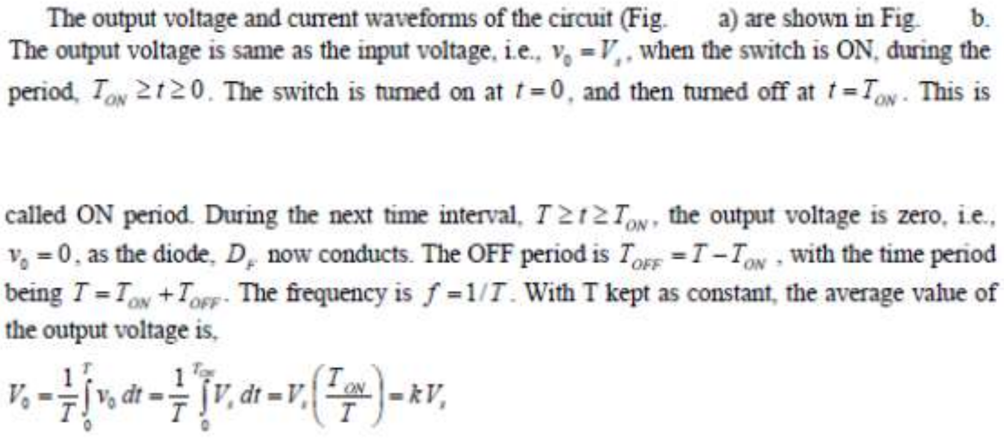


Fig. (a); Buck converter (dc-dc),





The output voltage and current waveforms of the circuit (Fig. a) are shown in Fig. b. The output voltage is same as the input voltage, i.e., $v_0 = V_s$, when the switch is ON, during the period, $T_{ON} \ge t \ge 0$. The switch is turned on at $t = 0$, and then turned off at $t = T_{ON}$. This is

called ON period. During the next time interval, $T \ge t \ge T_{ON}$, the output voltage is zero, i.e., $v_0 = 0$, as the diode, D_F now conducts. The OFF period is $T_{OFF} = T - T_{ON}$, with the time period being $T = T_{ON} + T_{OFF}$. The frequency is $f = 1/T$. With T kept as constant, the average value of the output voltage is,

$$V_0 = \frac{1}{T}\int_0^T v_0\,dt = \frac{1}{T}\int_0^{T_{ON}} V_s\,dt = V_s\left(\frac{T_{ON}}{T}\right) = kV_s$$

Normally, due to turn-on delay of the device used, the duty ratio (k) is not zero, but has some positive value. Similarly, due to requirement of turn-off time of the device, the duty ratio (k) is less than 1.0. So, the range of duty ratio is reduced. It may be noted that the output voltage is lower than the input voltage. Also, the average output voltage increases, as the duty ratio is increased. So, a variable dc output voltage is obtained from a constant dc input voltage. The load current is assumed to be continuous as shown in Fig. b. The load current increases in the ON period, as the input voltage appears across the load, and it (load current) decreases in the OFF period, as it flows in the diode, but is positive at the end of the time period, T.

Boost Converters (dc-dc)

A boost converter (dc-dc) is shown in Fig.a. Only a switch is shown, for which a device belonging to transistor family is generally used. Also, a diode is used in series with the load. The load is of the same type as given earlier. The inductance of the load is small. An inductance, L is assumed in series with the input supply. The position of the switch and diode in this circuit may be noted, as compared to their position in the buck converter (Fig.a).

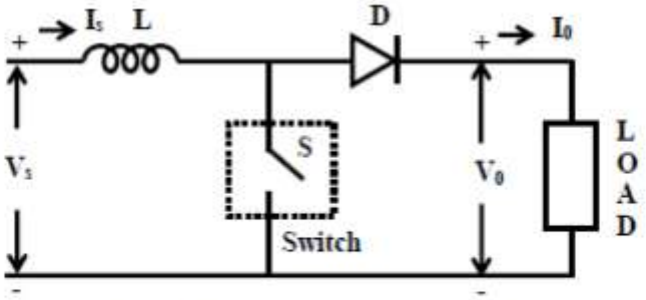


Fig. 17.2(a): Boost converter (dc-dc)

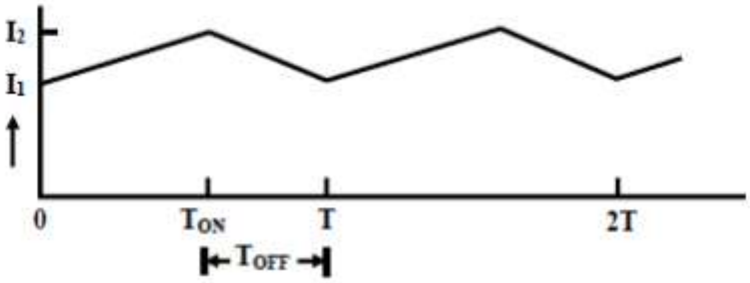
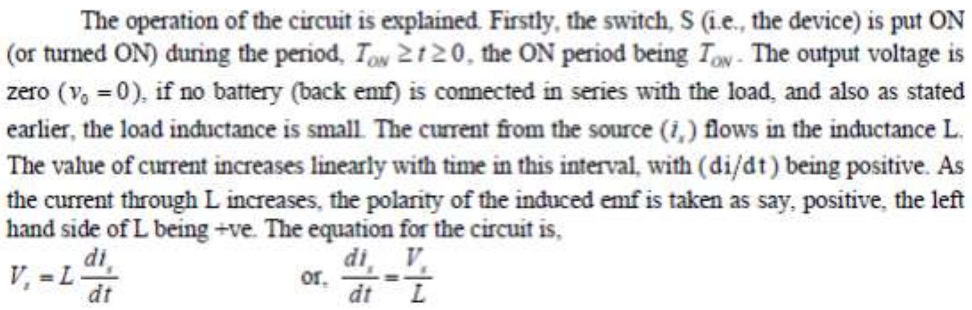
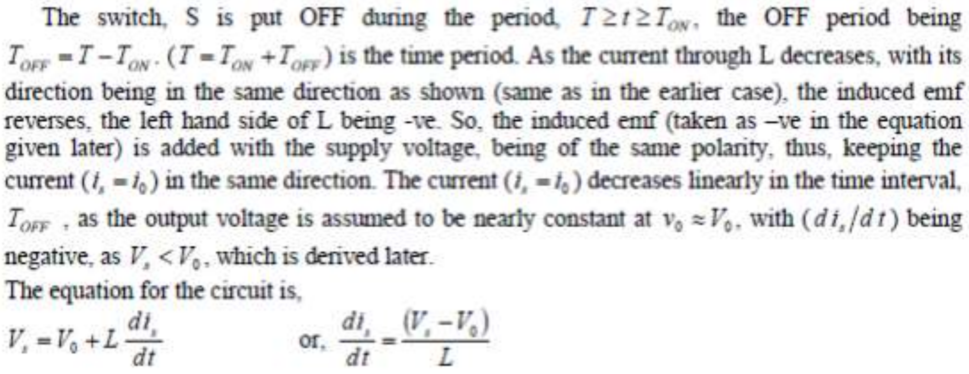


Fig. '(b): Waveforms of source current (i_S)



The operation of the circuit is explained. Firstly, the switch, S (i.e., the device) is put ON (or turned ON) during the period, $T_{ON} \geq t \geq 0$, the ON period being T_{ON}. The output voltage is zero ($v_0 = 0$), if no battery (back emf) is connected in series with the load, and also as stated earlier, the load inductance is small. The current from the source (i_s) flows in the inductance L. The value of current increases linearly with time in this interval, with (di/dt) being positive. As the current through L increases, the polarity of the induced emf is taken as say, positive, the left hand side of L being +ve. The equation for the circuit is,

$$V_s = L\frac{di_s}{dt} \qquad \text{or,} \quad \frac{di_s}{dt} = \frac{V_s}{L}$$

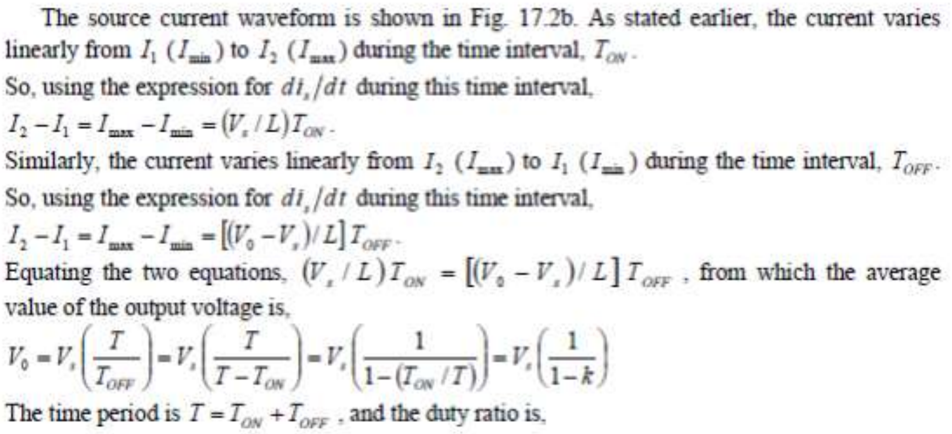


The switch, S is put OFF during the period, $T \geq t \geq T_{ON}$, the OFF period being $T_{OFF} = T - T_{ON}$. ($T = T_{ON} + T_{OFF}$) is the time period. As the current through L decreases, with its direction being in the same direction as shown (same as in the earlier case), the induced emf reverses, the left hand side of L being -ve. So, the induced emf (taken as –ve in the equation given later) is added with the supply voltage, being of the same polarity, thus, keeping the current ($i_s = i_0$) in the same direction. The current ($i_s = i_0$) decreases linearly in the time interval, T_{OFF} , as the output voltage is assumed to be nearly constant at $v_0 \approx V_0$, with (di_s/dt) being negative, as $V_s < V_0$, which is derived later.

The equation for the circuit is,

$$V_s = V_0 + L\frac{di_s}{dt} \qquad \text{or,} \quad \frac{di_s}{dt} = \frac{(V_s - V_0)}{L}$$

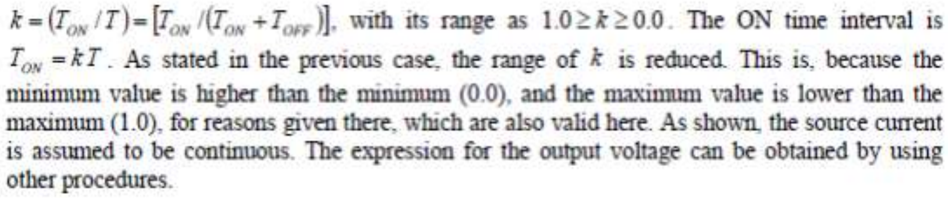
In this case, the output voltage is higher than the input voltage, as contrasted with the previous case of buck converter (dc-dc). So, this is called boost converter (dc-dc), when a selfcommutated device is used as a switch. Instead, if thyristor is used in its place, this is termed as step-up chopper. The variation (range) of the output voltage can be easily computed.



The source current waveform is shown in Fig. 17.2b. As stated earlier, the current varies linearly from I_1 ($I_{\min}$) to I_2 ($I_{\max}$) during the time interval, T_{ON}.
So, using the expression for di_s/dt during this time interval,
$I_2 - I_1 = I_{\max} - I_{\min} = (V_s/L)T_{ON}$.
Similarly, the current varies linearly from I_2 ($I_{\max}$) to I_1 ($I_{\min}$) during the time interval, T_{OFF}.
So, using the expression for di_s/dt during this time interval,
$I_2 - I_1 = I_{\max} - I_{\min} = [(V_0 - V_s)/L]T_{OFF}$.
Equating the two equations, $(V_s/L)T_{ON} = [(V_0 - V_s)/L]\,T_{OFF}$, from which the average value of the output voltage is,

$$V_0 = V_s\left(\frac{T}{T_{OFF}}\right) = V_s\left(\frac{T}{T - T_{ON}}\right) = V_s\left(\frac{1}{1-(T_{ON}/T)}\right) = V_s\left(\frac{1}{1-k}\right)$$

The time period is $T = T_{ON} + T_{OFF}$, and the duty ratio is,



$k = (T_{ON}/T) = [T_{ON}/(T_{ON} + T_{OFF})]$, with its range as $1.0 \geq k \geq 0.0$. The ON time interval is $T_{ON} = kT$. As stated in the previous case, the range of k is reduced. This is, because the minimum value is higher than the minimum (0.0), and the maximum value is lower than the maximum (1.0), for reasons given there, which are also valid here. As shown, the source current is assumed to be continuous. The expression for the output voltage can be obtained by using other procedures.

Buck-Boost Converters (dc-dc)

A buck-boost converter (dc-dc) is shown in Fig. Only a switch is shown, for which a device belonging to transistor family is generally used. Also, a diode is used in series with the load. The connection of the diode may be noted, as compared with its connection in a boost converter (Fig.a). The inductor, L is connected in parallel after the switch and before the diode. The load is of the same type as given earlier. A capacitor, C is connected in parallel with the load. The polarity of the output voltage is opposite to that of input voltage here.

When the switch, S is put ON, the supply current (i_s) flows through the path, V_s, S a during the time interval, T_{ON}. The currents through both source and inductor (i_L) increas are same, with ($d\,i_L/d\,t$) being positive. The polarity of the induced voltage is same as tl the input voltage. The equation for the circuit is,

$$V_s = L\frac{di_L}{dt} \qquad \text{or,} \quad \frac{di_L}{dt} = \frac{V_s}{L}$$

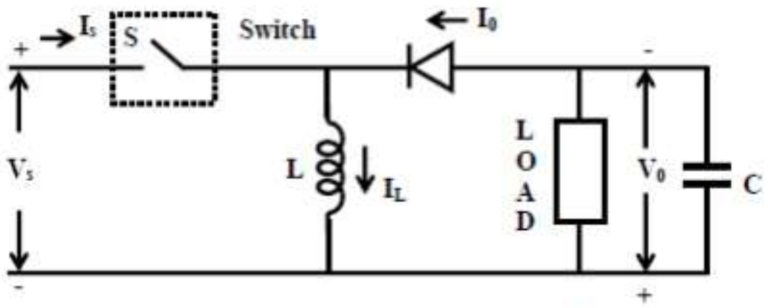


Fig. (a): Buck-boost converter (dc-dc)

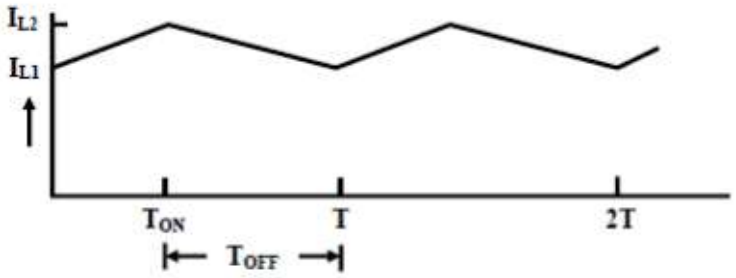
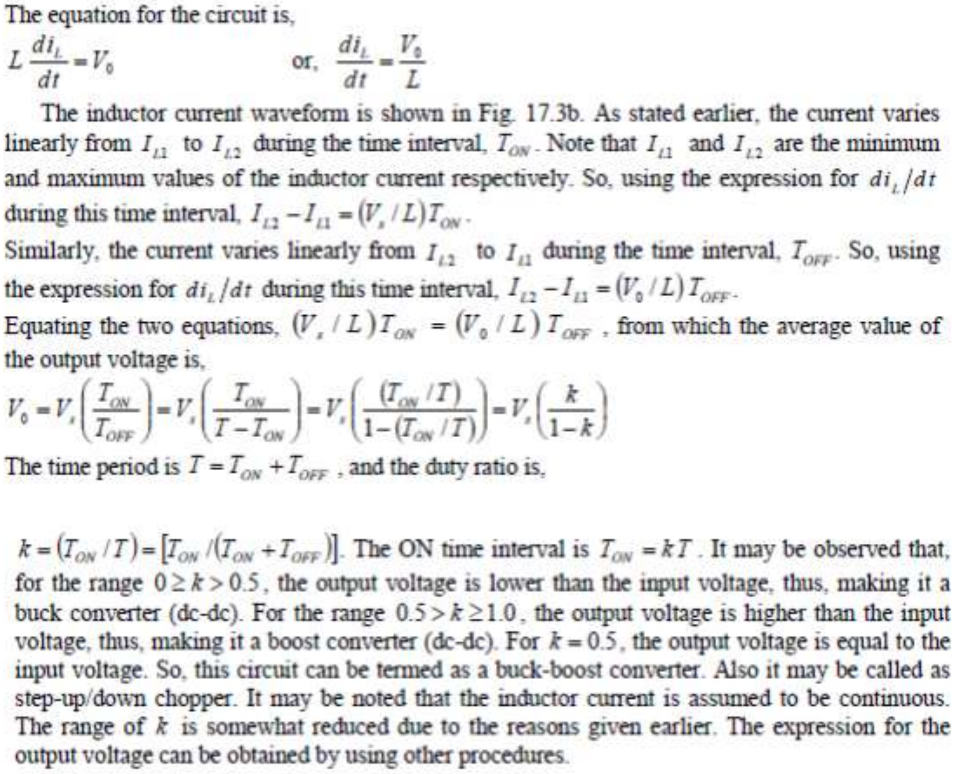


Fig. (b): Inductor current (i_L) waveform

Then, the switch, S is put OFF. The inductor current tends to decrease, with the polarity of the induced emf reversing. ($d\,i_L/d\,t$) is negative now, the polarity of the output voltage, V_0 being opposite to that of the input voltage, V_s. The path of the current is through L, parallel combination of load & C, and diode D, during the time interval, T_{OFF}. The output voltage remains nearly constant, as the capacitor is connected across the load.



The equation for the circuit is,

$L\frac{di_L}{dt}=V_0$ or, $\frac{di_L}{dt}=\frac{V_0}{L}$

The inductor current waveform is shown in Fig. 17.3b. As stated earlier, the current varies linearly from I_{L1} to I_{L2} during the time interval, T_{ON}. Note that I_{L1} and I_{L2} are the minimum and maximum values of the inductor current respectively. So, using the expression for di_L/dt during this time interval, $I_{L2}-I_{L1}=(V_s/L)T_{ON}$.

Similarly, the current varies linearly from I_{L2} to I_{L1} during the time interval, T_{OFF}. So, using the expression for di_L/dt during this time interval, $I_{L2}-I_{L1}=(V_0/L)T_{OFF}$.

Equating the two equations, $(V_s/L)T_{ON} = (V_0/L)T_{OFF}$, from which the average value of the output voltage is,

$$V_0=V_s\left(\frac{T_{ON}}{T_{OFF}}\right)=V_s\left(\frac{T_{ON}}{T-T_{ON}}\right)=V_s\left(\frac{(T_{ON}/T)}{1-(T_{ON}/T)}\right)=V_s\left(\frac{k}{1-k}\right)$$

The time period is $T=T_{ON}+T_{OFF}$, and the duty ratio is,

$k=(T_{ON}/T)=[T_{ON}/(T_{ON}+T_{OFF})]$. The ON time interval is $T_{ON}=kT$. It may be observed that, for the range $0\ge k>0.5$, the output voltage is lower than the input voltage, thus, making it a buck converter (dc-dc). For the range $0.5>k\ge1.0$, the output voltage is higher than the input voltage, thus, making it a boost converter (dc-dc). For $k=0.5$, the output voltage is equal to the input voltage. So, this circuit can be termed as a buck-boost converter. Also it may be called as step-up/down chopper. It may be noted that the inductor current is assumed to be continuous. The range of k is somewhat reduced due to the reasons given earlier. The expression for the output voltage can be obtained by using other procedures.

Speed control of dc motor

Speed Of A DC Motor

Back emf E_b of a DC motor is nothing but the induced emf in armature conductors due to rotation of the armature in magnetic field. Thus, the magnitude of E_b can be given by EMF equation of a DC generator.

$\mathbf{E_b = {}^{P\text{Ø}NZ}/_{60A}}$

(where, P = no. of poles, Ø = flux/pole, N = speed in rpm, Z = no. of armature conductors, A = parallel paths)

E_b can also be given as,

$\mathbf{E_b = V - I_aR_a}$

thus, from the above equations

$\mathbf{N = {}^{E_b\,60A}/_{P\text{Ø}Z}}$

but, for a DC motor A, P and Z are constants

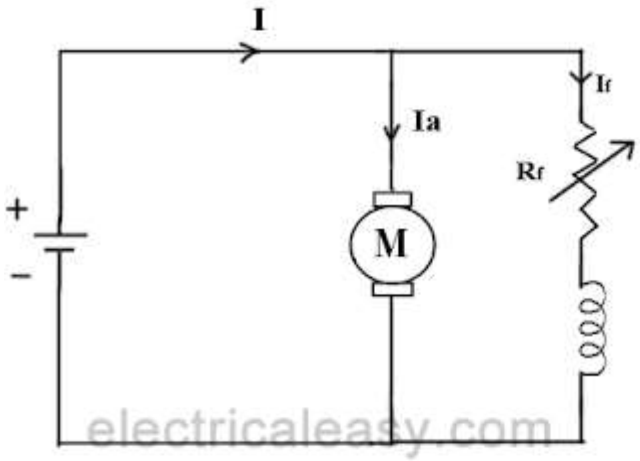
Therefore, $N \propto K\ {}^{E}b/ø$ (where, K=constant)

This shows the **speed of a dc motor** is directly proportional to the back emf and inversely proportional to the flux per pole.

Speed Control Methods Of DC Motor

Speed Control Of Shunt Motor

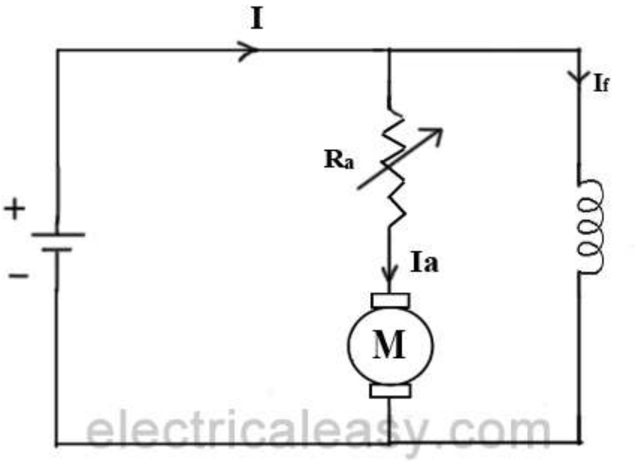
1. Flux Control Method



It is already explained above that the **speed of a dc motor** is inversely proportional to the flux per pole. Thus by decreasing the flux, speed can be increased and vice versa.

To control the flux, a rheostat is added in series with the field winding, as shown in the circuit diagram. Adding more resistance in series with the field winding will increase the speed as it decreases the flux. In shunt motors, as field current is relatively very small, I_{sh}^2R loss is small. Therefore, this method is quite efficient. Though speed can be increased above the rated value by reducing flux with this method, it puts a limit to maximum speed as weakening of field flux beyond a limit will adversely affect the commutation.

2. Armature Control Method



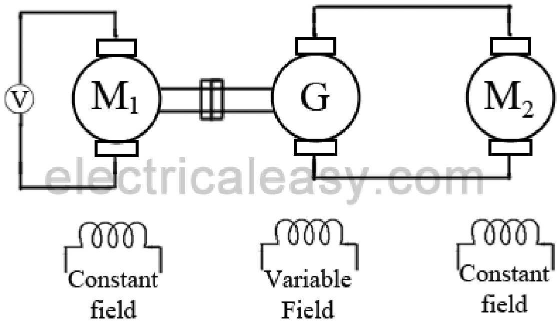
Speed of a dc motor is directly proportional to the back emf E_b and $E_b = V - I_aR_a$. That means, when supply voltage V and the armature resistance R_a are kept constant, then the speed is directly proportional to armature current I_a. Thus, if we add resistance in series with the armature, I_a decreases and, hence, the speed also decreases. Greater the resistance in series with the armature, greater the decrease in speed.

3. Voltage Control Method

a)Multiple Voltage Control

In this method, the shunt field is connected to a fixed exciting voltage and armature is supplied with different voltages. Voltage across armature is changed with the help of suitable switchgear. The speed is approximately proportional to the voltage across the armature.

b) Ward-LeonardSystem:



This system is used where very sensitive **speed control of motor** is required (e.g electric excavators, elevators etc.). The arrangement of this system is as shown in the figure at right.
M_2 is the motor to which speed control is required.
M_1 may be any AC motor or DC motor with constant speed.
G is a generator directly coupled to M_1.

In this method, the output from generator G is fed to the armature of the motor M_2 whose speed is to be controlled. The output voltage of generator G can be varied from zero to its maximum value by means of its field regulator and, hence, the armature voltage of the motor M_2 is varied very smoothly. Hence, very smooth **speed control of the dc motor** can be obtained by this.

Speed Control of Series Motor

1. Flux Control Method

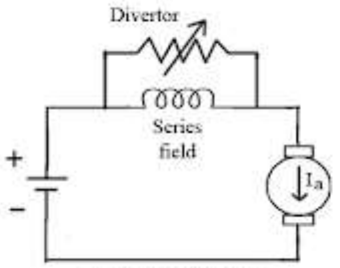


fig (a) Field Divertor

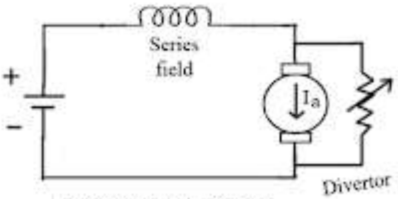


fig (b) Armature Divertor

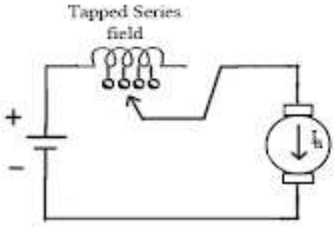


fig (c) Tapped field

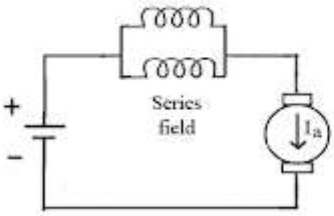


fig (d) Paralleling Field coils

- **Field diverter:** A variable resistance is connected parallel to the series field as shown in fig (a). This variable resistor is called as a diverter, as the desired amount of current can be diverted through this resistor and, hence, current through field coil can be decreased. Thus, flux can be decreased to the desired amount and speed can be increased.
- **Armature diverter:** Diverter is connected across the armature as shown in fig (b). For a given constant load torque, if armature current is reduced then the flux must increase, as Ta ∝ ØIa
  This will result in an increase in current taken from the supply and hence flux Ø will increase and subsequently **speed of the motor** will decrease.
- **Tapped field control:** As shown in fig (c) field coil is tapped dividing number of turns. Thus we can select different value of Ø by selecting different number of turns.
- **Paralleling field coils:** In this method, several speeds can be obtained by regrouping coils as shown in fig (d).

2. Variable Resistance In Series With Armature

By introducing resistance in series with the armature, voltage across the armature can be reduced. And, hence, speed reduces in proportion with it.

3. Series-Parallel Control

This system is widely used in electric traction, where two or more mechanically coupled series motors are employed. For low speeds, the motors are connected in series, and for higher speeds, the motors are connected in parallel.

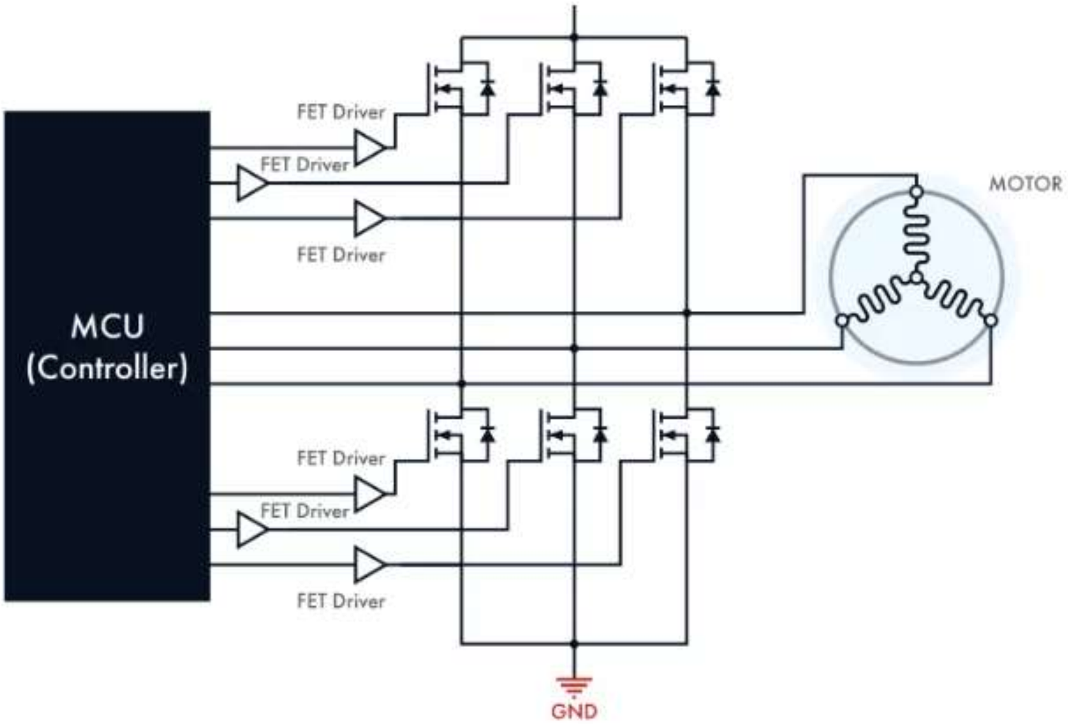
When in series, the motors have the same current passing through them, although voltage across each motor is divided. When in parallel, the voltage across each motor is same although the current gets divided.

BLDC motor driving schemes

A typical BLDC motor controller has a **half-bridge** or **half-H bridge** circuit. Unlike an **H bridge**, this circuit configuration has only two switches - one high-side and one low-side transistor.

Most brushless motors use two or three-phase power systems. So in a BLDC motor controller circuit diagram, this will look like two or three half-bridges (depending on the number of phases) with a pair of switches each.

Let's take a closer look at a 3 phase brushless DC motor controller with Hall-effect sensors to view the basic principles of its circuit design.



The stator has three-phase windings located at 120° to one another. Each winding has a vector representation of voltage and current applied to the stator.

The BLDC motor controller Hall sensors identify the rotor's position. Upon receiving the sensor data, the power **MOSFETs** switch the current, injecting it into the right winding. In a high power brushless DC motor controller, **IGBT**s and **GaN** switches can replace MOSFETs.

Either integrated or discrete gate drivers can control the transistors. The drivers of a brushless motor controller schematic act as intermediaries between the switches and a microcontroller (MCU).

The three-phase BLDC motor controller circuit includes six steps necessary to complete a full switching cycle (that is to energize all thethree windings of the stator). By turning the high-side and low-side transistors on and off, the current flows through the stator windings in sequence.

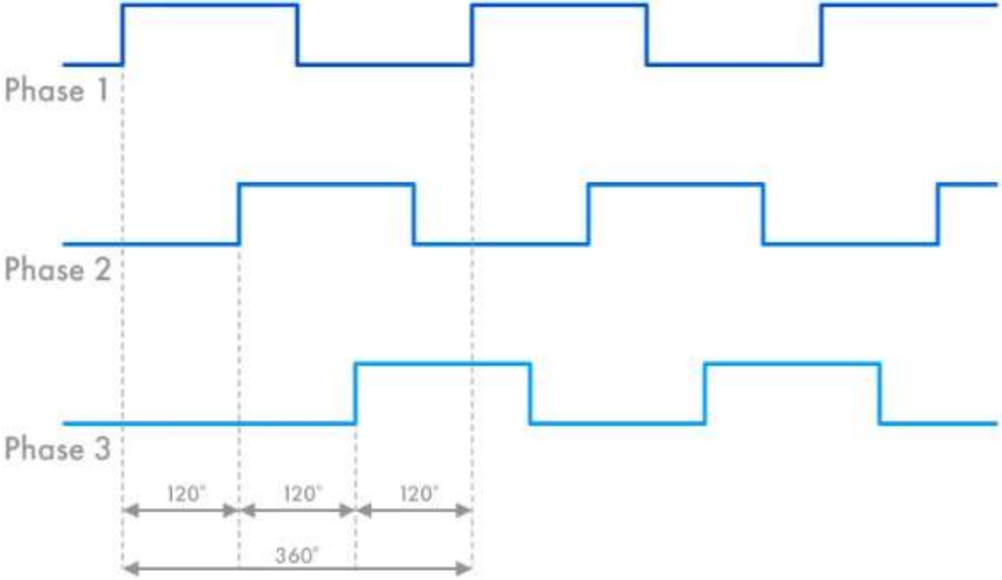
Designing a BLDC motor controller, you can consider different approaches to current switching, including **trapezoidal** and **sinusoidal** commutation. The names of these methods relate to the signal waveforms.

With the trapezoidal commutation, two windings out of three can stay energized at the same time. In the sinusoidal control method, the phase shift complies with the law of sines. It provides smoother current switching between the phases.

The trapezoidal commutation is simpler, but it may cause the vibration of the motor at low speeds. Implementation of sinusoidal current waveforms can ensure flawless operation of your motor. However, this type of commutation becomes challenging at high speeds.

Typically, a sinusoidal brushless motor controller circuit uses **pulse-width modulation** (**PWM**). It helps regulate the current injected into the rotor's windings and run the commutation process more smoothly and efficiently. This applies especially to **closed-loop** controllers that get feedback on the output signal and adjust the input power by varying the duty cycle.

A duty cycle is the percentage between the current pulse and the complete cycle of the current signal. A BLDC motor speed controller changes PWM duty cycles to create sinusoidal signals.



Three-phase pulse-width modulation (PWM)

PWM switching frequency can be different for various applications. Although it should be high enough to prevent power loss. The physical limitations of the stator determine the maximum frequency level. However, there are also the specifications of the control unit itself.

So even if the stator allows you to increase the PWM frequency, you will not be able to do that because of the limited capabilities of your DC brushless motor controller.