UNIT-2

ELECTRIC DRIVE-TRAINS

Introduction to various electric drive-train topologies

General configuration of electric vehicle

Compared to HEV, the configuration of EV is flexible. The reasons for this flexibility are:

The energy flow in EV is mainly via flexible electrical wires rather than bolted flanges or rigid shafts. Hence, distributed subsystems in the EV are really achievable.

The EVs allow different propulsion arrangements such as independent four wheels and in wheel drives.

- **In the general configuration of the EV is shown. The EV has three major subsystems:**
  1. Electric propulsion
  2. Energy source
  3. Auxiliary system
- **The electric propulsion subsystem comprises of:**
  1. The electronic controller
  2. Power converter
  3. Electric Motor
  4. Mechanical Transmission
  5. Driving Wheels
- **The energy source subsystem consists of**
  1. The Energy source
  2. Energy Management Unit
  3. Energy Refueling Unit
- **The auxiliary subsystem consists of**
  1. Power steering unit
  2. Temperature control unit
  3. Auxiliary Power unit

In the black line represents the mechanical link, the green line represents the electrical link and the blue line represents the control information communication. Based on the control inputs from the brake and accelerator pedals, the electronic controller provides proper control signals to switch on or off the power converter which in turn regulates the power flow between the electric motor and the energy source. The backward power flow is due to regenerative braking of the EV and this regenerative energy can be stored provided the energy source is receptive. The energy management unit cooperates with the electronic controller to control regenerative braking and its energy recovery. It also works with the energy-refueling unit to control refueling and to monitor usability of the energy source. The auxiliary power supply provides the necessary power with different voltage levels for all EV auxiliaries, especially the temperature control and power steering units.

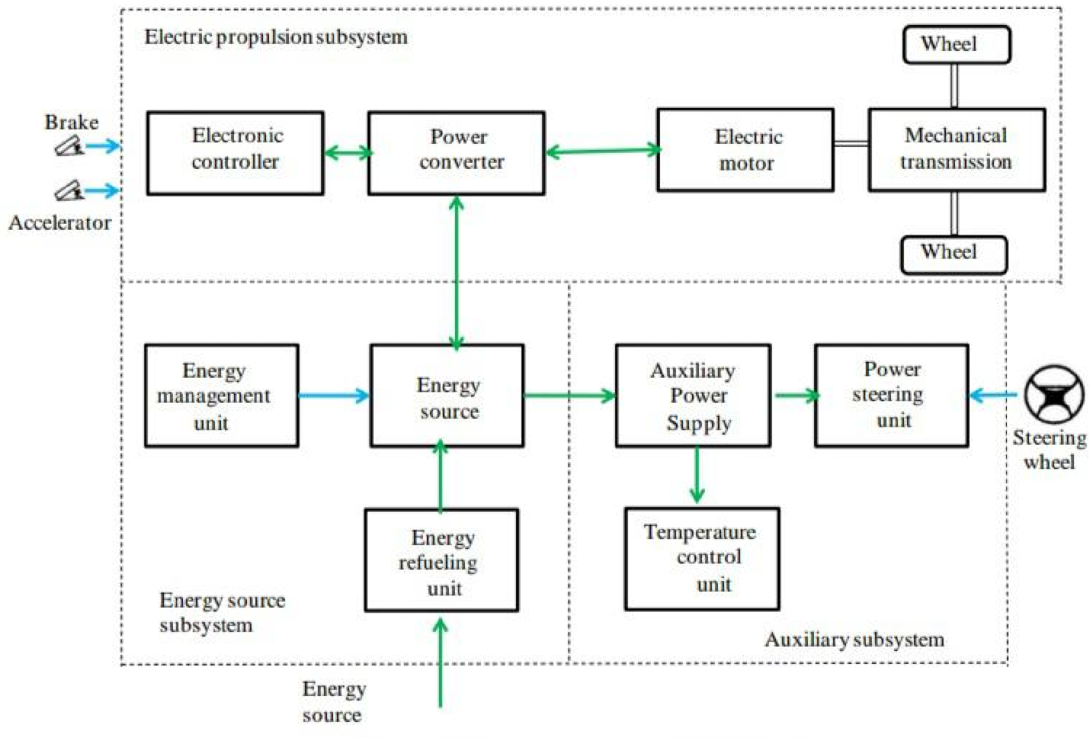


Figure 1:General Configuration of a Electric Vehicle [1]

Modern configuration of electric vehicle

- **Three phase motors are generally used to provide the traction force**
- **The power converter is a three-phase PWM inverter**
- **Mechanical transmission is based on fixed gearing and a differential**
- **Li-ion battery is typically selected as the energy source**

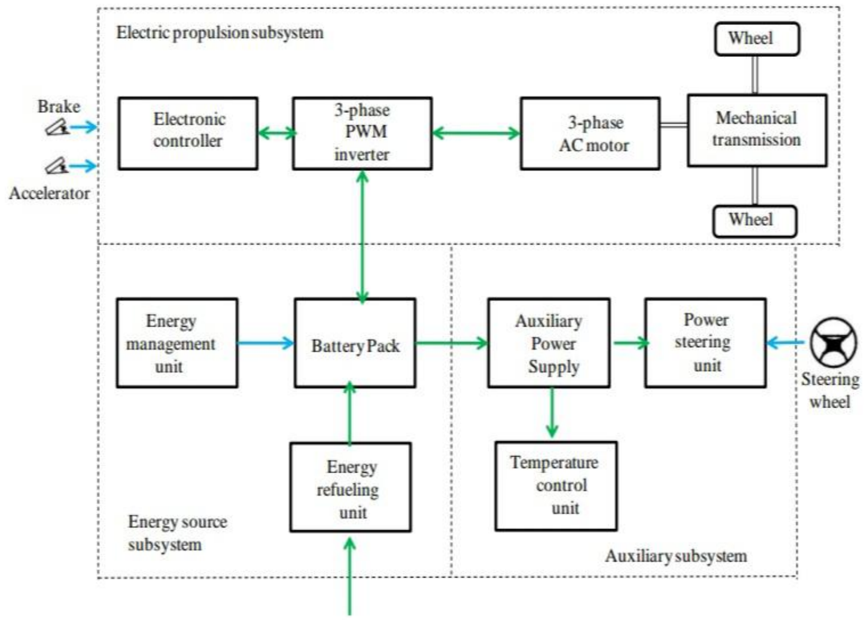


Figure 2:Typical Configuration of a Electric Vehicle [1]

Electric Vehicle (EV) Drive train Alternatives Based on Drive train Configuration

Different front wheel drive EV configurations.

In **Figure 3a** a single EM configuration with gearbox (GB) and a clutch is shown. It consists of an EM, a clutch (C), a gearbox, and a differential (D). The clutch enables the connection or disconnection of power flow from EM to the wheels. The gear consists of a set of gears with different gear ratios. With the use of clutch and gearbox, the driver can shift the gear ratios and hence the torque going to the wheels can be changed. The wheels have high torque low speed in the lower gears and high-speed low torque in the higher gears.
In **Figure 3b** a single EM configuration without the gearbox and the clutch is shown. The advantage of this configuration is that the weight of the transmission is reduced. However, this configuration demands a more complex control of the EM to provide the necessary torque to the wheels.
Figure 3c shows a configuration of EV using one EM. It is a transverse front EM front wheel drive configuration. It has a fixed gearing and differential and they are integrated into a single assembly.
In **Figure 3d** a dual motor configuration is shown. In this configuration the differential action of an EV when cornering can be electronically provided by two electric motors.

In order to shorten the mechanical transmission path from the EM to the driving wheel, the EM can be placed inside a wheel. This configuration is called in-wheel drive. **Figure 3e** shows this configuration in which fixed planetary gearing is employed to reduce the motor speed to the desired wheel speed.
In **Figure 3f** an EV configuration without any mechanical gearing is shown. By fully abandoning any mechanical gearing, the in-wheel drive can be realized by installing a low speed outer-rotor electric motor inside a wheel.

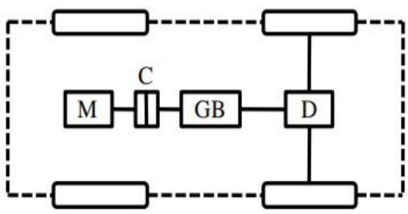


Figure 3a: EV configuration with clutch, gearbox and differential [1]

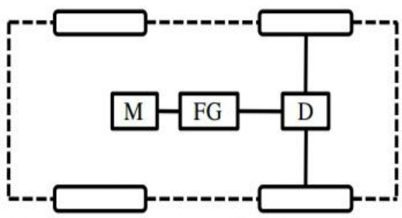


Figure 3b: EV configuration without clutch and gearbox [1]

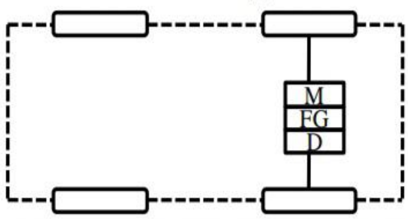


Figure 3c:EV configuration with clutch, gearbox and differential [1]

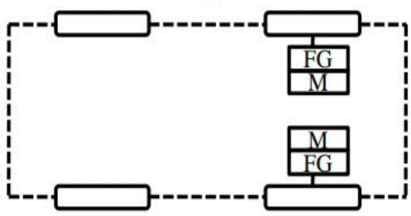


Figure 3d:EV configuration with two EM [1]

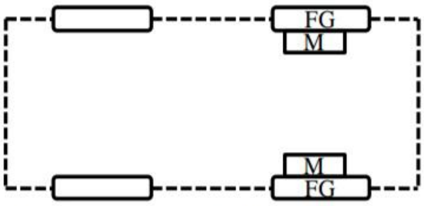


Figure 3e:EV configuration with in wheel motor and mechanical gear [1]

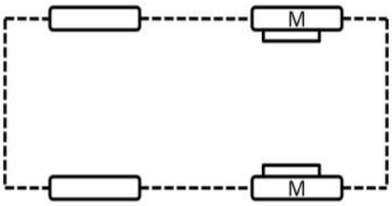


Figure 3f:EV configuration with in wheel motor and no mechanical gear [1]

C: Clutch
D: Differential
FG: Fixed gearing
GB: Gearbox
EM: Electric motor

Electric Vehicle (EV) Drive train Alternatives Based on Power Source Configuration

Electric Vehicle (EV) Drive train Alternatives Based on Power Source Configuration Besides the variations in electric propulsion, there are other EV configurations due to variations in energy sources. There are five configurations possible and they are:

Configuration 1: It is a simple battery powered configuration. The battery may be distributed around the vehicle, packed together at the vehicle back or located beneath the vehicle chassis. The battery in this case should have reasonable specific energy and specific power and should be able to accept regenerative energy during braking. In case of EVs, the battery should have both high specific energy and specific power because high specific power governs the driving range while the high power density governs the acceleration rate and hill climbing capability.

Configuration 2: Instead of two batteries, this design uses two different batteries. One battery is optimized for high specific energy and the other for high specific power.

Configuration 3: In this arrangement fuel cell is used. The battery is an energy storage device, whereas the fuel cell is an energy generation device. The operation principle of fuel cells is a reverse process of electrolysis.

In reverse and electrolysis, hydrogen and oxygen gases combine to form electricity and water. The hydrogen gas used by the fuel cell can be stored in an on-board tank whereas oxygen gas is extracted from air. Since fuel cell can offer high specific energy but cannot accept regenerative energy, it is preferable to combine it with battery with high specific power and high-energy receptivity.

Configuration 4: Rather than storing it as a compressed gas, a liquid or a metal hydride, hydrogen can be can be generated on-board using liquid fuels such as methanol. In this case a mini reformer is installed in the EV to produce necessary hydrogen gas for the fuel cell.

Configuration 5: In fuel cell and battery combination, the battery is selected to provide high specific power and high-energy receptivity. In this configuration a battery and super capacitor combination is used as an energy source. The battery used in this configuration is a high energy density device whereas the super capacitor provides high specific power and energy receptivity. Usually, the super capacitors are of relatively low voltage levels, an additional dc-dc power converter is needed to interface between the battery and capacitor terminals.

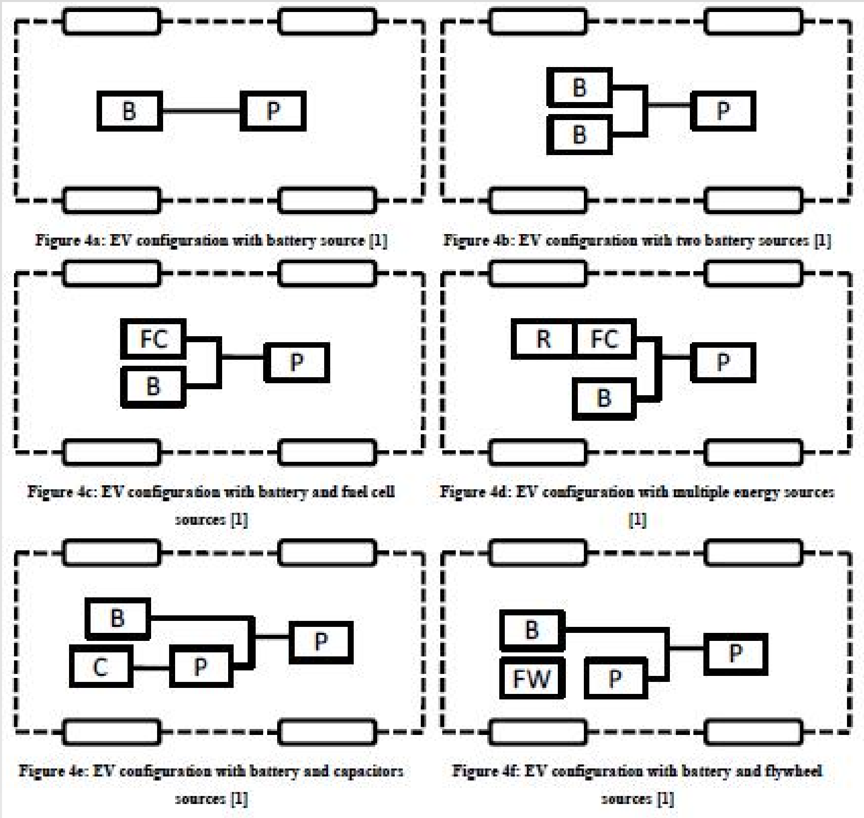


Figure 4a: EV configuration with battery source [1]

Figure 4b: EV configuration with two battery sources [1]

Figure 4c: EV configuration with battery and fuel cell sources [1]

Figure 4d: EV configuration with multiple energy sources [1]

Figure 4e: EV configuration with battery and capacitors sources [1]

Figure 4f: EV configuration with battery and flywheel sources [1]

Single and Multi-motor Drives

Most of the land crafts roll on wheels and are driven by internal rotating motor. The number of wheels and mechanical solutions for traction are very different in vehicle constructions. Regarding the number of motors the vehicle can be driven by a single motor or multi motor.
Single motor vehicle can be designed if requirements for motion force and traction power can be fulfilled with one motor.
Single motor vehicles can be divided into three groups:

a. electric cars, hybrid buses, trolleys,
b. electric bicycles and other low power electric vehicles,
c. linear motor vehicles, as a special case.

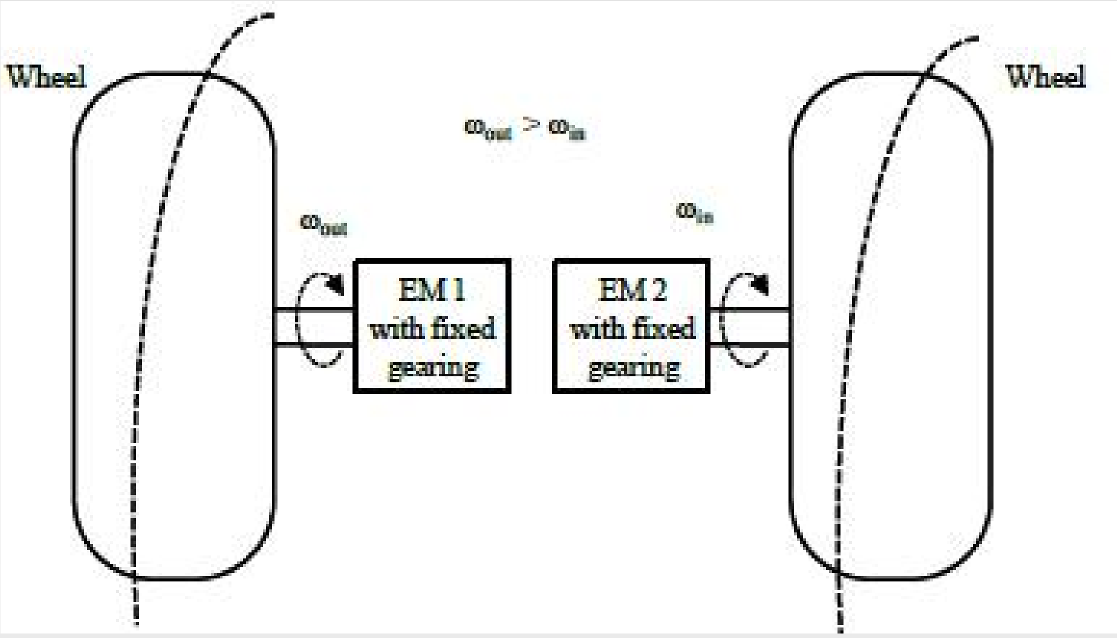
The construction of the vehicles in the first group is usually similar to vehicles with internal combustion engine, and electric motor is connected to front or back wheel axles with card an shaft and differential. Gearbox with variable transmission and clutch is not needed in electric vehicles.
If there is a fix transmission between the angular speed of motor and wheels then this transmission is required to fit the angular speeds. In low power vehicles even simpler, v-belt or chain-drive is used, or a wheel hub motor placed on the wheel with flat, disc-type shape.
Vehicles with linear motor drive can be considered as special single motor vehicles where motor is along the whole body.

Multi motor drive can be used in low or high power vehicles, too. An example for multi motor low power vehicle is an electric car with separately controllable wheel hub motors in every wheel. Usually, rpm of the motor and the wheel are the same. Motors drive the wheels directly and not the axle. Such a drive has mechanical problems as mass of wheels increase, and there is a flexible connection between rotor and stator of the motor.

There are several reasons to design high power multi motor vehicles:

One reason is electrical and is based on conventions. Voltage on one motor can be changed with serial or parallel connection of the motors. Changing serial and parallel connections of two motors is used in two-motor trams and underground trains, for example.

The other reason is mechanical. When using more motors construction can vary. Motive force can be divided to several wheels, power required for traction can be divided between motors, and more, smaller motors are easier to place inside the body.



Single Motor & Multi Motor Drive

UNIT-2

ELECTRIC PROPULSION UNIT

Classification of electric motor drives for EV and HEV applications

- **DC Motor**

DC motors are regarded as options for EV/HEV applications owing to their capability of achieving high torque at low speed. Their torque speed characteristics is fitting or traction requirement. Also the speed control is relatively simple, by varying the terminal voltage.Based on different topologies, DC Motors can be categorized into three types: series excited, shunt excited, and separately excited machine.
Both shunt and series DC motor have only one voltage source hence the controls of flux and torque are simultaneously. On the other hand, the separately excited DC motors are intrinsically capable for field weakening operation since the torque and flux controls are decoupled. As a result, the extended constant power range can be realized.
One the other hand, DC motors also suffer from several disadvantages such as bulky dimension, low efficiency, low maximum speed, low reliability and high demand for maintenance, especially for motors with mechanical commutators and brushes. Due to these drawbacks brushless DC motor is more generally used with improved efficiency and reduced size, compared with conventional brushed DC motor, BLDC motors do not contain brushes.
The commutation process is performed electrically bytheelectronic drive to excite the stator windings.Despite of aforementioned disadvantages, the DCmotor drives are preferred in low power conditions and they aremore than the alternatives in automotive industry especially for HEV applications.

- **Induction motor**

Induction motors are the most commonly used electric machines. Even without the DC-AC inverters, they can operate directly from an alternating current (AC) voltage supply. They have been widely used for constant-speed applications. IMmotor drives are regarded as one of the most competent candidate aselectric propulsion system for EVs and HEVs because of their robust construction, reliability, ruggedness, low maintenan cedem and, low cost and excellent peak torque capability.
IM drives are also the most mature technology among all types ofmotor drives. Without commutator and brush, the IM motors are free from brush friction hence the maximum speed limit is increased.
As a result, the constant power speed range can be extended. By changing the frequency of the excited voltage, speed variation of theIMmotor is achieved. In order to gain independent controls of the torque and the field flux,field orientation control (FOC) can be adopted, which is similar to the case of separately excited DC machine.For conventional IM, the critical speed is about two times the base speed.

Anyfurtherattempt to operate the motor above this speed with maximum current will stop the motor from running.

- **Permanent magnet brushless motor drives**

The PM motors is capable ofutilizingboth reluctance torque and magnetic torque to improve its efficiency and torquedensity. In these motors, a certainnumber of magnetsisrotorof the machine. Typically, permanent magnet brushless motor drives have better performance compared toIM drives as candidates for the electric propulsion system. Their major advantages include
Reducedoverall weight and volume for given output power (high power density) due to the highly energized magneticfield from PM
Inherently higher efficiency owing to the absence of the rotor windings (hence the associated copper loss)
More efficient heat dissipation since it is mainly generated by the stator;
High reliabilitydue totheir immunity tooverheatingissue or mechanical damage by PM excitation. Considering the above advantages, PM motors are the prior choice for most of the HEVs and EVs manufacturers. However, this type of motors has relatively short constant power range due to their limited field-weakening capability, which is mainly resulted fromthe presence ofstrong field fluxproduced by thePM. Nonetheless, at very high speed range, the efficiency may dropdrasticallydue to the fact that the PM may suffer from demagnetization caused by significant back EMFand possible fault occurrence.

- **Switched reluctance motor drive**

Switched reluctance motors (SRM) are gaining much interest from the academia and industry for its potential in EV/HEV applications. Originally, they are derived fromsingle stack variable reluctance stepping motors. This kind of motors have numerous salient advantages including simple and rugged construction, high fault tolerance, low manufacturing cost, and remarkabletorque-speed characteristics. The SRM drive has very high speed operation capability with wide
constant power range. It also has high starting torque and high torque-inertia ratio. The rotor structure is the simplest type compared to DC, IM, and PM motors with no rotor windings, magnets, commutators or brushes. An added benefit of this structure is simple external cooling of the motor, which makes SRM capable of operating at harsh ambient conditions (e.g. high temperature).

- **Synchronous reluctance motor drive**

Synchronous reluctance motor (SynRM) is a novel kind of synchronous machine, which combines the advantages of both IMmotors and PM motors. The main feature of such motor is that it incorporates therobustness of IMmotors with thecomparablesize,efficiency, and synchronous speed operation asPM motors. The stator of the SynRM motor has distributed windingsas IM and PM motors.
The rotor is designed such that the smallest possible and the highest reluctance areachieved in the two perpendiculardirections. In addition, the motor is fault tolerant as IM motors due to no flux in the rotor without energizing the stator windings. The control strategy is similar to that of PM motorsdue to identical stator structure.

Operation principle of a DC motor

An electric motor is an electrical machine which converts electrical energy into mechanical energy. The basic working principle of a DC motor is: "*whenever a current carrying conductor is placed in a magnetic field, it experiences a mechanical force".* The direction of this force is given by

- ➢ Fleming's left-hand rule and its magnitude is given by F = BIL.

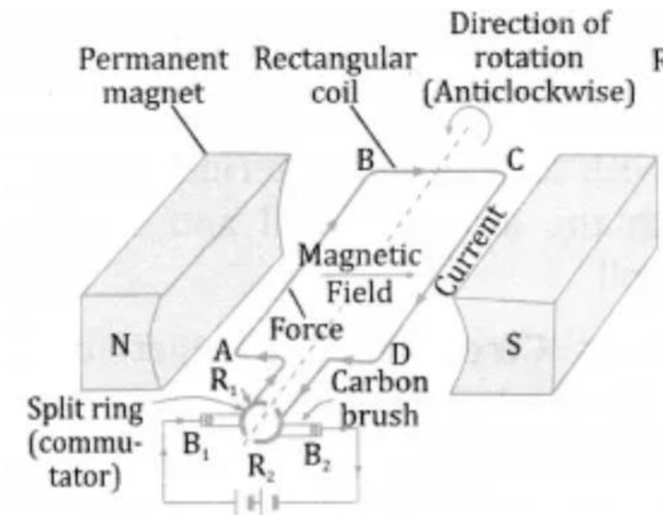
  Where, B = magnetic flux density,

  I = current and

  L = length of the conductor within the magnetic field.

➢ **Fleming's left hand rule**:

If we stretch the first finger, second finger and thumb of our left hand to be perpendicular to each other, and the direction of magnetic field is represented by the first finger, direction of the current is represented by the second finger, then the thumb represents direction of the force experienced by the current carrying conductor.



DC Motor

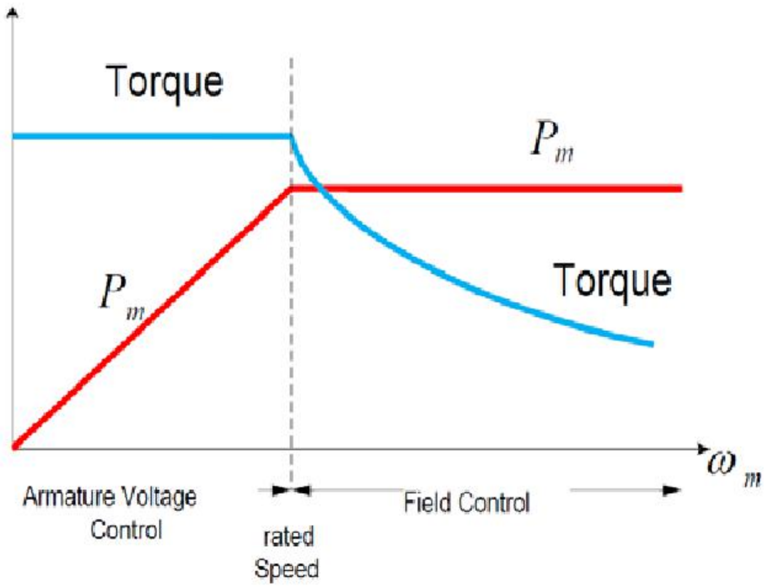
When armature windings are connected to a DC supply, an electric current sets up in the winding. Magnetic field may be provided by field winding (electromagnetism) or by using permanent magnets. In this case, current carrying armature conductors experience a force due to the magnetic field, according to the principle stated above.

Commutater is made segmented to achieve unidirectional torque. Otherwise, the direction of force would have reversed every time when the direction of movement of conductor is reversed in the magnetic field.

Combined Armature Voltage and Field Control

The greatest advantage of DC motors may be speed control. Since speed is directly proportional to armature voltage and inversely proportional to the magnetic flux produced by the poles, adjusting the armature voltage and/or the field current will change the rotor speed.

The speed of a separately excited dc motor could be varied from zero to rated speed mainly by varying armature voltage in the constant torque region. Whereas in the constant power region, field flux should be reduced to achieve speed above the rated speed. Torque and limitations in combined armature voltage and field control can be seen in the figure given below.

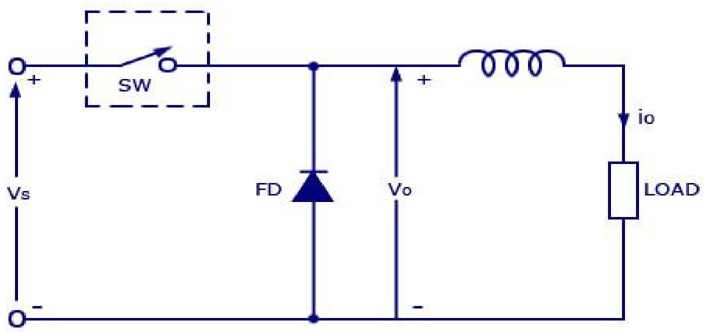


Combined Armature and field control of DC motor

Principle of operation of a step down chopper, basic chopper circuit, wave forms for control DC drives

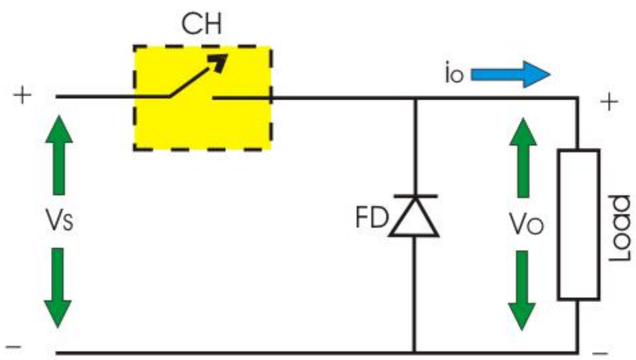
A chopper can be said as a high speed on/off semiconductor switch. Source to load connection and disconnection from load to source happens in a rapid speed. Consider the figure, here a chopped load voltage can be obtained from a constant dc supply of voltage, which has a magnitude $V_{s.}$ Chopper is the one represented by "SW" inside a dotted square which can be turned on or off as desired.

Chopper Circuit

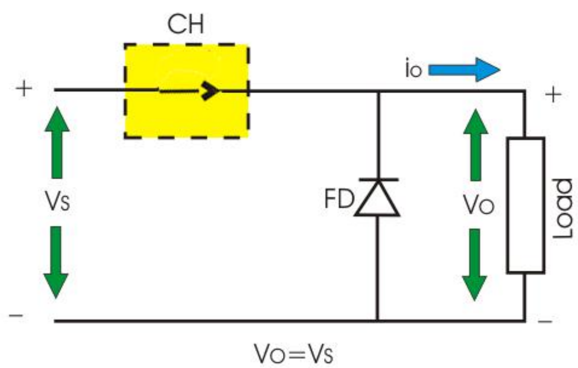


- **Step Down Chopper**

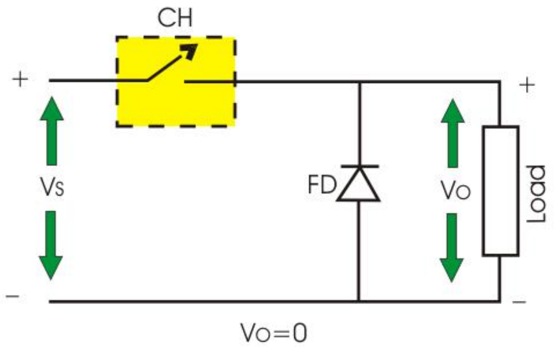
  Step down chopper as Buck converted is used to reduce the I/p voltage level at the output side. Circuit diagram of a step down chopper is shown in the adjacent figure.



When CH is turned ON, Vs directly appears across the load as shown in figure. So,V_o = VS.



When CH is turned off, Vs is disconnected from the load. So output voltage V_o = 0.



The voltage waveform of step down chopper is shown below

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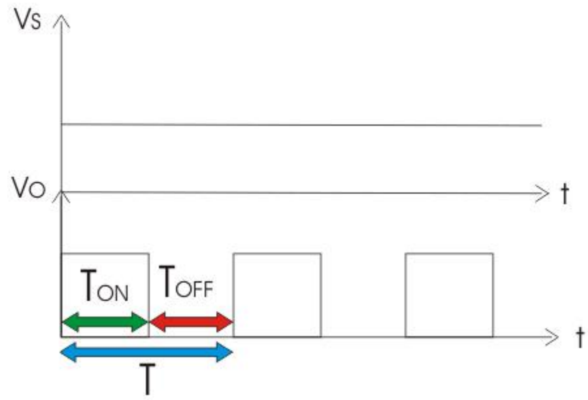
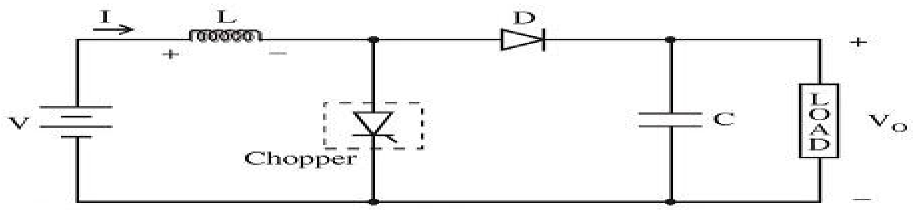


T_{ON} → It is the interval in which chopper is in ON state.
T_{OFF} → It is the interval in which chopper is in OFF state.
V_S → Source or input voltage.
V_o → Output or load voltage.
T → Chopping period = T_{ON} + T_{OFF}

Principle of operation of a step up chopper, basic chopper circuit, wave forms for control DC drives

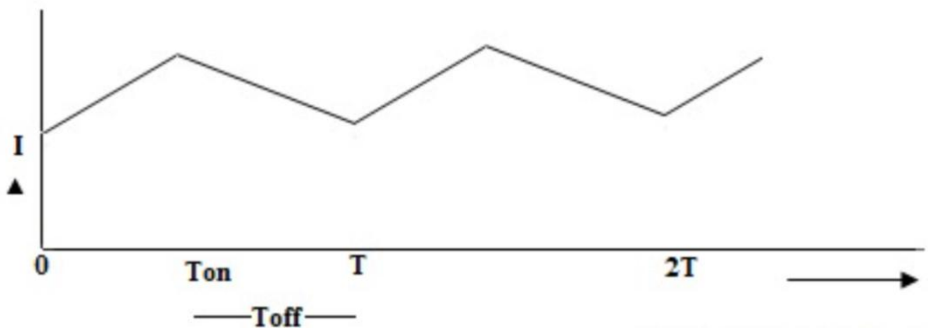
Chopper circuits are known as DC to DC converters. Similar to the transformers of the AC circuit, choppers are used to step up and step down the DC power.

They change the fixed DC power to variable DC power. Using these, DC power supplied to the devices can be adjusted to the required amount. Step-up chopper works as a step-up transformer on DC current. This chopper is used when the output DC voltage has to be made higher than the input voltage.
The working principle of a step-up chopper can be explained from the above diagram. In the circuit, a large inductor L is connected in series to the supply voltage. Capacitor maintains the continuous output voltage to the load. The diode prevents the flow of current from load to source.



Chopper Circuit

When the chopper is ON, supply voltage VS is applied to the load.i.e. V0 = VS and inductor starts storing energy. At this condition load current raises from Imin to Imax.
When the chopper is switched OFF, the supply voltage takes the path from L – D – Load – VS. During this period the inductor discharges the stored e.m.f through diode D to the load. Thus, the total voltage at the load V0 = VS + Ldi/dt which is greater than the input voltage. Current changes from Imax to Imin.



Waveform for dc drives

Where ΔI is the change in current, TON is is the duration, then

$L\frac{di}{dt} = V_{S,}\ \ \frac{\Delta I}{T_{ON}} = \frac{V_S}{L}$

$\Delta I = \frac{V_S}{L} T_{ON}$ ------1

During T_{OFF} condition…

$\Delta I = \frac{V_0 - V_S}{L} T_{OFF}$ ----- 2

from 1 and 2 Average output voltage is given as $V_0 = \frac{V_S}{T - T_{ON}/T}$

Basic operation principle of induction motors

The motor which works on the principle of electromagnetic induction is known as the induction motor. The electromagnetic induction is the phenomenon in which the electromotive force induces across the electrical conductor when it is placed in a rotating magnetic field.

The stator and rotor are two essential parts of the motor. The stator is the stationary part, and it carries the overlapping windings while the rotor carries the main or field winding. The windings of the stator are equally displaced from each other by an angle of 120°.

The induction motor is the single excited motor, i.e., the supply is applied only to the one part, i.e., stator. The term excitation means the process of inducing the magnetic field on the parts of the motor.

When the three phase supply is given to the stator, the rotating magnetic field produced on it. The figure below shows the rotating magnetic field set up in the stator.

Consider that the rotating magnetic field induces in the anticlockwise direction. The rotating magnetic field has the moving polarities. The polarities of the magnetic field vary by concerning the positive and negative half cycle of the supply. The change in polarities makes the magnetic field rotates.

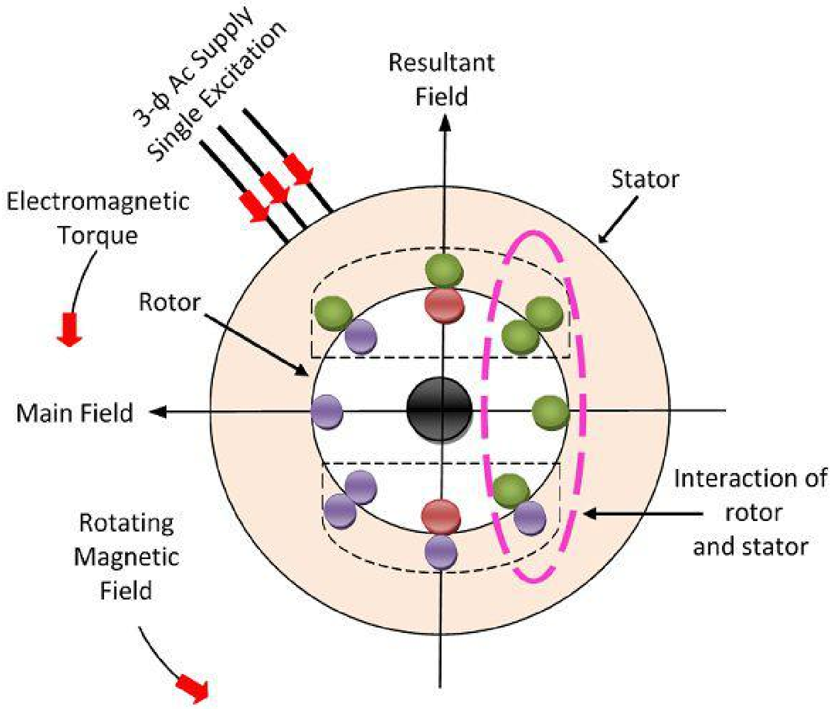
The conductors of the rotor are stationary. This stationary conductor cut the rotating magnetic field of the stator, and because of the electromagnetic induction, the EMF induces in the rotor. This EMF is known as the rotor induced EMF, and it is because of the electromagnetic induction phenomenon.

The conductors of the rotor are short-circuited either by the end rings or by the help of the external resistance. The relative motion between the rotating magnetic field and the rotor conductor induces the current in the rotor conductors. As the current flows through the conductor, the flux induces on it. The direction of rotor flux is same as that of the rotor current.

Now we have two fluxes one because of the rotor and another because of the stator. These fluxes interact each other. On one end of the conductor the fluxes cancel each other, and on the other end, the density of the flux is very high. Thus, the high-density flux tries to push the conductor of rotor towards the low-density flux region. This phenomenon induces the torque on the conductor, and this torque is known as the electromagnetic torque.

The direction of electromagnetic torque and rotating magnetic field is same. Thus, the rotor starts rotating in the same direction as that of the rotating magnetic field.

The speed of the rotor is always less than the rotating magnetic field or synchronous speed. The rotor tries to the run at the speed of the rotor, but it always slips away. Thus, the motor never runs at the speed of the rotating magnetic field, and this is the reason because of which the induction motor is also known as the asynchronous motor.



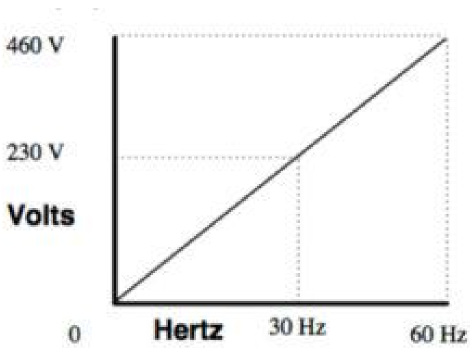
Three Phase Induction Motor

Constant Volt/Hertz Control for control Induction motor drives

AC motors are designed for a magnetic field (flux) of constant strength. The magnetic field strength is proportional to the ratio of voltage (V) to frequency (Hz), or V/Hz. But a VFD controls the motor speed by varying the frequency of the applied voltage, according to the synchronous speed equation:
N = 120*f / P

Where:

N = motor speed (RPM)
f = input voltage frequency
P = number of motor poles



V/Hz control maintains a constant ratio between voltage (V) and frequency (Hz).

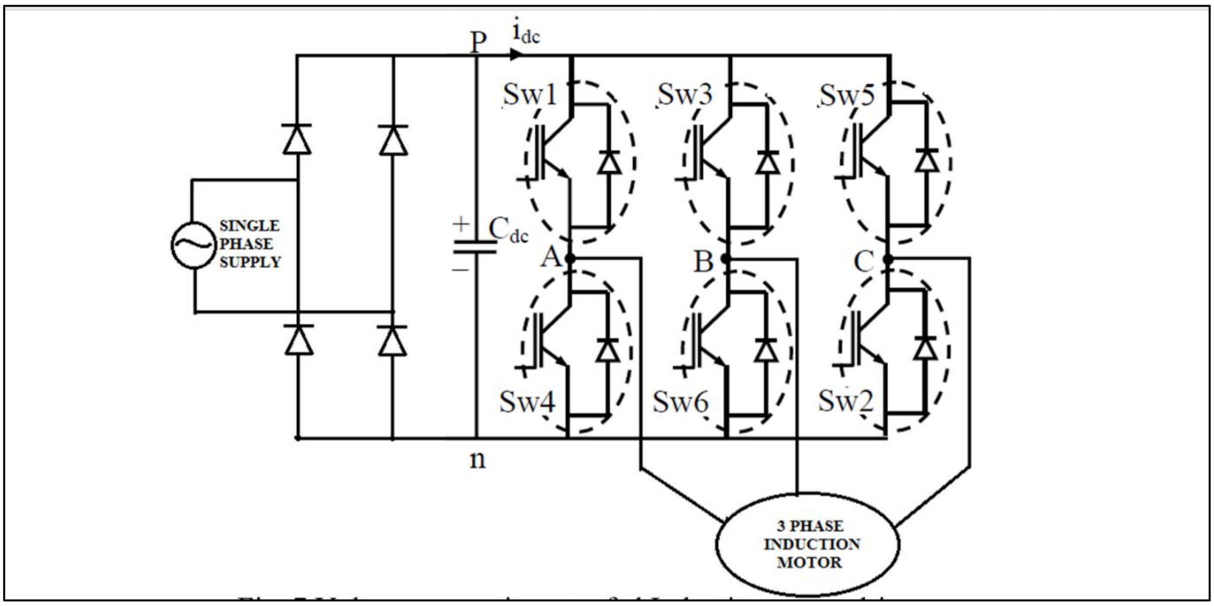
Varying the voltage frequency affects both the motor speed and the strength of the magnetic field. When the frequency is lowered (for slower motor speed), the magnetic field increases, and excessive heat is generated. When the frequency is increased (for higher motor speed), the magnetic field decreases, and lower torque is produced. In order to keep the magnetic flux constant, the V/Hz ratio must remain constant. This keeps torque production stable, regardless of frequency.
V/Hz control of a VFD drive avoids this variation in the magnetic field strength by varying the voltage along with the frequency, in order to maintain a constant V/Hz ratio. The appropriate V/Hz ratio is given by the motor's rated voltage and frequency. For example, a motor rated for 230 V and 60 Hz will operate best at a V/Hz ratio of 3.83 at all times (230/60 = 3.83).
Traditional V/Hz control does not use feedback, and only changes the voltage and frequency to the motor based on an external speed command. For closed-loop V/Hz control, encoder feedback can be added to measure the motor's actual speed. An error signal is generated based on the difference between actual speed and commanded speed, and the controller generates a new frequency command to compensate for the error. While it improves speed regulation, closed-loop V/Hz control isn't common due to the added cost and complexity of the encoder and feedback hardware.
V/Hz control is a simple, low-cost method for controlling variable frequency drives, and is generally regarded as the most common VFD control scheme. It is suitable for both constant torque and variable torque applications and can provide up to 150 percent of the rated torque at zero speed for startup and peak loads.
One unique benefit of V/Hz control over other methods is that it allows more than one motor to be operated by a single VFD. All the motors will start and stop at the same time, and they will all run at the same speed, which is beneficial in some processing applications, such as heating and cooling.

Current control in voltage source inverter for control of induction motor drives

The function of inverter is reverse of what ac-to-dc converter does. Usually input to an inverter circuit is a dc source, but it is not uncommon to have this dc derived from an ac source such as utility ac supply.

For example, the primary source of input power may be utility ac voltage supply that is converted to dc by an ac to dc converter and then inverted back to ac using an inverter. The final ac output may be of a different frequency and magnitude than the input ac of the utility supply. DC motors have been used during the last century in industries for variable speed applications due to its easy controllability of flux and torque by means of changing the field and armature currents respectively.
Additionally, operation in the four quadrants of the torque speed plane including temporary standstill was achieved.The function of inverter is reverse of what ac-to-dc converter does. Usually input to an inverter circuit is a dc source, but it is not uncommon to have this dc derived from an ac source such as utility ac supply.
For example, the primary source of input power may be utility ac voltage supply that is converted to dc by an ac to dc converter and then inverted back to ac using an inverter. The final ac output may be of a different frequency and magnitude than the input ac of the utility supply.

DC motors have been used during the last century in industries for variable speed applications due to its easy controllability of flux and torque by means of changing the field and armature currents respectively. Additionally, operation in the four quadrants of the torque speed plane including temporary standstill was achieved.
Almost for a century, induction motor has been the workhorse of industry due to its robustness, low cost high efficiency and less maintenance. Earlier induction motors were mainly used for essentially constant speed applications because of the unavailability of the proper speed control techniques.
The advancement of power electronics has made it possible to vary the speed of induction motor by varying supply voltage, supply frequency or both.
Voltage source inverters are most commonly used in industrial applications such as speed control of induction motor. For controlling speed of the induction motor, it is necessary to vary the voltage or frequency shows the three-phase voltage source inverter fed induction motor drive.
Single phase 230V, 50 Hz supply is used, which rectified into dc by using a diode bridge rectifier. Output of the diode bridge rectifier contains large number of ripples. In order to get a ripple free dc, a capacitor filter is used here.
This dc provided as input of the voltage source inverter. Voltage source inverter is operated in 180-degree conduction mode here. Output of the voltage source inverter is three stepped waves of sinusoidal characteristic and of 120-degree phase shift with each other, which is provided as input of the three-phase induction motor.

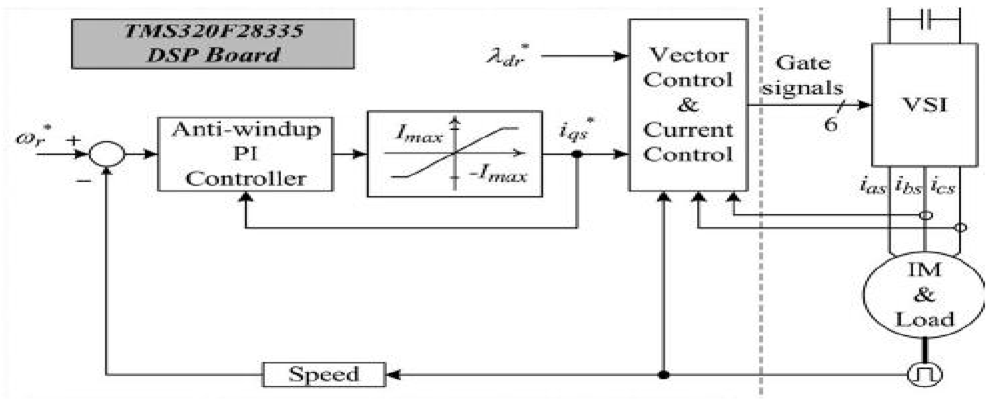


Current Control Inverter

A vector control system for an induction motor for control Induction Motor drives

- **Vector control system for Induction motordrive: -**

  The induction motor is the most widely used electrical motor due to its rugged structure, low cost and reliability.
  However, the nonlinearity in the Torque-Voltage relationship of an IM makes its analysis difficult. Also,it is a fifth order system making its dynamic response poor.
  Development of Vector Control analysis has enabled us to get as good dynamic performance from an IM as a dc motor. The torque and the flux components can be controlled independently using vector control just like in a dc motor.
  In order to analyses vector control, we need to develop a dynamic model of the IM. This is done by converting the 3-ø quantities into 2-axes system called the d-axis and the q-axis.
  Such a conversion is called axes transformation. The d-q axes can be chosen to be stationary or rotating. Further, the rotating frame can either be the rotor oriented or magnetizing flux oriented.
  However, synchronous reference frame in which the d-axis is aligned with the rotor flux is found to be the most convenient from analysis point of view.
  A major disadvantage of the per phase equivalent circuit analysis is that it is valid only if the three-phase system is balanced
  Any imbalance in the system leads to erroneous analysis. Even this problem is eradicated if we use the d-q model.



Vector control system

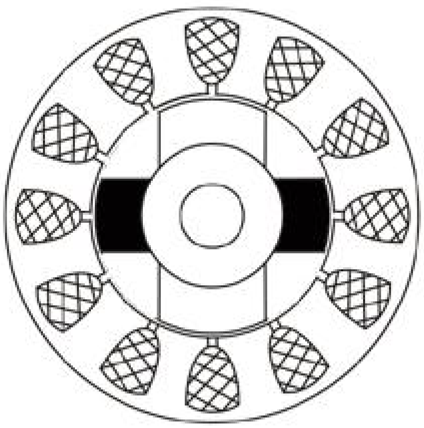
Basic Principles of BLDC Motor Drives (Permanent Magnet Motor drives)

- **Brushless DC motor principle: -**
  A brushless DC motor (also known as aBLDCmotororBL 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.
  The basic working principle for the brushed DC motor and for brushless DC motor is same i.e. internal shaft position feedback.
  Brushless DC motor has only two basic parts: rotor and the stator. The rotor is the rotating part and has rotor magnets whereas stator is the stationary part and contains stator windings. In BLDC permanent magnets are attached in the rotor and move the electromagnets to the stator. The high-power transistors are used to activate electromagnets for the shaft turns. The controller performs power distribution by using a solid-state circuit.

Types of Brushless DC motor: -

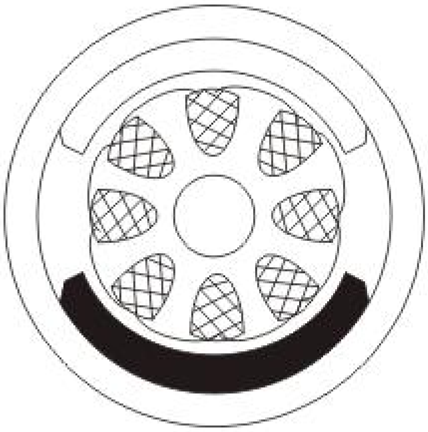
Basically, BLDC are of two types, one is outer rotor motor and other isinnerrotormotor. The basic difference between the two is only in designing, their working principles are same.

- **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 Motor: -** 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

Torque control method of the BLDC motor drives

- **Torque control method of the BLDC motor drives: -**

  In the conventional current control strategy only current will be controlled, with high ripples in torque. The Direct Torque Control scheme is extended to BLDC motor drives to minimize the Torque Ripples.

  The electro-magnetic torque and the stator flux linkage amplitude of the BLDC motor under 2-phase conduction mode can be controlled simultaneously. Here we are going to reduce the ripples in torque by using direct torque control. Mainly BLDC drive has a drawback of high torque pulsation.

  Basically, it is caused by two-components one is ripple torque and another one is commutation torque. The main components of ripple torque are motor related, and inverter related. Motor related components are produced by the non-idealities in the back e.m.f wave forms.

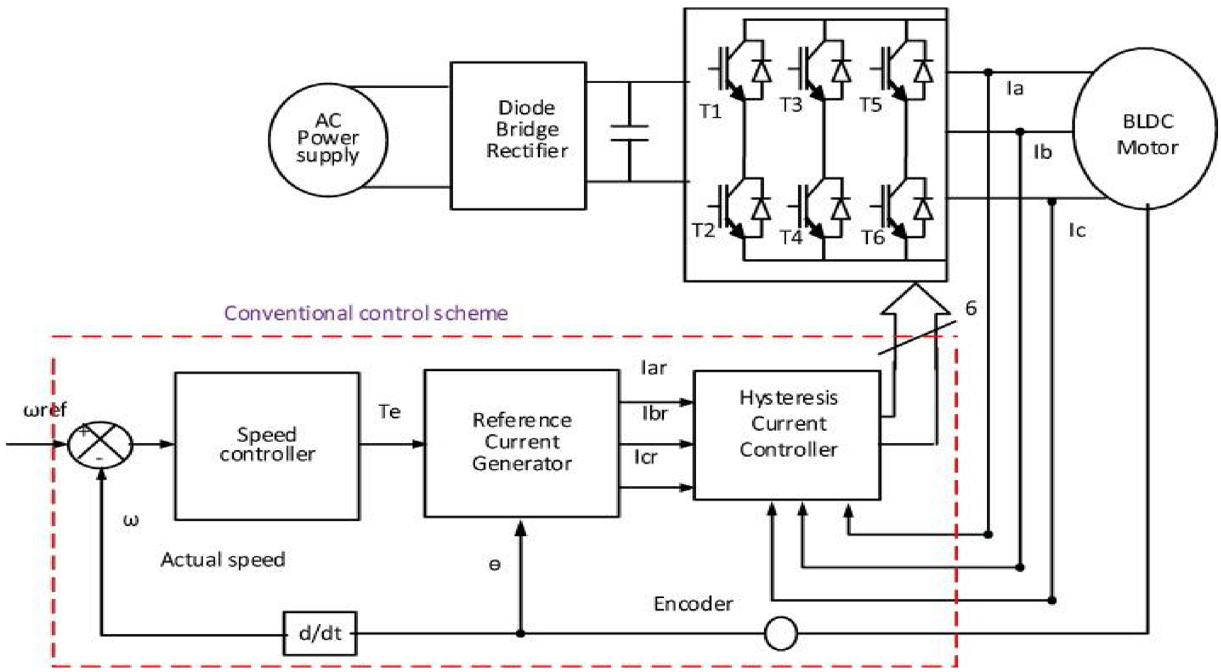
  Here Motor relates cogging torque, inverter relates ripple torque. Ripple torque is a consequence of the interaction of the armature currents with the machine back e.m.f wave forms.

  Cogging torque produced by variation of reluctance caused by the stator slot openings as rotor rotates. Cogging torque can be reduced by skewing and by choosing a fractional slot/pole motor design

  The inverter related ripple torque components departure from the ideal rectangular current profiles due to finite inductance. The inverter related ripple torque is caused by the Hysteresis controller because which produces high switching frequency current ripple.

  This high frequency ripple is caused by corresponding ripple in phase current. The back e.m.f related component has high frequency; it is Six times of the electrical frequency, corresponding to the six conduction intervals in each cycle.

  At low speeds they can affect the performance of the drive, but at high speeds it is not a problem as it is filtered out by load inertia. This high frequency torque ripple is reduced by controlling the current and rotor position.

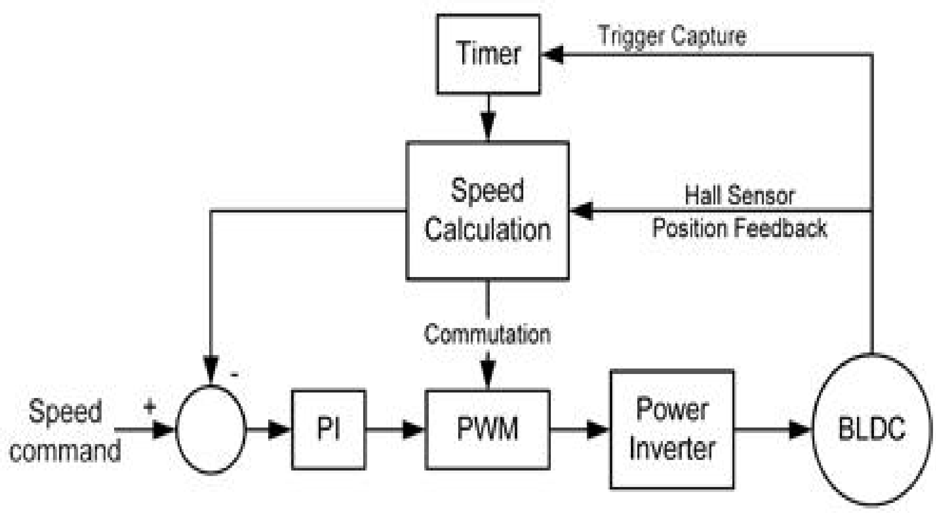


Brushless DC motor drive

Speed control method of the BLDC motor drives

- **Speed control method of the BLDC motor drives:-**
  Speed control of BLDC motor is essential for making the motor work at desired rate. Speed of a brushless dc motor can be controlled by controlling the input dc voltage / current. The higher the voltage more is the speed.
  Many different control algorithms have been used to provide control of BLDC motors. The motor voltage is controlled using a power transistor operating as a linear voltage regulator.
  This is not practical when driving higher-power motors. High-power motors must use PWM control and require a microcontroller to provide starting and control functions.
- **The control algorithm must provide three things:**
  PWM voltage to control the motor speed,
  Mechanism to commutate the motor,
  Method to estimate the rotor position using the back-EMF or Hall Sensor.

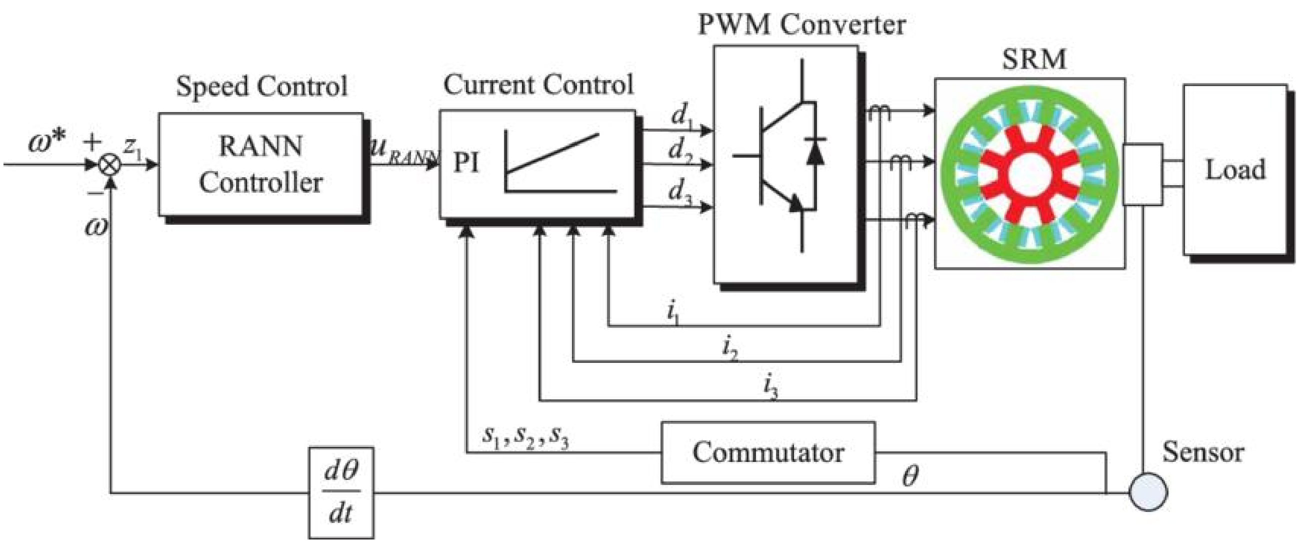
  Method to estimate the rotor position using the back-EMF or Hall Pulse-width modulation is used to apply a variable voltage to the motor windings. The effective voltage is proportional to the PWM duty cycle.
  When properly commutated, the torque-speed characteristics of the BLDC motor are identical to a dc motor. The variable voltage can be used to control the speed of the motor and the available torque.
  The commutation of the power transistors energizes the appropriate windings in the stator to provide optimum torque generation depending on the rotor position.
  In a BLDC motor, the MCU must know the position of the rotor and commutate at the appropriate time.



BLDC Layout

Basic structure of SRM drives

The switched reluctance motor (SRM) is a type of stepper motor, an electric motor that runs by reluctance torque. Unlike common DC motor types, power is delivered to windings in the stator (case) rather than the rotor.
This greatly simplifies mechanical design as power does not have to be delivered to a moving part, but it complicates the electrical design as some sort of switching system needs to be used to deliver power to the different windings.
Electronic devices can precisely time switch, facilitating SRM configurations. Its main drawback is torque ripple. Controller technology that limits torque ripple at low speeds has been demonstrated.
The SRM has wound field coils as in a DC motor for the stator windings. The rotor however has no magnets or coils attached. It is a solid salient-pole rotor (having projected magnetic poles) made of soft magnetic material (often laminated steel).
When power is applied to the stator windings, the rotor's magnetic reluctance creates a force that attempts to align the rotor pole with the nearest stator pole. In order to maintain rotation, an electronic control system switches on the windings of successive stator poles in sequence so that the magnetic field of the stator "leads" the rotor pole, pulling it forward.
Rather than using a mechanical commutator to switch the winding current as in traditional motors, the switched-reluctance motor uses an electronic position sensor to determine the angle of the rotor shaft and solid state electronics to switch the stator windings, which enables dynamic control of pulse timing and shaping.
This differs from the apparently similar induction motor that also energizes windings in a rotating phased sequence. In an SRM the rotor magnetization is static (a salient 'North' pole remains so as the motor rotates) while an induction motor has slip and rotates at slightly less than synchronous speed. SRM's absence of slip makes it possible to know the rotor position exactly, allowing the motor to be stepped arbitrarily slowly.



Block diagram of SRM drive system