1. Why adjustable speed drives are preferred over a fixed speed motor?
   The common reasons for preferring an adjustable speed drives over a fixed speed motor are: Energy saving e.g. Fan or pump flow process, Velocity and position control e.g. Electric train, portable tools, washing machine, Amelioration of transients: Starting and stopping of motors produce sudden transients. It can be smoothened using adjustable speed drives.

2. What is the structure of an adjustable speed drive system?
   The general structure of a motion control system or drive consists of the following elements: The load, the motor, the power electronic converter; and the control.

3. Write briefly about the construction and types of a Brushless DC machines.
   1) Brushless PM machines are constructed with the electric winding on the stator and PMs on the rotor. There are several conventional PM machine configurations and other more novel concepts conceived in recent years to improve performance. 2) The configuration of a PM machine and the relationship of the rotor to the stator determine the geometry and the shape of the rotating magnetic field. PM machines in which the magnetic flux travels in the radial direction are classified as radial-flux machines. 3) They are cylindrical in shape, and the rotor is usually located inside the stator but can also be placed outside the stator. PM machines in which the magnetic flux travels in the axial direction are classified as axial-gap machines. They can have multiple disk or pancake-shaped rotors and stators. The stator-rotor-stator configuration is typical.

4. What are the advantages of PM machine?
   1) In general, PM machines have a higher efficiency as a result of the passive, PM-based field excitation. PM machines have the highest power density compared with other types of electric machines, which implies that they are lighter and occupy less space for a given power rating. 2) The amount of magnet material that is required for a given power rating is a key cost consideration. The cost of magnet material is high compared with the cost of the other materials used in electric motors, and design attributes that minimize the required amount of magnet material are important considerations in motor selection. 3) The stators of PM machines are generally fabricated in the same manner as induction machine stators; however, modifications are sometimes necessary, such as the design of a stator lamination to accommodate high flux density.
5. What are the types of PM machines?
   1. Interior PM Machine and
   2. Surface mounted PM machine.

6. What are the differences between mechanical and electronic commutator? (Dec 13, Dec 2016)

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</tr>
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<td>5. No sliding contacts.</td>
</tr>
</tbody>
</table>

7. What is meant by permeance coefficient? (June 14)

The line drawn from the origin through the operating point is called load line and absolute value of its slope normalized to $\mu_0$ is called permeance coefficient.

Permeance coefficient = $\frac{\mu_{\text{rec}}(1 + P_{rl} R_g)}{(P_{mo} R_g)}$ where $\mu_{\text{rec}}$ = relative recoil permeability, $R_g$ = air gap reluctance, $P_{mo}$ = internal leakage permeance, $P_{rl}$ = normalized rotor leakage permeance.

8. Discuss briefly about the types of Permanent Magnets used in electrical machines.

**PM strength and other key properties**: The various types of PMs include the following:

- **Alnico** — a family of magnets made from aluminum, nickel, and cobalt characterized by excellent temperature stability, high residual induction, and enough energy for a number of industrial and commercial applications.
- **Ceramic** — a hard, low-cost ferrite made of barium and strontium ferrite with excellent stability. Ceramic magnets tend to be brittle, hard, and resistant to corrosion.

9. What is commutation? (June 13)

Because of hetropolar magnetic field in the air gap of DC machine the emf induced in the armature conductors is alternating in nature. This emf available across brushes as unidirectional emf because of commutator and brushes arrangement. It provides less spark, easy to control, less maintenance, more efficient, small in size (compact).
10. Draw the magnetic equivalent circuit of PMBLDC motor. (Dec 13)

![Magnetic equivalent circuit]

11. Compare brushless DC motor with P.M. commutator motor.

<table>
<thead>
<tr>
<th>Brushless DC motor</th>
<th>P.M. Commutator motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No Brushes. Maintenance problems (RFI, sparking, ignition and fire accidents) eliminated.</td>
<td>1. Commutator based DC machines need carbon brushes, so sparking and wear and tear is unavoidable.</td>
</tr>
<tr>
<td>2. More cross sectional available for armature windings. Conduction of heat through the frame is improved.</td>
<td>2. Armature winding is inside and the magnet is on the stator outside.</td>
</tr>
<tr>
<td>3. Increase in electric loading is possible, providing a greater specific torque. Higher efficiency.</td>
<td>3. Efficiency less.</td>
</tr>
<tr>
<td>4. Space saving, higher speed possible, with reduced inertia.</td>
<td>4. Commutator restricts speed.</td>
</tr>
<tr>
<td>5. Maximum speed limited by retention of magnet against centrifugal force.</td>
<td>5. Magnet is on the stator. No problem.</td>
</tr>
<tr>
<td>6. Shaft position sensor is a must.</td>
<td>6. Not mandatory.</td>
</tr>
<tr>
<td>7. Complex electronics for controller.</td>
<td>7. Simple</td>
</tr>
</tbody>
</table>

12. Give the emf and torque equations of the square wave BLDC motor.

The emf equation is given by \( E = k \phi \omega \) and the torque equation is given by \( T = k \phi I \) where \( k \) is the armature constant depending on the number of turns in series per phase in the armature winding, \( \omega \) is rotor speed in rad / sec and \( \phi \) is the flux (mainly contributed by the Permanent Magnet on the rotor). \( I \) is the load current.
13. What is meant by demagnetization in PM-BLDC motor. (Dec 14)
   In the absence of externally applies ampere turn, the magnets operating point is at the intersection of demagnetization curve and the load line.

![Demagnetization curve]

14. Write the principle of operation of PM-BLDC motor? (Dec 14)
   When a D.C supply is switched on to the motor the armature winding draws a current. The current distributes with the stator armature winding depends upon rotor position and the devices turned on. As per Faraday’s law of electromagnetic induction a emf is dynamically induced in the armature conductors. This back emf as per Lenz law opposes the cause. As a result developed torque reduces. Finally the rotor attain the steady speed.

15. Compare 120 degree and 180 degree operation of BLDC motor.
   The 180 degree magnetic arc motor uses 120 degree mode of inverter operation. The motor with 120 degree magnetic arc uses 180 degree mode of inverter operation. In 180 degree mode of inverter has 1.5 times copper losses but produce same torque with only 2/3 of magnetic material. Motor operation is less efficient.

   Self inductance is given by  \( L_g = \frac{(\psi/i)}{(\pi \mu_0 N^2 l_r l_1)}/(2g'') \) where \( g'' = g' + l_m/\mu_{rec} \), \( g' = K_c g \), \( N \) = Number of conductors in the slot, \( I = \) current, \( l_m = \) magnet length in radial direction, \( g' = \) air gap, \( g'' = \) air gap including radial thickness of the magnet, \( \mu_{rec} = \) relative recoil permeability, Mutual inductance is given by \( M_g = -(1/3)L_g \).

17. What are the types of sensors used with PMBLDC motors?
   Hall effect sensors are most commonly used for speed, position sensing with PMBLDC motors. Optical Disc based sensors are also used. Presently rotor position sensors are avoided by using alternative methods called as Sensorless control methods, which uses terminal emf measurement, third harmonic voltage measurement, flux estimation and neuro – fuzzy techniques etc.
18. Write the dynamic equations of the PMBLDC motor.

The dynamic model equations of PMBLDC motor is given by
\[
\begin{align*}
\frac{di_a}{dt} &= \frac{(v_{an} - Ri_a - e_a(\theta))}{L} \\
\frac{di_b}{dt} &= \frac{(v_{bn} - Ri_b - e_b(\theta))}{L} \\
\frac{di_c}{dt} &= \frac{(v_{cn} - Ri_c - e_c(\theta))}{L} \\
\frac{d\omega}{dt} &= \frac{[T_e - T_l - B\omega]}{J} \\
\frac{d\theta}{dt} &= \frac{P\omega}{2}
\end{align*}
\]

where the Torque developed is given by
\[T_e = (e(\theta)i_a + e_a(\theta)i_b + e_a(\theta)i_c)/\omega, T_L = \text{Load torque applied is the coefficient of friction and } J \text{ is the moment of inertia.}\]

19. What are the relative merits and demerits of brush less DC motor drives? (Dec 2016)

**Merits**: Commutator less motor, Specified electrical loading is better, Heat can be easily dissipated, No sparking takes place due to brush, Source of EMI is avoided.

**Demerits**: Above 10 kW, the cost of magnet is increase, Due to centrifugal force the magnet may come out.

20. How the direction of rotation is reversed in case of PMBLDC motor

The direction of rotation can be reversed by reversing the logic sequences in PMBLDC motor

21. What are the difference between conventional DC motor and PMBLDC motor? (Dec 12)

<table>
<thead>
<tr>
<th>DC</th>
<th>PMBLDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brushes are present.</td>
<td>Brushes are not present.</td>
</tr>
<tr>
<td>Sparking may occur due to brush.</td>
<td>Sparking will not occur as brush is not present.</td>
</tr>
<tr>
<td>Brush tend to produce RF1.</td>
<td>RF1 problem does not occur.</td>
</tr>
<tr>
<td>There is a need for brush maintenance.</td>
<td>No need of brush maintenance.</td>
</tr>
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22. What are the various kinds of permanent magnets? (June 14)

There are basically three different types of permanent magnets which are used in small DC motors Alnico magnets, Ferrite or ceramic magnet, and Rare - earth magnet (samarium – cobalt magnet).

23. What is meant by multiphase brushless motors? (May 12)

A multi-phase brushless motor including a stator having a plurality of drive coils each corresponding to a specific phase and a rotor having a plurality of field
magnet poles of successively alternating polarity. The stator further has a plurality of Hall generators for detecting the positions of the rotor and a speed sensor for detecting the rotational speed of the rotor.

24. Give the uses of sensors in motors. (May 12)
   It is used to identify the position of the rotor and it is also used to excite the coils in proper manner.

25. List some applications of BLPM DC motor. (Dec 15, June 2016)
   Fans, Pump drive, Traction and Hydraulic power steering, precision high speed spindle drivers for hard disk drivers etc.,.

26. Why brushless permanent magnet motor is called as electronically commutated motor? (Dec’15, June 2016)
   The switching instants of the individual transistor switches, Q1 – Q6 with respect to the trapezoidal emf wave is synchronized with the rotor. So switching the stator phases synchronously with the emf wave make the stator and rotor mmfs rotate in synchronism. Thus, the inverter acts like an electronic commutator that receives switching logical pulses from the rotor position sensor. This is why a BLDC drive is also commonly known as an electronically commutated motor (ECM).

27. How the demagnetization occurs in PMBLDC motor. (May 15)
   During the normal operation of motor, when the torque and back emf are constant, if the field flux level becomes low, then demagnetization occurs.

28. What are the classifications of BLPM dc motor? (May 15)
   1. BLPM square wave motor.
   2. BLPM sine wave motor.

29. What are the two types of BLPM SQW DC motor?
   1. 180° pole arc BLPM square wave motor.
   2. 120° pole arc BLPM square wave motor.

30. What are the ways by which demagnetization can be limited in permanent magnet?
   There are several ways to limit the demagnetization. One way is to keep the current below the maximum value and another way is by use of pole shoes to a permanent magnet to collect the flux and then transfer it to the air gap.
31. Define the energy product and maximum energy product of a permanent magnet.

The absolute values of the product of the flux density and the field intensity at each point along the demagnetization curve is called energy product. The maximum value of the energy product is called maximum energy product and this quantity is one of the strengths of the permanent magnet.

**PART B**

1. Derive the torque and EMF equations of the permanent magnet brushless DC motor. (June 14)

\[
\psi_{1\text{max}} = N_1 \int B(\theta) r_1 \, d\theta = N_1 B_r \pi r_1
\]

and the variation with \( \theta \) as the rotor rotates from 0 to 180° is given by

\[
\psi_1(\theta) = \left[ 1 - \frac{\theta}{\pi/2} \right] \psi_{1\text{max}}.
\]

The e.m.f. induced in coil \( a_1A_1 \) is given by

\[
e_1 = -\frac{d\psi_1}{dt} = -\frac{d\psi_1}{d\theta} \frac{d\theta}{dt} = -\omega \frac{d\psi_1}{d\theta}
\]

which gives

\[
e_1 = 2N_1 B_r l r_1 \omega \text{ V}.
\]

\[P = \omega T_e = 2eI.
\]

\[T_e = 4N_{ph} B_r l r_1 \bar{I} \text{ N m}.
\]
2. What are the differences between mechanical and electronic commutator? (May 12)

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Less spark, easy to control, less maintenance, more efficient, small in size (compact)

3. Sketch the structure of controller for permanent magnet brushless DC motor and explain the functions of various blocks. (Different types of power controllers (June 13, June 14, Dec 2016))

![Controller Diagram]

**Power circuit:**

It consists of six power semiconductor switching devices connected in bridge configuration across a DC supply. A suitable shunt resistance is connected in series to get the current feedback. Feedback diodes are connected across the device.

**Control circuit:**

The control circuit consists of a commutation logic unit which gets the information about the rotor shaft position and decides when switching devices should be turned on and which devices are to be turned off.

**Rotor position sensors:**
It converts the information of rotor shaft position into a suitable electrical signal. This signal is utilized to switch on and off the various semiconductor devices of electronic switching and commutation circuitry of BLPM motor.

Two popular rotor position sensors: Hall effect position sensors, Optical position sensors

**Driving circuits:**

The position sensors are kept in the stator such that they are influenced by the rotor positions. By suitably connecting the position sensors to the controller required pulses to the devices of the electronic commutator are given.

4. Explain in detail the various rotor position sensors used in permanent magnet brushless DC motor.(May 12)

A Hall effect sensor is a *transducer* that varies its output *voltage* in response to a magnetic field. Hall effect sensors are used for proximity switching, positioning, speed detection, and current sensing applications.

In its simplest form, the sensor operates as an *analog* transducer, directly returning a voltage. With a known magnetic field, its distance from the Hall plate can be determined. Using groups of sensors, the relative position of the magnet can be deduced. *Electricity* carried through a conductor will produce a magnetic field that varies with current, and a Hall sensor can be used to measure the current without interrupting the circuit. Typically, the sensor is integrated with a wound core or permanent magnet that surrounds the conductor to be measured.

Frequently, a Hall sensor is combined with circuitry that allows the device to act in a digital (on/off) mode, and may be called a *switch* in this configuration. Commonly seen in industrial applications such as the pictured *pneumatic cylinder*, they are also used in consumer equipment; for example some *computer printers* use them to detect missing paper and open covers. When high reliability is required, they are used in *keyboards*.

An optical sensor is a device that converts light rays into electronic signals. Similar to a *photoresistor*, it measures the physical quantity of light and translates it into a form read by the instrument. Usually, the optical sensor is part of a larger system integrating a measuring device, a source of light and the sensor itself. This is generally connected to an electrical trigger, which reacts to a change in the signal within the light sensor.
One of the features of an optical sensor is its ability to measure the changes from one or more light beams. This change is most often based around alterations to the intensity of the light. When a phase change occurs, the light sensor acts as a photoelectric trigger, either increasing or decreasing the electrical output, depending on the type of sensor. Optical sensors can work either on the single point method or through a distribution of points. With the single point method, a sole phase change is needed to activate the sensor. In terms of the distribution concept, the sensor is reactive along a long series of sensors or single fiber-optic array.

5. Sketch torque – speed characteristics of a permanent magnet brushless DC motor. (Dec 13, June 2016)

6.a. Explain in detail the magnetic circuit analysis of brushless DC motor on open circuit. (June 13)
Permeance coefficient \( \text{PC} = \mu_{\text{rec}} \left[ \frac{(1 + P_m R_g)}{(P_{\text{mn}} R_g)} \right] \)

b. What are the advantages of BLPM DC motor over conventional DC motor.
Brushless DC motors offer several advantages over conventional DC motors, including high torque to weight ratio, more torque per watt (increased efficiency), increased reliability, reduced noise, longer lifetime (no brush and commutator erosion), elimination of ionizing sparks from the commutator, and overall reduction of electromagnetic interference (EMI). With no windings on the rotor, they are not subjected to centrifugal forces, and because the windings are supported by the housing, they can be cooled by
conduction, requiring no airflow inside the motor for cooling. This in turn means that the motor's internals can be entirely enclosed and protected from dirt or other foreign matter.

7. Explain square wave permanent magnet brushless dc motor drives. (May 12, Dec 13)

![Brushless Motor Diagram]

**Brushless Motors**

Brushless motors such as permanent magnet and switched reluctance motors depend on electronic drive systems which produce rotating magnetic fields to pull the rotors around. The advent of new magnetic materials such as alloys of Neodymium with high levels of magnetic saturation and high coercivity, able to set up and maintain high magnetic fields, have enabled a range of innovative brushless motor designs by eliminating one set of the traditional motor's windings, either the stator or the rotor. The implementation of many of these brushless designs however has only been made possible by the availability of inexpensive high power switching semiconductors which have enabled radical new solutions to the commutation problem and much simpler mechanical designs.

**Permanent Magnet Motors**

By using permanent magnets, rotor windings and mechanical commutation can be eliminated simplifying manufacture, reducing costs and improving reliability. At the same time efficiency is improved by the elimination of the need for excitation of the rotor windings and by avoiding the frictional losses associated with the commutator.

**Brushless versions of both DC and AC motors are available.**

**Brushless DC (BLDC) Motors**

The speed and torque characteristics of brushless DC motors are very similar to a shunt wound "brushed" (field energised) DC motor with constant excitation. As with brushed motors the rotating magnets passing the stator poles create a back EMF in the stator windings. When the motor is fed with a three phase stepped waveform with positive and negative going pulses of 120 degrees duration, the back EMF or flux wave will be trapezoidal in shape. (See diagram below)

**Synchronous Operation**
Brushless DC motors are not strictly DC motors. They use a pulsed DC fed to the stator field windings to create a rotating magnetic field and they operate at synchronous speed. Although they don't use mechanical commutators they do however need **electronic commutation** to provide the rotating field which adds somewhat to their complexity.

**Rotating Field and Speed Control**

In the diagram below, pole pair A is first fed with a DC pulse which magnetises pole A1 as a south pole and A2 as a north pole drawing the magnet into its initial position. As the magnet passes the first magnetised pole pair, in this case poles A1 and A2, the current to pole pair A is switched off and the next pole pair B is fed with a similar DC pulse causing pole B1 to be magnetised as a south pole and B2 to be a north pole. The magnet will then rotate clockwise to align itself with pole pair B. By pulsing the stator pole pairs in sequence the magnet will continue to rotate clockwise to keep itself aligned with the energised pole pair. In practice the poles are fed with a polyphase stepped waveform to create the smooth rotating field.

A six step inverter is used to generate the three phase supply and the electronic commutation between the three pairs of stator coils needed to provide the rotating field. Only two out of three pole pairs are energised at any one time. This also means that only two of the six inverter switches are conducting at any one time. See the Motor Control diagram below.

The speed of rotation is controlled by the pulse frequency and the torque by the pulse current. In practice the system needs some fairly complex electronics to provide the electronic commutation.

**Position Sensing and Speed Control**

The inverter current pulses are triggered in a closed loop system by a signal which represents the instantaneous angular position of the rotor. The frequency of the power supply is thus controlled by the motor speed.
Rotor position can be determined by a Hall Effect device (or devices), embedded in the stator, which provide an electrical signal representing the magnetic field strength. The amplitude of this signal changes as the magnetic rotor poles pass over the sensor. Other sensing methods are possible including shaft encoders and also sensing the zero crossing points of currents generated in the unenergised phase windings. This latter method is known as "sensorless" position monitoring. The diagram below shows the system for controlling the voltage and speed with the associated current and voltage waveforms superimposed on the circuits.

![Brushless DC Motor Control Diagram](image)

Note that though the magnetising current pulses are in the form of a stepped square wave, the back EMF is in the form of a trapezoidal wave due to the transition periods as the rotor magnet poles approach and diverge from the stator coils when the rotor magnet is only partially aligned with the stator magnets. Power management is usually by means of a pulse width modulated controller (PWM) on the input supply which provides a variable DC voltage to the inverter.

**Mechanical Construction**

No current is supplied to, nor induced, in the rotors which are constructed from permanent magnets or iron and which are dragged around by the rotating field. With no currents in the rotors these machines have no rotor $I^2R$ losses. Without the mechanical commutator and rotor windings, the motors have low rotor inertia allowing much higher speeds to be achieved and with the elimination of this high current mechanical switch, the source of sparking and RFI is also eliminated. The stator windings are, easy to manufacture and install, bobbin windings.
Since all the heat generating circuits are in the stator, heat dissipation is easier to control and higher currents and motor powers can also be achieved.
Some brushless motors are supplied with the control electronics incorporated into the motor body.

**The Magnets**
Depending on motor size, the magnets can be arranged as a full-ring magnet, as spokes, or embedded in the rotor core.
The preferred magnets are manufactured from the rare earth element Neodymium in an alloy with Iron and Boron to produce the strongest permanent magnets currently available. (Most of the world's known supplies of Neodymium are found in China)
One drawback of permanent magnet machines is that the magnets are susceptible to high temperature complications and loss of magnetisation above the Curie temperature. Permanent magnet motors are inherently more efficient than wound rotor machines since they don't have conduction losses associated with rotor currents.

**Synchronous Operation**
The motor speed is directly proportional to the pulse frequency of the inverter. If the supply frequency is fixed and the motor operates in open loop mode then it will run at a fixed synchronous speed. Changing the supply frequency will change the motor speed accordingly.

**Variable Speed Operation**
The brushless DC motor can be made to emulate the characteristics of its brushed cousin in which the speed is controlled by changing the applied voltage, rather than by changing the supply frequency. The supply frequency still changes but it does so as the result of the changing motor speed not the cause.
Using this configuration, increasing the voltage of the pulsed DC supply from the inverter will increase the current through the stator windings thus increasing the force on the rotor poles causing the motor to speed up just as in a brushed DC motor. Although the motor runs at variable speed, it is still a synchronous application since the feedback loop triggers the inverter pulses in synchronism with the motor rotation thus forcing the supply frequency to follow the motor speed. This also means that the motor will be self starting.

**Characteristics**
High efficiency and power density.
No field windings needed to produce the flux as in induction and brushed motors (this is called the "excitation penalty") and hence no conduction losses.
More torque per Amp due to lower losses.
Compact, light weight designs. The magnets are generally smaller than the windings needed to provide the equivalent field.
Lower costs due to the elimination of the field windings.
Speeds up to 100,000 RPM possible whereas the speed in brushed motors is limited by centrifugal forces on the rotor windings and the commutator.
Torque is proportional to speed as in a brushed DC motor.
Trapezoidal wave form.
No commutator, hence low maintenance and long life.
The abrupt current transitions give rise to similarly abrupt torque transitions as well as magnetostriction in the magnetic materials resulting in cogging as well as acoustic noise which may be objectionable in some applications.

Applications
Permanent magnet motors are ideal for applications up to about 5 kW. Above 5kW, the magnets needed for higher power applications become progressively more expensive reducing the economic advantage of the design. The magnets in brushless motors are also vulnerable to demagnetisation by the high fields and high temperatures used in high power applications. Inverter switching losses also become significant at higher power levels. Brushed and induction motors do not suffer from these problems.
Permanent magnet motors are thus suitable for traction applications from low power wheel chairs and golf buggies for some higher power automotive uses. Brushless DC motors are preferred over brushed motors for powering electric bikes because they don't have the friction associated with the commutator brushes in the brushed version.

8. Analyse the operation of electronic commutator of PMBLDC motor with neat diagram. (May 15)
electronic commutators

ELECTRONICOMMUTATOR:
In electronic commutator, 6switching devices are employed. Here the winding may be connected either star or delta connections. Therefore, the winding should have 3 tappings. The power semiconductor switches can be on and off by information get it from the rotor position sensor signals. Interpoles windings are employed to have sparkles commutations. By suitably operating the switching devices better performance can be achieved.
9. A PMBLDC motor has torque constant 0.12 Nm/A referred to DC supply. Find the motors no load speed when connected to 48V DC supply. Find the stall current and stall torque if armature resistance is 0.15Ω/phase and drop in controller transistor is 2V. (Dec 12, Dec 13, June 2016)

Given data:
\( K_m = 0.1 \text{ Nm/A, } V = 48\text{V} \)

Solution:
\[
\omega_{no} = \frac{V}{K_m} = \frac{48}{0.12} = 400 \text{ rad/sec}
\]
\[
\omega_{no} = 2\pi N_o / 60
\]
\[
N_o = (480\times60) / 2\pi = 3819.71 \text{ rpm}
\]
\[
R_{ph} = 0.15\Omega
\]
\[
V_{dd} = 2V
\]

Starting current or stall current = \( I_{st} = \frac{V - V_{dd}}{2R_{ph}} = \frac{48 - 2}{2 \times 0.15} = 153.33\text{A} \)

Starting torque or Stall torque = \( T_{st} = K_m I_{st} = 0.12 \times 153.33 = 18.4 \text{ N-m} \)

10. A permanent magnet DC commutator motor has a no load speed of 6000 rpm when connected to a 120V dc supply. The armature resistance is 2.5Ω and rotational and iron losses may be neglected. Determine the speed when the supply voltage is 60V and the torque is 0.5 Nm. (Dec 12, Dec 13, Dec 2016)
\[ V = 120V \]
\[ R_a = 2.5\Omega \]
\[ T = 0.5N\cdot m \]
\[ E = K_m\omega_m \]
\[ V = K_m\omega_{mo} \]
\[ T = K_m I \]
\[ K_m = \frac{V}{\omega_{mo}} = \frac{120}{(2\pi N / 60)} = 0.19V/rad/sec \]
\[ I = \frac{T}{K_m} = (5/0.19) = 2.617A \]
\[ E = V - I_a R_a = (60 - 2.617 \times 2.5) = 53.45V \]
\[ \omega_m = \frac{E}{K_m} = (53.45/0.19) = 281.34rad/sec \]
\[ \omega_m = \frac{2\pi N}{60} \]
\[ N = \frac{281.34 \times 60}{2\pi} = 2686.6\text{rpm} \]
\[ Ra = 2.5\Omega \]

11. Illustrate in detail, the operation of PMBLDC motor with 180° magnet arcs and 120° square wave phase currents. (Dec 12)

(a) BLDC motor with 180° magnet arcs and 120° square-wave phase currents.
(b) BLDC motor with 120° magnet arcs and 180° square-wave phase currents.
The 180° magnet arcs were assumed to produce a rectangular distribution of flux density in the airgap. The phase windings are assumed to be star connected. The 120° pole arc motor is less efficient than 180° pole arcs motor, the phase current waveforms of delta connected converters is shown above. In this machine, the effect of fringing flux, slotting and commutation overlap combine to produce torque ripple.

12. Discuss the hysteresis type current regulation of PMBLDC motor with neat diagram. (May 15)
13. Discuss the construction and principle of operation of a Permanent magnet dc motor. (May 2016, Dec 2016)
47. CONSTRUCTIONAL FEATURES OF BLPM MOTORS

The BLPMDC motors can be constructed in several different physical configurations. Main two types are,

1. Conventional [Also known as in-runner] configuration

2. Out runner configuration

In the conventional in runner configuration, the permanent magnets are mounted on the rotor. The stator armature windings surround the core.

In the out runner configuration, the radial relationship between the coils and magnets is reversed. (i.e.,) the stator coils form the center (core) of the motor, while the permanent magnets spin on an over-hanging rotor, which surrounds the core.

Here, let us study about the conventional (in runner) configuration of BLPM motor. The following Fig.4.10 shows the arrangement of permanent magnet in the rotor. As this is an ‘in runner’ configuration, the stator surrounds the rotor.
Stator

The stator of the BLPMDC motor is made up of silicon steel stampings with slots in its interior surface. These slots accommodate either a closed or opened distributed armature winding. Usually it is closed one. This winding is to be wound for a specified (even) number of poles and the winding is suitably connected to a d.c. supply through a power electronic switching circuitry [named as electronic commutator].

Rotor

The rotor is made of forged steel. The rotor accommodates permanent magnet. The number of poles of the rotor is same as that of the stator. The rotor shaft carries a rotor position sensor. This position sensor provides information about the position of the shaft at any instant to the controller which sends suitable signals to the electronic commutator.

Armature winding

For normal electronic commutator, usually six switching devices are employed. Then the winding should have three tappings.

There are also two electrical configurations having to do with how the wires from the windings are connected to each other [not their physical shape or location]. The delta configuration, as already known, connects the three windings to each other [series circuit] in a triangle-like circuit, and power is applied at each of the connections.

The wye (“Y”-shaped) configuration, called a star winding, connects all of the windings to a central point [parallel circuit] and power is applied to the remaining end of each winding.
The BLDC motor with windings in delta configuration gives low torque at low rpm, but can give higher ranges of rpm. Wye configuration gives high torque at low rpm, but the motor can not be operated in higher rpm ranges.

Fig. 4.11. Star (WYE–Y) connected stator armature winding

Fig. 4.12. Delta (Δ) connected stator armature winding

Although the efficiency is greatly affected by the motor’s construction, the wye winding is normally more efficient. Delta-connected windings can allow high-frequency parasitic electrical currents to circulate entirely within the motor. A wye-connected winding does not contain a closed loop in which parasitic currents can flow, preventing such losses.
From the controller point of view, the two types of windings are treated exactly the same, although some less expensive controllers are needed to read the voltage from common centre of the wye winding.

The circuits shown in Fig.4.11 and 4.12 are same as that of the 3 phase bridge inverter, but the switching of power devices in the two circuits are influenced by rotor position sensor.

Hence, like other machines, the BLPMDC motor has stator and rotor. The stator carries the armature and the rotor carries the permanent magnet. So, the permanent magnets rotate and armature remains static. In all BLDC motors, the stator-armature coils are stationary.

4.8. PRINCIPLE OF OPERATION OF PMBLDC MOTOR

The brushless permanent magnet DC motor is a synchronous electric motor which is powered by DC supply and it has an electronically controlled commutation system instead of a mechanical commutation system based on brushes. In these motors, the current and torque, voltage and rpm are linearly related.

In order to study the principle of operation of permanent magnet brushless DC motor, let us analysis the starting and dynamic equilibrium conditions which will enable to understand the process of electromechanical power transfer in PMBLDC motor.

4.8.1. Starting

When d.c. supply is given to the motor, the armature winding draws a current. The current distribution within the stator armature winding depends upon the rotor position and the devices turned on. This current sets up an mmf which is perpendicular to the main mmf set up by the permanent magnet field. According to Fleming’s left hand rule, a force is experienced by the armature conductors. As it is in the stator, a reactive force develops a torque in the rotor. If this developed torque is more than the load torque and frictional torque, the motor starts rotating. It is a self starting motor.
4.8.2. Dynamic equilibrium [steady-state]

As the motor picks up speed, there exists a relative velocity between the stationary armature conductors & the rotating rotor. Therefore, according to Faraday’s law of electromagnetic induction, an emf is dynamically induced in the armature conductors. As per Len’z law, this emf opposes the cause [armature current (i.e., the current drawn from the mains)]. As the supply voltage is maintained constant, the current drawn is reduced. Thus the developed torque is reduced.

When the developed torque is exactly equal to the opposing load torque, the rotor attains a steady state speed. Thus the motor attains a steady state condition.

4.8.3. Electro mechanical power transfer

When the load torque is increased, the speed tends to fall. Therefore it reduces the back emf induced in the armature. Then the current drawn from the mains increased. Therefore more torque is developed. The motor attains the new equilibrium condition, when the developed torque is equal to the new load torque.

Now the power drawn from the supply \((V \times I)\) equals the mechanical power developed \((P = \frac{2\pi NT}{60} = \omega T)\) and the power loss in the machine and in the switching circuitry. Vice-versa takes place when the load torque \((T_L)\) is reduced. Thus the electrical to mechanical power transfer takes place.\footnote{10}