EE8005 - Special electrical Machines

Unit - 3 permanent magnet Brushless DC motors

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① i) A BLPM motor has a noload speed of 6000 rpm when connected to 120 V dc supply. The armature resistance is 2 Ω. Rotational and iron losses may be neglected. Determine the speed when the supply voltage is 60V and the torque is 0.5 N-m.

Soln:-

$V_s = 120\,V$, $T = 0.5\,N\text{-}m$, $R_a = 2\,\Omega$, $N_0 = 6000\,rpm$

Speed in rad/sec $\omega_{m0} = \dfrac{6000 \times 2\pi}{60} = 628$ rad/sec

In BLPM dc motor $E = K_e\,\omega_m$

Under noload $V = K_e\,\omega_{m0}$

$120 = K_e \times 628$

$K_e = \dfrac{120}{628} = 0.19$ volts/rad/sec

Under no-load condition, torque = 0.5 N-m

ie $K_t\,I = 0.5$

Since $K_t = K_e$, $K_t\,I = K_e\,I$

$0.19\,I = 0.5$

$I = \dfrac{0.5}{0.19} = 2.63$ Amps

Drop in voltage $E = V - I R_a = 60 - 2.63(2)$

$= 54.74$ Volts

but $E = K_e \omega_m$

$54.74 = 0.19\ \omega_m$

$\omega_m = \frac{54.74}{0.19} = 288$ rad/sec

W.K.T $\omega_m = \frac{2\pi N}{60}$

$\therefore$ Speed $N = \frac{60}{2\pi} \times \omega_m = 2750$ rpm.

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(1) ii) Explain the performance characteristics of PM brushless dc motors with their relevant diagrams.

Torque speed characteristics:

For ideal case, $V = E + RI$

$\frac{\omega_m}{\omega_{mo}} = 1 - \frac{T}{T_{stg}}$ but $\omega_{mo} = V/k_e$ rad/sec

Stall torque $T_o = k_e I_o$ but $I_o = V/R$

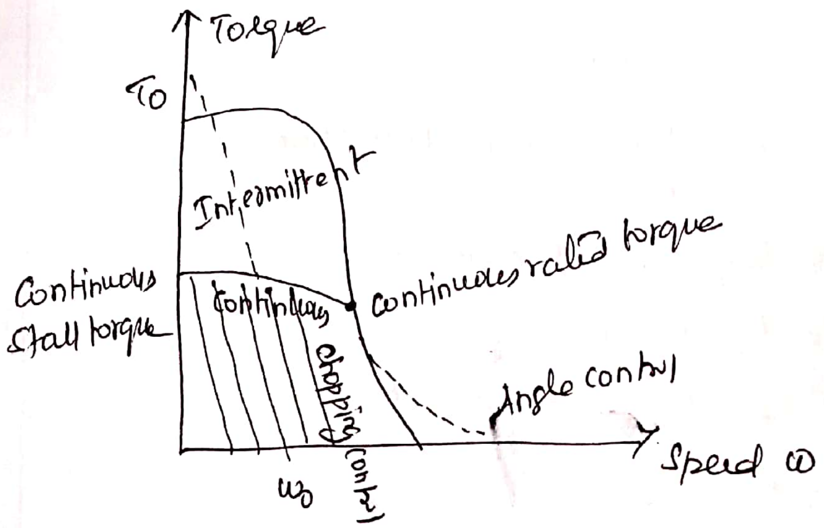

fig: Torque speed characteristics of PM BL DC motor

If phase resistance is small, the characteristics is similar to that of a dc shunt motor. The speed is controlled by the voltage V and may be varied by varying the supply voltage

The motor draws enough current to drive the torque at this speed. As the load torque is increased, the speed drops and the drop is directly proportional to the phase resistance and the torque. The voltage is usually controlled by chopping or pulse width modulation.

Here there are the boundaries of continuous and Intermittent operation. The continuous limit is determined by heat transfer and temperature rise. The intermittent limit may be determined by the maximum ratings of semiconductor devices in the controller or by the temperature rise.

In practical case,

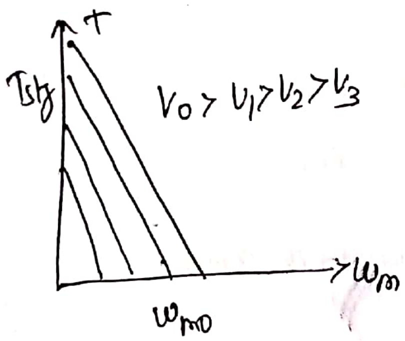

fig: T-ω_m curve

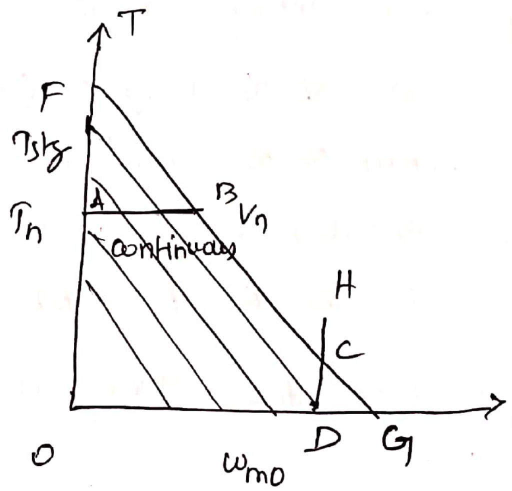

fig: permissible Torque-speed characteristics.

Constraints:

The continuous current should not exceed the maximum permissible current I_n, the torque should not exceed $T_n = K_e I_n$.

The supply voltage should not exceed its permissible limit V_n.

The speed should not exceed ω_{m0}.

Line AB → It is parallel to the x-axis and represents the maximum torque that can be developed.

Line FG → It represents T-ω_m characteristics for maximum voltage permissible V_n. This line intersects the maximum torque line at point B.

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Line DH: It is perpendicular to x axis. It represents the maximum permissible speed ω_{mn}. DH intersects the FCL line at point C.

The region OABCDO is the permissible region of operation.

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(2) i) Derive the expressions for EMF and Torque equations of PM brushless DC motor (squarewave).

EMF Equation:

Consider a BLPM square wave dc motor, let

$p \rightarrow$ No. of poles

$B_g \rightarrow$ Flux density in the airgap wb/m^2

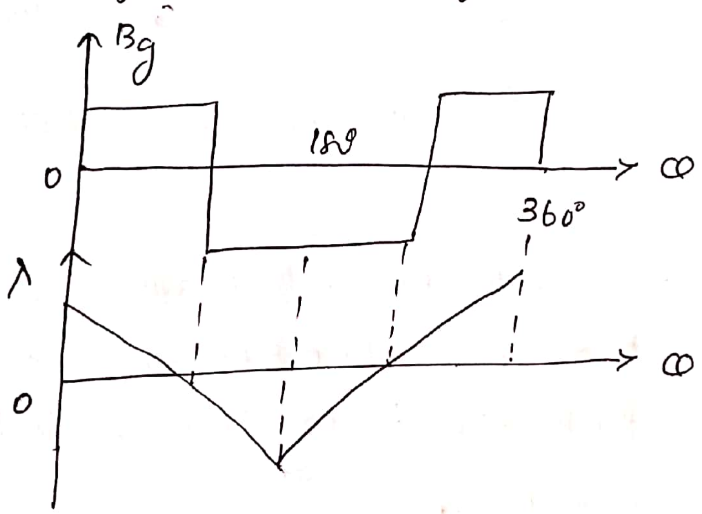
$r \rightarrow$ radius of the airgap (m)

$l \rightarrow$ Length of the armature (m)

$\omega_m \rightarrow$ Angular velocity in mech. rad/sec

$T_c \rightarrow$ Number of full pitch turns per coil

fig: Magnetic flux density distribution in the airgap



the flux enclosed by the coil $\phi_{max} = B_g \cdot \frac{2\pi r}{P} \cdot l$

at $\omega_m t = 0$, the flux linkage of the coil $\lambda_{max} = \left(B_g \cdot \frac{2\pi r}{P} \cdot l\right) T_c$

$$\lambda_{max} = 2 B_g r l T_c \pi/p \quad \text{wb-T}$$

Let the rotor rotating in counterclockwise direction and when $\omega_m t = \pi/2$ the flux enclosed by the coil $\phi = 0 \therefore \lambda = 0$

The rate of change of flux linkages of the coil $\Delta\lambda$ is

$$\frac{\Delta\lambda}{\Delta t} = \frac{\text{Final flux linkage} - \text{Initial flux linkage}}{\text{Final time} - \text{Initial time}}$$

$$= \frac{0 - 2B_g r l T_c \pi/p}{\frac{\pi}{p\omega_m} - 0}$$

$$= -2B_g r l T_c \omega_m$$

The emf induced in the coil $e_c = -\frac{d\lambda}{dt}$

$$e_c = 2B_g r l T_c \omega_m \text{ volts.}$$

Consider two coils a_1A_1 and a_2A_2 is shown in fig. Coil a_2A_2 is adjacent to a_1A_1 and is displaced by an angle 30° ie slot angle γ

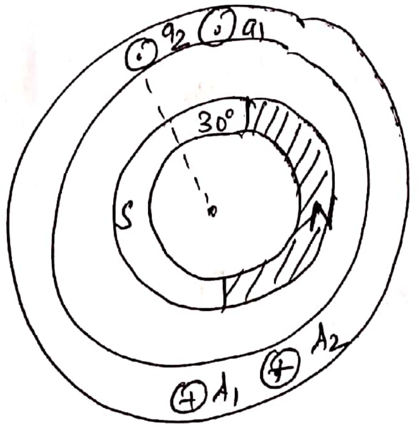


fig: motor with two coils of one phase

The magnitude of emf induced in coil a_1A_1

$$e_{c1} = 2B_g r l T_c \omega_m \text{ volts.}$$

The magnitude of emf induced in coil $a_2 A_2$ is

$$e_{c2} = 2 B_g r l T_c \omega_m \text{ volts.}$$

If the two coils are connected in series, $e = e_{c1} + e_{c2}$

$$e = 4 B_g r l T_c \omega_m \text{ Volts.}$$

If there are n_c no. of coils connected in series per phase then the emf induced /ph

$$e_{ph} = 2 B_g r l \omega_m (n_c T_c) \text{ volts}$$

where $n_c T_c = T_{ph}$ (no. of turns/ph)

$$\therefore e_{ph} = 2 B_g r l \omega_m T_{ph}$$

Torque equation:-

W.K.T $e_{ph} = 2 B_g r l \omega_m T_{ph}$

But $T_{ph} = 2 T_1$ because the two coils considered are assumed to be inseries.

Instantaneous power $P = \omega_m T_e \Rightarrow T_e = P/\omega_m$

$$P = 2 e_{ph} I$$

$$\therefore T_e = \frac{2 e_{ph} I}{\omega_m} = \frac{2 [2 B_g r l \omega_m T_{ph}] I}{\omega_m}$$

$$T_e = 4 B_g r l T_{ph} I \quad \text{N-m}$$

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(2) ii) Deduce the basic voltage equation of BLPM DC motor for no-load, starting and ON-load condition. Also draw and explain the I Vs ω_m curve.

Basic voltage equation of BLPM DC motor:

Let $V \rightarrow$ dc supply voltage, $I \rightarrow$ Armature current

$R_{ph} \rightarrow$ Resistance / phase, $e_{ph} \rightarrow$ emf induced / ph

$V_{dd} \rightarrow$ Voltage drop in the device (usually neglected)

Applied voltage $V = 2e_{ph} + 2IR_{ph} + 2V_{dd}$

neglecting V_{dd}, $V = 2IR_{ph} + 2e_{ph}$

$$V - 2e_{ph} = 2IR_{ph}$$

$$I = \frac{V - 2e_{ph}}{2R_{ph}} = \frac{V - E}{R}$$

where $E = 2e_{ph}$ and $R = 2R_{ph}$

case i) At starting condition

during starting $\omega_m = 0$, $I = I_{stg}$, $e_{ph} = 0$

$$\therefore I_{stg} = \frac{V}{R}$$

case ii) At No-loaded condition

At no load, the current is very small

$$I = I_0, \quad e_{ph} = e_{pho}, \quad \omega_m = \omega_{mo}$$

$$\therefore V = 2I_0 R_{ph} + 2e_{pho}$$

Since I_0 is negligible so that $V = 2e_{pho}$

but $e_{ph} = 2B_g r l \omega_m T_{ph}$

$$e_{pho} = 2B_g r l \omega_{mo} T_{ph}$$

$\therefore$ applied voltage $V = 4B_g r l \omega_{mo} T_{ph} = K_e \omega_{mo}$

where $K_e = 4 B_g r l T_{ph}$

no load speed (rad/sec) $\omega_{mo} = \frac{V}{K_e}$

Case iii) At ON-load condition

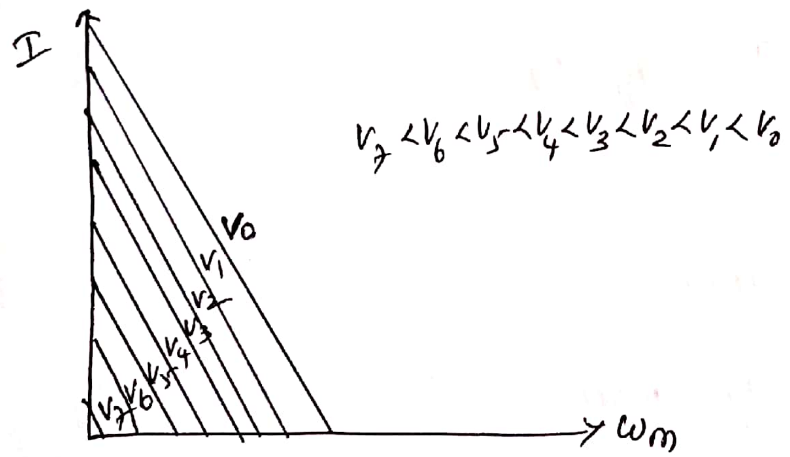
$V = 2e_{ph} + 2 I R_{ph}$

$V = 4 B_g r l \omega_m T_{ph} + 2 I R_{ph}$

$V - 2 I R_{ph} = 4 B_g r l \omega_m T_{ph}$

$$\frac{V - 4 B_g r l \omega_m T_{ph}}{2 R_{ph}} = I \Rightarrow I = \frac{V - K_e \omega_m}{2 R_{ph}}.$$

A family of curves are drawn between I & ω_m for various voltages $V_0, V_1, V_2 \ldots$ which is shown in fig.



The curves between I & ω_m are parallel lines for various voltages.

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(3) i) A PMBLDC motor has torque constant 0.12 Nm/A. Find a) no load speed when connected to 48 V dc supply. Also determine b) stall current and c) stall torque if armature resistance is 0.2 Ω/phase and drop in controller transistor is 2V.

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Given data:

$K_t = 0.12 \ Nm/A$

$V = 48$ volts

$R_a = 0.2 \ \Omega/ph$

$V_{dd} = 2V$

at no-loaded condition, $K_e = \frac{V}{\omega_{mo}}$

$\omega_{mo} = \frac{V}{K_e}$ but $K_e = K_t$

no load speed (rad/sec) $\omega_{mo} = \frac{48}{0.12} = 400$ rad/sec

No load speed (rpm) $N = \frac{60 \times \omega_{mo}}{2\pi} = 3820$ rpm.

Stall current or starting current $I_{stg} = \frac{V - \text{drop in the device}}{2 R_{ph}}$

$I_{stg} = \frac{48-2}{2(0.2)} = 115$ Amps.

Stall torque $T_{stg} = K_t \left(\frac{V - \text{drop in the device}}{2 R_{ph}} \right)$

$= \frac{0.12(48-2)}{2(0.2)}$

$T_{stg} = 13.8$ N-m

(3) ii) Sketch the structure of power controller for BLPMDC motor and explain the functions of various blocks with different modes of operation.

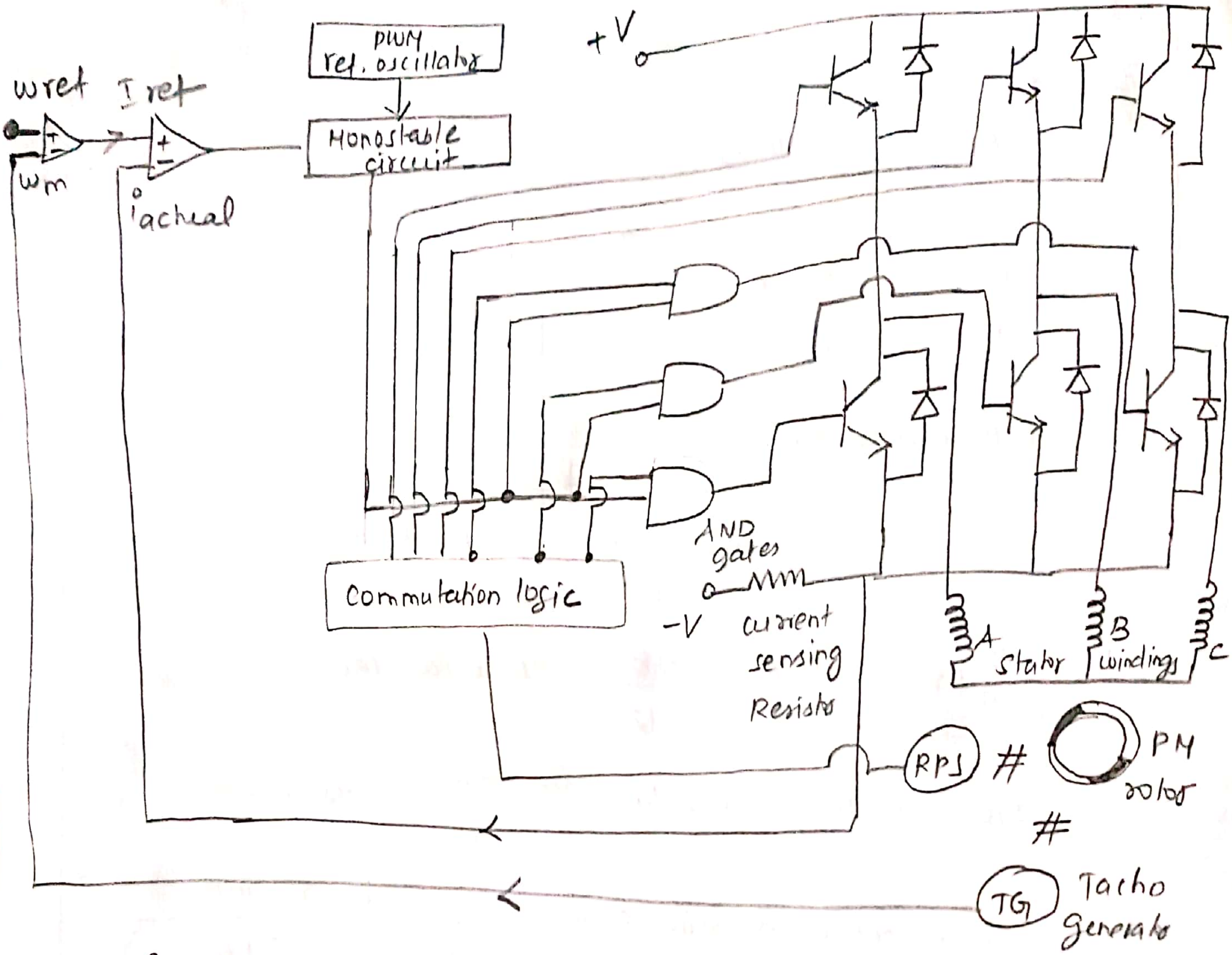

fig: power controller for BLPM squarewave DC motor.

power circuit:

It consists of 6 power switching devices that are connected in bridge configuration across the dc supply. A shunt resistance 'R' is connected in series to get the current feedback signal. Feedback diodes are connected across the main devices. The stator armature winding is assumed to be star connected. The rotor carries rotor position sensor and the shaft is coupled with tachogenerator to get the speed feedback signal.

Control circuit:

It consists of a commutation logic circuit which gets information about the rotor position and decides about which devices are to be turned ON and OFF.

Commutation logic circuit:

It provides 6 output signals. Three signals are used as the base drive for the upper leg devices. The other 3 signals are logically ANDed with high frequency pulses (PWM) which are the output from the monostable circuit. The resultant signals are used to drive the lower leg devices.

Speed comparator:

The speed comparator compares the reference speed (ω_{ref}) with the speed feedback signal (ω_m) obtained from the tachogenerator. The output of the speed comparator serves as the current reference for the current comparator.

Current comparator:

The current comparator compares the reference current I_{ref} with the actual current obtained from the current transducer. The resulting error signal is fed to the monostable circuit.

Monostable circuit:

It is excited by high frequency pulse signals. The duty cycle of the output of monostable multivibrator circuit is controlled by the error signal.

Rotor position sensor:

RPS converts the information of rotor shaft position into a suitable electrical signal. The signal from RPS is fed to the commutation logic circuit which inturn gives necessary

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Rotor position sensor:

RPS converts the information of rotor shaft position into a suitable electrical signal. The signal from RPS is fed to the commutation logic circuit which inturn gives necessary output signals in order to turn ON and OFF the various semiconductor devices of electronic switching and commutation circuitry of BLPM motor. optical position sensor and hall effect position sensor are the two types of RPS available for BLPM motors.

Function of the controller:

RPS is sensed by a hall effect sensor. These signals are decoded by commutational logic circuit to provide the firing signals for 120° conduction of each of the 3 phases.

The PWM signal is applied only to the lower leg transistors. It is not only reduce the current ripple but also avoids the need of wide band width in the level shifting circuit that feeds the upper leg transistors.

The use of AND gates of combining both the commutation signals and chopping signals.

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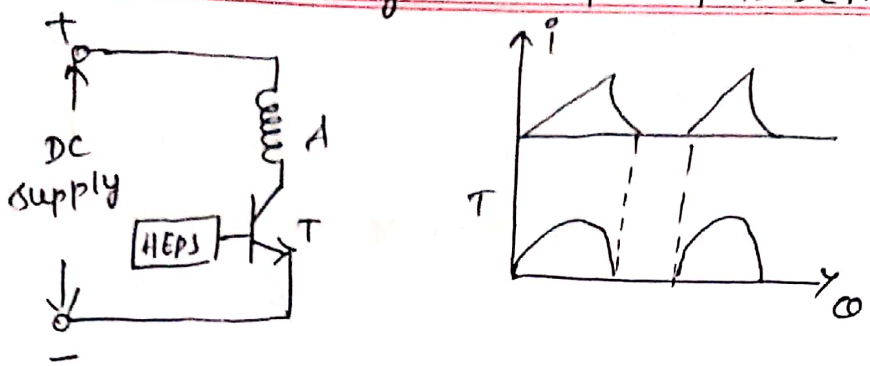
(4) Explain the various drive circuits of PMBLDC motor with relevant circuits.

The different types of drive circuits for PMBLDC motor are

1. single phase winding and one pulse PMBLDC motor
2. Single phase winding and two pulse PMBLDC motor
3. Two phase winding and two pulse BLPM DC motor
4. Three phase winding and three pulse BLPM DC motor
5. Three phase winding and 6 pulse BLPM DC motor

(1) One phase winding and one pulse PMBLDC motor:



The stator of BLPM motor with one phase winding is connected to the supply through a power semiconductor switch. When the rotor position sensor is influenced by north pole flux the stator is excited and the rotor develops a torque. When the RPS is under the influence of south pole, the transistor is in OFF state. So the rotor develops torque, whenever the RPS is under the influence of north pole.

Merit:

The circuit uses only one transistors. Hence one rotor position sensor is sufficient.

Demerits:

1. The utilization of transistor and winding are less.
2. Inertia should be such that the rotor rotates continuously.

(2) One phase winding and two pulse BLPM motor:

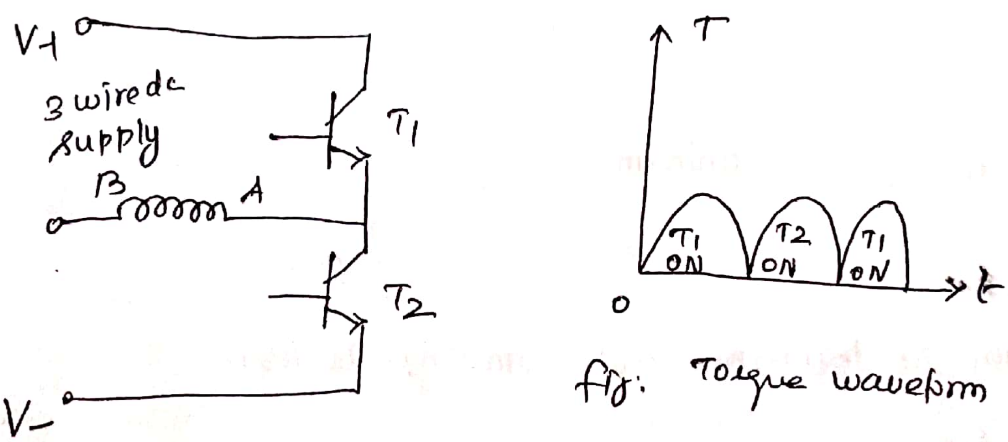


fig: Torque waveform

The stator has only one phase winding, it is connected to three wire dc supply through two semiconductor switches.

There is only one position sensor. when the position sensor is under the north pole influence T_1 is ON-state and T_2 is is OFF state. The phase winding carries current from A to B. when the position sensor is under the influence of south pole T_2 is ON and T_1 is OFF. The phase winding carries current from B to A.

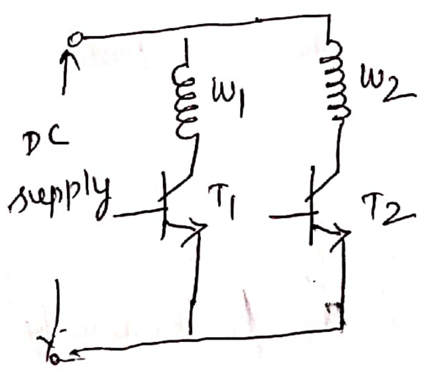
Merits:

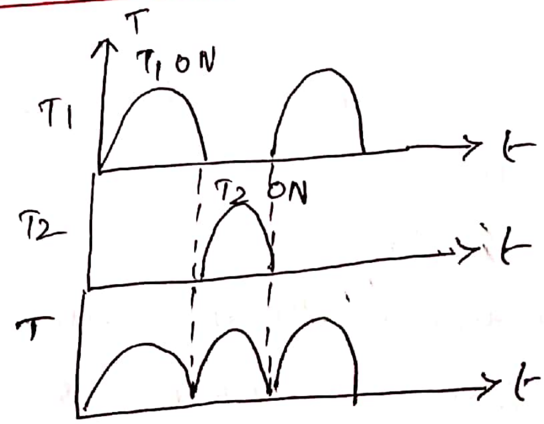
1. The winding utilization is better
2. Torque developed is more uniform.

Demerits:

1. The transistor utilization is less
2. The circuit needs a 3 wire dc supply

③ Two phase winding and two pulse BLPM motor:





The stator has two phase windings which are displaced by 180° electricals

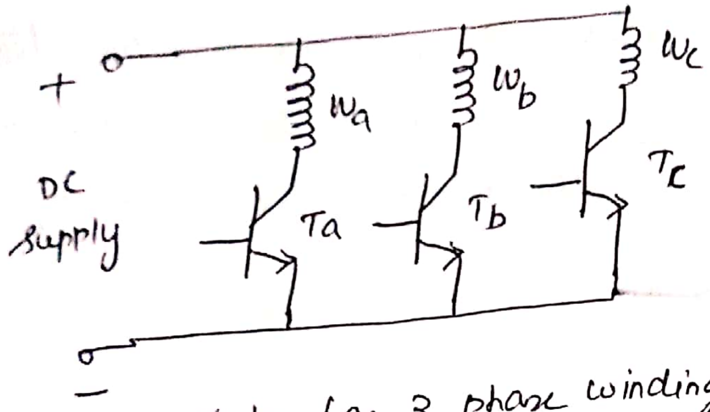
Merit:

Torque developed is uniform

Demerit:

Utilization of transistors and windings is less.

(4) 3 phase winding and 3 pulse PMBL motor:



The stator has 3 phase windings whose axis are displaced by 120° electrical apart. Each phase winding is controlled by a semiconductor switch which is operated depending upon the position of rotor. It requires three position sensors.

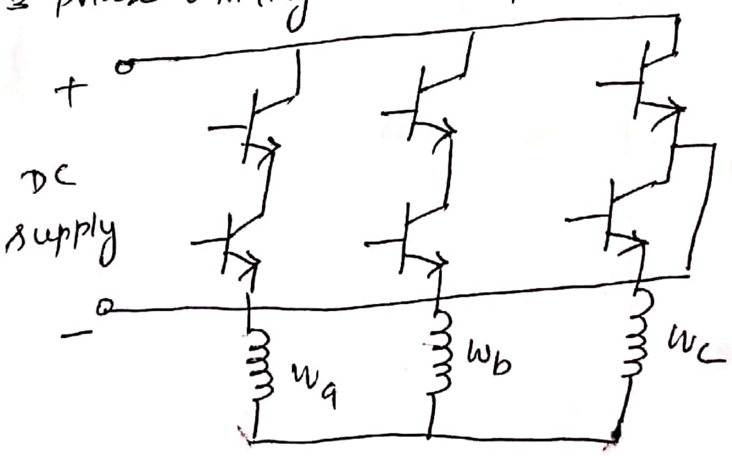
Merit:

Torque developed is better

Demerits:

1. Utilization of windings and devices are less
2. cables with RPS should be properly connected.

(5) 3 phase winding and 6 pulse BLPM motor:



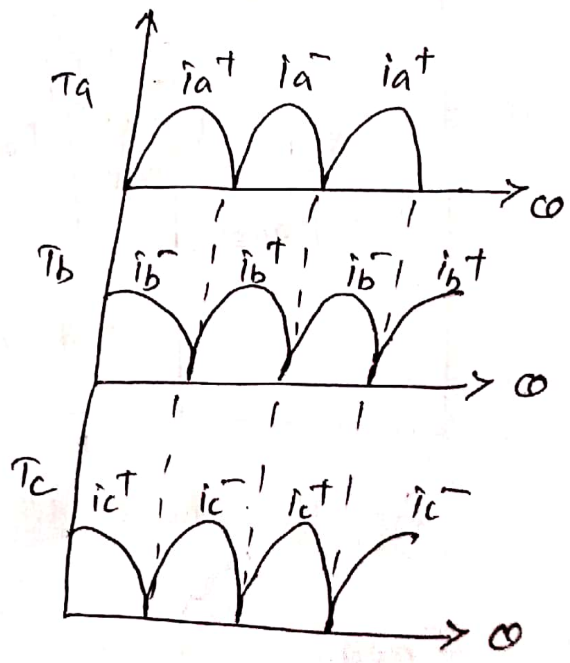


fig: Torque waveforms

This is the most commonly used circuit. It has 3 phase windings and six switching devices.

The stator windings can be either star connected or delta connected. It requires 6 position sensors. Usually 120° or 180° conduction is adopted. This circuit produces unidirectional torque in all the 3 phase winding excitations.

Merits:

1. The utilization of winding is better.
2. Torque and current ripple components are less.

Demerits:

1. Transistor utilization is less.
2. 6 position sensors are required.

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(5) Explain the magnetic circuit Analysis of BLPMDC motor with its fundamental structure and associated flux paths.

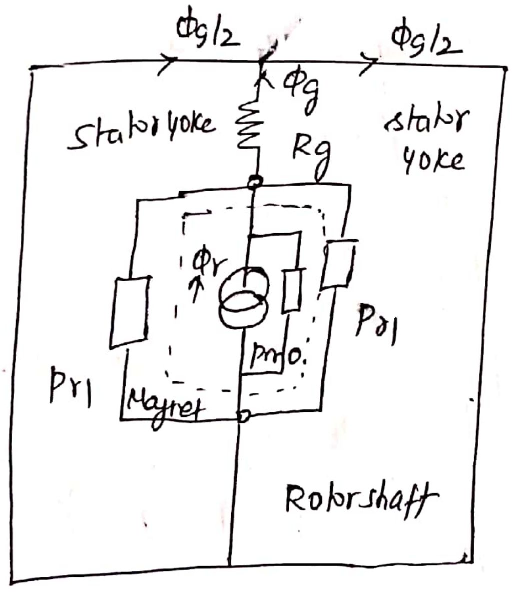


fig: Magnetic equivalent circuit

$$\omega_{mech} = \frac{\omega_{electrical}}{\text{pair of poles}} \Rightarrow \omega_e = \frac{P\omega_m}{2}$$

Each magnet is represented by a Norton' equivalent circuit consisting of a flux generator in parallel with an internal leakage permeance P_{mo}

$$\phi_r = B_r A_m \quad \text{and} \quad P_{mo} = \frac{\mu_0 \mu_{rec} A_m}{l_m}$$

where $l_m \rightarrow$ length of the magnet

$\mu_{rec} \rightarrow$ Relative coil permeability

$B_r \rightarrow$ Remanent flux density

$A_m \rightarrow$ pole area of the magnet.

In this case, the outer pole area is larger than the inner pole area with a magnet arc of $120°$,

$$A_m = \frac{2}{3}\pi\left[r_1 - g - \frac{l_m}{2}\right] l$$

where $r_1 \rightarrow$ Radius of the rotor, $g \rightarrow$ airgap length

Airgap Reluctance $R_g = g'/\mu_0 A_g'$

where $g' \rightarrow$ Equivalent airgap length allowing for slotting

$g' = K_c g$ where $K_c \rightarrow$ Constant

due to fringing effect, $A_g = \left[\frac{2}{3}\pi\left(r_1 - g/2\right) + 2g\right](l + 2g)$

modified internal permeance $P_m = P_{mo} + P_{rl}$

$$P_m = P_{mo}\left(1 + \frac{P_{rl}}{P_{mo}}\right)$$

where $P_{rl} \rightarrow$ Normalized rotor leakage permeance

Range $\rightarrow 0.05 - 0.2$

Equating the mmf across the magnet to the mmf across the airgap

$$F_m = \frac{\phi_r - \phi_g}{P_m} = \phi_g R_g$$

$$\frac{\phi_r - \phi_g}{P_m} = \phi_g R_g$$

$$\frac{\phi_r}{P_m} - \frac{\phi_g}{P_m} = \phi_g R_g$$

$$\frac{\phi_r}{P_m} = \frac{\phi_g}{P_m} + \phi_g R_g$$

$$= \phi_g \left[\frac{1}{P_m} + R_g \right]$$

$$\frac{\phi_r}{P_m} = \phi_g \left[\frac{1 + R_g P_m}{P_m} \right]$$

$$\boxed{\phi_g = \frac{\phi_r}{1 + R_g P_m}}$$

The flux concentration factor $C_\phi = \frac{A_m}{A_g}$

then $$\frac{\phi_g}{A_g} = \frac{\phi_r / 1 + R_g P_m}{A_g} = \frac{\phi_r}{1 + R_g P_m} \times \frac{1}{A_g}$$

$$\frac{\phi_g}{A_g} = \frac{\phi_r}{(1 + R_g P_m) A_g}$$

but $B_g = \phi_g / A_g$ $\therefore$ $B_g = \frac{\phi_r}{(1 + R_g P_m) A_g}$

$$B_g = \frac{\phi_r}{(1 + R_g P_m) A_g} \times \frac{A_m}{A_m} = \frac{A_m}{(1 + R_g P_m) A_g} \times \frac{\phi_r}{A_m}$$

$$B_g = \frac{A_m / A_g}{1 + R_g P_m} \times \frac{\phi_r}{A_m} = \frac{C_\phi}{1 + R_g P_m} B_r$$

where $C_\phi = \frac{A_m}{A_g}$ and $B_r = \frac{\phi_r}{A_m}$

III ly the magnetic flux density $B_m = \frac{1+P_{r1} R_g}{1+P_m R_g} B_r$

due to rotor leakage $\frac{B_g}{B_m} < C_\phi$

magnetizing force $-H_m = \frac{B_r - B_m}{\mu_0 \mu_{rec}}$ A/m.

-ve sign indicates a demagnetizing force and shows that the magnet operates in the second quadrant of the B-H curve.

The line drawn from the origin through the operating point is called the load line and absolute value of its slope normalized to μ_0 is called as permeance co-efficient (PC)

$$PC = \mu_{rec} \left[\frac{1+P_{r1} R_g}{P_{m0} R_g} \right]$$

It is useful to measure how far down the demagnetization curve the magnet operates on open circuit.

$$\frac{B_m}{B_r} = \frac{PC}{PC + \mu_{rec}}$$

⑥ Deduce the expressions for speed ratio and torque ratio of PMBLDC motor.

The applied voltage $V = 2e_{ph} + 2IR_{ph} + 2V_{dd}$

The electrical input power,

$$VI = \left[2e_{ph} + 2IR_{ph} + 2V_{dd}\right] I$$

$$= 2e_{ph} I + 2I^2 R_{ph} + 2V_{dd} I$$

where $2e_{ph}I$ → mechanical power developed

$2I^2R_{ph}$ → Cu loss in the armature winding

$2V_{dd}I$ → power loss in the device

Mechanical power developed $= 2e_{ph}I = 2[2B_g rl T_{ph}\omega_m]I$

$= 4B_g rl T_{ph}\omega_m I$

but mechanical power $= \frac{2\pi NT}{60} = \omega_m T$

where N → Speed (rpm), T → Torque (Nm), ω_m → Speed (rad/sec)

Hence $T = 4B_g rl T_{ph} I = K_t I$ where $K_t = 4B_g rl T_{ph} = K_e$

Case i) Starting Torque:

$\omega_m = 0$, $I_{stg} = \frac{V}{2R_{ph}}$

$T_{stg} = 4B_g rl T_{ph} \cdot \frac{V}{2R_{ph}}$

$T_{stg} = K_t \cdot \frac{V}{2R_{ph}}$

Starting torque or stalling torque depends upon V. To vary the starting torque the supply voltage is to be varied.

Case ii) ON load Condition:

$T = K_t I = 4B_g rl T_{ph} I$

but $I = \frac{V - 2e_{ph}}{2R_{ph}}$

$2IR_{ph} = V - 2e_{ph}$

$2e_{ph} = V - 2IR_{ph}$

$4B_g rl T_{ph}\omega_m = V - 2IR_{ph}$

$K_e\omega_m = V - 2IR_{ph}$ $[\because K_e = 4B_g rl T_{ph}]$

$$\omega_m = \frac{V - 2IR_{ph}}{K_e}$$

Also $\omega_{m0} = \frac{V}{K_e}$

Speed Ratio → speed on load to the no load speed.

$$\frac{\omega_m}{\omega_{m0}} = \frac{V - 2IR_{ph}}{K_e} \times \frac{K_e}{V} = \frac{V - 2IR_{ph}}{V}$$

$$\boxed{\frac{\omega_m}{\omega_{m0}} = 1 - \frac{2IR_{ph}}{V}} \quad -(1)$$

Torque ratio → ratio of full load torque to starting torque

$$T = K_t I$$

$$T_{st} = K_t \cdot \frac{V}{2R_{ph}}$$

$$\frac{T}{T_{st}} = \frac{K_t I}{K_t \cdot \frac{V}{2R_{ph}}} = \frac{2R_{ph} I}{V} \quad -(2)$$

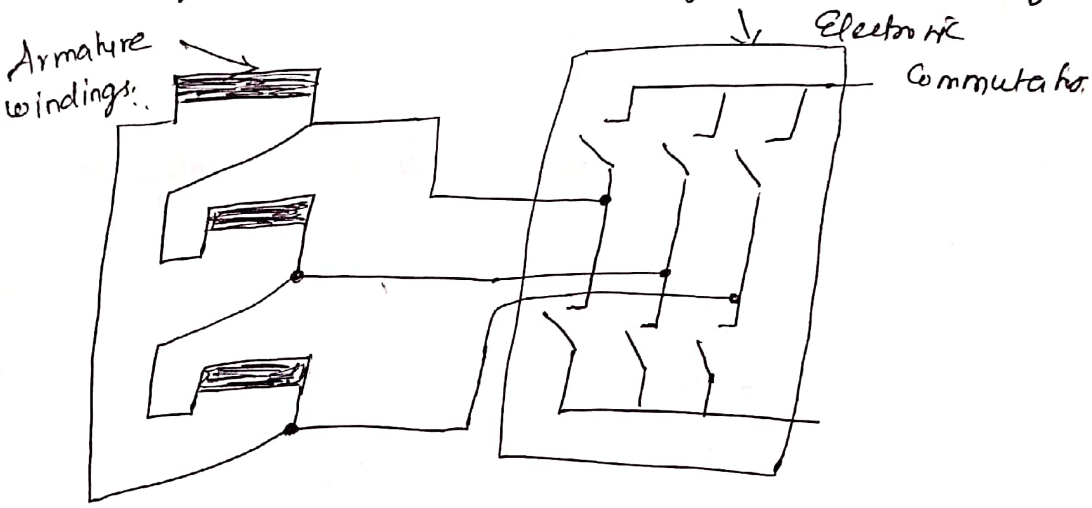
Sub (2) in (1) equation $\frac{\omega_m}{\omega_{m0}} = 1 - \frac{T}{T_{st}} = 1 - \frac{I}{I_{st}}$.

(9) Explain the working principle of PMBLDC motor with a circuit diagram?

It is a synchronous electric motor which is powered by DC supply and it has an electronically controlled commutation system. The current, torque, voltage and rpm are linearly related.

Starting:

When dc 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 the PM field. According to Fleming's left hand rule a force is experienced by the armature conductors. In the stator, a reactive force develops a torque in the rotor. If this developed torque is more than the load torque and the frictional torque the motor starts rotating. It is a self-starting motor.



Dynamic equilibrium (steady-state)

As the motor picks up speed, a relative velocity between the stationary armature conductors and the rotating rotor. According to Faraday's law of electromagnetic induction, an emf is dynamically induced in the armature conductors. As per Lenz's law this emf opposes the cause. As the supply voltage is maintained constant the current is reduced. Thus the developed torque is reduced. When the developed torque is equal to the opposing load torque, the rotor attains a steady state speed. Thus the motor attains a steady state condition.

Electromechanical power transfer:

mechanical power developed $P_m = \omega_m T = \frac{2\pi N T}{60}$

power drawn from the supply = VI

$VI = P_m +$ power loss.

Thus the electrical to mechanical power transfer takes place.