STUDY MATERIAL

SUB: ELECTRIC DRIVESBRANCH: EE/EEE

MODULE-01

1.1. INTRODUCTION

Systems employed for motion control are called drive. Diesel or petrol engine, gas or steam turbine, steam engine, hydraulicturbine , ELECTRIC MOTORS etc are termed as SOURCE OF MOTIVE POWER. These devices are used for supplying mechanical energy for motion control.

1.2 CONCEPT OF ELECTRIC DRIVE

Drives employing electric motors as source of motive power (Prime Mover) is known as electric drive.The basic components of an electric drive system are (a) Electric motor (b) Power controller (c) Energy transmitting device (d) Working machine or driven machine/Load (e) Control unit (f) Sensing unit (g) Main power source.

1.2.1 Electric motor

In many of the industrial applications, an electric motor is the most important component which is used as source of motive power. Electric motors commonly used in electric drives are

(a) DC motors--- shunt, series, compound and permanent magnet type

(b) Induction motors---- Squirrel cage and slip ring type

© synchronous motors--- wound field and permanent magnet type

(d) Special motors----- Brushless DC motor, Stepper motor and Switched reluctance motor.

1.2.2. Power controller or power modulator:

A power modulator may be a converter (ac to dc, ac to ac, dc to dc, dc to ac or ac to ac), or a variable impedance or a switching circuit. It performs one or more of the following functions.

(i) It modulates the flow of power from source to motor in such a manner that motor is imparted speed-torque characteristics required by the load.

(ii) It controls source and motor current within permissible value during transient operation.

(iii) It converts the electrical energy of the source in the form suitable to the motor.

(iv) It selects the mode of operation of the motor i.e motoring or braking.

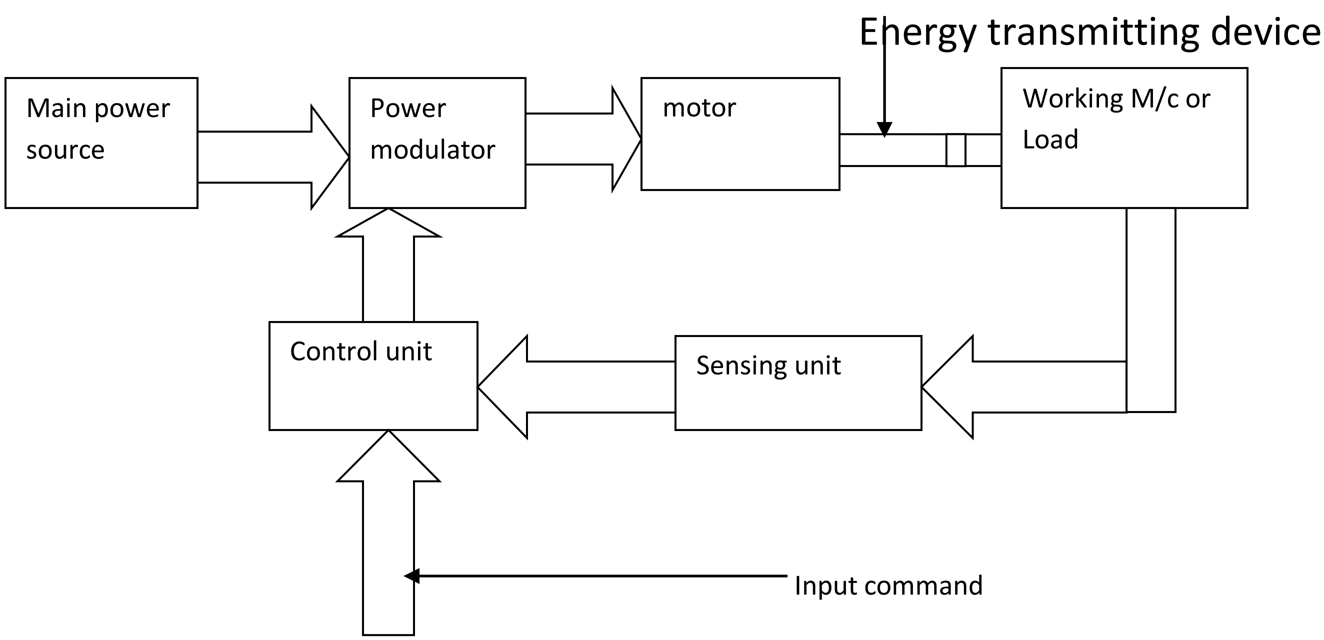


Fig.1.1 Block diagram of Electric drive system

1.2.3. Energy Transmitting Device

An energy transmitting device delivers power from electric motor to the driven machine or the load. It is usually consists of shaft, belt, chain, rope etc.

1.2.4. Working machine or Load:

Working machine is the driven machine that performs the required production process, eg lathes, centrifugal pumps, drilling machine, lift, food mixtures etc. Load requirement can be specified in terms of speed and torque demand.

1.2.5. Sensing Unit

Sensing unit senses certain drive parameters such as motor current or speed for either protection or close loop operation.

1.2.6. Control Unit

Control for power modulator are built in control unit which usually operates at much lower voltage and power levels. It also generates command for the protection of power modulator and motor. It consists of firing circuits which employ linear & digital integrated circuits and transistors & microprocessors where sophisticated control is required.

1.2.7. Main Power Source

In India, 1-phase & 3-phase 50 Hz AC supplies are available in most of the location. Low power and traction(high power) drive are fed from 1-phase supply source and rest of the drive (Medium and high power) are powered from 3-phase supply source. Some drives are powered from battery and depending size, battery voltage may be 6 V, 12V, 24V, 48V, 11oV DC. It is worth noted that choice of the motor does not depend on type of supply available.

1.3. Advantages of electric drives

Electric drives are widely used because of the following advantages.

(i) They have flexible control characteristics.

(ii) They are available in wide range of torque, speed & power.

(iii) They have high efficiency, low no load losses, short time over loading capability.

(iv)They can be started instantly and can be fully loaded immediately.

(v) They can operate in all four quadrants of speed-torque plane.

(vi) They do not pollute the environment.

(vii) There is no need to refuel the motor.

1.4. Fundamental of torque equations:

An electric motor drives the load or machine through energy transmitting devices. Motor always rotates, but the load may rotate or may undergo a translational motion or both. Load speed may or may not be equal to the speed of motor. Torque equation of motor-load system can be derived as follows. The motor-load system can be represented by an equivalent rotational system as shown in Fig.1.2.

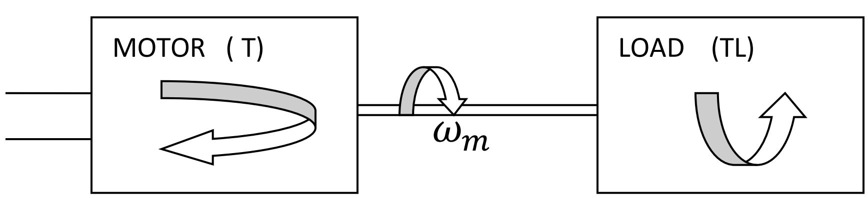


Fig.1.2 Equivalent motor-load system

Let T= instantaneous value of developed motor torque in N-m

TL=instantaneous value of load torque, referred to motor shaft in N-m

ω_m=Instantaneous angular velocity of the motor shaft in rad/sec=$\frac{2\times\pi\times N}{60}$

J= moment of inertia of motor load system referred to motor shaft in Kg-sqm.

N= speed of motor in rpm

Load torque includes friction and windage torque of motor.

Equivalent motor load system mathematically can be represented as follows.

Resultant torque=$T_r = T - T_L = \frac{d}{dt}$(J$\omega_m$)------------(1)

[Since T=J×∝ and ∝= $\frac{d\omega}{dt}$ where ∝= angular acceleration

Again for circular motion, J=m× r^2,

T=F×r= m× a × r=m×∝× r × r=(m× r^2) ×∝=J×∝

Where m=mass of the body and r= radius of the circular path and a= linear acceleration]

Hence T=T_L +J× $\frac{d\omega_m}{dt}$-----------------------(2)

Equation (2) shows that torque developed by the motor is counter balanced by a load torque T_L and a dynamic torque T_d=J× $\frac{d\omega_m}{dt}$.

1.5. Speed torque conventions and multi quadrant operation.

It is useful to establish suitable conventions about the signs of torque and speed in multi quadrant operation of drives.

1.5.1.Motor speed:

Motor speed is positive when the motor rotates in forward direction. The forward direction is considered as follows,

(i) For only one direction operation of motor, normal speed is the forward speed.

(ii) For up and down motion, upward movement is the forward direction.

(iii) For reversible drives, arbitrarily forward speed is chosen. If clock wise movement is treated as positive then anti clock wise movement is negative and vice versa.

Motor torque: Positive motor torque is defined as the torque which produces acceleration or positive motor speed. It also follows the direction of motor speed. For up and down motion, upward movement is the forward direction i.e if motor torque acts in upward direction, then it is positive else negative. But positive load torque is the opposite direction to the positive motor torque.

1.5.2. Multi quadrant operation:

A motor operates in two modes. (a) Motoring mode (b) Braking mode

In motoring, motor converts electrical energy to mechanical energy and provides motive power to the load and developed power is positive.

Whereas in braking mode, it converts mechanical energy into electrical energy & thus reduces the motive power and opposes the motion. A motor can provide motoring and braking operations for both forward (positive) and reverse (negative) motion as shown in Fig.1.3.

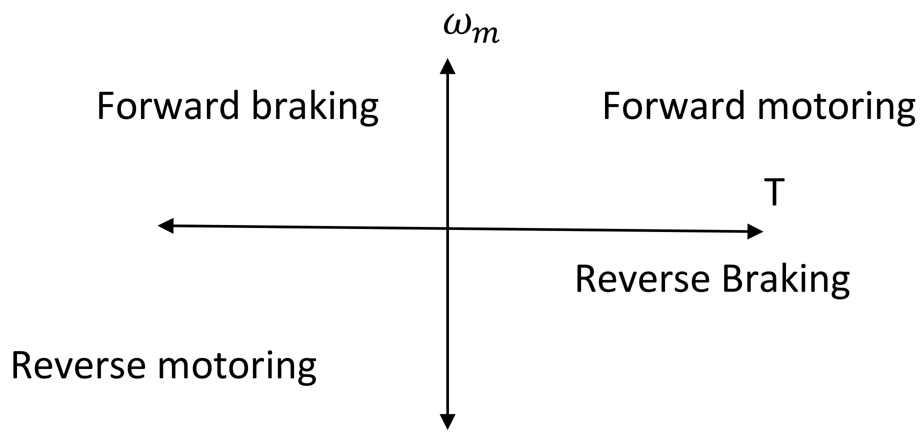


Fig.1.3. Motoring and braking mode in torque-speed plane

As we know rotational power =P = $\omega_m \times T$, in 1st and 3rd quadrant of speed-torque plane, P is positive and in 2nd and 4th quadrant of speed- torque plane, P is negative. Hence in 1st and 3rd quadrant of speed- torque plane, motor operates in motoring mode and in 2nd and 4th quadrant of speed-torque plane, motor operates in braking mode.

Example of multi quadrant operation:To demonstrate the multi quadrant operation of drive, let us consider the operation of a hoist in four quadrants as shown in Fig.1.4. A hoist consists of a rope wound on a drum coupled to the motor shaft. One end of the rope is tied to a cage which is used to transport the man or material from one level to another level. Other end of the rope has a counter weight. The weight of the counter weight is always more than that of the empty cage. Now let us discuss the operation of the hoist in each and every quadrant of speed-torque plane.

1st quadrant operation

Requirement:Hoist requires the movement of loaded cage upward.

Hence motor speed becomes positive as per the sign convention. Upward movement is possible if motor produces an accelerated torque i.e torque is also positive. So to satisfy above requirement, the hoist should operate in 1st quadrant of speed-torque plane.

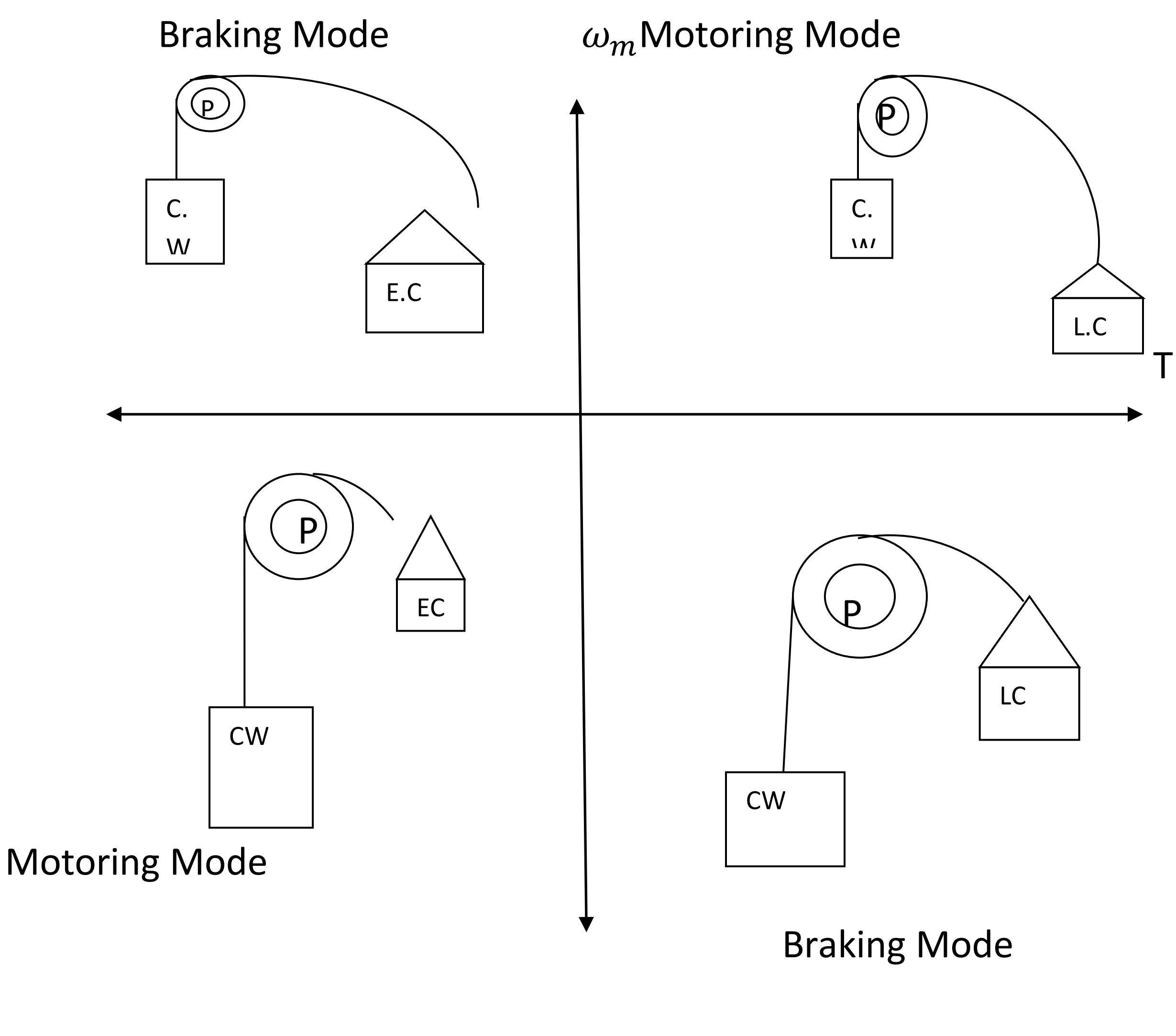


Fig.1.4. Multi quadrant operation of Drive.

2nd quadrant operation

Requirement:-Hoist requires the movement of empty cage (EC) upward. Since counter weight (CW) is heavier than an empty cage, it is able to pull it up suddenly. In order to limit the speed within the safe value, motor must produce a downward torque (braking torque) for smooth movement of empty cage. There- fore speed is positive and torque is negative and motor operates in forward braking mode.

3rd quadrant operation

Requirement:Hoist requires the movement of empty cage (EC) downward.Since counter weight (CW) is heavier than an empty cage, motor should produce downward (Motoring) torque to pull the counter weight upward for the downward movement of empty cage. Therefore speed and torque , both are negative and motor operates in reverse motoring mode.

4th quadrant operation

Hoist requires the movement of loaded cage downward. Since the weight of loaded cage is more than that of a counter weight, it is able to come down suddenly due to gravity itself. In order to limit the speed of the cage within a safe value, motor should produce an upward torque (Braking torque) for smooth movement of loaded cage. Therefore speed is negative and torque is positive and motor operates in reverse braking mode.

1.6.Equivalent values of drive parameters.

Moment of inertia (J) and load torque are generally known as drive parameter. Different parts of a load may be coupled through different mechanisms, such as gear, V-belt and crank shaft etc. These parts may have different speeds and different type of motion. So it is necessary to calculate the equivalent value of M.I. and load torque referred to motor shaft. There aretwo cases to be considered to calculate equivalent values of drive parameters, such as

(a) Load with rotational motion (b) Load with translational motion

(a) Load with rotational motion

The equivalent motor load system is shown in fig.1.5.

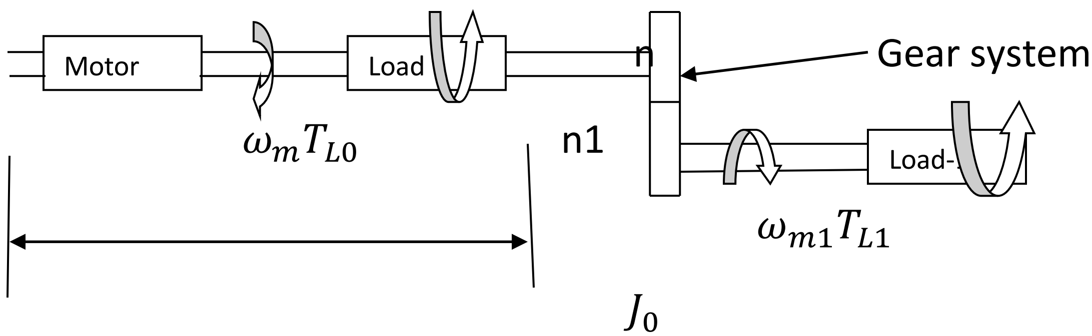


Fig.1.5.Equivalent motor load system

As shown in fig.1.5, motor drives two loads, one is directly coupled to the shaft of the motor and the 2nd load is connected through a gear with teeth n and n1 . Let the M.I. of motor and directly coupled load be J0, speed of the motor be ω_m and torque of directly coupled load be TL0. The M.I., speed and torque of second load are J1,ω_{m1} and T_{L1} respectively. Since in gear system, speed is inversely proportional to the number of teeth,

$\frac{\omega_{m1}}{\omega_m}$=$\frac{n}{n_1}$= a (say), Where ‘a’ is known as tooth ratio.

Equivalent Moment of inertia (J)

If the losses in the transmission line is neglected, then the kinetic energy due to equivalent inertia (J) must be equal to the sum of the kinetic energy of various moving parts in the system. Hence

$\frac{1}{2}J\times \omega_m{}^2 = \frac{1}{2}\times J_0 \times \omega_m{}^2 + \frac{1}{2}\times J_1 \times \omega_{m1}{}^2$

$=> J = J_0 + a^2 \times J_1$---------------------(3)

If 'm' number of loads are connected through gear along with a directly coupled load then

$J = J_0 + a1^2 \times J_1 + a2^2 \times J_2 + \ldots\ldots\ldots\ldots + a_m{}^2 \times J_m$..................(4)

Equivalent Load Torque (TL)

Power due to equivalent load torque must be equal to the sum of power in various loads i.e $\omega_m \times T_L = \omega_m \times T_{L_0} + \frac{\omega_{m1} \times T_{L1}}{\eta_g}$, Where η_g= gear efficiency

$=> T_L = T_{L0} + \frac{a}{\eta_g} \times T_{L1}$..........................(5)

In general $T_L = T_{L0} + \frac{a1}{\eta g1} \times T_{L1} + \ldots \frac{a2}{\eta g2} \times T_{L2} + \ldots\ldots\ldots\ldots + \frac{am}{\eta gm} \times T_{Lm}$.........(6)

(b) Load with translational motion along with a directly coupled load

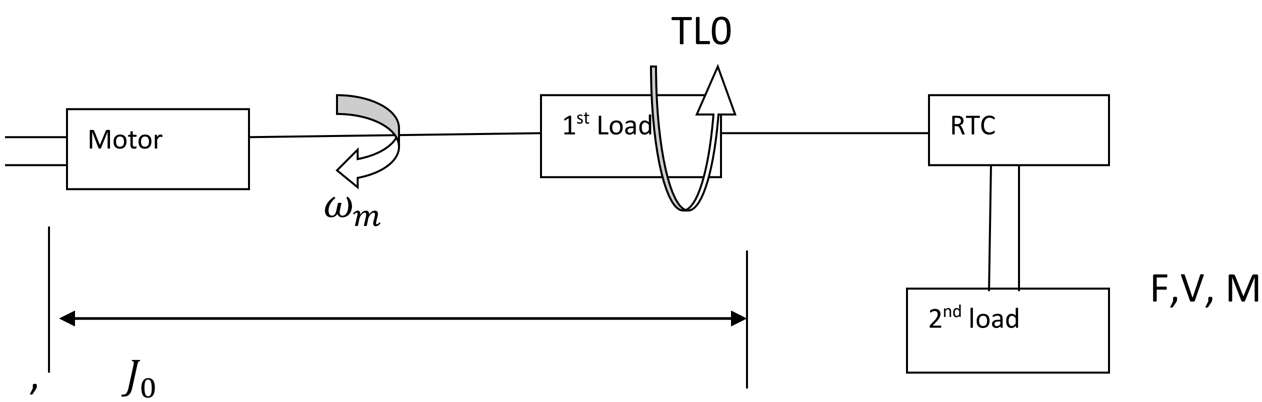


Fig.1.6Equivalent motor load system

As shown in Fig.1.6.,1st load is directly coupled to the shaft and 2nd load through a transmission system converting rotational motion to translation motion (RTC). J0,ω_m,T_{l0} are the M.I., speed and torque of 1st load respectively. V1,F,M are the speed, force and mass of 2nd load respectively and RTC=Rotational-Translational-Converter.

Equivalent MI (J)

Kinetic Energy due to equivalent MI (J) is equal to the sum of kinetic energy in various moving parts of system. Hence

$\frac{1}{2}J\times \omega_m{}^2 = \frac{1}{2}\times J_0 \times \omega_m{}^2 + \frac{1}{2}\times m \times v^2$

⇨ J = J0 +m $\frac{v^2}{\omega_m{}^2}$ =J_0 +m× $(\frac{v}{\omega_m})^2$............................(7)

If 'm' number of loads are connected through RTC along with a directly coupled load then

J =J_0 +m1 × $(\frac{v1}{\omega_m})^2$+m2× $(\frac{v2}{\omega_m})^2$+.................+m_m × $(\frac{v_m}{\omega_m})^2$........(8)

Equivalent Load Torque (TL)

Power due to equivalent load torque is equal to the sum of power of each load in the system. i.e. $\omega_m \times T_L$ = $\omega_m \times T_{L_0}$ +$\frac{F\times v}{\eta}$, Where η= efficiency of rotational to linear transmission system (RTC).

⇨ T_L =T_{L0} +$\frac{F}{\eta}$ × $(\frac{v}{\omega_m})$.................................(9)

If 'm' number of loads are connected through RTC along with a directly coupled load then

$$T_L = T_{L0} + \frac{F1}{\eta 1} \times \left(\frac{v1}{\omega_m}\right) + \frac{F2}{\eta 2} \times \left(\frac{v2}{\omega_m}\right) + \dots\dots\dots + \frac{Fm}{\eta m} \times \left(\frac{vm}{\omega_m}\right) \dots\dots\dots\dots(10)$$

1.7.Components of load torque.

Load torque is classified as active and passive load torque. The load torque which has the potential to drive the motor under equilibrium condition is called active load torque. Torque due to tension, compression, gravitational force etcare examples of active load torque.

Load torque which always opposes the motion and changes its sign on the reversal of the motion is called passive load torque. Torque due to friction and wind pressure are examples of passive load torque. Therefore

Load torque has following components,

(a) Friction torque (b) windage Torque (c) Useful torque

(a) **Friction torque**: It is present at the motor shaft and in the various parts of the load. It depends on the speed of the system. At stand still , it becomes maximum. Friction at zero speed is called stiction or static friction.

Friction torque can be resolved into three components, such as (i) viscous frictiontorque (ii) Coulomb frictiontorque (iii) Static friction torque.

(i) viscous friction torque(T_v): It varies linearly with speed and mathematically,

T_v =B× ω_m, where B is known as viscous friction coefficient.

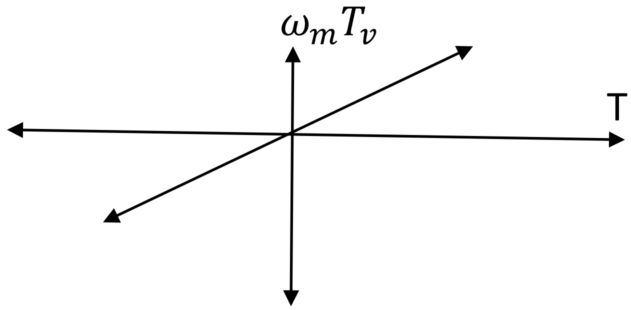


Fig.1.7 viscous friction

(ii) Coulomb friction torque (T_c) : It is also known as dry friction torque. At very low speed viscous friction torque is also known as coulomb friction torque. It is independent of speed and mathematically expressed as T_c =K.

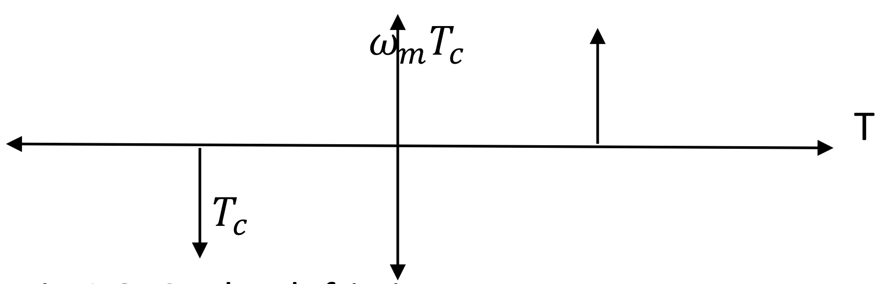


Fig.1.8. Coulomb friction torque.

(iii) Static friction torque (T_s): This is the torque which is present at stand still. It is not taken into account in dynamic analysis.

(b) Windage torque (T_w): When a motor runs, wind generates a torque in opposite direction of motion. This torque is known as windage torque. It is directly proportional to the square of the speed. Mathematically ,

T_w=C× ${\omega_m}^2$, where C is a constant.

©**Useful torque (T_u): T**orque required to do the useful mechanical work is known as useful torque.

Hence $T_L = \boldsymbol{T_u} + B\times \omega_m + T_c + C\times {\omega_m}^2 + T_s$

In many applications, $T_c + C\times {\omega_m}^2$ is much smaller than $B\times \omega_m$. So without any significant error $T_c + C\times {\omega_m}^2$ may be neglected. For dynamic analysis T_s is neglected. Hence $T_L = \boldsymbol{T_u} + B\times \omega_m$.

As per fundamental torque equation, $T = T_L + T_d$

Therefore $T = (\boldsymbol{T_u} + B\times \omega_m.) + T_d = T_{cp} + T_d$, where T_{cp} is known as coupling torque and T_d is known as dynamic torque.

1.8. **Calculation of time and energy loss in transient operations**:

Starting, braking, speed change, speed reversal are termed as transient operation in electric drive system. Time taken and energy dissipation in motor during transient operation can be calculated by solving following equations.

$T = T_L + J\times \frac{d\omega_m}{dt}$ => $T - T_L = J\times \frac{d\omega_m}{dt}$

⇨ Time=t $= \int_{\omega_{m1}}^{\omega_{m2}} \frac{J}{T - T_L}\, d\omega_m$,........................(11)

where T &T_L are function of ω_m.

Energy loss = E=$\int_o^t i^2 \times R\, dt$, ...(12)

where R=motor winding resistance and i=current flowing through the motor winding.

1.9. Steady state stability:

The point at which load torque is equal to motor torque is known as equilibrium point and the respective speed of drive is known as equilibrium speed. The equilibrium point is termed as stable when the operation will be restored to it after a small disturbance in the motor or load else it is unstable. At equilibrium speed,drive operates in steady state.

Let us take an example as shown in Fig.1.9 to illustrate the stablepoint of equilibrium.

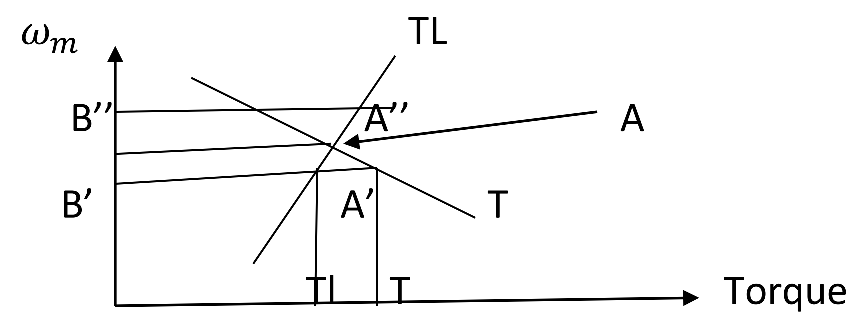


Fig.1.9.Stable point of equilibrium.

In Fig.1.9. point 'A' is an equilibrium point. Due to small disturbance in load or motor, there is a reduction of $\delta\omega_m$ in speed which is represented by point A'. It is observed that at new speed i.e at point A', motor torque (T) is greater than load torque (TL). Hence motor will be accelerated and the operation will be restored to point A.

Similarly an increase of $\delta\omega_m$ in speed caused by a disturbance will make load torque greater (at point A'') than the motor torque. Therefore, the motor will be decelerated and the motor will be restored.

Let us take another example to illustrate steady state stability with unstable equilibrium as shown in Fig.1.10. In Fig.1.10, point A is the equilibrium point. In this case ,if speed of the motor-load system is decreased due to some disturbance in load or motor, the system will be decelerated as TL> T at new speed. So the operating point moves away from point A and system can not be restored.

Again if speed of the motor-load system is increased due to some disturbance in load or motor, the system will be accelerated as T> TL at new speed. So the operating point moves away from point A and system can not be restored. Thus point A in Fig.1.10 is an unstable point of equilibrium

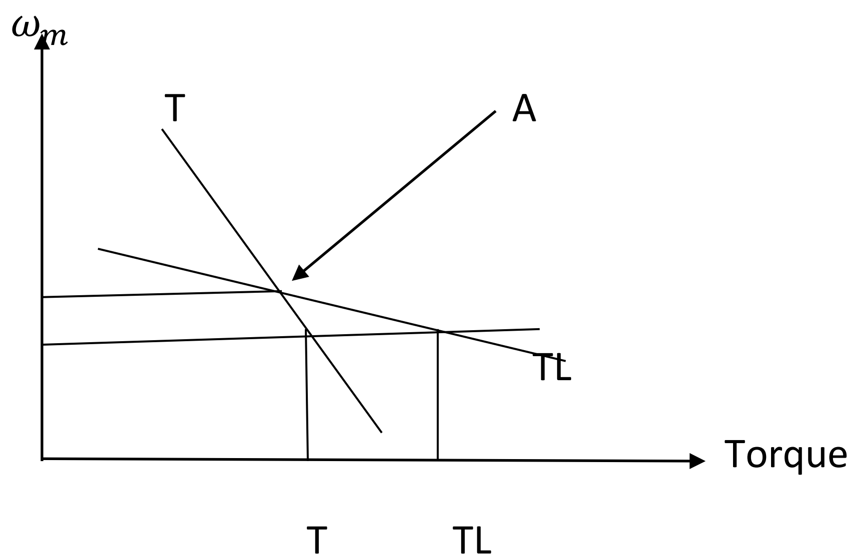


Fig.1.10 Unstable point of equilibrium

It is proved that equilibrium point will be stable when an increase in speed causes $\frac{dT_L}{d\omega_m} > \frac{dT}{d\omega_m}$

Proof: Let a small disturbance in speed $\delta\omega_m$ results in δT& δTL change in T and TL respectively. Hence from fundamental torque equation, we get

T +δT = $(T_L + \delta T_L)$ +J$\frac{d(\omega_m + \delta\omega_m)}{dt}$..............................(13)

&T=T_L +J× $\frac{d\omega_m}{dt}$..(14)

Subtracting equation 14 from Equ. 13, we get

δT =δT_L + J$\frac{\delta_{\omega_m}}{dt}$...(15)

But δT =$\frac{dT}{d\omega_m} \times \delta_{\omega_m}$ and δT_L=$\frac{dT_L}{d\omega_m} \times \delta_{\omega_m}$ … … … … … .. (16), [since $\frac{dT}{d\omega_m}$ is the per unit change w.r.t ω_m and δT is the change in torque due to δ_{ω_m}.]

Therefore from equ.15 & 16, we get

$\frac{d\delta_{\omega_m}}{dt} - \frac{1}{J}[\frac{dT}{d\omega_m} - \frac{dT_L}{d\omega_m}]\delta_{\omega_m}$=0....................................(17)

Solving the differential equation (17), we get

δ_{ω_m}=($\delta_{\omega_{m0}}$)× $e^{\frac{1}{J}[\frac{dT}{d\omega_m} - \frac{dT_L}{d\omega_m}]\, t}$ ....(18)

Where $\delta_{\omega_{m0}}$ is the initial change in speed at t=0

An operating point will be stable, when δ_{ω_m}=0 at 't' approaches infinite. So to satisfy this condition $\frac{dT}{d\omega_m} - \frac{dT_L}{d\omega_m}$ must be negative, i.e$\frac{dT_L}{d\omega_m}$>$\frac{dT}{d\omega_m}$ Proved.

1.10. Load equalization

In some drive applications load torque fluctuates widely within the short interval of time as shown in Fig.1.11. It affects other loads connected to the line because motor will draw a pulsating current from the supply which gives to the line voltage fluctuations. This problem can be overcome by mounting a fly wheel on the motor shaft in non-reversible drive system. During high load torque, fly wheel supplies power to the system and during low load torque, it stores power. As a result, fluctuation in motor torque as well as in speed are reduced. Since power drawn from the source fluctuates very little, it is called load equalization.

In variable speed drive and reversible drive system, a flywheel can not be mounted on the motor shaft because it will increase transient time of drive by a large amount. If motor is fed from a motor-generator set, then fly wheel can be mounted on the shaft of the motor-generator seti.e arrangement is made on the source. As a result, fluctuation in motor torque as well as in speed are reduced.

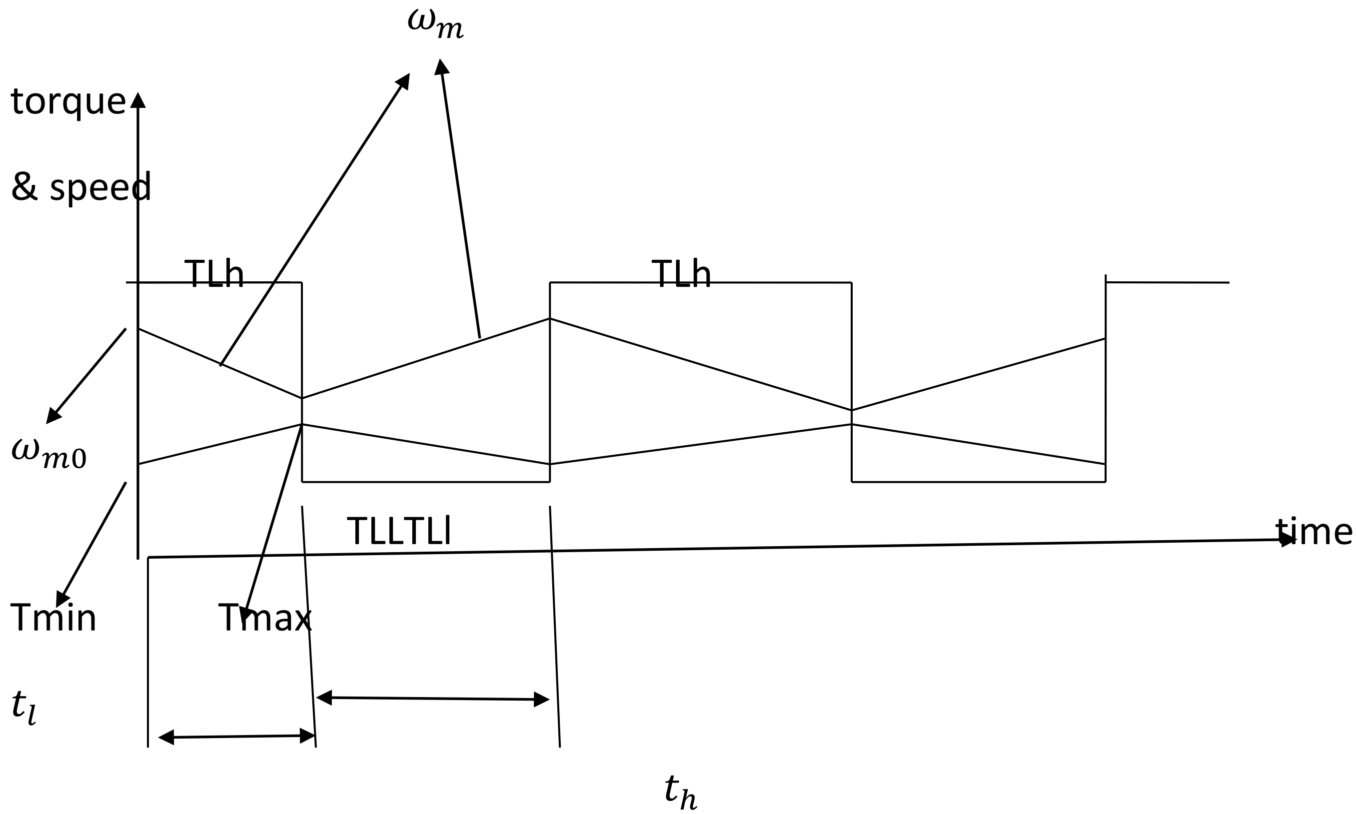


Fig.1.11. Torque, speed versus time curves for Load equalization

Moment of Inertia of Fly wheel (J_F)

The moment of inertia of flywheel required for load equalization is calculated as follows

In constant power drive $\omega_m \propto \frac{1}{T}$ as P=$\omega_m \times T$. The speed versus torque curve for constant power drive is shown in Fig.1.12.

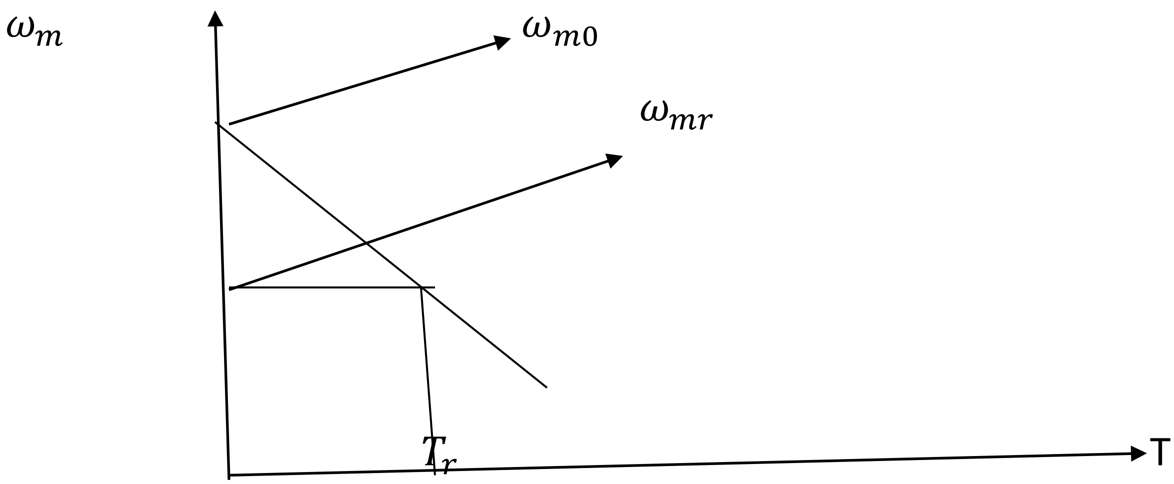


Fig.1.12 Speed Vs Torque curve for constant power drive

Let ω_{m0} , ω_{mr} and T_r are the initial speed, rated speed and rated torque respectively.

Change in speed at torque T

$$=\delta\omega_m = \frac{\omega_{m0} - \omega_{mr}}{T_r} \times T$$

Hence speed at torque T

$$=\omega_m = \omega_{m0} - \delta\omega_m \text{ due to dropping characteristics}$$

$$= \omega_{m0} - \frac{\omega_{m0} - \omega_{mr}}{T_r} \times T \text{ ....(19)}$$

⇨ $J \times \frac{d\omega_m}{dt} = -J \times \frac{\omega_{m0} - \omega_{mr}}{T_r} \times \frac{dT}{dt}$

⇨ $T_d = -\tau_m \times \frac{dT}{dt}$ ....(20)

$where \tau_{\cdot m} = J \times \frac{\omega_{m0} - \omega m_r}{T_r}$ =mechanical time constant ....(21)

and J= equivalent moment of inertia = MI of motor + MI of flywheel

$= J_m + J_F$

Again from fundamental torque equation we get,

$T - T_L = T_d$

=>$T - T_L = -\tau_{\cdot m} \times \frac{dT}{dt}$ ....(22)

=>$\frac{dT}{T - T_L} = -\frac{dt}{\tau_{\cdot m}}$

=>$\int \frac{dT}{T - T_L} = \int -\frac{dt}{\tau_{\cdot m}}$

=>ln$(T - T_L) = -\frac{t}{\tau_{\cdot m}}$+ K................................(23)

Where k= integral constant

Initial condition: when t=0, T= T0 (say)

Hence from equation (22), we get, K=ln ($T_o - T_L$)

Substituting the value of K in equation (22), we get,

$\tau_{\cdot m} = -t/ln(\frac{T - T_L}{T_o - T_L})$ ....(24)

During Heavy Load

T= $\boldsymbol{T_{max}}$, T_o=$\boldsymbol{T_{min}}$, **t=**$\boldsymbol{t_h}$, $\boldsymbol{T_L}$=$\boldsymbol{T_{Lh}}$ **,**

Hence $\tau_{\cdot m} = -t_h/ln(\frac{\boldsymbol{T_{max} - T_{Lh}}}{\boldsymbol{T_{min} - T_{Lh}}})$ ....(25)

From equations (21) & (25), we obtain

J=$\frac{T_r}{\omega_{m0} - \omega m_r} \times [t_h/ln(\frac{T_{min}-T_{Lh}}{T_{max}-T_{Lh}})]$..............................(26)

During Light load

T= T_{min}, T_o=T_{max}, t=t_l, T_L=T_{Ll} , substituting these values in equation (24), we get,

$\tau_{m}= -t_l/ln(\frac{T_{min}-T_{Ll}}{T_{max}-T_{Ll}})$ ....(27)

From equation (21) & (27), we get

J=$\frac{T_r}{\omega_{m0} - \omega m_r} \times [t_l/ln(\frac{T_{max}-T_{Ll}}{T_{min}-T_{Ll}})]$...................(28)

After getting the value of J, we can find out the value of J_F.

i.e J_F =$J - J_m$.

If weight(W)and radius(R) of fly wheel are known, then

J_F=$\frac{1}{2} \times W \times R^2$..................................(29)

1.11. Control of electrical drives

Feedback loops in an electrical drive may be provided to satisfy one or more of the following requirements. (a) Protection (b) Enhancement of speed response (c) To improve steady state accuracy. The basic close loop control circuits used in electric drives are (i) Current limit control circuit (ii) Torque controlcircuit (iii) speed controlcircuit (iv) Position controlcircuit (v) Phase locked loop (PLL) control (vi) Closed loop speed control of multi motor drive

(i) Current limit control circuit:

Current limit control circuit is used to limit the converter and motor current below a safe limit during transient operation. It has a current feed back loop with a threshold logic circuit. As long as the current is within a set maximum value, feed back loop does not work. During steady state operation, current will not have tendency to cross the maximum value. Therefore feed back loop has no effect on the drive operation. Butduring a transient operation, if current exceeds the reference value, feed back loop is activated and current is forced below the reference value. When it is achieved ,feed back loop becomes inactive. The block diagram of a current limit control is shown in Fig.1.13.

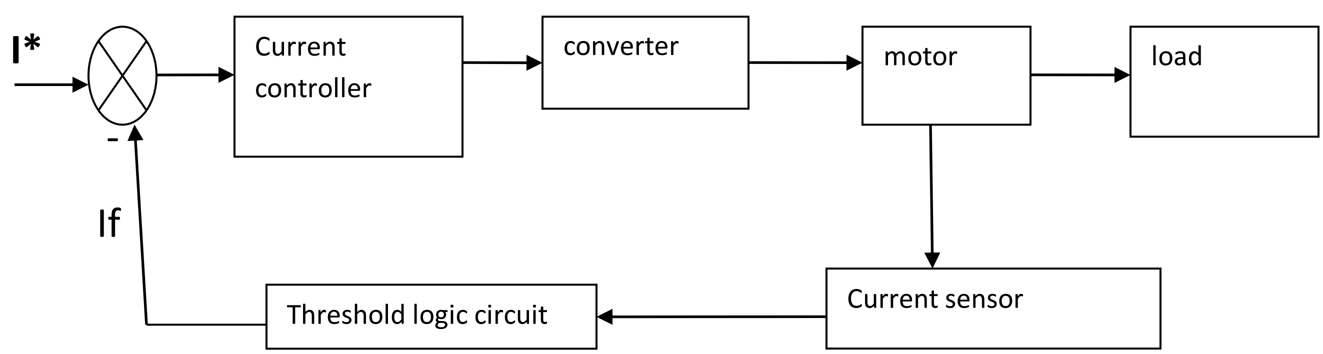


Fig.1.13 Current limit control circuit

(ii) **Close loop torque control circuit:**

In this method actual motor follows the reference torque for enhancement of speed response. Driver presses the accelerator to set reference torque. By putting appropriate pressure on the accelerator, driver adjust the speed. This method finds application in battery operated vehicles, rail cars, electric trains etc. The block diagram of Close loop torque control is shown in fig.1.14.

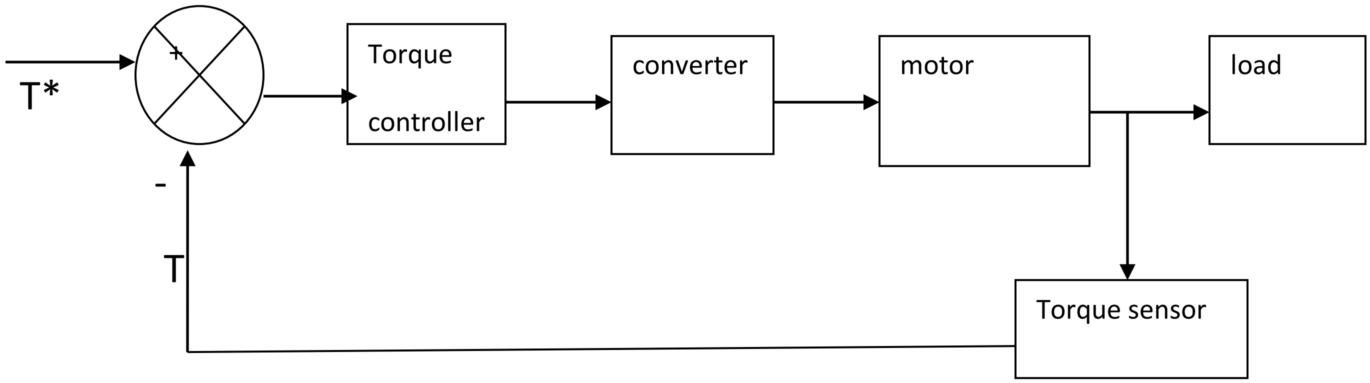
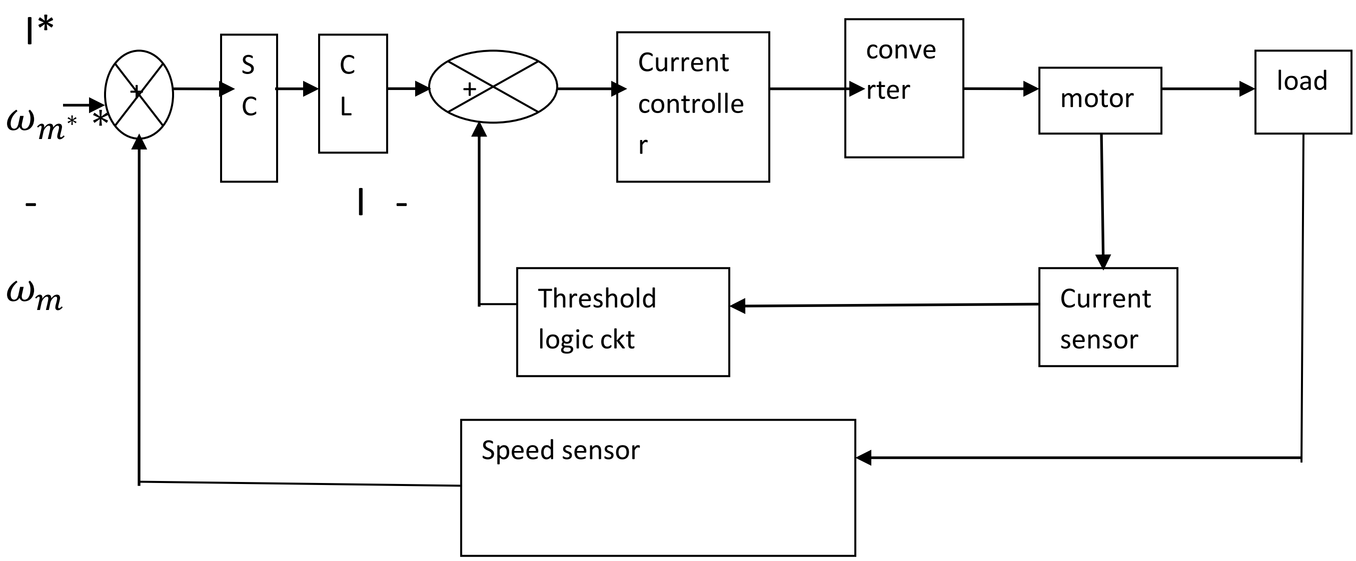


Fig.1.14.Close loop torque control circuit

(iii) Close loop speed control

This method is widely used in electric drives. It employs an inner current control loop within an outer speed loop. Inner current loop is provided to limit the converter and motor current or motor torque below a safe limit.



SC=speed controller, CL= current limiter

Fig.1.15.Close loop speed control

The block diagram of close loop speed control is shown in Fig.1.15.

An increase in reference speed ω_{m^*} produces a positive error which is processed through a speed controller and applied to a current limiter. The current limiter sets current reference for inner current control loop at a value corresponding to the maximum allowable current and accelerates in motoring mode. When close to the desired speed is reached, limiter isde-saturated and drive operates at desired speed.A decrease in reference speed ω_{m^*}produces a negative speed error. Hence the drive decelerates in braking mode. When required speed is developed, the operation is transferred from braking to motoring mode.

A current and speed controllers may consist of (a) proportional and integral (PI) controller (b) proportional & derivative (PD) (c) proportional, integral & derivative (PID) controller depending on steady state accuracy and transient response requirement.

(iV) Close loop position control

A close loop position control scheme is shown in fig.1.16. Position control is required in a number of drive applications like screw down mechanism in rolling mill.A close loop position control scheme employs inner current and speed loop within an outer position loop.

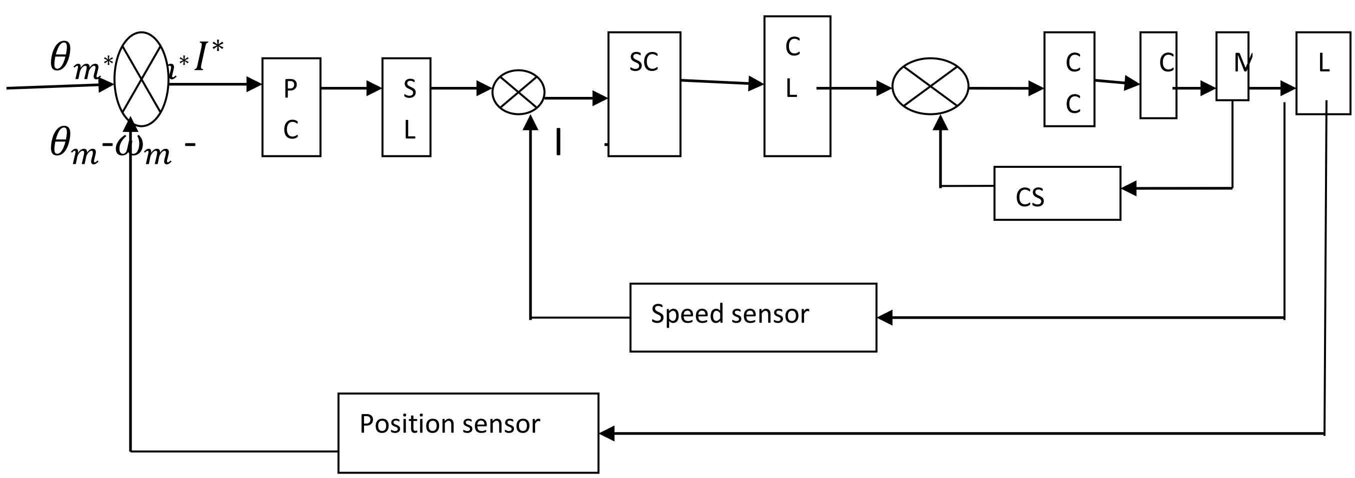


Fig.1.16 Close loop position control.

In Fig.1.16,PC= position controller, SL=speed limiter, SC= speed controller, CL=current limiter, CC= current controller, C=converter, M= Motor, L= load.

Current and speed loop restrict the current and speed within safe limit, enhance the speed response , reduces the effect of non-linearity in the converter, motor and load on the transient and steady state performance of the position control system.

(V) Phase locked loop control (PLLC).

It is a special type of speed control circuit. An electric drive employing PLL control is shown in fig.1.17.Excellent speed regulation is obtained by PLLC scheme. By PLLC scheme speed regulation is 0.002% which is very useful in conveyers for material handling, paper and textile mills etc.

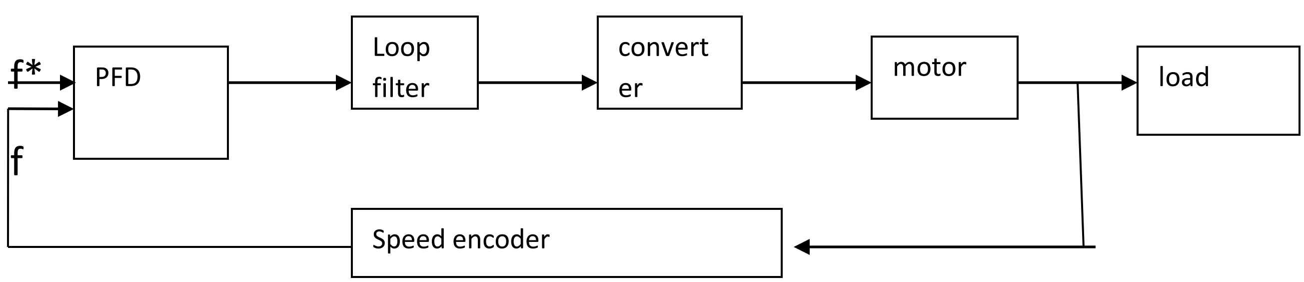


Fig.1.17. PLLC scheme

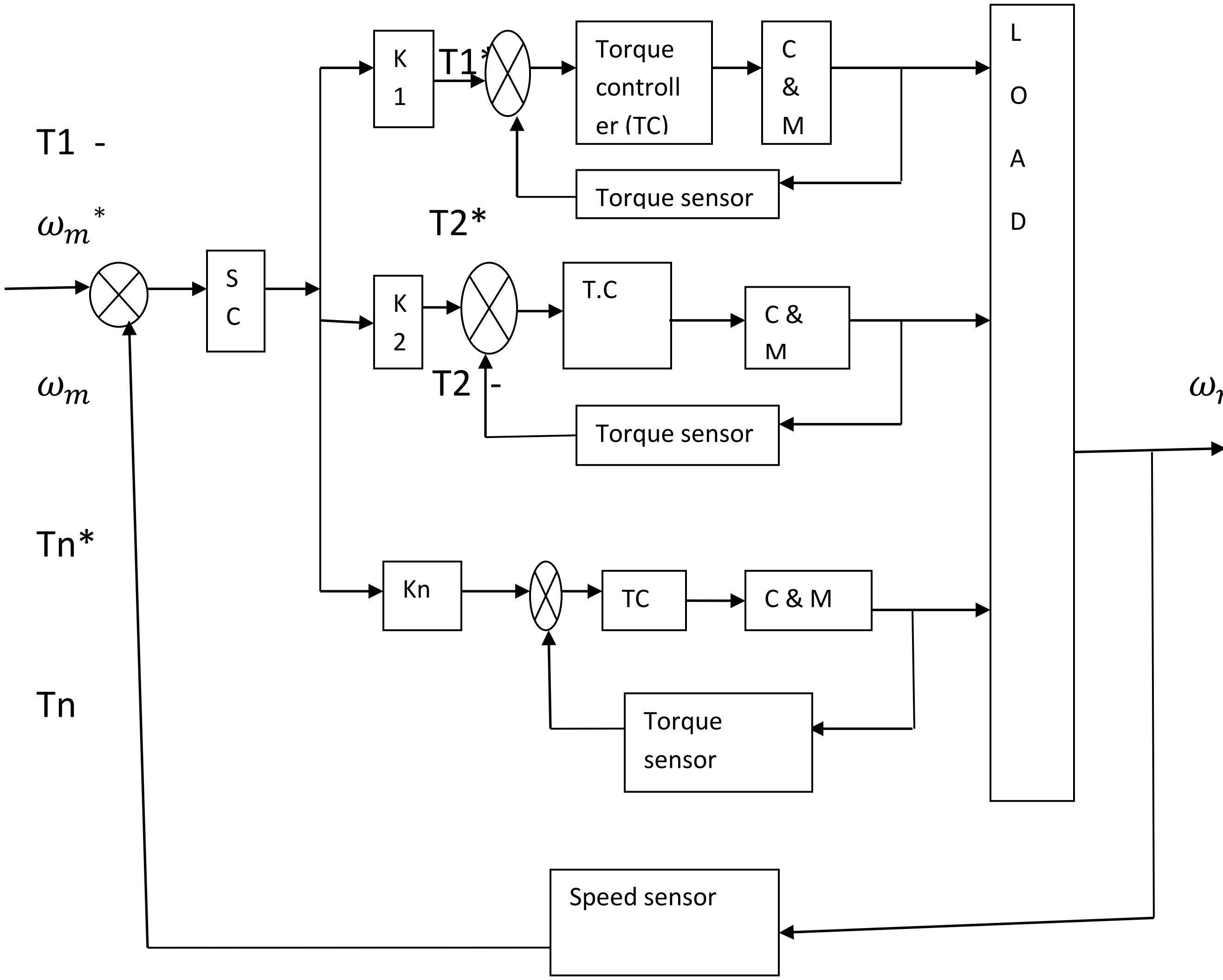
The reference frequency f* and output frequency 'f' are compared in a phase detector (PFD). Output of the phase detector produces a phase width modulated (PWM) output Vc. Pulse width of Vc depends on the phase difference between the two input pulse trains and polarity depends on the sign of phase difference i.e lag or lead between them. The output of phase detector is filtered by the loop filter to obtain a DC signal and applied as control voltage to converter which changes the converter operation and motor speed is adjusted and hence frequency. Because of the closed loop, output frequency changes in a direction that reduces the phase difference. When steady state is reached, output frequency f becomes exactly equal to reference frequency f* and the loop is said to have locked.

Advantages: (1) circuit is inexpensive (2) Excellent speed regulation is obtained.

Disadvantages: (1) Transient response is slow (2) It has low speed limit below which it becomes unstable.

(vi) Closed loop speed control of multi motor drive

When mechanical part of the load has large physical dimension, it becomes desirable to share the load between several motors. This type of drive is termed as multi motor drive. There are two classes of multi motor drive. Such as (a) various section of drive are mechanically coupled through a long shaft i.econstant speed multi motor drive (b) various section of drive are coupled through the material under processi.evariable speed multi motor drive **(a) constant speed multi motor drive**: In this type of drive, each section is driven by its own motor having same or different ratings depending on the load requirement. Once it is ensured that torque requirement of each section is met by its own driving motor, the drive shaft has to carry only small synchronizing torque. It consists of one common outer speed loop and one inner torque control loop for each section as shown Fig.1.18. All sections run at same speed. The common speed controller, through gain constantsK_1, K_2…………,K_n sets reference torques for the closed loop control of section 1,2,……….,n respectively. Thus ensuring that torques are shared in proportion to motor ratings.



SC=Speed controller, C & M= Converter & Motor

Fig. 1.18.Common shaft multi motor drive

(b) Variable speed multi motor drive : As the red hot strip passes through the rolling stand, its cross section decreases and therefore its length & velocity increase. In order to keep the strip tension within suitable limit, the motor of next rolling stand must run at an appropriate higher speed. This isachieved by (i) Simultaneously reference change in speed technique (ii) Progressive reference change in speed.

(i) Simultaneously reference change in speed:

This can be implemented by the close loop scheme as shown in fig.1.19. As the command reference speed(ω_m *) is changed, all other reference speeds ω_{m1} *,$\boldsymbol{\omega_{m2}}$***……….$\boldsymbol{\omega_{mn}}$* will** be changed simultaneously in proportional to K1, K2,……Kn respectively. $\frac{\omega^*{m_1}}{\omega_{m^*}}$ =K1,$\frac{\omega^*{m_2}}{\omega_{m^*}}$ =K2,$\frac{\omega^*{m_n}}{\omega_{m^*}}$ =Kn

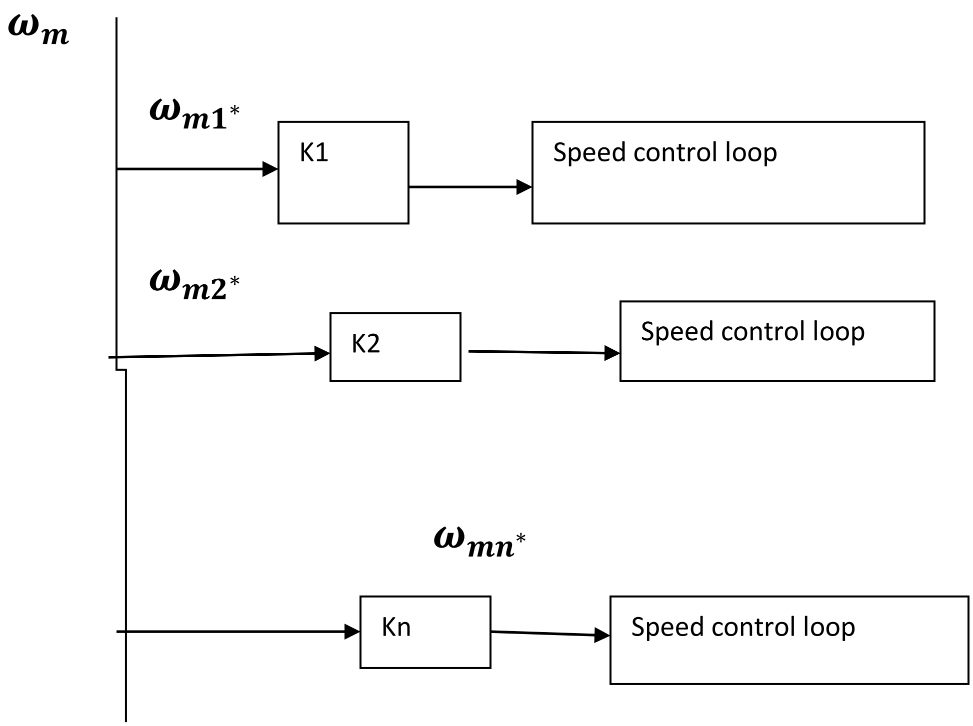


Fig 1.19.Simultaneously reference change in speed technique

(ii) Progressive reference change in speed technique

This can be implemented by the close loop scheme as shown in fig.1.20.

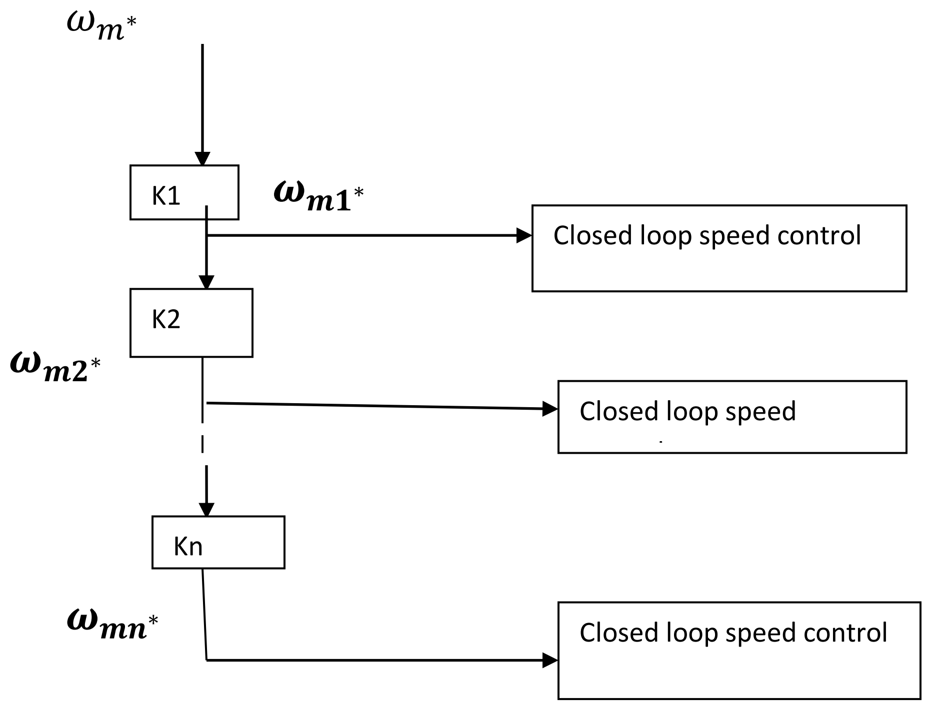


Fig.1.20 Progressive reference change in speed technique

It is observed that, for any r th rolling stand,

$\frac{\omega_{mr^*}}{\omega_{m^*}}$ = K1$\times K2 \times \ldots\ldots..\times Kr$ as $\frac{\omega_{m1^*}}{\omega_{m^*}}$ =K1, $\frac{\omega_{m2^*}}{\omega_{m1^*}}$ = K2 and so on.

1.12. Thermal model of motor for heating and cooling.

When motor operates, heat is produced inside the machine due to losses and its temperature rises. Since temperature rise has a direct relationship with the output power, it is termed as thermal loading on the machine. The steady state temperature is not the same at various parts of the machine. It is usually highest in the windings. Temperature in various parts of the motor should not exceed the safe limit otherwise thermal break down occurs. Let us develop thermal model of motor for heating and cooling which is required to

Calculate the temperature of the machine at any instant. Let us consider a motor having homogeneous body . The motor has the following parameters at time 't'.

P1= Heat developed in joule/sec,

P2= Heat dissipated to the cooling medium in joule/sec.

W= Weight of the active part of the machine in Kg.

h= specific heat in J/Kg/0_C

D=coefficient of heat transfer or specific heat dissipation in J/sec/m2/oC

θ = mean temperature rise in 0_C

<u>Heating/ Cooling</u>

Suppose , during a time increment dt, the machine temperature changes by dθ.

Hence heat developed inside the machine =P1$\times dt$

Heat dissipated to the surrounding or cooling medium =P2$\times dt$

And heat absorbed in the machine = W$\times h \times \mathrm{d}\theta$

Therefore W$\times h \times \mathrm{d}\theta$ =P1$\times dt$ $-$P2$\times dt$

- ⇨ W$\times h \times \mathrm{d}\theta$ = P1$\times dt - \theta \mathrm{D} \times dt$ as P2= $\theta \mathrm{D}$
- ⇨ C $\times \mathrm{d}\theta$ =(P1 $- \theta \mathrm{D}$) $\times dt$,

Where C=W$\times h$ = thermal capacity of the machine.

c$\times \frac{d\theta}{dt}$=(P1 $- \theta \mathrm{D}$)Type equation here.

⇨ $\frac{d\theta}{(\mathrm{P1}-\theta\,\mathrm{D})} = \frac{1}{C}\,dt$

⇨ $\boldsymbol{ln}(\mathrm{P1} - \theta\ \mathrm{D}) = -\frac{D\,t}{C} + K$…………………(30)

<u>$Initial$ condition</u>

$when$ t= 0, θ=θ_0 (say)

$Hence\,\boldsymbol{ln}(\mathrm{P1} - \theta_0\ \mathrm{D}) = K$ ………………..(31)

$From$ equation (30) and (31), we get

$\frac{\mathrm{P1}-\theta\,\mathrm{D}}{\mathrm{P1}-\theta_0\,\mathrm{D}} = e^{-t/(\frac{C}{D})} = e^{-t/\tau}$, where $\tau = C/D$ is known as thermal time constant.

$=> \frac{(\mathrm{P1}/D)-\theta}{(\mathrm{P1}/D)-\theta_0} = e^{-t/\tau}$

$=> \frac{\theta_{ss}-\theta}{\theta_{ss}-\theta_0} = e^{-t/\tau}$, Where $\theta_{ss} = \mathrm{P1}/D$ = steady state temperature.

$=> \theta = \theta_{ss}(1-e^{-t/\tau}) + \theta_0 \times e^{-t/\tau}$…………….(32)

Equation (32) is the general thermal model.

<u>Thermal model for heating</u>

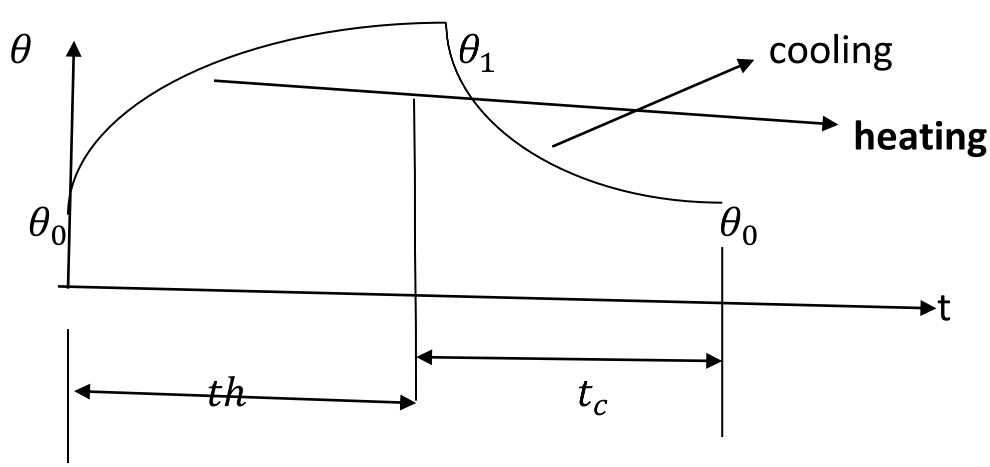


Fig.21. Temperature vs time curve

Referring fig.1.21, we get, initial temperature =θ_0 =θ_0

t= t_h and τ=τ_h. Substituting these values in equation (32), we get

θ=$\theta_{ss}(1-e^{-t_h/\tau_h})$ +$\theta_0 \times e^{-t_h/\tau_h}$...............(33)

Thermal model for cooling

If the load on machine be thrown off at temperature θ_1, heat loss will be reduced to a small value $P_1{}'$ and cooling operation of the motor begin with new value of heat dissipation constant (D').

Here initial temperature θ_0 =θ_1 and t=t_c, thermal time constant =τ_c=C/D'

Steady state temperature =$\theta_{ss'}$ =$\frac{P1'}{D'}$,

Therefore thermal model for cooling from equation (32) ,

θ=$\theta ss'(1-e^{-t_c/\tau_c})$ +$\theta_1 \times e^{-t_c/\tau_c}$...............(34)

If motor is disconnected from supply during cooling, $\theta_{ss'}$ =$\frac{P1'}{D'}$ =0. In this situation,thermal model for cooling will be θ =$\theta_1 \times e^{-t_c/\tau_c}$...............(35)

1.13. Classes of motor duty

There are eight standard classes of duty. Such as

(i) Continuous duty (ii) Short time duty (iii) Intermittent periodic duty (IPD)

(iv)Intermittent periodic duty with starting (v) Intermittent periodic duty with starting and braking (vi) Continuous duty with intermittent periodic load

(vii) Continuous duty withstarting and braking (viii) Continuous duty with periodic speed changer.

(i) Continuous duty

In continuous duty, a motor operates at a constant load torque for a duration long enough for the motor temperature to reach steady state value as shown in figure 1.22. This type of duty is characterized by a constant motor loss.Paper mill drives, compressors conveyers are the examples of continuous duty.

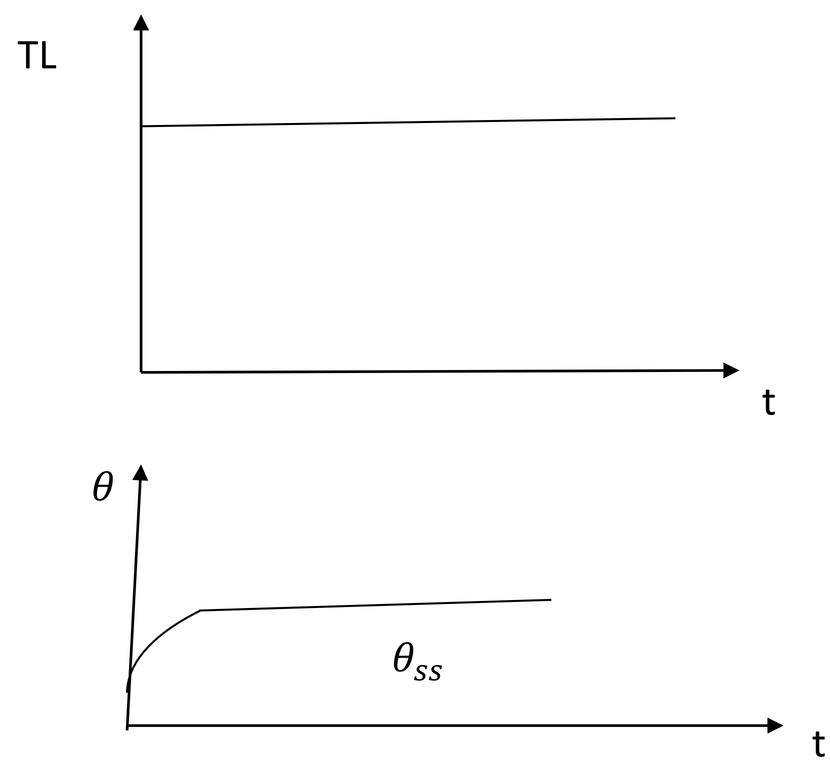


Fig.1.22continuous duty

(ii) Short time duty

In this type of duty , time of drive operation is less than the heating time constant. Machine is allowed to cool off to ambient temperature before the motor is required to operate again. In this type of duty, the machine can be over loaded .Crane drives, valve drives are examples of short time duty.

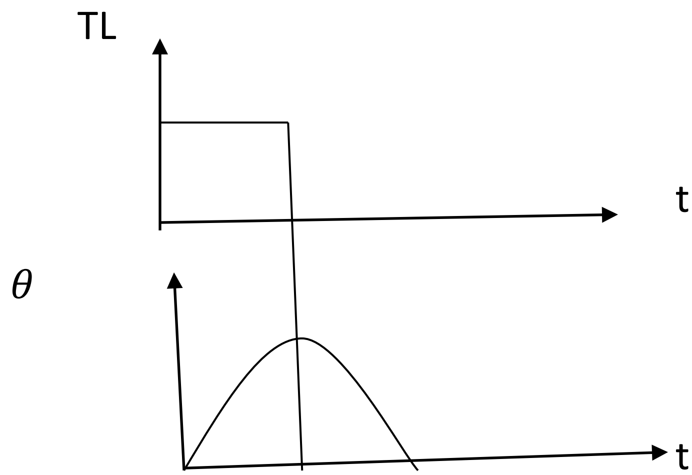


Fig.1.23. Short time duty

(iii) Intermittent periodic duty (IPD).

It consists of periodic duty cycle, each consisting of a period of running at a constant load and then a rest period. Heating of machine during starting and braking operation is negligible. Operation of cutting machine and drilling machine are examples of Intermittent periodic duty.

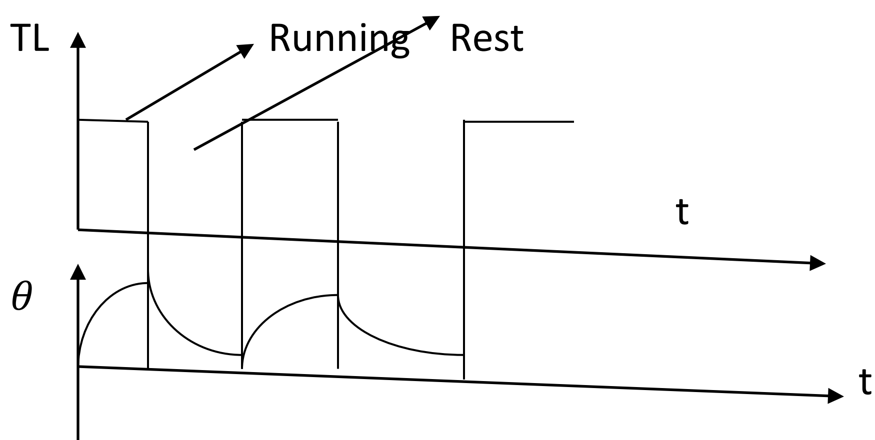


Fig.1.24.Intermittent periodic duty

(iv) Intermittent periodic duty with starting.

This type motor duty possessrunning period followed by a rest period and heating of machine due to starting,can not be ignored. Thus it consists of a period of starting, period of running at constant load and a rest period. Heating of machine due to braking is ignored. Metal cutting, drilling tool drives and mine hoist are examples ofIntermittent periodic duty with starting.

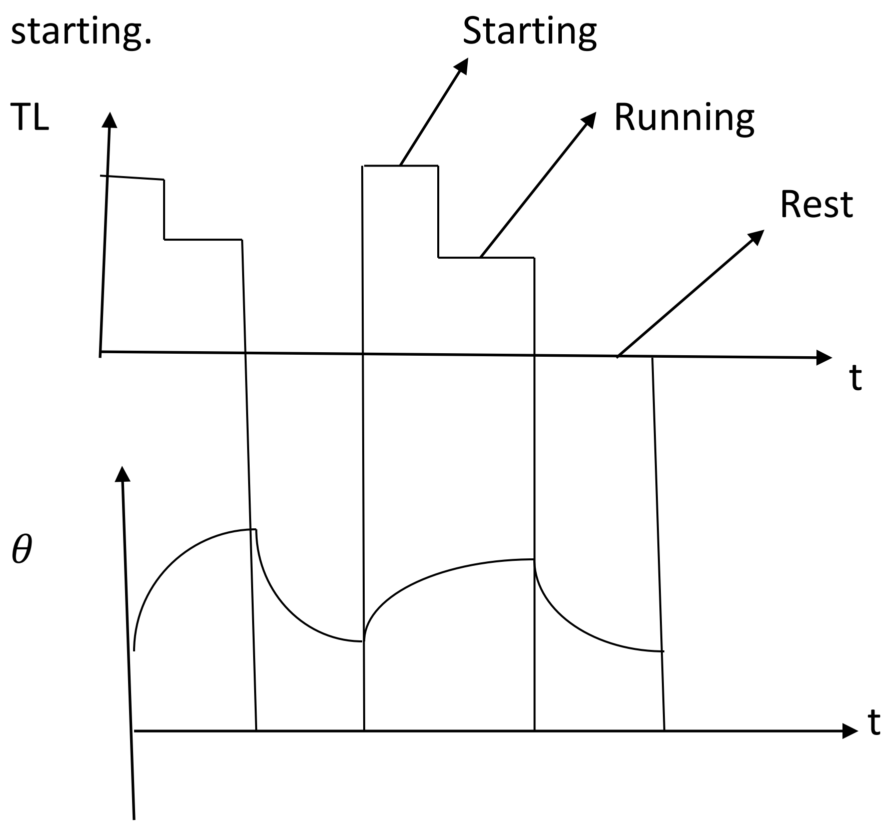


Fig.1.25.Intermittent periodic duty with starting

(v) Intermittent periodic duty with starting and braking:

In this mode of duty heat losses due to starting and braking are considered. Thus it consists of (a) a period of starting (b) a period of operation with a constant load (c) a braking period with electric braking (d) a short rest period as shown in fig.1.26. Billet mill drive, drive for electric train, mine hoist are the examples of Intermittent periodic duty with starting and braking.

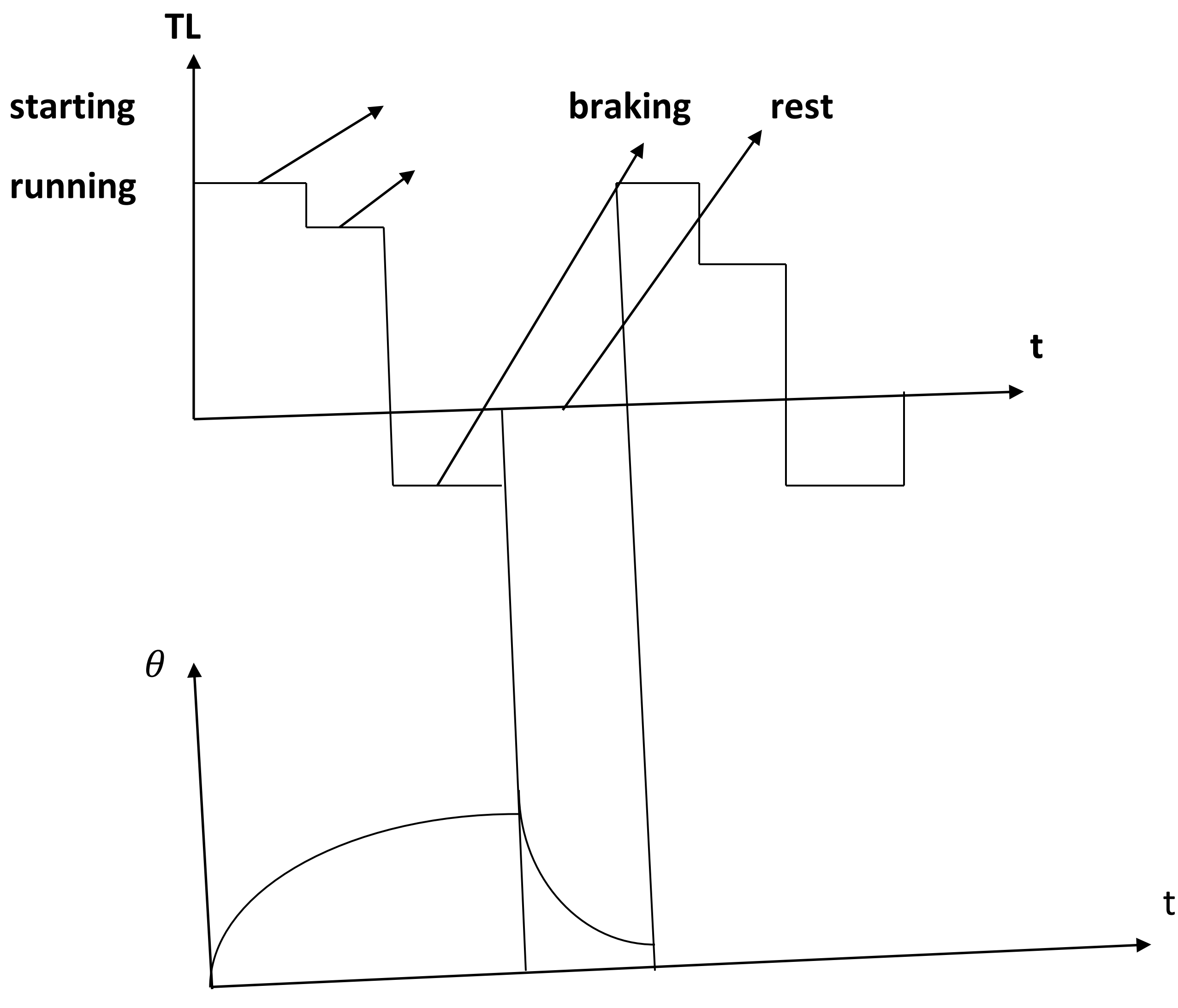


Fig.1.26.Intermittent periodic duty with starting and braking

(vi)**Continuous duty with intermittent periodic load**

It consists of a periodic duty cycle each having a period of running at constant load and a period of running at no load with normal voltage across the excitation winding. Operation of drilling machine, pressing machine, cutting machine are examples of continuous duty with intermittent periodic load.

(vii) Continuous duty with starting and braking.

It consists of periodic duty cycle, each having a period of starting, a period of running at constant load and a period of braking. There is no period of rest. Drive of blooming mill is an example of this type of mode of duty.

(viii) **Continuous duty with periodic speed changes.**

It consists of periodic duty cycle, each having a period of running at different speed & load (1^{st} period) and one speed & load.(2nd period). Both operating periods are too short for respective steady state temperature to be attained. There is no period of rest.

1.14. Determination of motor rating.

For the determination of motor rating, the 8 classes of motor duty can be classified as (a) Continuous duty (b) Fluctuating duty (c) Short time duty and intermittent duty.

(a) Continuous duty.

A motor with same or next higher power rating (from commercially available rating) is selected for continuous duty. In this mode of duty, motor speed should match load's speed requirement and motor should fulfill starting torque requirement.

(b) Fluctuating duty

In this type of load, variable motor current, load torque and power are replaced by their respective equivalent value for numerical analysis.

Equivalent current: Current is directly proportional to load. Due to variable load, current will vary. If I1, I2,………In are fluctuating motor current for duration t1,t2,……,tn respectively, then

Equivalent value of motor current=I = $\sqrt{\frac{I1^2 \ \times t1+I2^2 \times t2+\cdots \ldots\ldots\ldots+In^2 \times tn}{t1+t2+\cdots \ldots+tn}}$

Since Pw +$I^2 \times R$= $\frac{(Pw+I1^2 \ \times R)\times t1+\left(Pw+I2^2 \times R\right)\times t2+\cdots \ldots\ldots\ldots+(Pw+In^2 \times R)\times tn}{t1+t2+\cdots \ldots+tn}$

Where Pw=Constant power loss, R =motor resistance.

If current varies smoothly over a time period T, then

I= $\sqrt{\int_0^T \frac{i^2}{T} dt}$=RMS value

Equivalent Torque(T): When torque is directly proportional to current,

T=$\sqrt{\frac{T1^2 \ \times t1+T2^2 \times t2+\cdots \ldots\ldots\ldots+Tn^2 \times tn}{t1+t2+\cdots \ldots+tn}}$

Equivalent power(P): when motor operates at nearly fixed speed, its power will be directly proportional to the torque. Hence

P=$\sqrt{\frac{P1^2 \ \times t1+P2^2 \times t2+\cdots \ldots\ldots\ldots+Pn^2 \times tn}{t1+t2+\cdots \ldots+tn}}$

Motor rating for Short time duty and intermittent duty.

A motor of smaller rating can be selected for short time duty and intermittent duty as compared to continuous duty since in short time duty, motor is allowed to cool down to the ambient temperature before the motor is required to operate again. Similarly, in intermittent periodic duty, motor is allowed to cool down to the minimum temperature as rest period is provided.

Therefore motor which is used for continuous duty at load ‘x”, may be used for short time duty or intermittent periodic duty at load ‘k x’ , such that maximum temperature rise just reaches the permissible value. Here ‘K’ is a constant which is greater than 1.

Hence it is concluded that the rating of the motor for short-time duty or IPD for load ‘kx’ should be ‘x’. It is also noted that ‘k’ for short time duty is not same for IPD

Value of ‘k’ for short time duty

We haveθ=$\theta_{ss}(1-e^{-t_h/\tau_h})$ +$\theta_0 \times e^{-t_h/\tau_h}$

For short time duty $\theta_0 = 0$= initial temperature of the heating process.

Therefore θ=$\theta_{ss}(1-e^{-t_h/\tau_h})$

$\Rightarrow \frac{\theta}{\theta_{ss}}$ = $1-e^{-t_h/\tau_h}$ ....(36)

At load x, Let constant loss =Pw & Variable loss = Pc

Hence total losses= Pw + Pc , if Pw =$\propto$Pc, then

Pw + Pc =$\propto$Pc +Pc =Pc ($\propto$+1) = P1 ....(37)

For maximum efficiency, $\propto = 1$

At load k x, Pc’=k^2Pc

Therefore total losses at load (k x) be

Pc' +Pw =k^2Pc +∝Pc =(∝ $+k^2)\ Pc$ =P1k……………..(38)

As temperature is directly proportional to power loss, from equation (37) &(38),we get

$\frac{\theta}{\theta_{ss}} = \frac{P1}{P1k} = \frac{\propto+1}{\alpha+k^2}$……………………..(39)

Where θ= temperature at normal load(x) &θ_{ss}=temperature at over load(kx).

From equation (36) and (39), we obtain

$$k = \sqrt{\frac{1+\propto e^{\frac{-th}{\tau h}}}{1-\alpha e^{th/\tau h}}} \quad \text{………………………..(40)}$$

<u>Value of 'k' for Intermittent periodic duty</u>

We haveθ=$\theta_{ss}(1-e^{-t_h/\tau_h})$ +$\theta_0 \times e^{-t_h/\tau_h}$ ……………………..(41)

For IPD,$\theta_0 =$ initial temperature of the heating process

During cooling,θ_0=$\theta ss'(1-e^{-t_c/\tau_c})$ +$\theta \times e^{-t_c/\tau_c}$………………(42)

During rest motor is disconnected from supply, $\theta_{ss'}$ =$\frac{P1'}{D'}$ =0. In this situation,thermal model for cooling will be θ_0=$\theta \times e^{-t_c/\tau_c}$……………(43)

Substituting the value of $\theta_0$from equation (41) in(43), we get

θ=$\theta_{ss}(1-e^{-t_h/\tau_h})$ +$\theta \times e^{-t_c/\tau_c} \times e^{-t_h/\tau_h}$

⇨ $\frac{\theta}{\theta_{ss}} = \frac{1-e^{-th/\tau h}}{1-e^{-(\frac{tc}{\tau c}+\frac{th}{\tau h})}}$………………………………..(43)

$From$ Equation (39) & (43), we get

$$\frac{\alpha+1}{\alpha+k^2} = \frac{1-e^{-th/\tau h}}{1-e^{-(\frac{tc}{\tau c}+\frac{th}{\tau h})}}$$

$$\Rightarrow K = \sqrt{(1+\alpha)[\frac{1-e^{-(\frac{tc}{\tau c}+\frac{th}{\tau h})}}{1-e^{-th/\tau h}}] - \alpha} \text{.......................(44)}$$

NUMERICAL PROBLEMS

(1) A motor is used to drive a hoist. Motor characteristics (C/Cs) are given by quadrant 1 &2 is T=(200-0.2× N) N-m

In 3rd& 4th quadrant, T= $-200 - 0.2 \times N$, N-m. Where N is the speed of motor in rpm. When hoist is loaded the net load torque, T_L =100, N-m and when it is unloaded, the net load torque T_L=−80, N-m. Obtain the equilibrium speed for rotation in all four quadrants if in 1st&4th quadrant cages are loaded and in 2nd&3rd cages are empty.

Solution: For equilibrium speed, $\frac{d\omega_m}{dt}$ =0, Hence T=T_L

In 1st quadrant, T=(200-0.2× N) N-m and T_L =100, N-m for loaded cage.

Therefore 200-0.2× N=100 => N=500 rpm

In 2nd quadrant, T=(200-0.2× N) N-m and T_L=−80 N-m for empty cage

Therefore 200-0.2× N==−80 => N=1400 rpm

In 3rd quadrant, T=(−200-0.2× N) N-m and T_L=−80 N-m for empty cage

Therefore -200-0.2× N==−80 => N= -600 rpm

In 4th quadrant, T=(−200-0.2× N) N-m and T_L =100, N-m for loaded cage

Therefore =(−200-0.2× N)=100 => N= -1500 rpm

(2) A motor drives 2 loads, load one has rotational motion and it is coupled to the motor through a reduction gear with a=0.1 efficiency=90%, moment of inertia is 10Kg-m^2 and torque =10, N-m.

Load 2 has translational motion and consists of 1000 kg weight to be lifted up at an uniform speed of 1.5 m/sec. Coupling between this load and the motor has an efficiency of 85%. Motor has a moment of inertia of 0.2kg-m^2 and runs at a constant speed of 1420 rpm. Determine the equivalent inertia referred to the motor shaft and power developed by the motor.

Solution: Given data

J1=10Kg-m^2, J0= 0.2 Kg-m^2, a=0.1, m=1000 kg, v=1.5 m/sec,

N=1420rpm=>ω_m=$\frac{2\pi N}{60}$=$\frac{2\pi\times 1420}{60}$=148.7 rad/sec

$\eta_1 = 0.9$, η_2=0.85

We have, J= $J_0 + a^2 \times J_1 + m(\frac{v}{\omega_m})^2$

Substituting values of given parameter, we get J=0.4 Kg-m^2

We have,

Torque T= T_{L0} +$\frac{a}{\eta 1} \times T_{L1}$ +F× $\frac{v}{(\omega_{m)} \times \eta_2}$

Now substituting the given values, we get

T= 0+$\frac{0.1}{0.9} \times 10 + 1000 \times 9.81 \times \frac{1.5}{148.7 \times 0.85}$=117.53, N-m

Power P=$\omega_m \times T$= 148.7$\times$ 117.53 =17476.7 watt=17.477 Kw

(3)A drive has following equations for motor and load torque. Obtain the equilibrium points and determine their steady state stability.

T= $-1-2 \times \omega_m$ and T_L=$-3\sqrt{\omega_m}$

Solution: At equilibriumT= T_L

Therefore $-1-2 \times \omega_m = -3\sqrt{\omega_m}$

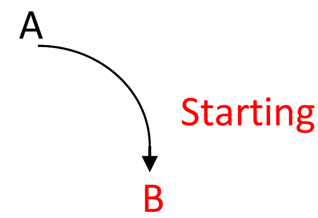
⇨ $(-1 - 2 \times \omega_m)^2$ =$(-3\sqrt{\omega_m})^2$
⇨ ω_{m1}=1 and ω_{m2}=0.25
$At\omega_{m1}$=1, T= -3 and at ω_{m2}=0.25, T= -1.5 since T= $-1-2 \times \omega_m$
Therefore equilibrium points are (-3,1) and (-1.5,0.25)
For steady state stability, $\frac{dT_l}{d\omega_m}$>$\frac{dT}{d\omega_m}$

$\frac{d(-3\sqrt{\omega_m})}{d\omega_m}$>$\frac{d(-1-2\times\omega_m)}{d\omega_m}$
⇨ $\frac{-3}{2\times\sqrt{\omega_m}}$>$-2$
⇨ ω_m>0.5625
Therefore (-3,1) is stable and (-1.5,0.25) is unstable.

(4) Calculate the starting time of a drive with following parameters.

J= 10kg-m^2,T=15+0.5 ω_m and T_L=5+0.6 ω_m

Solution: Starting is a transient phenomenon. Suppose this process is initiated at point A and completed at point B. At point A , speed is zero& at B the body is in steady state ie speed is ω_m . During A-B it is a transient phenomenon.



Therefore at B, T=T_L => 15+0.5 ω_m=5+0.6 ω_m

⇨ $\omega_m = 100\ rad/sec$=ω_{m2},It is worth noted that, practically the starting process is completed when the motor speed is 95% calculated speed. Hence ω_{m2}=95%100 =95 and ω_{m1}=0

During A-B,

T $-T_L$=J $\frac{d\omega_m}{dt}$

=>$\int_0^t dt$ =$J \int_0^{95} \frac{d\omega_m}{\mathrm{T} - T_L}$ = $10 \int_0^{95} \frac{d\omega_m}{15+0.5\ \omega_m - 5 - 0.6\omega_m}$

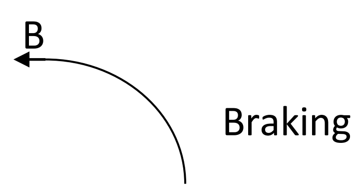
=> t=299.56 sec= starting time

(5) A drive has following parameters.

J= 10kg-m^2,T=15+0.05 N and T_L=5+0.06 N, N-m, where N is the speed in rpm. Initially the drive is working in steady state. Now the drive is braked by electrical braking. Torque of the motor in braking is given by T= -10-0.04N, N-m. Calculate time taken by the drive to stop.

Solution:

Braking is a transient phenomenon. Suppose this process is initiated at point A and completed at point B. At point A , speed isω_m& at B the body is in restie speed is zero . During A-B it is a transient phenomenon.



At point A,T=T_L. Therefore 15+0.05 N=5+0.06 N

⇨ N= 1000 rpm=N1

At point B, N=0=N2

During A-B,

$T_B - T_L$=J $\frac{d\omega_m}{dt}$, Since during braking T=T_B

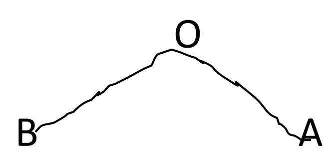
=>$\int_0^t dt$ =$J \int_{1000}^{0} \frac{d(\frac{2\pi N}{60})}{T_B - T_L}$ = $10 \frac{2\pi}{60} \int_{1000}^{0} \frac{dN}{-10-0.04\text{N}-5-0.06N}$

=> t=21.33 sec=Braking time

(6)A drive has following parameters, J=10 Kg-m^2

T=(100-0.1× N) N-m, where N is speed of motor in rpm, passive load torque=T_L=0.05 N, N-m. Initially the drive is operating in steady state. Now it is to be reversed, for this motor characteristic is changed to T= $-100 - 0.1 \times N, N - m$. Calculate the time of reversal.

Solution: Speed reversal is a transient phenomenon.



During steady state operation $\frac{d\omega_m}{dt}$ =0, Hence T=T_L

Let initial speed =N_1

Therefore 100$-0.N_1$ =0.05N_1, Here N is replaced by N_1

⇨ $N_1 = 666.67\ rpm$

<u>After reversal</u>

Let final speed =N_2 , since T=T_L (During reversal, it is transient. But after reversal steady state operation will be there.)

So, $-100 - 0.1 \times N_2$=0.05N_2

⇨ $N_2 = -666.67\, rpm$

<u>During reversal(i.etransient operation)</u>

T $-T_L$=J $\frac{d\omega_m}{dt}$ =J $\frac{d(2\pi N/60)}{dt}$ =$\frac{2\pi J}{60}\frac{dN}{dt}$

Since the process is associated with reversal, we should consider the motor characteristic during reversal, which is T= $-100 - 0.1 \times N$

Hence$\frac{2\pi J}{60}\frac{dN}{dt}$=$-100 - 0.1 \times N$ −0.05N

⇨ $\int_0^t dt\ \int_{N1}^{N2} \frac{2\pi\times 10}{60} \times \frac{dN}{-100-0.15\times N}$ ....(1)

⇨ It worth noted that, practically the reversal process is completed when the motor speed is 95% calculated speed. Hence $N_2 = -666.67 \times 0.95 = -633.365\, rpm.$ N1=$666.67\, rpm,$ $N_2 = -633.365$

Solving equation(1), we get
t=25.5 sec = reversal time

(7)A 6 pole 50 Hz, 3phase wound rotor induction motor has a flywheel coupled to its shaft. The total moment of inertia of motor-load-flywheel is 1000 kg-m^2. Load torque is 1000, N-m of 10 sec duration followed by a no load period which is long enough for the drive to reach its no load speed. Motor has a slip of 3% at a torque of 500, N-m. Calculate (a) maximum torque developed by the motor. (b)speed at the end of deceleration period.

Solution: Given data

Number of pole=P=6, frequency=f=50Hz, Moment of inertia=J=1000 kg-m^2

Torque during heavy load=T_{Lh}=1000, N-m, time for heavy load=t_h=10 sec, No load torque= T_{min}=T_0=0, Slip=s=3%=0.03, Rated torque = T_r =500, N-m.

Synchronous speed =Ns =$\frac{120\,f}{P}$ = $\frac{120\times50}{6}$ =1000 rpm.

Therefore angular speed at no load = ω_{m0} =$\frac{2\pi Ns}{60}$ =104.71 rad/sec

Hence rated speed =ω_r= (1-s)ω_{m0} =(1 -0.03) 104.71=101.57 rad/sec

(a) we have

$$J = \frac{T_r}{\omega_{mo} - \omega_r}\left[\frac{-t_h}{\ln\left(\frac{T_{Lh} - T_{\max}}{T_{Lh} - T_{min}}\right)}\right] \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

By substituting the given values in equation (1) & by solving it, we get T_{max}=797.24, N-m

(b) Speed at the end of deceleration period I.e at T_{max} as Fig.1.11

Change in speed =$\Delta\omega_m$= $\frac{\omega_{mo} - \omega_{mr}}{T_r} \times T_{max}$ =$\frac{104.71-101.57}{500} \times 797.24$ =5 rad/sec

So speed at the end of deceleration period =ω_m =$\omega_{mo} - \Delta\omega_m$=104.71$-$5 =99.71 rad/sec =952.06 rpm

(8) A motor equipped with a flywheel has to supply a load torque of 1000, N-m for 10 sec followed by a light load period of 200, N-m long enough for the flywheel to regain its steady state speed. It is desired to limit the motor torque to 700, N-m. What should be the moment of inertia of the flywheel? The no load speed of the motor is 500 rpm and it has a slip of 5% at torque of 500, N-m. Motor has an inertia of 10 kg-m^2.

Solution:

Given data

Moment of inertia of motor=J_m=10 kg-m^2

Torque during heavy load=T_{Lh}=1000, N-m, time for heavy load=t_h=10 sec, Light load torque = T_{LL}=T_{min}=200,N-m, Slip=s=5%=0.05, Rated torque = T_r =500, N-m.Synchronous speed =Ns=500 rpm

Therefore angular speed at no load = ω_{m0} =$\frac{2\pi Ns}{60}$ =52.36 rad/sec

Hence rated speed =ω_r= (1-s)ω_{m0} =(1 -0.05) 52.36=49.74 rad/sec

we have,

$$J = \frac{T_r}{\omega_{mo} - \omega_r}\left[\frac{-t_h}{\ln(\frac{T_{Lh} - T_{\max}}{T_{Lh} - T_{min}})}\right] \ldots\ldots\ldots\ldots\ldots(1)$$

By substituting the given values in equation (1) & by solving it, we get

J=1945.697kg-m^2

Therefore moment of inertia of flywheel

=J_F =$J - J_m$=1945.697$-$10 =1935.697kg-m^2

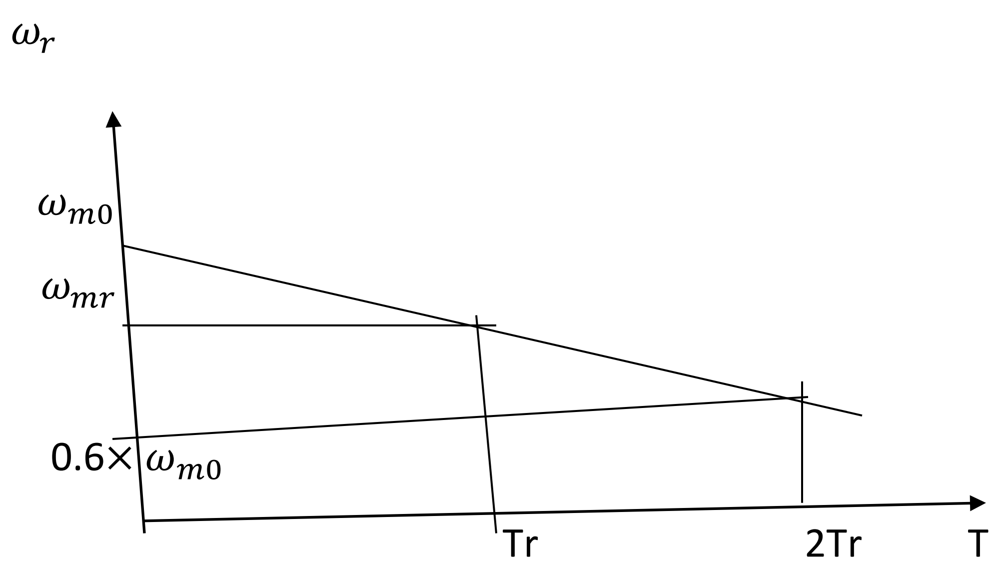
(9)A 6 pole,50 Hz, 3phase,100kw,wound rotor induction motor has a flywheel coupled to its shaft. It drives a load whose torque varies such that a torque of 3000, N-m of 10 sec duration is followed by a torque of 500, N-m of duration long enough for the motor to attain steady state speed. Calculate the moment of inertia of the flywheel, if motor torque should not exceed twice the rated value. Moment of inertia of the motor is 10kg-m^2.Minimum motor speed is to be restricted to 60% of the synchronous speed.

Solution:

Torque during heavy load=T_{Lh}=3000, N-m, time for heavy load=t_h=10 sec, Light load torque = T_{LL}=T_{min}=500,N-m

Synchronous speed =Ns =$\frac{120\ f}{P}$ = $\frac{120\times50}{6}$ =1000 rpm.

Therefore angular speed at no load = ω_{m0} =$\frac{2\pi Ns}{60}$ =104.71 rad/sec.



It is given that maximum torque =2Tr and minimum speed =0.6ω_{m0}

Therefore, referring above fig, we get

$\frac{\omega_{mo}\ -\omega_{mr}}{Tr}\times 2Tr$= $\omega_{mo}\ _{-0.6}\omega_{mo}$ = change in speed at (2Tr)

- ⇨ ω_{mr}= 0.8 ω_{m0}
- ⇨ ω_{mr}= 0.8× 104.71 =83.73 rad/sec

  Power =P =$\omega_{mr}\times Tr$
- ⇨ Tr=$\frac{P}{\omega_{mr}}$ =$\frac{100{,}000}{83.73}$ =1194.315, N-m

Therefore Tmax =2 Tr =2388.63, N-m

We have, J =$\frac{T_r}{\omega_{mo} - \omega_r}$ [$\frac{-t_h}{\ln(\frac{T_{Lh} - T_{\max}}{T_{Lh} - T_{min}})}$]................(1)

By substituting the given values in equation (1) & by solving it, we get

J=405kg-m^2

Therefore moment of inertia of flywheel

=J_F =$J - J_m$=405−10 =395kg-m^2

(10)A constant speed drive has the following duty cycle:

(i) Load rising from 0 to 400kw in 5 min

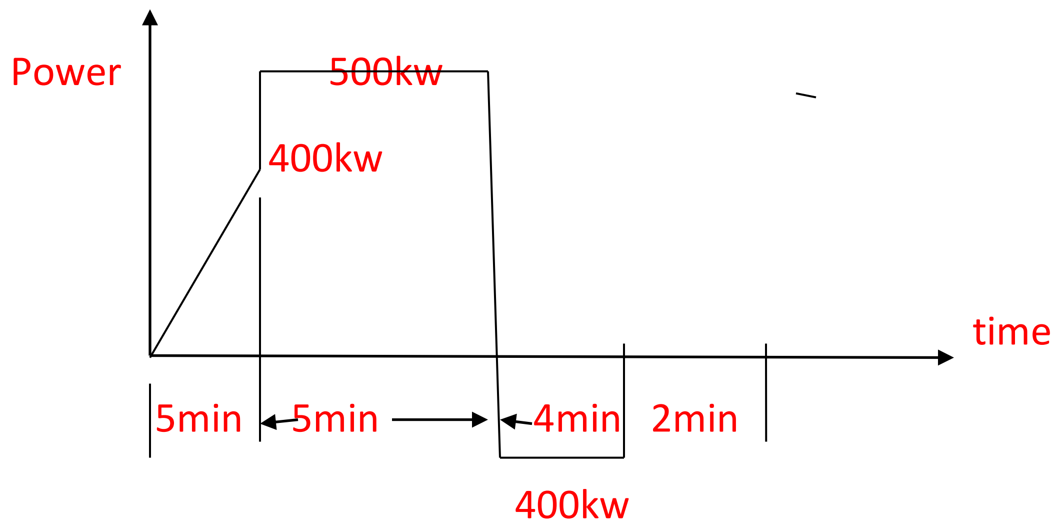
(ii) uniform load of 500kw in 5 min

(iii) Regenerative power of 400kw return to the supply in 4 min

(iv) Remains ideal for 2 min

Estimate power rating of the motor if losses to be proportional to square of power.

Solution:



(I) LOAD is rising linearlyi.e variable power

Hence instantaneous power P1(t)=(400/5)t=80t, (equation of straight line passing through origin)

Rms value of power = P1= $\sqrt{\int_0^5 P1(t)^2 \;\; dt/5}$ = $\sqrt{\int_0^5 (80t)^2 \;\; dt/5}$ =230.94kw

(ii) P2=500kw, t2=5min (iii) P3= -400kw, t3=4min (iv) P4=0, t4=2min

Hence equivalent power =$\sqrt{(P1^2 \;\; \times t1 + p2^2 \;\; \times t2 + P3^2 \times t3 + P4^2 \times t4)/(t1 + t2 + t3 + t4)}$

=$\sqrt{(231^2 \;\; \times 5 + 500^2 \;\; \times 5 + (-400)^2 \times 4 + 0^2 \times 2)/(5 + 5 + 4 + 2)}$

= 367.139 kw= Prms. In this type of duty , maximum power= 500kw is less than two times of Prms,hence motor rating is 367 kw

(11) A motor has a heating time constant of 60 min and cooling time constant of 90 min. when run continuously on full load of 20kw, the final temperature rise is 40degree C.

(i) What load motor can delivery for 10 min if this is followed by a shut down period long enough for it to cool?

(ii) If it is on an intermittent load of 10min followed by10minshut down, what is the maximum value of load it can supply during the on load period?

Solution:

Heating time=t_h=10min,Cooling time constant=τ_c=90min,Heating time constant=τ_h=60 min

Cooling time constant is greater than heating time constant. Hence motor operates in short time duty. Constant loss and copper loss are not given separately ,α=0.

Therefore, over loading factor = K= $\sqrt{\frac{1}{1-e^{th/\tau h}}}$ = $\sqrt{\frac{1}{1-e^{-10/60}}}$=2.552

Permitted load =2.55× 20=51 kw

(ii) Intermittent periodic duty.

Heating time=t_h=10min,cooling time=t_c=10min,Cooling time constant=τ_c=90min,Heating time constant=τ_h=60 min,α=0.

Hence over loading factor=K = $\sqrt{(1+\alpha)[\frac{1-e^{-\left(\frac{tc}{\tau c}+\frac{th}{\tau h}\right)}}{1-e^{-th/\tau h}}]-\alpha}$

= $\sqrt{[\frac{1-e^{-\left(\frac{tc}{\tau c}+\frac{th}{\tau h}\right)}}{1-e^{-th/\tau h}}]}$ =1.256

Hence maximum value of load it can supply is 1.256×20=25.12 kw

(12) Half hour rating of a motor is 100kw. Heating time constant is 80 min. Maximum efficiency occurs at 70% full load. Determine the continuous rating of the motor.

Solution:

Heating time=t_h=30min,Heating time constant=τ_h=80 min

Since heating time is much smaller than heating time constant, the motor operates in short time duty mode. Let Pw=constant loss in kw, Pc= full load copper loss in kw.Maximum efficiency occurs at 70% full load .As we know, at maximum efficiency copper loss=constant loss,0.7^2Pc =Pw => Pw/Pc =0.49=α

Hence over loading factor $k = \sqrt{\frac{1+\propto e^{\frac{-th}{\tau h}}}{1-\alpha e^{th/\tau h}}}$ = $k = \sqrt{\frac{1+0.49e^{\frac{-30}{80}}}{1-0.49e^{30/80}}}$

$k = \sqrt{\frac{1+0.49\times0.687}{1-0.49\times1.455}}$ =2.1584

Therefore continuous rating =100/2.1584=46.33 kw

Electrical Drive (Module 2)

Syllabus:

2.1 Steady state performance of DC/AC drives: DC Motors and their performances-starting-braking-transient analysis, Speed control-methods of armature voltage control, controlled rectifier fed DC drive.

2.2. Induction motor drives-speed control-pole changing-pole amplitude modulation, stator voltage control, variable frequency control from voltage source, voltage source inverter control, variable frequency control from current source, current source inverter control, current regulated voltage source inverter control, rotor resistance control, slip power recovery.

2.1. Steady state performance of DC/AC drives

Drives employing DC motor as prime mover are known as DC drives. DC drives are classified as (a) 1-phase DC drives (b) 3-phase DC drives (c) Chopper Drives as regards to main power source. DC motors have variable characteristics and are used extensively in variable speed drive. DC motor can provide a high starting torque and it is also possible to obtain speed control over a wide range.

Drives employing AC motor as prime mover are known as AC drives. AC drives are classified as (a) Induction motor drives (b) Synchronous motor drives. AC motors are light weight, inexpensive and low maintenance compared with DC motors. They require control of frequency, voltage and current for variable speed applications. AC drives are replacing DC drives and used in many industrial & domestic applications.

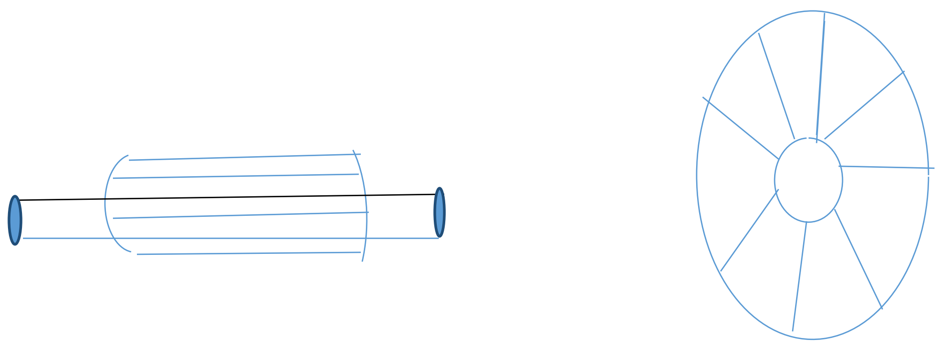
2.1.1. DC motors and their performances. DC motors are extensively used in adjustable speed drives and position control applications. Depending upon the type of ac source or the method of voltage control, DC drives are classified as (a) 1 phase DC drive (b) 3 phase DC drive (c) Chopper drive.

Different types of DC motor

(a) Shunt-wound DC motor: It is a constant speed motor. Starting torque is not high. It can be used in Lathes, drills, boring mills, spinning mills, weaving mills.
(b) Series wound motor: It is a variable speed motor and it possesses high starting torque. It can be used in elevator, electric traction, cranes, vacuum cleaners, hair driers etc.
(c) Compound Motor: Cumulative compound motors are used where constant speed is required with irregular loads or suddenly applied heavy loads. It is used in reciprocating machines. Differential compound motor is no longer used in practice.
(d) Permanent magnet DC (PMDC) Motor: In PMDC motor, field excitation is obtained by a permanent magnet mounted on the stator. Ferrites or rare earth (Samarium cobalt) magnets are used. In this type of motor, field flux remains constant for all loads. So speed torque c/c is more linear. As the flux is constant, speed cannot be controlled above base speed.
(e) DC servomotors: Normal Dc motor fails to provide good dynamic response and steady state accuracy when employed in a closed loop drive. But a servomotor is designed to achieve good dynamic response and steady state accuracy when employed in a closed loop drive in both directions of rotation. These motors are used in closed loop speed and position control system. Their ratings can be from few watts to megawatt.

(f) Moving coil motor: It is a high accelerated motor. It is classified as (i) Shell type (ii) Disc type

(i) Shell type: In this type of motor, rotor consists of only armature winding. So it has very low inertia. The commutator has cylindrical construction. It has large axial length and small diameter. Direction of flux is axial and armature current is radial.



(SHELL TYPE) (DISC TYPE)

Fig2.1

(ii) Disc Type: In this type of MC motor, armature is made in disc or pancake forms and armature conductors resemble spokes on a wheel. In this case, direction of flux is axial and armature current is radial. Due to lower inertia and low armature inductance, it possesses an excellent dynamic response. Where axial space is at a premium, this type of motor is used. It has small axial length and large diameter.

(g) Universal Motor: It is essentially a dc series motor. Most universal motors are manufactured for use at speed in excess of 3000rpm which is equal to the maximum speed of an induction motor. These motors are used in fans, electric drills, home appliances.

(h) Torque motor: DC motor designed to run long periods in a low speed is known as torque motor. It is based on brushless technology and designed for low speed operation where as a normal DC motor is designed to optimize full speed performance. It possesses high torque at low speed and silent operation. Vibration is reduced. Gear box is not needed. It is used to drive crushers, mixers etc.

BASIC PERFORMANCE EQUATIONS OF DC MOTORS

The Dc Motors used in conjunction with power electronics converters are DC separately excited motors or DC series motors.

DC separately excited motors: The equivalent circuit for a separately excited dc motor coupled with a load as shown in Fig2.2.

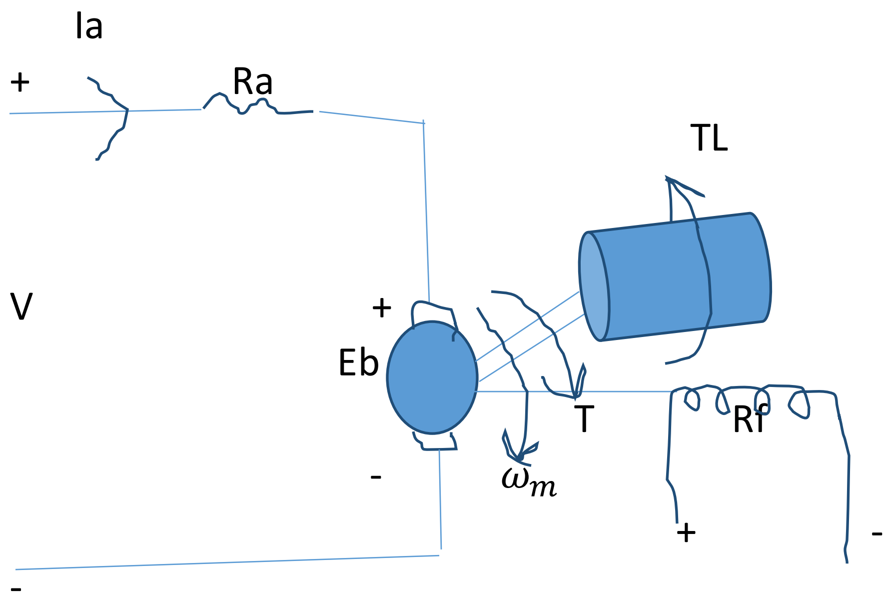


Fig.2.2

For armature circuit, V = Eb + Ia Ra

But Eb $=\frac{P\emptyset NZ}{60\ A}=\frac{P\emptyset\times 60\times\omega_m Z}{60\ A\times 2\pi}$, As $\omega_m=2\pi N/60$

Hence Eb=Ka$\times\ \emptyset\times\omega_m$=K$\times\ \omega_m$

Where Ka is the armature constant or (K) is the motor constant`

Therefore, V = K$\times\ \omega_m$+ Ia Ra……………………………(1)

Torque= T=Ka$\times\ \emptyset\times Ia$=K$\times\ Ia$………………………(2)

Rotational Power =P =T$\times\ \omega_m$………………………………..(3)

Angular Speed=$\omega_m=\frac{V-Ia\times Ra}{K}$………………………………(4)

(b) DC series motor:

For a series motor, field winding in series with armature circuit is designed to carry the rated armature current .The equivalent circuit of a DC series motor driving a load is shown in fig 2.3.

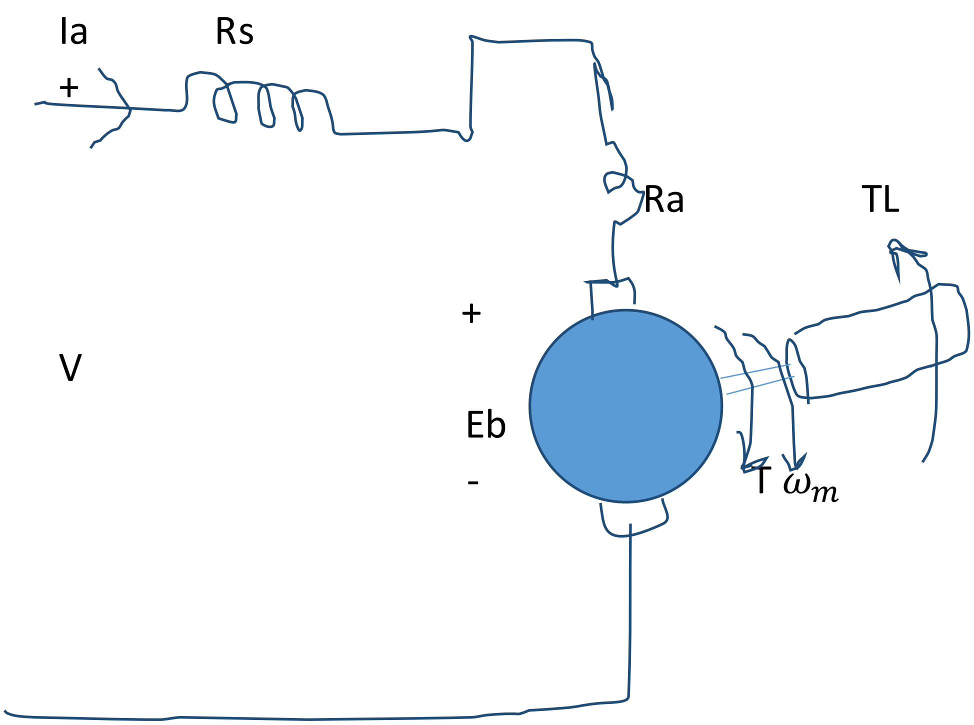


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Fig.2.3

For the armature circuit, V = Eb + Ia (Ra+Rs) ……………………………(5)
And Eb=Ka$\times$ $\emptyset \times \omega_m$=K2$\times$ $Ia \times \omega_m$, since $\emptyset\ \alpha\ Ia$ =>$\emptyset = K1\ Ia$.
Hence K2=Ka$\times$ $K1$
⇨ ω_m=$\frac{Eb}{K2Ia}$ ………………………………………(6)
⇨ T =Ka$\times$ $\emptyset \times Ia$=K2 $\times Ia^2$………………(7)

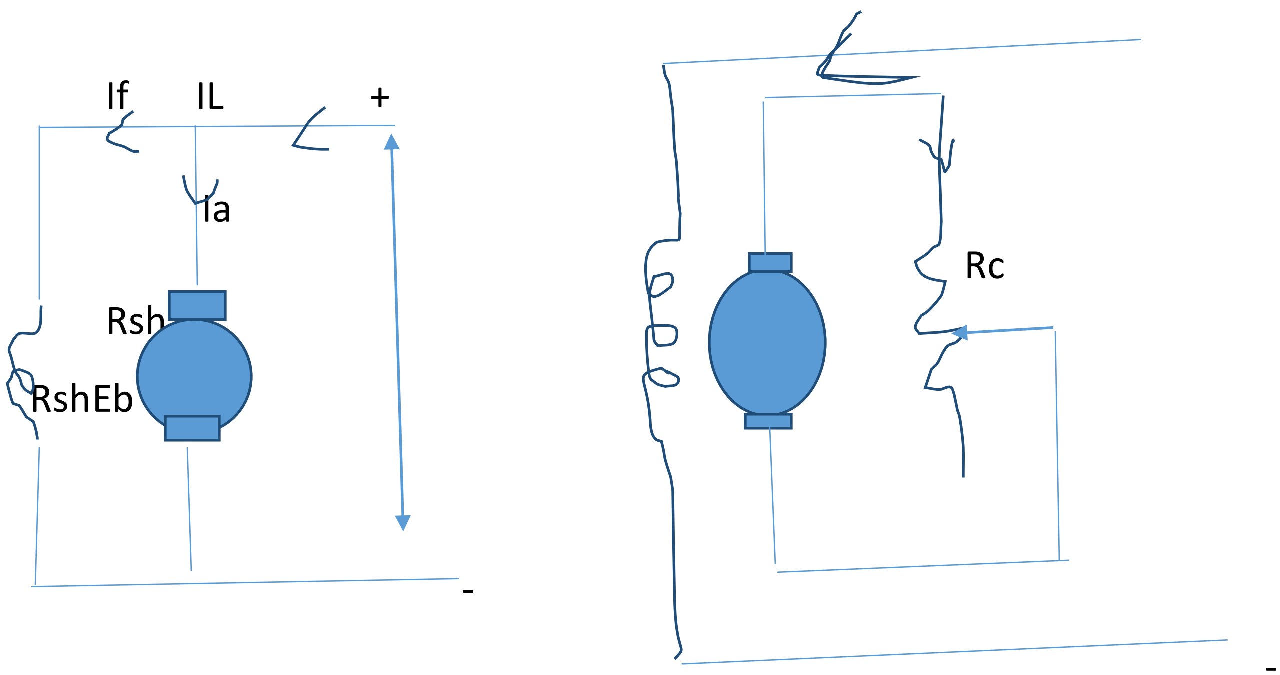
2.1.2. STARTING AND BRAKING:

STARTING: If a current carrying conductor is placed inside a magnetic field, it experiences mechanical force. The developed mechanical force is equal to the product of magnetic flux density (B), current through the conductor (I) and effective length of the conductor (L).

Similarly, mechanical force is developed in each conductor of the armature of a dc motor, when it is placed inside a magnetic field. The mechanical force of each conductor of the armature add together to produce a driving torque. Due to this driving torque, armature of the dc motor starts to rotate. Thus electrical energy is converted into mechanical energy. DC motor is started with the help of starter to limit the high initial starting current.

BRAKING: Sometimes it is desirable to stop a dc motor quickly. The motor and its load may be brought to rest quickly by using either friction braking or electrical braking. But, in friction braking, it is difficult to achieve a smooth stop because it depends on the condition of the braking surface which does not happen in case of electrical braking. In electrical braking, the motor works as a generator developing a negative torque which opposes the motion. Different types of electric braking are (a) Rheostat or dynamic braking (b) Plugging or reverse voltage braking (c) Regenerative braking.

DYNAMIC BRAKING: In this method, the armature of the running motor is disconnected from the supply and connected across a variable register. However the field winding is left connected to the supply as shown in Fig,2.4.



Motoring   Dynamic Braking

Fig.2.4

When armature is disconnected from supply, it rotates in a strong magnetic field with low speed due to inertia of motion. Therefore it operates as a generator and sends large current through resistance Rc. As a result, the kinetic energy possessed by the rotating armature to be dissipated quickly as heat in the resistance. Hence motor is brought to stand still quickly.

$I_a = \frac{E_b}{R_{a} + R_c} = \frac{Ka \times \emptyset \times \omega_m = K \times \omega_m}{Ra+Rc}$------------(8)

Braking torque T_B=K3Ia∅ =K4$\omega_m \emptyset^2 - - - - - - - - (9)$

K3,K4 are constants. K4=K3Ka/(Ra+Rc)

For Shunt motor, ∅ remains constant.

Therefore, $T_B \propto \omega_m$, So braking torque deceases as the motor speed decreases.

REGENERATIVE BRAKING

In this type of braking system, motor runs as generator during braking. As a result the kinetic energy of the motor is converted into electrical energy and returned to supply.

In this method, field winding is disconnected from the supply and field current is increased by exciting it from another source. Hence new induced emf exceeds the supply voltage and machine feeds energy into supply. The direction of armature current reverses but the direction of shunt field current remains unchanged. Hence torque is reversed and speed falls and generated emf falls. When generated emf is equal to supply voltage, torque will be zero and motor is brought to stand still. Thus braking is provided up to the speed at which induced emf is greater than supply voltage.

PLUGGING OR COUNTER CURRENT BRAKING

This involves the sudden reversal of the connection of either field or armature winding during motor operation for braking. It is common practice to reverse armature connection. Due to the reversal of armature connections, applied voltage(V) and back emf (Eb) start acting in the same direction around the circuit. The direction of armature current reverses but magnitude increases. Hence speed reduces with increase in torque for constant power drive. When speed decreases, back emf decreases, armature current decreases and torque which will be present in the circuit may not be sufficient to drive the motor. Hence motor is brought to stand still. In order to limit the armature current to a reasonable value, it is necessary to insert a resistor (Rb) in the circuit.

Hence Ia= (V+Eb)/(Ra+Rb)

When polarity of V is changed, the direction of rotation will be reversed. Hence angular speed reduces with increase in torque.

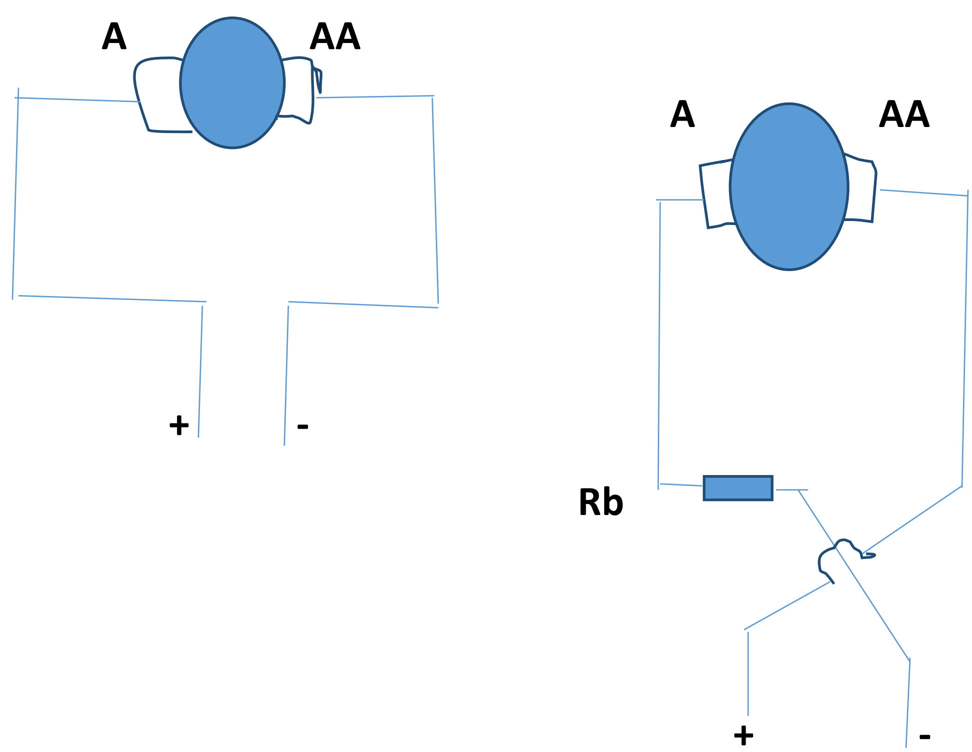


Fig.2.5

2.1.3. **TRANSIENT ANALYSIS**.- Starting, braking, speed changing, load changing are the transient operation which commonly occur in an industrial drive.

Dynamic equivalent circuit of a dc motor is shown in fig.2.6

Voltage equation of the armature circuit under transient is given by

V= iaRa +La(dia/dt) +Eb

=>V= iaRa +La(dia/dt) +Ka$\times \emptyset \times \omega_m$……………….(10)

For the dynamic of motor load system,

J$\frac{d\omega_m}{dt}$ =T-TL -B$\times \omega_m$, But T=Ka$\times \emptyset \times ia$. Where B is the viscous friction.

Therefore, J$\frac{d\omega_m}{dt}$ =Ka$\times \emptyset \times ia$-TL -B$\times \omega_m$……………………..(11)

Equations (10) & (11) are valid for any type of dc motor. Solving these equations, we can obtain the expression for speed and armature current of dc motor under transient condition.

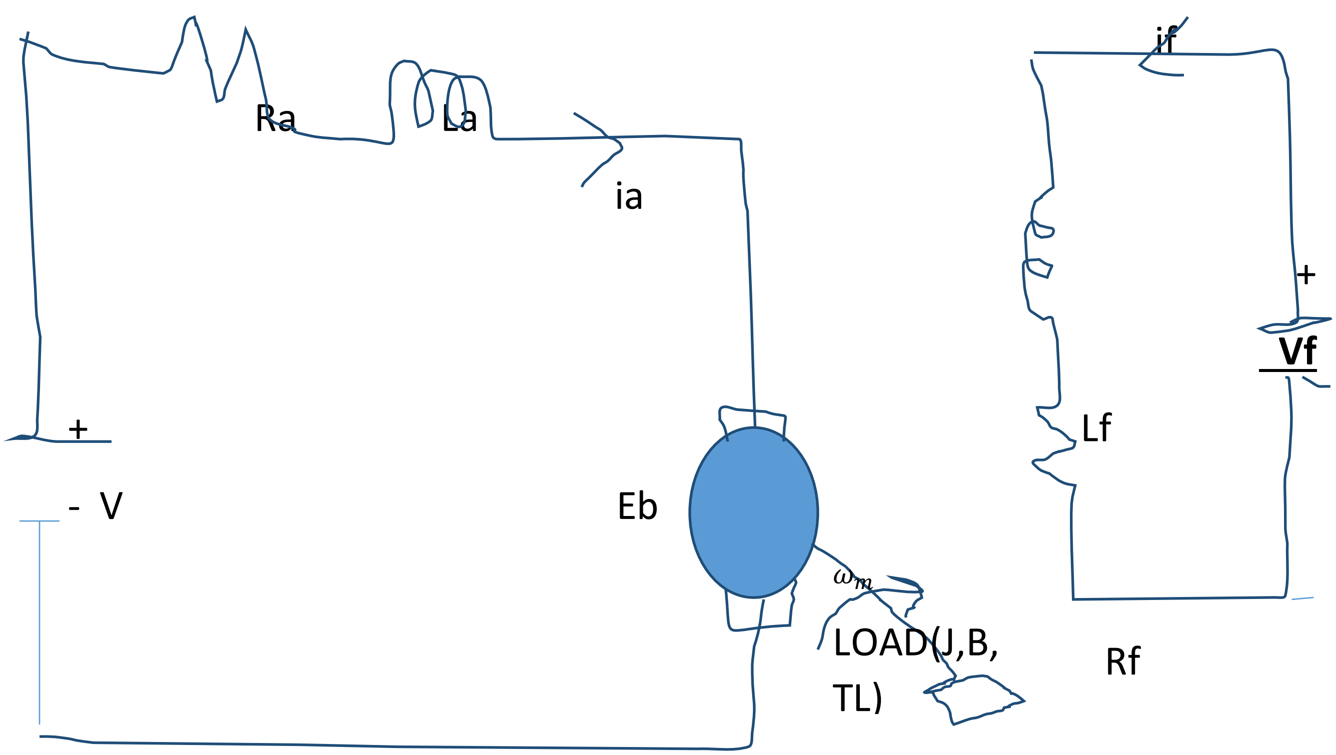


Fig.2.6

Transient analysis of separately excited motor with armature control

We have,V= iaRa +La(dia/dt) +Ka$\times$ Ø $\times$ ω_m (equ 10)

J$\frac{d\omega_m}{dt}$ =Ka$\times$ Ø $\times$ ia-TL -B$\times$ ω_m Equation 11)

Since Flux per pole remains constant, equation (10) can be written as,

V= iaRa +La(dia/dt) +K$\times$ ω_m……………………….(12)

where k=Ka$\times$ Ø and equation (11) can be written as,

J$\frac{d\omega_m}{dt}$ =K $\times$ ia-TL -B$\times$ ω_m………………………………….(13)

Transient analysis can be done either during starting or during braking.

(CASE-1)During Starting

Speed calculation

Step-1:Differentiate equ(13) w.r.t time(t) as equation (14).

$$k\frac{dia}{dt} = J\frac{d^2\omega m}{dt^2} + B\frac{d\omega m}{dt} + \frac{dTL}{dt} - - - - - (14)$$

Step-2: From equation (14), extract dia/dt

Step-3: From equation (13), extract ia

Step-4: By substitute the values of dia/dt and ia in equation (12), we will get Equation (15)

$$V = \frac{Ra}{k}(\mathrm{J}\frac{d\omega_m}{dt} + \mathrm{TL} + \mathrm{B}\times\omega_m) + La\left[\frac{J}{K}\frac{d^2\omega m}{dt^2} + \frac{B}{k}\frac{d\omega m}{dt} + \frac{1}{k}\frac{dTL}{dt}\right] + k\omega_{m - - - - - - - (15)}$$

Step-5: In equation (15), ω_m will be the variable. So re arranging equation (15) as $\frac{d\omega m^2}{dt^2}$, $\frac{d\omega m}{dt}$, and ω_m in left hand side and rest term in right hand side, develop equation (16)

$$\left[\frac{JLa}{K}\frac{d^2\omega m}{dt^2} + \left(\frac{BLa}{k} + \frac{RaJ}{K}\right)\frac{d\omega m}{dt} + (k + \frac{RaB}{k})\omega_m\right] = V - \frac{Ra \times TL}{K} - \frac{La}{K} \times \frac{dTL}{dt} - - - (16)$$

Step-6: Divide equation (16) by Ra$\times J$/K and then substitute $\tau_a = La/Ra$,$\tau_{m1=J/B}$, $\tau_{m2=(J\times Ra)}/(B \times Ra\ + K^2$), develop equation (17A).

$$\tau_a \frac{d^2\omega m}{dt^2} + \left[1 + \frac{\tau_a}{\tau_{m1}}\right]\frac{d\omega m}{dt} + [\frac{k^2}{JRa} + \frac{B}{J}]\omega_m = \frac{kV}{JRa} - \frac{1}{J}\left[TL + \tau_a\frac{dTL}{dt}\right] - -(17A)\ .$$

Step-7:

As $\frac{dTl}{dt}$=0. Equation (17A) can be written as (17B)

$$\tau_a \times \frac{d^2\omega m}{dt^2} + (1 + \frac{\tau a}{\tau m1})\frac{d\omega m}{dt} + \frac{1}{\tau m2} \times (\omega m) = \frac{K1}{\tau m2} \quad \text{-------------(17B)}$$

Where K1=$\frac{KV - Tl \times Ra}{J\ Ra} \times \tau m2$=steady state value of speed.

It is a second order differential equation and can be solved, if the appropriate initial conditions are known.

Initial conditions of starting are,

ω_m(0)=0, $\frac{d\omega m(0)}{dt}$=0, ia(0)=IL, $\frac{dia(0)}{dt} = \frac{V - IL \times Ra}{La}$, $\frac{dV}{dt}$=0

Solving equation (17B) with above initial condition, we get

$$\omega_m = \frac{\propto 2\ K1}{\propto 1 - \alpha 2} \times e^{-\alpha 1 t} + \frac{\propto 1 K1}{\propto 2 - \alpha 1} \times e^{-\alpha 2 t} + K1 \text{-----------------(17)}$$

Where $\propto 1, \propto 2 = \frac{(1+\frac{\tau a}{\tau m1})\mp\sqrt{(1+\frac{\tau a}{\tau m1})^2+\frac{2\tau a}{\tau m1}-\frac{4\tau a}{\tau m2}}}{2\tau a}$

In small size motor,τa is very small due to large armature winding resistance. Hence taking $\tau a = 0, we$ get

ω_m=K1($1-e^{\frac{-t}{\tau m2}}$)--------------(17C)

Armature current calculation

Step-1:Differentiate equ(12) w.r.t time(t) as equation (18).

Step-2: From equation (18), extract dω_m/dt

Step-3: From equation (12), extract ω_m

Step-4: By substitute the values of dω_m/dt and ω_m in equation (12), develop Equation (19)

Step-5: In equation (19), ia will be the variable. So rearranging equation (19) as $\frac{dia^2}{dt^2}$,$\frac{dia}{dt}$, and ia in left hand side and rest term in right hand side, develop equation (20)

Step-6: Divide equation (20) by Ra$\times J$/K and then substitute $\tau_a = La/Ra$,$\tau_{m1=J/B}$, $\tau_{m2=(J\times Ra)}/(B \times Ra + K^2)$, develop equation (21).

Step-7: Simplify equation (21) with initial conditions of starting,

$ia = 0$, dv/dt=0, dTL/dt=0.

$\tau_a \times \frac{d^2 ia}{dt^2}$ +(1+$\frac{\tau a}{\tau m1}$)$\frac{dia}{dt}$ +$\frac{1}{\tau m2} \times (ia)$=$\frac{K2}{\tau m2}$ -------------(21)

Where K2=$\frac{BV+KTl}{J\ Ra} \times \tau m2$=steady state value of current.

Solving equation (21) with above initial condition, we get ia= $\frac{V-\propto 2LaK2+(\alpha 2La-Ra)IL}{La(\propto 2-\alpha 1)} \times e^{-\alpha 1t}$+$\frac{V-\propto 1LaK2+(\propto 1La-Ra)IL}{La(\propto 1-\alpha 2)} \times e^{-\alpha 2t}$+K2-----------------(21a)

Where $\propto 1, \propto 2 = \frac{(1+\frac{\tau a}{\tau m1}) \mp \sqrt{(1+\frac{\tau a}{\tau m1})^2+\frac{2\tau a}{\tau m1}-\frac{4\tau a}{\tau m2}}}{2\tau a}$

For small motor

Ia=K2 +($\frac{V}{Ra}$ -K2)$e^{\frac{-t}{\tau m2}}$ as $\tau a = 0$----------(21b)

Similarly other transient conditions like dynamic braking, load changing can be analyzed.

Transient analysis of Dynamic Braking

In dynamic braking, the armature of the running motor is disconnected from the supply and connected across a variable register. However the field winding is left connected to the supply i.e V=0 and Ra is replaced by a new resistance (R).

We have,

$\tau_a \times \frac{d^2 \omega m}{dt^2}$ +(1+$\frac{\tau a}{\tau m1}$)$\frac{d\omega m}{dt}$ +$\frac{1}{\tau m2} \times (\omega m)$=$\frac{K1}{\tau m2}$ -------------(17B)

And

$\tau_a \times \frac{d^2 ia}{dt^2}$ +(1+$\frac{\tau a}{\tau m1}$)$\frac{dia}{dt}$ +$\frac{1}{\tau m2} \times (ia)$=$\frac{K2}{\tau m2}$ -------------(21)

For dynamic braking, Substituting V=0 and new resistance in equation (17) and (21), we get

$\tau_a \times \frac{d^2 \omega m}{dt^2}$ +(1+$\frac{\tau a}{\tau m1}$)$\frac{d\omega m}{dt}$ +$\frac{1}{\tau m2} \times (\omega m)$=$-\frac{K3}{\tau m2}$ -----------(22)

$\tau_a \times \frac{d^2 ia}{dt^2}$ +(1+$\frac{\tau a}{\tau m1}$)$\frac{dia}{dt}$ +$\frac{1}{\tau m2} \times (ia)$=$\frac{K4}{\tau m2}$ --------------------(23)

Where K3=$\frac{\tau m2\times TL}{J}$ and K4=$\frac{\tau m2\times KTL}{JRa}$

(−K3) and K4represent the steady state values of speed and current respectively.

By solving equations with initial conditions,$\omega_{m(0)}$=K1,v=0 and ia=0, we obtain

ω_m=$\frac{(J\propto 2-B)K1-(TL-J\alpha 2K3)}{J(\alpha 2-\alpha 1)}e^{-\propto 1t}$ +$\frac{(J\propto 1-B)K1-(TL-J\alpha 1K3)}{J(\alpha 1-\alpha 2)}e^{-\propto 2t}-K3$,-- (24)

ia=K4$-\frac{KK1+\alpha 2LaK4}{La(\alpha 2-\alpha 1)}e^{-\alpha 1t}-\frac{KK1+\alpha 1LaK4}{La(\alpha 1-\alpha 2)}e^{-\alpha 2t}$-------------(25)

Where,

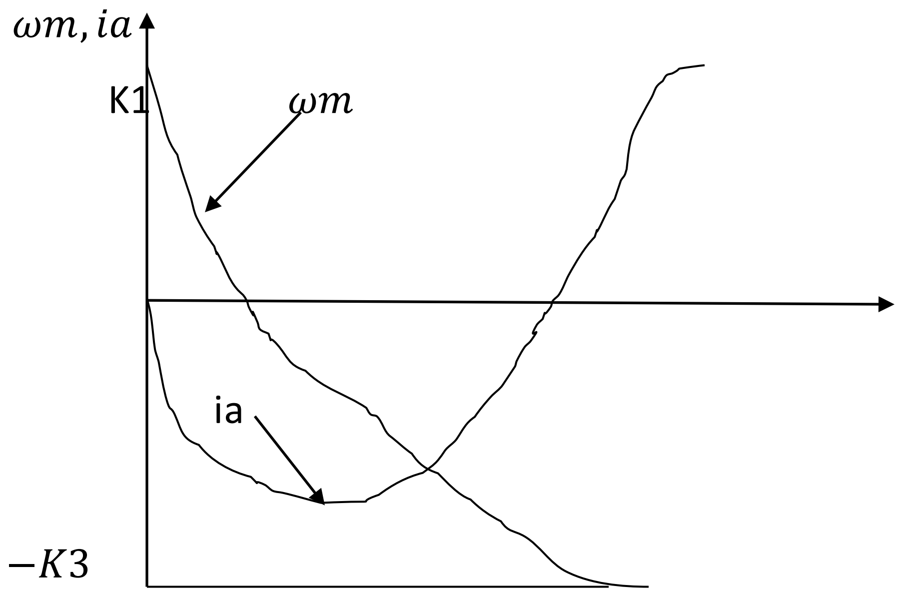
$$\propto 1,\propto 2=\frac{(1+\frac{\tau a}{\tau m1})\mp\sqrt{(1+\frac{\tau a}{\tau m1})^2+\frac{2\tau a}{\tau m1}-\frac{4\tau a}{\tau m2}}}{2\tau a}$$

K3=$\frac{\tau m2\ TL}{J}$, K4=$\frac{\tau m2\times KTL}{JRa}$,

K1=$\frac{KV-Tl\times Ra}{J\ Ra}\times\tau m2=\frac{d\omega m}{dt}\times\tau m2+\omega m$,(for small size motor since$\tau a=0$)

K2=$\frac{BV+KTl}{J\ Ra}\times\tau m2$=$\frac{dia}{dt}\times\tau m2+ia$ (for small size motor).

K=TL/IL, $\tau_{m2=(J\times Ra)}/(B\times Ra\ +K^2\ )$,



2.1.4. Speed control:-Methods of armature voltage control, controlled rectifier fed dc drives.

As $\omega_m = \frac{Eb}{Ka \times \emptyset} = \frac{V - Ia \times R}{Ka \times \emptyset}$, where R is the armature circuit resistance

It is noted that,

(i) Speed below base speed is obtained by armature voltage control.

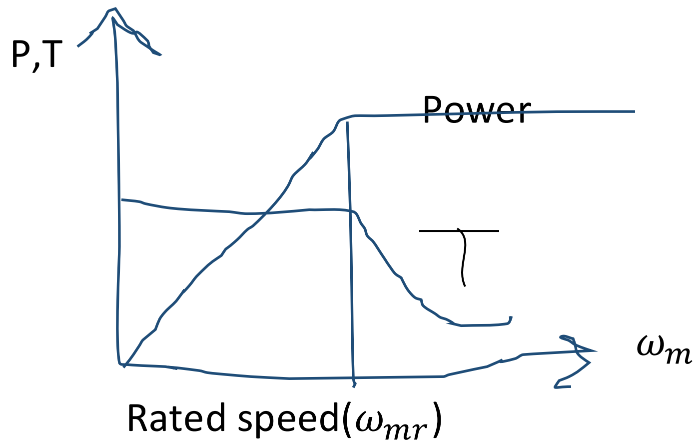
(ii) During this control, armature current and field flux are kept constant, so as to meet the torque demand.

(iii) Therefore, armature voltage control method is known as constant torque drive, because T=Ka$\times \emptyset \times Ia$ remains constant.

(iv) Speed above base speed is obtained by varying the field current or field flux and by keeping supply voltage(V) and armature current(Ia) constant at the rated values.

(v) As V = Eb + Ia Ra, back emf Eb remains constant.

(vi) Since mechanical power Pm= Eb×Ia, this method is known as constant power drive.



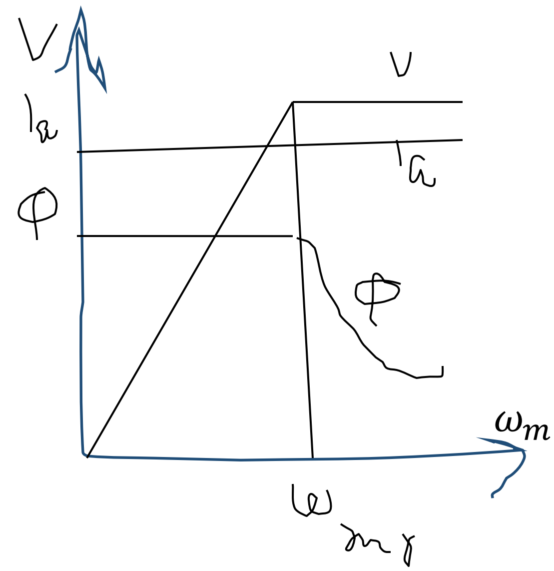


Fig 2.

Methods of armature voltage control : Variable armature voltage is obtained by using following methods.

When the supply is AC

(1)Ward-Leonard Scheme

(2) Transformer with taps and an uncontrolled rectifier bridge

(3) Static Ward- Leonard scheme or controlled rectifiers

When the supply is DC

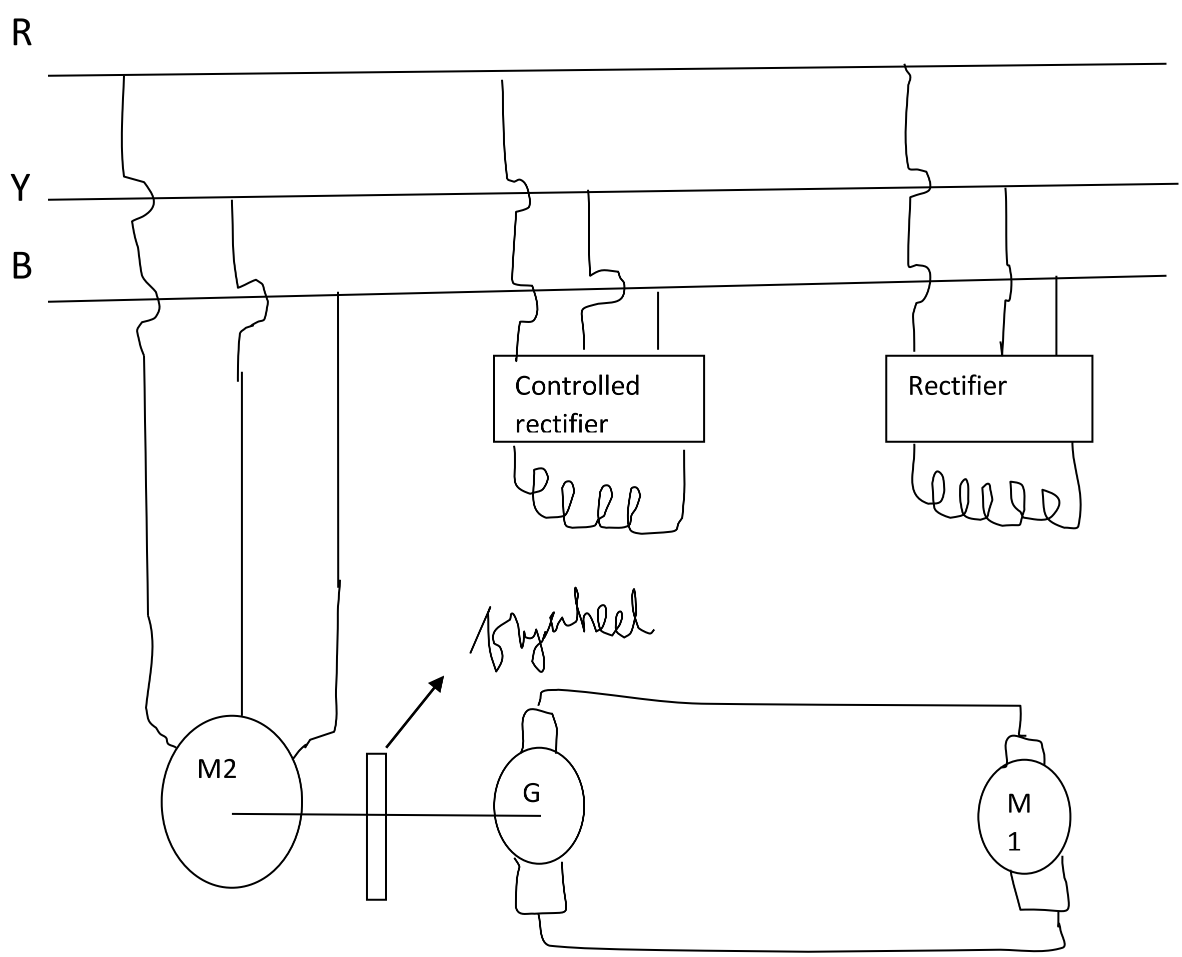
(4) Chopper control

(1)Ward-Leonard Scheme

In this method, the DC motor is fed by a generator instead of dc supply. The generator is driven by either electric motor (Induction motor or synchronous motor, dc motor) or non electrical prime mover if electric power is not available.

Motor terminal voltage is controlled by adjusting the field current of the generator. Accordingly, speed of the main dc motor is controlled.

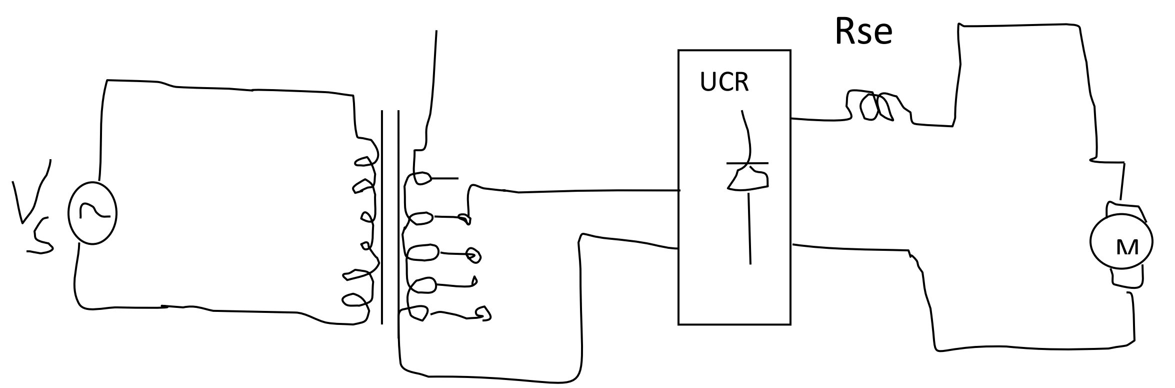
When load is heavy and intermittent, a slip ring induction motor with a flywheel is used to drive the generator. The flywheel is mounted on the shaft of slip ring induction motor. This method is known as Ward-Leonard-Ilgener method.



(With flywheel-Ward-Leonard-Ilgener, Without flywheel-Ward-Leonard)

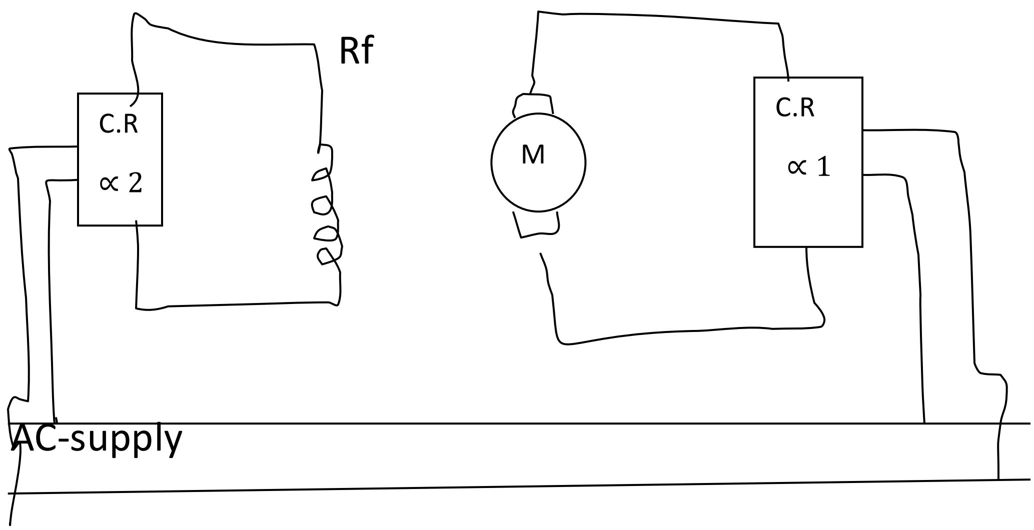
TRANSFORMER AND UNCONTROLLED RECTIFIER CONTROL

In this control scheme, DC motor is powered through a transformer with taps and an uncontrolled rectifier(UCR). The armature voltage of the motor can be changed in steps only. For low power rating, auto transformer can be used.



CONTROLLED RECTIFIER FED DC DRIVE

In this method, either field current or armature voltage is controlled by a controlled rectifier(CR) since Controlled rectifiers convert input AC into variable DC. Controlled rectifier fed DC drive is also known as static Ward-Leonard drive.



Armature voltage is controlled by($\propto 1$) and Field flux is controlled by ($\propto 2$). In Fig. C.R stands for controlled rectifier. During transient operation, DC motor circuit behaves as R-L-E load. When armature current flows continuously, the motor is said to operate in continuous conduction. When armature current does not flow continuously, the conduction is said to be discontinuous.

(A)SINGLE PHASE FULL CONTROLLED RECTIFIER DC DRIVE(separately excited motor)

CONTINUOUS CONDUCTION

Let us consider a single phase full converter. For continuous conduction,

Vo=Va=$\frac{2Vmax}{\pi} Cos\alpha$ ----------(26)

We have angular Speed=ω_m=$\frac{V-Ia\times Ra}{K}$.................................(4)

Hence $\omega_m = \frac{2Vmax}{K\pi} Cos\alpha - \frac{Ra}{K^2} T$ ------------(27), [as Ia=T/k]

At no load Ia=0 and it also happens when both thyristor pairs(T1,T2 and T3,T4) fail to fire ie E>Vs. For $0 \leq \propto \leq \pi/2$, E should be greater or equal to Vmax and for $\frac{\pi}{2} \leq \propto \leq \pi$, E should be greater or equal to Vmax Sin∝

Therefore no load speed,

$\omega_{m0=\frac{Vmax}{K}}$, For $0 \leq \propto \leq \pi/2$ and }

$\omega_{m0=\frac{Vmax}{K}} \text{Sin} \propto$, for $\frac{\pi}{2} \leq \propto \leq \pi$ } --------------(28)

DISCONTINUOUS CONDUCTION

Let us consider a single phase full converter. For discontinuous conduction, Vo=Va=$\frac{Vmax(cos\propto - cos\beta)+(\pi+\alpha-\beta)E}{\pi}$, Since E=$E_B$=K× ω_m

Therefore $\omega_m = \frac{Vmax(cos\propto - cos\beta)}{K(\beta-\alpha)} - \frac{\pi Ra}{K^2(\beta-\alpha)}T$----------(29)

Boundary between continuous and discontinuous conduction is reached, when $\beta = \pi + \alpha$

Therefore, for a given value of α, critical speed can be calculated by using following formula.

$\omega_{mc=\frac{Ra \times Vmax}{K\,Z}}$ sin $(\propto - \emptyset)[\frac{1+e^{-\pi cot\emptyset}}{e^{-cot\emptyset}-1}]$, ---------------(30)

where $\emptyset = phase\ angle = tan^{-1}(\frac{\omega La}{Ra})$, Impedance z=$\sqrt{Ra^2 + (\omega La)^2}$

Note:

In numerical problem, if mode of conduction is not specified, then

Step-1: 1st calculate critical speed

Step-2: (a)If motor speed is greater than the critical speed or (b)motor torque is less than the critical torque, then mode of operation is discontinuous else continuous.

Step-3: β can be evaluated by iterative solution.

Step-4: If motor speed is not given, but motor torque is given, then, we have to calculate critical torque (Tc)=K (Ia)c

(Ia)c=[va-(Eb)c]/Ra. (Eb)c=counter emf at critical speed.

=back emf, at critical speed.

Step-5: If motor torque is less than critical torque, then mode of operation is discontinuous else continuous.

(B)SINGLE PHASE HALF CONTROLLED RECTIFIER DC DRIVE:

CONTINUOUS CONDUCTION

Va=Vo=$\frac{Vmax}{\pi} \times (1 + cos \propto)$--------------(31)

$So, \omega_{m=}\frac{Vmax}{K\pi}(1+cos\propto)-\frac{Ra}{K^2}T$,------------------(32)

DISCONTINUOUS CONDUCTION($\boldsymbol{\beta} < \pi + \alpha$)

In this mode of operation, there are three intervals.

(1)Duty interval ($\propto \leq \omega t \leq \pi$)
(2)Freewheeling interval($\pi \leq \omega t \leq \beta$)
(3)Zero current interval ($\beta \leq \omega t \leq \pi + \alpha$)

Va=Vo=$\frac{Vmax(1+cos\propto)+(\pi+\alpha-\beta)E}{\pi}$ ------------(32), E=E_B=K× ω_m

$So, \omega_{m=}\frac{Vmax}{K(\beta-\alpha)}(1+cos\propto)-\frac{\pi Ra}{K^2(\beta-\alpha)}T$,-----------------(33)

Boundary between continuous and discontinuous conduction is reached, when $\beta = \pi + \alpha$

Therefore, for a given value of α, critical speed can be calculated by using following formula.

$\omega_{mc} = \frac{Ra}{K}\frac{Vmax}{z}[\frac{sin\emptyset .e^{-\alpha cot\emptyset} - \sin(\alpha-\emptyset)e^{-\pi cot\emptyset}}{1-e^{-\pi cot\emptyset}}]$-------(34)

(C)3-PHASE FULLY CONTROLLED RECTIFIER DC DRIVE(separately excited motor)

The discontinuous conduction is neglected because it occurs in a narrow region of its operation.

CONTINUOUS CONDUCTION

For motor terminal voltage, cycle from $\propto + \frac{\pi}{3}\ to\ \alpha + \frac{2\pi}{3}$

Va=Vo=$\frac{3}{\pi} Vmax\ cos\alpha$ -----------------(35)

and

$\omega_m = \frac{3Vmax}{K\pi} cos \propto - \frac{Ra}{K^2} T$,----------------(36)

(D)3-PHASE HALF CONTROLLED RECTIFIER DC DRIVE(separately excited motor)

Va=Vo=$\frac{3}{\pi} Vmax\ (1 + cos\alpha)$ ----------------(37)

$\omega_m = \frac{3Vmax}{2K\pi} (1 + cos \propto) - \frac{Ra}{K^2} T$,-----------(38), where Vmax=Peak value of line voltage.

CHOPPER-CONTROLLED DC DRIVE

Choppers are used to get variable dc voltage from a dc source of fixed voltage. In this method, **for motoring** step down choppers are used and armature voltage, Va=Vo=$(\delta)V$, where $\delta = \frac{Ton}{T_c} = duty\ ratio$,V=dc source voltage,Va=armature voltage. T_c =Chopping period

Ia=$\frac{(\delta)V-E}{Ra}$ and $\omega_m = \frac{(\delta)V}{K} - \frac{Ra}{K^2}T$, whereT=torque

NUMERICAL PROBLEMS ON DC DRIVE

GK Dubey:

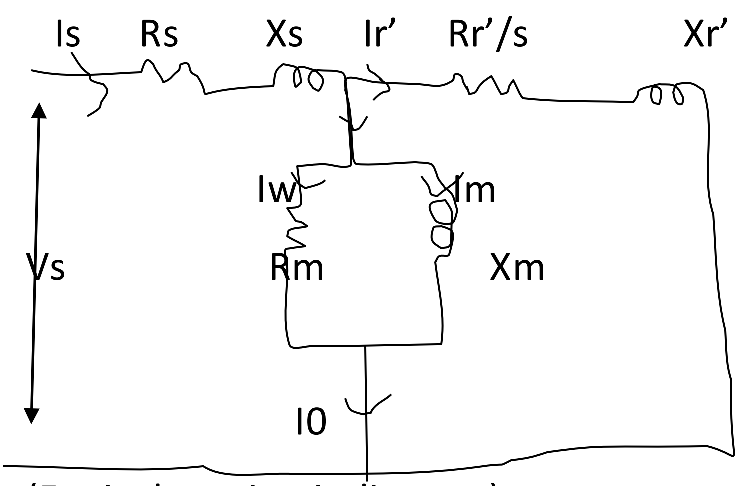
Examples:5.3(page69),5.4(pg70),5.8(pg74), 5.11(pg89),5.13(pg102),5.14(pg103), 5.15(pg105),5.16(pg110),5.17(pg113).

Exercise:5.10,5.11,5.12(page134), .5.30(page135),5.36,5.37,5.38,5.39,5.40,5.41,5.42(page136)

Refer Numerical section of this note.

2.2. INDUCTION MOTOR DRIVES

PERFORMANCE EQUATIONS



(Equivalent circuit diagram)

(1) Is=Im+Ir'

(2)Rotor input=3$Ir'^2 \frac{Rr'}{s}$

(3)Rotor copper loss=s× $rotor\ input$= s× $3Ir'^2 \frac{Rr'}{s}$=$3Ir'^2 \times Rr'$

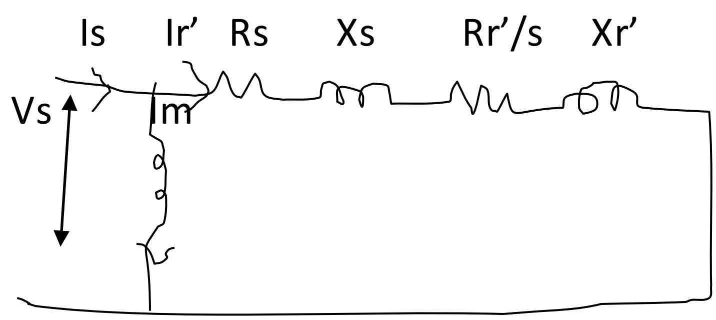
(4)Mechanical power developed by rotor(gross power)=

$P_{g=}P_{m=}$rotor input –rotor copper loss=$3Ir'^2 \frac{Rr'(1-s)}{s}$

(5)Gross torque developed by the rotor=$T_{g=} \frac{P_g}{\omega_m}$=$3Ir'^2 \frac{Rr'}{s(\omega_{ms})}$

Where ω_{ms}=synchronous speed=$\omega_m/(1-s)$, s= per unit slip

Approximate equivalent circuit diagram



(6)Ir' =$\frac{Vs}{\sqrt{(Rs+\frac{Rr'}{s})^2+(Xs+Xr')^2}}$

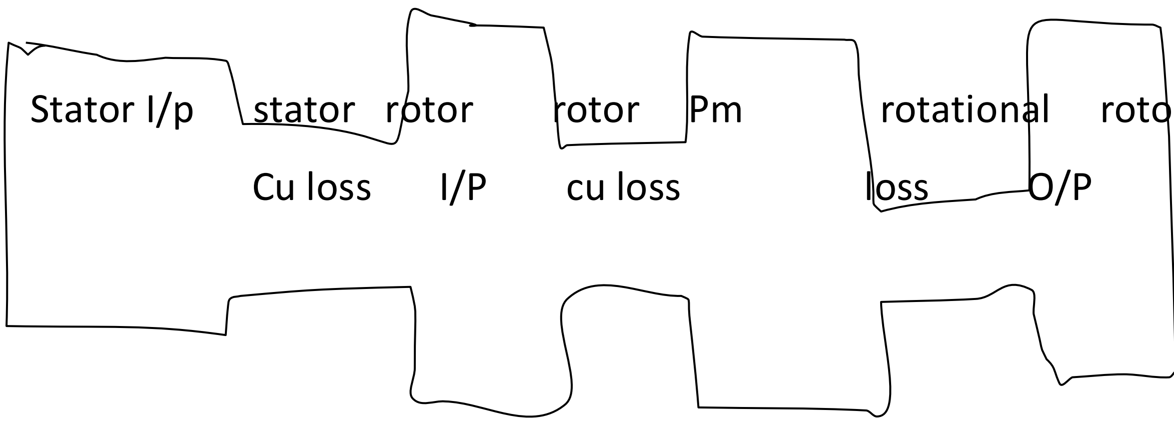
(7)Hence Tg=$3Ir'^2 \frac{Rr'}{s(\omega_{ms})}$=$\frac{3}{\omega ms} \times \frac{Vs^2 \times \frac{Rr'}{s}}{(Rs+\frac{Rr'}{s})^2+(Xs+Xr')^2}$

$\omega ms = 2\pi Ns$ and Ns=synchronous speed in rps.

(8)Rotor output=(1 –s) Rotor input

(9) Rotor efficiency= 1 –s

(10) Rotor frequency= fr=s× f, where f=supply frequency



Speed control:

We have, Ns =120f/P, RPM

Ns=2f/P, RPS 0r 120f/p in rpm, N=(1-s)Ns

$\omega_m = (1-s)\omega_{ms}$and Tr=$\frac{3}{\omega ms} \times \frac{Vs^2 \times \frac{Rr'}{s}}{(Rs+\frac{Rr'}{s})^2+(Xs+Xr')^2}$, Therefore speed of induction motor can be controlled by controlling

(1) Pole(P)

(a)pole changing, (b) pole amplitude modulation,

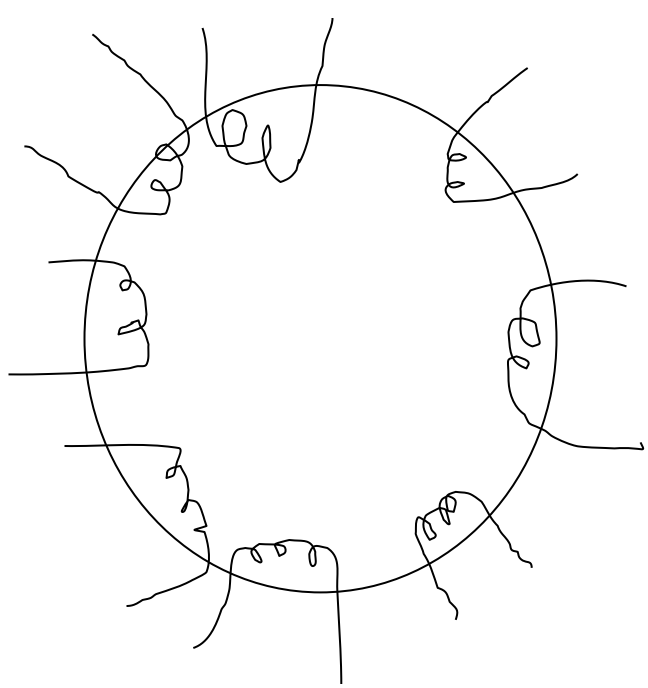
(2) supply voltage(stator voltage control)

(3) frequency (a)variable frequency control from voltage source(vfvs/VSI), (b) variable frequency control from current sourcevfcs/CSI), (4) current regulated voltage source inverter control, (5) rotor resistance (a)static rotor resistance control(b) conventional rotor resistance control,(6) slip power recovery (a) static Scherbius drive (b)static Kramer drive.

POLE CHANGING

We have, Ns=120f/P and N=(1-s)Ns.

For a given frequency, the synchronous speed is inversely proportional to number of stator pole and speed of induction motor is directly proportional to synchronous speed at constant slip. Provision for changing the number of poles has to be incorporated at the manufacturing stage and such machines are called pole changing motors or multi speed motors. In this method, two windings are provided in the stator .These windings are electrically separated. Using a switching arrangement required number of poles is created. Only, in a squirrel cage induction motor, this arrangement is possible as squirrel cage rotor is not wound for any specific number of poles. This method is more costly and less efficient as two different stator windings are required. Smooth speed control is also not possible.



This may be a 8 pole,4pole or 2 pole machine by proper arrangement of the windings.

POLE AMPLITUDE MODULATION

Pole changing method allows a change of speed by a factor of 2 ie 8 or 4 or 2. But in some applications, speed change is required only by a small amount which can be done by pole amplitude modulation technique.

[The mmf developed in 3-phase induction motor may be written as

$F_R = F_{Rm \sin P\theta}$,------due to R phase,p=pair of poles

Electrical angle=(Pole/2) mechanical angle

$F_Y = F_{Ym \sin(P\theta-120)}$,------------- due to Y- phase

$F_B = F_{Bm \sin(P\theta+120)}$, due to B -phase.

Where θ is the mechanical angle and F_{Rm}, F_{Ym}, F_{Bm} are maximum value or amplitude of mmf in R-phase, Y-phase and B-phase respectively. In an induction motor, F_{Rm}, F_{Ym}, F_{Bm} are constant and equal. But in this control strategy, original sinusoidal mmf wave is modulated by another sinusoidal mmf wave having the different number of poles.

F_{Rm}=F sin Kθ, where K=modulation cycle or pair of poles of sinusoidal mmf wave used for modulation.

F_{Ym}= F sin(K$\theta - \propto$)

F_{Bm}= F sin (K$\theta - 2 \propto$)

So $F_R = F_{Rm} sinP\theta$= F sin Kθ $sinP\theta$=$\frac{F}{2}$[cos(P-k) θ-cos(P+k) θ]

It is observed that F_R has two sets of mmfs with P –K and P+k poles.

Similarly, F_Y, F_B have two sets of mmfs with P –K and P+k poles. Theoretically, k and ∝ may have any value. This is known as modulation law.

Since two sets of poles will produce torques in opposite directions, one of them must be suppressed to produce unidirectional torque. This can be achieved by choosing the value of ∝ either $\frac{2\pi}{3} or - 2\pi/3$.]

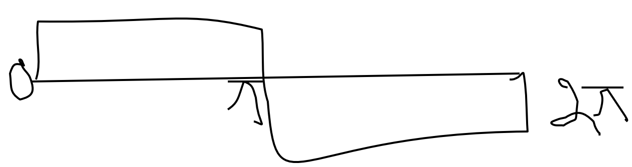
. It is very difficult to implement the modulation law because of its sinusoidal nature. So it can be simplified by using simple laws of modulation ie (1) Coil inversion (2) Coil inversion and omission

Coil inversion

Maximum value of mmf due to R-Phase is,

F_{Rm}=F for 0<$\theta < \pi$

= -F for $\pi < \theta < 2\pi$



Similarly for Y phase and B phase

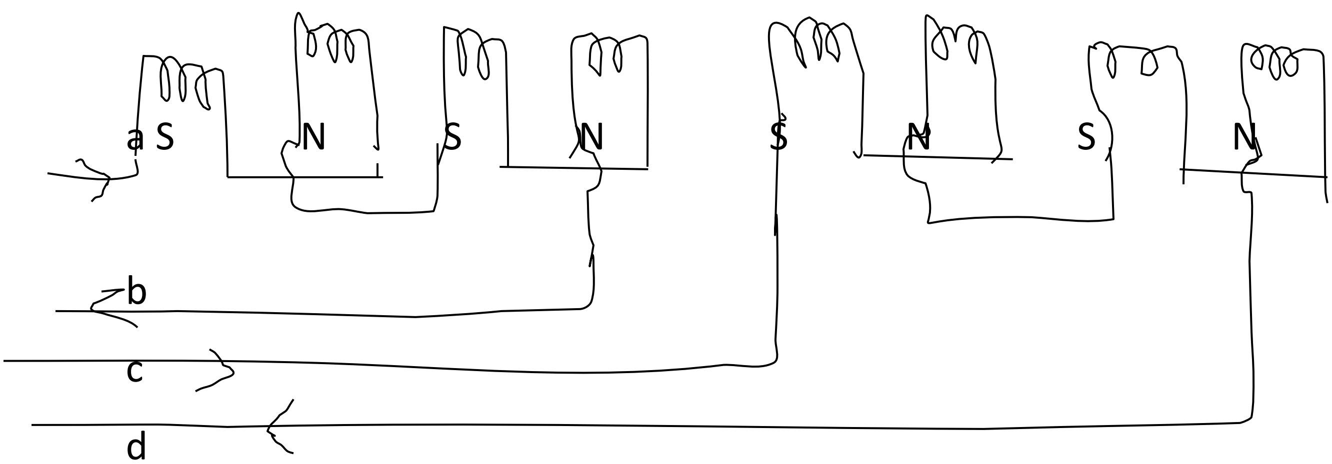
F_{Ym}=F for$\frac{2\pi}{3} < \theta < 5\pi/3$

= -F for$\frac{5\pi}{3} < \theta < 8\pi/3$

F_{Bm}=F for$4\frac{\pi}{3} < \theta < 7\pi/3$

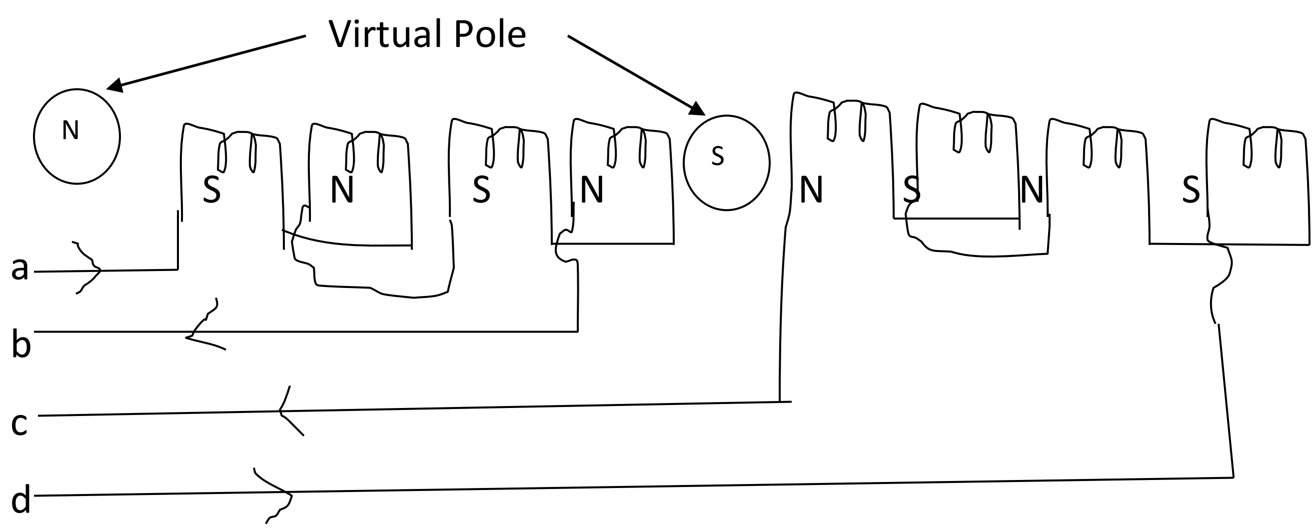
= -F for $7\frac{\pi}{3} < \theta < 10\pi/3$ by substituting $\propto = 2\pi/3$

Above cited expressions indicate that for change in pole number, current in the latter half of coils in each phase is reversed. This is known as coil inversion.



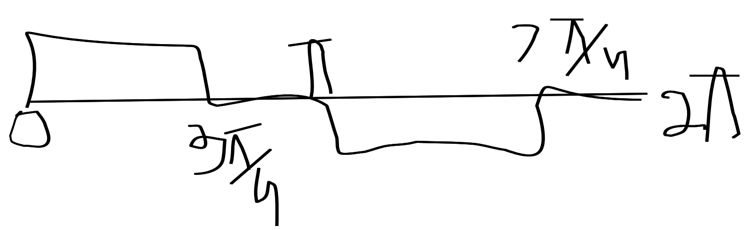
(8-Pole stator)

The reversal of coil group c-d changes the number of poles to 10 as shown in below fig.



(10 pole machine)

By inversion and omission law, modulation of 8 pole machine gives 6 pole machines. It is achieved by omitting one- one coil from both coil groups.

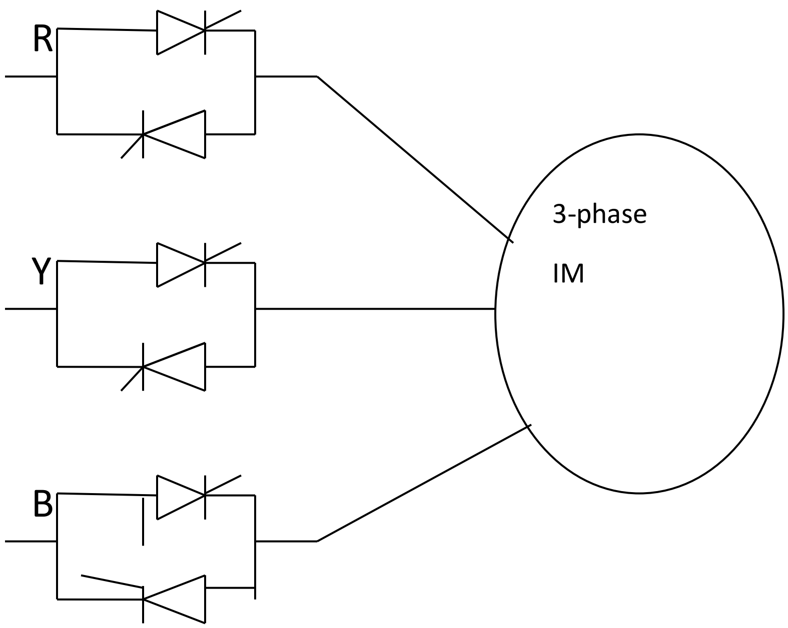


STATOR VOLTAGE CONTROL(SOFT START)

We have, $Tr = \frac{3}{\omega ms} \times \frac{Vs^2 \times \frac{Rr'}{s}}{(Rs + \frac{Rr'}{s})^2 + (Xs + Xr')^2}$,

According to above equation, Tr is proportional to the square of the stator supply voltage. A reduction in supply voltage will reduce the motor torque, so as to achieve a speed control in constant power drive (Pm=$\omega_m \times Tr$).

Fig. shows a three phase ac voltage controller feeding a 3-phase induction motor. By controlling the firing of the thyristors connected in anti parallel in each phase, the rms value of stator voltage can be regulated. Hence motor torque and thus speed of the drive system is controlled.



SUPPLY FREQUENCY CONTROL METHOD

By changing the supply frequency, synchronous speed of motor can be changed and thus torque and speed of a 3phase induction motor can be controlled.

For a 3-phase induction motor, per phase supply voltage

$V_{ph} = K\phi f$

This expression shows that under rated voltage and frequency operation, flux will be rated.

In case of supply frequency is reduced with constant Vph, the air gap flux increases, the magnetic circuit of IM gets saturated. Hence inaccurate speed torque characteristic results. Further at low frequency, reactance will be low, leading to high motor current, more losses and low efficiency.

With constant supply voltage, if the motor supply frequency is increased, the syn. Speed and therefore motor speed rises but flux and torque get reduced.

Due to above reasons, variable frequency control below rated frequency is generally carried out at rated air gap flux by varying terminal voltage with frequency, so as to maintain (V/f) ratio constant.

(a) <u>VARIABLE FREQUENCY CONTROL FROM VOLTAGE SOURCES(VFVS):</u>

This is the most popular method for speed control of an induction motor. In this method, variable frequency control below rated frequency is carried out at rated air gap flux by varying terminal voltage with frequency, so as to maintain (V/f) ratio constant.

We have, Tr=$\frac{3}{\omega ms} \times \frac{Vs^2 \times \frac{Rr\prime}{s}}{(Rs+\frac{Rr'}{s})^2+(Xs+Xr')^2}$,------(1) and condition for maximum running torque is, $\frac{Rr\prime}{s} = \pm\sqrt{Rs^2 + (Xs + Xr')^2}$

Xs=$2\pi f Ls$, Xr'=$2\pi f Lr'$. Substituting these values in equation (1), we get

(Tr)max=$\frac{3}{4\pi} \frac{(\frac{V}{f})^2}{\frac{Rs}{f} \pm \sqrt{(\frac{Rs}{f})^2+(2\pi Ls+2\pi Lr\prime)^2}}$-------------(2)

For large frequency, (Rs/f) is much smaller than $2\pi Ls + 2\pi Lr'$. Hence neglecting Rs/f factors from equation (2), we get

Tmax =K$\frac{(\frac{V}{f})^2}{2\pi(Ls+Lr')}$----------------(3)

Therefore it is concluded that with constant V/f ratio, motor develops a constant torque. It means it operates in constant torque mode.

To maintain V/f ratio constant, V increases with increase in frequency and when V reaches at rated value, at base speed, it can't be increased with frequency.

Therefore above base speed, frequency is changed with constant V.

According to equation (3), with V maintained constant, maximum torque decreases with increase in frequency. Hence motor operates in constant power mode as shown in Fig.1

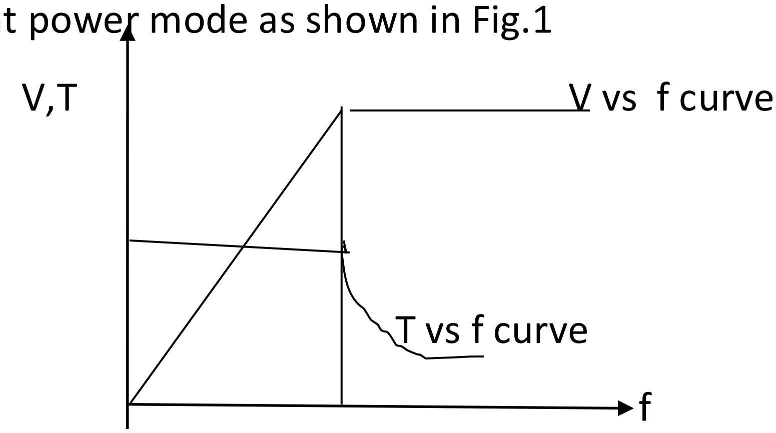


Fig.1

Block diagram of a variable frequency speed control scheme is shown in fig.2.

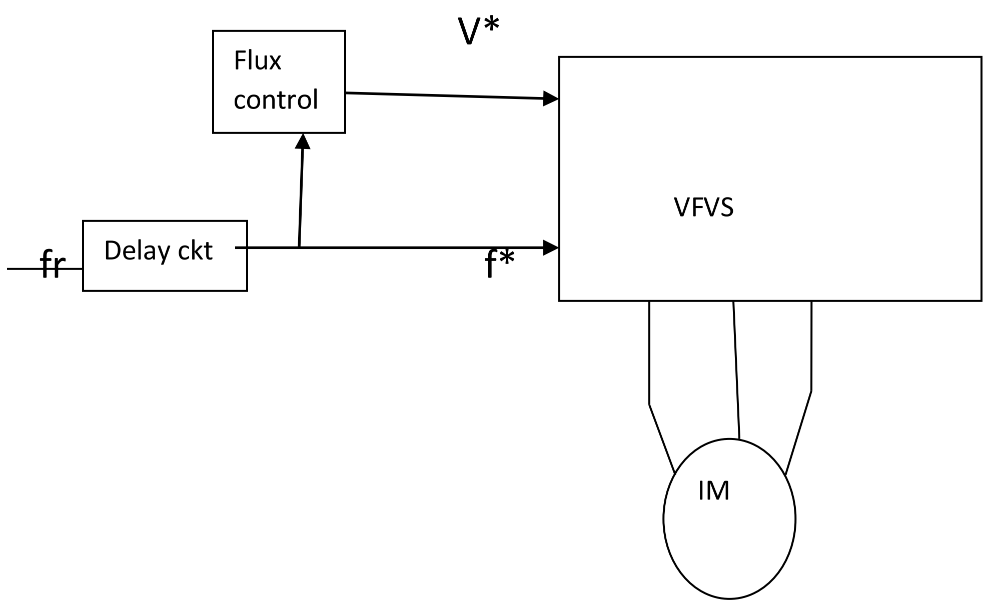


Fig.2

The motor is fed from VFVS.

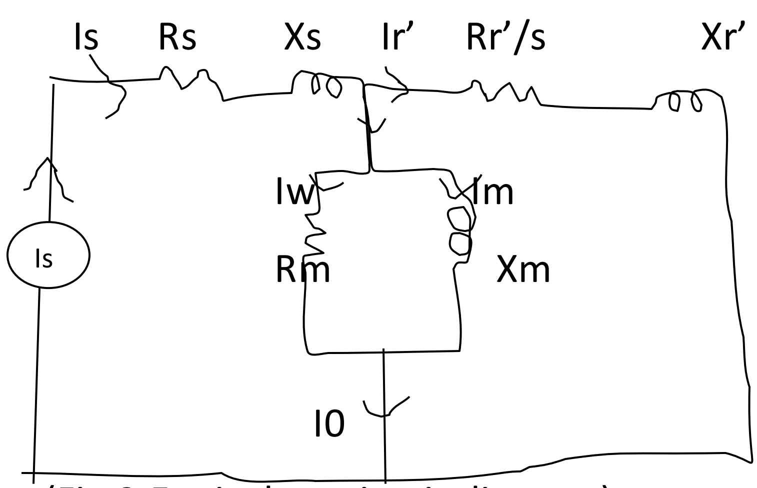
V* &f* are voltage and frequency commands respectively.

VFVS can be a voltage source inverter or cyclo-converter`

(b)<u>VARIABLE FREQUENCY CONTROL FROM CURRENT COURSES(VFCS):</u>

Let us discuss the speed control of induction motor by using variable frequency current source. The equivalent circuit for motor fed from a current source is shown in Fig.3. Since rated flux operation is preferred, Im should remain constant. Therefore a fixed relationship is maintained between the slip frequency (s f) and stator current (Is) for the rated flux in the air gap. When frequency is changed to control the speed of induction motor, i.e sf increases, Is increases as shown in fig.4. since in below equation(A), Im remains constant. $(2\pi Lm + 2\pi Lr')^2 > (2\pi Lr')^2$.

At given slip speed (rotor frequency), the motor draws a constant current and develops a constant torque at all frequencies. Therefore, the motor operates in constant torque mode from zero to base speed. At base speed VFCS voltage saturates. Above base speed, motor operates at constant terminal voltage and provides constant power operation mode. Variable frequency current supply is provided by CSI.



(Fig.3.Equivalent circuit diagram)

Ignoring Iw,

$$Im=\frac{Is\sqrt{(\frac{Rr'}{s})^2+(Xr')^2}}{\sqrt{(\frac{Rr'}{s})^2+(Xs+Xr')^2}}=Is\frac{\sqrt{(\frac{Rr'}{sf})^2+(2\pi Lr')^2}}{\sqrt{(\frac{Rr'}{sf})^2+(2\pi Lm+2\pi Lr')^2}} \text{---------------(A)}$$

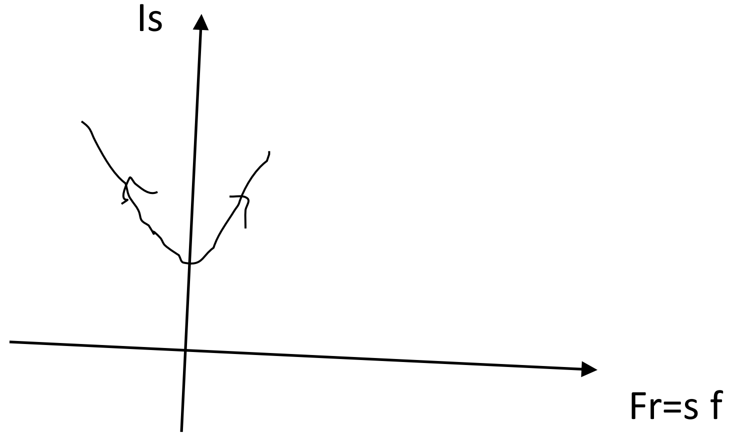


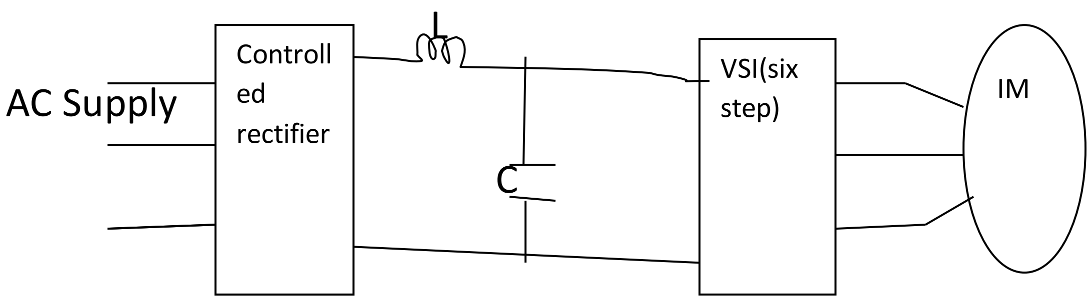
Fig.4

This type of control is simpler than voltage control.

VSI INDUCTION MOTOR CONTROL

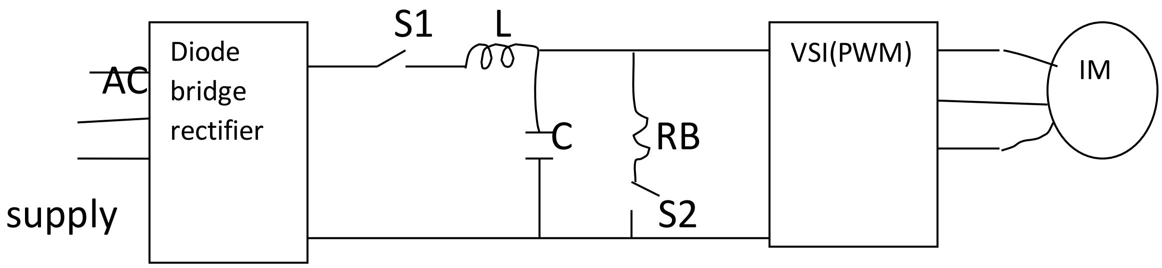
(a)VSI INDUCTION MOTOR DRIVE

Variable frequency and variable voltage supply for induction motor control is obtained from a voltage source inverter. Because of a low internal impedance, the terminal voltage of a voltage source inverter remains constant with variation in load. It is therefore equally suitable to single motor and multi motor drives. The speed of an induction motor has to be controlled from an ac or dc source. AC is converted to DC by controlled rectifier or dual converter or diode rectifier or diode rectifier with chopper and after filtration, it is feed to VSI. The wave shape of the input voltage of induction motor may be either quassi square wave and synthesized sine wave(PWM wave form). Motors operate successfully at high speeds with quassi square applied wave forms. The PWM wave forms allow sinusoidal currents to flow in motor even at low frequencies and provide smooth operation of the motor.



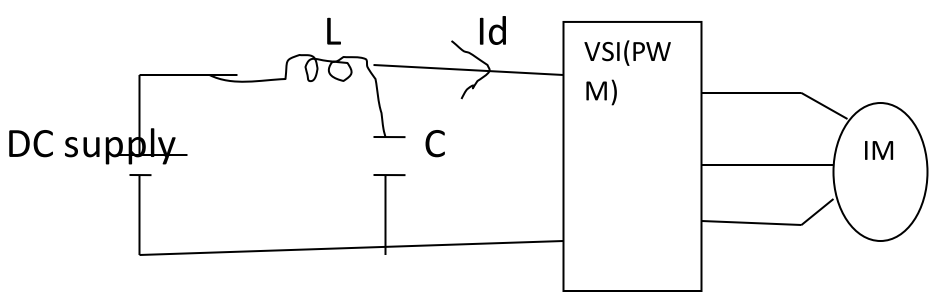
(b) **BRAKING**: A reduction in frequency makes the synchronous speed less than the rotor speed. This reverses the rotor induced emf (Er=s V and s becomes negative) and power flow reverses. Regenerative braking is obtained when the power flowing from the inverter to the dc link and dynamic braking is obtained when it is wasted in a resistance.

DYNAMIC BRAKING: For dynamic braking, switch S1 and a self commutated switch S2(transistor) in series with braking resistance R_B connected across the DC link as shown in Fig. When operation of the motor is shifted from motoring to braking switch S1 is opened. Generated energy will flow to capacitor and its voltage rises. When it crosses a set value switch S2 is closed. As a result, energy stored in the capacitor and generated energy will flow through the resistance(R_B), DC link voltage reduces. When it falls to its nominal value, S2 is opened. Thus by closing and opening switch S2, generated energy is dissipated in the resistance, giving dynamic braking.



REGENERATIVE BRAKING:

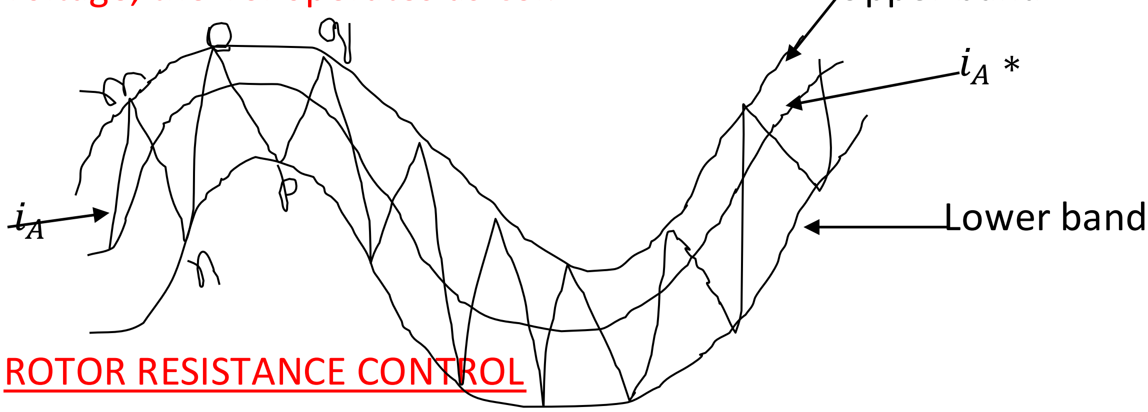
When machine operation is shifted from motoring to braking, dc link current Id reverses. Generated energy flows into dc supply as shown in fig. Thus regenerative braking is obtained.



(c) MULTI QUADRANT OPERATION: Four quadrant operation of 3 phase induction motor can be obtained with braking capability. To transfer the operation from quadrant I to II, a reduction of inverter frequency, to make synchronous speed less than the motor speed, is required. The inverter frequency and voltage are progressively reduced as speed falls to brake the machine up to zero speed. Now the phase sequence of the inverter output voltage is reversed by interchanging the firing pulses between switches of any two legs of the inverter. This transfers the operation to quadrant II. The inverter frequency and voltage are increased to get the required speed in the reverse direction.

CURRENT REGULATED VOLTAGE SOURCE INVERTER CONTROL

Current regulated VSI operated with current controlled PWM. In current controlled PWM, machine phase current is made to follow a sinusoidal reference current within a hysteresis band. Two bands, separated from reference current i_A* by an amount∇I, are shown in figure. Switching in the inverter is carried out such that the actual motor current i_A remains within these two bands. For this, voltage source inverter is used. In a 3phase VSI, phase current i_A is shaped by switches T1,T4, phase current i_B is shaped by switches T3,T6, phase current i_C is shaped by switches T5,T2. When T1 is ON and T4 is OFF, phase current i_A is positive and when T1 is OFF and T4 is ON, phase current i_A is negative. Therefore, i_A is rising in path no, pq during the conduction of T1 and falling in the path mn, op as shown in Figure during the conduction of T4. When the band is small, the motor current is nearly sinusoidal. Since the magnitude and wave forms of motor currents are independent of change in motor impedance and source voltage, the VSI operates as CSI.



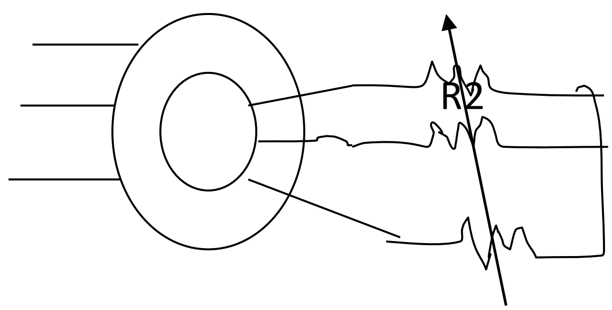
ROTOR RESISTANCE CONTROL

(a)CONVENTIONAL METHOD

In slip ring induction motor, a 3 phase variable resistance R2 can be inserted in the rotor circuit. By varying the rotor circuit resistance R2, the motor torque can be controlled. The starting torque and starting current can be controlled by controlling the rotor circuit resistance.

The disadvantages of this method of speed control are (1) reduced efficiency at low speeds (2) speed changes very widely with load variation (3) unbalances in voltages and currents if rotor circuit resistances are not equal. In spite of these disadvantages, this method is used when speed drop is required for a short time.

3ph suppply

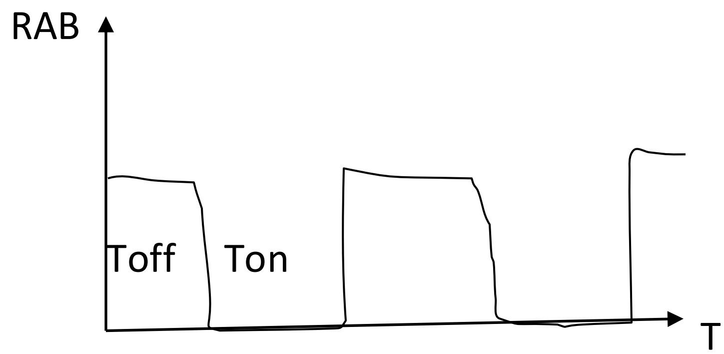


(b)STATIC ROTOR RESISTANCE CONTROL:

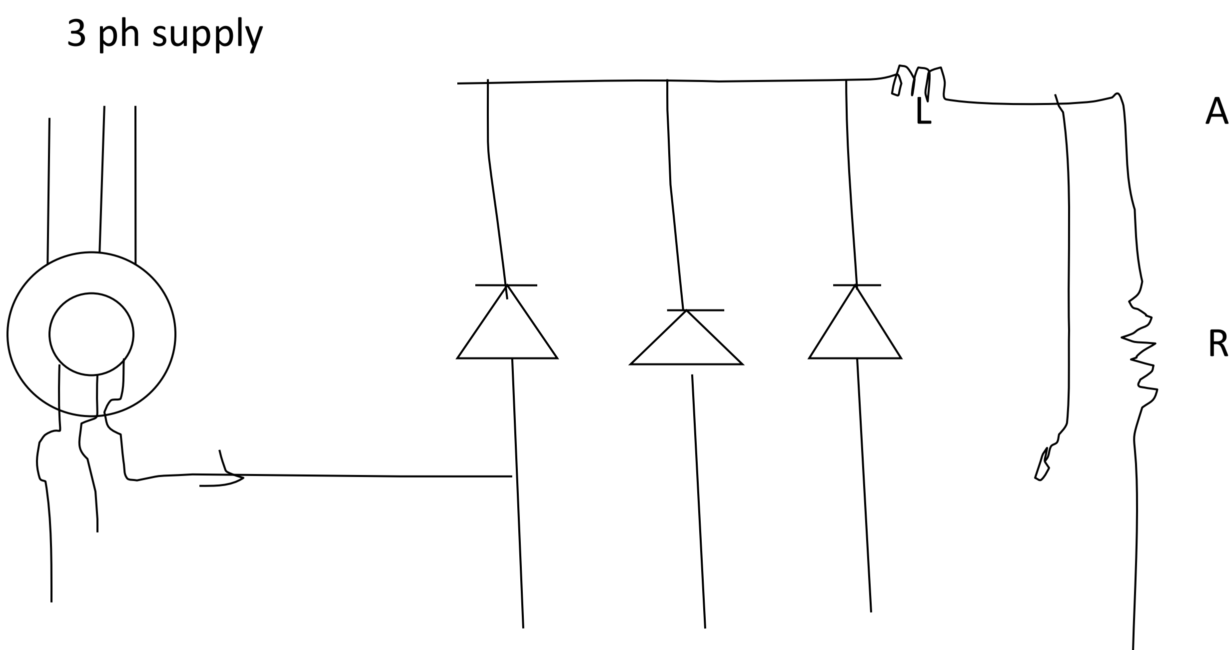
In this type of speed control technique, three phase external resistance of the rotor circuit is replaced by a 3 phase diode rectifier, parallel combination of a fixed resistance R and semiconductor switch as shown in Figure. Effective value of resistance across terminals A & B (RAB) is varied by varying duty ratio of semiconductor switch (S).

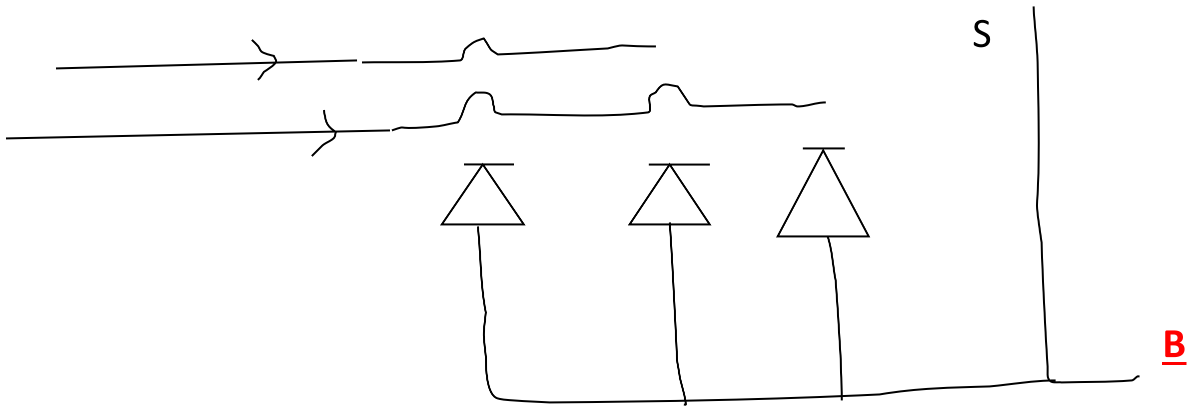
$$R_{AB} = (1 - \delta)R$$

As a result, rotor circuit resistance is varied. Hence speed of the slip ring induction motor is controlled.



$R_{AB} = \int_0^{Toff} Rdt$/T=$(1 - \delta)R$, where $\delta = \frac{Ton}{T} = duty\ ratio$



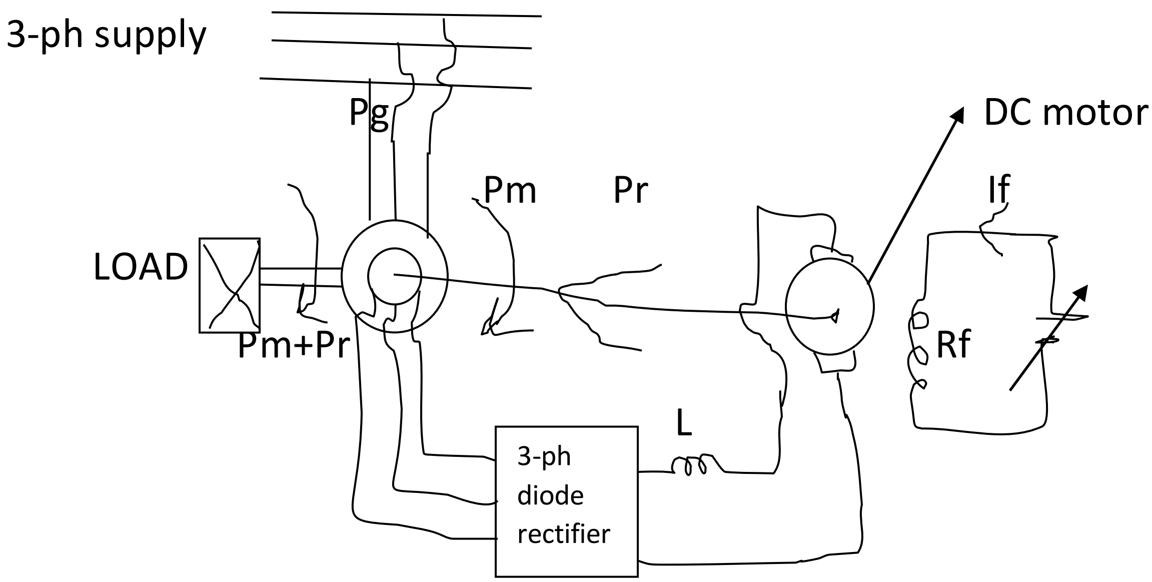


SLIP POWER RECOVERY

In static rotor resistance control, the slip power is dissipated in the external resistance and it reduces the efficiency of the system. Instead of wasting the slip power in the external circuit, it can be recovered by various schemes during speed control of slip ring induction motor. Two important slip power recovery schemes are (1) Static Kramer drive (2) Static Scherbius drive.

STATIC KRAMER DRIVE:

Rotor slip power is converted into dc power by diode bridge rectifier. The dc power is then fed to dc motor which is mechanically coupled to induction motor. The mechanical power produced by dc motor is supplied to induction motor. Hence constant power is delivered to the load at different speed. Thus constant power control is obtained by static Kramer drive. Speed control is obtained by controlling field current of dc motor. When large speed range is required, diode bridge is replaced by a thyristor bridge and speed is controlled by controlling firing angle. Speed control is possible from synchronous speed to half of synchronous speed by using diode bridge rectifier and from synchronous speed to zero speed by using thyristor bridge rectifier.



This type of drive has better power factor and lower harmonics content in line current.

STATIC SCHERBIUS DRIVE

In this drive, a portion of the rotor ac power is converted into dc by a diode bridge rectifier and then fed to an inverter through a smoothing inductor. This inverter converts it back to ac and feeds it back to the ac source. Thus rotor slip power is fed back to the source. So drive has high efficiency. But in static Scherbius drive, reactive power and harmonics are associated with the power feed back to the line. The drive has applications in fan and pump drives which require speed control in a narrow range only. This drive is widely used in medium and high power fan and pump drives due to high efficiency and low cost. This drive provides a constant torque control.

Neglecting drop across inductor

$$V_{d1+V_{d2}=0} ----(1)$$

Neglecting stator and rotor drops, we get

$V_{d1} = \frac{3\sqrt{6}}{\pi} \times \frac{sV}{n}$ -------------(2), [output voltage of 3 phase diode rectifier]

$V_{d2} = \frac{3\sqrt{6}}{\pi} \times \frac{V}{m} cos \propto$----------(3), [output voltage of 3 phase inverter]

Where ∝ is the inverter firing angle,

n= stator turn/rotor turn,

m= (motor side turn of t/f)/ (source side turn of t/f)=t/f turn ratio, v=phase voltage, s=slip.

From equations (1),(2),(3), we obtain,

s=$-\frac{n}{m} cos \propto$=-a× $cos \propto$-------------(4)

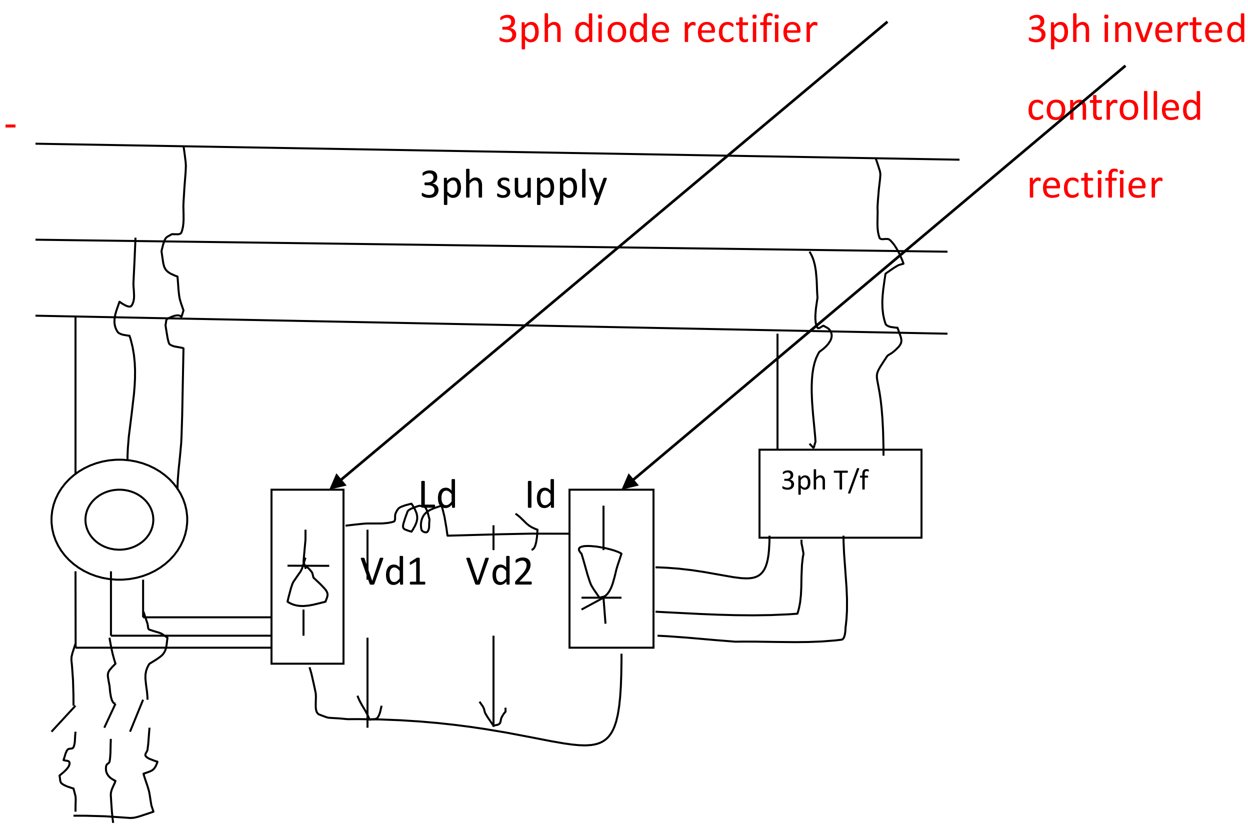
For dc link, copper loss at rotor= copper loss in dc link due to equivalent value of rotor resistance.

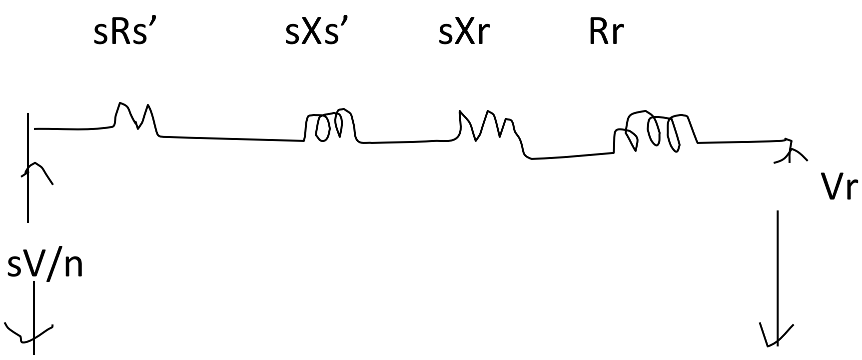
⇨ $3Ir^2(sRs'$+Rr)=$Id^2 \times R_{rd}$ and $I_r = \sqrt{\frac{2}{3}}$ Id
⇨ $R_{rd} = 2(sRs'$+Rr)
⇨ $Id = \frac{Vd1+Vd2}{2(sRs'+\mathrm{Rr})+\mathrm{Rd}}$----------(5), From fig.3

If rotor copper loss is neglected,

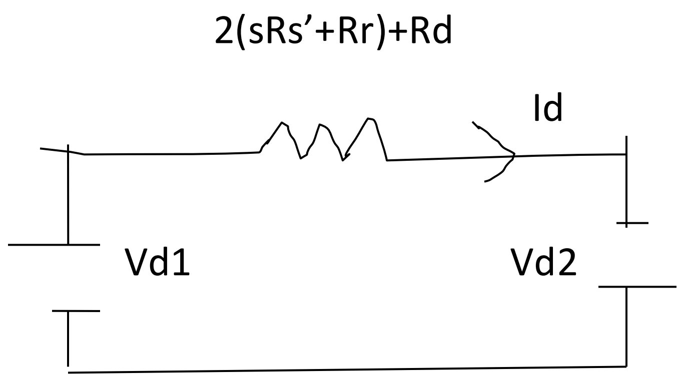
sPg=Vd2× Id

⇨ Pg= (Vd2× $Id)/s$------------(6)
⇨ T=Pg/ω_{ms}=(Vd2× $Id)/s\omega_{ms}$-------(7)





(Equivalent circuit of IM referred to rotor)



(Equivalent circuit of drive)

NUMERICAL PROBLEMS ON DC DRIVE

GK Dubey:

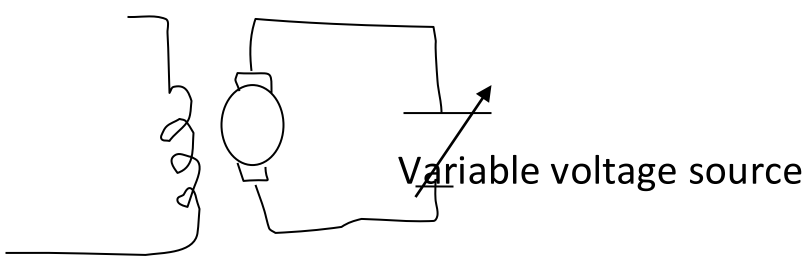
Examples:
5.3(page69),5.4(pg70),5.8(pg74),5.11(pg89),5.13(pg102),5.14(pg103),
5.15(pg105),5.16(pg110),5.17(pg113).

Exercise: 5.10,5.11,5.12(page134),
5.30(page135),5.36,5.37,5.38,5.39,5.40,5.41,5.42(page136)`

P1. [Example5.3] A 220V, 200A, 800rpm Dc separately excited motor has an armature resistance of 0.06 ohm. The motor armature is fed from a variable voltage source with an internal resistance of 0.04 ohm. Calculate internal voltage of the variable voltage source when the motor is operating in regenerative braking at 80% of the rated motor torque and 600rpm.

Solution:

Given data, Rated voltage=V=220 volt, Rated current=Ia=200A, Rated speed=N=800 rpm, armature resistance =Ra=0.06 ohm, internal resistance of variable voltage source=Rs=0.04 ohm. Braking torque=TB=80% of rated motor torque=0.8T



Back emf at rated speed=$E_B = V - IaRa = 220 - 200 \times 0.06 = 208\ volt.$

In separately excited motor, Flux Ø remains constant. So T∝ Ia and N∝ E_B.

At regenerative braking, Ia1/Ia= TB/T, => Ia1=0.8$\times$ $200 = 160\ A$

And back emf =$E_{B1} = \frac{N1}{N} \times E_B = \frac{600}{800} \times 208 = 156\ volt$

Since in regenerative braking, back emf is greater than source voltage,

Source voltage=$E_{B1} - Ia1(Ra + Rs) = 156 - 160(0.06 + 0.04) = 140\ volt$. Internal voltage of the variable voltage source =140 volt

P2. [Example5.4] A 220V,100A, 1000rpm Dc series motor has an armature and field winding resistance of 0.05 ohm each. It is operated under dynamic braking at twice the rated torque and 800 rpm. Calculate the value of braking current and resistance. Assume linear magnetic circuit.

Solution: Linear magnetic circuit means reluctance remains constant.

Given data:

Rated voltage= V=220 volt, Armature current=Ia=100A, rated speed=N=1000 rpm, Ra=Rse=0.05 ohm, Braking torque=TB=2T, speed N1=800rpm

In series motor flux is the function of armature current ($\emptyset \propto I_a$).

Hence T$\propto$ $\emptyset Ia$ =>T$\propto$ Ia^2

In dynamic braking armature current=Ia1=Ia$\times \sqrt{\frac{T_B}{T}}$ =100$\times \sqrt{2}$ =141.4 A.=Braking Current

In series motor N$\propto \frac{E_B}{\emptyset}$ =>$E_B \propto NIa$

Therefore $\frac{E_{B1}}{E_B} = \frac{N1Ia1}{NIa}$=>$E_{B1} = \frac{N1Ia1}{NIa} \times E_B = \frac{800\times141.4}{1000\times100} \times (220 - 100 \times 0.1) = 237.55\ volt$.

In dynamic braking, motor armature is disconnected from the source and connected across a resistance RB. The generated energy is dissipated in RB and armature circuit resistance.

Therefore $E_{B1} = Ia1(RB + Ra + Rse) = 141.4(RB + 0.1)$

=>237.55=$141.4(RB + 0.1)$=> RB=1.58 ohm`

P3. [Example5.8] A 220V, 100A, 970rpm Dc separately excited motor has an armature resistance of 0.05 ohm. It is braked by plugging from an initial speed of 1000rpm. Calculate

(a) Resistance to be placed in the armature circuit to limit braking current to twice the full load current.

(b) Braking torque

©Torque when the speed has fallen to zero. .[Example5.8]

SOLUTION:

Given data

Rated voltage=V=220 volt, Rated armature current=Ia=100A, Rated speed=N=970 rpm, armature resistance =Ra=0.05 ohm, Initial speed during braking=N1=1000 rpm, Ia1=2Ia=200A

Back emf at rated speed=$E_B = V - IaRa = 220 - 100 \times 0.05 = 215\ volt.$

Back emf at speed 1000rpm =$E_{B1} = \frac{N1}{N} \times E_B = \frac{1000}{970} \times 215 = 221.65\ volt$

(a) For plugging, RB+Ra=$\frac{E_{B1}+V}{Ia1}$=$\frac{221.65+220}{200}$=2.21 ohm

=>RB=2.21-0.05=1.16 ohm

(b) TB=$\frac{E_{B1}\times Ia1}{\omega_{m1}}$=$\frac{221.65\times 200}{\frac{2\pi N1}{60}}$=423.3, N-m

© At zero speed, back emf=0=E_{B2}

Ia2= $\frac{V}{R_B+Ra}$=$\frac{220}{2.21}$=99.55A.

In separately excited motor, Flux Ø remains constant. So T∝ Ia.

Therefore, $\frac{T2}{TB}$=$\frac{Ia2}{Ia1}$ =>T2=$\frac{Ia2}{Ia1}\times TB$=$\frac{99.55}{200}\times 423.3 = 210.7, N-m$

P.4. [Example 5.11] A 220V, 500A, 600rpm Dc separately excited motor has armature & field resistance of 0.02 ohm and 10 ohm respectively. The load torque is given by the expression TL=2000 -2N, N-m, where N is the speed in rpm. Speed below the rated are obtained by armature voltage control and speed above the rated are obtained by field control.

(a) Calculate motor terminal voltage and armature current when the speed is 450 rpm.

(b) Calculate field winding voltage and armature current, when the speed is 750 rpm.

SOLUTION:

V1=220 volt, Ia1=500A, N1=600rpm,N2=450 rpm, N3=750 rpm, Ra=0.02 ohm, TL=2000 −2N, N-m

At rated speed N1=600rpm

EB1=V1-Ia1Ra=220-500$\times$ $0.02 = 210\ volt$

Rated torque=$\frac{EB1\times Ia1}{\omega_{m1}}$ =$\frac{210\times 500}{2\pi\times 600/60}$=1671, N-m=T1

[Rated parameter is independent of load. So TL equation is not applicable to calculate rated torque] (a)At 450 rpm, N2<N1, So armature voltage control method is employed i.e flux remains constant.

TL2= 2000 -2$\times$ $450 = 1100, N - m$

EB2=(N2/N1)EB1=(450/600)210=157.5 volt

Ia2=(T2/T1)Ia1=(1100/1671)500=329 A=armature current

V2=EB2+Ia2Ra=157.5+329$\times$ 0.02 $= 164\ volt$=motor terminal voltage

(b)At speed 750 rpm N2>N1, So flux control method is employed i.e flux will vary and armature voltage remains constant.

TL3= 2000 $-2\times$ $750 = 500, N - m$

Let flux and armature current at this torque are $\emptyset_3$ and Ia3 respectively.

Since T$\propto$ $\emptyset \times Ia$, $\frac{T3}{T1}$=$\frac{\emptyset3\times Ia3}{\emptyset1\times Ia1}$

=>$\frac{\emptyset3}{\emptyset1} = \frac{T3\times Ia1}{T1\times Ia3}$=$\frac{500\times500}{1671\times Ia3}$=$\frac{149.611}{Ia3}$

=>$\frac{\emptyset3}{\emptyset1}$=$\frac{149.611}{Ia3}$---------------(1)

Since armature voltage remains constant, V=$E_{B3} + Ia3Ra$

⇨ 220=$E_{B3} + Ia3 \times 0.02$-----------(2)

Again $\frac{EB3}{EB1} = \frac{\emptyset3}{\emptyset1} \times \frac{N3}{N1}$=$\frac{149.611}{Ia3} \times \frac{750}{600}$=$\frac{187}{Ia3}$

=>$E_{B3} = \frac{187}{Ia3} \times 210 = 39273/Ia3$

=>$E_{B3} = 39273/Ia3$----------(3)

From equations (2) & (3), we get

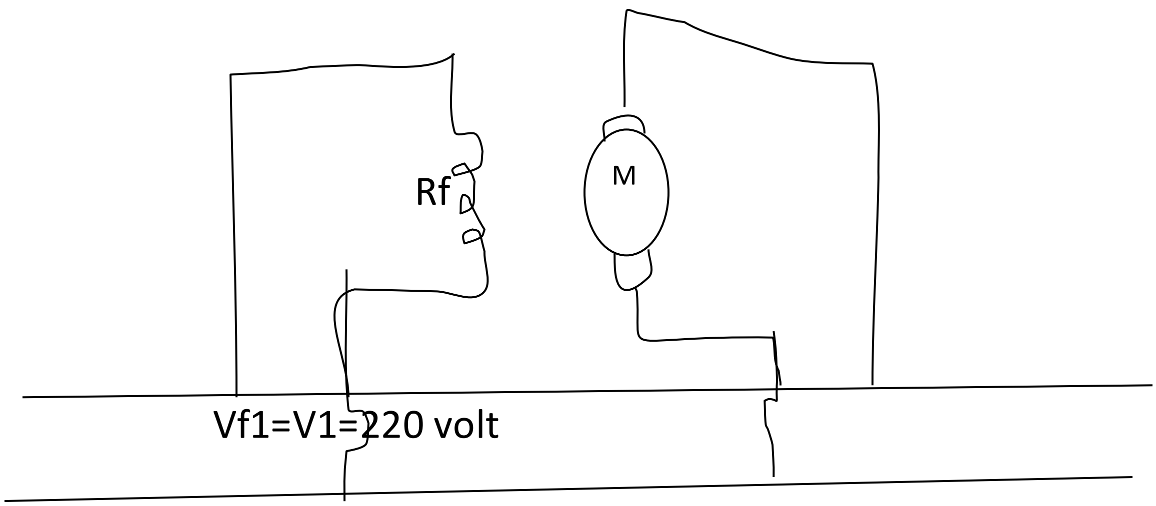
220=$\frac{39273}{Ia3} + \ Ia3 \times 0.02$=> Ia3=181.5A or 21647A

=> $Ia3 = 181.5\ A$= armature current as lower current is taken for safety and to reduce the cost of switch gear.

Field winding voltage=$If \times Rf, If \propto Vf, \emptyset \propto If => \emptyset \propto Vf$

=>$Vf3 = \frac{\emptyset 3}{\emptyset 1} \times Vf1 = \frac{149.611}{Ia3} \times 220 = \frac{149.611}{181.5} \times 220 = 181.35\ volt$

(As Vf1=V1=220 volt)



P5.[Example5.13] A 200 Volt,875 rpm, 150A Dc separately excited motor has armature resistance of 0.06 ohm. It is fed from a single phase fully controlled rectifier with an ac source voltage of 220 v,50Hz. Assuming continuous condition, calculate

(a) Firing angle for rated motor torque & 750 rpm

(b) Firing angle for rated motor torque & -500 rpm

©Motor speed for ∝ =160 degree and rated torque.

SOLUTION:

Given data

Rated voltage=V=200 Volt, Rated Speed=N=875 rpm, Rated armature current=150A, Armature resistance=0.06 ohm, Fully controlled rectifier is used to vary armature voltage. Supply voltage =Vs=220 volt, 50 Hz ac, continuous condition.

Back emf at reted speed = $E_B = V - IaRa = 200 - 150 \times 0.06 = 191\ volt.$

(a)Back emf at 750 rpm =$E_{B1} = \frac{N1}{N} \times E_B = \frac{750}{875} \times 191 = 163.7 volt$

Therefore armature voltage at 750 rpm =Va=$E_{B1} + IaRa = 163.7 + 150 \times 0.06 = 172.7\ volt$

Output voltage of rectifier =Vo=Va

⇨ $\frac{2Vmax}{\pi} \times cos \propto = 172.7$

⇨ $2 \times 220\sqrt{2}/\pi \times cos \propto = 172.7$

⇨ $\propto = 29.3\ degree$

(b) At -500 rpm, Back emf=$E_{B2} = \frac{N2}{N} \times E_B = \frac{-500}{875} \times 191 = -109\ V$

Therefore armature voltage at -500 rpm =Va1=$E_{B2} + IaRa = -109 + 150 \times 0.06 = -100\ volt$

⇨ $\frac{2Vmax}{\pi} \times cos \propto = -100$

⇨ $2 \times \frac{220\sqrt{2}}{\pi} \times cos \propto = -100$

⇨ $\propto = 120\ degree$

(c)At$\propto = 160\ degree$,Va2=$\frac{2Vmax}{\pi} \times cos \propto$=2 $\times \frac{220\sqrt{2}}{\pi} \times cos160 = -186\ Volt$

Va2=$E_{B3} + 150 \times 0.06$=>$E_{B3} = -195\ volt$

Therefore speed for $\propto = 160\ degree\ and$ rated torque=$\frac{-195}{191} \times 875 = -893.2\ rpm$

P6. [Example5.14-i]

A 200 Volt,875 rpm, 150A Dc separately excited motor has armature resistance of 0.06 ohm and inductance of 0.85 mH. It is fed from a single phase fully controlled rectifier with an ac source voltage of 220 v,50Hz. Calculate motor torque for 60 degree firing angle & 400 rpm.

SOLUTION:

Given data, Rated voltage=V=200 Volt, Rated Speed=N=875 rpm, Rated armature current=150A, Armature resistance=Ra=0.06 ohm, Armature inductance=La=0.85mH, fully controlled rectifier is used to vary armature voltage. Supply voltage =Vs=220 volt, 50 Hz ac.

Let us find out the mode of operation, whether continuous or discontinuous by calculating critical speed.

$\omega_{mc=\frac{Ra \times Vmax}{K\,Z}}$ sin $(\propto -\emptyset)[\frac{1+e^{-\pi cot\emptyset}}{e^{-cot\emptyset}-1}]$,

Phase angle $\emptyset = tan^{-1}\left(\frac{\omega La}{Ra}\right) = tan^{-1}\left(\frac{2\pi f La}{Ra}\right) = 77.34\ degree$

$\cot\emptyset = 0.2247$

Z=$\sqrt{Ra^2 + (\omega La)^2}$ =$\sqrt{0.06^2 + (2\pi \times 50 \times 0.85 \times 10^{-3})^2}$

=0.2737 ohm

Back emf at reted speed $= E_B = V - IaRa = 200 - 150 \times 0.06 = 191\ volt.$

Therefore motor constant=K=$\frac{E_B}{\omega_m} = \frac{191}{875} \times \frac{60}{2\pi} = 2.084$

Therefore critical speed=$\omega_{mc=\frac{Ra \times Vmax}{K\ Z}}$ sin $(\propto - \emptyset)[\frac{1+e^{-\pi cot\emptyset}}{e^{-cot\emptyset}-1}]$=28.8 rad/sec=275 rpm

Since motor speed=400rpm>ω_{mc}, the drive is operating in discontinuous mode. Hence

Vo=Va=$\frac{Vmax(cos\propto - cos\beta)+(\pi+\alpha-\beta)E}{\pi}$

Since$\pi < \beta < \pi + \alpha\ and\ \alpha = 60,$ we assume a value of $\beta\ which\ remains\ in\ b$etween 180 degree and 240 degree. Let us take $\beta = 230\ degree$

Counter emf =E =back emf

Back emf at 400rpm=(400/875)191=87.3 volt

Therefore Vo=Va $=$

$\frac{Vmax(cos\propto - cos\beta)+(\pi+\alpha-\beta)E}{\pi} = \frac{220\times\sqrt{2}(cos60-cos130)+\left(\pi+\frac{\pi}{3}-\frac{\pi}{180}\times 230\right)\times 87.3}{\pi}$

=118 volt

Ia=$\frac{Va-E}{Ra} = \frac{118-87.3}{0.06} = 512\ A$

Torque T=KIa=2.084$\times\ 512 = 1067, N - m$

P7.[Example5.15-i] A 200 Volt,875 rpm, 150A Dc separately excited motor has armature resistance of 0.06 ohm and inductance of 2.85 mH. It is fed from a single phase fully controlled rectifier with an ac source voltage of 220 v,50Hz. Calculate motor speed for $\propto = 120 degree\ and\ T = 1200, N - m.$

SOLUTION:

Given data, Rated voltage=V=200 Volt, Rated Speed=N=875 rpm, Rated armature current=150A, Armature resistance=Ra=0.06 ohm, Armature inductance=La=2.85mH, fully controlled rectifier is used to vary armature voltage. Supply voltage =Vs=220 volt, 50 Hz ac.

Let us find out the mode of operation, whether continuous or discontinuous by calculating critical speed and torque at critical speed.

$\omega_{mc=\frac{Ra \times Vmax}{K\,Z}}$ sin $(\propto -\emptyset)[\frac{1+e^{-\pi cot\emptyset}}{e^{-cot\emptyset}-1}]$,

Phase angle $\emptyset = tan^{-1}\left(\frac{\omega La}{Ra}\right) = tan^{-1}\left(\frac{2\pi f La}{Ra}\right) = 86.17\ degree$

cot$\emptyset = 0.067$

Z=$\sqrt{Ra^2 + (\omega La)^2}$ =$\sqrt{0.06^2 + (2\pi \times 50 \times 2.85 \times 10^{-3})^2}$

=0.8974 ohm

$\omega_{mc=\frac{Ra \times Vmax}{K\,Z}}$ sin $(\propto -\emptyset)[\frac{1+e^{-\pi cot\emptyset}}{e^{-cot\emptyset}-1}]$=-52.94 rad/sec= -505.5rpm

Back emf at reted speed = $E_B = V - IaRa = 200 - 150 \times 0.06 = 191\ volt.$

Back emf at -505.5 rpm =$E_{B1} = \frac{N1}{N} \times E_B = \frac{-505.5}{875} \times 191 = -110.34 volt$

At critical speed, the drive operates in continuous mode. So

Va=$\frac{2Vmax}{\pi} \times cos \propto = -99\ volt$

Ia=$\frac{Va-E}{Ra}$=$\frac{-99-(-110.34)}{0.06} = 189\ A$

motor constant=K=$\frac{E_B}{\omega_m} = \frac{191}{875} \times \frac{60}{2\pi} = 2.084$

Torque at critical speed=Tc=KIa=2.084$\times\ 189 = 393.9, N-m$

Since T>Tc, the drive is operating in continuous conduction.

At T=1200,N-m, Ia=T/K=1200/2.084=576.9A

Va=$\frac{2Vmax}{\pi} \times cos \propto = -99\ volt$

E=Va-IaRa=-99-576.9$\times\ 0.06 = -133.6\ volt$

Therefore speed for T=1200, N-m =$\frac{-133.6}{191} \times 875 = -612\ rpm$

P8.[Example5.16] A 220 Volt, 960 rpm, 12.8A Dc separately excited motor has armature resistance of 2 ohm and inductance of 150 mH. It is fed from a single phase half controlled rectifier with an ac source voltage of 230 v,50Hz. Calculate(a) motor torque for $\propto = 60 degree\ and\ speed = 600\ rpm$ (b) motor speed for $\propto = 60 degree$ and T=20, N-m.

SOLUTION:

Given data, Rated voltage=V=220 Volt, Rated Speed=N=960 rpm, Rated armature current=12.8A, Armature resistance=Ra=2 ohm, Armature inductance=La=150mH, half controlled rectifier is used to vary armature voltage. Supply voltage =Vs=230 volt, 50 Hz ac.

Let us find out the mode of operation, whether motor operates continuous or discontinuous.

$$\omega_{mc} = \frac{Ra}{K}\frac{Vmax}{z}\left[\frac{sin\emptyset\ .\ e^{-\alpha cot\emptyset} - \sin(\alpha - \emptyset)e^{-\pi cot\emptyset}}{1 - e^{-\pi cot\emptyset}}\right]$$

Phase angle =$\emptyset = tan^{-1}\left(\frac{\omega La}{Ra}\right) = 87.57^0$

=>$\cot\emptyset = 0.04244$, Z=$\sqrt{Ra^2 + (\omega La)^2}$=47.17ohm

Back emf at rated speed=E=220-12.8$\times\ 2 = 194.4\ volt$

K=E/$\omega_m = \frac{194.4}{\frac{2\pi N}{60}}$=$\frac{194.4\times 60}{2\pi\times 960} = 1.9337$

Therefore

$\omega_{mc} = \frac{Ra}{K}\frac{Vmax}{z}\left[\frac{sin\emptyset\ .e^{-\alpha cot\emptyset} - \sin(\alpha-\emptyset)e^{-\pi cot\emptyset}}{1-e^{-\pi cot\emptyset}}\right]$=77.76rad/sec or 742.54 rpm

(a) Motor speed=600 rpm <ω_{mc}, hence drive is operating under continuous conduction.

Va=Vo=$\frac{Vmax}{\pi} \times (1 + cos \propto)$= $\frac{230\sqrt{2}}{\pi} \times (1 + cos60)$=155.3 volt

Back emf at 600 rpm=E1=$\frac{600}{960} \times 194.4 = 121.5\ volt$

Ia1=(Va-E1)/Ra=(155.3 -121.5)/2=16.9 A

Torque=T=KIa=$1.9337 \times 16.9 = 32.68, N-m$

(b)Critical speed=ω_{mc}=742.54 rpm

Ec=Back emf at critical speed=(742.54/960) 194.4=150.37 volt

Va=Vo=$\frac{Vmax}{\pi} \times (1 + cos \propto)$= $\frac{230\sqrt{2}}{\pi} \times (1 + cos60)$=155.3 volt

Tc=K (Ia)c=1.9337($\frac{Va-Ec}{Ra}$) $= 4.77, N-m$

Motor torque =T=20, N-m >Tc. Hence drive is operating in continuous conduction.

Now Ia2=T/K=20/1.9337=10.34 A

Back emf=E2=Va-Ia2Ra=155.3-10.34$\times 2 = 134.6\ volt$

Hence speed=$\frac{134.6}{194.4} \times 960 = 664.8\ rpm$

P9.[Example5.17-a] A 220 Volt, 1500 rpm, 50A Dc separately excited motor has armature resistance of 0.5 ohm. It is fed from a three phase fully controlled rectifier with an ac source voltage of 440 v,50Hz. A star-delta connected T/f is used to feed the armature so that motor terminal voltage equals rated voltage when converter firing angle is zero. Calculate (a) transformer turn ratio (b) the value of firing angle when motor is running at 1200rpm and rated torque. Assume continuous conduction.

SOLUTION: Given data

Rated voltage=V=220 volt, rated speed= N=1500rpm,rated armature current=50A, Armature resistance=Ra=0.5 ohm, 3ph fully controlled rectifier. Source voltage=Vs=440V(line-line), f=50 Hz,

(a)Output of 3ph fully controlled rectifier=vo=Va=$\frac{3}{\pi} Vmax\ cos\alpha$

$\alpha = 0\ degree,$ va=$\frac{3}{\pi} Vmax$=> $Vmax = \frac{\pi}{3} \times Va$=maximum value of line voltage

For rated terminal voltage, Va=220 volt

Therefore Vmax=$\frac{\pi}{3} \times 220 = 230.4 volt$

=>rms value of converter input voltage between lines=$230.4/\sqrt{2}$ =162.9 volt

For star-delta transformer connection, turn ratio between phase windings of primary and secondary=$\frac{440/\sqrt{3}}{162.9} = 1.559$

(b)Back emf at rated speed=E=V-IaRa=220- $50\times 0.5 = 195\ volt$

Hence back emf at speed 1200 rpm =E1=$\frac{1200}{1500} \times 195 = 156\ volt$

Armature voltage at 1200 rpm=Va =E1+Ia Ra=156+$50\times 0.5 = 181 volt$

But Va=$\frac{3}{\pi} Vmax\ cos\alpha$

=>$cos\alpha$=$\frac{\pi}{3} \times \frac{Va}{Vmax} = \frac{\pi}{3} \times \frac{181}{230.4} = 0.8227$

=> Firing angle $\propto = 34.65^0$

P10. A dc series motor is fed from 600 volt source through a chopper. The dc motor has the following parameters,

Ra=0.04ohm,Rse=0.06 ohm, motor constant =K=4×10^{-3}N-m/amp^2, The average armature current is 300 A. For a chopper duty cycle of 60%,deternine (a) Input power from source (b) motor speed (c)motor torque.

SOLUTION: Given data

Source voltage=Vs=600volt, duty ratio=δ =60%=0.6, Armature current=Ia=300A, Ra=0.04ohm,Rse=0.06 ohm, motor constant =K=4×10^{-3}N-m/amp^2

(a) Power input to the motor=VaIa= $\delta VsIa = 0.6 \times 600 \times 300 = 108000\ watt = 108KW$

(b) In dc series motor, Va=E+Ia(Ra+Rse)=> $\delta Vs = KIa\omega_m + 300(0.04 + 0.06) => 0.6 \times 600 = 4 \times 10^{-3} \times 300 \times \omega_m + 30$

=>$\omega_m = 275\ rad/sec$

© T=K$Ia^2 = 4 \times 10^{-3} \times 300^2 = 360, N - m$

P11. A dc separately excited motor is fed from 230 volt source through a chopper. The dc motor has the following parameters,

Ra=3 ohm, motor constant =K=0.5 V/rad/sec. Turn ON and Turn OFF time of chopper are 10 microsec and 15 micro sec respectively. Calculate the average load when motor speed=1500rpm.

SOLUTION: Duty ratio=Ton/T=10/(10+15)=0.4

Va=$\delta Vs = 0.4 \times 230 = 92\ volt$

Back emf at 1500 rpm =E=K× $\omega_m = 0.5 \times \frac{2\pi N}{60}$=78.5 volt

Ia=$\frac{Va-E}{Ra} = \frac{92-78.5}{3} = 4.5\ A$

P12. A 230 Volt, 870 rpm, 100A Dc separately excited motor has armature resistance of 0.05 ohm. It is coupled to an overhauling load with a torque of 400, N-m. Determine the speed at which motor can hold the load by regenerative braking.[Exercise 5.10]

SOLUTION: Given data

Supply voltage V=230 V, Rated speed=N1=870 rpm, Rated current=Ia1=100 A, Ra=0.05 ohm, TL=load torque=400, N-m=T2

Hence Eb1=V-Ia1Ra=230-100× $0.05 = 225\ volt$

T1=$\frac{E_{b1}\times Ia1}{\omega_{m1}} = \frac{225\times100}{2\times\pi\times870/60} = 246.965, N-m$

Separately excited motor => $\emptyset$ *remains constant*

Hence T$\propto Ia$

⇨ $\frac{T2}{T1} = \frac{Ia2}{Ia1} => Ia2 = \frac{T2}{T1}\times Ia1 = \frac{400}{246.965}\times 100 = 162\ A$

$$For\ regenerative\ braking, Eb2 = V + Ia2Ra$$

$$= 230 + 162 \times 0.05 = 239\ volts$$

Again for separately excited motor, Eb$\propto N$, as$\emptyset$ *remains constant*

⇨ Hence $\frac{N2}{N1} = \frac{Eb2}{Eb1} => N2 = \frac{Eb2}{Eb1}\times N1 = \frac{239}{225}\times 870 = 924.5\ rpm$

$$=> N2 = 924.5\ rpm$$

P.13. A 230 Volt, 960 rpm, 200A Dc separately excited motor has armature resistance of 0.02 ohm. It is driving a overhauling load whose torque may vary from zero to rated motor torque. Field flux can be changed and field saturates at 1.2 times the rated flux.Calculate the speed range in which motor can hold the load by regenerative braking twice the rated motor current. .[Exercise 5.11]

SOLUTION:

Given data

Supply voltage V=230 V, Rated speed=N1=960 rpm, Rated current=Ia1=200 A, Ra=0.02 ohm.

Since 0$\leq T2 \leq T1, When\ T2 = 0, Ia2 = 0$

⇨ (Ia2)min=0, (Ia2)max=2Ia1=2$\times$ $200 = 400\ A$

Rated flux=$\emptyset 1 => \max flux = 1.2\,\emptyset 1 = \emptyset 2$

Rated emf= Eb1=V-Ia1Ra=230-200$\times\ 0.02 = 226\ volt$

For regenerative braking,

(Eb2)min=V+(Ia2)min$\times$ Ra=230+0$\times\ Ra = 230\ volt$

(Eb2)max=V+(Ia2)max$\times$ Ra=230+400$\times\ 0.02 = 238\ volt$

Hence (Eb2)min$= 230\ volt$ and (Eb2)max=238 $volt$

Minimum Speed.

N$\propto \frac{Eb}{\emptyset}$, => N$min \propto \frac{(Eb)min}{\emptyset max}$,

=>$\frac{(Eb2)min}{Eb1} = \frac{N2min}{N1} \times \frac{\emptyset 2}{\emptyset 1} => N2min = \frac{230}{226} \times \frac{1}{1.2} \times 960 = 814\ rpm$

$$N2min = 814\ rpm$$

Maximum Speed

Minimum flux is not provided.

As $T_B \propto \omega_m$, [since braking torque decreases as the motor speed decreases]

For maximum speed, braking torque becomes maximum.

i.e T2=T1 as 0$\leq T2 \leq T1$

$\frac{(Eb2)max \times Ia2max}{\omega_{m2max}} = \frac{Eb1 \times Ia1}{\omega_m}$, [As T= Eb×Ia/$\omega_m$]

=>$\frac{((Eb2)max \times Ia2max)}{\frac{2\pi (N2)max}{60}} = \frac{Eb1 \times Ia1}{\frac{2\pi (N1)}{60}}$

=>(N2)max=$\frac{238 \times 400}{228 \times 200} \times 960 = 2004\ rpm$

=>(N2)max=2004 rpm

Therefore range of speed during braking is 807$\leq N2 \leq 2004\ rpm$

P14. .[Exercise 5.12]

A 230 Volt, 960 rpm, 200A Dc separately excited motor has armature resistance of 0.02 ohm. It is required to hold the rated torque by dynamic braking at 1200 rpm without emf exceeding 230 volt. Calculate the value of external resistance to be connected across the armature.

SOLUTION:

Given data

Supply voltage V=230 V, Rated speed=N1=960 rpm, Rated current=Ia1=200 A, Ra=0.02 ohm.

Rated emf= Eb1=V-Ia1Ra=230-200$\times$ $0.02 = 226\, volt$

Rated torque=T1=$\frac{Eb1\times Ia1}{\frac{2\pi(N1)}{60}} = 450, N-m$

As per the question, it is required to hold the rated torque at speed1200 rpm

⇨ T1=T2=TB=450, N-m

For dynamic braking, $T_B = \frac{Eb\times Ia}{\frac{2\pi(N)}{60}} = \frac{Eb\times {Eb}/{Ra+RB}}{\frac{2\pi(N)}{60}} = \frac{Eb^2}{Ra+RB} \times \frac{60}{2\pi\times 1200}$

It is required to hold the rated torque by dynamic braking at 1200 rpm without emf exceeding 230 volt i.e Eb=230 volt

Hence 450=$\frac{230^2}{0.02+RB} \times \frac{60}{2\pi\times 1200}$=>RB=0.915 ohm

P15. .[Exercise 5.30]

A 220 Volt, 750 rpm, 200A Dc separately excited motor has armature resistance of 0.05 ohm. It is driving a load whose torque has an expression TL=500-0.25N,N-m, where N is speed in rpm.

Speed below the rated are obtained by armature voltage control and speed above the rated are obtained by field control.

(a) Calculate motor terminal voltage and armature current when the speed is 400 rpm.

Calculate value of flux as percent of rated flux when speed is 1500 rpm.

SOLUTION:[Hints]

Refer P4. (a) Ans Armature current=149.6A and terminal voltage=119.5 V

(b)

At 1500 rpm,T2=125,N-m=K $\emptyset 2 Ia2$

=> K $\emptyset 2 = 125/ Ia2$--------(1)

Rated torque=534.76, N-m=K$\emptyset r Ia$

K∅r=534.76/200-----------(2)

From equations (1) & (2) we get the relation $\emptyset 2/\emptyset r$=51.2%

P.16 .[Exercise 5.36]

A 220 Volt,1500 rpm, 10A Dc separately excited motor has armature resistance of 2 ohm. It is fed from a single phase fully controlled rectifier with an ac source voltage of 230 v,50Hz. Assuming continuous condition, calculate the firing angle for

(a) Half the rated motor torque & 500 rpm (b)rated motor torque & -1000 rpm

[same as Example5.13]

SOLUTION:

Given data

Rated voltage=V=220 Volt, Rated Speed=N=1500 rpm, Rated armature current=10A, Armature resistance=2 ohm, Fully controlled rectifier is used to vary armature voltage. Supply voltage =Vs=230 volt, 50 Hz ac, continuous condition.

Back emf at reted speed = $E_B = V - IaRa = 220 - 10 \times 2 = 200\ volt.$

Rated torque =T=Eb× Ia/ω_m= 200× 10/(2$\pi \times 1500/60) = 12.73, N - m$

(a) N1=500 rpm, T1=T/2=6.365,N-m

As N1<N, armature voltage controlled method is used. So flux remains constant.

Hence Ia1/Ia=T1/T => Ia1=(1/2)10=5A

And Eb1/Eb=(N1/N) => Eb1=(500/1500)200=66.65 volt

Therefore Va1=Eba+Ia1 Ra=66.65 + 5× $2 = 76.65\ volt$

It is fed from a single phase fully controlled rectifier.

Therefore Va1=(2Vmax/$\pi)cos\alpha$

=>(2Vmax/$\pi)cos\alpha$=76.65 => (2× $230\sqrt{2}\ /\pi)\ cos\alpha = 76.65 => \alpha = 68.27 degree$

(b) N2=-1000rpm, T2=T=12.73 N-m

Solve as per bit (a)

Ans. $\alpha = 123.18\ degree$

P17.[Exercise 5.37]

A 220 Volt,1500 rpm, 10A Dc separately excited motor has armature resistance of 2 ohm and inductance 50mH. It is fed from a single phase fully controlled rectifier with an ac source voltage of 230 v,50Hz. calculate (a) speed and torque on the boundary between the continuous and discontinuous conduction and(b) No load speed for $\alpha = 60\ degree$

SOLUTION:

Given data

Rated voltage=V=220 Volt, Rated Speed=N=1500 rpm, Rated armature current=10A, Armature resistance=2 ohm, Fully controlled rectifier is used to vary armature voltage. Supply voltage =Vs=230 volt, 50 Hz ac, continuous condition.

Back emf at reted speed = $E_B = V - IaRa = 220 - 10 \times 2 = 200\ volt.$

Speed between continuous and discontinuous mode is the critical speed. It is fed from a single phase fully controlled rectifier.

Therefore,$\omega_{mc=\frac{Ra \times Vmax}{K\ Z}}$ sin $(\propto -\emptyset)[\frac{1+e^{-\pi cot\emptyset}}{e^{-cot\emptyset}-1}]$,

K=Eb/$\omega_m = 200/(2\pi \times 1500/60) = 1.273$

Phase angle $\emptyset = tan^{-1}\left(\frac{\omega La}{Ra}\right) = tan^{-1}\left(\frac{2\pi f La}{Ra}\right) = 84.744\ degree$

cot$\emptyset = 0.127$

Z=$\sqrt{Ra^2 + (\omega La)^2}$ =$\sqrt{2^2 + (2\pi \times 50 \times 50 \times 10^{-3})^2}$

=15.83 ohm

$\omega_{mc=\frac{Ra\times Vmax}{K\,Z}}$ sin $(\propto -\emptyset)[\frac{1+e^{-\pi cot\emptyset}}{e^{-cot\emptyset}-1}]$=63.15 rad/sec= 603 rpm

Back emf at 603 rpm $=E_{B1} = \frac{N1}{N} \times E_B = \frac{603}{1500} \times 200 = 80.4\, volt$

At critical speed, the drive operates in continuous mode. So

Va=$\frac{2Vmax}{\pi} \times cos \propto = \left(2 \times 230\sqrt{2}\,\frac{1}{\pi}\right) cos60 = 103.54\, volt$

Ia=$\frac{Va-E}{Ra}$=$\frac{103.54-80.4}{2} = 11.57\, A$

Torque at critical speed=Tc=KIa=1.273$\times\, 11.57 = 14.73, N-m$

(b) No load speed $=\omega_{mo} = \frac{Vmax}{K}, for\ 0 \le \alpha < 90^0$

& $=\frac{Vmax\times sin\propto}{K}, for\ 90^0 \le \alpha < 180^0$

Here $\propto = 60^0$

Hence No load speed $=\omega_{mo} = \frac{Vmax}{K} = \frac{230\sqrt{2}}{1.273}\ rad/sec$=2440 rpm

P.18 [Exercise 5.38], [refer solution of P6]

A 220 Volt,1200 rpm, 15A Dc separately excited motor has armature resistance of 1.8 ohm and inductance of 32 mH. It is fed from a single phase fully controlled rectifier with an ac source voltage of 230 v,50Hz. Calculate motor torque for

60 degree firing angle & 450 rpm

P.19 [Exercise 5.39], [refer solution of P7]

A 220 Volt,1200 rpm, 15A Dc separately excited motor has armature resistance of 1.8 ohm and inductance of 32 mH. It is fed from a single phase fully controlled rectifier with an ac source voltage of 230 v,50Hz. Calculate motor speed for $\propto = 45\ degree\ and\ T = 40, N - m$.[

P.20 [Exercise 5.40] [refer solution of P17] but single phase half controlled rectifier is used in this problem.

A 230 Volt,960 rpm, 20A Dc separately excited motor has armature resistance of 1.2 ohm and inductance 50mH. It is fed from a single phase half controlled rectifier with an ac source voltage of 230 v,50Hz. calculate (a) speed and torque on the boundary between the continuous and discontinuous conduction and(b) No load speed for $\alpha = 45\ degree$

P.21 [Exercise 5.41] [refer solution of P7]

A 230 Volt,650 rpm, 100A Dc separately excited motor has armature resistance of 0.08 ohm and inductance of 8 mH. It is fed from a single phase half controlled rectifier with an ac source voltage of 230 v,50Hz. Calculate motor speed for $\propto = 60\ degree\ and\ T = 1000, N - m$.

P.22 [Exercise 5.42] [refer solution of P6]

A 230 Volt,650 rpm, 100A Dc separately excited motor has armature resistance of 0.08 ohm and inductance of 8 mH. It is fed from a single phase half controlled rectifier with an ac source voltage of 220 v,50Hz. Calculate motor torque for 60 degree firing angle & 200 rpm.

NUMERICAL PROBLEMS ON AC DRIVE

GK Dubey: EXAMPLES:

6.8(Pg184-2011), 6.9-ii(Pg189),6.15(Pg210-2014),6.17(pg217),6.18-I,ii(Pg223-2012)

EXERCISE: 6.36(2011), 6.51(pg241-2013),6.52(pg241),6.68(pg243)

P1. (Example 6.8), A 2.8kw, 400v,50 Hz, 4 pole, 1370 rpm, delta connected squirrel-cage induction motor has following parameters referred to the stator: Rs=2 ohm, Rr'=5 ohm, Xs=Xr'=5 ohm, Xm=80 ohm. Motor speed is controlled by stator voltage control. When driving a fan load it runs at rated speed at rated voltage. Calculate (i) motor terminal voltage, current and torque at 1200 rpm (ii) motor speed, current and torque for the terminal voltage of 300 V.

SOLUTION:

Given data

Rated power =P=2.8 Kw=2800 Watt, rated speed=N=1370 rpm, supply voltage=VL=400 Volt, delta connected, supply frequency=f=50Hz, Rs=2 ohm, Rr'=5 ohm, Xs=Xr'=5 ohm, Xm=80 ohm. Number of pole=p=4

Motor speed is controlled by stator voltage control i.e Vs will be replaced by Vt.

When driving a fan load it runs at rated speed at rated voltage (given).

[Note:For fan and pump drive, LoadTorque $\propto (speed)^2$],

Synchronous speed=Ns=120f/p=1500 rpm

⇨ $\omega_{ms} = 50\pi\ rad/sec$

Slip at rated speed=s=(Ns –N)/Ns ==(1500 –1370)/1500=0.0867

We have

Tr=$\frac{3}{\omega ms} \times \frac{Vt^2 \times \frac{Rr\prime}{s}}{(Rs+\frac{Rr'}{s})^2+(Xs+Xr')^2}$-------------(1), [Vs is replaced by Vt]

Hence rated torque =T=$\frac{3}{50\pi} \times \frac{400^2 \times \frac{5}{0.0867}}{\left(2+\frac{5}{0.0867}\right)^2+(5+5)^2}$

$= 48.13, N-m$ [due to delta connection VL=Vph]

For fan load, LoadTorque ∝ $(speed)^2$ [as windage torque=Tw=C ωm^2,refer components of load torque]

⇨ TL∝ N^2,=> TL∝ $[Ns(1-s)]^2$,=>

TL= $K(1-s)^2$---------------(2)

As T=TL => $48.13 = K(1-0.0867)^2$

⇨ K=57.7

(I)AT SPEED=N1=1200 RPM,

(a)T=?

Torque at 1200 rpm to be calculated:

Slip= s1=(Ns –N1)/Ns =

(1500 –1200)/1500=0.2

Hence TL1 $= K(1-s1)^2$ =57.7$(1-0.2)^2$=36.9 N-m

Since T=TL, Torque at 1200 rpm =36.9, N-m

(b)Motor terminal voltage:

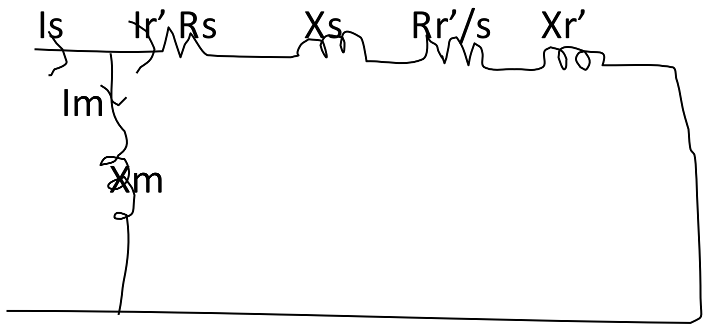
T=$\frac{3}{\omega ms} \times \frac{Vt^2 \times \frac{Rr\prime}{s}}{(Rs+\frac{Rr'}{s})^2+(Xs+Xr')^2}$

⇨ 36.9=$\frac{3}{50\pi} \times \frac{Vt^2 \times \frac{5}{0.2}}{\left(2+\frac{5}{0.2}\right)^2+(5+5)^2}$

=>Vt=253.2 volt= phase voltage

=> Motor terminal voltage=253.2 volt [as in delta connection, VL=Vph}

© Motor current:



Ir’=$\frac{232.2<0}{(2+\frac{5}{0.5})+j10} = 8.246 - j3.054$

Im=$\frac{Vt}{jXm} = \frac{253.2<0}{j80} = -j3.165$

Is= Ir’+Im=$8.246 - j3.054 - j3.165 = 8.246 - j6.219$ =10.328<-37^0

Hence line current =IL=$\sqrt{3} \times Is$=17.89 A, [due to delta connection]

<u>(ii)TERMINAL VOLTAGE VT=300 VOLT</u>

(a) Speed to be calculated:

⇨ $\frac{3}{50\pi} \times \frac{300^2 \times \frac{5}{s2}}{\left(2+\frac{5}{s2}\right)^2 + (5+5)^2} = K(1-s2)^2$, [as TL=T]

⇨ $\frac{3}{50\pi} \times \frac{300^2 \times \frac{5}{s2}}{\left(2+\frac{5}{s2}\right)^2 + (5+5)^2} = 57.7(1-s2)^2$

⇨ $104{s_2}^4 - 188{s_2}^3 + 89{s_2}^2 - 179s_2 + 25 = 0$

⇨ S2=0.147, [It is solved by using polynomial solution method]

Therefore speed= N2=Ns(1-s2)=1500(1-0.147)=1279 rpm

(b) Torque produced by the motor T2=TL2= $K(1-s2)^2$=57.7 $(1-0.147)^2$=41.94 N-m

(c) Ir’=$\frac{300<0}{(2+\frac{5}{0.147})+j10}$=$\frac{300<0}{36.014+j10}$

$Im = \frac{Vt}{jXm} = \frac{300<0}{j80}$

Is= Ir'+Im=9.75<-37.3^0

Hence line current =IL=$\sqrt{3} \times Is$=$\sqrt{3} \times 9.75$ =16.88 A

P2. (Example 6.9-ii)

A Y-connected squirrel cage induction motor has following ratings and parameters:

400 V, 50Hz, 4pole, 1370 rpm, Rs=2 ohm, Rr'=3 ohm, Xs=Xr'=3.5 ohm. Motor is controlled by a voltage source inverter at constant v/f ratio. Inverter allows frequency variation from 10 to 50 Hz. Calculate starting torque and current of this drive as a ratio of their values when motor is started at rated voltage and frequency.

SOLUTION:

Given data

Rated speed=Nr=1370 rpm, supply voltage=VL=400 Volt, Y- connected, supply frequency=f=50Hz, P=4, Rs=2 ohm, Rr'=3 ohm, Xs=Xr'=3.5 ohm.

Inverter allows frequency variation from 10 to 50 Hz and minimum frequency is 10Hz, it will be started at 10Hz. We have to calculate

$\frac{Tst'}{Tst}$ *and* $\frac{Ist'}{Ist}$, where Tst' and Ist' are the starting torque and current at 10Hz.

Synchronous speed=Ns=120f/p=1500 rpm

⇨ $\omega_{ms} = 50\pi \; rad/sec$

Full load slip=s=(Ns –N)/Ns ==(1500 –1370)/1500=0.0867

<u>At 50Hz</u>

We have, $T = \frac{3}{\omega ms} \times \frac{Vs^2 \times \frac{Rr'}{s}}{(Rs+\frac{Rr'}{s})^2+(Xs+Xr')^2}$

=>Tst=$\frac{3}{\omega ms} \times \frac{Vs^2 \times Rr'}{(Rs+Rr')^2+(Xs+Xr')^2}$, since at stand still s=1

Tst=$\frac{3}{\omega ms} \times \frac{(\frac{400}{\sqrt{3}})^2 \times 3}{(2+3)^2+(3.5+3.5)^2} = 41.29, N-m$

Ist=$\frac{Vs}{\sqrt{(Rs+Rr')^2+(Xs+Xs')^2}}$=$\frac{400/\sqrt{3}}{\sqrt{(2+3)^2+(3.5+3.5)^2}}$=26.85

<u>At 10 Hz</u>

Motor is controlled by a voltage source inverter at constant v/f ratio.

For a frequency k times the rated frequency, the supply voltage will be k times the rated voltage to maintain v/f ratio constant.

K= 10/50=0.2

Tst'=$\frac{3}{K\omega ms} \times \frac{(\frac{400K}{\sqrt{3}})^2 \times 3}{(2+3)^2+K^2(3.5+3.5)^2}$, [as $\omega_{ms} \propto f, and\ Xs, Xr' \propto f$]

Tst'=$\frac{3}{0.2 \times 50\pi} \times \frac{(\frac{400 \times 0.2}{\sqrt{3}})^2 \times 3}{(2+3)^2+0.2^2(3.5+3.5)^2}$=22.67 N-m

Ist'=$\frac{kVs}{\sqrt{(5^2+k^2(3.5+3.5)^2}} = \frac{Vs}{\sqrt{(\frac{5}{k})^2+(3.5+3.5)^2}}$

Ist'=$\frac{\frac{400}{\sqrt{3}}}{\sqrt{(\frac{5}{0.2})^2+(3.5+3.5)^2}}$=8.895 A

Therefore Tst'/Tst=0.549 and Ist'/Ist=0.33

P3 [Example6.15-i,ii] A Y-connected squirrel cage induction motor has following ratings and parameters:

400 V, 50Hz, 1370 rpm, 4 pole, Rs=2 ohm, Rr'=3 ohm, Xs=Xr'=3.5 ohm, Xm=55 ohm

It is controlled by a current source inverter at a constant flux. Calculate

(i) Motor torque, speed and stator current when operating at 30 Hz and rated slip speed.
(ii) Inverter frequency and stator current for rated motor torque and motor speed of 1200 rpm

Solution:

Given data

Rated speed=Nr=1370 rpm, supply voltage=VL=400 Volt, Y- connected, supply frequency=f=50Hz, P=4, Rs=2 ohm, Rr'=3 ohm, Xs=Xr'=3.5 ohm. Xm=55 ohm

Synchronous speed=Ns=120f/p=1500 rpm

⇨ $\omega_{ms} = 50\pi \ rad/sec$

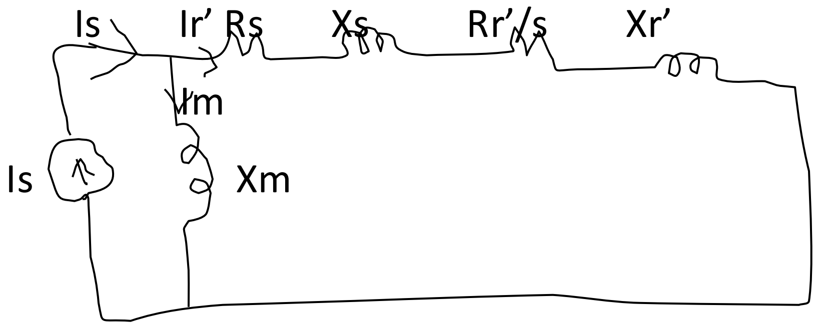
Full load slip=s=(Ns –N)/Ns ==(1500 –1370)/1500=0.0867

We have, $T=\frac{3}{\omega ms} \times \frac{Vs^2 \times \frac{Rr'}{s}}{(Rs+\frac{Rr'}{s})^2+(Xs+Xr')^2}$, for VSI------------(1)

It is controlled by a current source inverter. So T should be expressed in term of current instead of voltage.

Hence $T=\frac{3}{\omega ms} \times \frac{Vs^2 \times \frac{Rr'}{s}}{(Rs+\frac{Rr'}{s})^2+(Xs+Xr')^2} = \frac{3}{\omega ms}\left[\frac{Vs}{\sqrt{\left(Rs+\frac{Rr'}{s}\right)^2+(Xs+Xr')^2}}\right]^2 \times \frac{Rr'}{s}$

$=>T = \frac{3}{\omega ms}(Ir')^2 \times \frac{Rr'}{s}$-------------(2)



<u>At 50 Hz</u>

Impendance= Z= (jXm) || {(Rs+Rr'/s)+j(Xs+Xr')}=28.5<41.38

Hence Is=Vs/Z=$\frac{\frac{400}{\sqrt{3}}<0}{28.5<41.38}$=8.1<-41.38

Ir'=Is× $\frac{jXm}{j(Xm+Xs+Xr')+(Rs+\frac{Rr'}{s})}$=6.1875<-10.81

(i) For a given slip speed, motor torque and current are independent of frequency. Hence **Is** at 50Hz is equal to **Is** at 30Hz

Therefore **Is** at 30 Hz=8.1 A   Ans1

T $=\frac{3}{\omega ms}(Ir')^2 \times \frac{Rr\prime}{s} = \frac{3}{50\pi} \times (6.1875)^2 \times \frac{3}{0.0867} = 25.3, N-m \; at \; 50 \; Hz$

Hence at 30Hz, Torque=25.3, N-m   Ans2

At 30 Hz , Ns1= 120×$\frac{30}{4} = 900 \; rpm$

Slip speed at 50 Hz=1500-1370=130 rpm

As per the question, slip speed remains constant.

Hence Speed at 30 Hz =N1=900-130=770 rpm   Ans3

(ii) At rated motor torque stator current **Is** remains constant.

Hence Is=8.1 A   Ans1

Motor speed =1200 rpm and same slip speed

Hence Ns2=1200+130=1330 rpm

Therefore frequency at 1330 rpm =f2=$\frac{Ns2}{Ns} \times f = \frac{1330}{1500} \times 50 = 44.33Hz => f2 = 44.33Hz$---------Ans2

P4 [Example-6.17] A Y-connected wound rotor motor has following ratings and parameters:

440 V, 50Hz, 6 pole, Rs=0.5 ohm, Rr'=0.4 ohm, Xs=Xr'=1.2 ohm, Xm=50 ohm, stator to rotor turn ratio=a=3.5.

Motor is controlled by static rotor resistance control. External resistance is chosen such that the breakdown torque is produce at standstill for a duty ratio of zero. (a)Calculate the value of external resistance.

(b) How duty ratio should be varied with speed so that the motor accelerates at maximum torque.

SOLUTION:

Given data

Supply voltage=VL=440 Volt, Y- connected, supply frequency=f=50Hz, P=6, Rs=0.5 ohm, Rr'=0.4 ohm, Xs=Xr'=1.2 ohm. Xm=50 ohm

Stator to rotor turn ratio =a=3.5

At maximum torque, slip

Sm=$\frac{Rr\prime}{\sqrt{Rs^2+(Xs+Xr\prime)^2}}$

(a) With an external resistance of rotor whose equivalent value as referred to stator=Re, slip at maximum torque be

Sm=$\frac{Rr'+Re}{\sqrt{Rs^2+(Xs+Xr\prime)^2}}$=$\frac{0.4+Re}{\sqrt{0.5^2+(1.2+1.2)^2}} = \frac{0.4+Re}{2.45}$

⇨ Re=2.45sm-0.4------------(1)

Motor is controlled by static rotor resistance control
Hence total rotor circuit resistance per phase=RrT
=Rr+0.5R(1-δ)=> Re=0.5R(1-δ)a^2-----------(2)

[Just like in t/f, R2'=R2/K^2 and k=N2/N1, but here a=N1/N2]

From equations (1) & (2), we get

2.45sm-0.4=0.5R(1-δ)a^2---------------(3)

As per question, breakdown torque is produce at standstill for a duty ratio of zero.

At standstill sm=1, $\delta = 0$

Hence from equation (3), we get

2.45$\times$ 1-0.4=0.5R(1-0)3.5^2=>R=0.3347 ohm

(b) Ns=120f/p=120$\times \frac{50}{6} = 1000rpm$

Let speed at maximum torque=N rpm

=>sm=(Ns-N)/Ns=1-0.001N

Substituting the values of R and sm in equation (3), we get

$$\delta = 1.195 \times 10^{-3} \times N => \delta \ \alpha \ N$$

Therefore, for accelerating the motor at maximum torque, the duty ratio (δ), must changes linearly.

P5[Example 6.18] A Y-connected 3 phase wound rotor motor has following ratings and parameters:

440 V, 50Hz, 6 pole,970 rpm, Rs=0.1 ohm, Rr'=0.08 ohm, Xs=0.3 ohm, Xr'=0.4 ohm, stator to rotor turn ratio=a=2.

Motor is controlled by static Scherbius Drive. Drive is designed for a speed range of 25% below the synchronous speed. Maximum value of firing angle is 165 degree. Calculate (a) T/f turn ratio (b) Torque for a speed of 780 rpm and firing angle of 140 degree. Dc link inductor has resistance of 0.01 ohm.

SOLUTION:

Given data

Supply voltage=VL=440 Volt, Y- connected, supply frequency=f=50Hz, P=6, N= 970 rpm Rs=0.1 ohm, Rr'=0.08 ohm, Xs=0.3 ohm, Xr'=0.4 ohm.

Stator to rotor turn ratio =n=2. Motor is controlled by static Scherbius Drive. Speed range is 25%. Maximum value of firing $=\propto_{max}= 165^0, Rd = 0.01\ ohm$

(a) We have, slip =s=$-\frac{n}{m} cos \propto => s_{max} = -\frac{n}{m} cos \propto_{max}$

Where m=t/f turn ratio=motor side turn/source side turn of the t/f

n=stator turn/rotor turn=2

For 25% speed range, i,e N=75% of Ns=>$s_{max} \frac{Ns-75\%Ns}{Ns} = 0.25$

Therefore 0.25=$-\frac{2}{m} cos165 => m = 7.722 \cong 8$

(b) N=780 rpm, $\propto= 140^0$

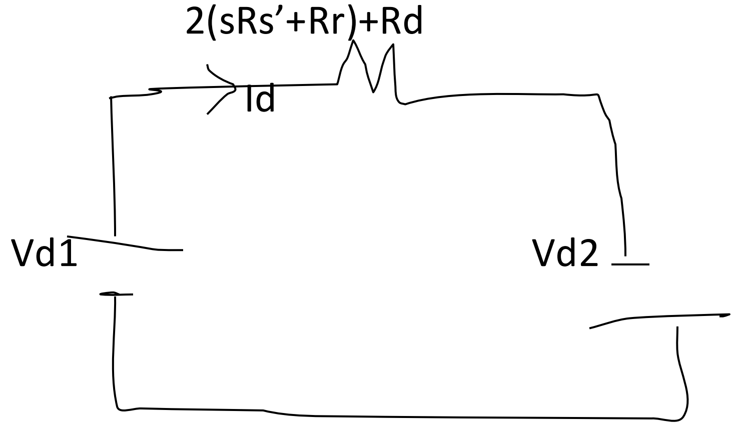
Torque=T=$\frac{|Vd2|\times Id}{s\omega_{ms}}$

Vd2=$\frac{3\sqrt{6}}{\pi} \times \frac{V}{m} cos \propto = \frac{3\sqrt{6}}{\pi} \times \frac{440/\sqrt{3}}{m} cos140 = -58.95\ V$

Vd1=$\frac{3\sqrt{6}}{\pi} \times \frac{sV}{n}$, V is the per phase voltage

Here slip=s=$\frac{Ns-N}{Ns} = \frac{1000-780}{1000} = 0.22$

Hence Vd1=$\frac{3\sqrt{6}}{\pi} \times \frac{sV}{n} = \frac{3\sqrt{6}}{\pi} \times \frac{0.22\times{}^{440}/_{\sqrt{3}}}{2}$=65.363 V



.

Id=$\frac{Vd1+Vd2}{2(sRs'+Rr)+Rd}$

Rs=0.1 ohm=> Rs'=stator resistance as referred to rotor =Rs/$n^2 = \frac{0.1}{2^2} = 0.025\ ohm$

Rr'=0.08=> Rr= Rr'/$n^2 = \frac{0.08}{2^2} = 0.02\ ohm$

Therefore Id=$\frac{65.363-58.95}{2(0.22\times0.025+0.02)+0.01} = 105.13\ A$

$$\omega_{ms} = \frac{2\pi Ns}{60} = 104.72\ rad/sec$$

Hence Torque=T=$\frac{|Vd2|\times Id}{s\omega_{ms}} = \frac{58.95\times105.13}{0.22\times104.72} = 269, N-m$

P6[Exercise6.36]

A 440v,50 Hz, 6 pole, 945 rpm, delta connected squirrel-cage induction motor has following parameters referred to the stator: Rs=2 ohm, Rr’=2 ohm, Xs=3 ohm,Xr’=4 ohm. Motor speed is controlled by stator voltage control. When driving a fan load it runs at rated speed at rated voltage. Calculate (i) motor terminal voltage, current and torque at 800 rpm (ii) motor speed, current and torque for the terminal voltage of 280v.

SOLUTION: Refer solution of problem P1 of this note.

P7[Exercise 6.51-I,ii]

A 440v,50 Hz, 4 pole, 1420 rpm, delta connected squirrel-cage induction motor has following parameters referred to the stator: Rs=0.35 ohm, Rr’=0.4 ohm, Xs=0.7 ohm,Xr’=0.8 ohm. Motor is fed from a voltage source inverter. The drive is operated with a constant v/f control up to 50Hz and at rated voltage above 50 Hz. Calculate the (a)beak down torques for a frequency of 75 Hz (i) for motor operation (ii) for braking operation (b)frequency of motoring operation at 950 rpm and full load torque.

SOLUTION:

Given data

Supply voltage=VL=440 Volt, delta connected, supply frequency=f=50Hz, P=4, N= 1420 rpm Rs=0.35 ohm, Rr’=0.4 ohm, Xs=0.7 ohm, Xr’=0.8 ohm. Motor is fed from a voltage source inverter.$\omega_{ms} =$

Synchronous speed=Ns=120f/p=1500 rpm

⇨ $\omega_{ms} = 157\ rad/sec$

(a)(i)Motoring:

At 75 Hz, v remains constant, k=75/50=1.5

At 50 Hz, Tmax=$\frac{3}{2\omega_{ms}}\frac{V^2}{Rs+\sqrt{Rs^2+(Xs+Xr')^2}}$

At 75 Hz, Tmax=$\frac{3}{2k\omega_{ms}}\frac{V^2}{Rs+\sqrt{Rs^2+k^2(Xs+Xr')^2}}$ =469, N-m

(ii)For Braking operation

At 50 Hz, sm=$-\frac{Rr'}{\sqrt{Rs^2+(Xs+Xr')^2}}$

At 75 Hz, sm=$-\frac{Rr'}{\sqrt{Rs^2+k^2(Xs+Xr')^2}}$=-0.176

Ir'=$\frac{V}{\sqrt{\left(Rs+\frac{Rr'}{sm}\right)^2+k^2(Xs+Xr')^2}}$=$\frac{440}{\sqrt{\left(0.35+\frac{0.4}{-0.176}\right)^2+1.5^2(0.7+0.8)^2}}$

=$\frac{440}{2.96} = 148.67A$

Therefore Tbmax=$\frac{3(Ir')^2\times {Rr'}/{sm}}{k\times\omega_{ms}} = \frac{3(148.67)^2\times {0.4}/{-0.176}}{1.5\times157} = -639.84, N-m$

(b) Synchronous speed=1500 rpm

Full load speed=1420 rpm

Hence at full load, slip speed=1500-1420=80 rpm

New speed=950 rpm

Hence at full load New synchronous speed=950+80=1030 rpm=Ns1

Therefore frequency at new speed=f1=PNs1/120=4$\times\frac{1030}{120} = 34.33Hz$

P8[Exercise 6.52-I,ii] A Delta-connected squirrel cage induction motor has following ratings and parameters:

440 V, 50Hz, 1415 rpm, 4 pole, Rs=0.6 ohm, Rr'=0.8 ohm, Xs=0.5 ohm,Xr'=0.6 ohm, Xm=15 ohm

It is controlled by a current source inverter at a constant flux. Calculate

(i) Motor torque, speed and stator current when operating at 40 Hz and rated slip speed.
(ii) Inverter frequency and stator current for rated motor torque and motor speed of 1000 rpm

SOLUTION: Refer solution of P3

P9[Exercise 6.68] A Y-connected 3 phase wound rotor motor has following ratings and parameters:

440 V, 50Hz, 6 pole,970 rpm, Rs=0.2 ohm, Rr'=0.15 ohm, Xs=0.4 ohm, Xr'=0.4 ohm, stator to rotor turn ratio=a=3.5.

Motor is controlled by static Scherbius Drive. Drive is designed for a speed range of 30% below the synchronous speed. Maximum value of firing angle is 170 degree. Calculate (a) T/f turn ratio (b) Torque for a speed of 750 rpm and firing angle of 140 degree. Dc link inductor has resistance of 0.01 ohm.

SOLUTION: Refer solution of P5

P10 [2010 exam] The rotor of an 8pole, 50 Hz, 3 phase Induction motor has resistance of 2 ohm per phase and runs at 720 rpm. If the load torque remains unchanged, calculate the additional rotor resistance that will reduce the speed by 10%, neglecting stator impedance.

SOLUTION: Ns=120f/p=750

N1=720 rpm, N2= 720-10%720=648 rpm, s1=(NS- N1)/Ns=0.04

s2=(NS-N2)/Ns=0.136

Without external resistance T1=K× s1/Rr

With external resistance(R), T2=K ×s1/(Rr+R), [since Xs=0, Xr'=0 & T=$\frac{3}{\omega_{ms}} \times V^2 \times \frac{s}{Rr\prime}$]

As per question, load torque remains unchanged.

Hence T1=T2=> K× s1/Rr

= K ×s1/(Rr+R)=>s1/s2=Rr/(Rr+R)=> 0.04/0.136=2/(2+R)=>R=4.8 ohm

ASSIGNMENT-2

PART-I $[2\times 8]$

Q1.(i) Why a dc series motor is more suited to deal with torque over loads than other dc motor. Explain.

(ii)State the important features of various braking methods of dc motor.

(iii)What factors limit the maximum speed of field controlled dc motor?

[Hints: for rectifier control------- firing angle

for chopper control-------duty ratio

for conventional controlling method- supply voltage to field winding/resistance connected with field winding]

(iv)Define and state the application of torque motor.

(v) Why is armature resistance control replaced by armature voltage control?

(vi)Define soft start of induction motor.

[Hints: In some applications, starting torque must be controlled steplessly. Such starting arrangement is termed as soft start. Thyristor voltage control scheme is widely used for soft start.]

(vii)Which method of speed control for dc motor gives faster response?

[hints: Armature voltage control method due to its high efficiency, good transient response and good speed regulation.]

(viii)What is constant power dc drive? [hints: field control]

PART-II [6×6]

Q2. Armature voltage control is known as constant torque drive whereas field control is known as constant power drive, explain.

Q3. State and explain the different methods for braking dc motor.

Q4.Describe, Ward-Leonard-Ilgener speed control scheme for DC motor.

Q5. A 220V,100A, 1000rpm Dc series motor has an armature and field winding resistance of 0.05 ohm each. It is operated under dynamic braking at twice the rated torque and 800 rpm. Calculate the value of braking current and resistance. Assume linear magnetic circuit.

Q6. A 220V, 500A, 600rpm Dc separately excited motor has armature & field resistance of 0.02 ohm and 10 ohm respectively. The load torque is given by the expression TL=2000 -2N, N-m, where N is the speed in rpm. Speed below the rated are obtained by armature voltage control and speed above the rated are obtained by field control.

(a) Calculate motor terminal voltage and armature current when the speed is 450 rpm.

(b) Calculate field winding voltage and armature current, when the speed is 750 rpm.

Q7. A 230 Volt, 870 rpm, 100A Dc separately excited motor has armature resistance of 0.05 ohm. It is coupled to an overhauling load with a torque of 400, N-m. Determine the speed at which motor can hold the load by regenerative braking.

PART-III [16$\times$ 3]

Q8. Explain transient analysis of starting of separately excited motor with armature control.

Q9. A 200 Volt,875 rpm, 150A Dc separately excited motor has armature resistance of 0.06 ohm and inductance of 0.85 mH. It is fed from a single phase fully controlled rectifier with an ac source voltage of 220 v,50Hz. Calculate motor torque for 60 degree firing angle & 400 rpm.

Q10

A 220 Volt, 1500 rpm, 50A Dc separately excited motor has armature resistance of 0.5 ohm. It is fed from a three phase fully controlled rectifier with an ac source voltage of 440 v,50Hz. A star-delta connected T/f is used to feed the armature so that motor terminal voltage equals rated voltage when converter firing angle is zero. Calculate (a) transformer turn ratio (b) the value of firing angle when motor is running at 1200rpm and rated torque. Assume continuous conduction.

ASSIGNMENT-3

PART-I $[2\times 8]$

Q1.(i)Why is CSI fed IM operated at constant rated flux?

[Ans:For a given stator current (Is) operation of motor, above the natural characteristic takes place for a flux higher than rated and below it at lower than the rated flux. Also an increase in flux beyond the rated value is undesirable from the consideration of saturation effects. A decrease in flux is also avoided to retain the torque capability of the motor. Therefore rated flux operation is preferred.]

(ii)Why is it necessary to maintain constant terminal voltage for variable voltage control of induction motor drive above base speed?

(iii)Variable frequency control of induction motor develops high torque to current ratio during starting. Justify.

(iv)Why stator voltage control is suitable for speed control of Induction motor in fan and pump drives?

[Ans: In fan and pump drive, torque demand reduces with speed. In this type of drive, T$\propto N^2$, T$\propto V^2$, I$\propto V$. By reducing stator voltage, speed of a high slip induction motor can be reduced by an amount which is sufficient for the speed control of fan and pump drive. That's why stator voltage control is suitable for speed control of Induction motor (IM) in fan and pump drives.]

(v)How are speed and power factor of a slip ring induction motor controlled by injecting a voltage in the rotor circuit?

[Ans: When we insert a voltage which is in phase opposition to the rotor induced emf, it amounts to increase the rotor resistance where as inserting a voltage source which is in phase with rotor induced emf, is equivalent to decrease its resistance. Thus by injecting a voltage (

controlling rotor resistance), speed and power factor can be controlled.]

(vi)why is slip power recovery scheme suitable for drives with a low speed range?

[Ans: when rotor copper loss is neglected, Pm=Pg-Pr. When Pr is zero, motor runs on its natural speed-torque characteristic. A positive Pr will reduce Pm and therefore motor will run at lower speed for the same torque. When Pr is equal to Pg, Pm will be zero and speed will be zero. Thus variation of Pr from o to Pg, will allow speed control from synchronous to zero speed.]

(vii)For an induction motor, if the input voltage is changed by 10%, then what will be the percentage change in torque developed?

(viii)What is slip power recovery scheme for an induction motor?

PART-II [6×6]

Q2. State and explain the coil inversion law for speed control of 3 phase induction motor.

Q3.Explain, Static Kramer's drive with complete diagram.

Q4.Describe the variable frequency voltage source drive of a 3 phase induction motor.

Q5.Describe the variable frequency current source drive of induction motor.

Q6. A Y-connected squirrel cage induction motor has following ratings and parameters:

400 V, 50Hz, 4pole, 1370 rpm, Rs=2 ohm, Rr'=3 ohm, Xs=Xr'=3.5 ohm. Motor is controlled by a voltage source inverter at constant v/f ratio. Inverter allows frequency variation from 10 to 50 Hz. Calculate starting torque and current of this drive as a ratio of their values when motor is started at rated voltage and frequency.

Q7. A Y-connected wound rotor motor has following ratings and parameters:

440 V, 50Hz, 6 pole, Rs=0.5 ohm, Rr'=0.4 ohm, Xs=Xr'=1.2 ohm, Xm=50 ohm, stator to rotor turn ratio=a=3.5.

Motor is controlled by static rotor resistance control. External resistance is chosen such that the breakdown torque is produce at standstill for a duty ratio of zero. (a)Calculate the value of external resistance.

(b) How duty ratio should be varied with speed so that the motor accelerates at maximum torque.

PART-III [16$\times$ 3]

Q8 Describe VSI Induction motor control with required diagrams.

Q9. (a) State and explain the static Scherbius drive of induction motor.

(c) State and explain current regulated voltage source inverter control of Induction motor.

Q10.(a) A Y-connected 3 phase wound rotor motor has following ratings and parameters:

440 V, 50Hz, 6 pole,970 rpm, Rs=0.2 ohm, Rr'=0.15 ohm, Xs=0.4 ohm, Xr'=0.4 ohm, stator to rotor turn ratio=a=3.5.

Motor is controlled by static Scherbius Drive. Drive is designed for a speed range of 30% below the synchronous speed. Maximum value of firing angle is 170 degree. Calculate (a) T/f turn ratio (b) Torque for a speed of 750 rpm and firing angle of 140 degree. Dc link inductor has resistance of 0.01 ohm.

(b) The rotor of an 8pole, 50 Hz, 3 phase Induction motor has resistance ofh 2 ohm per phase and runs at 720 rpm. If the load torque remains uncanged, calculate the additional rotor resistance that will reduce the speed by 10%, neglecting stator impedance.

MCQS

Q1 DC drives are widely used in the applications requiring

(a)Adjustable speed

(b)Good speed regulation and frequent starting

©Braking and reversing

(d)All of these

Ans: (d) All of these

Q2.In case of series motor

(a)Field flux is a function of armature current

(b)Mmf is a function of armature current

(c) Field flux and mmf are functions of armature current

(d) none of these

Ans: (c) Field flux and mmf are functions of armature current

(3) In case of DC shunt motor

(a) Field flux is a function of armature current

(b) Mmf is a function of armature current

(c) Field flux and mmf are functions of armature current

(d) none of these

Ans: (d) none of these

(4)The motor which is suitable for applications requiring high starting and heavy torque overloads is

(a) DC shunt motor

(b) DC series motor

(c) DC separately excited motor

(d) None of these

Ans: (b) DC series motor

(5)In DC series motor, speed

(a) is inversely proportional to the square root of torque

(b) is directly proportional to the square root of torque

(c) is inversely proportional to the square of torque

(d) None of these

Ans: (a) is inversely proportional to the square root of torque

(6)Base speed of a DC motor is the

(a) Rated Speed (b) Full load speed (c) Operating speed (d) Rated or full load speed.

Ans: (d) Rated or full load speed.

(7)In cumulative compound dc motor, no load speed depends on

(a) the strength of shunt field (b) the strength of series field

(c) the strength of both shunt field and series field

(d) none of these

Ans: (a) the strength of shunt field

(8) In cumulative compound dc motor, slope of the characteristic depends on

(a) the strength of shunt field (b) the strength of series field

(c) the strength of both shunt field and series field

(d) none of these

Ans: (a) the strength of series field

(9)Universal motor are manufactured for use at speeds

(a)in excess of 3000 rpm

(b)in excess of 1500 rpm

(a)in excess of 500 rpm

(d) None of these

Ans: (a)in excess of 3000 rpm

(10) For the use at speed in excess of 3000 rpm,

(a) Induction motor is preferred

(b) Universal motor is preferred

(c) Both Induction motor and Universal motor are preferred

(d) None of these

Ans: (b) Universal motor is preferred

(11)For the use at speed below 3000 rpm,

(a)Induction motor is preferred

(b)Universal motor is preferred

(c) Both Induction motor and Universal motor are preferred

(d) None of these

Ans: (a) Induction motor is preferred

(12)Electric supply is not required for field winding of

(a) Universal motors

(b) DC series motors

(c) DC separately excited motor

(d) Permanent magnet motor

Ans: (d) Permanent magnet motor

(13) The motor used in closed loop and position control systems are

(a) Universal motors

(b) DC series motors

(c) DC separately excited motors

(d) dc servo motors

Ans: (d) dc servo motors

(14) The dc motor designed to run for long periods in a stalled or a low speed condition is known as

(a) moving coil motor

(b) dc servo motors

(c) Induction motor

(d) Torque motor

Ans: (d) Torque motor

(15) For normally designed Dc motor

(a) Starting current= rated current is allowed

(b) Starting current=2 times of rated current is allowed

(c) Starting current=3.5 times of rated current is allowed

(d)None of these

Ans: (b) Starting current=2 times of rated current is allowed

(16)) For specially designed Dc motor

(a) Starting current= rated current is allowed

(b) Starting current=2 times of rated current is allowed

(c) Starting current=3.5 times of rated current is allowed

(d)None of these

Ans: (c) Starting current=3.5 times of rated current is allowed

(17) In regenerative,

(a) Mechanical energy is converted to electrical energy and fed to supply

(b) Mechanical energy is converted to electrical energy and wasted through a resister.

(c) Mechanical energy is converted to mechanical energy and fed to motor

(d) None of these

Ans: (a) Mechanical energy is converted to electrical energy and fed to supply

(18) In dynamic braking,

(a) Mechanical energy is converted to electrical energy and fed to supply

(b) Mechanical energy is converted to electrical energy and wasted through a resister.

(c) Mechanical energy is converted to mechanical energy and fed to motor

(d) None of these

Ans: (b) Mechanical energy is converted to electrical energy and wasted through a resister.

(19) The braking in which the supply voltage of a separately excited motor is reversed is known as

(a) Counter current braking

(b) Dynamic braking

(c) Regenerative braking

(d) All of these

Ans: (a) Counter current braking

(20) The braking in which the supply voltage of a separately excited motor is reversed is known as

(a) Counter current braking

(b) Counter torque braking

(c) Plugging

(d) All of these

Ans: (d) All of these

(21) Transient operations commonly occur in an industrial drive are

(a) Starting and braking

(b) Starting and speed changing

(c) Starting, braking, reversing, speed changing and load changing

(d) None of these

Ans: (c) Starting, braking, reversing, speed changing and load changing

(22) The speed-controlling parameters of DC motors are

(a) Armature voltage

(b) Field flux

(C) Armature resistance

(d) All of these

Ans: (d) All of these

(23) The speed, below base speed of dc motor is controlled by controlling

(a) Armature voltage

(b) Field flux

(C) Armature resistance

(d) All of these

Ans: (a) Armature voltage

(24) The speed, above base speed of dc motor is controlled by controlling

(a) Armature voltage

(b) Field flux

(C) Armature resistance

(d) All of these

Ans: (b) Field flux

(25) The most inefficient speed controlling technique is

(a) Armature voltage control

(b) Field flux control

(C) Armature resistance control

(d) None of these

Ans: (C) Armature resistance control

(26) In electric drive, armature resistance control has been replaced by

(a)Armature voltage control

(b) Field flux control

(C) Either armature voltage control or field flux control

(d) None of these

Ans: (a) Armature voltage control

(27) Variable armature voltage for speed control is obtained by

(a) Ward-Leonard Schemes

(b) Static Ward-Leonard Schemes

(c) T/f with taps and an uncontrolled rectifier bridge

(d) All of these

Ans: (d) All of these

(28) For heavy and intermittent load, the motor used to drive the generator in Ward-Leonard scheme is

(a) DC shunt motor

(b) DC series motor

(c) DC compound motor

(d) Slip ring induction motor

Ans: (d) Slip ring induction motor

(29) In Ward Leonard Ilgener scheme, the motor used to drive the generator is

(a) DC shunt motor with flywheel

(b) DC series motor with flywheel

(c) DC compound motor with flywheel

(d) Slip ring induction motor with flywheel

Ans: (d) Slip ring induction motor with flywheel

(30) To prevent the crawling effect in Ward-Leonard scheme

(a) Armature circuit is opened

(b)A differential field winding on the generator is connected across the armature terminals to oppose the residual magnetism.

(c) The field winding of generator is connected across the armature terminals to oppose the residual magnetism.

(d) All of these

Ans: (d) All of these

(31) To prevent the crawling effect in Ward-Leonard scheme

(a) The residual magnetism of generator is reduced to zero

(b) The residual magnetism of generator field is equal to the rated flux

(c) The residual magnetism of generator field is 50% of the rated flux

(d) None of these

Ans: (a) The residual magnetism of generator is reduced to zero

(32) Ward Leonard drive

(a) Has high initial cost and low efficiency

(b) Requires frequent maintenance and produces more noise

(b) Needs large floor area and foundation

(d) All of these

Ans: (d) All of these

(33) Static Ward Leonard drive

(a) Has high initial cost and low efficiency

(b) Requires frequent maintenance and produces more noise

(b) Needs large floor area and foundation

(d) None of these

Ans: (d) None of these

(34) In case of high power intermittent load drive or where continuity of supply must be maintained at all costs or supply system is weak, then

(a) Ward Leonard drive scheme is employed

(b) Static Ward Leonard drive scheme is employed

(c) Either static Ward Leonard drive or Ward Leonard drive scheme is employed

(d) None of these

Ans: (a) Ward Leonard drive scheme is employed

(35) For low power drive

(a) Auto transformer is employed

(b) Transformer with tappings is employed

(c) Either auto transformer or transformer with tappings is employed

(d) None of these

Ans: a) Auto transformer is employed

(36) For high power drive

(a) Auto transformer is employed

(b) Transformer with tappings is employed

(c) Either auto transformer or transformer with tappings is employed

(d) None of these

Ans: (b) Transformer with tappings is employed

(37) Controlled rectifier fed dc drive is known as

(a) Static Ward Leonard drive

(b) Ward Leonard drive

(c) Ward- Leonard-Ilgener drive

(d) All of these

Ans: (a) Static Ward Leonard drive

(38) In Static Ward Leonard drive, the drive is operating under discontinuous conduction, if

(a) motor speed is greater than critical speed

(b) motor speed is smaller than critical speed

(c) motor speed is equal to the critical speed

(d) None of these

Ans: (a) motor speed is greater than critical speed

(39) In Static Ward Leonard drive, the drive is operating under discontinuous conduction, if

(a) motor torque is greater than critical torque

(b) motor torque is smaller than critical torque

(c) motor torque is equal to the critical torque

(d) None of these

Ans: (b) motor torque is smaller than critical torque

(40) In Static Ward Leonard drive, at critical speed or at critical torque the drive is operating,

(a) Under discontinuous conduction

(b) Under continuous conduction

(c) Either under discontinuous conduction or under discontinuous conduction

(d) None of these

Ans: (b) Under continuous conduction

AC DRIVE

(41) The three phase induction motor in which number of stator pole equal to number of rotor pole is

(a) Squirrel cage Induction motor

(b) Slip ring Induction motor

(c)Either Squirrel cage Induction motor or Slip ring Induction motor

(d) None of these

Ans: (b) Slip ring Induction motor

(42) In speed control of 3 phase induction motor scheme, controlling variables are

(a) Number of poles and supply frequency

(b)) Stator voltage and Supply frequency

(c) Stator voltage and rotor resistance

(d) Number of poles, Stator voltage, supply frequency and rotor resistance

Ans: (d) Number of poles, Stator voltage, supply frequency and rotor resistance

(43) Pole changing speed control scheme is applicable for

(a) Squirrel cage induction motor

(b) Slip ring induction motor

(c) Both Squirrel cage and Slip ring induction motor

(d) None of these

Ans: (a) Squirrel cage induction motor

[In slip ring induction motor, stator pole= rotor pole. If we will change the number of stator poles, then number of poles in rotor is required to be changed which complicates the machine]

(44) Rotor resistance speed control scheme is applicable for

(a) Squirrel cage induction motor

(b) Slip ring induction motor

(c) Both Squirrel cage and Slip ring induction motor

(d) None of these

Ans: (b) Slip ring induction motor

(45) Soft start of 3 phase induction motor is the speed control

(a) By primary resistor controller

(b) By primary inductor controller

(c) AC voltage controller

(d) All of these

Ans: (c) AC voltage controller

(46) Any reduction in the supply frequency, without change in terminal voltage, causes

(a) an increase in air gap flux

(b) a decrease in air gap flux

(c) an increase in air gap flux which will saturate the motor

(d) a decrease in air gap flux which will saturate the motor

Ans: (c) an increase in air gap flux which will saturate the motor

(47) The variable frequency control below the rated frequency is generally carried out

(a) at rated air gap flux

(b) below the rated air gap flux

(c) above the rated air gap flux

(d) None of these

Ans: (a) at rated air gap flux

(48) The variable frequency control below the rated frequency is generally carried out

(a) by varying terminal voltage with frequency

(b) by varying terminal voltage

(c) by varying terminal voltage with frequency so as to maintain (v/f) ratio constant at the rated value.

(d) None of these

Ans: (c) by varying terminal voltage with frequency so as to maintain (v/f) ratio constant at the rated value.

(49) The variable frequency control above the rated frequency is generally carried out

(a) by varying terminal voltage with frequency

(b) by varying frequency with terminal voltage maintained constant

(c) by varying terminal voltage with frequency so as to maintain (v/f) ratio constant at the rated value.

(d) None of these

Ans: (b) by varying frequency with terminal voltage maintained constant

(50) For a given slip speed

(a) Motor current is independent of frequency

(b) Motor torque is independent of frequency

(c) Motor current and torque have same values at all frequencies

(d) None of these

Ans: (c) Motor current and torque have same values at all frequencies

MODULE-3

3.1 SYNCHRONOUS MOTOR DRIVES- Synchronous motor variable speed drives, variable frequency control of multiple Synchronous motors.

3.2.Electric traction-system of electric traction, mechanics of train movement, speed-time, distance-time and simplified speed-time curves.-attractive effort for acceleration and propulsion-effective weight-train resistance-adhesive weight-specific energy output and consumption-traction motors-review of characteristics of different types of dc and ac motors used in traction and their suitability.

MODULE-4

4.1 Drives for specific application like textile mills, steel rolling mills, cranes and hoist drives, cement mills, sugar mills, machine tools, paper mills, coal mines, centrifugal pumps.

4.2 Application areas and functions of microprocessors in drive technology.

Text BooK

Gkdubey, v.subrahmanyam

Reference book—R. Krishnan

Digital learning resources:

Course name: fundamentals of electric drives

Course link: htts://nptel.ac.in/courses/108/104/108104140/

MODULE-3

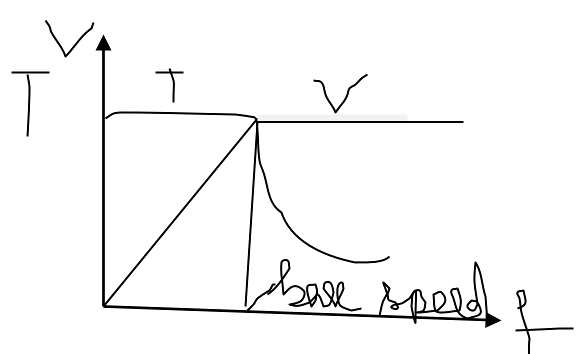
3.1 SYNCHRONOUS MOTOR DRIVES- Synchronous motor variable speed drives, variable frequency control of multiple Synchronous motors.

3.2. Electric traction-system of electric traction, mechanics of train movement, speed-time, distance-time and simplified speed-time curves.- tractive effort for acceleration and propulsion-effective weight-train resistance-adhesive weight-specific energy output and consumption-traction motors-review of characteristics of different types of dc and ac motors used in traction and their suitability.

SYNCHRONOUS MOTOR DRIVES

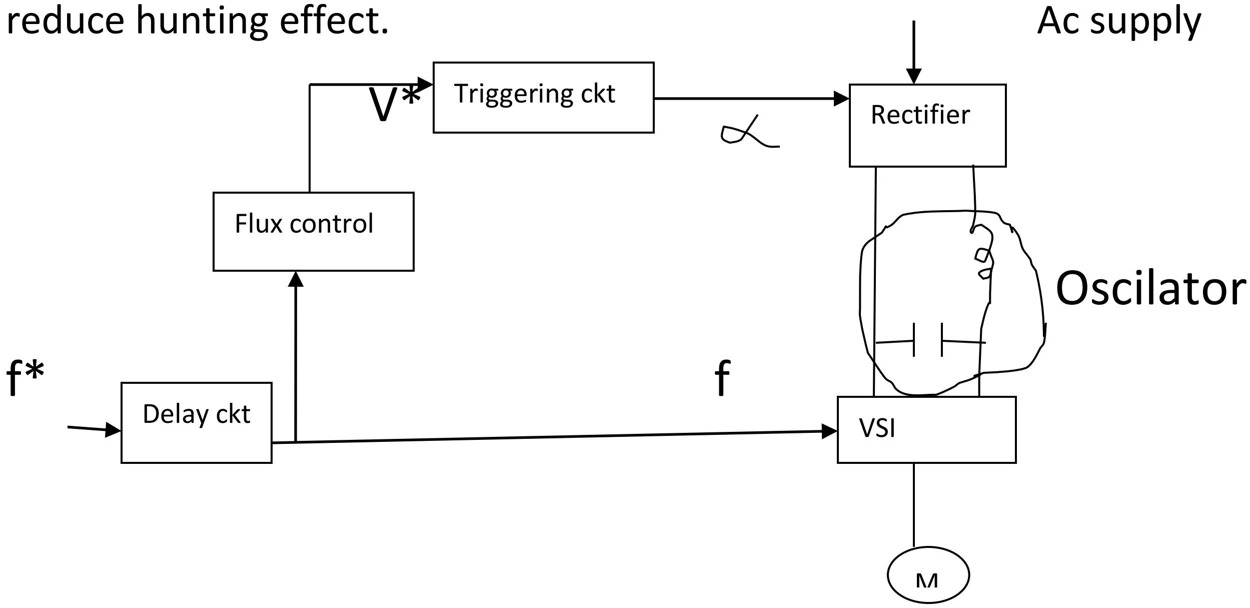
Synchronous motor variable speed drives: Speed of Synchronous motor is directly proportional to the frequency as $\omega m_s = \frac{4\pi f}{p}$. Hence motor speed can be controlled by varying the frequency. Constant flux operation below base speed is achieved by operating the motor with constant v/f ratio as in case of induction motor. Rated voltage is reached at the base speed. So for higher speed operation, the motor is operated at rated terminal voltage and variable frequency. As frequency increases, pull out torque decreases after base speed.

Pull-out torque=Tmax=$\frac{3|V|Eb||}{\omega m_s Xs}$



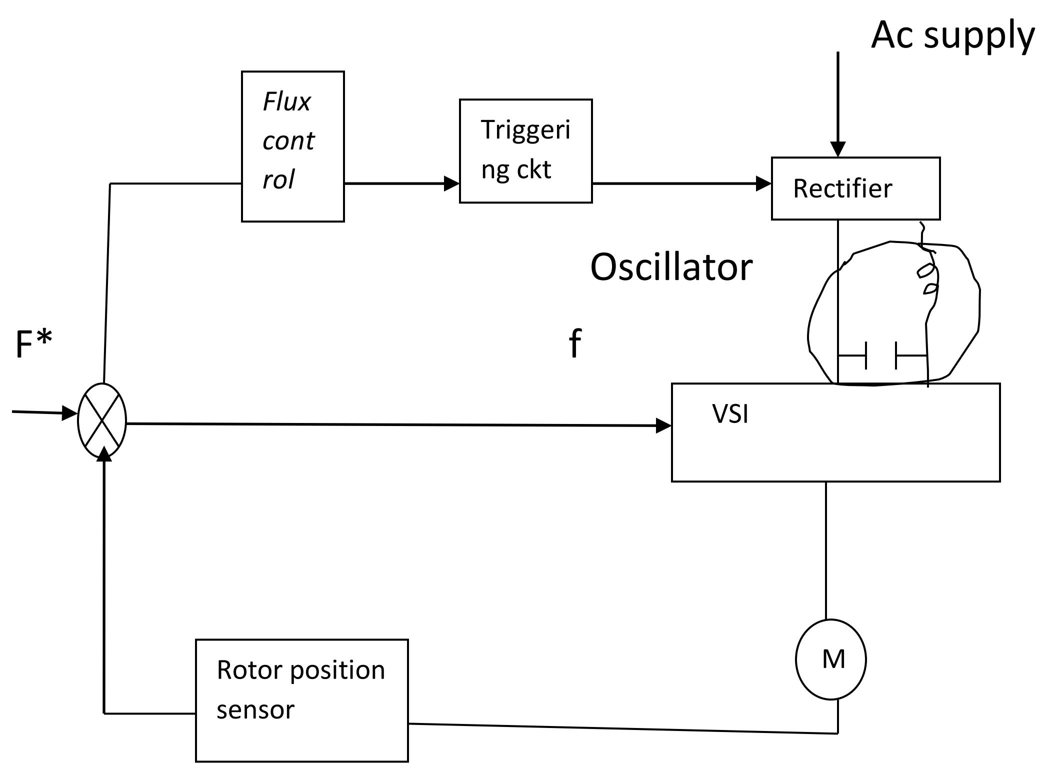
There are two modes of variable frequency control. Such as (a) True synchronous mode (b) self synchronous mode or self controlled mode.

(a)TRUE SYNCHRONOUS MODE: In this mode, stator supply frequency (f) is controlled from an independent oscillator. Frequency from its initial to the desired value is changed gradually so that, the difference between synchronous speed and rotor speed is always small. When desired synchronous speed is reached, the motor pulls into step. A motor with damper winding is used for pull-into synchronization. Here damper winding is used to start the synchronous motor and also to reduce hunting effect.



Frequency command f* is applied to a voltage source inverter through a delay circuit, so that rotor speed is able to track the change in frequency. A flux control block changes stator voltage with frequency (v/f) to maintain a constant flux below rated speed and a constant terminal voltage above rated speed.

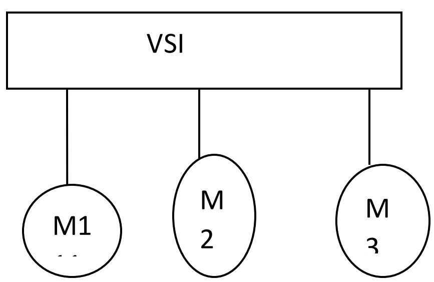
(b)SELF CONTROL MODE: In this mode of control, the stator supply frequency is changed in proportion to the rotor speed. So rotor position sensor (close loop control) is mounted on the stator to track the rotor position. As a result, the rotating field produced by the stator always moves at the same speed as the rotor. Rotor speed is developed by prime mover. So motor may not require damper winding.



(C)VARIABLE FREQUENCY CONTROL OF MULTIPLE SYNCHRONOUS MOTOR: In this mode, stator supply frequency (f) is controlled from an independent oscillator. Frequency from its initial to the desired value is changed gradually so that, the difference between synchronous speed and rotor speed is always small. When desired synchronous speed is reached, the motor pulls into step. A motor with damper winding is used for pull-into synchronization. Here damper winding is used to start the synchronous motor and also to reduce hunting effect.

Frequency command f* is applied to a voltage source inverter through a delay circuit, so that rotor speed is able to track the change in frequency. A flux control block changes stator voltage with frequency (v/f) to maintain a constant flux below rated speed and a constant terminal voltage above rated speed. This method is employed where accurate speed tracking between motors is used.

Fig: Same as fig of bit (a) besides--------.



P.A 6Mw, 3 phase,11kv, Y –connected, 6 pole,50 Hz,0.9 power factor leading synchronous motor has Xs=9 ohm, Rs=0, rated field current is 50 A. Machine is controlled by variable frequency control at constant (v/f) ratio upto the base speed and at constant V above base speed. Calculate torque ,field current for the rated armature current,750 rpm and 0.8 leading power factor.

Solution: Given data

Rated power=Pm=6 Mw, Rated line voltage =VL=11kv=11000 v, supply frequency=50 Hz, P.f=cosØ $= 0.9$, number of pole=P=6, Xs=9 ohm, Rs=0, Rated field current=If=50 A

We have to calculate torque and field current for 750 rpm and0.8 pf at rated armature current.

Since Rs=0, Pm=Pin=$\sqrt{3}$ VL IL cosØ $= \sqrt{3} \times 11000 \times IL \times 0.9$

=>6$\times 10^6 = \sqrt{3} \times 11000 \times IL \times 0.9$

=>IL=349.9 A=Is for pf=0.9=>Ø $= 25.84\ degree$, leading

Hence Is=349.9<25.84

Eb=V<0-Is(jXs)=$\frac{11000}{\sqrt{3}} < 0 - (9 < 90 \times 349.9 < 25.84) = 8227 < -20.15$

Synchronous speed= 120f/p=1000 rpm=Ns, Ns1/Ns=f1/f

At 750 rpm i.e Ns1=750 rpm, f1=(750/1000)50=37.5Hz,Ns1=120f1/P

Since v/f ratio is constant, supply voltage will be reduced in the proportion of frequency.

v/f=v1/f1=> v1=$\frac{v\times f1}{f} = 4763\ volts$=Phase voltage

since Xs is directly proportional to frequency

Xs1/Xs=f1/f=>Xs1=(37.5/50)9=6.75 ohm

cosØ$1 = 0.8\ leading$. $|Is1|$=$|Is| = 349.9\ amp$,=>
Is1=349.9<cos^{-1}0.8=349.9<37, X<$\theta = X[cos\theta + jsin\theta]$

Hence Eb1=V1 –Is1(jXs1)=4763<0 -349.9<$cos^{-1}0.8 \times 6.75 < 90 = 6462.3 < -17$

Torque at 750 rpm =T1=Pm1/ω_{m1}

$$\omega_{m1} = 2\pi \times \frac{750}{60} = 78.54\, rad/sec$$

Pm1=Pin1=$\sqrt{3}$ VL1 IL1 cos∅1 $= \sqrt{3} \times 4763\sqrt{3} \times 349.9 \times 0.8 = 3999.6kw$

Hence T1=Pm1/ω_{m1}=$\frac{3999.6\times10^3}{78.54} = 50924.4, N-m$

Field current at 750 rpm

Eb∝ $N \times If$, So $\frac{Eb1}{Eb} = \frac{N1\times If1}{N\times If}$ => $If1 = 52.37\ A$, Ns1=750 RPM, Ns=1000 RPM, If=50 Amp

[As, NαEb/∅ and ∅ ∝ If]

ELECTRIC TRACTION

3.2.1. SYSTEMS OF ELECTRIC TRACTION: The application of electric drives to transport men and materials from one place to another place is known as electric traction. There are five system for electric traction work such as (1)The Dc system (2) The single phase ac system (3) The three phase ac system (4) The composite system (5) The diesel-electric system. The three phase ac system is yet not adopted on account of two over head contact wires. The dc system is ideally suited for heavy sub-urban services and the ac single phase and composite system for main line electrification. AC single phase system (composite) is now being widely used.[EMU=Electric multiple unit,DMU= Diesel multiple unit, DEMU= Diesel Electric multiple unit,MEMU=Mainline Electric multiple unit]

(1)The Dc system: In the system the vehicles operate on DC supplied from substations. The sub stations receive power from a three phase high voltage transmission system equipped with power modulator. The operating voltage for urban and sub urban lines is 600 to 750 volts and for longer distances 1500 volts and 3000 volts.

(2) The single phase ac system: In this system, power may be supplied at 15KV to 25 KV and 16.67Hz,25Hz or 50 Hz. Single phase ac series motors are fed at low voltages through T/fs carried in the locomotive.

(3) The three phase ac system: In this system,3 phase induction motor is used for traction service and operates at voltages between 3000 volt to 3600 volt at 16.67 Hz.

(4) The composite system: In this system, power is received by the locomotive by single phase high tension transmission lines and converted into 3-phase ac or dc at low voltage. The locomotive must carry the converting machineries.

(5) The diesel-electric system: In this system, a dc generator is worked from a diesel engine and supplies power to dc traction motors. There is no over head line.

3.2.2 ELECTRIC TRACTION SERVICES: Traction services can be classified as (a) Electric trains (b) Electric buses, tramps, trolleys (c) Battery driven vehicles.

Electric trains are classified as (a) Main line trains (b) sub-urban trains.

Intercity passenger and goods trains are termed as main line trains. Sub-urban trains are employed within a city or between two cities located at small distances.

Electric buses have a single motor driven coach. The supply is low voltage dc over head line running along the road.

The tramps are electric buses or cars which run on the rails and consist of single motor coach.

Electric trolleys are used to transport materials in mines, factories, mostly run on rails.

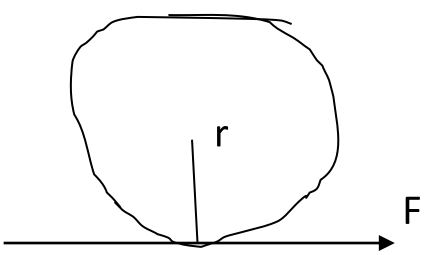
3.2.3 MECHANICS OF TRAIN TRACTION

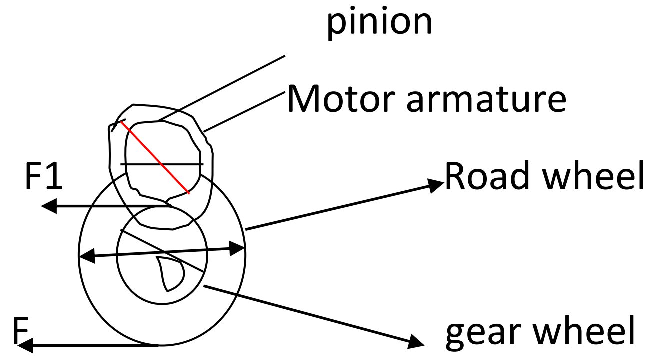
The armature of the driving motor has a pinion meshed with the gear wheel on the driving wheel. The torque developed by motor is transferred to the road wheel through the gear. The tractive effort on the driving wheel=F= $\eta T \times \frac{2\gamma}{D}$, where $\eta = efficiency\ of\ gear$

$$\gamma = gear\ ratio = \frac{d}{d1} = \frac{\text{diameter of the gear wheel}}{\text{diameter of pinion}},$$

$$T = torque\ exerted\ by\ drining\ motor,$$

$$D = diameter\ of\ the\ driving\ wheel$$





Far=T/(d2/2)=>T=Far*d2/2, Tp=F1*d1/2,T=Tp

Here d1=diameter of pinion, d2=diameter of armature, d=diameter of the gear wheel,F1=tractive effort at the pinion.

Force on the armature= Far=T/moment arm=T/(d2/2)=2T/d2

Far/F1=d1/d2=> 2T/d2=F1$\frac{d1}{d2}$ => $F1 = 2T/d1$=force at the gear wheel

Force at road wheel/Force at gear wheel=diameter of gear wheel/diameter of road wheel. Output power=F×D, Input Power=F1 ×d for unit time.

Efficiency= $\eta = \frac{Output\ power}{Input\ power}$= (F×D)/ (F1 ×d)

=>$\frac{F}{F1} = \eta\frac{d}{D}$ => $F = \eta\frac{d}{D} \times F1 = \eta\frac{d}{D} \times \frac{2T}{d1} = \frac{2\eta T}{D} \times \frac{d}{d1} = \frac{2\eta T}{D} \times \gamma$

[In meshing pair of gears, the smaller gear is called pinion gear. It meshes with a rack in a rack and pinion mechanism which transforms rotational motion to linear motion]

=>F=$\frac{2\eta T}{D} \times \gamma$----------(A)

TRACTIVE EFFORT FOR ACCELERATION AND PROPULSION

(i) **TRACTIVE EFFORT**: Force needed to drive the train is known as tractive effort. It has to perform the following functions.

(a) **overcome the train resistance (b) Overcome the force due to gravity when moving up gradient (c) Accelerate the rotating parts of the train such as wheels, gears, axles and the rotor of the motor (d) Accelerate the train mass horizontally.**

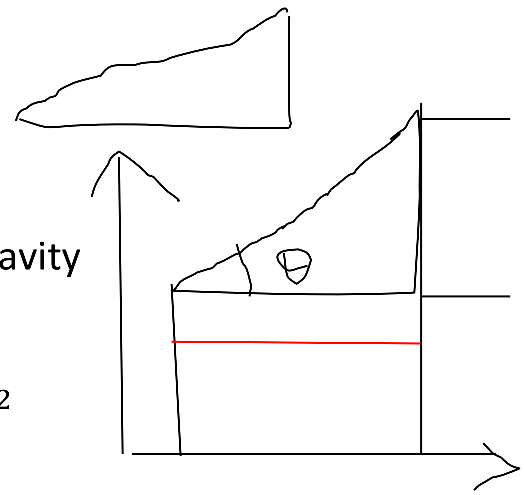
(a) **TRACTIVE EFFORT REQUIRED TO OVERCOME THE TRAIN RESISTANCE**: Force used to overcome the train resistance

= Fr=K1+K2V+K3V^2, where V is the speed of the train. It is generally expressed in Newton.

If 'r' is the force in Newton per tone and 'M' is the mass of train in tone, then Fr=$r \times M$----------------(1)

(b) **TRACTIVE EFFORT REQUIRED OVERCOMING THE FORCE DUE TO GRAVITY WHEN MOVING UP GRADIENT**: When moving up gradient, the drive has to produce tractive effort to overcome force due to gravity.

As per railway practice, gradient is expressed as “rise in mts in a track distance of 1000mts and is denoted by ‘G’.



If G=8, In SI system G=8/1000.

If G=2:500, In SI system G=4/1000

Hence tractive effort to overcome force due to gravity

=Fg=M$\times$ $G \times g$----------------(2)

Where g=acceleration due to gravity=9.81 m/sec^2

When train is going down, Fg is negative.

(c) **TRACTIVE EFFORT REQUIRED TO ACCELERATE THE ROTATING PARTS:**

Rotating parts of a train are wheels, axles, gears, rotor of the motor.

Moment of inertia of gears and axles can be ignored in comparison to that of the wheels.

M.I. of wheels=J1=2Nx Jw-------------(3)

Where Jw= M.I of one wheel in Kg-m^2=$\frac{1}{2}mR^2$------------(4)

m=mass of a wheel in kg

R= radius of a wheel in mt

Nx= number of axles => 2Nx= number of wheels

Moment of inertia of motors as referred to wheels=J2=$\frac{NJm}{a^2}$-------(5)

Where Jm= MI of a motor=$\frac{1}{2}m1R1^2$---------------(6)

m1=mass of a motor in kg

R1= radius of a motor in m

a=wheel speed/motor speed, [ref. kinetic energy]

N=Number of motors

Hence equivalent MI=J =J1+J2

If $\propto$ *is linear acceleration in m/sec²,* then angular acceleration =$\propto/R$

As T=J$\frac{d\omega m}{dt} = J \times \frac{\propto}{R} => \frac{\propto}{R} = \frac{T}{J} = \frac{Fa1 \times R}{J} => Fa1 = \frac{J \times \propto}{R^2}$--------(7)

Hence tractive efforts for driving rotating parts=Fa1= (J1+J2)$\times \frac{\propto}{R^2}$

(d) **TRACTIVE EFFORT REQUIRED FOR LINEAR ACCELERATION(Fa2):**

Fa2=Mass of the train$\times$ $linear\ acceleration = M \times \propto$

TRACTIVE EFFORT FOR ACCELERATION

Total tractive effort required for accelerating the train on a level track=Fa1+Fa2

=Fa=$\frac{J \times \propto}{R^2} + M \times \propto$`=$(\frac{J}{R^2} + M) \propto$=Me$\times\propto$

=>Fa= Me$\times\propto$------------------(8)

Where Me=effective mass of the train=$\frac{J}{R^2} + M$

$=> \mathrm{Me} = [\{2(\mathrm{Nx})\ \mathrm{Jw} + \frac{NJm}{a^2}\} \times \frac{1}{R^2} + M]$,----------(9)

TRACTIVE EFFORT FOR PROPELLING A TRAIN:

Therefore total tractive effort for propelling a train=Ft

=Fr$\pm$Fg+Fa1+Fa2= Fr$\pm$Fg+Fa

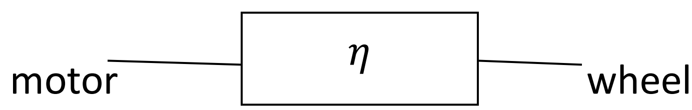
=>Ft=M$\times r \pm (M \times G) \times g + Me \times \propto$---------------(10)

(ii) MOTOR TORQUE RATING:

Total torque at the rims of driving wheels=Ft$\times R, N - m$

Total torque referred to motor shaft=Tmt=$Ft \times R\frac{a}{\eta}$

Where a=wheel speed/ motor speed, η=efficiency of the energy transmission system, R=radius of the wheel



[wheel power as referred motor=Pw/ η=(Tw)$(\omega_{w)/\eta}$

Equivalent wheel torque as referred to motor=Tw'=Tw$\frac{a}{\eta}$

SinceTw'$\omega_{m=Tw\times\frac{\omega w}{\eta}=>Tw'=Tw\times\frac{\omega_w}{\omega_m}\times\frac{1}{\eta}=Tw\times\frac{a}{\eta}}$]

Torque per motor=Tm=$\frac{aRFt}{\eta\times N}$, --------------(11)

where N=Number of motors

<u>3.2.4.DUTY CYCLE OF TRACTION DRIVE(</u>speed-time, distance-time and simplified speed-time curves):

The actual run of a train can graphically be represented by a speed-time curve. The duty cycle of a train has five sections such as (1) constant torque or notching up (2) constant power or acceleration (3) free running or constant speed running (4) coasting or running with power cut off (5) braking.

In diagram, OA=Notching, AB=accelerating, BC=free running, CD=coasting, DE=Braking

NOTCHING PERIOD (OA):

In this period the traction motors accelerate from rest. The current taken by the motor and tractive effort are practically constant. Here power increases, speed increases but torque remains constant up to base speed. This is known as notching period.

ACCELERATING PERIOD (AB):

In this period, train still continues to accelerate along the curve 1-2. The torque gradually falls, speed increases. Finally the train reaches a speed at which tractive effort to the train resistance.

FREE RUNNINGPERIOD(BC):

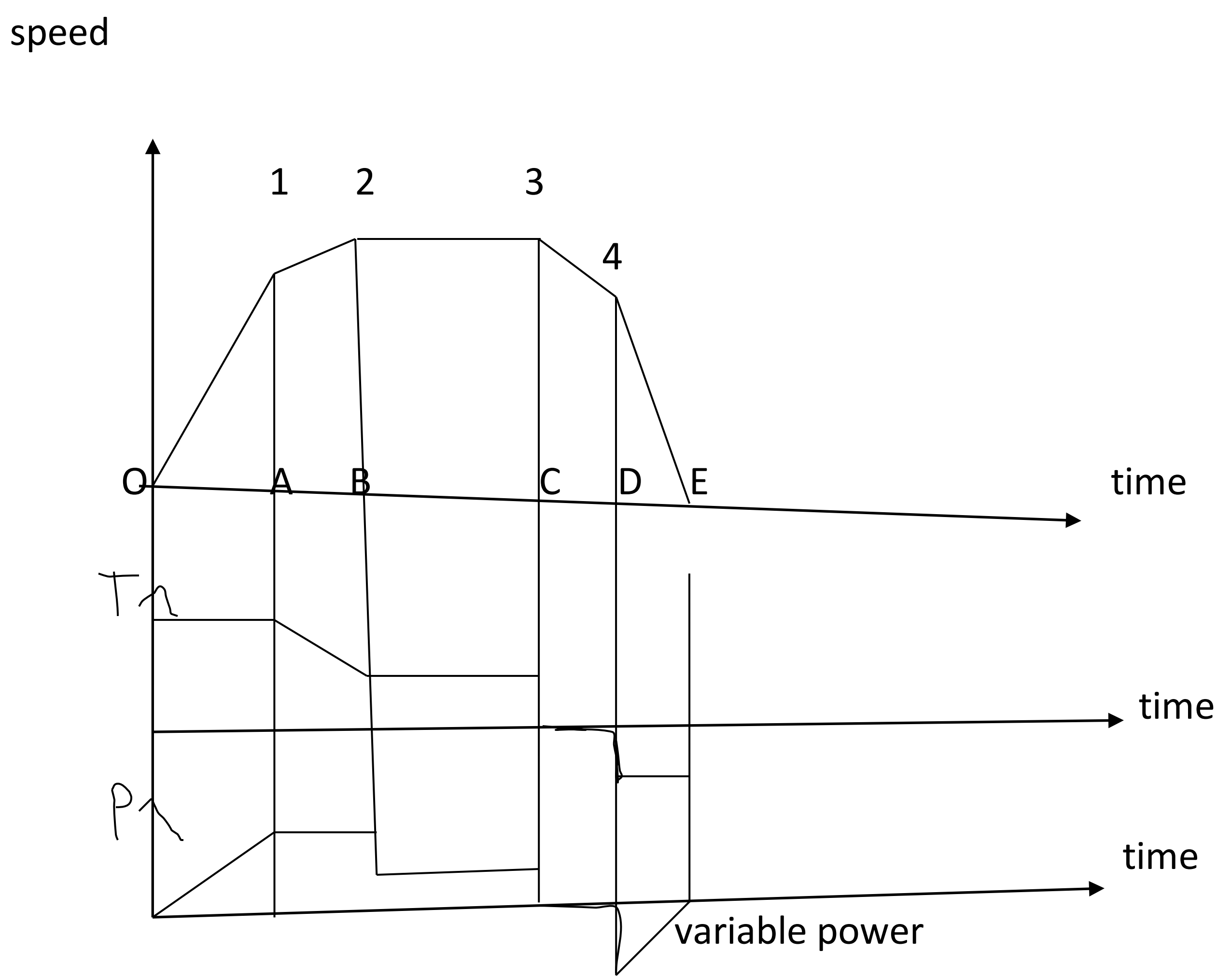
In this period the train runs at constant speed.

COASTING(CD)

At point 3, power is cut off. But train will continue to run due to its own kinetic energy. The retardation is produced by friction experienced by the train. In this period Power (P)=0,T=0 and speed decreases.

BRAKING PERIOD(DE)

During this period, brakes are applied and the train is brought to stop. Power and Torque become negative (regenerative braking) and speed decreases to zero.

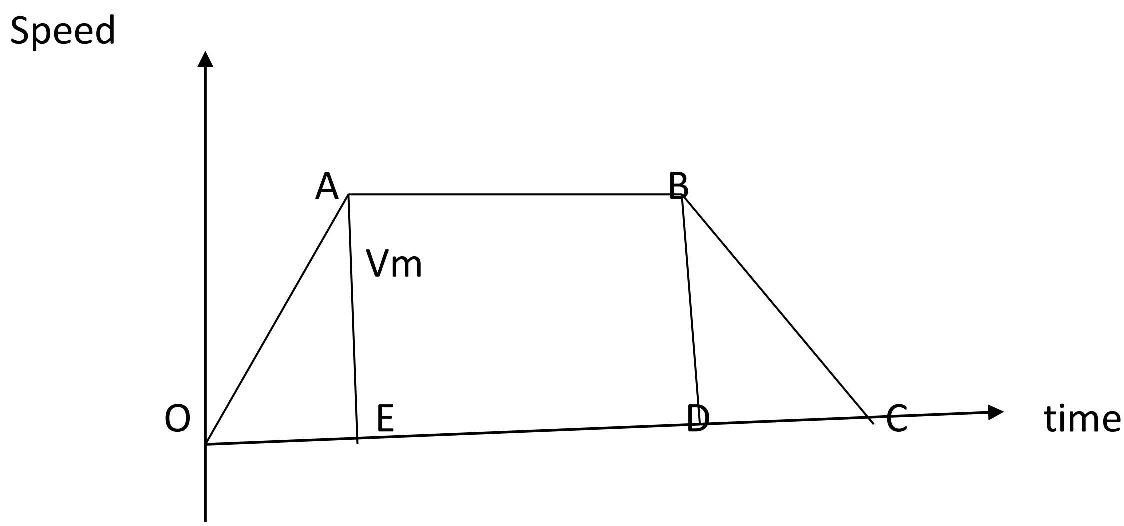


The area of the time-speed curve represents the distance covered by the train.

SIMPLIFIED SPEED-TIME CURVES:

The actual time-speed curve is replaced by an equivalent time-speed curve of simple geometric shape as shown in figure. As per simplified speed-time curves, the duty cycle of a train has three sections such as

(1) constant power or accelerating period(OA) (2) free running or constant speed running(AB) (3) decelerating period(BC).



OE=t1,ED=t2, DC=t3

<u>Calculation of traction drive rating:</u>

Let us take

Vm=free running speed in m/sec

$\propto = acceleration\ in \frac{m}{sec^2},$

$\beta = deceleration\ in\ m/sec^2,$

t1,t2,t3=time in sec, D=distance in mt

Total distance=D= area of OAE+ area of ABDE +area of BCD=$\frac{1}{2} \times OE \times AE + ED \times AE + \frac{1}{2} CD \times BD = \frac{1}{2} \times t1 \times Vm + t2 \times Vm + \frac{1}{2} t3 \times Vm$

$=> D = Vm(0.5t1 + 0.5t3 + t2) - - - - - (1),$

D=Vm(t1+t3+2t2)/2=Vm(t1+t2+t3+t2)/2=Vm(t+t2)/2

=Vm(t+t-t1-t3)/2

But t1=Vm/∝ ,t3=Vm/β ,[since V=u+at=0+at=at]

And t=t1+t2+t3

Hence D=$\frac{Vm}{2}\left[2t - \left(\frac{Vm}{\propto} + \frac{Vm}{\beta}\right)\right]$------------(2)

There are five variables. If values of 4 variables are provided, then 5th one can be calculated from equation (2)

Average velocity =Vav=D/t-------------(3)

3.2.5. ADHESIVE WEIGHT: Weight on the driving wheels or axles is known as adhesive weight(Md). It is equal to the ratio of maximum tractive effort applied on the wheel to coefficient of adhesion. i.e

coefficient of adhesion=
$$\frac{\text{maximum tractive effort applied on the wheel}}{\text{adhesive weight}} = \mu$$

The normal value of μ in clean dry soil is 0.25 and maximum value is 0.3. Coefficient of adhesion decreases with increase in speed. Presence of oil, grease, water, snow and mud reduces the coefficient of adhesion.

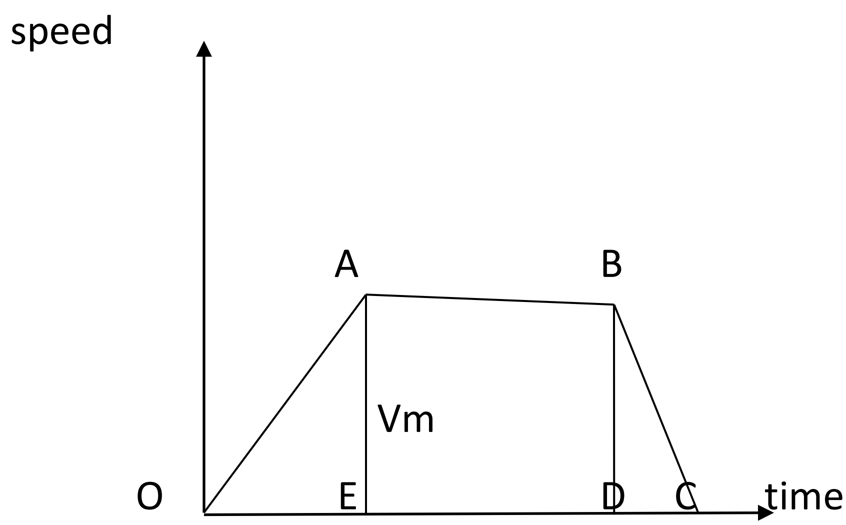
3.2.6 SPECIFIC ENERGY OUTPUT AND CONSUMPTION

Specific energy consumption is defined as the energy consumed in watt-hours per tonne weight and per km of distance travelled. The energy output at the driving axles is spent to (a) accelerate the train (b) overcome the gradient (c) overcome the train resistance.

(a) Output Energy to accelerate the train=Ea

Ea= total tractive effort required for accelerating the train× $distance\ travelled\ during\ acceleration = Fa \times area\ of\ tringle\ OAE = Fa \times \frac{1}{2} \times t1 \times Vm = Fa \times \frac{1}{2} \times \frac{Vm}{\propto} \times Vm = Me \times \propto \times \frac{1}{2} \times \frac{Vm^2}{\propto} = \frac{1}{2} \times Me \times Vm^2$

=>Ea=$\frac{1}{2} \times Me \times Vm^2$ watt-sec -------(1)



OE=t1,ED=t2, DC=t3

Vm=free running speed in m/sec.

$\propto = acceleration\ in \frac{m}{sec^2},$

$\beta = deceleration\ in\ m/sec^2,$

t1,t2,t3=time in sec, D=distance in mt

Me =effective mass of the train in kg=mass of the rotating parts +mass of the train

(b) Energy output to overcome the gradient (Eg)

Eg= Tractive effort required to overcome the force due to gravity in newton $(Fg) \times distance\ for\ which\ the\ supply\ remains\ on(D1) = Fg \times D1 = Fg \times area\ of\ the\ quadrilaterof\ OABD = Fg(total\ distance - distance\ for\ which\ power\ remains\ off) = Fg(D - area\ of\ triangle\ BCD) = Fg(D - \left|\frac{1}{2} \times \frac{Vm^2}{\beta}\right|)$-------(2)

OR

Eg= Tractive effort required to overcome the force due to gravity in newton $(Fg) \times distance\ for\ which\ the\ supply\ remains\ on(D1) = Fg \times D1 = Fg \times area\ of\ the\ quadrilaterof\ OABD$=Fg($\frac{1}{2} \times t1 \times Vm + Vm \times t2) = Fg \times Vm\left(\frac{1}{2}t1 + t2\right) = Fg \times Vm(\frac{1}{2}$ ×t1+t−t1−t3)= Fg×Vm($t - \frac{1}{2}t1 - t3$)= Fg×Vm(t$-\frac{1}{2}\frac{Vm}{\propto} - \frac{Vm}{\beta}$)

Eg= $Fg \times Vm$(t$-\frac{1}{2}\frac{Vm}{\propto} - \frac{Vm}{\beta}$)----------(3)

(c) Energy output to overcome the train resistance(Er)

Er= Tractive effort required to overcome the train resistance in newton $(Fr) \times distance\ for\ which\ the\ supply\ remains\ on(D1) = Fr \times D1 = Fr \times area\ of\ the\ quadrilaterof\ OABD = Fr(total\ distance - distance\ for\ which\ power\ remains\ off) = Fr(D - area\ of\ triangle\ BCD) = Fr(D - \left|\frac{1}{2} \times \frac{Vm^2}{\beta}\right|)$-------(4)

OR

Er= Tractive effort required to overcome the train resistance in newton $(Fr) \times distance\ for\ which\ the\ supply\ remains\ on(D1) = Fr \times D1 = Fr \times area\ of\ the\ quadrilater of\ OABD$=Fr($\frac{1}{2} \times t1 \times Vm + Vm \times t2) = Fr \times Vm\left(\frac{1}{2}t1 + t2\right) = Fr \times Vm(\frac{1}{2} \times \mathrm{t1} + \mathrm{t} - \mathrm{t1} - \mathrm{t3})$= $Fr \times Vm(t - \frac{1}{2}t1 - t3)$= $Fr \times Vm(\mathrm{t} - \frac{1}{2}\frac{Vm}{\propto} - \frac{Vm}{\beta})$----------(5)

Therefore total energy output=E=Ea+Eg+Er

Specific energy output= Total energy output per unit mass per unit distance=Eo=$\frac{E}{M \times D}$

Specific energy output=Eo=$\frac{E}{M \times D}$----------------(6)

Specific energy consumption=$\frac{Eo}{\eta}$---------------(7)

Where $\eta = efficiency\ of\ transmission\ and\ motor$

3.2.7TRACTION MOTORS-REVIEW OF CHARACTERISTICS OF DIFFERENT TYPES OF DC AND AC MOTORS USED IN TRACTION AND THEIR SUITABILITY

Series , compound motors and separately excited motors are used on dc traction systems where as single phase series and three phase induction motors are used on ac systems. The service conditions are extremely sever. The motors should have very robust design and must be mechanically totally enclosed type to protect them from vibration, water and sleet. They should be capable to develop high starting torque and should be self protective against over loading.

The series motors either dc or ac are ideally suited for traction as (1) it is capable of high starting torque (2) it possesses high free running speed (3) the speed decreases as the torque increases thereby protecting the motor against over load (4)Capable of withstanding voltage fluctuations (5) Share the load almost equally when operated in parallel.

Compound motors are being used for traction work as in incorporates the advantages of both series and separately excited motor.

With availability of semiconductor converters, separately excited motor is now preferred over series motor. With independent control of armature and field, the speed-torque characteristic of separately excited motor can be shaped to satisfy the traction requirements in the optimum manner. Due to low regulation of its speed- torque characteristics, the coefficient of adhesion also has higher value.

The 3-phase induction motors have the advantages of simple and robust construction, trouble free operation, less maintenance, high voltage operation. But due to their flat speed-torque characteristics, constant speed operation, developing low starting torque, drawing high starting current, complicated speed control system, they are not suitable for electric traction work. Now it is possible to use 3-phase induction motor in electric traction work due to the availability of reliable variable frequency semiconductor inverters.

Note: In derivation, we have used S.I. units instead of commercial units, though in book, commercial units are used.

Term	Symbol	S.I. unit	Commercial unit
Mass of the	M	Kg	Tonne(=1000kg)

train			
Acceleration	$\propto$	m/sec^2	Km/hr/sec (1000/3600 m/sec^2)
Retardation	β	m/sec^2	Km/hr/sec
time	t	sec	sec
Velocity	V	m/sec	Km/hr(=1000/3600 m/sec)
Force	F	Newton	Newton
Distance	D	mt	Km
M.I	J	Kg-m^2	Kg-m^2

NUMERICAL PROBLEM

P1.A sub-urban train consists of motor and trailer coaches in the ratio of 1:1. Each motor coach is driven by 4 dc motors, each geared to a driving axle through a reduction gear for which the gear ratio a=0.4. All the wheels in the motor coach are driving wheels and the trailer coach has the same number of wheels as motor coach. All wheels have a wheel tread of 0.54 m in radius and each has a mass of 450 kg. The mass of each motor armature is 0.48 tonne and average diameter of armature cora is 0.5 m. The combined weight of one motor and one trailer is 40 tonne when fully loaded. Determine the coupling torque per motor required to accelerate the train at 5kmphps. Assume train resistance to be 20N/tone of the train weight.

SOLUTION: Given data

One motor and one trailer coach has 4 motors and 4 trailers. So

M=40 tonne=40,000 kg, number of motor=N=4

Train resistance =r=20 N/tone=20/1000 N/kg

Number of trailer (vehicle pulled by another)=4

Gear ratio =a=0.4

Radius of wheel=R=0.54 m, mass of wheel=m=450 kg

Mass of each motor armature =m1=0.48 tonne=480 kg

Average armature core diameter=0.5 m => Average armature core radius=R1=0.25m

We have to calculate coupling torque per motor™.

We have, Tm=$\frac{a\ Ft\ R}{\eta \times N}$, assuming $\eta = 1$,

Tm=$\frac{a\ Ft\ R}{N}$=$\frac{0.4 \times Ft \times 0.54}{4}$-----(1)

Ft=Fa1 +Fa2 +Fr +Fg= (2Nx Jw+$\frac{NJm}{a^2}$) $\frac{\propto}{R^2} + M \times \propto + M \times r + 0$

But Nx= number of axle=4+4=8

Jw=(1/2)m$R^2 = (1/2) \times 450 \times (0.54)^2 = 65.61$

Jm==(1/2)m1$R1^2 = (1/2) \times 480 \times (0.25)^2 = 15$

Therefore Ft=(2$\times 8 \times 65.62$ +$\frac{4 \times 15}{(0.4)^2}$) $\frac{\left(\frac{50}{36}\right)}{(0.54)^2} + 40000 \times \frac{50}{36} + 40{,}000 \times \frac{20}{1000} = 63141.68\ Newton$

Therefore Tm=$\frac{0.4 \times 63141.68 \times 0.54}{4} = 3409.65, N - m$

P2. (2012)An electric train weighing 500 tonnes climbs up gradient with G=8 and following speed-time curve:

(i) Uniform acceleration of 2.5 km/hr/sec for 60 sec
(ii) Constant speed for 5 min
(iii) Coasting for 3 min
(iv) Dynamic braking at 3kmphps=3km/hr/sec

The train resistance is 25 N/tone, rotational inertia effect 10% and combined efficiency of transmission and motor is 80%. Calculate the specific energy consumption.

SOLUTION: Given data

Mass of the train =M=500 tonne=500× 10^3kg

G=8/1000 {in S.I system}

Resistance of train=r=25 N/tone=25 N/$10^3 Kg$

Equivalent mass =Me=M+ rotational inertia effect=M+10% M=1.1M

=>Me=1.1×500× 10^3kg=550× 10^3kg, $\eta = 0.8$

$\propto = \frac{\frac{2.5km}{hr}}{sec} = \frac{2.5\times1000}{3600}\ m/sec^2$,t1=60 sec

$$\beta = \frac{\frac{2.5km}{hr}}{sec} = \frac{3 \times 1000}{3600}\ m/sec^2$$

$$t2 = 300sec, t3 = 180\ sec, t = ?$$

We have to calculate specific energy consumption.

total energy output=E=Ea+Eg+Er

Specific energy output= Total energy output per unit mass per unit distance=Eo=$\frac{E}{M\times D}$

Specific energy output=Eo=$\frac{E}{M\times D}$

Specific energy consumption= $\frac{Eo}{\eta}$,

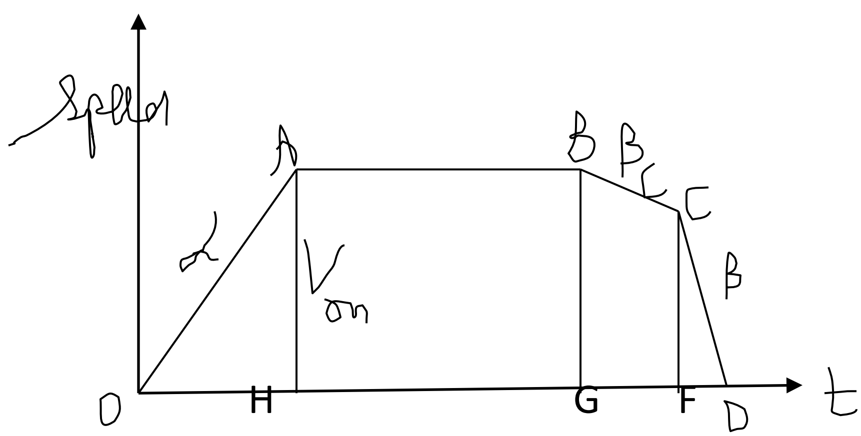
Speed at constant speed operation=Vm=$\propto\times t1 = \frac{2.5\times1000}{3600} \times 60 =$ 41.667m/sec

When supply is disconnected, the train comes retardation mode due train resistance and gradient force.

Hence retarding force during costing=Fc=Fg+Fr=M$\times G \times g + M \times r = 500 \times 10^3 \times \frac{8}{1000} \times 9.81 + 500 \times 10^3 \times \frac{25}{10^3} = 51740, Newton$

=>Fc=$51740, Newton$

=> Deceleration during coasting=$\beta_c = \frac{Fc}{Me} = \frac{51740}{550\times10^3} = 0.094\, {}^{m}/_{sec^2}$



OH=t1, HG=t2, GF=t3, FD=t4

Speed at point B=Vm=41.667 m/sec

Speed at point at C=Vc=Vm$-\beta c \times t3 = 24.747 \frac{m}{sec}$

In path CD, speed at point D=0

Hence 0=Vc$-\beta \times t4 => t4 = \frac{Vc}{\beta} = 29.7\ sec$

Total time =T=t1+t2+t3+t4=60+300+180+29.7=569.7 sec

Total distance covered= area of[triangle OAH +rectangle ABGH +trapezium BCFG + triangle CDF)

=D=$\frac{Vm\times t1}{2} + Vm \times t2 + \frac{(Vm+Vc)\times t3}{2} + \frac{Vc\times t4}{2}$=20094.5 m

[Area of trapezium=$\frac{sum\ of\ the\ parallel\ lines\times perpendicular\ distance}{2}$]

Distance upto coasting =D1 = area of[triangle OAH +rectangle ABGH +trapezium BCFG]= $\frac{Vm\times t1}{2} + Vm \times t2 + \frac{(Vm+Vc)\times t3}{2}$=13750m

Eg=Fg$\times\ D1 = MGg \times D1 = 500 \times 10^3 \times \frac{8}{1000} \times 9.81 \times 13750 = 539.55 \times 10^6 joules$

Er=Fr$\times\ D1 = M \times r \times D1 = 500 \times 10^3 \times 25\ /10^3 \times 13750 = 171.875 \times 10^6 joules$

Ea=$\frac{Me\times Vm^2}{2}$=$\frac{550\times 10^{3\times 41.667^2}}{2} = 477.44 \times 10^6 joules$

Hence specific energy output=$\frac{Ea+Eg+Er}{M\times D} = \frac{(477.44+539.55+171.875)\times 10^6}{500\times 10^3\times 20094.5} = 0.118 \frac{Joule}{kg}/m$

Specific energy consumption=$\frac{\text{specific energy output}}{\eta} = \frac{0.118}{0.8} = 0.1479\ \frac{Joule}{kg}/m$=41.1 Wh/tone/km

P3. A 100 tonne motor coach is driven by 4 motors, each developing a torque of 5000 N-m during acceleration. If up gradient is 50 in 1000, gear ratio a=0.25, gear transmission efficiency 98%, wheel radius 0.54

m, train resistance 25 N/tone, effective mass on account of rotational inertia is 10% higher. Calculate the time taken to attain a speed of 100kmph.

SOLUTION:

N=number of motors=4, Mass of train =M=100 tonne=100,000 kg

Motor torque=Tm=5000, N-m, G=50/1000=0.05, gear ratio=a=0.25, gear efficiency= $\eta = 0.98, R = 0.54m, r = \frac{25}{1000} N/kg$

Effective mass=Me=110% of M=1.1$\times 100 = 110\ tonne = 110{,}000kg$

Vm=100 km/hr=100$\times \frac{1000}{3600}\ m/sec$

Tm=$\frac{Ft\times a\times R}{N\times\eta} => Ft = \frac{\eta\times Tm\times N}{a\times R} = \frac{0.98\times5000\times4}{0.25\times0.54} = 145185.2\ Newton$

But Ft= Me$\times\propto + M \times G \times g + M \times r$

=>$\propto = \frac{Ft - M\times G\times g - M\times r}{Me} = \frac{145185.2 - 100{,}000\times0.05\times9.81 - 100\times25}{110{,}000} =$
$0.851\ m/sec^2$

Therefore t1=Vm/$\propto = \frac{1000/36}{0.851} = 32.64\ sec$

P4. A train service consists of following:

Uniform acceleration of 5 km/hr/sec for 30 sec

Free running for 10 min, uniform braking at 5 km/hr/sec to stop

A stop of 5 min

Calculate (a) distance between the stations (b) average speed (c) scheduled speed.

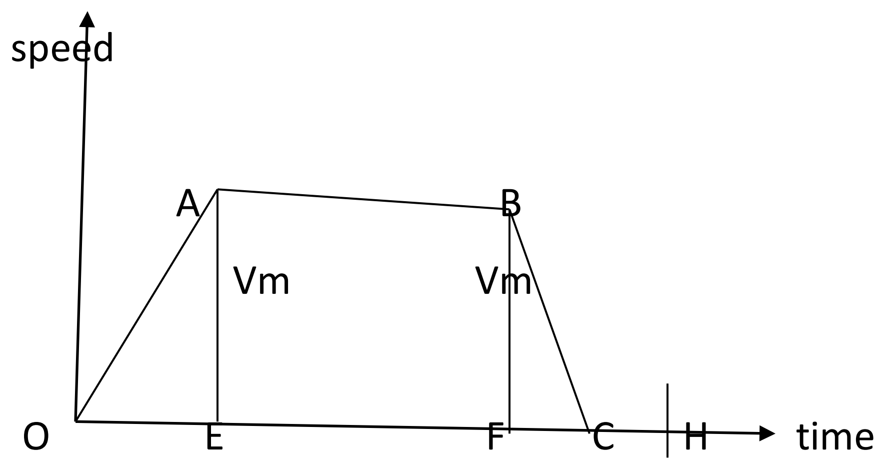
Solution:

$\propto = \frac{\frac{5km}{hr}}{sec} = \frac{25}{18} m/sec^2$**, t1=30 sec**

Free running period =t2=10 min=600 sec

Braking period=t3=?

$\boldsymbol{\beta} = \frac{\frac{5km}{hr}}{sec} = \frac{25}{18} m/sec^2$**, A stop period=t4=5min=300 sec**



OE=t1, EF=t2, FC=t3, CH=t4

Vm=$\propto\times \boldsymbol{t1} = \frac{25}{18} \times \mathbf{30}$**=41.67**

In path BC, equation of speed be

Vm$-\beta \times t3 = 0$, $(Since\ speed\ at\ point\ C = 0\ and\ at\ point\ B = Vm\ \&\ V = u + at)$

$$=> \propto \times t1 - \beta \times t3 = 0 => t3 = \frac{\propto}{\beta} \times t1 = t1 = 30\,\text{sec}, [as\ \propto = \beta]$$

=>Braking period =t3=30 sec

(a) Total distance =D= area of (OABC)=$\frac{1}{2} \times t1 \times Vm + t2 \times Vm + t3 \times \frac{Vm}{2} = \frac{1}{2} \times 30 \times \mathbf{41.67} + 600 \times \mathbf{41.67} + 30 \times \frac{\mathbf{41.67}}{2} = 26250\ m = 26.25\ Km$

(b) Average speed=$\frac{D}{t1+t2+t3} = \frac{26250}{660} = 39.773 \frac{m}{sec} = 143.182\ km/hr$

(c) Schedule speed=$\frac{D}{t1+t2+t3+t4} = \frac{26250}{960} = 27.344 \frac{m}{sec} = 98.44 km/hr$

P5.A train service consists of following:

Uniform acceleration of 1 kmphps for 2 min,

Free running for 30 min,

Coasting for 2 min at a deceleration of 0.1 kmphps,

Uniform braking at 1.2 kmphps to stop,

A stop of 5 min. Calculate (a) distance between the stations (b) schedule speed.

SOLUTION:

$\propto = \frac{\frac{1km}{hr}}{sec} = \frac{5}{18} m/sec^2$, **t1=60 sec**

Free running period =t2=30 min=1800 sec

$\boldsymbol{\beta c = \frac{\frac{0.1km}{hr}}{sec} = \frac{1}{36} m/sec^2,}$

Coasting period=t3=120 sec

$\boldsymbol{\beta = \frac{\frac{1.2km}{hr}}{sec} = \frac{1}{3} m/sec^2}$, **Braking period=t4=?**

A stop period=t5=5min=300 sec

Vm=$\propto\times t1 == \frac{5}{18}\times 120 = \frac{100}{3} m/sec$

In path BC,

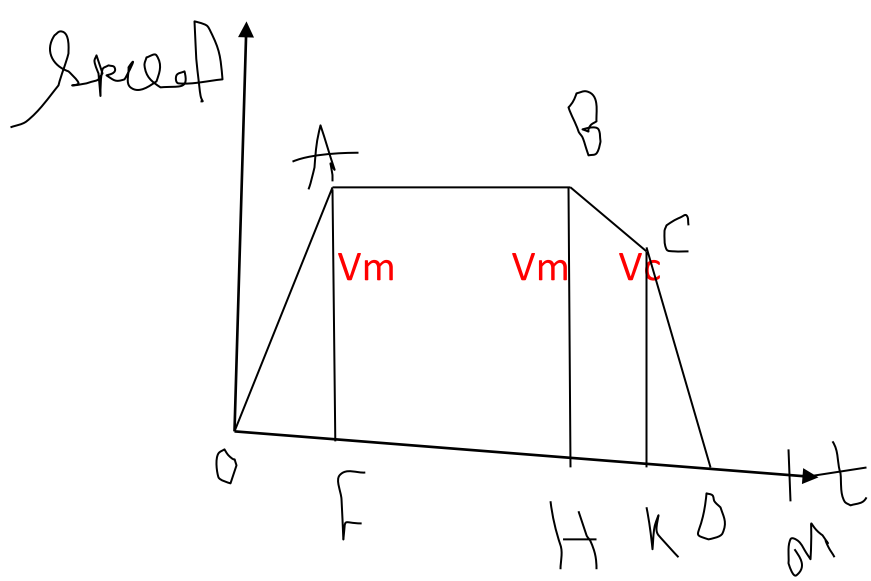
Speed at the end of coasting (at point C)=Vc= Vm $-\beta c \times t3 =$
$\frac{100}{3} - \frac{1}{36}\times 120 = 30\ m/sec$

In path CD, 0=$Vc - \beta \times t4 => t4 = \frac{Vc}{\beta} = \frac{30}{1/3} = 90\ sec$

(a)Hence total distance=D=$\frac{1}{2}\times Vm \times t1 + Vm \times t2 + \frac{1}{2}(Vm + Vc)\times t3 + \frac{1}{2}\times Vc \times t4 = 2000 + 60000 + 3800 + 1350 = 67150m = 67.15\ Km$

=>D= $67.15\ Km$

(b) Schedule speed=$\frac{D}{t1+t2+t3+t4+t5} = \frac{67150}{2430} = 27.634\frac{m}{sec} =$
$99.48\ Km/hr$



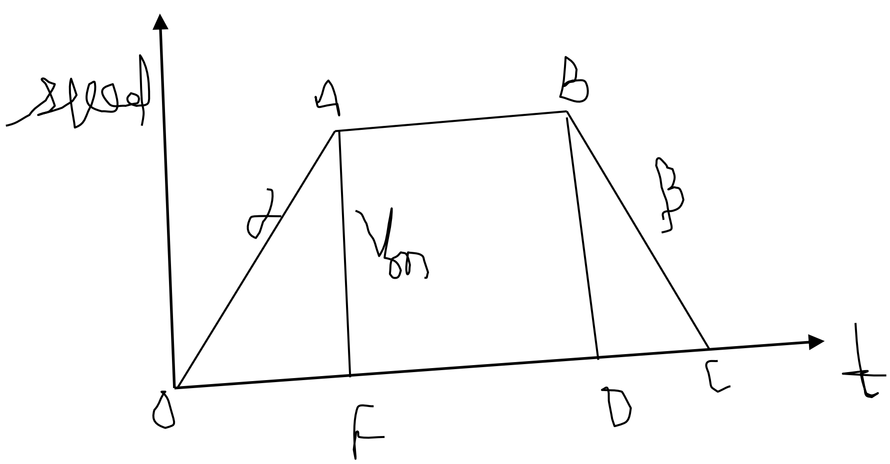
OF=t1, FH=t2, HK=t3, KD=t4, DM=t5

P6. An electric train has acceleration and deceleration of 5kmphps between two stations at 15 km apart. Assuming a trapezoidal speed – time curve, calculate speed during free running if the running time of train is 6 min.

SOLUTION:

D=15 Km=15000 m, $\propto = \beta = \frac{\frac{5000}{3600}m}{sec^2} = \frac{25}{18}\ m/sec^2$

Total time=t=OC=6 min=360 sec=t1+t2+t3



OF=t1, FD=t2, DC=t3, OC=t

Hence total distance=D=$\frac{1}{2} \times \boldsymbol{Vm} \times \boldsymbol{t1} + \boldsymbol{Vm} \times \boldsymbol{t2} + \frac{1}{2} \times \boldsymbol{Vm} \times \boldsymbol{t3}$

=>D=$\frac{1}{2}\times \boldsymbol{Vm} \times \frac{\boldsymbol{Vm}}{\propto} + \boldsymbol{Vm} \times \boldsymbol{t2} + \frac{1}{2} \times \boldsymbol{Vm} \times \frac{\boldsymbol{Vm}}{\boldsymbol{\beta}} = \frac{\boldsymbol{Vm}^2}{\boldsymbol{\alpha}} + \boldsymbol{Vm} \times \boldsymbol{t2},$

$$\boldsymbol{as} \;\propto = \boldsymbol{\beta}$$

But t2=t-t1-t3=360 -$\frac{\boldsymbol{Vm}}{\propto} - \frac{\boldsymbol{Vm}}{\boldsymbol{\beta}} = \mathbf{360} - \frac{\mathbf{2}\boldsymbol{Vm}}{\boldsymbol{\alpha}}$, D=1500m (given)

Hence 1500=$\frac{\boldsymbol{Vm}^2}{\boldsymbol{\alpha}} + \boldsymbol{Vm} \times \left(\mathbf{360} - \frac{\mathbf{2}\boldsymbol{Vm}}{\boldsymbol{\alpha}}\right)$

=>1500=$\frac{\boldsymbol{Vm}^2}{25/18} + \boldsymbol{Vm} \times \left(\mathbf{360} - \frac{\mathbf{2}\boldsymbol{Vm}}{25/18}\right)$

=>Vm=$\frac{500 \pm 408}{2}$ =>Vm=46 m/sec, considering lower speed

=>Vm=165.6Km/hr

(You may solve Q12,13,14,15,16 and 17 of G.K.Dubey ,Page352)

ED MODULE-4

MODULE-4

4.**1 Drives for specific application like textile mills, steel rolling mills, cranes and hoist drives, cement mills, sugar mills, machine tools, paper mills, coal mines, centrifugal pumps.**

4.2 **Application areas and functions of microprocessors in drive technology.**

01**. TEXTILE MILL DRIVES** : In a textile mill, the production of cloth takes place from its basic raw materials in several stages.

The requirements of a drive motor for each stage are discussed in the following.

(a)**Ginning**: The process of separating seeds from the raw cotton picked from the field is called ginning. The ginning motors must have speed ranges of 250-1450 rpm. The load speeds are fairly constant. No speed control is required.

Commercially available squirrel cage induction motor may be employed for this purpose.

(b)**Blowing:** The ginned cotton in the form of bales is opened up and is cleaned up very well in a blowing room. No speed control is required.

The motor having synchronous speed of 1000 rpm or 1500 rpm is employed. Normal 3 phase induction motor is used for this purpose.

(c)**Cording**: The process for converting cleaned cotton into Laps and Laps into slivers is called cording.

The motor used for this purpose should have high starting torque and low starting current. It must have sufficient thermal capacity to withstand the heat produced.

Normally, 3-phase, totally enclosed or totally enclosed fan cooled squirrel cage induction motor is preferred for this purpose.

(d)**Drawing**: The slivers are converted into uniform straight fibre by means of drawing machine. 3-phase squirrel cage induction motor of rating 3.7 to 5.6 kw are used for drawing. Another motor having 1.5 to2.2 kw is used for dust collection.

(e) **Spinning**: In this stage the thread is thinned down by processing it on a fly or speed frame.

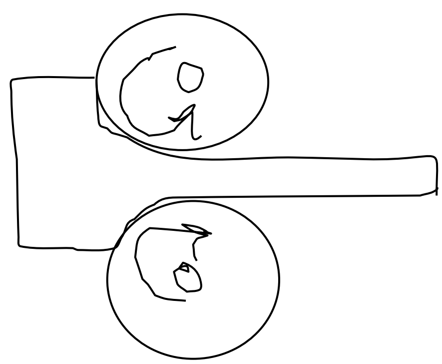
A motor with smooth acceleration is necessary to drive this frame. During spinning, the yarn is twisted and made to have sufficient strength. Then it is wound on bobbins.

A single speed, 4/6 pole squirrel cage induction motor of rating 7.5-11.3 Kw is required for this purpose.

(f)**Weaving**: The weaving of yarn into cloth is done in Looms. The drives may be semi group drives or individual drives depending upon the quality of cloth required. The speed of operation is normally 600 to 750 rpm. 3-phase, totally enclosed or totally enclosed fan cooled squirrel cage induction motor is used for this purpose. The size of the motor depends upon the weight of fabric. For light fabric, motor of rating upto 1.5 Kw and for heavy fabric, motor of rating 2.2 to 3.7 Kw is required.

(2) STEEL ROLLING MILL DRIVES: In metal working, rolling is a metal forming process. In this process, metal stock is passed through one or more pairs of rolls to reduce the thickness, to make the thickness uniform, and/or to impart a desired mechanical property. Most steel mills have rolling mill divisions that convert the semi finished casting products into finished products.

Rolling is classified according to the temperature of the metal rolled. If the temperature of the metal is above its re-crystallization temperature, then the process is known as hot rolling. If the temperature of the metal is below its re- crystallization temperature, then the process is known as cold rolling. Hot rolling is normally used to make blooms, slabs and billets. Cold rolling is normally used for producing sheets of good quality of uniform gauge. Steel rolling mills may be reversing type or continuous type. In reversing type, steel is passed in the mill stand in both directions alternately, till it reduces to the required size. In continuous mills, steel is passed in one direction through several stands which press the sheet simultaneously. Roll stands holding pairs of rolls are grouped together into rolling mills that can quickly process metal, typically steel into products such as structural steel (channel, angle, I-beam, rails etc).The choice of the motor to meet the requirements and the choice of the mill-stand depends upon the products required.



(Rolling schematic view)

For reverse cold rolling, one or two individually driven motors may be used. The inertia of the motor must be kept low and lower than that of roller. Torque control and speed control must be possible to maintain constant tension of the strip. The acceleration of the drive must be uniform to avoid breaking. A dc motor/three phase ac commutator motor/cyclo converter fed synchronous motors are used for this purpose.

For reverse hot rolling, AC motors, employing a variable frequency supply for speed control may be used. Cyclo converter fed synchronous motors are commonly used for this purpose.

For continuous cold rolling mill, thyristorized DC motors can be used.

For continuous hot rolling mill, thyristorized DC drive is suitable.

DC motors are very versatile as motors for mill drives due to the following characteristics.

(1)High starting torque (2) wide range of speed control (3) Precise speed setting (4) Large over load capacity (5) Large pull out torque

The motors for mill operations are normally TEFC (totally enclosed and fan cooled) motors with a high class of insulation. AC motors with frequency controlled device can be also used for mill drive. Cyclo-converter fed synchronous motors are used for this purpose.

3. **CRANES AND HOIST DRIVES**

Requirements: (i) The motion of the crane-hook is in all three dimensions (ii) acceleration and retardation must be uniform (iii) creep speed must be possible (iv) No braking problem during horizontal movement. (v) Mechanical braking must be available under emergency condition.(vi) the motor must have high speed at light load.

The crane motors can be either dc or ac motor. Series motors are highly suitable for crane operation. Among AC motors, squirrel cage induction motors are commonly used.

4. CEMENT MILL DRIVES:

In a Cement mill, the production of cement takes place from its basic raw materials (lime-stone & silica) in several stages. Such as

(i) Collection of raw materials (ii) Feeding of crushed lime to the hot cement kiln. (iii) Then hot clinker is air cooled and made ready for storage.(iv) After storing for few days, gypsum is added in the required quantities.

Every state has its own drive. The main types of drive system in cement mill are (a) Kiln drive (b) Crusher drive (c) fan drive (d) compressor drive.

(a) **Kiln drive**: A cyclo converter fed synchronous motor, AC commutator motors and Ward-Leonard controlled dc motors are used for this drive. The rating of motor used for this purpose varies from 100 to 1000 kw.The basic features of the selected motors are (i) Very high power (ii) 1:10 speed control ratio (iii) 200 to250% of full load torque as starting torque.

(b) **Crusher Drive**: Slip ring induction motor with rotor resistance control is suitable for crusher drive. The features of motor used for crusher drive are (i) starting torque =160% of full load torque (ii) Maximum torque=200 to 250% of full load torque (iii) Over load capacity of 15% for 15 sec and 20% for 10 sec

(c) **Fan or Blower Drives: The drive motors are located** in outdoor or semi outdoor locations. So totally enclosed fan cooled motors are suitable for this purpose. Starting torque is 120% of full load torque. Maximum torque=200 to 250% of full load torque. The speeds are in the range of1000 to 1500 rpm. Slip ring induction motor with rotor resistance control is suitable for this drive.

(d) Compressor drive: The drive motors for air compressor have a power rating of 300 to 450 Kw. Since compressors are started on load, high starting torque motor is required for compressor drive. Totally enclosed fan cooled induction motors (squirrel cage or slip ring) with speed range from 750 to1000 rpm are used for this purpose.

5. **SUGAR MILL DRIVES**: In a sugar mill, the production of sugar takes place from sugar cane in several stages. Sugar cane juice is extracted by pressing the prepared cane through mills. Each mill consists of three rollers.

   Extracted juice mixed with water is sent to the boiling house for further processing. This juice is heated and then treated with milk of lime and sulphur dioxide. The treated juice then further heated and clarifies for continuous settling. The settled mud is filtered by vacuum filters and filtered juice is returned to be further processed. The clear juice is evaporated to a syrup stage. The sugar crystals are separated from the syrup by means of a centrifuge. The centrifuge is started to a speed of 200 rpm at which the charging of syrup takes place. The motor used to drive the centrifuge must be a variable speed motor. Pole changing induction motors or slip ring induction motors are suitable for this purpose. The motors must have humid proof insulation.

6. **MACHINE TOOL DRIVES**: The motors used for machine tool drive should have the following features.

   (a)The motors must be reliable, low cost and requiring less maintenance.

   (b)They must be capable of speed control.

   ©Starting torque may vary from 10% to 25% of full load torque.

(d)The acceleration of the motor should be sufficiently fast to avoid motor heating during starting.

(e)The braking must be effective and fast.

(f)Variable speed operation with constant torque at all speeds should be possible.

The duty cycles are specified for the machine tool operation. So the KW rating of the motor is decided by the duty cycle. Hence squirrel cage induction motors are suitable for driving machine tools. A 4 or 6 pole induction motor may be selected for better power factor, starting torque and efficiency.

7. PAPER MILL DRIVES: In a paper mill, the production of paper takes place from its basic raw materials in two stages. Such as (a)pulp making (b) paper making

The drive required for making pulp is different from that required for paper making.

(a)pulp making:

The following operations are done for making pulp from the raw materials.

(i) The raw materials are cut to pieces with a chopper (cutting machine) for which slip ring induction motors are used without any specific control.

(ii) Chips are crushed in a grinder. A slip ring induction motor or synchronous motor with gear drive is used as the grinder requires a very large power and low speed.

(b) Paper making: The watery pulp fibres are transferred to a fine wire mesh and water is removed from pulp and it is pressed to sheets of paper which are finally wound up on mandrel. The different sections for paper making are wire section, pressing section, drying section and reel sections.

The paper making may employ either group drive or individual drive for several sections. In case of individual drive, each section has its own drive motor. The speed of these motors is controlled by means of voltage variation. In group drive, one motor is used to drive the whole system. It is also noted that automatic close loop speed control is possible in individual drive.

The drive motor may be either a dc motor with Ward-Leonard speed control system or ac motor with variable frequency speed control system.

8.COAL MINES DRIVE: The motors used in coal mines can be classified into two groups. The motors in 1st group are used to drive mine auxiliaries such as compressors, pumps. The motors of the second group are used to drive the cutters, drillers etc.

The motors used for mining process must satisfy the following requirements.

(a)Coal cutting and drilling machines do not require any speed control.

(b)High starting torque may be required

High torque squirrel cage induction motors are commonly used for this purpose. Ward-Leonard controlled dc motor, slip ring induction motors with resistance control are also used as mine winder (motor).

9.DRIVE FOR CENTRIFUGAL PUMP: Centrifugal pumps are used as boiler feed pumps and for pumping water in water pipe lines. The requirements of a centrifugal pump load are

(a) A smooth starting of load
(b) The system used should have operating safety and flexibility. In case of any failure in the system, it may be able to drive the load so that the continuity is maintained.
(c) The centrifugal pumps are developed for all powers and speeds up to 1800 rpm.
(d) The drive motor used is based on the power requirement. The power consumption must be optimum.

Basing on the above requirements, wound rotor induction motors with static Scherbius drive or static Kramer drive (slip power recovery) are selected for centrifugal pump drive.

(10) MICROPROCESSOR IN DRIVE TECHNOLOGY

(A)**Advantages:**

(1) Reduces complexity of the system like controller feedback and decision making.

(2) Cost effective than hardware.

(3) Higher reliability.

(4) Control may be extended with host computer.

(5) Speed detection scheme is completely digital, which improves the accuracy.

(6) The limiting properties of a microprocessor based compensator are adaptable to any operating conditions by changing the values in memory.

Disadvantages:

(1)There will be a sampling error.
(2)The micro processors process the signals in a sequence causing a delay in the processing.
(3)The development of necessary soft ware is costly and time consuming.

(B)**APPLICATION AREAS OF MICRO PROCESSORS IN DRIVE TECHNOLOGY:** Powerful and reliable microprocessors are widely used in the control of electrical drives. Application areas of micro processors in drive technology are

(1) Static Ward-Leonard control of dc motor using dual converter.

(2) Four quadrant operation of dc motor using chopper.

(3) Control of PWM inverter for ac motors.

(4) Four quadrant operation of cycloconverter of ac drives.

(5) Static motor starters.

(6) Four quadrant operation of CSI fed ac drives.

(7) Generating and providing firing pulses to the converters.

(8) Processing the measured signals like voltage, current and speed.

(9) Storing and processing the information of controlled quantities.

(10) Estimation of feedback signal.

(11) Computation of reference quantities such as torque, flux which can't be directly measured.

(12) Identification and adaptation of variable parameters.

(13) Monitoring and warning.

(14) Diagnostic and tests etc.

(C) **FUNCTION OF MICRO PROCESSORS IN DRIVE TECHNOLOGY**:

Specific functions of micro processors in drive technology are:

(1) **Speed detection**: The speed measurement is carried out by means of a shaft encoder or pulse generator. It generates a train of pulse depending upon the speed in micro processor. In this method speed measurement is qualified by high resolution, high accuracy, fast response and quick sampling.

(2) Gate firing of the converter: In variable frequency applications, especially at high frequency, firing angle control using analog means is appropriate, since it depends on the precision and stability of analog components used such as resistor, inductor and capacitor. In microprocessor, suitable soft ware may be written to obtain the firing pulse which can be realized with adequate symmetry.

(3) Feedback control: The microprocessor may be programmed to implement the necessary controllers and limiters. The Laplace transfer function of an analog controller is suitably transformed to time domain difference equations to develop an equivalent digital controller.

The limiting properties of a microprocessor based compensator are adaptable to any operating conditions by changing the values in memory.

(4)**Function generation and linearization**: The non-linear function can be easily carried out by microprocessor which is very difficult to implement using discrete analog component.

The linearization techniques can be very well employed when a microprocessor is used in the control. The non linear transfer characteristics of the system can be linearized by producing an inverse non linear function in the processor.

(5)**Processing the feedback signals**: The microprocessor is capable of synthesizing the feedback signals such as torque, flux etc.

(6) **Implementation of PWM technique**: The microprocessor can develop the PWM waveforms using all the principles of PWM. The necessary reference and carrier waves are generated in microprocessor by soft ware programs to determine the points of triggering the thyristor.

(7) **Programmable time delay:**

Programmable time delay (eg delay angle in gating thyristor) can be obtained in microprocessor by means of up and down counters.

(8) **Protection:** Over current protection, protection against single phasing etc may be provided with suitable soft ware in the microprocessor.

…………………………..×……………………….

<u>ASSIGNMENT-4(MODULE 3 and MODULE 4)</u>

PART-A ----------------------------$[\mathbf{2}\times \mathbf{8} = \mathbf{16}]$

Q1. (a)What do you mean by true synchronous mode control of synchronous of motor?

(b). Define 'coefficient of adhesion.

©What are the factors which affect the coefficient of adhesion?

[hints: vehicle speed, nature of speed-torque characteristics, type and condition of the surface at the point of contact, motor connection, type of the power modulator]

(d) What is the difference between mass of train and effective mass of train?

(e) How can you explain the duty cycle of traction drive?

[Hints: with the help of speed-time curve, torque-time curve and power-time curve]

(f) Define the specific energy consumption of traction drive.

(g) What is the nature of torque-speed characteristics suitable for traction drives?

(h) What is the function of a damper winding in a synchronous motor?

PART-B ----------------------------[$6\times 6 = 36$]

Q2. State and explain the systems of electric traction.

Q3. Write short note on textile mill drive.

Q4. What are the advantages of microprocessor in drive technology.

Q5. An electric train weighing 500 tonnes climbs up gradient with G=8 and following speed-time curve:

(i) Uniform acceleration of 2.5 km/hr/sec for 60 sec
(ii) Constant speed for 5 min
(iii) Coasting for 3 min
(iv) Dynamic braking at 3kmphps=3km/hr/sec

Q6. A 100 tonne motor coach is driven by 4 motors, each developing a torque of 5000 N-m during acceleration. If up gradient is 50 in 1000, gear ratio a=0.25, gear transmission efficiency 98%, wheel radius 0.54 m, train resistance 25 N/tone, effective mass on account of rotational inertia is 10% higher. Calculate the time taken to attain a speed of 100kmph.

Q7. What are the functions of microprocessor in drive technology.

PART-C ----------------------------$[\mathbf{16}\times \mathbf{3} = \mathbf{48}]$

Q8. Write short notes on

(a) Drives for sugar mills.

(b) Drives for cement mills

Q9. State and explain the mechanics of train movement.

Q10. (a)A 6Mw, 3 phase,11kv, Y –connected, 6 pole,50 Hz,0.9 power factor leading synchronous motor has Xs=9 ohm, Rs=0, rated field current is 50 A. Machine is controlled by variable frequency control at constant (v/f) ratio up to the base speed and at constant V above base speed. Calculate torque, field current for the rated armature current,750 rpm and 0.8 leading power factor.

(b) State and explain the speed control of synchronous motor.